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Technical Session I

Technical Session II and III

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Energy, Moisture and Climate in Buildings

3 - 6 September 1990
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Novem

NOVEM (Netherlands Agency for Energy and the Environment)

Netherlands Ministry of Housing, Physical Planning and Environment

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Preface

The primary call for papers for the International Symposium on Energy, Moisture and Climate in Buildings enjoyed an overwhelming response. Over 180 contributions were announced and by September 1989 most of the abstracts were submitted to the scientific secretariat.

A Paper Selection Panel, with members from the Executive Committee, screened the abstracts on the sole criterion for acceptance: a significant affinity with the topic of any of the Seminars or Technical Sessions. According to the Panel twenty papers had to be refused on that basis. A few other contributions were allocated to a Seminar or Session different than originally indicated by the authors.

In the course of time several contributions were withdrawn by the authors, mostly for reasons of time-pressure. By the end of April 1990, well after the previously set deadline, 125 final papers had come in. The Paper Selection Panel reviewed all these carefully and selected a number of authors to be invited for oral presentation at the Symposium. It must be emphasized that the criteria for oral presentation should by no means be understood as a standard for the judgement of quality of the contributions. In the selection procedure other, sometimes practical or trivial, reasons have played a part as well.

I am convinced that all papers included in these Proceedings are of high quality and that each of them include interesting features connected with the topics of the Symposium. Therefore the result of the Symosium will be of considerable importance to the field of research and practice.

September 1990
Eltjo Tammes
Chairman of the International Symposium Committee

DESIGN CONSEQUENCES FOR THE CRAWL-SPACE FOUNDATION, REDUCING MOISTURE PROBLEMS

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ABSTRACT

Foundations with a crawl-space ventilated by outdoor air are common in Sweden. In summertime the relative humidity in these crawl-spaces becomes high and conditions for mould-growth and putrefaction of organic materials are good.

This paper presents measured and calculated temperatures and humidity in an outdoor ventilated crawl-space and in an unventilated crawl-space with all the insulation placed on the ground and the foundation walls. The results show that warm humid outdoor air coming into a chilly outdoor ventilated crawl-space can be sufficient to create problems with moisture. If all the insulation is placed on the ground and on the foundation walls in an unventilated crawl-space, the heat transfer through the floor and the temperature gradient through the insulation produces a crawl-space with a lower relative humidity and a lower heating cost.

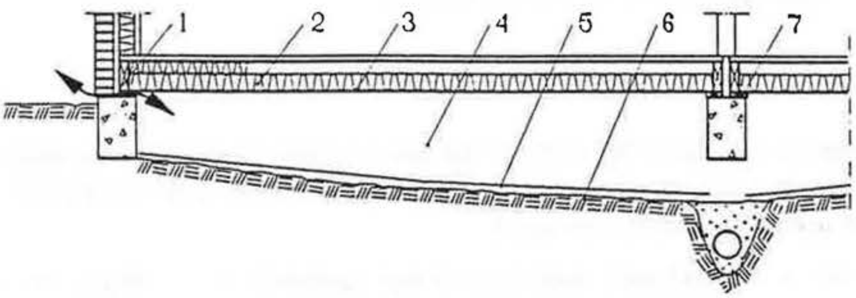
1. INTRODUCTION

When constructing the foundation of a house without a basement, one common method in Sweden is to use a low foundation wall on which a floor framing is placed. The floor does not come into contact with the ground, and an enclosed space is formed which can be used for crawling in if perhaps pipes and plumbing installation have to be serviced. Most of the constructions are ventilated with outside air.

Crawl-space foundations have a long tradition and their value has been proven in many old buildings. Mould growth and also rot have however occurred on organic materials and reinforcement in aerated concrete has been attacked by corrosion in some houses built during the last 30 years. The worst problems with rot and corrosion can nowadays be eliminated, but houses are still attacked by mould growth and putrefaction, which sometimes cause bad smells and create problems for the owners.

2. OUTDOOR VENTILATED CRAWL-SPACE

In a village in southern Sweden moisture conditions have been investigated in two crawl-spaces in a group of terraced houses, A and B. To study the effect of ventilation on moisture conditions the air change was increased in B by using fans in the gables. The measurements have been complemented with calculations describing how the moisture level changes if the construction is changed. This type of foundation is shown in Figure 1.



Length = 40.0 m
Width = 8.0 m
Highth = 0.5 m

Air changes per hour
A = 1
B = 2-3

1 screened vent 2 floor framing 3 sheathing 4 crawl-space
5 vapour barrier 6 ground surface 7 sill

FIGURE 1. Crawl-space ventilated with outdoor air.

The lowest humidity one can expect in an outdoor ventilated crawl-space is the humidity of the outdoor air. The relative humidity is then depending on the temperature. During the winter the temperature in the crawl-space is higher than the outdoor temperature and the relative humidity becomes low. During the summer the temperature in the crawl-space is lower than the outdoor temperature and the relative humidity becomes high. Measured temperature during a year is shown in Figure 2.

Apart from the outdoor humidity there is often an additional moisture from the ground and the foundation walls. In this village the ground contents of moraine clay. On 90 to 95 % of the ground surface there is a plastic sheeting which prevents evaporation. In A the ventilation is approximately 1 air changes per hour. The evaporation area is always wet and the additional moisture is approximately 2 g/m^3. In B the ventilation is approximately 2-3 air changes per hour. The evaporation surface sometimes becomes dry and the additional moisture varies from approximately 0 to 1.5 g/m^3. The effect on the moisture content (u %) underneath the hardboard sheathing is shown in Figure 3.

The moisture content becomes lower when the additional moisture is reduced by increased ventilation. In spite of this the relative humidity is still high during the summer, if the critical level for mould growth is set at 85 %. Even if the evaporation could be eliminated the relative humidity must be decreased in order to obtain a moisture safe construction. In wich case the temperature in the crawl-space must be higher.

Modifications in the construction that may affect the air temperature in the crawl-space have been calculated with a calculation program for PC-computers called Crawl, ref 1.

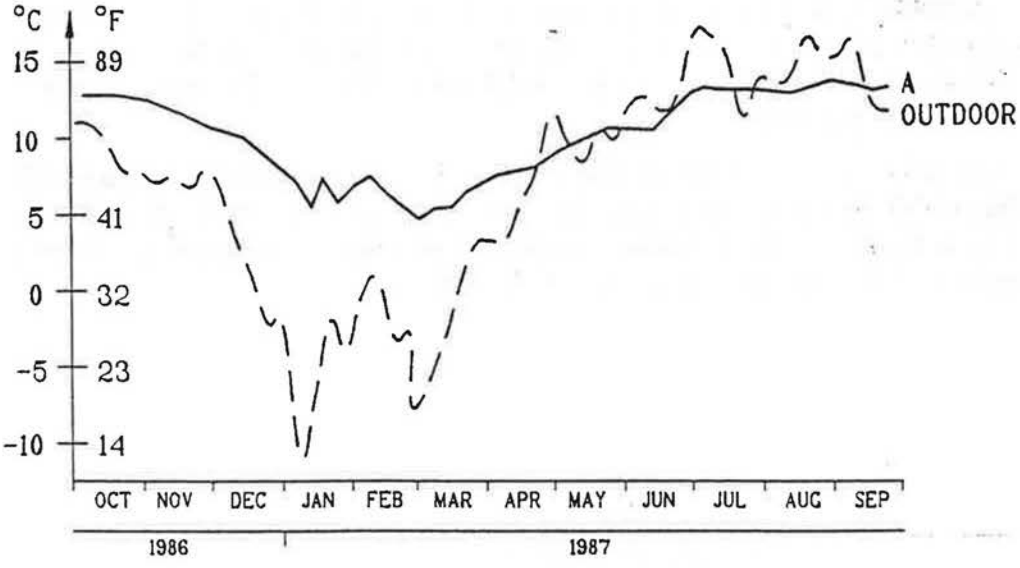


FIGURE 2. Air temperature in an outdoor ventilated crawl-space.

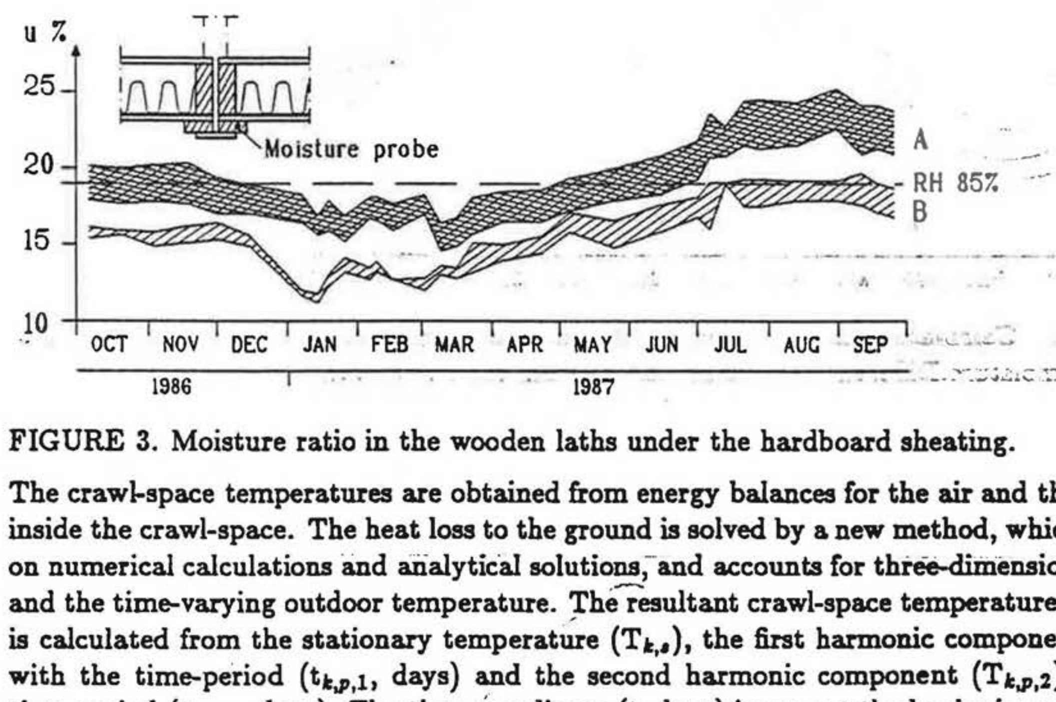


FIGURE 3. Moisture ratio in the wooden laths under the hardboard sheating.

The crawl-space temperatures are obtained from energy balances for the air and the surfaces inside the crawl-space. The heat loss to the ground is solved by a new method, which is based on numerical calculations and analytical solutions, and accounts for three-dimensional effects and the time-varying outdoor temperature. The resultant crawl-space temperature ($T_{k,t}$, °C) is calculated from the stationary temperature ($T_{k,s}$), the first harmonic component ($T_{k,p,1}$) with the time-period ($t_{k,p,1}$, days) and the second harmonic component ($T_{k,p,2}$) with the time-period ($t_{k,p,2}$, days). The time coordinate (t, days) is zero at the beginning of the year. The coefficients are calculated for Sweden, ref 2.

$$T_{k,t} = T_{k,s} + T_{k,p,1}\sin\left(\left(t-(113.5+t_{k,p,1})\right)\frac{2\pi}{365}\right) + T_{k,p,2}\sin\left(\left(t-(129.5+t_{k,p,2})\right)\frac{2\pi}{0.5\cdot 365}\right)$$

The relative humidity has been calculated from the outdoor monthly mean humidity for a normal year, and from the saturated vapour concentration for the temperature ($T_{k,t}$).

The thickness of the heat insulation influences the temperature in the crawl-space. The calculated relative humidity without additional moisture is shown in Figure 5. The coefficient of thermal conductance (U-value) is 0.30 W/m^2 °C. The high U-value is valid for houses built in the 1960:s and the low U-value is valid for new well insulated houses. The ventilation has been set at 2 air changes per hour.

Extra heat insulation on the ground surface is one way to raise the temperature in the crawl-space. The effect of 0.05 m mineral wool with the plastic sheating remaning underneath has been calculated, see Figure 6. The ventilation has been set at 2 air changes per hour. During the summer there can be some condensation on the sheathing.

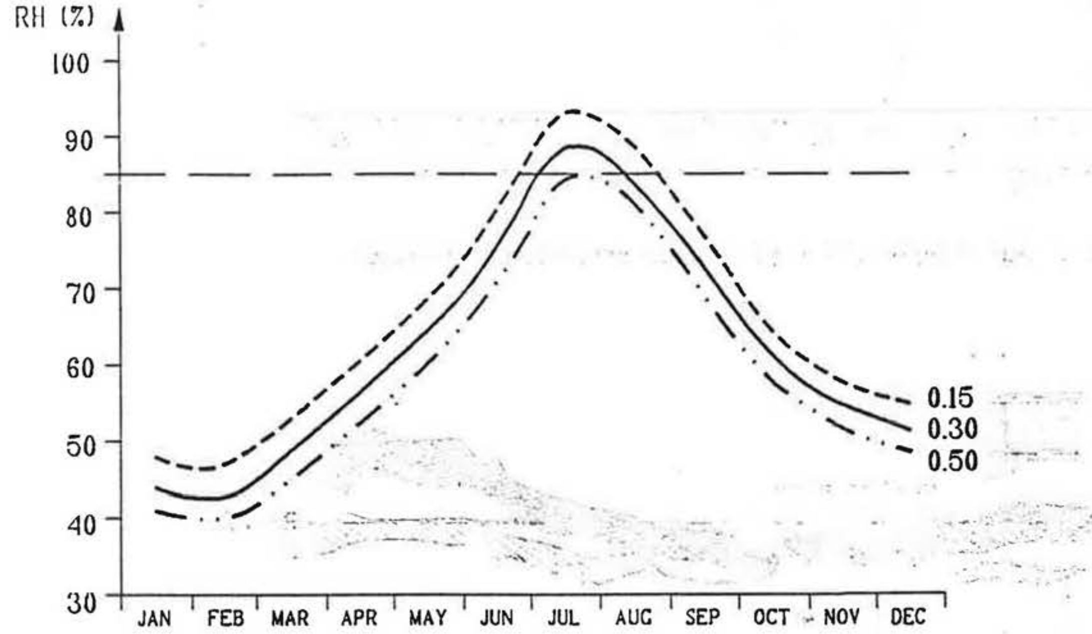


FIGURE 4. Calculated relative humidity in the crawl-space during a normal year. No additional moisture.Different heat insulation between the framework.

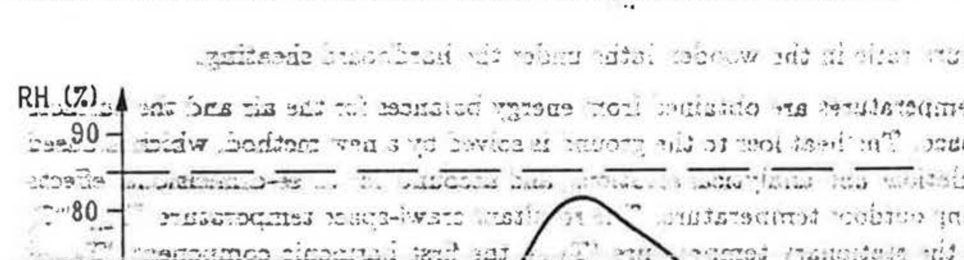
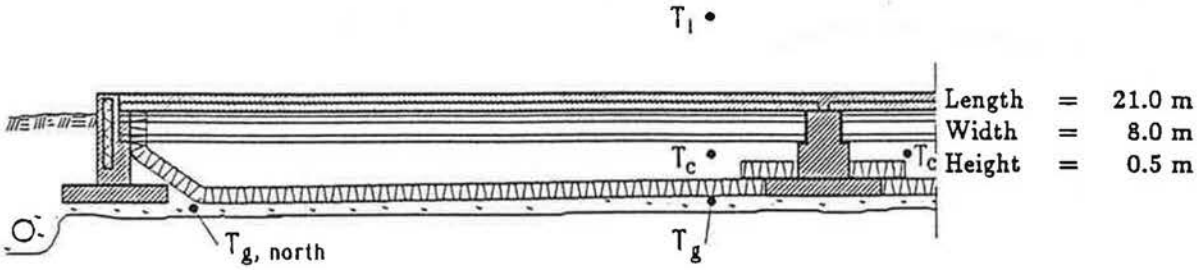


FIGURE 5. Calculated relative humidity in the crawl-space with extra insulation on the ground, during a normal year. No additional moisture.

3. UNVENTILATED CRAWL-SPACE

Another way of designing the foundation is to place all heat insulation under the framwork. The relative humidity in the space is then determined from the temperature gradient over the heat insulation and the space does not need to be ventilated. If the ground emits radon or the building is very large then the space can be ventilated by indoor air. In southern Sweden there is an unventilated crawl-space, as shown in Figure 6.



$T_{g,south}$ is equal to $T_{g,north}$ on the north side of the house.

FIGURE 6. Unventilated foundation with heat insulation under the subfloor.

Measurements of the temperatures and the relative humidity have been carried out. They are shown in Figure 7 and 8. The measuring was carried out during an extremely warm winter season with a monthly mean temperature of + 4.7 °C in February. Normal monthly mean temperature is -0.5 °C. Condensation will sometimes occur underneath the insulation and on the inside of the foundation wall. Any water can be drained into the ground.

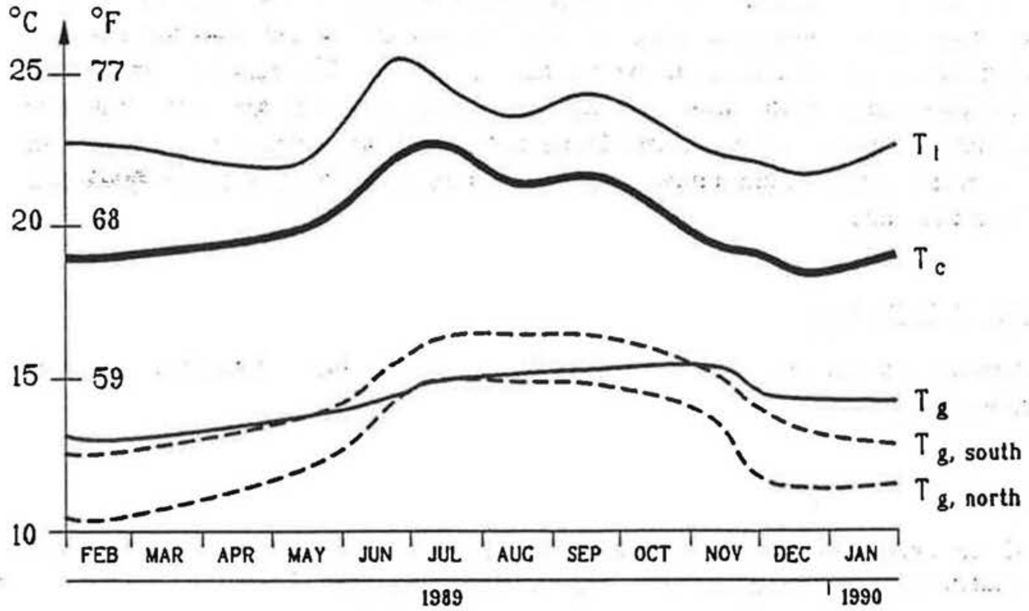


FIGURE 7. Measured temperatures.

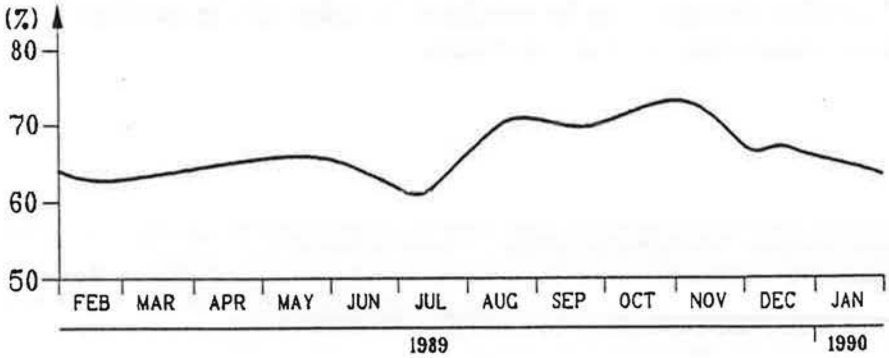


FIGURE 8. Measured relative humidity in the crawl-space.

4. CONCLUSIONS

A foundation with a crawl-space is a popular construction, but when ventilated with outdoor air there is a risk for mould growth. The possibility of improving the construction is small. This can only be done by raising the temperature in the crawl-space. One way is to reduce the heat insulation between the framework. Another way is to put extra heat insulation on the ground surface. The first solution will result in a poor heating economy and a cold floor surface. The other solution is unknown for many building contractors. Apart from these solutions the variations in the outdoor climate will always be an uncertain point.

A foundation can be made in another way. If all the heat insulation is placed on the ground surface and the space is not ventilated, then the relative humidity underneath the subfloor depends on the gradient of temperature above the heat insulation. The relative humidity in the space will be lower than for the other type of construction, provided the indoor temperature is higher than the ground temperature. Other advantages are lower heating costs and a warmer floor surface. If the ground emits radon or the building is very large the space can be ventilated by indoor air.

ACKNOWLEDGEMENTS

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DIAGNOSIS OF MOISTURE PROBLEMS IN LIGHTWEIGHT BUILDING ENCLOSURE SYSTEMS

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ABSTRACT

The current significant rise in claims related to building enclosure failures, which in many cases can be attributed to the action or presence of moisture, has caused concern in the building industry. Lightweight building enclosure systems are encompassed by this concern, as failures have occurred as a result of insufficient knowledge pertaining to their in-service performance.This has resulted in a heightened awareness of the importance of correctly diagnosing the causes of failure. The Centre for Building Studies has initiated a research and development project to address this issue. A comprehensive, logical approach to building diagnostics, in the form of a decision methodology which functions within a multi-level generic framework, is currently in the development stage. This framework will be targeted for use by practicing diagnosticians. Following such a unified procedure would not only lead to a quicker and more accurate diagnosis, but would also decrease inconsistencies when two or more experts are brought in to assess the cause of a given failure. The significance of the economic and legal implications of these aspects cannot be underestimated.

INTRODUCTION

Moisture problems in building enclosures can manifest themselves in a variety of ways, such as visible surface moisture, cracks in finish materials due to freezing and expansion of interstitial moisture, deterioration of enclosure components, and reduced thermal performance caused by moist insulation. An accurate diagnosis of such symptoms has become of prime concern to the building industry, as the consequences of an inaccurate diagnosis can include substantial repair costs as well as subsequent legal costs when litigation is involved.

In recent years, the use of lightweight insulated enclosure (cladding) systems has increased due to its ease of construction and speed of installation. A significant number of premature failures have occurred (1), some within the first year after completion. In the majority of cases these failures have manifested themselves through various forms of moisture penetration or damage.

As a means of addressing this concern, a research project has recently been undertaken at the Centre for Building Studies in Montreal. A comprehensive, logical approach to building diagnostics, in the form of a decision methodology which functions within a multi-level generic framework, is currently in the development stage. It is anticipated that the approach which is developed will be used to assess the most probable causes of failure, as well as the appropriateness of a diagnostic technique for a given situation.

One component of this approach will be a hierarchical impact assessment of building performance factors on a specific building performance criteria which is in question. Through process of elimination, this impact assessment will focus in on the performance criteria which have an impact on the failure in question, as well as the most probable causes of moisture-related and other failures in lightweight cladding systems and other types of building enclosure systems.

A compatible aid for assessing the suitability of a given diagnostic technique for determining the cause of a specific failure will also be developed. For the purpose of illustrating the method and practical use of the proposed approach, a recent lightweight cladding system failure will be used as a field investigation example.

DIAGNOSTIC FRAMEWORK

The basis of the diagnostic framework will be the assessment of the relative impact of performance criteria on each other. These performance criteria are classified into six primary categories: building integrity, thermal comfort, acoustical comfort, visual comfort, air quality, spatial comfort (2). The primary component of framework development will be establishing the procedure and criteria required to assess the relative impact between performance criteria. The objective of this impact assessment is to make the diagnostician aware of all the possible performance areas/criteria which could have an impact on the specific failure in question.

The performance criteria impact assessment is in the preliminary stages of development, and it is anticipated that the results of the impact assessment will be presented in a multi-level matrix format. A 5-point rating system, for use within the matrix, is proposed as a means of identifying the relative level of impact between the performance criteria. A rating of 5 would indicate a direct impact between two specific performance criteria, while a rating of 0 would indicate no impact.

The scope of the diagnostic framework is quite extensive, as it is being developed to cover all primary building performance areas. The framework, and associated diagnostic procedures, will be further developed on a more detailed level by focusing on building enclosure failures.

Failure/Cause Assessment

Once the preliminary diagnostic framework has been established, a failure/cause assessment of building enclosure failures will be conducted. Information gathered from failure databases, such as the Architecture and Engineering Performance Information Center (AEPIC) database (3), and case studies will be analyzed. Typical failures and primary causes will be categorized for use within the diagnostic procedure. It is proposed that this procedure be in matrix format in order to be compatible with the performance impact assessment. This matrix would present typical symptoms of failure, categorized according to building enclosure category, and their most probable causes (as statistically determined from database/case study information). In keeping with the matrix proposed for performance criteria impact assessment, it is anticipated that the same 5-point rating system would be used to identify the most probable causes of failure for a given set of symptoms.

Field Investigation Example

In order to illustrate the development and use of the proposed diagnostic approach, a recent field investigation pertaining to building enclosure failure will be presented. An 11 storey hotel, located in Atlantic Canada on a site which is prone to significant amounts of wind-driven rain, was constructed in the late 1980's. The building enclosure consisted of a system of lightweight cladding panels (a prefabricated assembly of impermeable insulation, supported by metal studs, covered in polymer-modified concrete with a coarse aggregate finish), with a single stage polysulphide sealant in the panel joints. Within the first year after completion, moderate to severe moisture penetration was observed in approximately 80% of the guest rooms after heavy wind-driven rainstorms.

The building owner hired a consulting engineering firm to diagnose this problem. They conducted pressure tests at several key locations (ie. upper storeys and corners), and essentially concluded that since the guest rooms were individually controlled in terms of ventilation and air conditioning, the pressure differential created between the interior and the exterior was so significant that the building was actually sucking in water from the exterior. The building was recaulked with a two-stage joint, which apparently improved the situation.

The consultant's report was not made available to the building designers. As these designers had another ongoing project which used the same building enclosure system, and fearing possible future litigation from the owner, the designers hired their own consultant to assess the situation. This consultant approached the problem from a different perspective, suggesting that the design and/or fabrication of the panels, including the joint and sealant system, could have caused the failure. Upon inspection, it was revealed that these were the apparent causes of building enclosure failure. The panel and joint design did not take into account, and therefore did not specify, the fact that the surface layer of the panels had to have sufficient depth to withstand the stresses created by the cohesive and adhesive strength of the sealant. The fabrication of the panels also proved to be contributing to the deficiency, caused by a lack of quality control during surface aggregate application.The manufacturer and/or designer did not realize that to achieve proper adherence, the sealant had to be applied to a smooth surface, which was not not observed at joint locations during site inspection. This second consultant concluded that this situation could not be completely remedied without a complete removal and redesign of the building enclosure system. However, the severity of the water penetration problem could be alleviated by recaulking the joints with a two stage system, and possibly shielding the joints with some form of water resistant cap.

The first consultant used a more sophisticated technique, namely on-site pressure testing, than the second consultant, who used surface observation, interviews, and plan analysis techniques only. Yet the second consultant realized the root of the problem without the need for a more sophisticated diagnostic technique. If these two consultants, both highly qualified, were brought in to court to testify with respect to this case, would the court rule in favour of the first consultant's results as they used a more sophisticated diagnostic technique (even though the second consultant's findings were actually the cause of the failure)? Considering the lofty sums that have been awarded in such court cases, consultants that deal with building diagnostics have a legitimate concern with respect to the liability and risk associated with this practice. Thus a procedure which could be followed during a diagnostic investigation would be of benefit to the consultants.

Procedure Involved with Failure/Cause Diagnosis

Three failure symptoms were involved in the above mentioned field investigation, which were panel surface cracking, loss of sealant adhesion, and significant moisture penetration across the building enclosure. A hypothetical failure/cause matrix representing these symptoms is presented in Figure 1. A diagnostician would scan each row, and would observe that a rating of 5 is given to several probable causes. As mentioned previously, a rating of 5 would be given to a cause of failure which, after failure database analysis and expert opinion, most likely contributes to the appearance of a given symptom. Thus the most probable causes would be noted and would become a point of departure for the investigation process. Should none of these causes prove to be the actual cause of the symptoms, the same rows would be scanned again to note which causes have the next highest rating, and the investigation process would continue. This method is evidently an iterative process which allows for the investigation of a failure starting with the most likely cause (as substantiated by the database and expert information).

As it is anticipated that these matrices will be dynamic entities whose accuracy depends on the amount of relevant information which is fed into them, they should be in the form which accommodate updates at regular intervals. Ideally, well documented information on failure causes would be analysed and results entered into the matrix as soon as it becomes available. One matrix would not be sufficient to cover all types of building enclosures, therefore several matrices representing the different types of enclosures must be developed and presented as a set. In further development stages other aspects of buildings such as indoor air quality could be analyzed in a similar manner, resulting in sets of matrices for these specific aspects.

LIGHTWEIGHT ENCLOSURE SYSTEMS	CAUSES	Structural movement	Temperature changes	Moisture changes	Wind forces	Transportation	Manufacturing	Design/specifications	Material properties	Installation method	Quality control	Climate during installation	Surface condition
SYMPTOMS													
Moisture penetration		0	5	5	5	0	0	5	4	5	5	4	5
Surface cracking		4	2	1	2	5	5	5	3	4	5	1	5
Sealant adhesion		4	5	4	3	0	4	5	5	5	5	5	5

FIGURE 1. Hypothetical failure/cause matrix

APPROPRIATE DIAGNOSTIC TECHNIQUE SELECTION

The matrices mentioned above provide information on which performance aspects should be investigated when attempting to find the cause of a building failure, and which are the most likely causes of a given type of failure. They will not, however, provide any information on which diagnostic technique is the most appropriate to use during a failure investigation. With the multitude of diagnostic techniques currently used or available, searching for the appropriate technique could be a costly endeavour in terms of both time and money.

Therefore it is proposed that the subsequent phase of development for this diagnostic approach would be to create a tool to facilitate the selection of an appropriate diagnostic technique or procedure. As with the previous phases, a two-dimensional matrix approach is suggested as a point of departure. One axis would be the performance criteria, or symptoms/causes of failure in the more detailed level of development, as mentioned above, while the second axis would be a list of diagnostic techniques (a hypothetical matrix is presented in Figure 2). A 5-point rating system would be used to indicate the relative level of appropriateness of a specific technique to a given performance criteria or cause of failure. A rating value of zero would indicate that the diagnostic technique under consideration is not appropriate under any circumstances. A rating value of 5 would indicate the most appropriate technique, or one that should be used regardless of which other techniques are chosen (for example, review of drawings and specifications should be done whether other techniques are used or not).

LIGHTWEIGHT ENCLOSURE SYSTEMS	DIAGNOSTIC TECHNIQUES	Plans analysis	Specifications analysis	Surface observations	Water penetration tests	Pressure tests	Coloured dye injection tests	Laboratory results analysis	Laboratory testing
SYMPTOMS									
Moisture penetration		5	4	5	5	4	4	3	2
Surface cracking		3	4	5	4	3	1	4	2
Sealant adhesion		2	5	5	3	2	1	5	3

FIGURE 2. Hypothetical diagnostic technique matrix

A method of determining an appropriate rating value for each diagnostic technique would need to be developed. It is anticipated that failure databases, case studies, and expert knowledge would provide the base from which the developed method would operate. The method, and the associated matrices, would have to be flexible enough to allow for the addition of new diagnostic techniques as they are introduced to the industry. Updating the matrices at regular intervals to allow for this would keep them dynamic, thus satisfying their intended purpose more closely.

ADVANTAGES OF USING THE PROPOSED APPROACH

The proposed approach is still in preliminary stages of development, therefore it must be emphasized that the matrices presented in this paper are for illustration purposes only, and information contained within them is not to be used for actual failure investigations. Once development, refinement and validation is completed, these sets of matrices could be made available to design professionals and others involved with building diagnostics on a subscription basis. The sets would be updated and expanded as new developments in the industry are analysed, and matrices for other performance areas/building aspects are added on as they become available.

The use of these matrices would provide a quicker and more accurate solution to the cause of failure. This would inherently save time and money for both the professional brought in to diagnose the failure and the building owner as well. This approach would be an advancement in conflict resolution between professionals involved in this area, in terms of failure assessment, for they would have access to identical information regarding the most logical point of departure for failure investigation. The proposed diagnostic approach and matrices could become a tool which could be used to reduce inconsistencies between expert witness testimonies in cases of litigation resulting from building failures. Two or more professionals, using the proposed approach, would have a greater probability of reaching the same conclusion regarding the cause of failure, thereby increasing the accuracy of the assessment.

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THE HYGROSCOPIC BUFFER CAPACITIES OF FIXTURES AND FURNITURE

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ABSTRACT

In addition to the hygroscopic capacity of walls, floors and ceilings to absorb moisture, it was thought that fixtures and furniture also acted as a hygroscopic buffer and likewise influenced the moisture balance of a room. Therefore a living-room situation was simulated and measurements conducted to determine the influence, if any, of the fixtures and furniture on the moisture content of the room. The measurements confirmed the supposition under study.
Experiments with water vapour production ascertained the amount of moisture absorbed hygroscopically by the fixtures and furniture. From the experiments the coefficient of water vapour absorption a (m/h), defined as:

$$a = \frac{\text{the quantity of water vapour absorbed by the surface material} \quad (g/m2.h)}{\text{the increase of water vapour concentration in the surrounding air} \ (g/m3)}$$

is determined. The values were respectively 2.2 and 2.5 m/h for the fixtures and 2.3 and 1.7 m/h for the furniture.

INTRODUCTION

It is presumed that in addition to the hygroscopic capacity of walls, floors and ceilings, fixtures and furniture also act as a hygroscopic buffer and likewise influence the moisture balance of a room.
Little is understood of the scope of the latter role and the rate at which the exchange process takes place in either a semi-furnished of fully-furnished room.
In view of the presumed connection between the relative humidity in the air, especially at peak periods, and the problems of mould and surface condensation, it is considered of importance to understand the hygroscopic buffer effects of fixtures and furniture. Therefore measurements were conducted in a simulated living room.
The study, commissioned by "Netherlands Agency for Energy and the Environment" (NOVEM), was undertaken within the terms of reference of the REGO-programme and constitutes part of the Dutch contribution to Annex XIV (Condensation and Energy) of the International Energy Agency (IEA).

TEST SET-UP.

At present, hardly any published work deals with the extent of the total hygroscopic absorption and/or emission of moisture of fixtures and furniture in a practical situation. It was therefore of initial interest to determine the actual influence on the moisture balance of a room by the hygroscopic buffer capacities of fixtures and furniture. In the second instance an attempt was to be made to indicate the extent to which moisture was absorbed, respectively emitted.

With these objectives in view, the experiment was set up as follows:
A living room is simulated (35 m^3) where all the parameters of importance are registered - temperature, relative humidity, water vapour production, ventilation rate. For accurate water production an "infusion system" is developed with an evaporation capacity of 0 to 1000 gr of water/hour.
The following situations in the "living room" are created:

A. Empty room, no fixtures or furniture; walls, floor and ceiling covered with foil ("zero" hygroscopicity). In theory the moisture buffer capacity of the room is solely determined by the moisture absorption capacity of the air.

B. Semi-furnished room, identical to A with the following additions:
   - carpeting: 100% wool on rubber underlay, 10.3 m^2;
   - curtains : cotton reinforced with synthetic fibre, 4.2 m^2.

c. Fully furnished room, identical to B with the following additions:
   - a settee : velours, upholstered surface 4.5 m^2
   - a armchair : 100% cotton, upholstered surface 2.1 m^2
   - a magazine rack: paper, effective surface 0,2 m^2

Three experiments were conducted to determine the effects, if any, of the hygroscopic capacities of the fixtures and furniture on the room's moisture balance:

1. The temperature of the air in the living room was increased from circa 18°C to 25°C.
   In sit. A the decrease of relative humidity could, in principle, be accredited to the increase of air temperature.
   If, in sit. B. and C., the added elements (fixtures and furniture) really contain hygroscopic storage capacities, the decrease of relative humidity will be lesser due to the (hygroscopic) emission of humidity by these elements than for the situation without any hygroscopic storage capacities.
2. The relative humidity was increased from 40% to 65% by the evaporation of water. How much moisture should be added?
3. A fixed amount of water - 280 gr - was evaporated. What is the resulting increase of the relative humidity?

By determining the loss of humidity through ventilation and moisture absorption by the air, the last two experiments give an indication of the order of magnitude with respect to the amounts of moisture involved in the hygroscopic process.

MEASUREMENT RESULTS

In this paper we only present the combined measurement results. For the complete results of the seperate measurements see Ref. (1).

For the experiment with warm-up of air in the living room, see Fig.1, the development of relative humidity (RH) in the furnished situations (sit. B and C) was decidedly tardier in comparison to the empty room (sit. A); a clear demonstration that moisture emission had occurred due to the addition of fixtures and furniture.

The difference between the RH development in the empty room ("hygroscopic zero situation") and a theoretically calculated RH development cannot reasonably be explained.
Similar differences have been noticed in comparable experiments conducted by Künzel (Ref. (2)). However they have been attributed to a temperature interdependent change in the water vapour absorption of the wall surfaces. In this connection, if the water vapour absorption coefficient "a" is calculated for the foil, values are produced (a = 0.3 and 0.5 m/h) which are on the same scale as those for a apparently comparable material such as linoleum (a = 0.43 m/h).

The development of the relative humidity when increased from 40 to 65%, see Fig. 2, demonstrated that moisture absorption took place as well as water vapour production.
Absorption is greater and therefore the increase of RH slower as more fixtures and/or furniture are added.

In the experiment with evaporation of 280 gr of water the pattern of development of RH, see Fig. 3, illustrates that the presence of fixtures and furniture causes it to increase only slightly, otherwise the case if the room is empty. This also implies a less steep "gradient of RH development" than in the case of a empty room.

From the measurement results we can conclude that the fixtures and furniture effect the moisture balance of the room. In conjunction with current methods (see Ref. (3)), the water vapour absorption coefficient a (m/h) is used, for a more detailed quantification of the effects. This coeffient is defined as:

$$a = \frac{\text{the quantity of water vapour absorbed by the surface material} \quad (g/m2.h)}{\text{the increase of water vapour concentration in the surrounding air } (g/m3)}$$

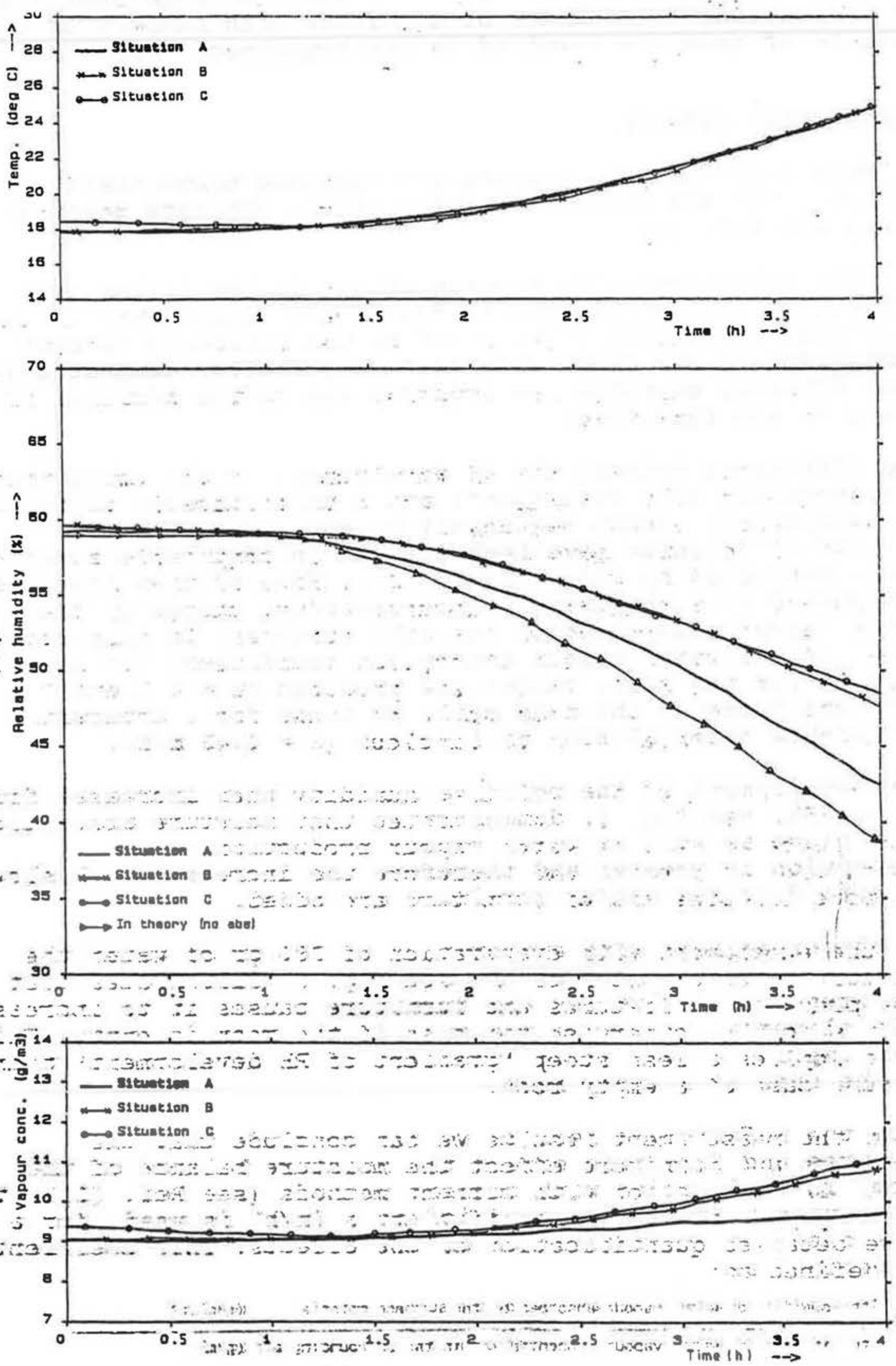

FIGURE 1. Temperature, relative humidity and water vapour concentration as a result of the warm-up of air in the empty (A), the semi-furnished (B) and the fully-furnished (C) room. (Conditions: ventilation rate 0,07 h^{-1}).

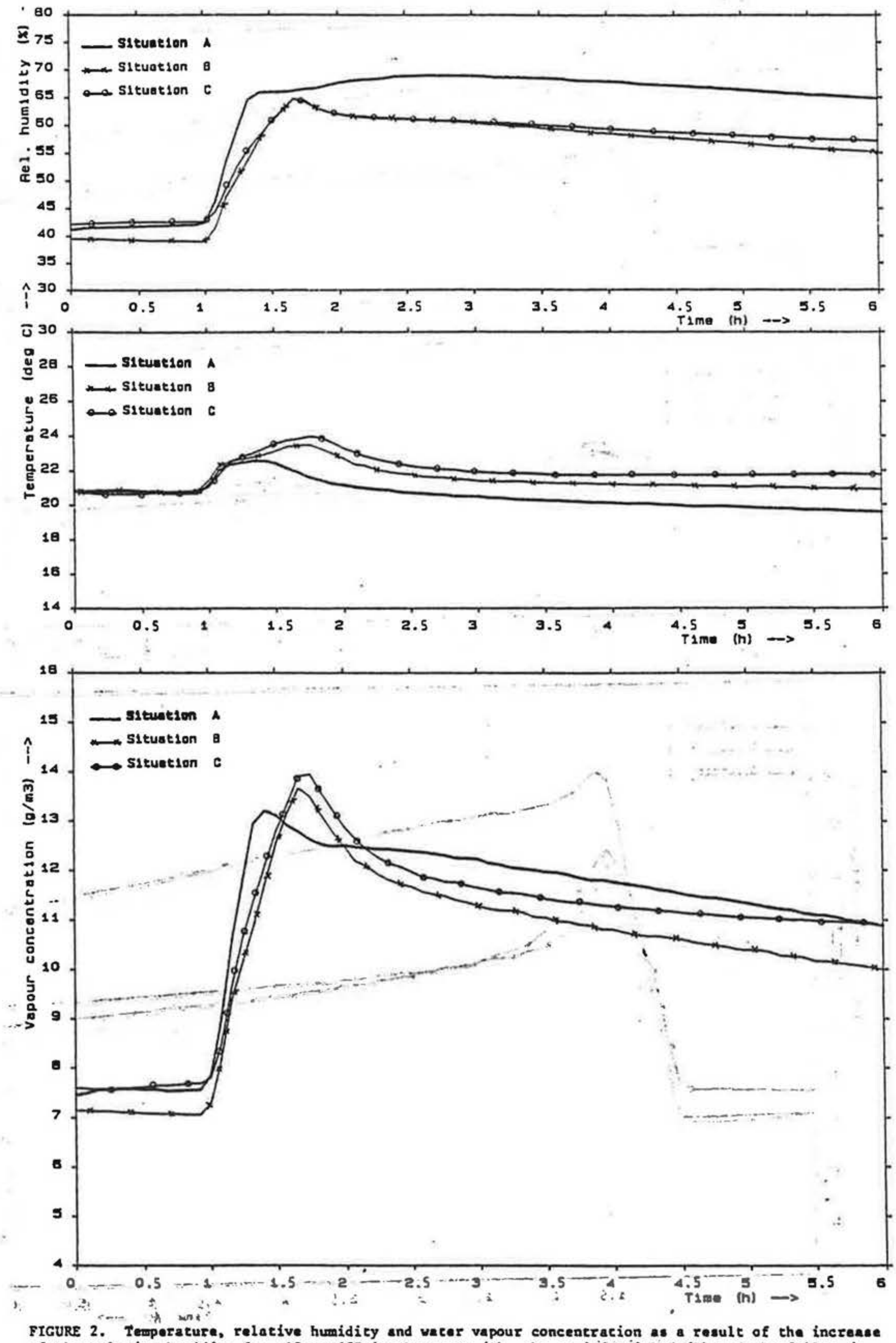

FIGURE 2. Temperature, relative humidity and water vapour concentration as a result of the increase of the relative humidity from 40 to 65% in the empty (A), the semi-furnished (B) and the fully-furnished (C) room. (Conditions: ventilation rate 0.07 h^{-1}; evaporation rate 600 g/h; no condensation)

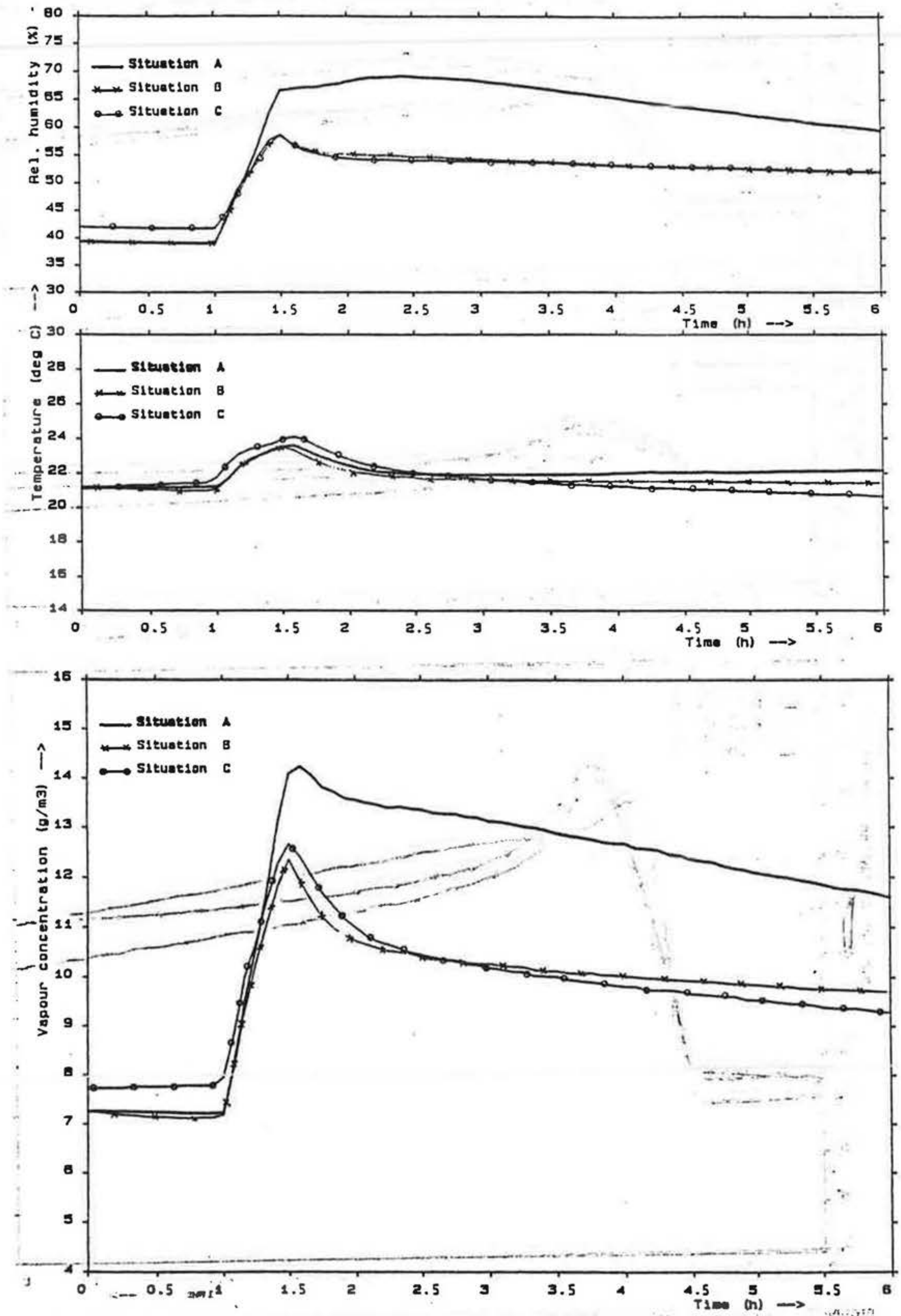

FIGURE 3. Temperature, relative humidity and water vapour concentration as a result of the evaporation of 280 g of water in the empty (A), the semi-furnished (B) and the fully-furnished (C) room. (Conditions: ventilation rate 0.07 h^{-1}; evaporation rate 600 g/h; no condensation)

Thus the development of water vapour concentration in a room plus simultaneous moisture production can be expressed as:

$$Ct - Co = \frac{Q}{a.A + n.V} \quad (1-\exp\ (- \frac{a.A + n.V}{V} \ .\ t)\ )$$

In which:

Ct	= water vapour concentration at time t	(g/m^3)
Co	= water vapour concentration at commencement of humidification (moisture production)	(g/m^3)
Q	= water vapour production	(g/h)
a	= water vapour absorption coefficient	(m/h)
A	= moisture absorption surface	(m^2)
n	= ventilation rate	(h^{-1})
V	= volume	(m^3)
t	= period of duration from commencement of humidification	(h)

The water vapour absorption coefficient of the fixtures and/ or furniture can be calculated on the basis of the pattern of development of the water vapour concentration measured during the period of moisture production. Table 1 gives the water vapour absorption coefficients as calculated from the measurements. The different values for fixtures and furniture have been determined from the extra absorption with respect to the earlier situation. The values derived here for fixtures and furniture are of the same order of magnitude as some building materials as plaster board (a = 2.29 m/h), cellular concrete (1.97) and lime and cement plaster (1.70); see Ref. (2).

Table 1. Calculated water vapour absorption coefficients (at 21°C).

Situation	Material	Water vapour absorption coeff. (m/h) on the increase of RH from 40 to 60%	on evaporation of 280 gr of water
A	only foil	0,3	0,5
B	fixtures	2,5	2,2
C	furniture	1,7	2,3

In the water vapour absorption coefficient moisture absorption on the surface is given as a function of change of the absolute moisture content of the air although, in fact, the hygroscopic absorption and emission is primarily caused by modifications in the relative humidity. Therefore the choise of the coefficient to describe hygroscopic buffer capacity is not an optimum one. In this study the quantity was chosen to conform with usage in existing publications and the numerical values used for other (building) materials.

However further study should be worthwhile for a more suitable quantity which could also be used to predict the effects of certain hygroscopic materials on the moisture balance of a room. The analogy between non-stationary heat transport to material surfaces and non-stationary interchange of moisture to surfaces could lead to such a quantity; analogous to the coefficient of heat penetration b ($J/m^2.K.s^{0,5}$) a coefficient of water vapour absorption b' ($kg/m^2.s^{0.5}$) could well be defined. The further study would have to decide whether such a quantity is usable and under which conditions.

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THE DYNAMIC BEHAVIOUR OF THE WATER VAPOUR PRESSURE IN BUILDINGS DURING THE YEAR

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1. ABSTRACT

This paper presents an analysis of the average water vapour pressure difference during the year under the influence of the outdoor climate, the moisture production, the ventilation rate and the hygroscopicity of the building materials and furniture.
A dynamic model is described and results of calculations are given.
It appeared that the average water vapour pressure difference between indoor and outdoor is related to the average outdoor temperature in such a way that the water vapour pressure difference increases with decreasing outdoor temperature.
The variations in outdoor water vapour pressure leads to moisture absorption by the indoor hygroscopic materials during summer followed by desorption during winter. Moisture production will lead to a more or less constant increase in water vapour pressure for a constant ventilation rate. When the ventilation rate varies linear with the average outdoor temperature the water vapour pressure difference due to moisture production increases linear with decreasing outdoor temperature.

2. INTRODUCTION

The water vapour pressure in a room is relevant to the study of problems due to surface condensation, the causes of mould growth on building materials and the presence of allergen generating organisms(such as mites). To study in which way the water vapour pressure variates in time a model has been developped.
With this model calculations have been made to study the yearly course of the water vapour in a room under the influence of the moisture production, the ventilation rate and the hygroscopic behaviour of the materials and furniture.
The results will be summarized in this article.

3. BASIS OF THE MODEL

The water vapour pressure in a room is determined by the moisture production in the room, the vapour diffusion through the roompartitions, the ventilation of the room, vapour transport by air flow from other rooms, condensation on windows and the accumulation of water vapour in building materials, furniture and furnishings.
Assuming ideal mixing of water vapour takes place, vapour diffusion through the room partitions is negligible and no air flow from other rooms exist the moisture balance can be described as:

$$\frac{V}{R.T_i}\frac{dp_i}{dt} = \frac{p_e}{R.T_i}\frac{dq_e}{dt} - \frac{p_i}{R.T_i}\frac{dq_i}{dt} + \Phi - \beta.A_h(p_i - p_s) - \beta.A_g(p_i - p'_g)$$

where:

V is the volume of the room, im m^3
p_i is the water vapour pressure in the room, in Pa
p_e is the water vapour pressure of the outdoor air, in Pa
p_s is the water vapour pressure at the surface of the hygroscopic materials, in Pa
p'_g is the maximum water vapour pressure at the inner surface of the glazing,in Pa
q_i is the air flow out of the room, in m^3/s
q_e is the air flow from outside into the room, in m^3/s
R is gasconstant of water vapour (= 462 J/(kgK)
T_i is the temperature in the room, in K
Φ is the moisture production, in kg/s
β is the surface coëfficiënt of mass transfer, in s/m

The term $\beta.A_g(p_i-p'_g)$ only counts when condensation occurs.

Because no air flow from others rooms is assumed $q_e = q_i$; when however air is transported from other rooms to the concerning room an extra term must be added which takes into account the transport from water vapour from these rooms. Besides that the air flow q_i must be adjusted.
The vapour transport in the hygroscopic material is considered to be 1-dimensional. The material is divided into a number of elements of finite thickness (mostly 1 mm). The vapour pressure of each element is assumed to be constant during the time-interval Δt and the vapour transport between the elements is then calculated and adjusted on the basis of this.

3. CALCULATIONS

In order to analyse the influence of the different parameters on the indoor air humidity calculations with the model have been made.
The parameters were choosen as follows:
- roomvolume : 100 m^3
  (because ideal mixing is assumed the dimensions of the room play no role)
- hygroscopic materiaal : 100 m^2
  diffusion resistance factor : 30
  hygroscopic moisture content : see figure 1a and 1b

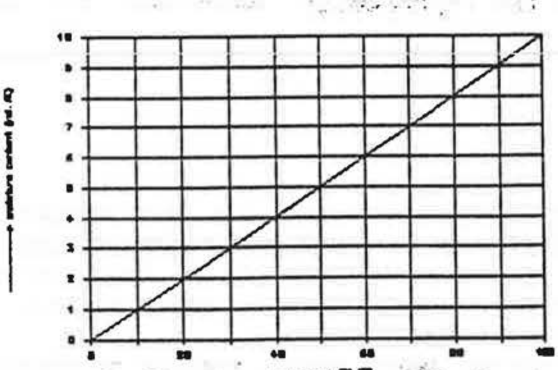

FIGURE 1a

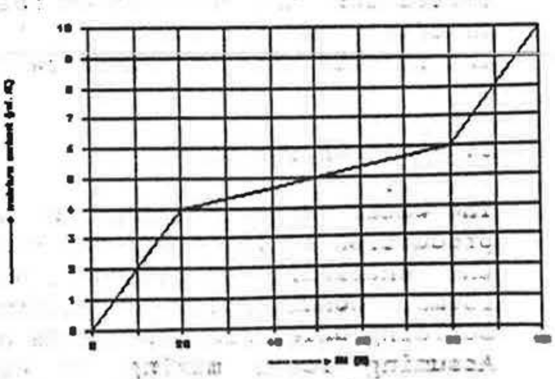

FIGURE 1b

- course of air-temperature in the room
  a daily course : figure 2a (for january)
  monthly increase during the year : see figure 2b

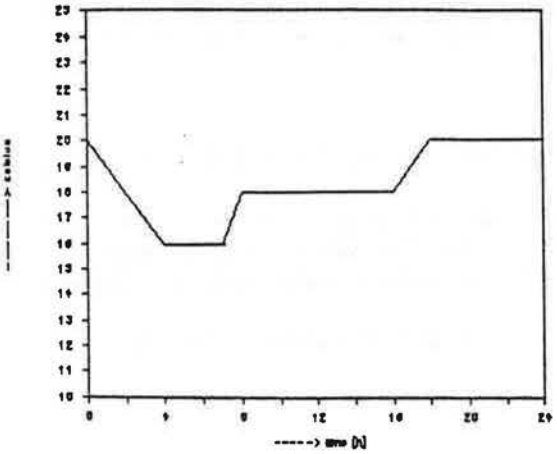

FIGURE 2a : Daily course of the air temperature in the room (january)

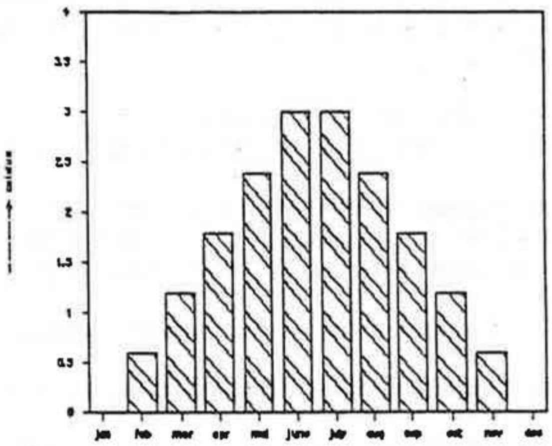

FIGURE 2b : Monthly variation of the roomtemperature

- the outdoor climate : the hourly values of air-temperature and RH at the K.N.M.I-station Airport Rotterdam for the year 1985, 1986 and 1987. Only the results of the calculations for 1987 are used for analyses.
- moisture production : see figure 3

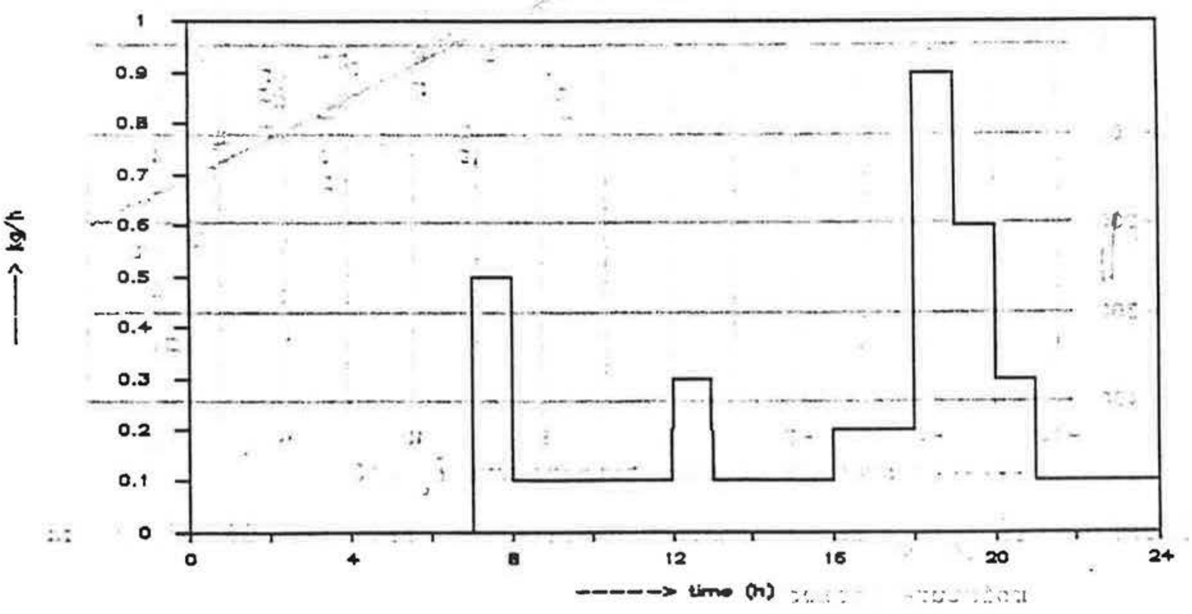

FIGURE 3 : Moisture-production during a day

- ventilation regime : a constant ventilation rate or a ventilation rate depending on the outside air-temperature.

4. RESULTS

The results of the calculations are presented as the weekly average vapour pressure difference between indoor and outdoor ($\Delta\bar{p}_{i,e}$). The individual values of $\Delta\bar{p}_{i,e}$ are related to the weekly average outdoor temperature ($\bar{\theta}_{i,e}$) by means of regression expressed as the function $\Delta\bar{p}_{i,e}(\bar{\theta}_e)$.

4.1 The outdoor climate

First of all calculations were made to determine in which way $\Delta\bar{p}_{i,e}$ variates under the influence of the outdoor climate. This means no moisture production in the room. Further more the ventilation rate was assumed to be constant; the hygroscopicity was taken according to figure 1a.

In figure 4 the individual values of $\Delta\bar{p}_{i,e}$ are given related to the average outdoor temperature $\bar{\theta}_e$ for a ventilation rate of 25 m^3/h.

The regression line is also drawn.

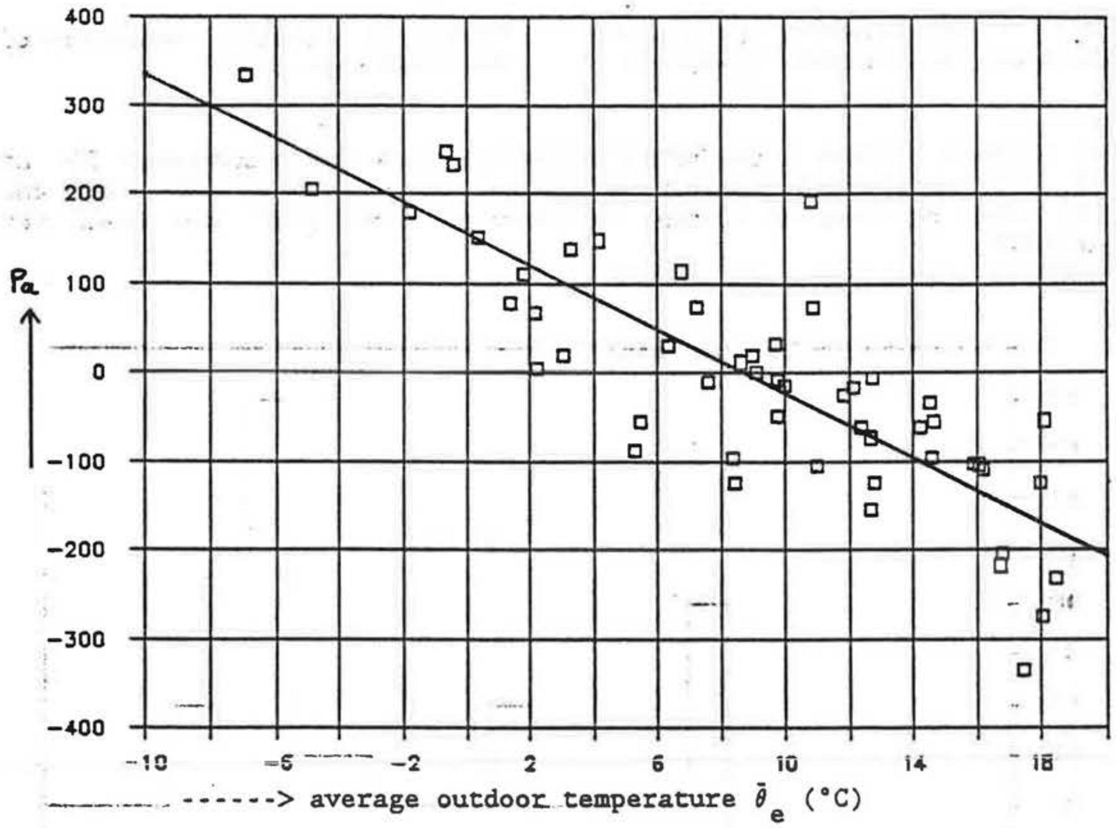

FIGURE 4 : $\Delta\bar{p}_{i,e}(\bar{\theta}_e)$ for a constant ventilation rate of 25 m^3/h; no moisture production.

In figure 5 the regression lines for 5 different ventilation rates are drawn. In table 1 the functions and the corresponding correlation coëfficiënt are given.

As can be seen in figure 5 the crossing of the lines with the x-axis occurs at about 9 °C (the yearly average outdoor temperature).

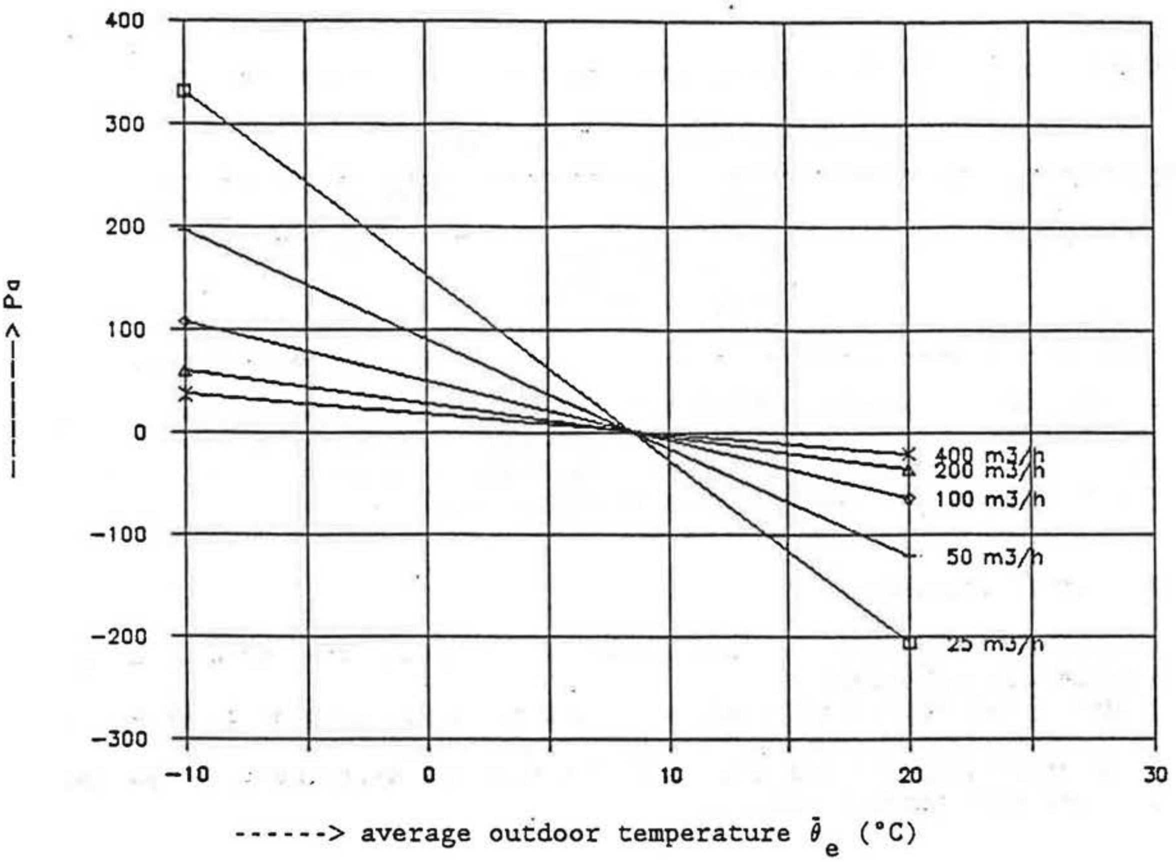

FIGURE 5 : Regression lines for 5 different ventilation rates; no moisture production

TABLE 1 : $\Delta\bar{p}_{i,e}(\bar{\theta}_e)$ for 5 different ventilation rates, no production

Ventilation rate	$\Delta\bar{p}_{i,e}(\bar{\theta}_e)$	Correlation coëfficiënt
25 m³/h	$152.5 - 17.85\ \theta_e$	0,83
50 m³/h	$90.6 - 10.53\ \theta_e$	0,75
100 m³/h	$49.4 - 5.72\ \theta_e$	0.69
200 m³/h	$28.3 - 3.19\ \theta_e$	0.66
400 m³/h	$17.7 - 1.91\ \theta_e$	0.66

It can be concluded that:
- the yearly average vapour pressure difference will be equal to zero when no moisture production takes place;
- during summer moisture is absorbed by the hygroscopic materials followed by desorption during winter;
- the amount of absorption/desorption decreases with increasing ventilation rate.

4.2 Hygroscopicity

In table 2 the regression lines for 3 different ventilation rates are drawn related to the hygroscopic curve as given in figure 1b.

TABLE 2 : $\Delta\bar{p}_{i,e}(\bar{\theta}_e)$ for 3 different ventilation rates, no production, hygroscopicity according to figure 1b

ventilation rate	$\Delta\bar{p}_{i,e}(\bar{\theta}_e)$	correlation coëfficiënt
25 m^3/h	$109.5 - 12.60\ \theta_e$	0.78
50 m^3/h	$60.4 - 6.95\ \theta_e$	0.71
100 m^3/h	$31.7 - 3.65\ \theta_e$	0.66

Comparing this regression lines with the regression lines in table 1 it appeared that a decrease in hygroscopicity means a decrease in accumulation of moisture. However the individual values of $\Delta\bar{p}_{i,e}$ will show more variation (compare the correlation coëfficiënts).

4.3 Moisture production

When moisture production in the room takes place the water vapour difference will increase.
In figure 6 the regression lines for 3 different ventilation rates and a moisture production according to figure 3 are drawn.
Also are drawn the 3 regression lines for the same ventilation rates but without moisture production.

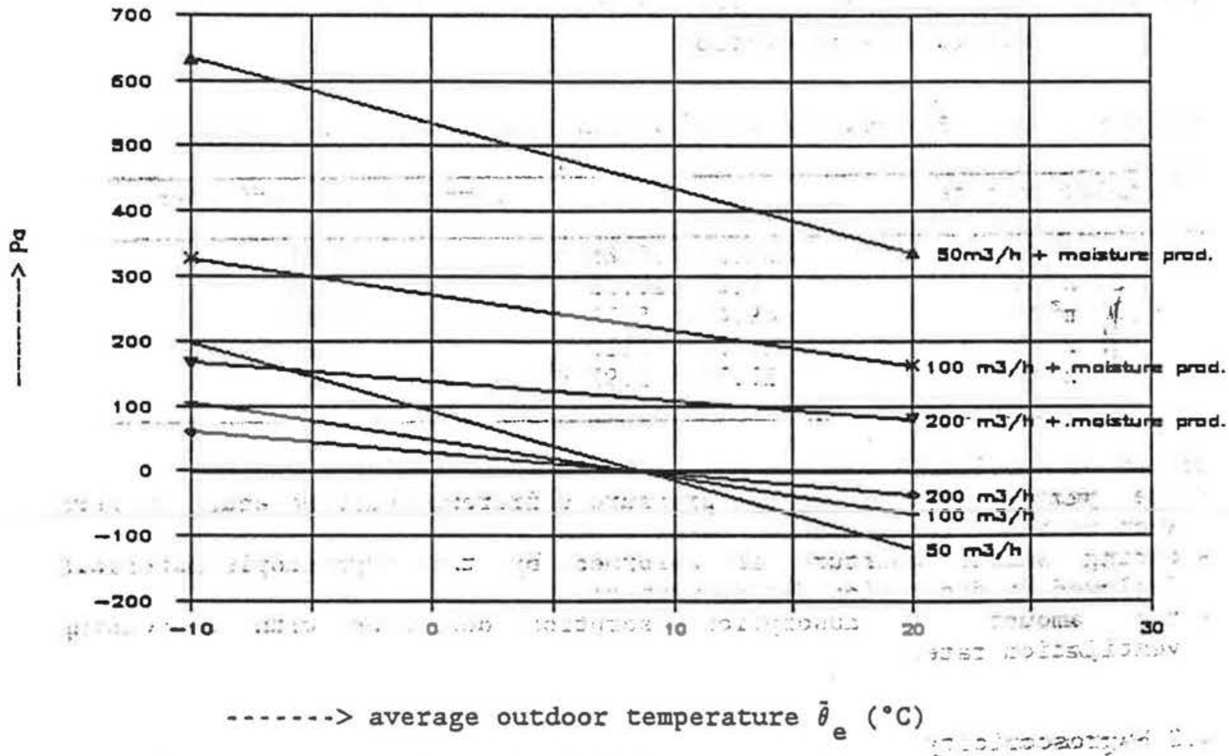

FIGURE 6 : Regression lines for 3 different ventilation rates and a moisture production according to figure 3.

As can be seen from the regression lines the distance between two lines that differ only in moisture production is more or less constant. The difference between two lines for the same ventilation rate equals the difference calculated from the relation:

$$\Delta p = \frac{\Phi . R . Ti}{q_i} \qquad (1)$$

where:

Δp is the water vapour difference, in Pa
Φ is the average moisture production, in kg/s
R is the gasconstant of water vapour, in J/(kgK)
Ti is the temperature in the room, in K
q_i is the ventilation air flow, in m^3/s

Using this relation the water vapour difference due to the moisture production of 4 kg/day amounts to about 451 Pa for a ventilation rate of 50 m^3/h, 226 Pa for 100 m^3/h and 113 Pa for 200 m^3/h.

4.4 The ventilation regime

Untill now it was assumed that the ventilation during the year remains constant. It is however known from research in practice that for instance the opening of windows and doors by inhabitants depends on the outdoor climate. In [1] a relationship is given between the use of windows and doors and the average outdoor temperature. This relationship is given in figure 7. It appeared that the percentage open windows and doors is next to linear with the average outdoor temperature.

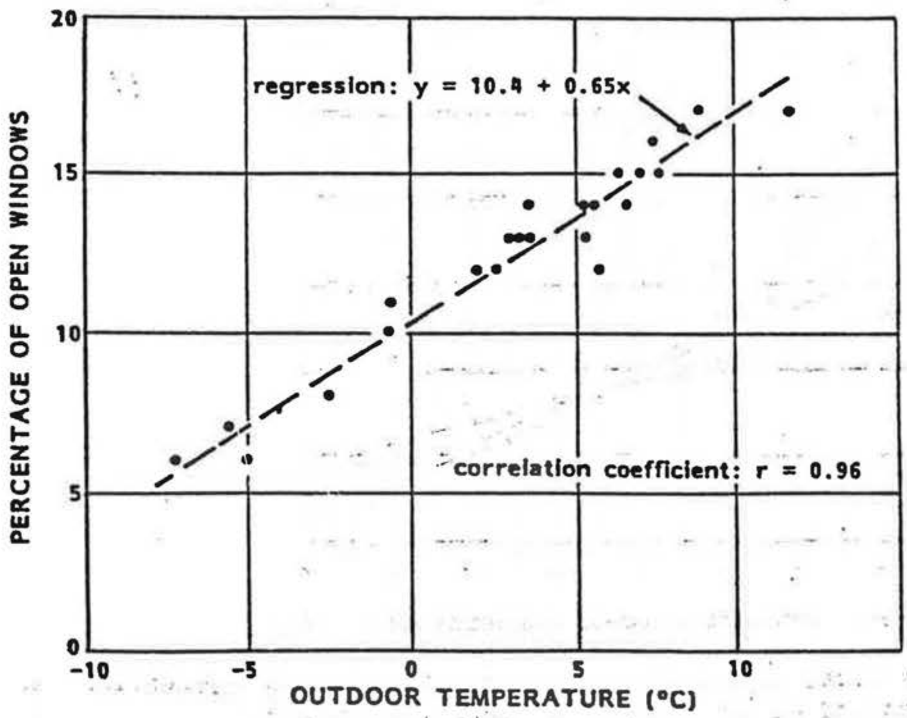

FIGURE 7 : Relationship between the average use of windows and doors and the average outdoor temperature (Schiedam project [1])

Calculations are made assuming that the ventilation rate varies linear to the percentage open windows and doors and that at -10 °C the ventilation rate is only 50 % of the yearly average ventilation rate.
In table 3 the regression lines are given for 3 different ventilation functions related to 3 different moisture production levels. The relation between moisture production and yearly average ventilation rate is kept constant. This means that at a yearly average ventilation rate of 25 m³/h the moisture production amounts to 2 kg/day (50 % of the production given in figure 3), at 50 m³/h the moisture production is 4 kg/day (as given in figure 3) and that at 100 m³/h the moisture production is 8 kg/day (twice as much as given in figure 3).

TABLE 3 : $\Delta\bar{p}_{i,e}(\bar{\theta}_e)$ for 3 different ventilation functions related to 3 different moisture production levels

Ventilation function	Moisture production	$\Delta\bar{p}_{i,e}(\bar{\theta}_e)$
$19.0 + 0.65\ \theta_e$	2 kg/day	$523.0 - 6.16\ \bar{\theta}_e$
$37.9 + 1.30\ \theta_e$	4 kg/day	$553.0 - 9.76\ \bar{\theta}_e$
$75.8 + 2.60\ \theta_e$	8 kg/day	$571.6 - 11.59\ \bar{\theta}_e$

To eliminate the influence of the outdoor climate and its accumulation by the hygroscopic materials the regression lines in table 3 are corrected. These corrected lines are drawn in figure 8.
Also is drawn the water vapour difference calculated with relation (1), that means when no absorption/desorption in taken into account.

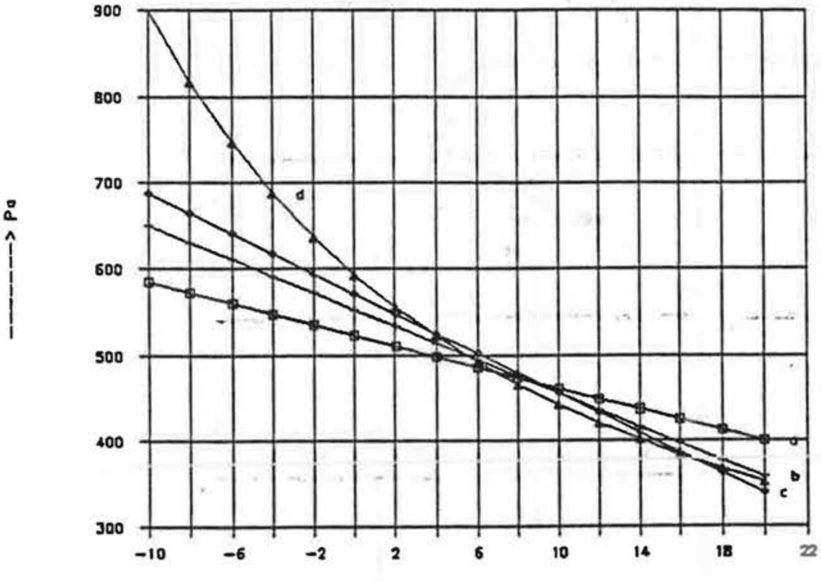

FIGURE 8 : The water vapour difference due to moisture production as a function of the average outdoor temperature.
line a : yearly average ventilation rate of 25 m³/h; production 2 kg/day
line b : yearly average ventilation rate of 50 m³/h; production 4 kg/day
line c : yearly average ventilation rate of 100 m³/h; production 8 kg/day
line d : constant relation between moisture production and ventilation rate (2 kg/day for 25 m³/h)
no absorption/desorption by hygroscopic materials

It appears that at relative high outdoor temperatures (relative high ventilation rates) no significant absorption/desorption occurs.
At relative low outdoor temperatures however some absorption must occur. Further more a constant relation between moisture production and ventilation rate shall not lead to a equal increase of water vapour pressure under the given circumstances.

5. CONCLUSIONS

Under the influence of the variation in water vapour pressure of the outdoor climate and due to absorption/desorption of moisture by the hygroscopic building materials and furniture moisture is absorbed during summer and desorbed during winter.
The amount of absorption/desorption depends among others on the ventilation rate and the hugroscopic capacity.
At a constant ventilation rate and moisture production during the year the increase of the water vapour pressure difference is constant and determined by the ventilation rate, the moisture production and the volume of the room.
When however the ventilation rate varies with the outdoor temperature especially during winter when relative low ventilation rates will occur part of the moisture production will be absorbed by the hygroscopic materials.

6. LITERATURE

[1] AIVC : Inhabitant behaviour with respect to ventilation - a summary report of IEA Annex VIII. Technical note aivc23. Air Infiltration and Ventilation Centre. Berkshire RG12 4AH, Great Britain (1988)

RELATIVE HUMIDITY INSIDE ACCOMODATION

Presentation of a Computation Method and its Experimental Validation

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INTRODUCTION

Inside temperature is not the only factor acting on the sensation of comfort or discomfort felt by the person living in the dwelling. Relative humidity, whose perception and consequences are less direct, also plays a major role.

Water vapour due to our presence and activity is produced every day in our accommodation, increased by a certain quantity of water carried by air renewal. Water retention in accommodation also occurs owing to the hygrostatic buffer formed by the furniture and the walls. The different phenomena combined listed above therefore tend to act on inside relative humidity.

The present article gives a computation method for the water vapour balance in a dwelling room, taking account of the absorption-resorption phenomenon together with an initial approach to test validation in a laboratory cell.

1 - THE COMPUTATION METHOD

1.1 - Vapour exchanges with the furniture

After having expressed the known part of the water vapour balance entering a dwelling room, an attempt has been made to describe the term reflecting vapour exchanges between ambient air and the furniture.

Taking it that these exchanges follow a "linear flow" type law, the flow per unit of mass density of water vapour "$\dot{M}_m$" crossing surface "S" of a material "m" is written :

$$\dot{M}_m = h' \cdot S \cdot (C_a - C_m) \qquad (kg.s^{-1})$$

with $C_{a,m}$: vapour concentration in ambient air and in the material (kg per m^3),

h' : exchange per unit of mass coefficient ($m.s^{-1}$).

Taking water vapour to be a perfect gas at room temperature, this vapour flow can be expressed as a function of the volume of water involved, namely :

$$\dot{M}_m = \lambda_m \cdot M_a - \delta_m \cdot M_m \qquad (kg.s^{-1}) \qquad (1)$$

with $M_{a,m}$: volume of water vapour in ambient air and material "m",

and $$\lambda_m = \frac{\beta \cdot S \cdot r_v \cdot Ta}{V \cdot P_{sat}} \quad ; \quad \delta_m = \frac{\beta \cdot S}{\rho_{ms} \cdot V_m \cdot \alpha}$$

$\beta = \dfrac{h' . P_{sat}}{r_v \cdot T_a}$: by definition, coefficent β is a surface exchange coefficient reduced to the average water content of the material. It is highly dependent on surface mass exchanges and includes vapour diffusion between the surface and the heart of the material, whence its dependence on the thickness of the material (very few experimental values are presently available) [kg water.m^{-2}.sec^{-1}] ;

α : coefficient α is an intrinsic characteristic of the material. This mean value represents the slope of an absorption isothermal unit (hysteresis of the phenomenon is not taken into account) [kg water/kg mat. sec./degree of relative humidity] ;

r_v : constant of perfect gases for water vapour (r_v = 461,51 J. K^{-1}.kg^{-1}) ;

T_a : ambient temperature [K] ;

V : volume of the room [m^3] ;

V_m : volume of the material [m^3] ;

ρ_{ms} : mass per unit of volume of the dry material [kg/m^3].

1.2 - Vapour exchanges with the walls

Diffusion phenomena in the walls have been neglected for the surface exchanges in the first layer of the materials so as not to over-complicate the model and maintain reasonable "computation times".

The walls are thus considered as furniture from the point of view of vapour transfers.

With a simplified model at hand allowing relative humidity inside premises to be computed while taking account of the absorption effect of the furniture and the walls, an attempt has been made to validate this model experimentally.

2 - METHODOLOGY OF EXPERIMENTAL VALIDATION

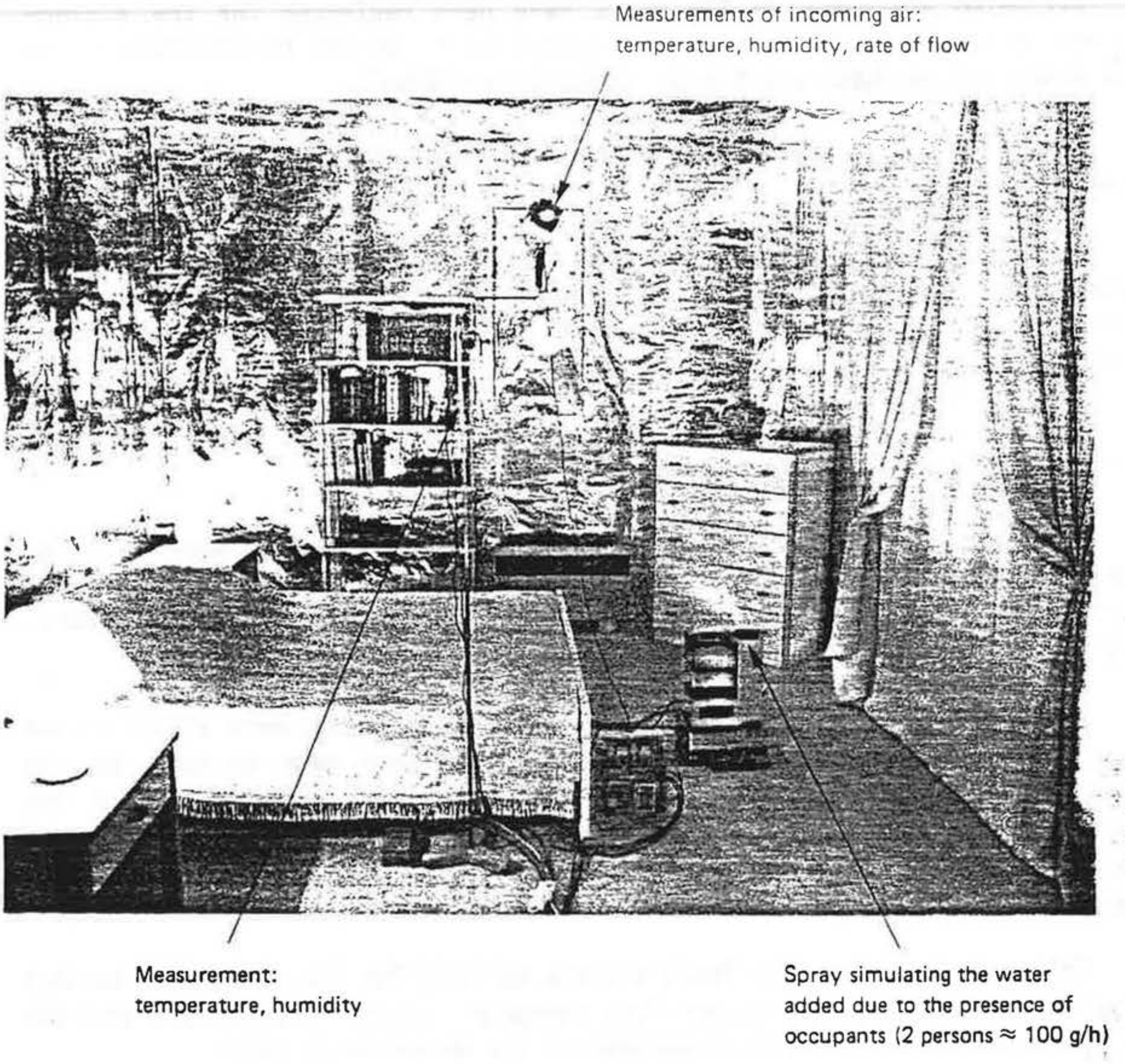
As indicated earlier, there are few materials whose mass transfer coefficients α and β are known. An attempt has thus been made to aggregate and identify these coefficient numerically, separately for the furniture, the wall facing out and inside partitions.

Availing, for each test described below, of a measurement cycle scaled over several 24 hours periods, an attempt has been made to minimise the difference between "measured and calculated" values so as to deduce the optimum values of computation parameters. These parameters are coefficients and δ entered in equation (1) as well as the initial water volume (M_m) contained in a piece of furniture or a wall.

This search, using the least squares method, for the minimum error has covered the value of the vapour flow exchanged between ambient air and the internal masses over the first periode of the measurement cycle.

3 - EXPERIMENTAL VALIDATION IN A REAL CASE OF A FURNISHED ROOM

The aim was to check that a first order model can point up vapour exchanges between the air and internal masses, both for the furniture and the walls. To this end, phenomena have, in a first stage, been dissociated by water-proofing the wall with tinfoil (see photograph below).



Experimental furnished cell

After satisfactory completion of initial comparisons of "Measurements and Computations" conducted on furniture alone, the second phase of the study has consisted of removing the tinfoil protection to secure the real conditions of a room.

Figure 1 presents the comparison of vapour flow measured (following an indirect method) and then calculated for the room in real conditions.

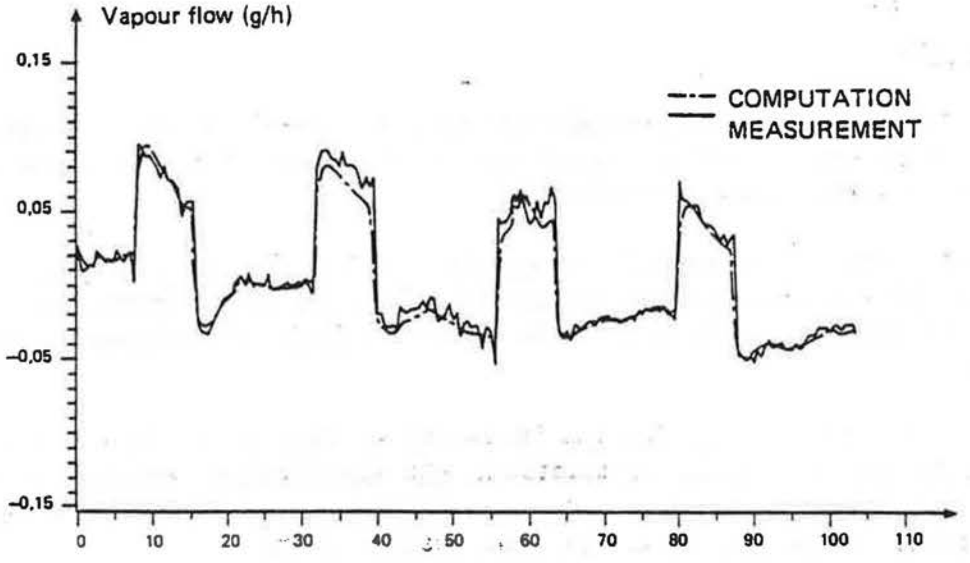


Figure 1 — Flow of water vapour exchanged with the furniture and the walls.

Finally, and this was our objective, figure 2 shows how important it is to take hygroscopic inertia phenomena into account for the computation of relative humidity inside premises.

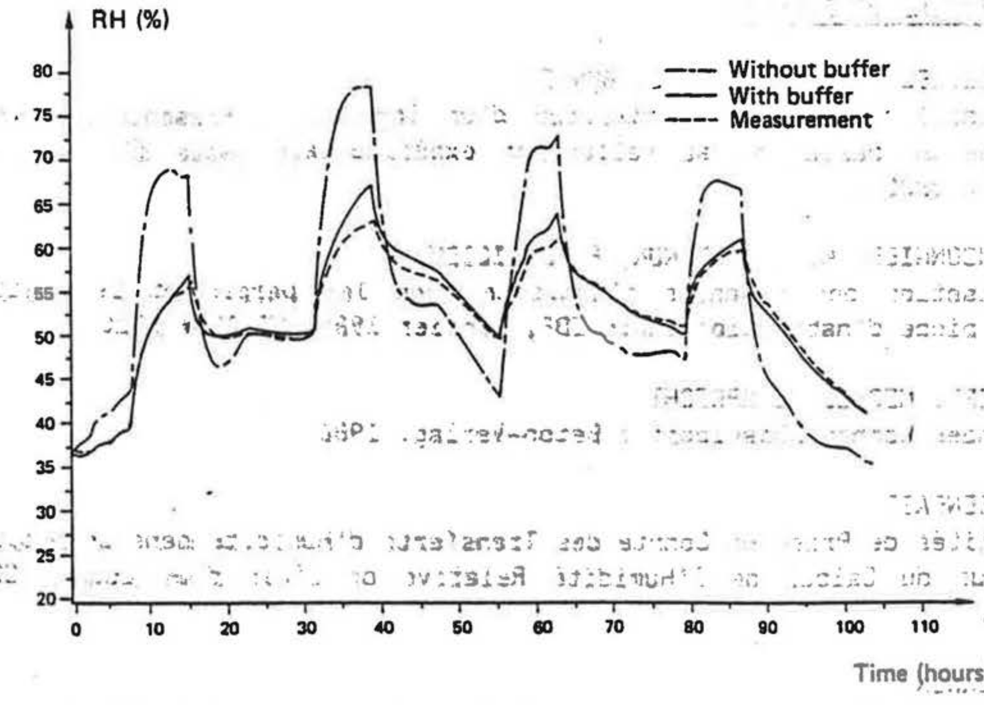


Figure 2

4 - CONCLUSION

Relative humidity inside premises can only be estimated with accuracy by taking the hygroscopic buffer formed by the furniture and the walls into account in a thermal model for buildings.

Although the experimental validation presented here gives some credibility to the computation method followed, it would nevertheless be desirable to extend it to a different configuration of external weather conditions.

It would be interesting, for the follow-up of this study, to confirm the adequate consistency between calculations and measurements observed over a period of more than three days and, in particular, to include a sequence involving major variations in the external water volume.

It is nevertheless encouraging to observe that a first order model gives quite a good portrayal of hygroscopic inertia in a dwelling room and that this formulation is easy to integrate into an aggregate thermal model for buildings.

Refer to reference [1] for more details.

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COMPUTATION OF ENERGY SAVINGS AND CONDENSATION RISKS BY INSTALLING LOW EMISSIVITY CEILINGS IN INDOOR ICERINKS

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ABSTRACT

To check the possible ways of preventing condensation in indoor icerinks and cutting down on cooling load, the simplified mathematical model and simulation program have been developed. It calculates temperatures, heat fluxes, the condensation risks and the cooling load required to maintain the ice temperature on the desired level.
The four model cases of an icerink fabric have been compared: an icerink with a ceiling made from ordinary building material, with an aluminum foil applied to the ceiling surface and with a suspended shield of aluminum plates mounted below the roof construction, which surface facing roof is unpainted or painted to increase its emissivity. The comparison is done also for a few different strategies for ventilating and heating and for different aluminum emissivity. The results have shown clearly the high profits from using bright aluminum surfaces in indoor icerinks.

INTRODUCTION

Indoor icerinks often have condensation problems in the roof construction. The consequences of this phenomenon such as greater maintenance or even deterioration of the ceiling or roof construction, water drips from the ceiling falling on the skaters and on the ice surface causing discomfort and more frequent need for the ice resurfacing - are unprofitable and should be avoided.
The condensation is caused by radiant heat transfer between the ice and the ceiling together with the high air humidity. Heat transfer by radiation also accounts for about 25 percent of the cooling capacity required to maintain the ice at the desired temperature, thus is very important for an energy consumption.
Condensation on the ceiling can be prevented by a few different ways: heating, lowering the dew point by dehumidification etc. But these attempts result in a considerable increase of the energy consumption, hence none of them should be recommended as a good solution of the problem in question. The ceiling temperature may be increased by applying a material with low emissivity at its surface or by mounting a suspended shield of this material below the roof construction. The last solution has been realized in Denmark in the Rodovre and Horsholm icerinks where suspended shields of corrugated bright aluminum plates were mounted below the roof construction. However, under certain weather conditions condensation still occurred whence there was a need for further investigation. To fulfill that need the computer simulation program was elaborated (1), (2) which was used to answer some questions concerning

the possibilities of improving the existing situation. Would painting the top of an aluminum shield to increase its absorptivity on the surface facing the roof be a reasonable solution or not? - for example.
Below, the model of an indoor icerink and its solution method are briefly described and some exemplary results are presented. The paper ends with conclusions.

PHYSICAL AND MATHEMATICAL MODEL

The physical phenomena taking place in an icerink are very complex. Several different processes of the heat and mass transfer, air movement etc. are occurring; there is lack of available data regarding values of physical constants and variables.
Taking into account several pros and contras it was decided that the model icerink should be a simple one which would, however, allow to investigate the system response to some changes in its maintenance.
Two cases are taken into account depending on the existence of the suspended shield of corrugated bright aluminum plates mounted below the roof construction. Figure 1 illustrates the simple geometry of the model icerink in both cases as well as numbering of surfaces and spaces involved.

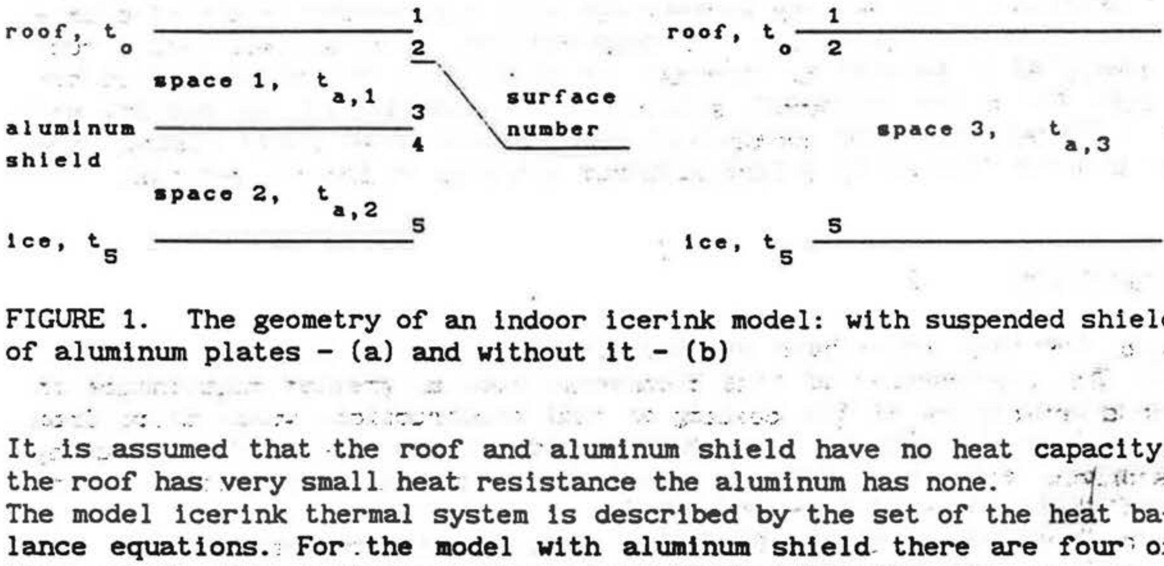

FIGURE 1. The geometry of an indoor icerink model: with suspended shield of aluminum plates - (a) and without it - (b)

It is assumed that the roof and aluminum shield have no heat capacity; the roof has very small heat resistance the aluminum has none.
The model icerink thermal system is described by the set of the heat balance equations. For the model with aluminum shield there are four of them; at the time τ they are given by following formulas
- for the surface 2 (the inside surface of the roof)

$$q_{k,2} + q_{r,2} + q_{c,2} + q_{e,2} = 0 \qquad (1)$$

- for surfaces 3 and 4 (aluminum shield)

$$q_{c,3} + q_{r,3} + q_{e,3} + q_{c,4} + q_{r,4} + q_{e,4} = 0 \qquad (2)$$

- for the air enclosed in space 1

$$C_1 (t_{a,1}^{\tau} - t_{a,1}^{\tau-d\tau})/d\tau = Ah_{c,2}(t_2 - t_{a,1}) + Ah_{c,3}(t_3 - t_{a,1}) + cG_1(t_o - t_{a,1}) + Q_1 \qquad (3)$$

- for the air enclosed in space 2, after arrangement

$$-Ah_{c,4} t_3 + \frac{C_2}{d\tau} + A(h_{c,4} h_{c,5}) + cG_2 t_{a,2} = cG_2 t_o + \frac{C_2}{d\tau} t_{a,2}^{\tau-d\tau} + Ah_{c,5} t_5 + Q_2 \qquad (4)$$

The radiant heat transfer between model surfaces is described by employing the gray body concept. It is assumed that all the surfaces are isothermal, uniformly irradiated and have constant radiative properties. As the distances between surfaces are small compared to their size, the radiant heat exchange with the surroundings can be neglected.
Magnitude of the convective heat transfer coefficient depends on the type of convection process. For the low air velocities, occurring in the icerink, the transfer takes place by free convection thus the convective coefficients are functions of the temperature differences. It is assumed that they are a function of the direction of the heat flow. Outside the building the forced convection is predominant, and convective heat transfer coefficient is the function of the air velocity.
Substituting all the terms in equations (1) and (2) by the appropriate formulas and rearranging them we have the final system of heat balance equations in matrix form as follows

$$\begin{bmatrix} \frac{C_1}{d\tau}+A(h_{c,2}+h_{c,3})+cG_1 & 0 & -Ah_{c,2} & -Ah_{c,3} \\ 0 & \frac{C_2}{d\tau}+A(h_{c,4}+h_{c,5})+cG_2 & 0 & -Ah_{c,4} \\ -h_{c,2} & 0 & h_{c,2}+U+W_{2,3} & -W_{2,3} \\ -h_{c,3} & -h_{c,4} & -W_{2,3} & h_{c,2}+h_{c,4}+W_{2,3}+W_{4,5} \end{bmatrix}$$

$$\begin{bmatrix} t_{a,1} \\ t_{a,2} \\ t_2 \\ t_3 \end{bmatrix} = \begin{bmatrix} cG_1 t_0 + \frac{C_1}{d\tau} t_{a,1}^{\tau-d\tau} + Q_1 \\ cG_2 t_0 + \frac{C_2}{d\tau} t_{a,2}^{\tau-d\tau} + Ah_{c,5} t_5 + Q_2 \\ q_{e,2} + Ut_0 + U \frac{A_b I}{h_1} \\ q_{e,3} + q_{e,4} + W_{4,5} t_5 \end{bmatrix} \qquad (5)$$

For an icerik without aluminum shield there are only two heat balance equations: for the inside surface of the roof and for the air. They can be expressed as follows

$$\begin{bmatrix} \frac{C_3}{d\tau} + A(h_{c,2} + h_{c,5}) + cG_3 & -Ah_{c,2} \\ -h_{c,2} & h_{c,2} + U + W_{2,5} \end{bmatrix} \begin{bmatrix} t_{a,3} \\ t_2 \end{bmatrix} =$$

$$= \begin{bmatrix} cG_3 t_0 + \frac{C_3}{d\tau} t_{a,3}^{\tau-d\tau} + Q_3 + Ah_{c,5} t_5 \\ q_{e,2} + Ut_0 + U \frac{A_b I}{h_1} + W_{2,5} t_5 \end{bmatrix} \qquad (6)$$

where variables C, G, Q, t with subscript 3 are evaluated for the whole volume of air in an icerink.
The equations (5) and (6) may be written in more compact form as

$$B * t = u \quad (7)$$

where t represents the unknown column vector of temperatures, u represents the column vector of values which are known or which are functions of the unknown vector t, and B is the matrix of coefficients which are dependent on the unknown vector of temperatures.

METHOD OF SOLUTION

The convective heat transfer coefficients are dependent on the unknown vector of temperatures and on the direction of the heat flow, the coefficients of radiation heat transfer depend on the unknown temperatures. Thus the systems of equations (5) and (6) are nonlinear. On the other hand, the number of equations is very small. In such cases direct techniques are useful and assuming negligible computational round-off error, they give exact solution in a finite number of operations.
Taking the above into account the method using both: iterative and direct techniques was chosen. At each time step the heat transfer coefficients are evaluated as function of temperatures computed in the previous time step. Then the system of equations is solved directly and all coefficients are corrected. This procedure is repeated until the vector of differences is smaller than a given value. At each iteration the set of

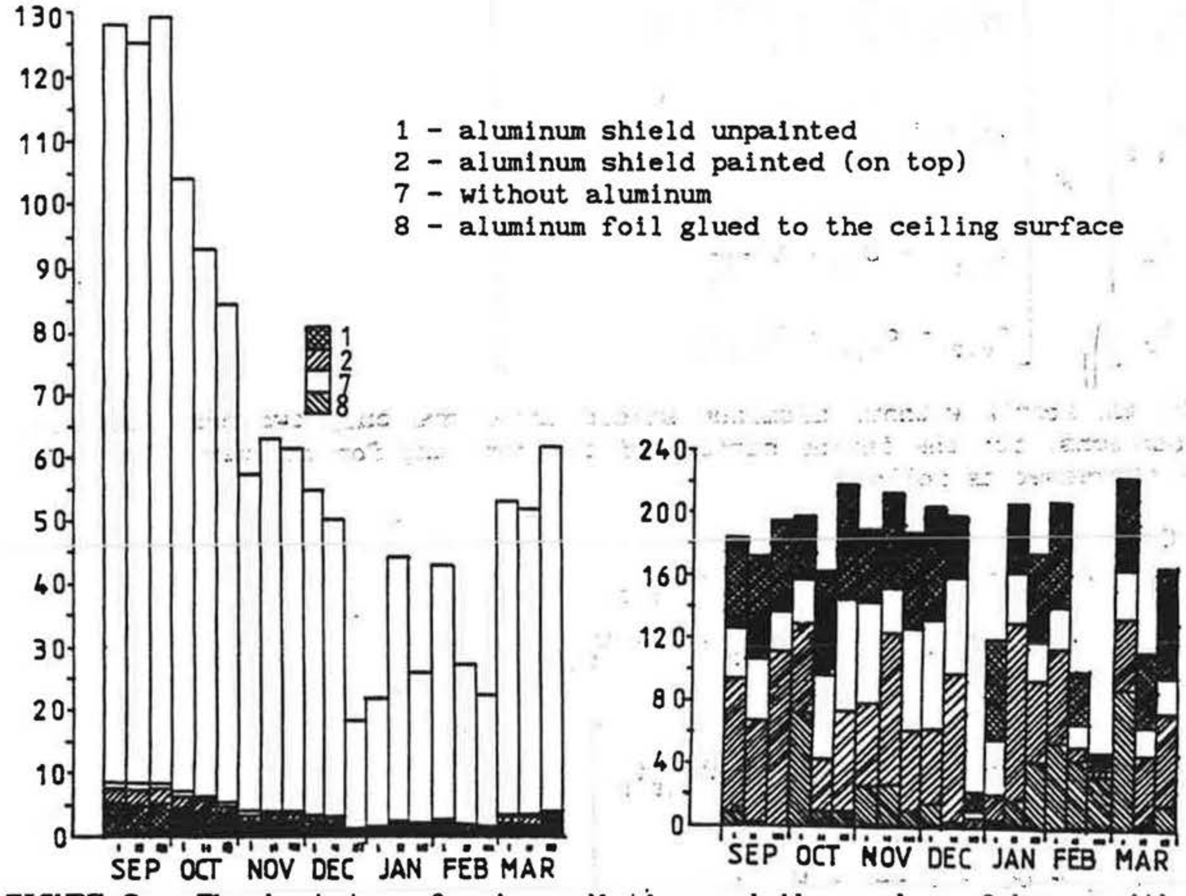

FIGURE 2. The heat transfer by radiation and the number of hours with condensation for four base model cases

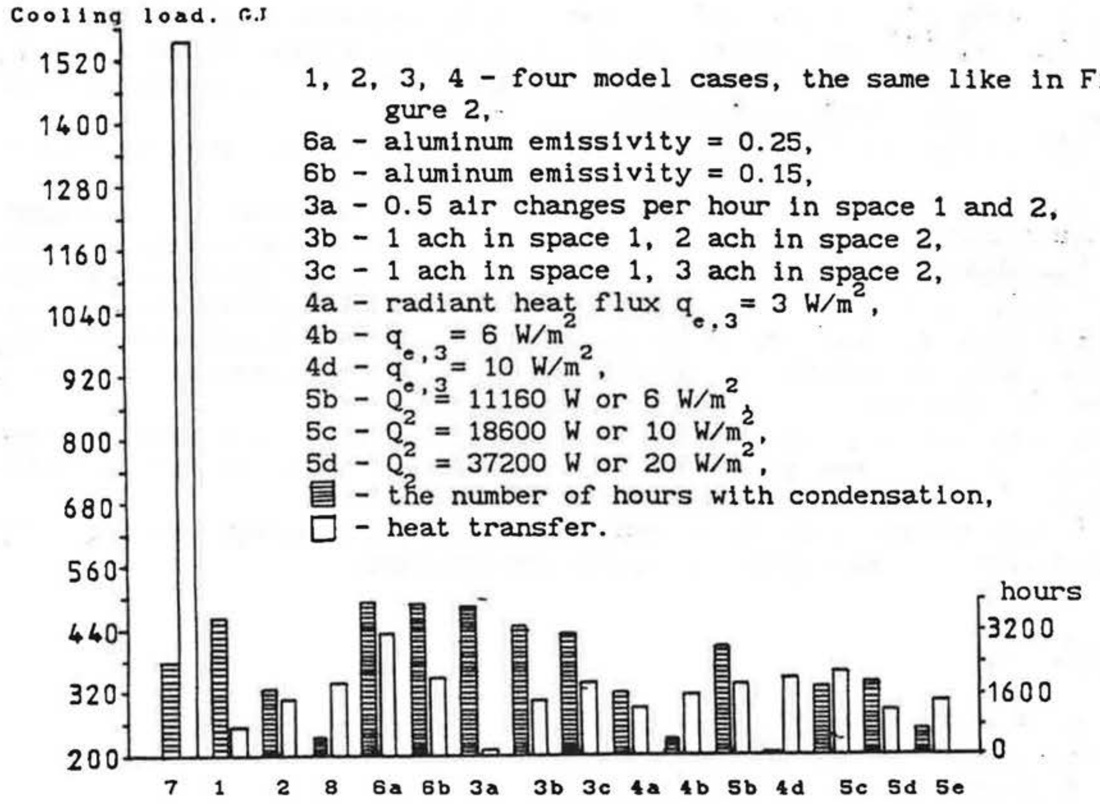

FIGURE 3. The number of hours with condensation and the cooling loads during the whole season

equations is solved directly employing the Gauss-Jordan reduction method with maximum pivot strategy (3).

EXEMPLARY RESULTS OF SIMULATION

Some exemplary results of computations are shown in figures 2 and 3. Figure 2a illustrates the radiation heat transfer between the ice and the surroundings, 2b - the sums of hours with condensation, for any of the ten-day periods during the ice-skating season for four base model cases of icerink maintenance.
Figure 3 indicates the general comparison between the number of hours with condensation as well as between the cooling loads required to maintain the temperature of the ice at the level -5°C due to the heat transfer - during the whole season - for the four basic model cases in question as well as for different values of the aluminum shield emissivity, the ventilation air quantity and the different modes of heat input to the icerink.

CONCLUSIONS

Because of the model simplicity one should bear in mind that the number of hours with condensation can be taken only as an index for the probability of this phenomenon. The emissivity of the bright aluminum changes drastically when the condensation starts; it will further the process.
The influence of the heat input to the icerink on its parameters in que-

stion depends considerably on the way heat is delivered inside (fig. 3); the most effective is irradiation of the aluminum shield. However, this, as well as the other modes of heat input, results in a significant increase of the energy consumption.

The ventilation rate effect depends on the fact which space is ventilated.

The aluminum shield mounting has a big influence on both: the condensation and energy consumption. Painting the top surface of shield reduces the condensation but increases the cooling load (fig. 2,3); which is, however, still only 20 percent of the cooling load needed where there is no aluminum shield. This model can be regarded as a good solution of the problem under consideration. Another way of solving the problem is gluing the bright aluminum foil to the ceiling surface.

The reported results show clearly the high benefits to be gained in terms of energy consumption and reducing condensation, from the use of higly polished aluminum surfaces in indoor icerinks.

One should notice that in a heated icerink the heating load will be reduced with the same quantity as the cooling load.

NOMENCLATURE

A - the surface area, m^2,
A_b - roof absorption coefficient,
c - the specific heat of air, J/(kg K),
C - heat storage capacity of the air, J/K,
$d\tau$ - time step, s
G - the infiltration and ventilation air quantity, kg/s,
h - heat transfer coefficient, $W/(m^2K)$,
I - solar radiation flux on outside surface of the roof, W/m^2,
q - heat flux, W/m^2,
q_e - surface heat flux, e.g. energy input to a unit surface area by radiation from occupants, lighting, heating, etc., W/m^2
Q - heat transferred to the air from people, lighting, etc, W,
t - temperature, ^{o}C,
τ, $\tau-d\tau$ - superscripts designating the level of time when the terms are evaluated. Those quantities without superscripts are evaluated at time level τ,
U - overall heat transfer coefficient between outdoor air and the roof internal surface, $W/(m^2K)$,
W - radiative heat transfer coefficient - a function of Stefan-Boltzman constant, emissivities and absolute temperatures of surfaces, $W/(m^2K)$
the remaining subscripts:
a, o - air and outside air, respectively,
1, 2, 3, 4, 5 - the numbers of the surfaces and spaces,
c, k, r - convection, conduction and radiation, respectively.

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RISING DAMPNESS IN MASONRY: CAUSES AND REMEDIES

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ABSTRACT

Water in masonry is still a common problem in the buildings, and it's one of the main cause which produces damage in the walls through the corrosion and disintegration of the building elements.

Dampness in the walls has a great part in the physical degradation, and it's the main liable for chemical and biological damages.

The paper attends to identify the methods and the remedies to contend the problem; in particular, those one which have a great interest are based on the air transport. Dump in the walls can be prevent, removed or subdued by appropriate design solutions, aimed to make possible the replacement of the air and the ventilation of the interior and exterior surfaces of the building components.

Water in masonry is still a common problem in the buildings, and it's one of the main cause which produces damage in the walls through the corrosion and disintegration of the building elements.

Dampness in the walls has a great part in the physical degradation, and it's the main liable for chemical and biological damages.

Physical damages are produced by different causes, like wind action, traffic vibrations, shrinkage and settling of building elements.

The degrading action bears only a not macroscopic consequences, like small lesions and the removal of small pieces. Generally, they don't give rise to a real pathology and they only pave the way for the following disgregative action of the water.

Rain and moisture find an easy passage in the small lesions and they get full of water the plaster and the lower layers; afterwards, they give rise to all the macroscopic results such as the blowing up of the plaster and separation of material.

The water entered in the wall is not able to evaporate in a short time; consequentely it puts pression from inside to outside exalted if the water freezes, increasing the volume.

Chemical damages are due to the pollution in the air and to the capillary rising of the water.

The degrading action due to the pollution is nowdays the most diffused kind, expecially in the big towns and in the industrial areas. It's due to the disintegrating action caused by smoke in the gaseous wastes by cars, industries, heating systems burning gas oil or coal.

The most noxious gas contained in the smokes is the sulphurous anhydride which combines with atmospheric water or with water contained in the wall. The result is the making of the sulphurous acid which attacks the carbonates present in masonry according to the reaction:

$$SO_2 + \frac{1}{2}O_2 \rightarrow SO_3 + H_2O \rightarrow H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2CO_3$$

The capillary rising of water in masonry produces an inorganic type of degradation and an organic one.

The first one is due to salts present in the subsoil and transported by water; the subsequent evaporation leaves them on the surfaces of the walls like inorganic limes known as efflorescences. If water contains organic substances the visual effects appear with different tonalities.

The biological damages are also due to the rising water by capillarity, that's the main responsible producer of the natural habitat for moulds and heads which grow very fast.

The study of the damp in the wall due to the capillarity climbing is so important as the research about the techniques to remove the damp.

Main causes for the presence of water in masonry

The main causes for water in the masonry can be summarized as following:

Cracking of the protective layer of plaster, due to the vibrations, shrinkage, settling.....

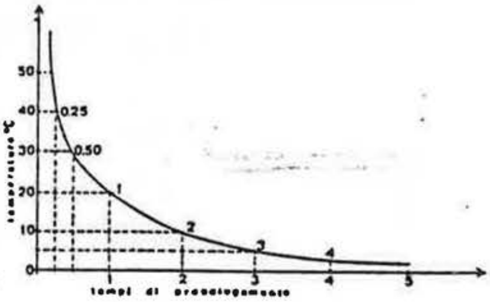
Rising dampness due to:
- water contained in the soil;
- the amount of water which increases with the deepness to saturate the soil at 20-30 cm over the water-bearing stratum;
- masonry dipped in the soil; if they are not isolated at all the present water can soack up and rises inside. Thicker is the wall, greater is the amount of water soaked up;
- if the water-bearing stratum is on pression, as sometime happens, the phenomenon is exalted.

Building dampness
- masonry can content water until 200 l/mc;
- the evaporation of water is made easier if the wall is ventilated or exposed at sun;
- on the same conditions, water evaporation is function of the thickness of the wall and of its inner constitution;
- the drying up is function of a draining coefficient **p** and

of the thickness of the wall;
- the relation between the time necessary for evaporation and **p** is

$$t = ps$$

- coefficientes **p** for the most common building materials are : concrete = 1,2 - 1,6; masonry = 0,28; calcareous stone = 1,2; mortar = 0,25;
- the drying up is also function of the temperature and of the relative humidity according to the following diagramm



Atmospheric humidity
- moisture in the air;
- inner condensation in the floors;
- condensation on surfaces;
- inner condensation in the wall (interstitial condensation).

Dampness due to the rain infiltration
- penetration through the rooofs;
- penetration through the cracks in the horizontal levels;
- penetration through the joints;
- penetration through the cracks in the plaster.

Penetrating humidity due to unforseen events
- accidental breakages of pipes, roofing,...

Main remedies

The main remedies to protect masonry from water are based on three different criteria which are:
- suitably ventilation of the masonry;
- barring up the access of water;
- draining of the surrounding soils.

The building procedures which can be done are divided in to three different kinds:

Ventilation principle
Knappen procedure (Fig. 1)
to built air spaces (Figg.2-4)

Draining principle
drining wells (Figg. 5,6)
electric-osmotic procedure

Barring up principle
Use of waterproofing mortar
Waterproofing with syntetic resin layers
Waterproofing on horizontal and vertical levels (Fig.10)
Silicone-latex injections (Figg.7-11)

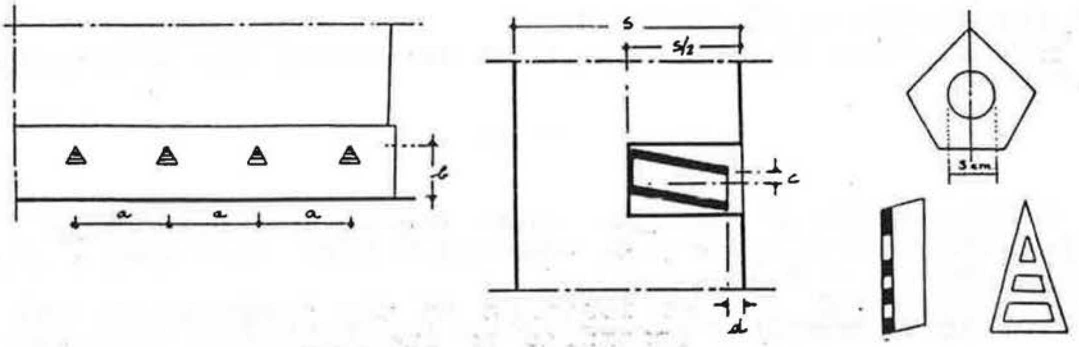


Fig. 1 The Knappen procedure: a = 30-40 cm; b > 15 cm; c = 4 mm; d = 30 mm.

Fig. 2

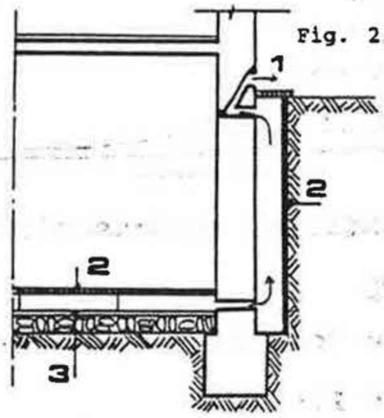


Fig. 3

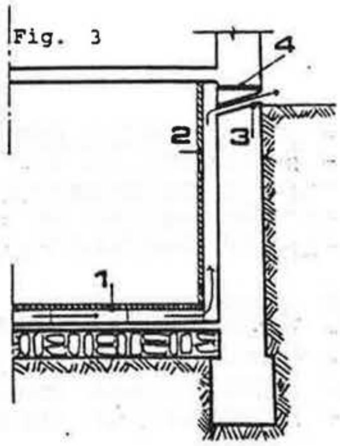


Fig. 2 Air space for ventilation: 1 ventilation holes in the wall; 2 pre-fabricated elements; 3 existing floor.

Fig. 3 Air space for the drainage from dampness of a basement: 1 raised floor; 2 arch brick partition wall; 3 ventilation holes in the wall; 4 waterproofing by cutting the wall.

Fig. 4

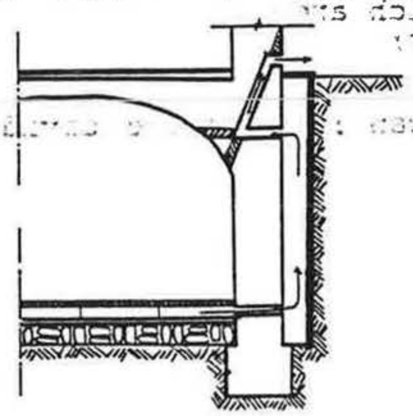


Fig. 5

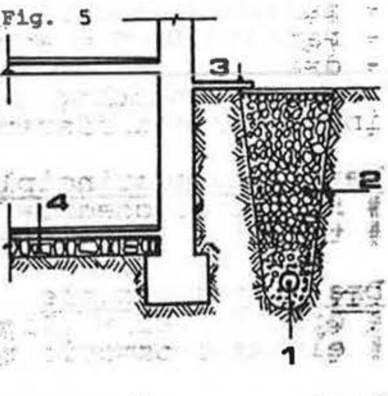
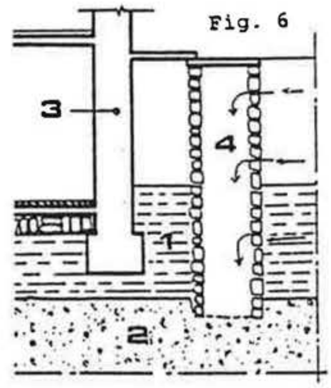


Fig. 4 Air space for ventilation of a basement wall.

Fig. 5 Draining of a basement wall: 1 draining pipe; 2 drainage; 3 pavement; 4 French drain.



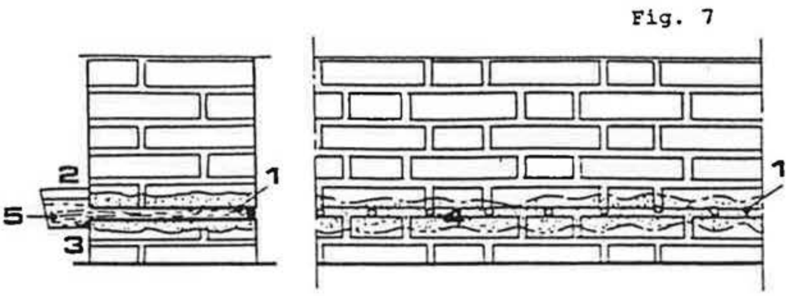
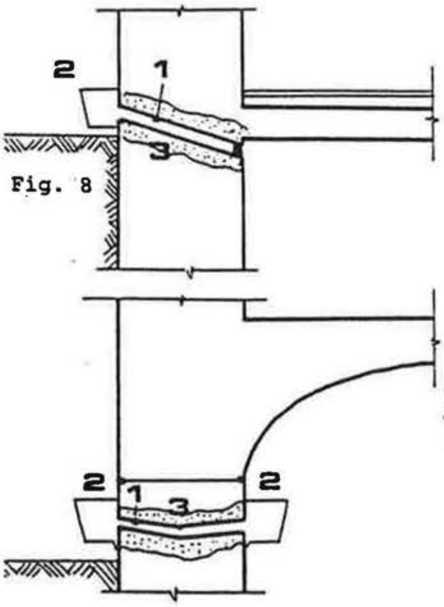
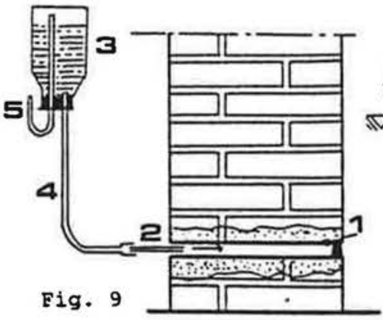
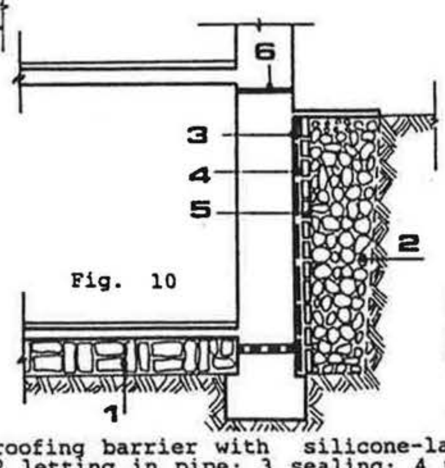


Fig. 6 Absorbing well to dry the soil close to a building: 1 damp soil; 2 absorbing soil; 3 basement wall; 4 absorbing well.
Fig. 7 Waterproofing barrier with silicone-latex: 1 holes in the wall; 2 letting in pipe; 3 sealing; 4 waterproofing layer with diffused silicone-latex; 5 silicone-latex solution.







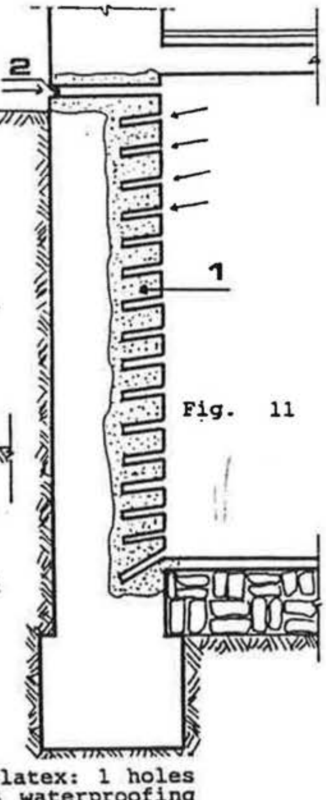


Fig. 7 Waterproofing barrier with silicone-latex: 1 holes in the wall; 2 letting in pipe; 3 sealing; 4 waterproofing layer with diffused silicone-latex; 5 silicone-latex solution.
Fig. 8 Waterproofing layer with silicone-latex: 1: holes in the wall; 2 pipes for the liquid; 3 diffused latex layer in the wall.
Fig. 9 Waterproofing barrier with silicone-latex: 1 letting in holes; 2 connecting joint; 3 container; 4 letting in pipe; 5 ventilation pipe.
Fig. 10 Waterproofing barrier of a basement wall: 1 French drain; 2 drainage; 3 cement-mortar plaster; 4 waterproofing layer; 5 brick wall; 6 horizontal waterproofing.
Fig. 11 Horizontal and vertical waterproofing with silicone-latex: 1 vertical layer; 2 horizontal layer.

MOISTURE PROBLEMS CAUSED BY HYGROSCOPIC BEHAVIOUR OF MATERIALS

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ABSTRACT

A case-study on moisture and salt problems in walls is discussed. The way of correctly diagnosing the problem is given. The measurements undertaken as well as a practice experiment, showing the hygroscopic effects, are described.
On samples taken from the wall and from the plasterlayer the hygroscopic behaviour was also studied in lab. As a result of the diagnosis it became clear that the problems mainly had been caused by soluable salts that at some locations were present in the plasterlayer. Because of the hygroscopic behaviour of these salts moist spots appeared and more or less disappeared under influence of changes in the relative humidity.
Practical consequences and solutions for the present problem are given.

INTRODUCTION

In a research program that TNO-IBBC is performing on behalf of the Ministry of WVC (culture, monuments) one of the most important items is damage caused by moisture in combination with soluable salts (1).
The unwanted effects of soluable salts can show in two different forms in practice:

1. plasterlayers are loosened from their subsoil; the adhesion has gone and sometimes also the plasterlayer has been crumbled. These effects are often to be seen in combination with rising damp. The damage can be described as 'saltburst'.
2. Moist spots or zones in plasterlayers, that sometimes can appear rather suddenly; the appearance does have some relation with outdoor climate changes and rising damp could also be involved.

The research program should have as much as possible connections with practice problems in (to be) restored buildings.

The second of the already mentioned moisture/salt problems was subject of a case-study carried out in 1989 (2). As a part of the case-study the hygroscopic behaviour of plasterwork was studied in lab.

DESCRIPTION OF THE PROBLEM

In two renovated dwellings in the old center of Breda the inhabitants were, after a restoration, confronted with severe moisture problems in the newly plastered walls.

The structure of the walls was brickwork, plastered with a gypsum plasterlayer (thickness 10 to 30 mm) and finished with wallpaper. The load bearing (=founded) indoor walls were covered with visually moist areas, partly just above floor level, giving the problem at least a little bit the appearance of rising damp. On a second view the situation appeared to be more complicated: also on a higher level a pattern of moist and dry zones could be seen (fig. 1).

The inhabitants stated that the moisture seemed to come and go, related to certain periods of outdoor climate changes. In accordance with the first (perhaps to obvious) idea, a producer of acryl-amide gels diagnosed the existence of rising damp. And immediately (!) measures had been undertaken to attack the rising damp by injection of an acryl-amide gel.
Nevertheless after one year the problem still existed and the situation even seemed to have become worse. In this stage TNO was asked to judge the problem.

HYPOTHESIS AND TESTING

The research carried out was based on two different hypotheses:
1. The damage is caused by rising damp, introducing the point whether the measures taken had been effective or not.
2. The moist spots are caused by hygroscopic behaviour of the wall finishing (i.e. plasterlayer and wallpaper).

To investigate the first hypothesis, grit samples were taken from the plasterlayer and the underlying brick. In this way the moisture distribution over the height of the wall was determined. The same samples were used to determine the uptake of hygroscopic moisture at RH's of 75 and 92% respectively. The results are shown in fig. 2a and 2b. From the course of the moisture content, in relation to the hygroscopic uptake the existence of rising damp up to a height of 1.00 m in the center of the wall can be concluded. For the plasterlayer this height is only 0.50 m.

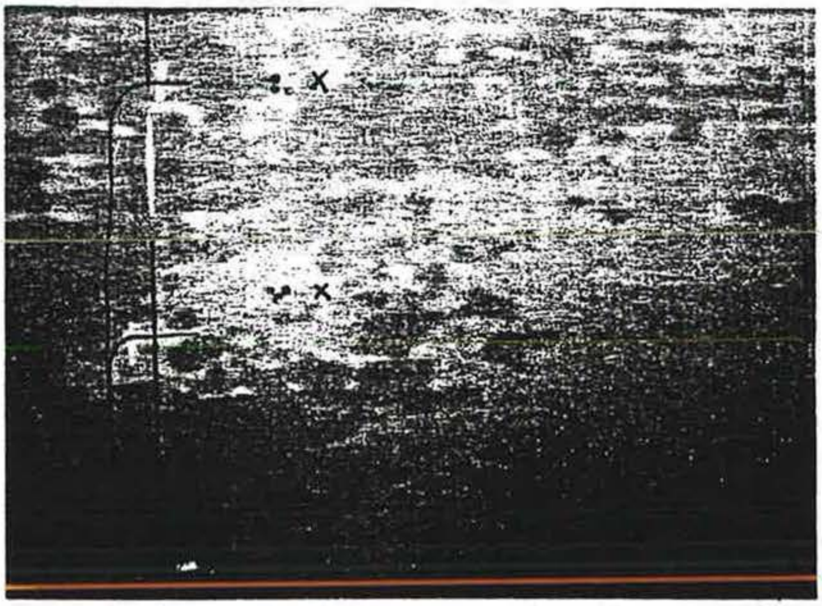

FIGURE 1. Moist areas on a plastered indoor brick wall; the spots where samples were taken are indicated by "x"

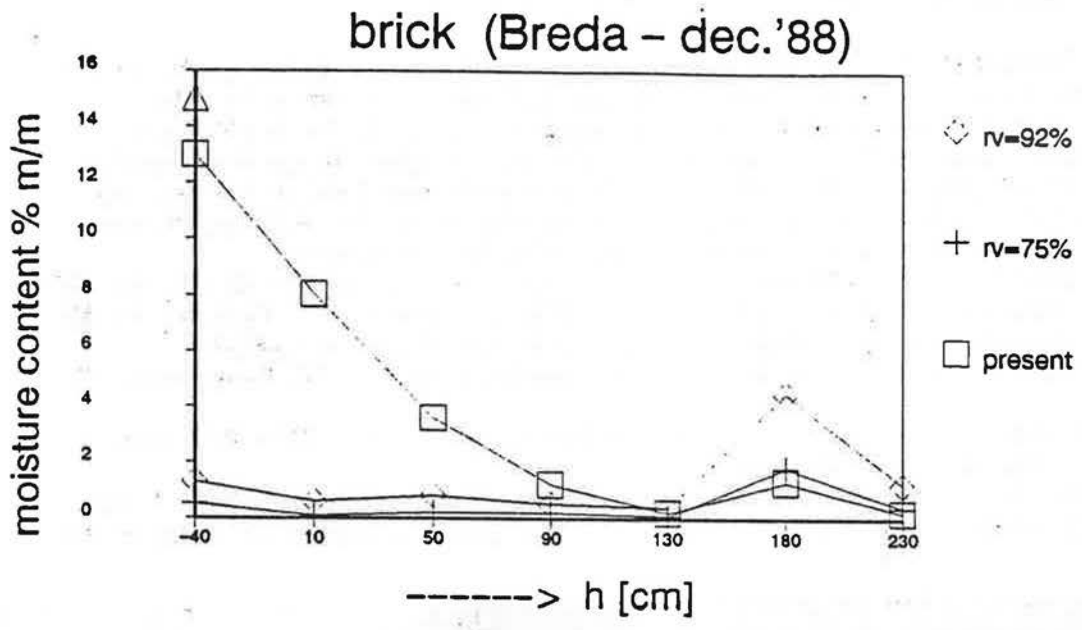

FIGURE 2a. Moisture distribution over wall height (brick) and hygroscopic moisture uptake

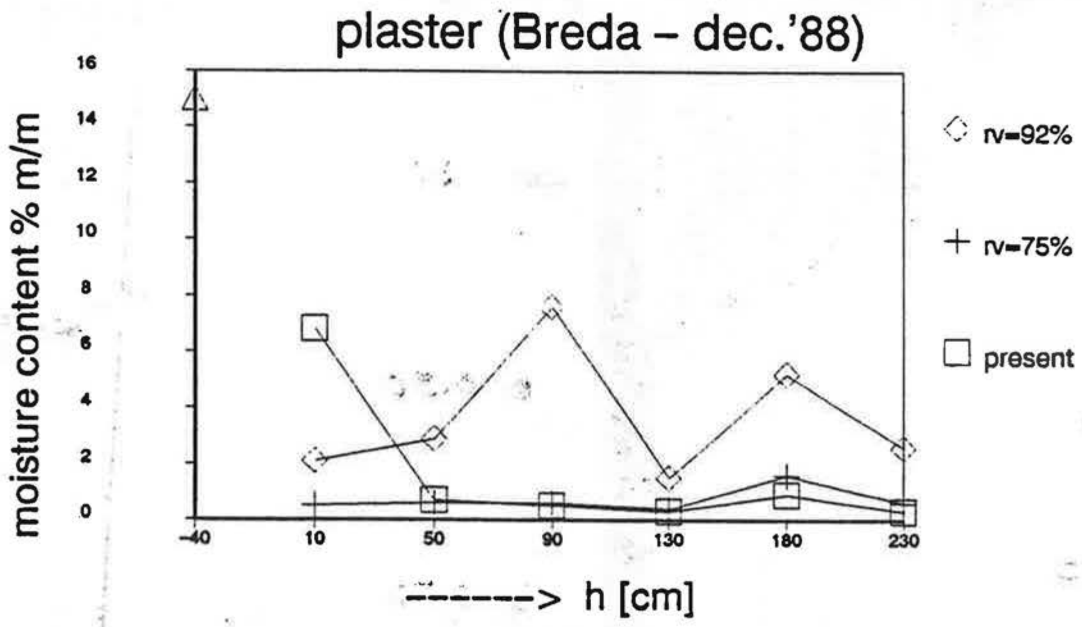

FIGURE 2b. Moisture distribution over wall height (plaster) and hygroscopic moisture uptake

Two conclusions can be drawn already:
- up to a certain height there is still rising damp involved.
- On heigher levels the moist spots cannot be attributed to rising damp.

Especially the hygroscopic behaviour of the plaster is most remarkable. The peaks in the hygroscopic curve of 92% RH do correspond to the "moist" areas in practice !

The fenomenon of the second hypothesis, stating that moist areas might arise more or less spontaneously under influence of the relative humidity, had been supposed already earlier by us to be a possible "moisture-fenomenon" (3), but was as far as we know never thoroughly described or proved. Therefore this hypothesis was really a challenge and also the motive for an experiment on the spot. In this experiment the RH in the adjoining room was artificially increased.
The duration of the experiment was two hours in which the RH of the air in the room was increased from almost 50% to almost 80%. Figures 3a and 3b are showing the situation at the start (an almost invisible discoloration) and in the end (a very obvious pattern of moist and dry areas).
This result, in combination with the behaviour of the grit samples, confirms the second hypothesis.
There can be concluded that the main cause of the visual problems is the hygroscopic behaviour of the plaster under influence of changes in RH.

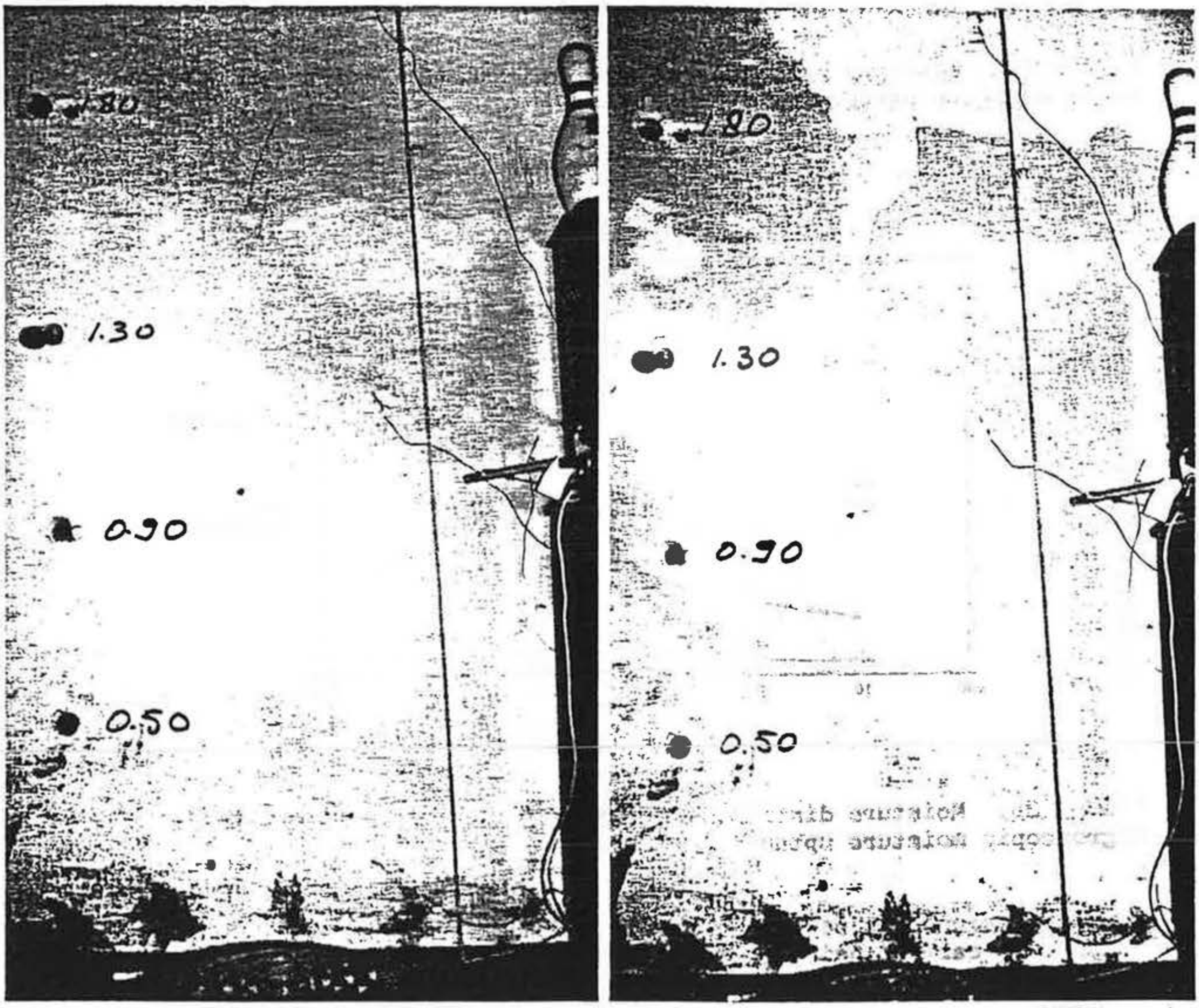

FIGURE 3a/3b. Situation at the start (3a) and at the end (3b) of the RH-experiment. During the experiment room RH increased to 80%. Height above floorlevel is indicated

FURTHER ANALYSES

Thin slices of plaster (2 mm) both from a "dry" and from a "wet" spot were taken from the affected wall. Part of the samples was used again for studying hygroscopic effects, another part was used for SEM/EDAX analysis.

Hygroscopicity

The samples were conditioned at RH's of 52%, 75% and 92% succesively, always until a constant mass was achieved. Table 1 shows the results. The difference between a "dry" and a "wet" spot is rather big. The behaviour of the "dry" sample can be considered normal for a gypsum plaster.

TABLE 1. Hygroscopic moisture uptake; thin slices of plaster

height [m]	1.30 dry spot	1.80 wet spot
present [% m/m]	0.34	0.90
RH = 52% [% m/m]	0.40	0.90
RH = 75% [% m/m]	0.55	2.00
RH = 92% [% m/m]	1.30	8.50

SEM / EDAX

The SEM/EDAX technique was used to detect type and structure of the salt crystals in some of the thin samples. Several crystals of Sodium salts were found near the surface; fig. 4 shows salts embedded in the gypsum of the material surface. It was established that no chlorides or sulphates were involved. We suppose that the salts found are nitrates. Alas SEM/EDAX is not able to detect nitrates.

PRACTICAL SOLUTIONS

It will be obvious that each solution has to start with a proper diagnosis of the problem, otherwise 'solutions' will be either not sound or insufficient.
In this case the result of the performed injection of acryl-amide is even doubtful, as there still appears to be rising damp. However being not familiar with the situation before (former moisture content and distribution) it is difficult to jugde and completely reject the method. The solution proposed was in the first place focused on combating the hygroscopic problem.

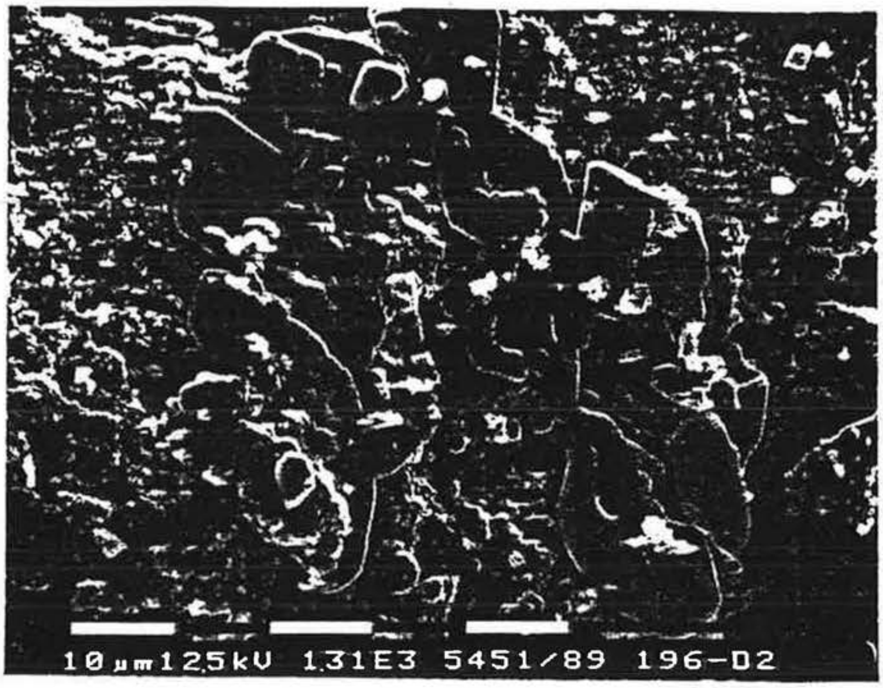

FIGURE 4. SEM/EDAX picture showing (Sodium) salt crystals on the plaster surface

Dealing with the present situation and the fact that the dwelling was inhabited, after a period of complete restoration and renovation a solution was proposed causing as little as possible trouble to the inhabitants and leaving the existing wall finishing intact.

Suggested was to cover the wall surface with a foil of high diffusion resistance, to prevent changes in room RH to effect the plaster. The new wall finishing can be a plasterlayer or gypsum board.
Apart from that and in order to reach an optimal solution it was suggested to combate the rising damp using a mechanical device to be installed underneath the floor level; see also (4). This was possible via the existing crawl space.

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MODELLING HEAT-AIR-MOISTURE TRANSFER IN AND THROUGH CONSTRUCTION PARTS

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ABSTRACT

The paper introduces some systematics in the vaste number of moisture transport models. After a general introduction in mass transport, with an emphasis on vapour transfer by convection and water transfer by gravity and external pressures, a recapitulation of the conservation laws and the empirical transfer laws, governing air and moisture transport is given. Using this basis, a commented overview of model possibilities, with links to practice and research, is given, showing that also rather simple models may contain more information than expected.

1. INTRODUCTION

In the frame of an IEA, executive committee on Energy Conservation in buildings and Community Systems, Annex proposal on HEAT-AIR-MOISTURE TRANSFER IN BUILDING PARTS, HYGRIC AND ENERGETICAL CONSEQUENCES, an enquiry was organised in in the EXCO- participating countries. The results revieled a remarkable lack, in different countries, in practice linked tools and models to evaluate moisture problems and to come to moisture linked design aids and performance judgment (1). This inspired this paper, who aims to bring together, in a condensed way, some air and moisture transport knowledge and modelling abilities.

2. MASS TRANSPORT

In building parts, two kinds of mass transport are predominant: air and moisture.
Air transfer is directly linked to temperature differences, introducing stack effects, to pressure differences, responsible for forced flow, and to lack of air tightness. The last one may follow from the use of porous materials or air open layers or from the presence of joints, cracks, perforations, overlays, mostly in combination with cavities.
Typical examples of air open layers/ constructions are: a tiled deck, a timber slab ceiling, an insulating layer of slabs with restricted dimensions, a timber framed wall...
Moisture transfer is artificially splitted in vapour and unsaturated or saturated water flow, althrough both being linked together in a very complex way. Vapour transfer is governed by diffusion and air transfer, the last being called convective vapour flow. In many cases, diffusion is the minor problem. Water transfer is caused by suction, gravity and external pressure differences. Of these, suction governs the unsaturated

flow in porous materials, gravity and external pressure differences only becoming active for high saturation ratio's.

Mass transport is closely linked to heat transport: each mass flow means transfer of sensible heat, called the enthalpee. The changes of state water- vapour, water- ice and ice- vapour release or absorb latent heat, influencing in a direct way the sensible heat flow. Enthalpee flow and latent heat release/ absorption also change temperature curves in building parts.

3. THE BASICS OF MODELLING

In general, a hygrothermal model means, looking for the potential field (temperature, vapour pressure, relative humidity, suction, moisture contents) and the flow densities (heat, air, vapour, water, moisture). To do that, as much equations as unknowns are needed. The equations rely at one side on the fundamental conservation laws of classic physics, at the other side on so called emperical flow density expressions, linking the flow to the potential field.

3.1 Conservation laws

These are: conservation of heat and mass. Applied to an infinitesimal volume of material, one has:

MASS moisture $$-\delta w/\delta t = \sum_{i=1}^{3} \mathrm{div}(q_{mi}) \qquad \text{(eq 1)}$$

air $$-\delta w_a/\delta t = \mathrm{div}(q_a) \qquad \text{(eq.2)}$$

In 1 and 2, div stays for the divergence vector operator - the flow per unit of volume-, q_{m1} is the' vapour flow density by diffusion' vector, q_{m2} the' vapour flow density by convection' vector, q_{m3} the water flow density vector and q_a the air flow density vector. Both equations say that the resulting in or outflow of mass pro unit of volume equals the change in mass content. In the moisture equation the changes of state are hidden in the $\delta w/\delta t$- term. As far as air flow is concerned, the time derivate $\delta w_a/\delta t$ may be omitted, air reacting so quick that on the time scale used for hygrothermal problems (days, weeks, months, years), air flow has no inertia.

HEAT

$$-\mathrm{div}(\underbrace{q}_{1}+\underbrace{\theta.[\Sigma(q_{mi}.c_i)+q_a.c_a]}_{2})=\underbrace{\delta(\rho.c'.\theta)/\delta t}_{3}-\underbrace{\Sigma I.l_b(\theta)}_{4} \qquad \text{(eq 3)}$$

1 stays for the heat transfer by conduction

2 represents the enthalpee transfer, with c_i the specific heat capacity of the moisture and c_a the specific heat capacity of the air;

3 gives the heat storage in the material matrix, the air and the moisture, present in the infinitesimal volume, c' is the combined material-air-moisture specific heat, referred to the dry volumic mass

of the porous material;
4 contains the uptake/ release of latent heat l_b. Σ means: for all changes of state.

In air spaces, the equations have to be completed with the conservation of momentum (Navier- Stokes).

3.2 Transport laws

The flow density equations are emperical expressions. Normally, simple linear expressions are used linking the flow density vector to the gradient of the potential. However, empirical means: a choice, open for discussion. That concerns as well the potential as the outlook of the equation. Here, the linear option is presented, with as potentials: air pressure, temperature, vapour pressure, generalised suction.

MASS	potential :	equations :	
AIR	air pressure p_a temperature (stack eff.)	porous mat.	$q_a = -k_a \cdot grad(p_a - \rho_a g z)$
		layers, cav. cracks, joints..	$q_a = -K_a \Delta(p_a - \rho_a g z)$
		k_a = air permeability (s) K_a = air permeance (s/m)	
MOISTURE vapour, diffusion	vapour pressure p	materials	$q_v = -\delta . grad(p)$
		layers	$q_v = -\Delta p/(\mu d . N)$
		δ = vapour permeability (s) μd = diffusion thickness (m) N = diffusion constant (s^{-1})	
vapour, convection	air pressure p_a temperature (stack)	all	$q_v = q_a . p/(\rho_a . 462.T)$
water	suction, gravity, external pressure, the 3 combined in 1 suction potential	materials	$q_m = -k_m . grad(s - g.\rho.z + p)$
		km = moisture conductivity (s)	

HEAT: Fouriers law of conduction - $q = -\lambda . grad(\theta)$ - is used, with λ, the thermal conductivity of the material (W/(mK)). In air spaces, heat transport must be splitted in radiation between the air space defining surfaces, convection between surfaces and air and convection/conduction in the air.

3.3 General solutions

An analytical solution of the hygrothermal equations, given under 3.1 and 3.2 is hardly possible, except if far reaching simplifications are accepted. Reasons: the equations as such, the fact that all properties introduced are potential- dependant,t.m., that the thermal conductivity, moisture conductivity, vapour permeability a.o. change with varying temperature, moisture content, relative humidity...., the difficulty to define analytically the boundary and initial conditions and problems with continuity laws between different materials. Therefore, in most cases, a FEM (finite elements) or CONTROL VOLUME approach is needed.

4 SIMPLIFIED MODELS (= FIRST ORDER)

4.1 Glasers scheme (2)

A traditional Glaser calculation supposes:

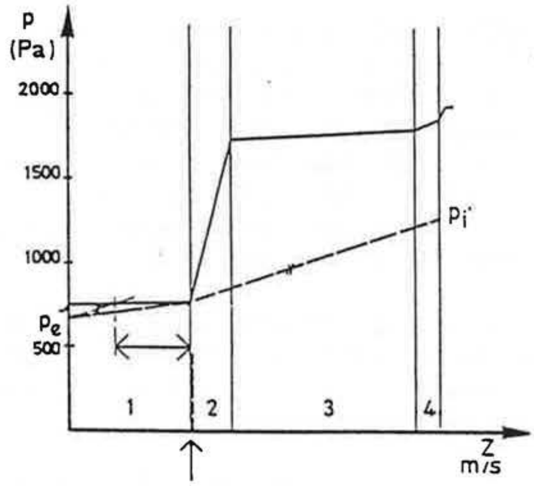
- hygrically and thermally steady state ($\delta w/\delta t=0$, $\delta\theta/\delta t=0$);
- moisture transport by VAPOUR DIFFUSION only;
- mo influence, on the heat balance, of enthalpee transport and latent heat uptake/ release;
- all material properties constant;
- starting condition: a dry construction
- flat walls.

In that case, moistening is only possible by interstitial condensation. The equations become:

THERMAL	heat flow density	: $q=\Delta\theta/R$ with R the thermal resistance air to air of the flat wall ($R= 1/U$).
	temperature line	: θ linear in each layer, a straight line through the wall in a $[R,\theta]$-axis system. The θ- line directly gives the p'-line. ($p'=$ saturation pressure)
HYGRICS	vapour pressure line	: p linear in each layer, a straight line through the wall in a $[Z,p]$-axis system If $p_x \geq p'_x$, interstitial condensation in the wall is inevitable and the p-course in the wall changes to the so called p' tangent course (figure 1)
	vapour flow density	: $q_v=\Delta p/Z$ with Z the diffusion resistance of the flat wall. If condensation, the flow density remains constant outside the condensation zone and changes in it, this change, given by $\delta p'^2/\delta Z^2$ or, in a singular point, $(\delta p'/\delta Z)_1-(\delta p'/\delta Z)_2$, being the condensation flow density I.

Interesting at the Glasers scheme is that:

- only two material properties are needed: the thermal conductivity and the vapour permeability or diffusion resistance factor μ ($\mu= \delta_a/\delta$ with δ_a the vapour permeability of stagnant air)
- the whole calculation is easely hand made.



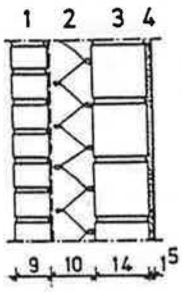


FIGURE 1. Glaser calculation of a cavity wall

The last fact has made the scheme a reference method.

4.2 The adapted Glasers scheme

drying
Start is the presence of water in a plane or layer, t.m. 1 of the 6 hypotheses omitted. Taking there p=p',the tangent construction to in- and outside surface can be made, reveiling or drying (outgoing vapour flow density), or condensation of the water in another plane/ zone, resulting in a shift of moisture from the wet plane/layer to another. This construction allows to understand a lot about initial moisture content condensation, succed rain condensation, the possibility or impossibility of drying. It was at the base of todays warm flat roof with screed construction rules...: figure 2 (3).

The limit state concept
If long lasting interstitial condensation goes on, the question 'What will be the limit state?'comes. An answer is given in (4),(5), introducing the critical moisture content:the value w_{cr} below which vapour and above which water transport in a material is dominant. For

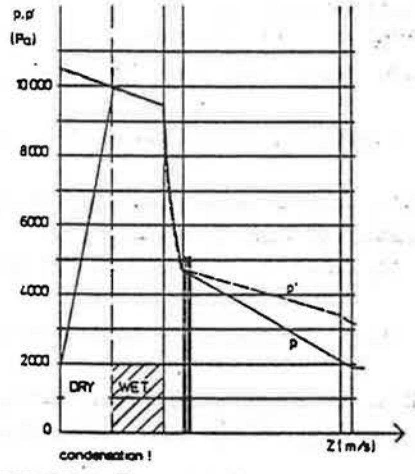


FIGURE 2. Drying..

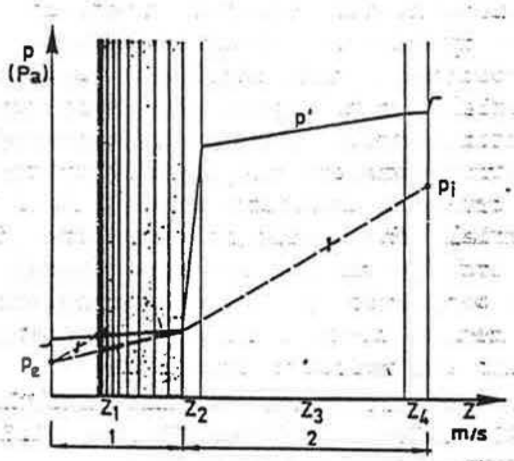


FIGURE 3. Limit state

capillar materials, $w_{cr} \leq w_c$ (w_c= the capillar moisture content), for non capillar materials, w_{cr}= w_m (w_m= the maximal moisture content). Interstitial condensation will go on, the condensation zone expanding, until the ingoing vapour flow density (q_{vi}) equals the outgoing (q_{vo}). The moisture content in the limit state condensation zone is the critical one. If equality never can be achieved, the result will be a permanent rise in moisture content in the condensation zone, until capillar saturation and more, with dripping or leaking water...

Safe now are all constructions where q_{vi}= q_{vo} is possible, with in the condensation zone materials with low critical moisture content, unsafe these where equality isn't possible. An example of the first is a wall in cellular concrete, of the last a flat timber cold roof: figure 3.

This limit state concept can also be translated in a better modelling of drying. Some recent software packages include that possibility (5)(6).

Better boundary conditions

At the beginning, Glasers method was used with daily mean extremes of in- and outside temperature and vapour pressure, this, because of inertia, in direct contrast with the steady state hypothesis. Therefore, the boundary conditions have shifted to, for massive constructions, yearly mean climate data, for less heavy to lightweight systems, yearly mean +first harmonic on yearly basis values with corrections for solar gains, undercooling and the non linear relationship temperature-saturation pressure (7).

Better acceptance conditions

In early literature, constructions were condemned if interstitial condensation was possible. This led to the vapour barrier chase of the sixties. Now, it's generally accepted that, only if on yearly basis resulting condensate is found, one should non accept, except if winterly condensate ranks to high for the material wetted (f.e.,in wood,an increase $\Delta X = 3\%$kg/kg is tolerated)

4.3 Judgment

The adapted Glasers scheme is at first sight a lovely, simple, nice to understand method. However, there are mayor inconvenients:

- the hypothesis behind restrict the correct application to non hygroscopic, (non capillar) materials Only part of the insulation materials, ± no other, obey that condition;
- Omitting vapour transfer by convection is so farreaching, that lots of constructions end misjudged with the method;
- the critical moisture concept is a poor model for a capillar material material, not usable in computing (introduction of discontinuity);
- 2D- and 3D- models are a necessity to come to better knowledge of the HAM- behaviour of real constructions
- the method doesn't allow a judgment on the heat transfer consequences of air and moisture transport
- **important from a practice point of view is that, with Glaser, interstitial condensation as cause of moisture problems has been overemphasised.**

5. MODIFIED MODELS

5.1 Introducing convective vapour transfer

T.m.:changing hypothesis 1 to 'moisture transport by VAPOUR DIFFUSION AND VAPOUR CONVECTION', the other, except the simplification of the thermal balance, remaining.
The system of equations become (1- dimensional):

- transport of air $d^2p_a/dx^2= 0;$ $q_a= k_a.d(p_a- \ _agz)/dx$
- transport of vapour $d^2p/dx^2+A.dp/dx=I,$ $qv= \delta.(dp/dx+A.p)$
  with $A= q_a/(\ _a.462.T.\delta)$
  I: condensation flow density
  if no condensation, I=0
- transport of heat $d^2\theta/dx^2+B.d\theta/dx=I.l_b$ $q = \ (d\theta/dx+B.\theta)$
  with B= ca.qa/..

(eq 4)

As soon as composite walls are tackled, an analytical solution turns to very cumbersome, a control volume approach being preferred. Also 1D-problems in air transport are so rare, that, once a control volume approach adopted,tuning the more real 2D- and 3D- problems goes on easy. Taking into account convective air and vapour flow has and is introducing a far better understanding of the behaviour of leight weight constructions, including the thermal as well as the hygric aspects: see figure 4.

5.2 Introducing hygroscopic inertia

This is done to get a better view on the hygric reaction,in the lower saturation degree interval, of hygroscopic materials. Because in most cases, these material are micro porous, vapour convection in and through

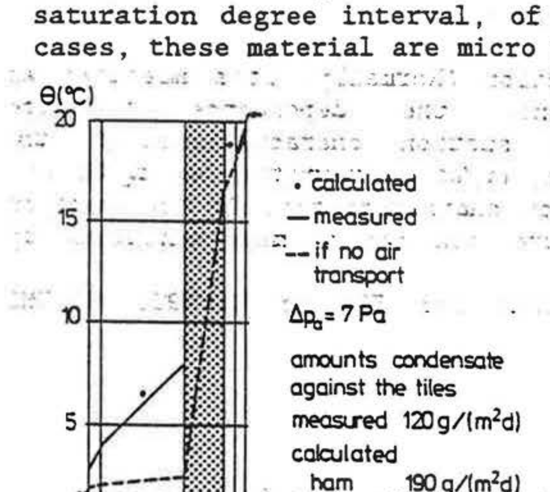


FIGURE 4: Sloped roof section calculated with a HAM- model

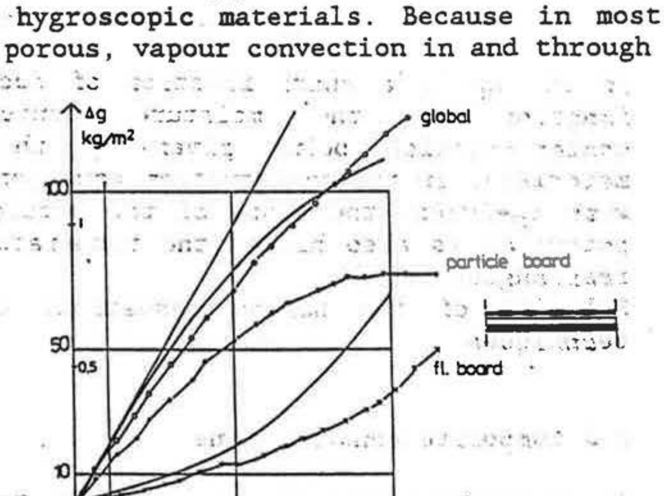


FIGURE 5. Influence of hygroscopicity on the hygric reaction of a MPS-particle board composite wall

them may be neglected. The assumptions left in a first step are: .1D, no water transport.
A simple choice to start is, limiting the non steady state response to hygrics. By this, only long lasting changes are correctly studied (f.e., what's going on on yearly basis) The hygric balance equation becomes:

$$\delta/\delta x[\delta p/(\mu N \delta x)] = \delta w/\delta t \qquad \text{(eq 5)}$$

Writing $\delta w/\delta t$ as $\delta w/\delta\varphi.\delta\varphi/\delta t$, with φ the relative humidity in the material and $\delta w/\delta\varphi$ the specific vapour capacity c_H, to be deduced from the suction curve of the material (figure 5), and δp as $\delta(p'.\varphi)$, (eq.5) turns to:

$$\delta/\delta x[\delta(p'.\varphi)/(\mu N \delta x)] = c_H.\delta\varphi/\delta t \qquad \text{(eq 6)}$$

(eq 6), containing relative humidity and temperature as potentials, can easely be solved with a control volume approach, linking it to the steady state thermal equation, in which, without mayor inaccuracy, enthalpee and latent heat transfer may be omitted. For an example: see figure 5.
If shorter periods have to be studied (f.e. the influence of insolation on the hygric reaction of an outside rendering) hygric as well as thermal inertia play and both have to be solved non steady state.

5.3 Introducing water transport

This step allows a better understanding of the moisture transport over the whole saturation degree scale in capillar materials. It gives not only a better judgment of interstitial condensation or drying, it also broadens the moisture analysis to rain penetration, rising damp, initial moisture content, external pressure problems..

Water transport is introduced by using the generalised suction formula:

$$q_m = -k_m.\text{grad}(s - gz + p) \qquad \text{(eq 6)}$$

In it, k_m is a sharp function of suction (Normally, it's measured as function of the moisture content, the dependance moisture content→suction being given by the suction characteristic.of the material). In the conservation equation, $\delta w/\delta t$ is rewritten as $c_m\ \delta s/\delta t$, with $c_m = \delta w/\delta s$, the slope of the suction characteristic. In the suction potential is also hidden the temperature, who can be made explicite by rearranging (eq 6).
Solution of the balance equations asks for FEM or CONTROL VOLUME techniques.

5.4 Composite constructions

In composite constructions, the HAM- transport not only is two- and three- dimensional but the construction itself will be made of materials, some non hygroscopic and non capillar, others hygroscopic but ± non capillar, others capillar. Hygric- air modelling in this case is only possible by combinig the models, discussed above: pure vapour diffusion + convection in the first kind of materials, the potentials

being vapour pressure, air pressure and temperature (if p=p'), the hygroscopic approach in the second kind of materials, the potentials being relative humidity and temperature, the suction approach in the last kind of materials, the potentials being generalised suction and temperature.
T.m. that, when shaping a model, the 5 potentials have to be taken into account, with the possibility to jump, depending of the material, from one to another.In the equations, all transport and capacitive coefficients are potential depending.
Making that kind of HAM- models remains a challenge for the near future.

5.5 Two- and three-dimensional problems

As suggested, once a control volume approach adopted, switching to 2- and 3- dimensional problems is only a question of mathematics and software development, not of physical law manipulation. The only new thing to be added is the possible non- isotropicity of materials, making properties direction depending. However, the extra information, gained, may be very interesting and important (the hygrics of maconry work - a mortar joint-stone problem-, the consequances of stone repair, leaks, joint influences...are all 2- and 3- D problems!)[8].

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THE HYGROTHERMAL BEHAVIOUR OF SLOPED ROOFS

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ABSTRACT

There is a widespread conviction that, to avoid moisture damage in insulated sloped roofs, they should be ventilated under the roof covering and between the thermal insulation and the underroof. However, recent research shows that the assumptions behind - an airtight, vapour retarding roof covering, a longitudinal air flow in the cavities, a surface temperature of the covering always higher than the outside temperature and diffusion as the only vapour transfer mechanismus - oversimplify things. In fact, most coverings are air open, vapour flow is convection rather than diffusion linked and undercooling must be taken into account. The first fact makes venting features in the covering superfluous, the two last aggravate, rather than ameliorate the hygrothermal reaction of vented roofs and suggest a better section alternative: the sandwich solution

1. INTRODUCTION

In most countries, tile and slate manufacturers and roofers defend the vented sloped roof: the necessity of outside air ventilation under the tiles or slates and between the underroof and the insulating layer. Product development is governed by it - venting tiles, venting ridges -, standardisation too, imposing batten heights, venting sections, the use of venting tiles..a.o.
However, from a physics point of view, that conviction isn't so sound, two questions remaining unanswered: does one really need special features to induce ventilation under a tiled or slated deck, and, is ventilation necessary or, worse, could it harm rather then ameliorate the hygric behaviour of the roof?

To clarify both questions, a longlasting stepwise research was set up : first analysing damage cases, then studying the vapour resistance and air tightness of layers and whole roof sections, next looking to the undercooling phenomenon and to interstitial condensation as a function of vapour and air pressure differences and last, testing solutions under real weather conditions, a step still going.

2. A SHORT OVERVIEW OF THE VENTILATION THEORY (1)

The traditional way of looking to ventilation is based on a simple model: in each cavity with in and outlets, there's a longitudinal airflow, resulting in an exponential temperature in- or decrease from the outside temperature at the inlet to a value, nearer to the non vented cavity equilibrium temperature $\theta_{c\infty}$, the longer the cavity and the lower the air velocity:

$$\theta_c = \theta_{c\infty} + (\theta_e - \theta_{c\infty}).\exp[(R_1+R_2).x/(R_1.R_2.1200.v.b)] \qquad \text{(eq 1)}$$

with: $$\theta_{c\infty} = (R_1.\theta_e + R_2.\theta_i)/(R_1+R_2) \qquad \text{(eq 2)}$$

Also an exponential vapour pressure course developes:

$$p_c = p_{c\infty} + (p_e - p_{c\infty}).\exp[462.T_c.(Z_1+Z_2).x/(Z_1.Z_2.v.b)] \qquad \text{(eq 3)}$$

with: $$p_{c\infty} = (Z_1.p_e + Z_2.p_i)/(Z_1+Z_2) \qquad \text{(eq 4)}$$

In these equations, R_1 and R_2 are the thermal resistances (m^2K/W) and Z_1 and Z_2 the diffusion resistances (m/s), of the in- and outside parts alongside the cavity, b is the width of the cavity (m), v the air velocity (m/s), x the lenght coordinate (m), θ_i the inside temperature (°C), θ_e the outside temperature (°C), p_i the inside vapour pressure (Pa), p_e the outside vapour pressure (Pa).and $p_{c\infty}$ the non vented cavity equilibrium vapour pressure (Pa) (figure 1).

Winterly condensation problems arise, when the vapour pressure in the cavity p_c equals the saturation pressure against or in the outside part. That reality becomes more probable, the better insulated the sloped roof (if R_1 increases, then $\theta_{c\infty}$ becomes lower , see eq 2).

Diminuishing the condensation probability is possible, or by increasing the ventilation flow (a wider cavity, more in and outlet area, a higher air velocity) or by increasing the inside part diffusion resistance Z_1. The better insulated a roof, the more important both tools. Because the flow velocity depends of the non controlable temperature and pressure differences over in- and outlets, all design aids and standards focus on cavity width, in and outlet area and vapour retarders in the inside part. To be at the save side in dimensioning, the outside part - in a sloped roof the tiles, slates or these + the underroof - is supposed air and vapourtight.

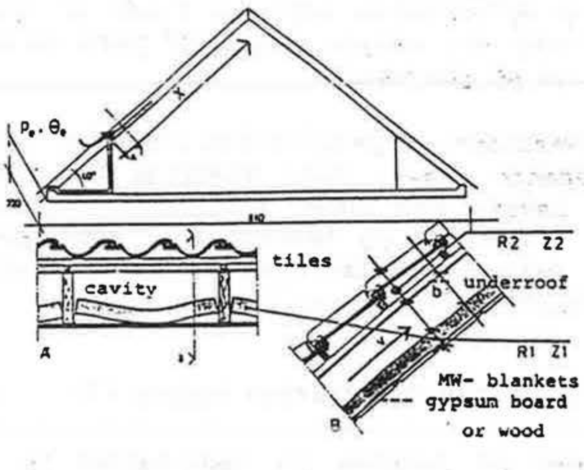


FIGURE 1. The ventilation model ((eq 1) to (eq 4))

3. WEAK POINTS IN THE MODEL

The model overlooks some very important facts:

- wind and temperature differences introduce pressure gradients in the roof an between the roof air spaces and the in - and outside environment;
- roof coverings, more , most roof layers aren't vapour and air tight;
- pressure differences and air openess cause convective flows in and through the roof section, increasing the heat losses and influencing in a very negative, orientation dependant, quick reacting way the hygric behaviour;
- undercooling lowers the temperature of covering and underroof so, that active ventilation may cause condensation instead of excluding it;
- suction of the materials used may be dominant in moisture behaviour.

These discrepancies between model and reality were convincingly proved by analysing a major damage case of insulated sloped roofs in a social estate in the neighbourhood of Leuven, Belgium (1), well or no condensation depending more of orientation than of room use, dripping moisture only after clear sky cold nights, a lower conduction loss, but higher temperatures in the roofs than expected (convective inflow lifts the temperature profile).

3. ARE SPECIAL VENTILATION FEATURES IN COVERINGS NEEDED?

This first question has been answered by studying the diffusion thickness and air permeance of different covering choices (tiles, slates, corrugated plates) and analysing the ventilation pattern (2)(3).

3.1. Diffusion Thickness and Air permeance

3.1.1 Measuring Methods

The diffusion resistance factor μ or -thickness μd of the roof covering materials (tiles, slates, ...) was measured with the wet cup- dry cup method.

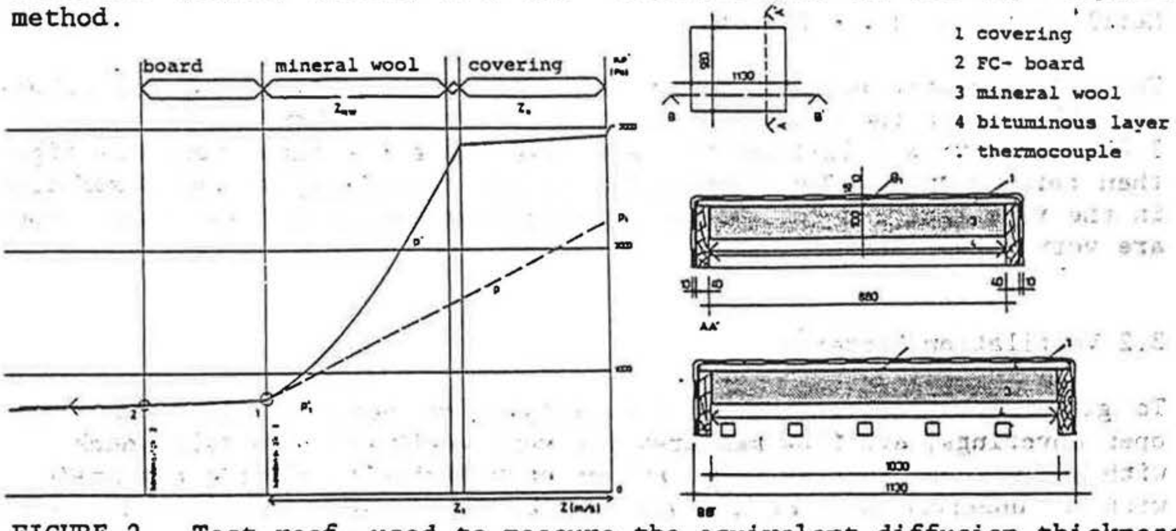


FIGURE 2. Test roof, used to measure the equivalent diffusion thickness of different sloped roof covering deck solutions

The equivalent diffusion thickness of the deck was derived from long lasting interstitial condensation tests on flat roofs in a Hot Box-Cold Box apparatus with the deck as internal lining:

Roof Section (Area: 0.906 m^2/ from down to top- figure 2):

- roof covering;
- air cavity;
- thermal insulation: Mineral Wool, d= 10cm, μd= 0.15m;
- a capillar fibro-cement board, d= 18mm;
- bituminous layer, d= 10mm, μd> 100m

Interstitial condensation is generated in the fibrocement board (figure 2), the amounts being determined by weekly weighting, during 8 to 10 weeks, the roofs. If the temperature and vapour pressure in the Hot and Cold Box are known, then, from the measured condensation rate, the diffusion resistances of the ceiling= covering can be calculated. For the tests performed, we had: HOT BOX : θ= 24.1 ± 0.2 °C, RH= 70 ± 5 %/ COLD BOX: θ= 2.4 ± 0.2 °C

The air permeance K_a was measured by fixing a frame with the covering, against an under-pressure box, measuring area 0.896 m^2, coupled to a dust aspirator by way of a flow gauge. After determining, as function of the air pressure difference , the air flow through the covering, K_a can be deduced from the resulting 'flow-pressure'-diagram.
For all covering systems, a relation $K_a = a \Delta p^{-b}$ is found, t.m., a permeance, decreasing with higher pressure difference.

3.1.2 Results
See table 1
The table shows that roof covering decks with an important length L of locks/overlaps, have an equivalent diffusion thickness significantly lower then the elements, and a high air permeance, in spite of the elements being airtight. For example:

Ceramic tiles : L = 8.3 à 9.2m/m^2
Concrete tiles : L = 6.2m/m^2
Metallic tiles : L = 3.5m/m^2

The air permeance being high, becomes very clear in comparing the values of table 1 with the <specific> air permeance of masonry work: 1.0E-4$\Delta p^{-0.36}$ à 3.7E-5$\Delta p^{-0.20}$ s/m, t.m.160 à 430 times more air tight than ceramic tiles. The consequence is that, contrary to the assumption in the ventilation model, supposing coverings vapour and air tight, they are very vapour and air open.

3.2 Ventilation Patterns

To get some understanding of the ventilation patterns under these air open coverings, air flow measurements were performed on a tiled deck with and without venting tile, and on an underroof- covering air space, with an underpressure at the air inlet. The results of the first step showed no significant difference in air permeance between ± 1 m^2 of

Table 1. Diffusion thickness μd, equivalent diffusion thickness $[\mu d]eq$ and air permeance K_a of roof coverings.

COVERING	μd material RH % -	- m	$[\mu d]_{eq}$ deck (RH= 75%) m	K_a deck s/m a	b
ceramic tiles, single lock	75	1.5	0.16	1.6E-2	-0.49
	86	0.8 σ=0.13			
ceramic tiles, double lock	86	0.85 σ=0.09	0.26	(1) 1.3E-2 (2) 1.2E-2	-0.50 -0.32
concrete tiles (sneldek)	70	3.9 σ=0.35	0.46	7.8E-3	-0.46
fibro-cement slates	52	0.9 (0.6 à 1.1)	0.85 à 1.4	1.7E-3	-0.21
	70	0.35 σ=0.07			
	86	0.34 σ=0.12			
natural slates		> 10	2.1	5.4E-3	-0.34
corrugated (1) fibro-cement (2) plates	70 75	0.64 1.5	0.84	9.1E-4	-0.37
metallic tiles		∞	1.8	2.1E-3	-0.43

tiling with and without venting tile: $1.5E\text{-}3\Delta p^{-0.5}$ vs $1.3E\text{-}3\Delta p^{-0.5}$.
The second step learned that, with ceramic tiles (highest permeance), inlet under- or overpressure only generates local flow between the vent and the adjacent tiles, that with concrete tiles partially a flow in the cavity, partially local flow developes and that with fibro-cement slates a clear cavity flow exists: figure 3.
These measurements were completed with calculations, using the KONVEK-

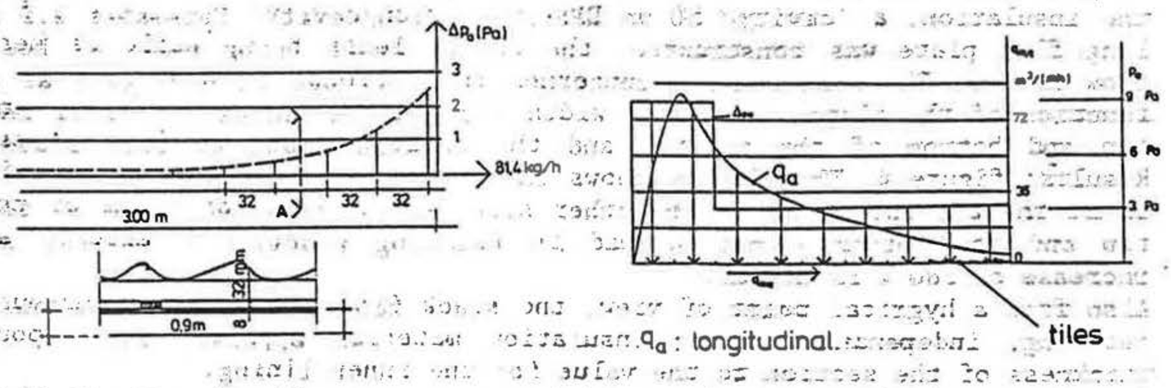


FIGURE 3. Pressure line (measured) and air flow (calculated) under a tiled deck

air flow model [3]. The results confirmed the measurements : with ceramic tiles no vent tiles needed to get outside air ventilation, the flow pattern being very local (figure 3). Also concrete tiles, metallic tiles and slates reveiled air open enough to give venting.

4. IS VENTILATION NEEDED?

Remains the question, if the unavoidable ventilation between covering and underroof and the induced ventilation between underroof and thermal insulation is really necessary, more, could harm? The answer is coupled to two realities:

- the air permeance and possible rotative stack flow in vented sloped roof sections;
- undercooling.

4.1 The air permeance of layers and roof sections

See table 2 (For the measuring method: 3.1.1)
The air permeabilities look high enough to give, when pressure and temperature differences exist -and these are pronounced in a vented roof-, important convective air flows through sections, composed of the layers of the table. This results in extra heat losses and, if inside air passes through, excessive interstitial condensation.

Both has been proven by a series of long lasting Hot Box- Cold Box tests on 2 roof sections, composed of (from outside to inside): tiles, air cavity, mineral wool blanket d= 5.4 cm with vapour barrier, air cavity, timber slabs ceiling, the one with , the other without the vapour barrier air tight fitted. Boundary conditions and measuring results: table 3. These results confirm the excessive heat loss and interstitial condensation, when no air tightness is achieved. The spontaneous Cold Box air ventilation under the tiles, with local air velocities up to 0.28 m, didn't prevent the problem[2].

4.2 Rotative stack flow [4]

To get some estimation of the importance of rotative stack flow around the insulation, a 'cavity/ 50 mm EPS-insulation/cavity' rotatable 1.5 m long flat plate was constructed, the cavity leafs being build as heat flow meters. The measurements concerned the increase in heat loss as a function of the slope, the joint width between the insulation layer and top and bottom of the cavity, and the cavitie width at both sides. Results: figure 4. This figure shows that, with cavity widths of only 35 mm at the one and 16 mm at the other side, and a joint of 14 mm at the top and the bottom - not so bad in building practice - already an increase of 380 % is noted!!
Also from a hygrical point of view, the stack flow may be very ennuyous, reducing, independant of the insulation material applied, the vapour thickness of the section to the value for the inner lining.
Or, this stack effect must be avoided by all means. The pity now is that exactly the demand for a vented cavity between underroof and insulating

Table 2. The diffusion thickeness and air permeance of sloped roof layers

LAYER/SECTION	$[\mu d]_{eq}$ RH %-	- m	K_a s/m a	b
gypsum board, the joints plastered	30 77 90	0.1 0.05 0.04	3.1E-5	-0.19
gypsum board, open joints			3.3E-4	-0.27
gypsum board, open joints perforated (electr.)			6.3E-4	-0.27
timber slabs ceiling	55	0.85	4.2E-4	-0.32
timber slabs ceiling, perforated (electr.)			7.6E-4	-0.37
MW-blankets, perfectly closed overlays	70 à 86	0.3 à 5	6.5E-5	-0.29
MW-blankets, current practice			3.2E-3 à 8.9E-4	-0.15
underroof in FC-board d= 3.3mm, correctly installed	74	0.14	4.2E-4	-0.34
underroof in FC-board d= 3.3mm, current practice			1.0E-2	-0.45
micro-perforated plastic foil, glass fibre fabric reinforced, d= .1 à .2mm	86	1.7 à 8	5.0E-4	-0.35

Table 3. Measured interstitial condensation in 2 sloped roof sections, one with and the other without air barrier

SLOPED ROOF → ↓	θ_{cb} °C	Pcb Pa	θ_{hb} °C	Phb Pa	ΔPa Pa	air tight $U^{(a)}$ W/(m²K)	air tight $m_c^{(b)}$ g/d	air open U W/(m²K)	air open m_c g/d
+ with airtight vapour barrier									
no leak in the ceiling	1.5	580	20.3	1573	1.5	0.465	5	1.0	1.7
leak φ 20 mm in the ceiling	1.2	569	20.1	1554	1.0	0.46	4.9	1.1	26.0
leak φ 20 mm in the ceiling	1.5	612	20.3	1335	7.0	0.45	4.5	2.8	120.0

(a) related to the sensible heat loss
(b) condensation against the tiles, the water dripping on the MW.

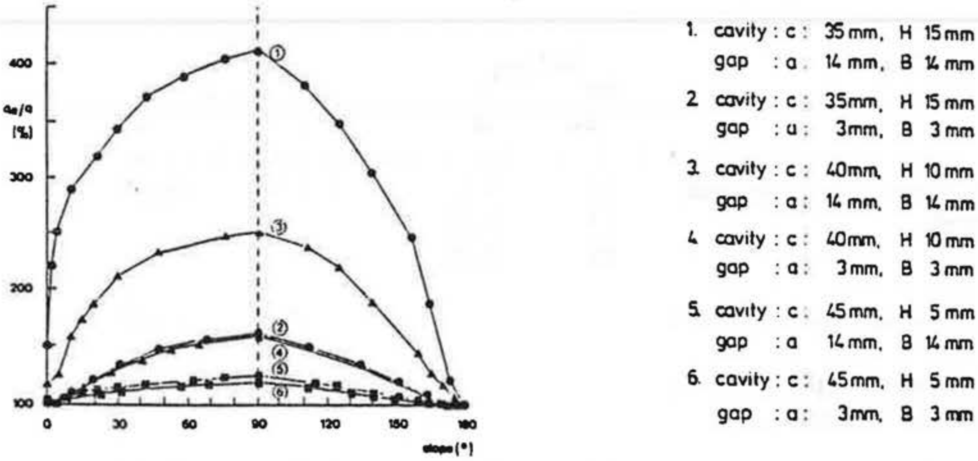


FIGURE 4. The increase in heat loss because of rotative stack flow

layer gives one of the two air spaces needed, the other being found under the insulation not in close contact with the internal lining. Gaps at the ridge and the gutter parapet are almost always present.
Still worser reveals the combination of rotative stack flow and air flow through the roof.

4.3 The Undercooling effects

Undercooling by long wave radiation of the covering has been analysed by temperature measurements, during the autumn, winter and springtime of 1983-1984, on 2 tiled decks above dwellings in use, one insulated (U-0.32 $W/(m^2K)$) the other not, both with underroof, the insulated deck with battens, the other not. Measuring results: see table 4.

Table 4. Undercooling effects.

ROOF	U-VALUE W/(m^2K)		SURFACE TEMPERATURES undercooling °C	no undercooling °C
Dwelling 1	0.33(1)	SE night	$-0.6+\theta_e$	
		day	$0.9+0.9.\theta_e$	
	0.38(2)	NE night	$-1.4+1.2.\theta_e$	$0.3+0.98.\theta_e$
		day	$-1.3+1.2.\theta_e$	
	0.33(2)	SW night	$-0.4+1.1.\theta_e$	$0.2+0.99.\theta_e$
		day	$1.0+\theta_e$	
Dwelling 2	2.35(1)	SE night	$-1.0+0.9.\theta_e$	$0.7+0.95.\theta_e$
		day	$0.4+0.9.\theta_e$	
	1.19(2)	NE night	$-1.1+0.9.\theta_e$	
		day	$-0.8+0.9.\theta_e$	
	1.27(2)	SW night	$-0.9+0.9.\theta_e$	
		day	$0.9+0.8.\theta_e$	

(1) calculated
(2) measured for the orientation given

The effect is undoubtly present, more pronounced on the insulated than on the uninsulated roof. In both,- orientation plays a role, as important as the insulation value, with NE the worsiest.
The insulated roof becomes colder than the air, for θ_e lower than 7°C - t.m. from November to March -, the uninsulated only if θ_e drops below - 11°C - t.m. with very cold weather.
However, undercooling isn't only linked to nightly clear sky long wave radiation but also to condensation on and drying of the tiles. The whole phenomenon is condensed in a steady state formula for the surface temperature θ_s:

$$\theta_s=[A.\theta_i+(h_{ce}+4.F_s.e_L)-F_s.e_L.(100-87c)+1.3e_L.F_{ss}+0.019h_{ce}.(p_e-p'_s)]/B \quad \text{(eq 5)}$$

with $A=1/(1/U-1/h_e)$ and $B=1/[1/(1/U-1/h_e)+h_{ce}+4.F_{ss}.e_L]$

In (eq 5), h_{ce} is the convective outside film coefficient, e_L the longwave emissivity of the covering, c the cloudiness factor, F_s the view factor roof- sky, F_{ss} the view factor roof- surroundings, h_e the outside film coefficient, U the U-value of the roof and p'_s the covering saturation pressure.

As a consequence, the covering turns wet in autumn, stays wet during the whole winter, and dryes not earlier than springtime.How wet,is inversely proportional to the U-value: table 5.

Table 5. The mean saturation degree of the tiles from december 1983 to march 1984

ORIENTATION	INSULATED ROOF $U=0.34\ W/(m^2K)$	NON INSULATED ROOF U=?
NE	0.94	0.87
SE	0.94	0.73
SW	0.77	0.75

5. TEST ROOF CONFIRMATION

All aspects analysed above, have been checked in a TEST ROOF PROGRAM: 4 NE oriented tiled sloped roofs with underroof and internal lining,

- the first, well insulated (18 cm MW), build following the sandwich-concept, with air- vapour barrier;
- the second vented between the covering and the underroof and the underroof and the insulation (6 cm of MW- blankets, practice mounted);
- the thirth not insulated;
- the fourth insulated between the underroof and the tiles;

were constructed at the laboratory site in 1987 and followed since.
The results approve the previous work, with convincing additional information:
- in the ventilated roof 2, a clear stack effect developed, with much higher heat losses than by pure conduction;
- with very cold weather, surface condensation was seen on the internal

lining of roof 2, near the vent openings in the gutter parapet, showing that ventilation and stack effect together may be very ennuyous;
- venting tiles had not a minor influence on the winterly saturation degree in the tiles, but the hygroscopic timber laths and bathens became wetter with then without;
- a hygroscopic underroof was found wetter, the lower the U-value, independant from well or no ventilation between it and the insulation and well or no air-vapour barrier at the inside;
- a plastic foil underroof remained perfectly dry in the sandwich roof 1 with air- vapour barrier, but gave ennuyous interstitial condensation in the ventilated roof 2, with moisture dripping on the insulation. and in the sandwich roof, when the air barrier was omitted;

6. CONCLUSIONS

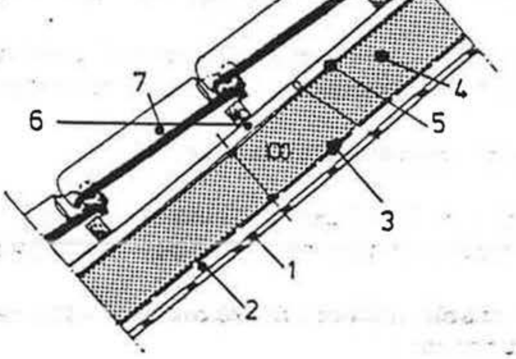
The research gave interesting conclusions and showed how insulated sloped roofs should be constructed:

- tiled and slated decks are air open enough to need no extra venting features;
- no positive effects of deck-ventilation on the moisture load of tiles underroof, laths and battens found. Reasons:undercooling, neutralising effective winterly drying + the suction behaviour laths and battens, making them wetter if, undercooled, ventilation is increased!
- a ventilation space between the underroof and the thermal insulation can be the step to get very ennuyous stack effects with extra heat losses and more interstitial condensation.
- At the lewside, a ventilation space, being in underpressure, activates inside air and vapour flow through each non airtight roof with, extra condensation, loss of thermal quality, etc;
- at the windside, outside air may flow through, causing very high ventilation rates and cooling the internal lining or, locally, the leaky zones...

These conclusions are alarming enough to leave the ventilation concept and introduce a new design philosophy for insulated sloped roofs:

THE SANDWICH SOLUTION.

From in- to outside (figure 5):



1. inside lining
2. wiring cavity
3. AIR and VAPOUR barrier
4. MW- thermal insulation, filling the whole space
5. UNDERROOF, acting as secundary rain barrier, wind barrier, dust barrier
6. laths and battens, the battens for drainage reasons
7. roof covering

FIGURE 5. The sandwich solution

3 and 4 or 3, 4 and 5 may hygrothermally be combined in 1 layer: airtight mounted, airtight insulation slabs. However, from an acoustical and form freedom point of view, this choice performs poorer.

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AN INVESTIGATION INTO THE POSSIBILITY OF USING LITHIUM- AND RUBIDIUM SALTS AS TRACERS FOR MOISTURE TRANSPORT IN BUILDING MATERIALS

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ABSTRACT

The results of experiments performed to investigate the possibility of tracing moisture transport in brick walls by injection of solutions containing lithium and rubidium as tracer elements, are described. Lithium and rubidium show to be promising tracer elements. Sampling and analitical techniques have been developed.

INTRODUCTION

Capillary moisture transport and ion-diffusion through pore water play a major role in several types of damage to building materials such as moisture stains, salt efflorescence and disintegration of bricks, joints, mortar etcetera.
In order to investigate ion tracer movement as a possible detection technique for moisture transport in building materials in general and in brick masonry walls in particular, a number of tests was carried out at the TNO-IBBC laboratories (1).
At this moment there is little experience in using tracer elements for following moisture transport in building materials. In (2) and (3) some experiments are described, showing that rubidium (Rb) and cesium (Cs) may be used. Tungsten and molybdenum proved to be unsuitable. A tracer element should comply with the following requirements:

- The salt of the tracer element should be easily soluble in water;
- The tracer element should be detectable in small concentrations
- The salt should be capable of moving in aqueous solution through building materials without being hampered by absorption or adsorption effects and it should not react with the building materials;
- The tracer element should not occur in building materials, or occur in small amounts only;
- The salt should be not too expensive.

The first two requirements are important, because the element will be spread out through the building material by the moisture transport, which means that at some distance away from the injection point, the concentration of the element will show a large decrease.
The alkali elements Li, Na, K, Rb and Cs can be expected to fulfill the first three requirements. Na and K cannot be used because they occur in large amounts in building materials. From the other three elements it can be expected that Li, because of its relatively small ionic size, will have the greatest mobility in aqueous solutions. On the other hand, some Li salts are, compared to other alkalis, less soluble (the hydroxide and carbonate for example). Also Li is more strongly adsorbed, for instance by clays, than the other alkalis.

EXPERIMENTS

In this study, it was decided to perform the experiments using Rb and Li. Cs was not used because it is expected to be the least mobile element of the alkalis due to its relatively large ionic size. The salts used were rubidiumcarbonate (Rb_2CO_3) and lithiumacetate ($CH_3COOLi.2H_2O$). Both are highly soluble in water. Lithiumacetate had the advantage of being readily available, while rubidiumcarbonate showed to be very expensive.

The general procedure followed was injection of the solution containing the tracer elements in small brickwork panels in a small drilled hole with a diameter of 8 mm and a depth of approximately 25 mm. In the hole 1 ml of a solution of the salt of the tracer element was injected using a micropipette. The panels were placed in a shallow pond of tap water. After allowing water transport to take place for some time, samples were taken by drilling at various locations. Li and Rb were extracted from the powder samples by shaking with demineralized water. After centrifuging, the clear solution was analyzed by Atomic Absorption Spectroscopy. The detection limits for Li and Rb were 30 and 100 ppb respectively.
The experiments that were performed included:
- Analysis of the amounts of Li and Rb present in several building materials;
- Optimization of experimental conditions such as concentrations of solutions, injection methods, sampling and sample preparing techniques and analyzing methods;
- Experiments to confirm that Li and Rb in fact are being transported in building materials by water movement;
- Experiments to investigate how the tracer elements in the brick walls are distributed by the moving moisture in different conditions, and give information on the reproducibility of the method chosen at the hand of preceding experiments.

The occurrence of Li and Rb in building materials.

Several common building materials were analyzed for their Li and Rb content. Samples were crushed and milled. Li and Rb were extracted by shaking with cold, demineralized water. Also the total amount of Li and Rb in two samples was determined by extraction with a concentrated mixture of hydrochloric and nitric acid. The results of the analyses are shown in table 1.

Transport of the tracer elements

From the initial experiments, performed on single bricks and small brick walls, it was concluded that injected solutions with a high concentration of Li or Rb were transported by water moving in the building materials. The sampling and sample preparation method, as well as the analysis of the sample solutions, gave satisfying results.
The following experiments were performed using the conditions that according to these first experiments seemed optimal. In a series of experiments, concentrated solutions of lithiumacetate and rubidiumcarbonate were injected in the lower bricks or joints of small brickwork panels with a size of approximately 200 x 200 x 100 mm^3. After that, the panels were placed in tap water, and were allowed to take up

Table 1. Analyzed Li and Rb concentrations in building materials.

Sample description	Li (ppM)	Rb (ppM)
brick (IJssel clay)	120	-
brick (clay from Noord Brabant)	200	-
brick (clay from Noord Brabant)	320	-
brick (Rhine clay)	200	-
brick (Rhine clay)	220	-
sand from Noord Brabant	80	-
sand from Groningen	60	-
sand from Drenthe	100	-
travertine	-	-
black marble	80	-
green granite	-	200
unhardened portland cement	1380	2680
tap water	-	-
sea water	210	650
brick (clay from Noord Brabant)[1]	-	200
sand from Drenthe[1]	-	150

[1] : extracted with HCl-HNO_3 solution
-: concentration below detection limit

take up water by capillary suction. Several kinds of bricks were used. Samples were taken by drilling powder after 72 hours. In general, at this moment the waterfront reached to just below the third layer of bricks. The solutions used contained 50 g/l Li, and/or 50 g/l Rb. The results of the analysis of drill samples taken from the brick walls were the following:

Both Li and Rb were distributed by the moisture transport that took place in the walls. The distribution patterns varied for the different walls that were examined, but in general it appeared that at certain distances away from the injection spot, larger Li concentrations were present than Rb concentrations. This means, that Li is transported faster by the moving moisture than Rb.
Also it was evident that in mortar samples the concentrations of Li and Rb were higher than in samples taken from the bricks. In case the solution of the tracer elements was injected in joints, this effect was more pronounced then if injection took place in the bricks. Also Rb showed a higher tendency than Li to get concentrated in the joint mortar.
These effects are illustrated by figure 1, where some typical examples of distribution patterns are shown. In this figure the distribution patterns in the bricks and the joints are shown separately.
Overall, it appeared that the results of this series of experiments, regarding the maximum distribution distances of Li and Rb, showed a good reproducibility.
Similar experiments were performed with a solution containing 3 % by mass of NaCl instead of tap water. From the observed distribution patterns it was clear that the salt solution was capable of raising to a higher level in the walls than tap water. Also it showed that there were much smaller differences in concentrations between brick and mortar samples.

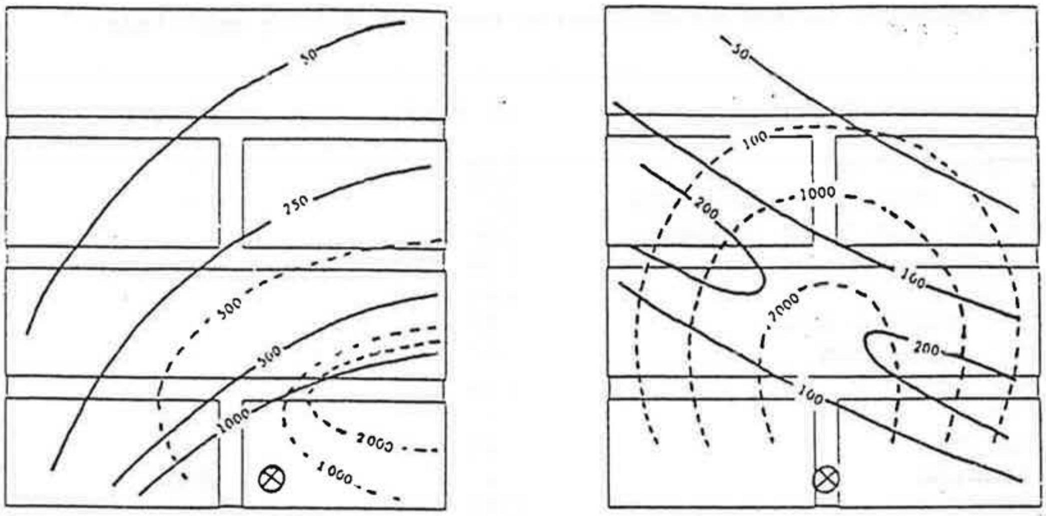

FIGURE 1. Schematic illustration of distribution patterns of the tracer elements in brickwork panels, shown by isoconcentration lines, after injection and upward movement of water.
Left: distribution of Li in bricks (solid lines) and joints (dotted lines); injection in brick.
Right: distribution of Li in bricks (solid lines) and joints (dotted lines); injection in joint.
Concentration values in ppM. ⊗ : injection spot.

INTERPRETATION

As shown, both tracer elements are transported by moisture transport in the investigated brick walls. The fact that Li is found in higher concentrations than Rb, means that Li moves faster than Rb.
The fact that in some way the elements seem to be concentrated in joints is probably due to physical rather than chemical effects. The mortar is capable of retaining a larger water content than the bricks, because it contains more and finer pores. This means that mortar can take up water out of the pores of the bricks by capillary action, while for the bricks it is difficult to take up water out of the mortar. This also causes the moisture front to stop raising at the second joint/brick interface when no NaCl is added to the transporting solution. In general, one should bear in mind, that differences in concentrations are partially caused by differences in water content of the samples.
A chemical effect, for example the precipitation of lithiumhydroxide or lithiumcarbonate in the joints, is unlikely, because Rb (that does not form hydroxide or carbonates with low solubility) also is found in higher concentrations in the mortar.
This is also clear from the experiments, in which a salt solution instead of water was used. Salt generally makes capillary action faster, and allows water to pass more easily through brick/joint interfaces. In these experiments the water front reaches the top of the panels. Li also reaches the top, while Rb stays behind. Also it was evident that differences between concentrations of samples of mortar and bricks differed much less using NaCl solutions as transport medium than when water was used.

CONCLUSIONS

From the conducted experiments the following conclusions can be drawn:

- By injection of an aqueous solution of lithiumacetate or rubidiumcarbonate in brick panels and subsequent analysis of drilled powder samples the movements of moisture can be traced. Li seems to be more mobile in the panels than Rb;
- The method used for sampling, sample preparation and analysis gave satisfying results;
- The possibility that lithium compounds (carbonate, hydroxide) with low solubility could precipitate in mortar joints was not confirmed;
- The natural occurring amounts of Li and Rb in building materials have no influence on the possibility of tracing moisture transport. The relatively high concentrations in uncured portland cement were not found in hardened mortar;
- The salt concentrations after injection and transport by moisture movement are not homogeneously spread. The highest concentrations are found near the injection point. Mortar can hamper the transport of water and of the tracer elements. These effects are smaller when a salt solution moves through the building material instead of relatively pure water.

FURTHER RESEARCH

Before the proposed method can be used in practice, further experiments are needed. It seems necessary to perform more tests, using different combinations of building materials and test structures of greater size. At present, at the TNO-IBBC laboratory experiments are in progress on brick walls, made from different brick/mortar combinations, in which a stationary moisture transport takes place. Also tests using the method in practice, in buildings that suffer damage caused by moisture transport, are being developed.
Also more experiments are needed which give more insight into the physical and chemical processes that take place in building materials in which moisture, containing tracer elements and other salts, is transported. These experiments could explain unexpected effects that are likely to occur when using the method in practice. In this way, it might be possible to develop a satisfying method for tracing moisture transport in buildings, which could be of great help in evaluating and solving the problems caused by moisture transport in building materials, such as massive masonry walls.

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MODELLING WATER VAPOUR CONDITIONS IN AN ENCLOSED SPACE

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INTRODUCTION

In the U.K. the usual method for calculating inside vapour pressure is the mass transfer equation where the mean moisture generation rate is equated to the mean outside vapour pressure and the ventilation rate, so;

p(gen) = n (p(in) - p(out)) ;

where: p(gen) = vapour pressure generation rate.
n = ventilation rate.
p(in), p(out) = inside and outside vapour pressures.

This equation was used by Loudon in his 1971 paper on condensation and mould growth, and as shorthand it will be refered to as the Loudon equation. When the moisture behaviour in a building was monitored in detail, this model proved unsatisfactory in both the equilibrium and dynamic cases. It was necessary to allow for the fact that building materials absorb and desorb moisture. Here, this effect will be termed 'moisture admittance' because it is useful to draw attention to the similarity between this and thermal admittance. Additional terms to account for absorption, desorption and condensation are required for this equation, and the following proposes such an equation and sketches in the method whereby the various coefficients used were derived.

MOISTURE ADMITTANCE MODEL

In order to study the moisture admittance effect, two experimental rooms were arranged at BRE which enabled the temperatures, vapour pressures, ventilation rates and moisture inputs to be measured. One room had all surfaces covered with metallic foil so it would behave as the 'Loudon' model, and the other room had the four walls and ceiling lined with pine matchboarding to give a high moisture admittance.

Experiments in the wood lined room with no moisture input, showed that the relative humidity of the air tended to remain constant if the temperature was varied slowly. Thus at low temperatures, water was absorbed into the material and at high temperatures water was desorbed from it.

If the extreme case of a small sealed test chamber is considered, where there is a large volume of material and a small volume of air, the relative humidity of the air is determined by the amount of moisture held in the material. Much work has been done on the subject of sorption isotherms, particularly in Denmark, which link the moisture content and equilibrium relative humidities for a wide variety of materials. In real buildings however, the relative humidity cannot be defined so readily since, (1) the limiting case of material to air volume ratio does not apply and (2) the ventilation to outside has a considerable effect.

If the Loudon model is extended to describe the dynamic situation, the equation would be;

$$\frac{d(p(in))}{dt} = n(p(in) - p(out)) + p(gen);$$

To account for the moisture movement into and from the materials of the room and the condensation on a window the following equation is proposed;

$$\frac{d(p(in))}{dt} = n(p(in)-p(out)) - a\,p(in) + b\,p(svp) + p(gen) - g(p(in)-p(win))$$

p(svp)	=	inside saturation vapour pressure.
p(win)	=	vapour pressure at the surface of the window.
a	=	absorbtion coefficient.
b	=	desorbtion coefficient.
g	=	condensation factor.

The method adopted to solve for the inside vapour pressure was to use a finite difference computer program which derived values of p(in) calculated from the measured values of values of n, p(out), p(gen) and p(svp), which is derived from the inside air temperature. Measured and simulated profiles of the inside vapour pressure for periods of up to 6 days were produced and compared with each other. The values of 'a', 'b' and 'g' which produced the best fit were adopted.

As already mentioned, when the temperature is varied slowly, the relative humidity tends to stay constant. In order to decouple the effect of ventilation and determine the RH associated with moisture content of the wood, a small metal cone was fixed around the temperature and humidity sensors and the wide, open end was sealed against the wood surface. The RH values given by this instrument proved to be remarkably steady.

In the equilibrium state when p(in) is steady, and there are no moisture inputs,

$$n(p(out) - p(in)) - a\,p(in) + b\,p(svp) = 0;$$

and when the ventilation rate is zero,

$$\frac{p(in)}{p(svp)} = \frac{b}{a}$$

i.e. this leads to the relative humidity.

When conditions in the wood room were steady it was assumed that the area sampled by this cone has equilibriated with the rest of the wood in the room, i.e. there were no significant moisture content gradients across the surfaces. Thus measurements made from a small sample of wooden surface could be applied to all the wood in the room. Since the b/a ratio found in this way depended on the moisture content of the wood, it was influenced by the immediate past history of the conditions in the room. Experiments involving humidification in the room subsequently increased the moisture content of the wood giving an a/b ratio of about 0.7, whilst periods of drying out gave a ratio of about 0.55.

When the value of the ratio b/a obtained by this method was used in simulations of dynamic situations with varying temperature and moisture inputs the results proved consistant. In the three examples which follow, all the measurements were made in the centre of the room and the ventilation rates were measured using SF6 decay techniques.

Case (1). The desorption of water vapour under cyclic changes of temperature.

When the temperature is cycled the vapour pressure profile follows the temperature profile very precisely. Fig (1) shows an example of the measured and simulated profiles of vapour pressure obtained when a fan heater was run for 8 hours a day in the wood lined room. The ratio b/a was given from previous cone experiment, and it was found that any value of 'a' from about 0.002 to about 1.5 gave good agreement for the max and min of the observed values. However the absolute values of 'a' and 'b' affected the shape of the simulated vapour pressure profile. In this case the most satisfactory simulation was obtained using values for a = 0.1. and b = 0.057, i.e. b = (b/a)/10.

Also shown in this figure is a comparable simulation using the 'Loudon' model, here the small variation of the vapour pressure is due to air exchange with outside.

Case (2). The absorption of cycling moisture input at steady low temperature.

Water vapour was introduced into the wooden room using an evaporator humidifier which was weighed before and after each input period of six hours. There was no heating and there was virtually no condensation observed. Fig (2) shows the measured vapour pressure profile and the simulations obtained by the two models, here the 'Loudon' simulation gave an exaggerated response to the vapour input. In this case the admittance model profile proved to be sensitive to the absolute values of 'a' and 'b' but again the value of a = 0.1 gave the best fit.

Case (3). The combined absorption, desorption and condensation effects.

In this experiment the heating was cycled and produced high maximum temeratures of about 30 C, water vapour was input from the evaporator at the same time as the heating, and because of the resulting high humidities and cold outside temperatures there was considerable condensation produced on the window surface.

The processes of condensation and evaporation can be modelled with some complexity, but for this relatively simple situation with single glazing, it was assumed that the inside window surface temperature was the same as the outside air temperature. The term p(win) was thus equal to the outside saturation vapour pressure, which was derived from the measured values of outside temperatures. The condensation function (g), applicable to the particular window was found by doing simulation runs in the foil room where the terms 'a' and 'b' were zero, in this case the value of 'g' was found to be 0.03.

Fig (3) gives the three profiles for vapour pressure; measured, moisture admittance and 'Loudon' simulations. In this situation the Loudon simulation is not as far out as in the previous cases, because the absorption and condensation effects are compensated by the desorption effect.

These examples show the scope of the proposed moisture admittance model, but if it is to be taken further the values of 'a' and 'b' need to be explored. Here the coefficients have been derived empirically for an unfurnished test room lined with wood and heated with a fan heater placed near the centre of the room. That is, there was little variation of the surface temperatures around the room. In practice, surface temperatures will vary widely, and the surfaces will be made up of a variety of materials, consequently, one area could be acting as a moisture source and another area could be acting as a moisture sink.

The vapour exchange between surfaces may be likened to the radiant energy exchanges between six surfaces modelled in thermal analysis. The environmental temperature seen at the centre of the room is derived from a summation of the thermal admittance factors AY, and it is suggested that the vapour pressure at the centre of the room can be predicted using an integrated moisture admittance function.

In order to calculate the 'a' and 'b' values a summation is required which needs the sorption properties of the various materials, their respective areas, their average water contents, and surface temperatures. For general use this calculation is unmanagable and needs to be simplified. For most practical purposes, categories of high, medium and low moisture admittances applicable to summer and winter conditions could be defined, and values for these cases evaluated.

To conclude, consideration should be given to the use of this admittance model and its advantages over the previous Loudon type model. The examples have shown that the moisture admittance model gives consistent agreement with measured results over a wide range of situations, but the Loudon model only applies when conditions are such that the condensation and absorbtion balance the desorption.

Clearly for dynamic modelling the moisture admittance model is a significant improvement. Accurate dynamic modelling of buildings can be important for example, when conditions for mould growth are considered. One important parameter is the 70% index, this is the percentage of time that the room air is at a relative humidity at or above 70%. The moisture admittance functions could be incorporated into many of the building humidity prediction programs to give such an index at a design stage. Some steady state models such as recent versions of BREDEM use the 'Loudon' model to predict humidity levels. In spite of the inherent smoothing of the data because mean values are used, there are some circumstances such as cases (1) and (2) considered here, where the accuracy of the modelling may be improved if moisture admittance terms were included. It would be worthwhile to investigate the sensitivity of such models to the inclusion of the additional terms.

FIG.1 CYCLING TEMPERATURES ONLY, NO MOISTURE INPUT.

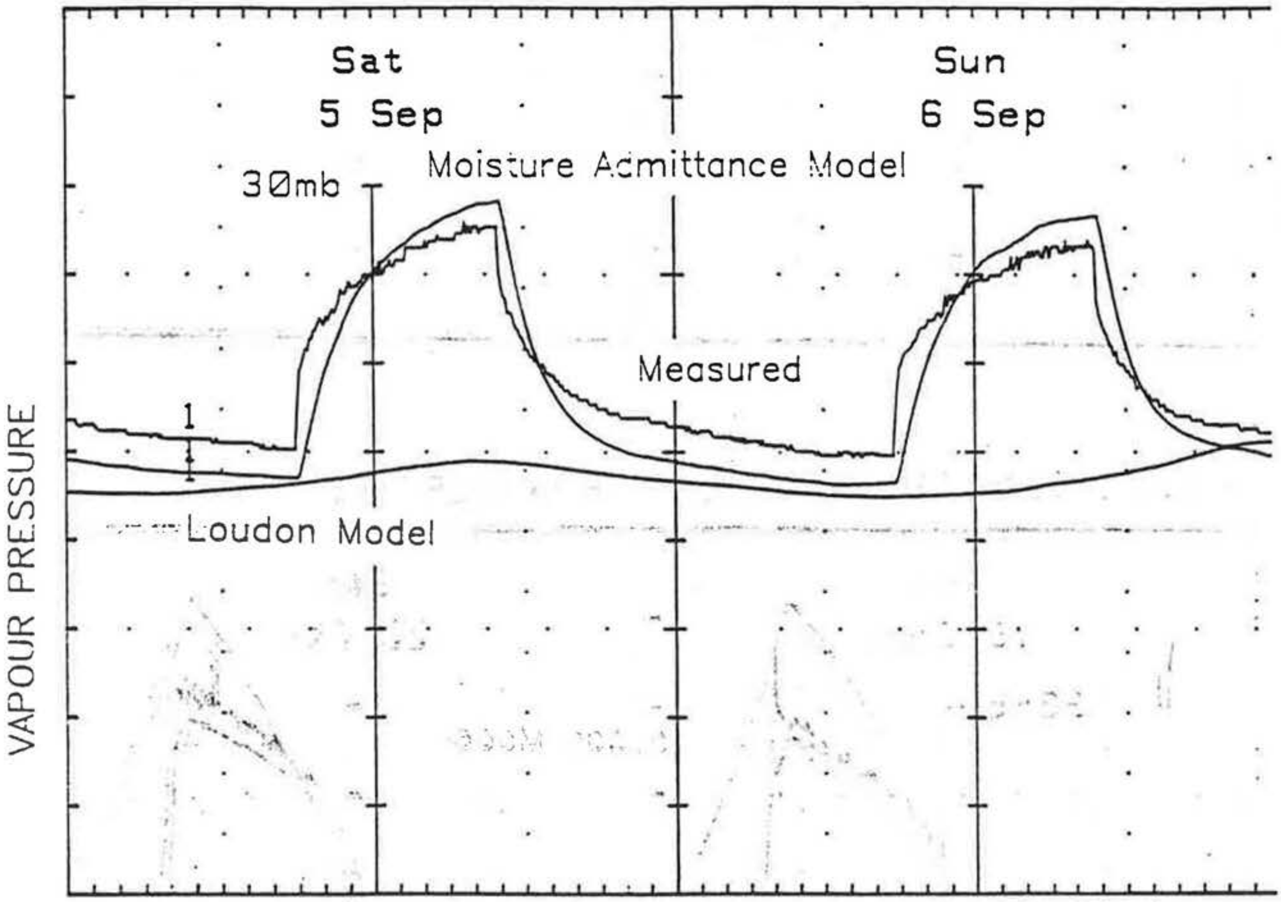


FIG.2 CYCLING VAPOUR INPUT AT CONSTANT TEMPERATURE.

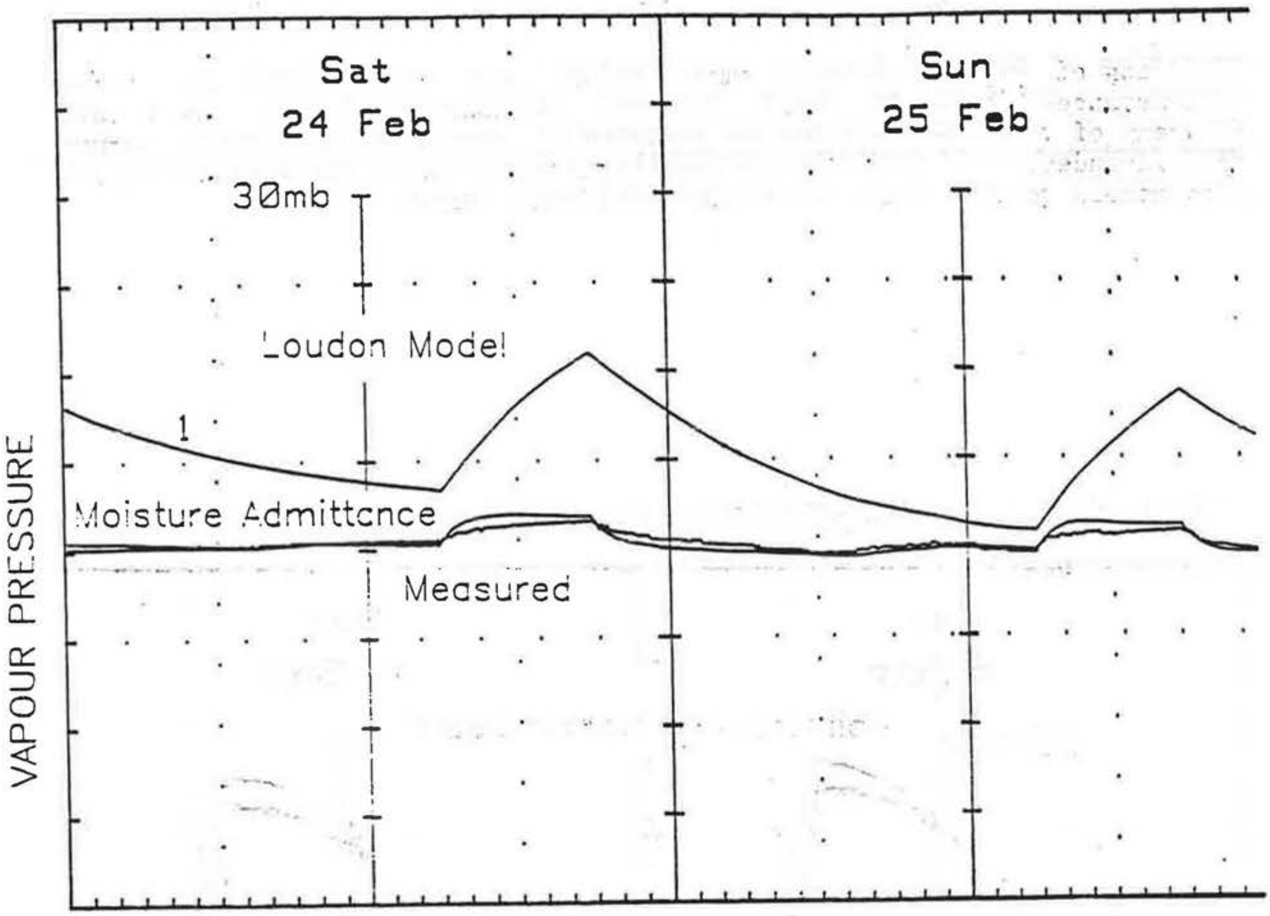
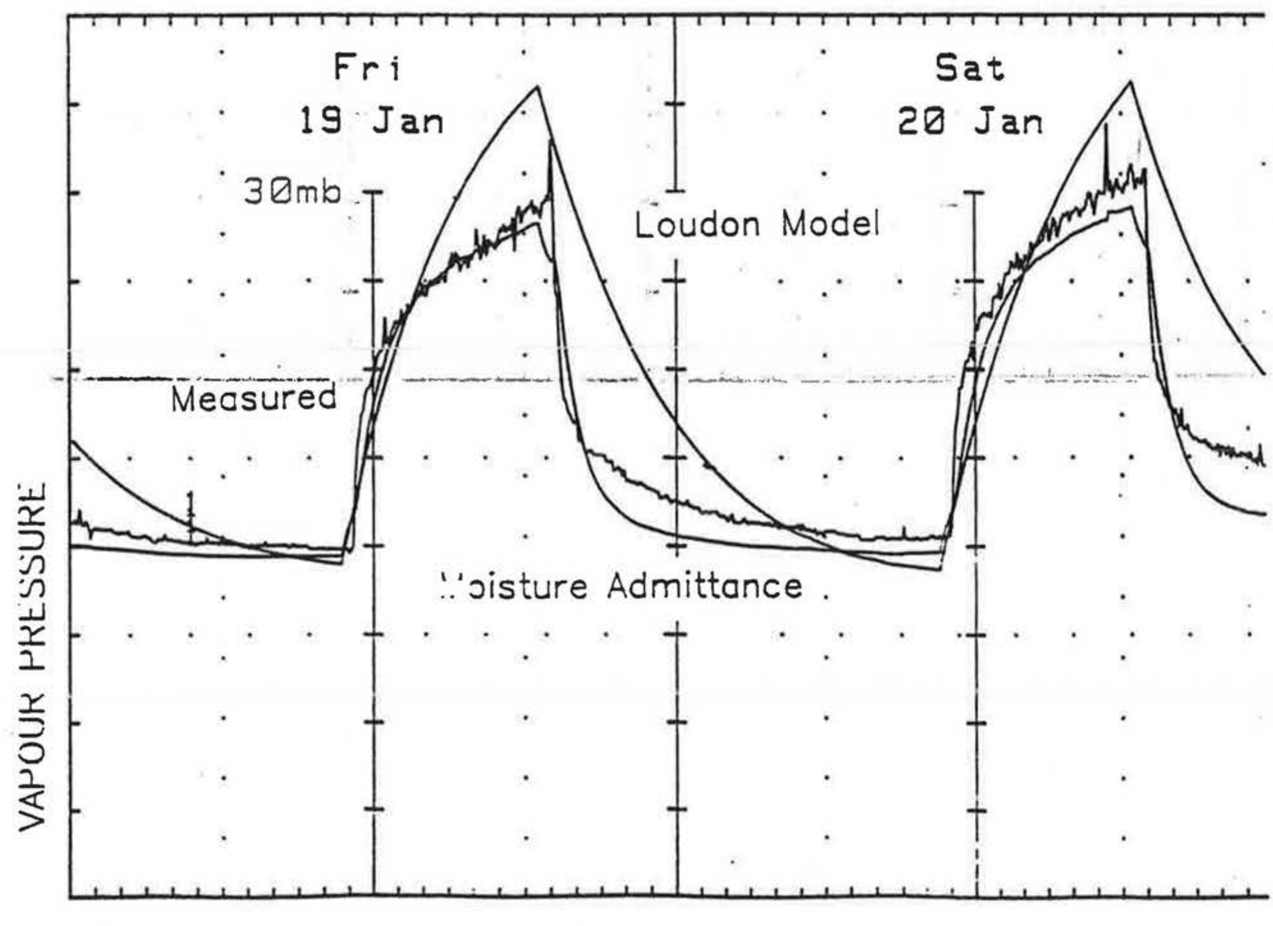


FIG.3 CYCLING TEMPERATURES WITH VAPOUR INPUT.



PREVENTION OF INTERSTITIAL MOISTURE PROBLEMS IN THE BUILDING ENVELOPE BY MEANS OF A NEW VAPOUR RETARDER

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ABSTRACT

Experience over the years has shown that the traditional remedy against interstitial moisture problems, to install a vapour barrier on the warm side of the insulation in the exterior building envelope in many cases is not a safe way to prevent interstitial moisture problems. This is especially the case for flat roof systems.

In the paper a new approach to prevent moisture problems in flat roofs, the Hygrodiode concept, is introduced. The concept is composed of two main parts. First, the main reason for moisture migration into a flat roof system which is convection through leaks in the vapour barrier shall be eliminated by not ventilating the roof system. Second, a new membrane, the Hygrodiode, shall be used as vapour barrier or vapour retarder. The Hygrodiode membrane has a sufficiently low permeability to reduce the moisture migration into the roof system by vapour diffusion to an insignificant amount, but is permeable to moisture which condenses on the membrane in sunny periods. This also means that moisture trapped in the roof system during construction or later through leaks can migrate to the underlying room.

In the paper, results from a test hut with a number of different flat roof systems are described which prove the validity of the Hygrodiode concept.

KEY WORDS: Vapour retarders, Hygrodiode, drying of constructions, field test.

INTRODUCTION

To prevent interstitial moisture problems in the building envelope due to condensation, it has been common practice in most countries in the cold or temperate climate zones to install a vapour barrier or vapour retarder with a low water vapour permeability on the warm side of the thermal insulation layer. The purpose of the vapour retarder is to reduce the amount of water vapour migrating into the envelope by diffusion to an amount to be small enough to migrate through the envelope to the outside without causing condensation.

Experience has shown that the amount of water vapour which migrates into the envelope by diffusion through a vapour retarder with even a moderate diffusion resistance is insignificant compared to the amount that will migrate into the envelope by convection through small leaks in the vapour retarder membrane. Unfortunately experience has also shown that it is very difficult in practice to install a vapour retarder to be air proof. The problem of interstitial condensation is less pronounced in walls than in roofs.

Flat roofs constitute a special problem owing to the highly impermeable roofing membrane.

The traditional solution to this problem is for warm deck roof systems to install a vapour barrier with a very low permeability on the structural deck below the insulation. For cold deck roof systems a vapour retarder with a somewhat higher permeability is installed in combination with a ventilated void between the insulation and the deck. Experience over the years has shown that many such roofs suffer from moisture diseases. The reasons are that rain water entering during construction or later through leaks will be trapped between the two impermeable membranes, the vapour barrier and the roofing, when there is no ventilation. For ventilated cold deck roof systems, moist room air will enter through unavoidable leaks in the vapour retarder by convection due to the stack effect during the cold season and cause condensation in periods when the roofing is colder than the dew point of the room air.

In the following, a new remedy against moisture disease in flat roofs, the Hygrodiode concept (1), will be introduced.

THE HYGRODIODE CONCEPT

To prevent water vapour from migrating into the roof system by convection through leaks in the vapour retarder both warm and cold deck roof systems shall be unventilated, making use of the air tightness of the roofing.

Water vapour migrating into the roof system by diffusion during the cold season shall be reduced to an amount which will not increase the moisture content to a critical value for fungal attack in timber based roof systems, cause corrosion on metal parts or decrease the insulation value significantly. This means that a vapour retarder with a sufficiently low permeability shall be included below the insulation.

To allow moisture trapped in the roof during construction or later through leaks in the roofing to migrate out of the roof system the vapour retarder membrane shall be permeable to water. Such a membrane has been developed a few years ago and is patented in most industrialized countries.

In the first two years of marketing the Hygrodiode has been installed in approximately 100.000 m^2 of flat roof systems in Denmark.

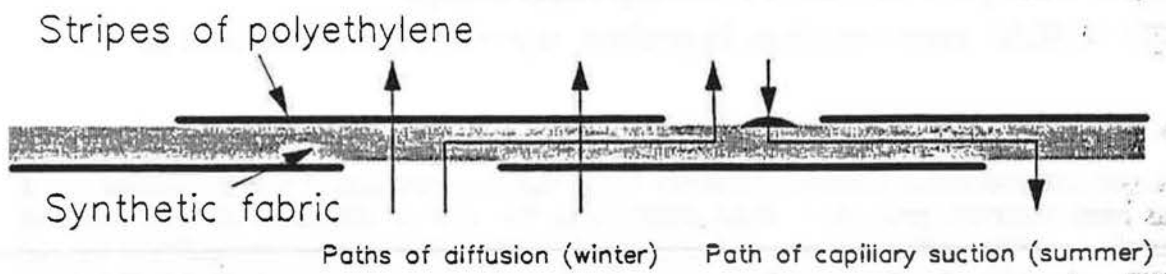

FIGURE 1. Design of the Hygrodiode.

The Hygrodiode (R), figure 1, consists of synthetic fabric with good capillary suction properties sandwiched between stripes of diffusion tight plastic film. The stripes are staggered with an overlap. The size of the overlap and the thickness of the fabric together with the permeance of the plastic film stripes determine the diffusion resistance of the Hygrodiode. With a fabric thickness of 0.3 mm, an overlap of 60 mm, a film width of 180 mm and a permeance of 0.2 ng/m^2sPa the diffusion resistance of the Hygrodiode is approximately 100 $GPam^2s/kg$ corresponding to an 0.05 mm PE-film. This means that less than 100 g/m^2 of moisture will diffuse through the membrane during a typical northern European winter.

Moisture trapped or migrating into the roof system will accumulate directly under the roofing during the winter. When the sun heats the roofing, the partial saturation pressure will increase drastically with temperature and drive the moisture by diffusion through the insulation layer where it will condense on the relatively cold Hygrodiode membrane. By wicking action the condensate will pass through the membrane to the supporting deck and migrate into the underlying room.

The drying capacity of the Hygrodiode is shown in figure 2.

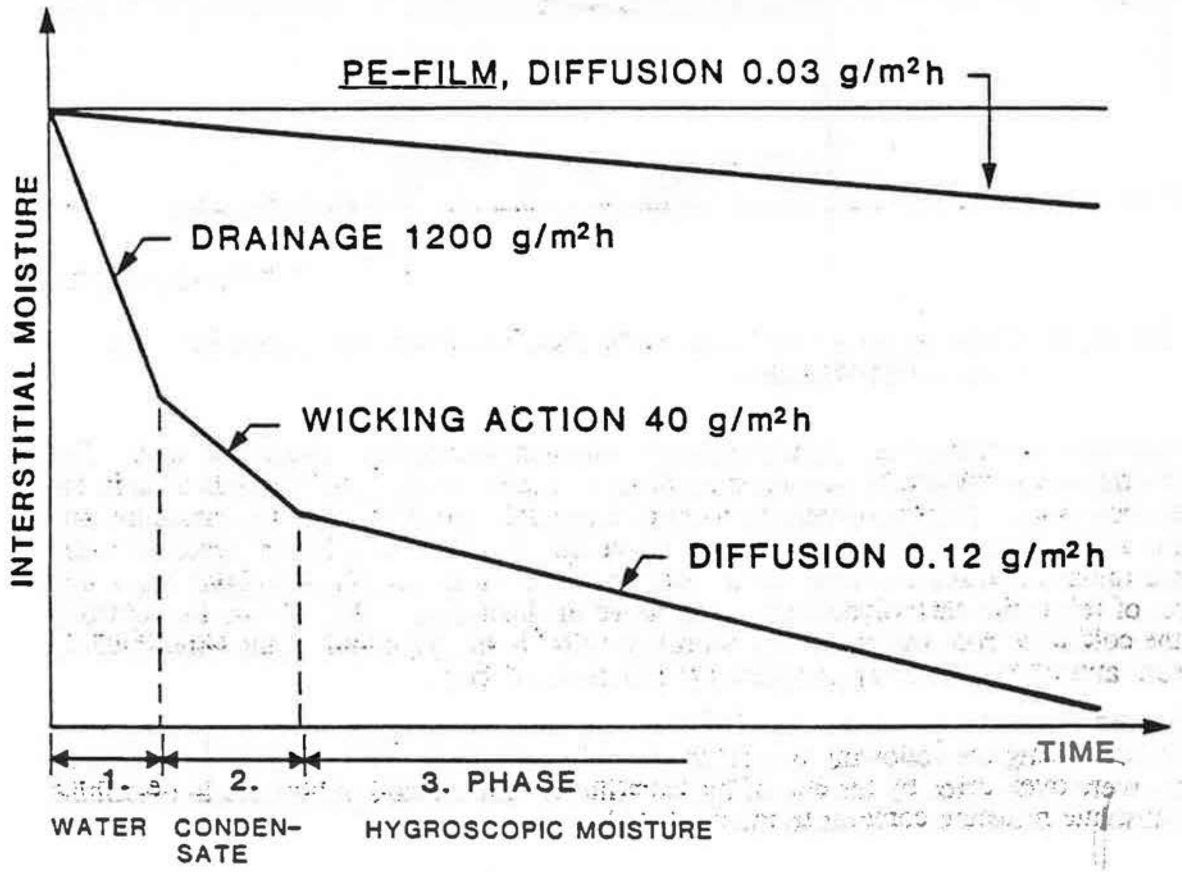

FIGURE 2. Drying capacity of the Hygrodiode.

TEST HUT

A small test hut has been built in the field at the Technical University of Denmark. The building consists of two rooms. One room was kept at typical dwelling conditions for temperature and humidity, i.e. 20°C and 3 g more moisture per cubic meter in the indoor than in the outdoor air. The other room was kept constantly at 20°C and 60% RH. The temperatures of both rooms were allowed, however, to exceed 20°C in the summer as no cooling was provided. The roof of the test hut had 8 rectangular holes, each 35 by 40 cm, over each of the rooms. Different roof specimens with the Hygrodiode as vapour retarder were located in each of these holes as shown in figure 3.

The specimens were wrapped in an envelope of heavy polyethylene on all but the bottom side with the vapour retarder. The sealing between the Hygrodiode and the polyethylene wrap was done by carefully taping the two materials together. The specimens were mounted so that they could be pulled down and weighed regularly.

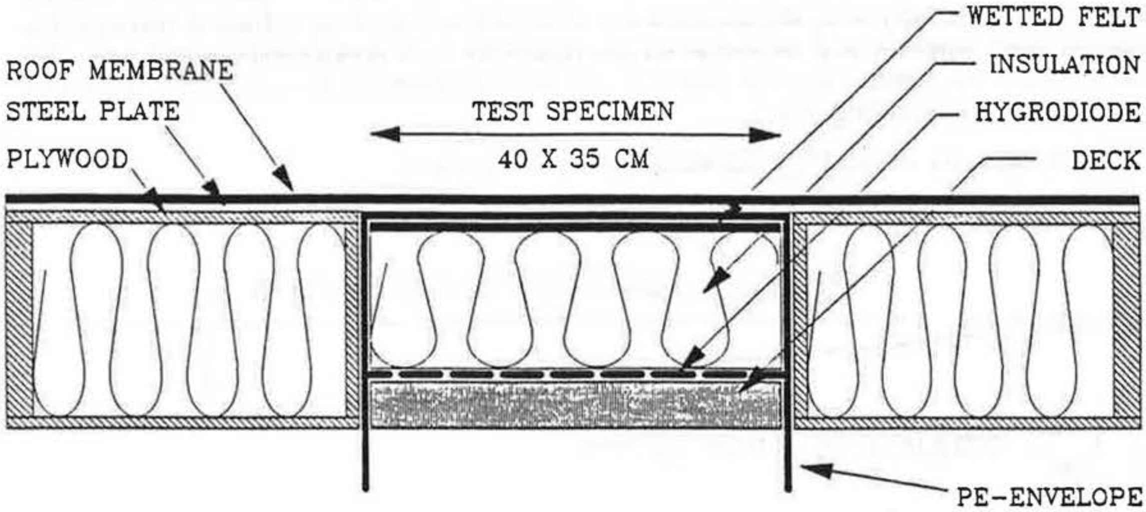

FIGURE 3. Cross section of one of the warm deck roof specimens for the field test with the Hygrodiode.

Above the specimens was a dark roofing of bitumen strewn with granulated slate. The membrane was supported over the specimens by a steel deck. The materials used in the specimens were 150 mm of mineral wool or expanded polystyrene for the insulation and either a cold deck of 12.5 mm plywood above the insulation or different types of warm decks under the insulation and vapour retarder. The warm deck constructions had a thin layer of felt inside the polyethylene wrap above the insulation. This felt and the plywood in the cold deck roof was immersed shortly in water at the beginning of the experiment to absorb approximately 500 g moisture per square meter roof.

The experiment was started in May 1988 and the moisture contents of the specimens were followed during the following two summers and one winter. The materials in the specimens were oven dried by the end of the experiment, thus making it possible to determine the absolute moisture contents in the test panels.

TEST RESULTS

Results of the weighings are shown in figure 4 for four of the test panels. Two of the panels are from the room with dwelling conditions while the other two are from the humid room. The materials in the test specimens are listed in the figure. Apart from the deck material two of the panels, one from each room, are practically identical. They are of the warm deck type and have mineral wool as insulation. The second panel from the room with dwelling conditions was insulated with expanded polystyrene, while the second panel from the humid room was a cold deck roof with plywood on the outer side of the insulation.

Despite of the fact that the summer of 1988 was not a very sunny one, the added moisture was dried out of all four panels within the three to four summer months. There are some differences, however, in the drying rates and in the amount of moisture that was accumulated in the winter that followed.

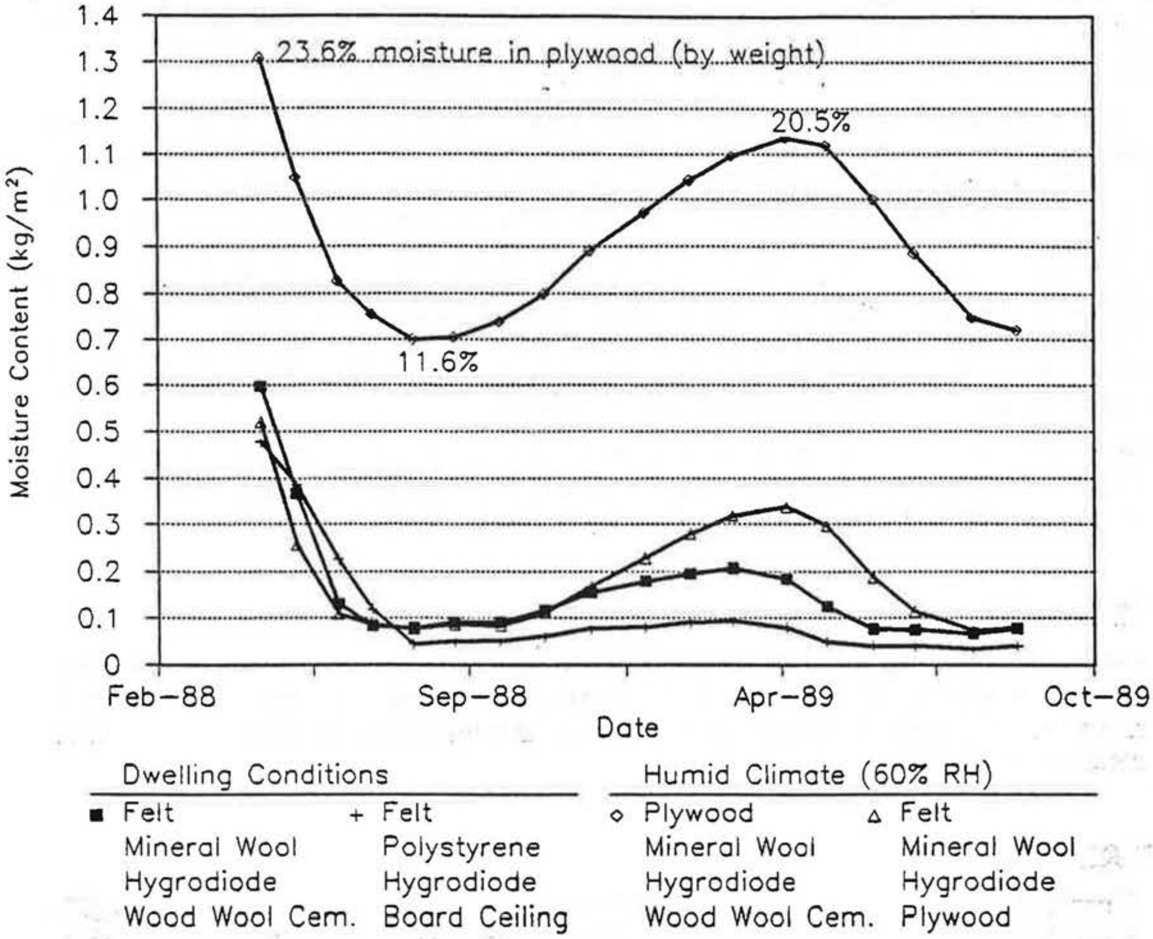

FIGURE 4. Moisture content in four of the roof test panels from the field test with the Hygrodiode vapour retarder.

The two warm deck panels with mineral wool had the same high drying rates. They dried out in only two months. The identity in drying rates between the two rooms may be explained by the relative humidity in the room with dwelling conditions to be close to 60% as the moisture content of the air is highest in the summer. The rate of moisture absorption in the winter was much higher, though, in the humid room than in the room with dwelling conditions. In this room, the panel gained more than 0.2 kg/m^2 while the gain was only half of this in the room with dwelling conditions. This moisture dried out again within the first months of the second summer.

The drying rate in the panel with expanded polystyrene insulation was approximately half of that of the drying rate in the similar panel with mineral wool. But this panel hardly gained any moisture in the winter. The primary cause for these observations is the smaller permeability of the polystyrene. Less moisture will migrate from the top of the roof through the insulation and condense on the Hygrodiode on a summer day when polystyrene is used. The moisture does however accumulate at the bottom of the insulation during the summer and it will finally be dried out.

The moisture content in the panel with the cold plywood deck looks differently because the plywood holds not only the moisture that was added initially but also hygroscopic moisture which will never be dried out. The major concern is to get the moisture content in the plywood deck below 20% by mass as this is considered the critical limit for fungal attack. This corresponds to approximately 1.1 kg moisture per square meter roof, disregarding the moisture content in the other layers of the construction.

The moisture content in the plywood started from 23.6% and fell to 11.6% the first summer. The drying rate was slightly smaller for this panel than it was for the warm deck panels with the same, permeable insulation. The reason is the hygroscopic capacity of the wood, i.e. the moisture is released at a vapour pressure less than saturation. This hygroscopically low vapour pressure is also responsible for the faster moisture gain in the winter. The moisture content ends up around the critical limit by the end of the winter when the temperature is still low, which means that the growing conditions for fungi are poor. The moisture dries out again in the next summer. It may be assumed that the moisture content in the plywood would have been safely below 20% if the roof panel had been installed over the room with dwelling conditions.

Assuming effective water vapor permeabilities for the Hygrodiode in its dry and wet state, some of the results shown above have been verified by a computer program, MATCH, for combined heat and moisture transfer in composite constructions (2).

CONCLUSION

The results from the test hut measurements of the seasonal moisture content in a number of different flat roof systems prove that the Hygrodiode concept described in the paper is able to dry out moisture trapped in the roof system and make sure that the roof insulation will continue to stay dry.

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CORROSION STOP IN REINFORCED CONCRETE WALLS CAUSED BY THERMAL INSULATION SYSTEMS

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ABSTRACT

Concrete structures often show surface deterioration by rebar corrosion - and outer walls of reinforced concrete do so, too. State-of-the-art repair of these walls is expensive and may cause some imperfections, because the usual working method provides numerous repair steps.

This paper presents a new concept in arresting rebar corrosion in outer layers of sandwich walls made of reinforced concrete. Rebar corrosion in concrete simultaneously requires oxygene, an electrolyte and a depassivated steel surface. As tests made so far confirm it is possible to keep dry the outer walls of buildings in Central European climate by means of thermal insulation systems so that there is no electrolyte and corrosion stops. Consequently a usual concrete repair is not necessary.

1. PHYSICAL CONDITIONS OF REBAR CORROSION

Rebar corrosion in concrete requires the following physical conditions at the same time:

- oxygene is necessary,
- the passivation of the steel surface must be ruptured (by carbonation or chlorides) and
- the concrete moisture must enable an electrolyte.

The penetration of oxygene is inevitable because of the concrete porosity. Only a watertight coating of the reinforcement can prevent steel from getting in touch with oxygene (usual concrete repair, figure 1 left).

The carbonation of concrete is a slow but inavoidable process, the penetration of chlorides can be avoided. When the deterioration is visible, the passivation of the rebar surface is broken through.

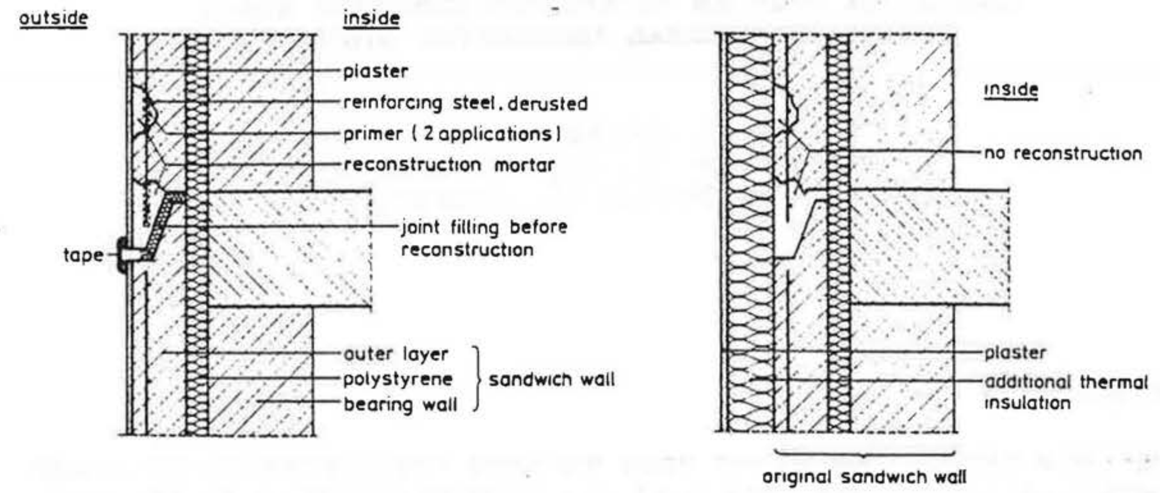

FIGURE 1. Thermal insulation instead of concrete repair: usual repair (left) and by a thermal insulation system (right) [1].

The third possibility of corrosion stop is to dry the concrete in a way that there is no electrolyte. Experiences in existing dwelling and office buildings show that the bearing walls are considerably carbonated, but there rebars do not corrode.

Calculations and experiments upon sandwich walls in Central European climate demonstrate that an additional thermal insulation (figure 1 right)

- reduces the moisture of the bearing wall a little bit,
- but significant reduces the moisture of the outer layer below the values of the bearing wall.

After mounting of a thermal insulation system the outer layer of the sandwich wall will not be moistened by stormy rain, too.

2. TESTS

As a practical test temperatures and moistures in sandwich walls with newly mounted thermal insulation systems are measured - in laboratory experiments and long time field tests. On the other hand reinforced and carbonated concrete specimens are stored at different relative humidities. Later the specimens are investigated for steel corrosion by weighing the material consumption (mass loss).

2.1 Measurement of Temperature and Humidity in Sandwich Walls

To verify the above mentioned theory temperatures and moistures in sandwich walls of reinforced concrete buildings with additional thermal insulation are recorded for a long time. The investigated thermal insulation systems are shown in table 1.

TABLE 1. Investigated thermal insulation systems.

No.	Thermal Insulation	Weather Protection
1	- (zero test)	-
2	rock wool	lime plaster
3	polystyrene foam	polymer plaster
4	fiberglass	curtain wall

Combined measuring transducers for temperature and equilibrium humidity are installed

- rain and sun protected in the atmosphere,
- in the bearing walls and the outer layers of the sandwich walls and
- in the used apartments behind the walls.

The measurements are recorded automatically by a print recorder on paper and by a personal computer on diskette.

As an example the evaluation of the temperature and moisture measurements in the bearing walls and outer layers behind two of the thermal insulation systems is shown in figures 2 and 3 from May 1988 to December 1989:

- The thermal insulation system made of rock wool with lime plaster shows about the same humidity in the bearing wall and the outer layer during the drying period of 1988, in 1989 only the bearing wall is moistening in summer (figure 2).
- The fiberglass insulation with a curtain wall is drying similar to the rock wool system with lime plaster (figure 3).

It is known by experience that the reinforcement in bearing walls of sandwich systems do not corrode in Central European climate - and in these figures it is evident that the outer layer is not as moist as the bearing wall. Thus the rebars in the outer layer will not corrode any more.

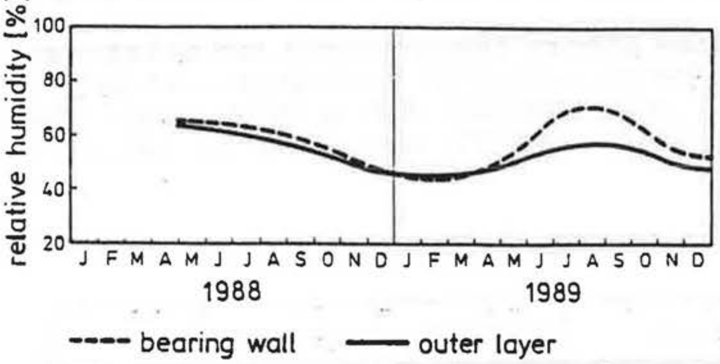

FIGURE 2. Relative humidity in a sandwich wall behind rock wool insulation with lime plaster.

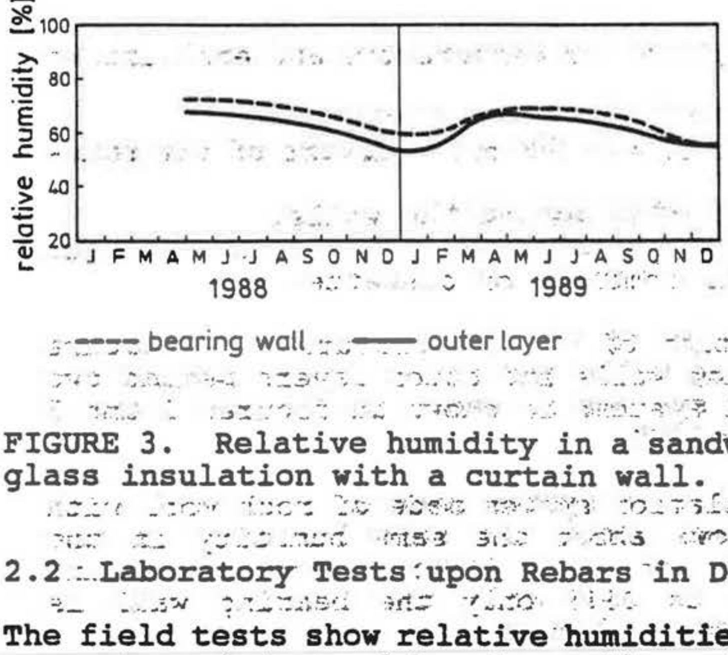

FIGURE 3. Relative humidity in a sandwich wall behind fiberglass insulation with a curtain wall.

2.2 Laboratory Tests upon Rebars in Different Climates

The field tests show relative humidities in equilibrium to the concrete moisture of bearing walls and outer layers of sandwich walls. The laboratory tests may show the maximum moisture, respectively the equilibrium humidity, in which reinforcing steel will corrode.

First reinforcing steel was tested in the atmosphere, i.e. the industrial atmosphere of Berlin (figure 4 left). Depending on the relative humidity of the surrounding climate the mass loss of different steel types can be found [2]. Perceptible corrosion seems to be possible at 60 % relative humidity or more.

On the other hand reinforcing steel specimens were outdoor tested behind thermal insulation systems over some months (figure 4 right). Protected by the above mentioned thermal insulation systems (cp. table 1), not by cement or epoxy coatings, the steel shows no corrosion. But in the atmosphere (annual average in Berlin 77 % r.h.), although rain protected, the specimens corrode.

Usually reinforcing steel is build in concrete and is passivated there. Outer walls of buildings not often show chloride corrosion, but often are carbonated. Presumably steel in carbonated concrete will corrode in another way than steel in the atmosphere, because

- the penetration of oxygene is more difficult,
- the index of pH of carbonated concrete is still higher than in industrial atmosphere and
- the electrolyte on the rebar surface is different to the electrolyte on unprotected steel.

In our laboratory concrete specimens with two steel types are made, which are carbonated in a carbon dioxide atmosphere. These specimens are stored in 60, 70, 80 and 90 % relative humidity and opened after different times, so the mass loss by corrosion is measured. The work is still in progress.

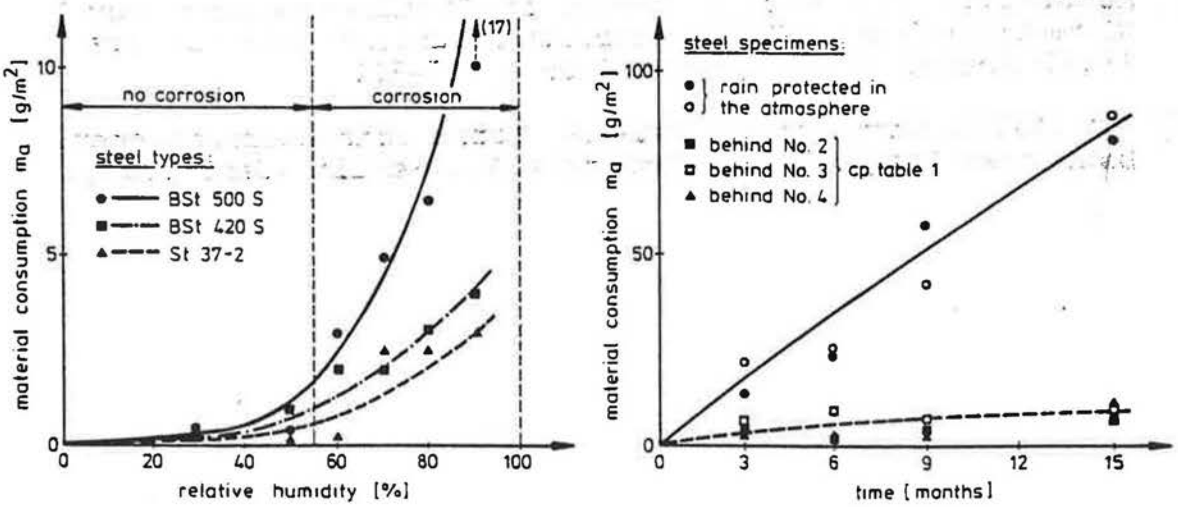

FIGURE 4. Mass loss of reinforcing steel specimens: after a 40 day storage in atmospheres of different humidities [1] (left) and in the real atmosphere respectively behind the thermal insulation systems mentioned in table 1 (right).

3. SUMMARY AND OUTLOOK

The field and laboratory experiments confirm the possibility to stop rebar corrosion in outer walls by means of thermal insulation systems:

- Reinforcing steel needs at least 60 % relative humidity (equilibrium humidity) for corrosion.
- An additional thermal insulation lowers the moisture in the concete layers of outer walls of reinforced conrete nearly to this value.

A state-of-the-art repair of the concrete surface seems not to be necessary in the future, because in dried concrete the electrolyte is missing.

The work is still in progress, now tests are started over a long time:

- the drying of sandwich walls with additional thermal insulation,
- the corrosion of reinforcing steel in carbonated concrete and
- the real corrosion stop in reinforced concrete walls of existing buildings with thermal insulation systems.

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A HARMONIC ANALYSIS OF PERIODIC STEADY STATE SOLUTION OF THE INTERNAL CONDENSATION PROCESS.

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ABSTRACT

To avoid internal moisture condensation damage in building wall, it is necessary to predict the annual variation of moisture content process through the wall. To evaluate moisture behavior of wall, periodic steady state solution is most reasonable.

In this paper, the periodic steady state solution of internal moisture condensation process in building wall is presented. Non-linear responses of the process are evaluated, under the condition that Fourier Series representation of inputs, out/indoor air humidity and temperature, is of 2 components of daily and annual cycle. From results of this analysis, the solution of this process can be discribed approximately with average term and 13 harmonic components whose frequencies are linear combinations of two frequencies included in inputs.

INTRODUCTION

Internal moisture condensation damages in building wall have occurred frequently even in the mild climate as Japan, because of the increase of thermal insulation of building wall and decrease of natural ventilation for the energy conservation. To obtain the reasonable solution of the problem, it is necessary to predict or compute the internal condensation process and variation of moisture content through the porous wall.

Internal moisture condensation process can be analyzed by the coupled heat and moisture transfer equations. The equations are non-linear equation due to the strong dependency of moisture conductivities and capacity on water chemical potential and temperature.

Since internal moisture condensation process is non-linear process and this process is described by the intensively coupled equations of heat and moisture transfer, procedure for solving the equations needs tedious calculations repeatedly to obtain the periodic steady state solution of the process (1). Assuming finite terms of Fourier Series as this periodic steady state solution, we can obtain the solution immediately (2).

In this paper, this periodic steady state solution of this process is analyzed by spectral analysis under the condition that Fourier Series representation of inputs, out/indoor air humidity and temperature, is of 2 components of daily and annual cycle.

Accuracy of finite Fourier Series representation is discussed.

GOVERNING EQUATIONS AND NUMERICAL ANALYSIS

The governing equations of heat and moisture transfer in the porous wall are written in the form (3) with the assumption of local equilibrium of moisture(4).

(moisture balance)

$$\rho_W \frac{\partial \psi_W}{\partial \mu} \cdot \frac{\partial \mu}{\partial t} = \frac{\partial}{\partial x}\left(\lambda'_\mu \cdot \frac{\partial \mu}{\partial x}\right) + \frac{\partial}{\partial x}\left(\lambda'_T \cdot \frac{\partial T}{\partial x}\right) \qquad [1]$$

(heat balance)

$$c\rho\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda e + r \cdot \lambda'_{TG}) \cdot \frac{\partial T}{\partial x} + \frac{\partial}{\partial x}\left(r \cdot \lambda'_{\mu G} \cdot \frac{\partial \mu}{\partial x}\right) \qquad [2]$$

where $\lambda'_T = \lambda'_{TG} + \lambda'_{Tl}$, $\lambda'_\mu = \lambda'_{\mu G} + \lambda'_{\mu l}$ [3]

Boundary conditions are as follows at the outer surface of the wall.

(moisture flow)

$$\alpha'_\mu \cdot (\mu - \mu_0) + \alpha'_T \cdot (T - T_0) = -\left(\lambda'_\mu \cdot \frac{\partial \mu}{\partial x} + \lambda'_T \cdot \frac{\partial T}{\partial x}\right) \qquad [4]$$

(heat flow)

$$\alpha \cdot (T - T_0) = -\lambda e \cdot \frac{\partial T}{\partial x} + r \cdot \left(\lambda'_{\mu l} \cdot \frac{\partial \mu}{\partial x} + \lambda'_{Tl} \cdot \frac{\partial T}{\partial x}\right) \qquad [5]$$

Moisture conductivities λ'_μ , λ'_T depend strongly on water chemical potential(moisture content or humidity) and temperature. Non-linearity of the equation[1],[2] is due to this strong dependency of the conductivities, mentioned above.

By the finite difference method using Crank-Nicolson scheme, non-linear differential equations [1]-[5] are solved numerically.

Usually, procedure to calculate the periodic stady state solution of the equations, needs tedious calculations repeatedly. To avoid this tediousness, in this study, a numerical method of periodic steady state solution which had been presented (5), are applied. In the periodic steady state solution, initial states of temperature and moisture are equal to the states at the time after 1 year,i.e. after one cycle. This numerical method is the shooting method for 2 points boundary value problem(6) to search the initial state.

NUMERICAL SOLUTION

The structure treated in this paper is internally insulated foam concrete building wall as shown as Fig.1. In this calculation, insulation layer and moisture barrier layer are assumed that thermal and moisture capacity are negligible, for convenience of calculation.

The annually periodic steady state solution is obtained using finite difference method. In finite difference equations, time and space increments are Δt=3600(s) and Δx=0.01(m) respectively.

Periodic steady state solution is obtained by the method(5) using finite difference equation. The solution obtained are analyzed by finite Fourier anlysis. The number of terms of Fourier Series is 4380 becouse discrete points of solution of finite difference equation are 8760 through a year.

Variations of out/indoor air temperature and humidity are as follows;

(indoor air variation)

moisture : $\mu r = -48273.52 + A\mu r \times SIN(\omega t)$ [6]

temperature: $Tr = 293.16 + ATr \times SIN(\omega t)$ [7]

(outdoor air variation)

moisture : $\mu o = -44731.69 + 8570.102 \times SIN(\Omega t - \phi) + A\mu o \times SIN(\omega t)$ [8]

temperature: $To = 288.8 + 11.3 \times SIN(\Omega t) + ATo \times SIN(\omega t)$ [9]

where $F=1/(365*24)$, $f=365/(365*24)$, $\Omega=2\pi*F$, $\omega=2\pi*f$, $\phi=2\pi*17*24*F$.
The amplitudes ($A\mu r$, ATr, $A\mu o$ and ATr) are listed in the Table 1.

NUMERICAL RESULS AND DISCUSSION

Calculated results of amplitude of water chemical potential at inner sarface is shown in Fig.2 and Fig.3.

Due to the non-linearity of the equations, Fig.2 shows that there are higher frequency components whose frequencies are 2F, 3F etc. in CASE5. Amplitudes of the higher frequency components are lower than 5% of annual cyclic component except for 2F component.

Fig.3 shows that there are components of higher frequency 2f,3f etc. of daily cycle and higher frequency 2F,3F etc. of annual cycle in CASE0.

Table 1. Amplitude of Outer Condition

	Indoor Condition		Outdoor Condition	
	$A\mu r$(J/Kg)	ATr(deg)	$A\mu o$(J/Kg)	ATo(deg)
CASE0	5000.	5.	-15000.	5.
CASE1/2	2500.	2.5	-7500.	2.5
CASE1	5000.	——	——	——
CASE2	——	5.	——	——
CASE3	——	——	-15000.	——
CASE4	——	——	——	5.
CASE5	0.	0.	0.	0.

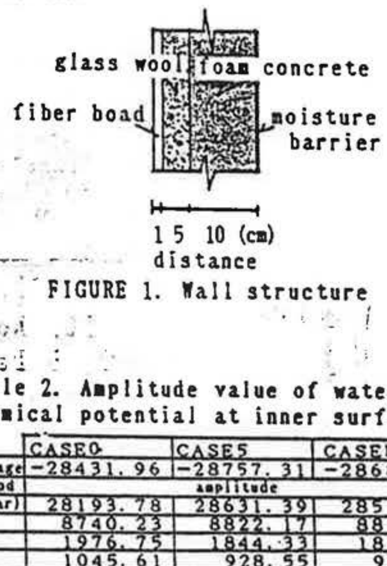

FIGURE 1. Wall structure

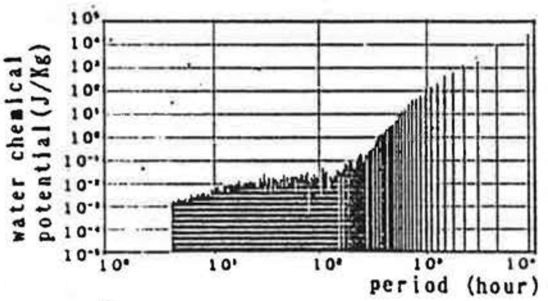

FIGURE 2. Amplitude of harmonic components of CASE5 at inner surface

Table 2. Amplitude value of water chemical potential at inner surface

	CASE0	CASE5	CASE1/2
average	-28431.96	-28757.31	-28682.95
period	amplitude		
1(year)	28193.78	28631.39	28530.56
1/2	8740.23	8822.17	8801.96
1/3	1976.75	1844.33	1879.99
1/4	1045.61	928.55	958.03
1/5	620.61	653.45	645.24
1/6	481.84	466.84	470.51
1/7	241.14	203.32	212.89
1/8	161.53	153.97	155.87
1/9	123.67	122.49	122.79
1/10	71.66	65.73	67.07
1/360	132.04	7.45E-3	68.14
1/361	466.08	8.39E-3	234.82
1/362	955.21	2.84E-3	482.44
1/363	2568.92	4.54E-3	1314.05
1/364	5424.09	7.04E-3	2793.06
1(day)	6670.44	5.11E-3	3436.91
1/366	4397.40	2.03E-3	2265.68
1/367	1197.75	2.22E-3	615.44
1/368	289.29	2.86E-3	151.65
1/369	272.71	2.16E-3	134.33
1/370	288.74	2.71E-3	115.92

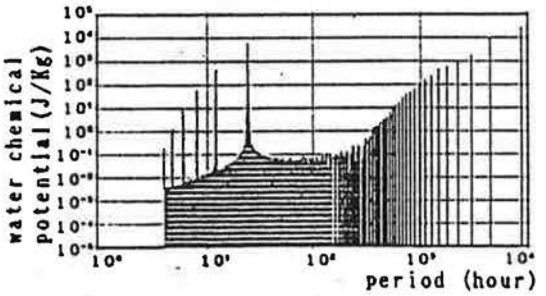

FIGURE 3. Amplitude of harmonic components of CASE0 at inner surface

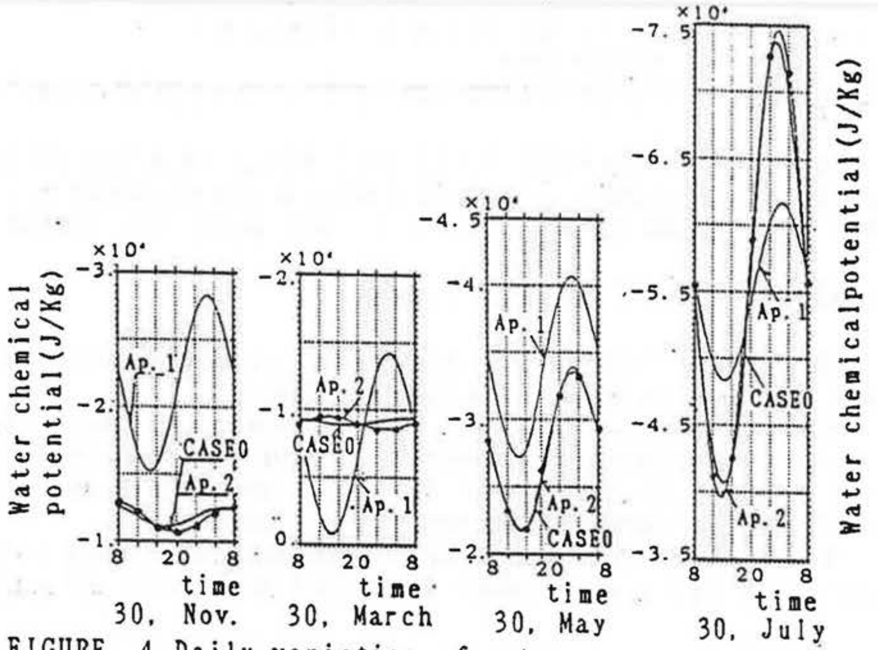

FIGURE. 4 Daily variation of water chemical potential at inner surface

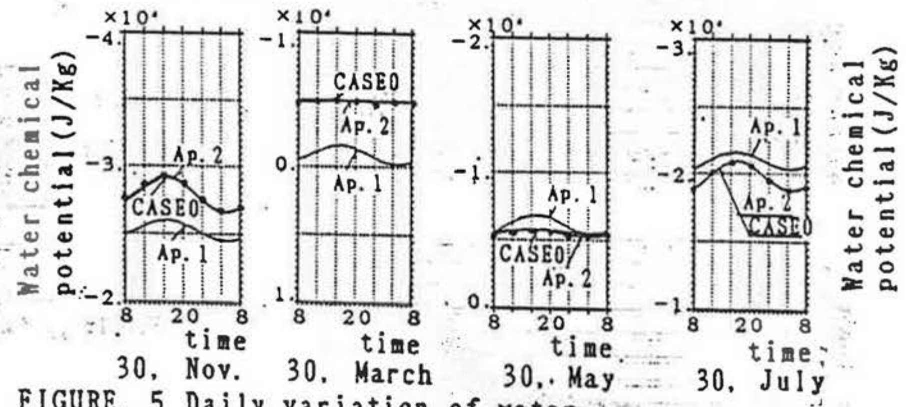

FIGURE. 5 Daily variation of water chemical potential at outer surface

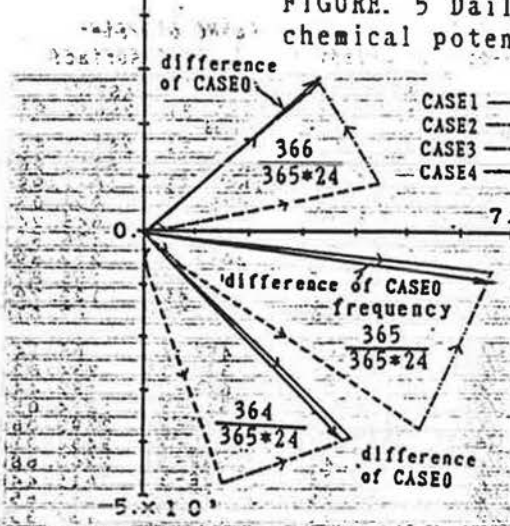

FIGURE 6. Result of vectorial summation of water chemical potential at inner surcace

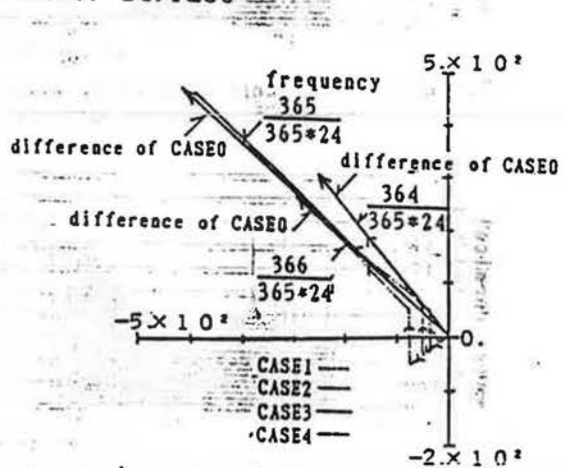

FIGURE 7. Result of vectorial sammantion of water chemical potential at outer surface

Results of CASE0 show that additional components such as $f \pm F, f \pm 2F$ etc. are generated by product of annual and daily cyclic component. Those amplitudes are comparable with daily cyclic component as shown in Table 2. Consequently, those components must be considered to describe the condensation process.

Comparison of results between CASE0 and CASE5 shows that daily cyclic input affects insignificantly on amplitude of annual cyclic component and it's higher frequency components as shown in Table 2.

Phases of annual cyclic components agree well between CASE0 and CASE5.

Daily variations of moisture potemtial are shown in Fig.4 and Fig.5. Approximation 2 (shown Ap.2 in Fig.4,Fig.5) means the approximate solution which includes average term and 13 components such as F, 2F, 3F, 4F, 5F, 6F,362F, 363F, 364F, f, 366F, 367F, 368F. Approximation 1 (shown Ap.1 in Fig.4 and 5) means approximate solution which includes average term and 2 components such as F, f. Fig.4 and Fig.5 show that approximation 2 agrees fairly well with the exact solution. Ratio of norm between approximation 2 and exact solution is 0.931 at inner surface. At outer surface, this ratio is 0.979.

The differences of amplitude between CASE5 and CASE1/2,CASE0 are calculated. The differences of amplitude in CASE1/2 are almost 1/2 of the differences in CASE0 of components whose frequencies are f and $f \pm F, f \pm 2F$ etc. as shown in TAble 2. It indicates that amplitude of component discussed above can be evaluated with linear operation.

Results of vectorial summation of the differences of CASE1, CASE2, CASE3 and CASE4 are shown in Fig.6 and Fig.7 with the exact solution, difference of CASE0, for frequency $f, f \pm F$. Fig.6 shows that the approximate solutions obtained by summation agree well with the exact solutions, difference of CASE0, at inner surface. Fig.7 shows good agreement between them as same as in Fig.6.

As for temperature, amplitudes of higher frequency component are insignificant. Temperature results can be described by solely 2 components whose frequencies are F and f. This indicates that system is almost linear in temperature.

CONCLUSION

The harmonic solution of moisture condensation process in building wall is evaluated with the boundary condition of 2 harmonic terms input.

It is shown that 4 or 6 components of higher frequency components of annual cycle are necessary to describe the annual variation of the moisture condensation process.

It is shown that contribution of higher frequency components (2f,3f etc.) of daily cycle is insignificant.

It is shown that the 6 product components, $f \pm F, f \pm 2F, f \pm 3F$, must be taken account for describing the daily variation of the process.

The periodic steady state solution of the process is approximated fairly well by average term and 13 components (6 annual components, daily component and 6 product components) of Fourier Series.

The daily variation of the process is approximated by summation of responses which are excited by each daily cyclic input.

NOMENCLATURE

T : temperature (K)
μ : water chemical potential (J/Kg)
ψw: volumetoric water content
r : heat of phase change (J/Kg)
ρw: water density of wet material (Kg/m^3)
$c\rho$: heat capacity of wet material (Kg/m^3)
λe: heat conductivity (w/mK)
x: space coordinate (m)
α: heat transfer coeficient (w/m^2 K)
t: time (s)
α'_μ : mass transfer coeficient of μ (Kg/m^{2}s J/Kg)
α'_T : mass transfer coeficient of T (Kg/m^{2}s J/Kg)
λ'_T : total moisture conductivity of T (Kg/msK)
λ'_{TG}: water vapor conductivity of T (Kg/msK)
λ'_{Tl}: liquid water conductivity of T (Kg/msK)
λ'_μ : total moisture conductivity of μ (kg/ms J/Kg)
$\lambda'_{\mu G}$: moisture conductivity of water (Kg/ms J/Kg)
$\lambda'_{\mu l}$: moisture conductivity of liquid water (Kg/ms J/Kg)

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AN ANALYSIS OF MOISTURE AND HEAT TRANSFER IN POROUS BUILDING WALL BY QUASILINEARIZED EQUATIONS

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ABSTRACT

In order to evaluate the hygric performance and the durability of building materials, understanding of transient thermal and hygric behavior in building wall, especially, the maximum values of moisture states in materials are required. As heat and moisture transfer equations are non linear equations of which nonlinearity depends on dependency of physical parameters on dependent variables, it takes a lot of time and labor to solve these equations. Avoiding those difficulties, linearized equations derived by quasilinearization of the nonlinear equations are shown. In this paper, degree of approximation of the linearized equations is discussed with varying dependency of physical parameters on dependent variables. It is concluded that the linearized equations give good approximate solutions for predicting moisture states in building structures.

INTRODUCTION

The equations which describe the heat and moisture transfer process in the porous building materials are nonlinear, for its coefficients are strongly dependent on dependent variables, such as water chemical potential and temperature [1·2·3]. And those equations are to be solved under variation of boundary values, such as outdoor weather condition, indoor air temperature and humidity. To solve the transient equations, tedious numerical calculations are required.
Approximated linear equations through the use of linear expansion for variations around the reference solutions of the nonlinear equations were presented, and the method of calculations of these equations was presented [4·5]. The accuracy of the approximation has been discussed with comparison between exact solutions and approximated solutions [6]. In this paper, relationship between dependency of physical parameters on dependent variables and nonlinearity of heat and moisture transfer equations is discussed. For the internally thermal insulated building wall, annual variations of temperature and moisture distributions are calculated. The approximated solutions by linearized equations are com pared with the exact solutions, and degree of approximation of the linearized equations is discussed.

THE GOVERNING EQUATIONS

The governing equations for describing the heat and moisture transfer in the porous building elements are as follows [5].

$$k(\mu,T)\cdot\frac{\partial \mu}{\partial t} = \nabla\lambda'_{\mu}(\mu,T)\cdot\nabla\mu+\nabla\lambda'_{T}(\mu,T)\cdot\nabla T \tag{1}$$

$$C(\mu,T)\cdot\frac{\partial T}{\partial t} = \nabla\lambda_{\mu}(\mu,T)\cdot\nabla\mu+\nabla\lambda_{e}(\mu,T)\cdot\nabla T \tag{2}$$

$$k(\mu,T)\doteqdot k(\mu)=\rho_{W}\cdot\frac{\partial\phi}{\partial\mu}, \qquad C(\mu,T)\doteqdot C(\mu)$$

Boundary conditions at the outer surface of the building wall are

$$-\lambda'_{\mu}(\mu,T)\cdot\frac{\partial\mu}{\partial n}-\lambda'_{T}(\mu,T)\cdot\frac{\partial T}{\partial n} = \alpha'_{\mu}(\mu,T)\cdot(\mu_0-\mu)+\alpha'_{T}(\mu,T)\cdot(T_0-T) \tag{3}$$

$$-\lambda_{\mu}(\mu,T)\cdot\frac{\partial\mu}{\partial n}-\lambda_{e}(\mu,T)\cdot\frac{\partial T}{\partial n} = \alpha_{\mu}(\mu,T)\cdot(\mu_0-\mu)+\alpha_{e}(\mu,T)\cdot(T_0-T) \tag{4}$$

Initial conditions are: at $t=0$; $\mu=f_{\mu}(x)$, $T=f(x)$ (5)

QUASILINEARIZATION OF THE EQUATIONS

Let $\tilde{\mu}$ and T are the solutions of Eq.(1)-(5). Other solutions under the different boundary values $({}_b\mu+\Delta\mu, {}_bT+\Delta T)$ are written as μ and T. Variations between them, i.e. $\mu-\tilde{\mu}$ and T-T are written as h_{μ} and h_T. By linearly expanding the second (exact) solutions around the first (reference) solutions, linearized equations for h_{μ}, h_T are obtained as follows, neglecting higher terms than the second order of h_{μ}, h_T [5].

$$k(\tilde{\mu})\cdot\frac{\partial h_{\mu}}{\partial t} = \nabla(\lambda'_{\mu}(\tilde{\mu},T)\cdot\nabla h_{\mu}) + \nabla(\lambda'_{T}(\tilde{\mu},T)\cdot\nabla h_T)$$
$$+ \left(\left(\frac{\partial\lambda'_{\mu}}{\partial\mu}\Big|\nabla\tilde{\mu}+\frac{\partial\lambda'_{T}}{\partial\mu}\Big|\nabla T\right)\cdot h_{\mu}\right)$$
$$+ \left(\left(\frac{\partial\lambda'_{\mu}}{\partial T}\Big|\nabla\tilde{\mu}+\frac{\partial\lambda'_{T}}{\partial T}\Big|\nabla T\right)\cdot h_T\right) - \frac{\partial k}{\partial\mu}\Big|\frac{\partial\tilde{\mu}}{\partial t}h_{\mu} \tag{6}$$

$$C(\tilde{\mu})\cdot\frac{\partial h_T}{\partial t} = \nabla(\lambda_{\mu}(\tilde{\mu},T)\cdot\nabla h_{\mu}) + \nabla(\lambda_{e}(\tilde{\mu},T)\cdot\nabla h_T)$$
$$+ \left(\left(\frac{\partial\lambda_{\mu}}{\partial\mu}\Big|\nabla\tilde{\mu}+\frac{\partial\lambda_{T}}{\partial\mu}\Big|\nabla T\right)\cdot h_{\mu}\right)$$
$$+ \left(\left(\frac{\partial\lambda_{\mu}}{\partial T}\Big|\nabla\tilde{\mu}+\frac{\partial\lambda_{T}}{\partial T}\Big|\nabla T\right)\cdot h_T\right) - \frac{\partial C}{\partial\mu}\Big|\frac{\partial T}{\partial t}h_{\mu} \tag{7}$$

These equations are linear and time variant equations.
Suppose that variations of boundary values are:

$\Delta\mu_b = {}_b\mu_0-{}_b\tilde{\mu}_0$ or ${}_b\mu_i-{}_b\tilde{\mu}_i$ (8)

$\Delta T_b = {}_bT_0-{}_bT_0$ or ${}_bT_i-{}_bT_i$ (9)

Quasilinearized boundary conditions, obtained by expanding around the reference solution $\tilde{\mu}$, T, are

$$-\lambda'_{\mu}(\tilde{\mu},T)\cdot\frac{\partial h_{\mu}}{\partial n} - \lambda'_{T}(\tilde{\mu},T)\cdot\frac{\partial h_{T}}{\partial n} = \alpha'_{\mu}(\tilde{\mu},T)\cdot(\Delta\mu_{b}-h_{\mu}) + \alpha'_{T}(\tilde{\mu},T)\cdot(\Delta T_{b}-h_{T})$$
$$+\left(\frac{\partial\alpha'_{\mu}}{\partial\mu}\Big|({}_{b}\tilde{\mu}-\tilde{\mu}) + \frac{\partial\alpha'_{T}}{\partial\mu}\Big|({}_{b}T-T) + \frac{\partial\lambda'_{\mu}}{\partial\mu}\Big|\frac{\partial\tilde{\mu}}{\partial n} + \frac{\partial\lambda'_{T}}{\partial\mu}\Big|\frac{\partial T}{\partial n}\right)\cdot h_{\mu}$$
$$+\left(\frac{\partial\alpha'_{\mu}}{\partial T}\Big|({}_{b}\tilde{\mu}-\tilde{\mu}) + \frac{\partial\alpha'_{T}}{\partial T}\Big|({}_{b}T-T) + \frac{\partial\lambda'_{\mu}}{\partial T}\Big|\frac{\partial\tilde{\mu}}{\partial n} + \frac{\partial\lambda'_{T}}{\partial T}\Big|\frac{\partial T}{\partial n}\right)\cdot h_{T} \qquad (10)$$

$$-\lambda_{\mu}(\tilde{\mu},T)\cdot\frac{\partial h_{\mu}}{\partial n} - \lambda_{e}(\tilde{\mu},T)\cdot\frac{\partial h_{T}}{\partial n} = \alpha_{\mu}(\tilde{\mu},T)\cdot(\Delta\mu_{b}-h_{\mu}) + \alpha_{e}(\tilde{\mu},T)\cdot(\Delta T_{b}-h_{T})$$
$$+\left(\frac{\partial\alpha_{\mu}}{\partial\mu}\Big|({}_{b}\tilde{\mu}-\tilde{\mu}) + \frac{\partial\alpha_{e}}{\partial\mu}\Big|({}_{b}T-T) + \frac{\partial\lambda_{\mu}}{\partial\mu}\Big|\frac{\partial\tilde{\mu}}{\partial n} + \frac{\partial\lambda_{e}}{\partial\mu}\Big|\frac{\partial T}{\partial n}\right)\cdot h_{\mu}$$
$$+\left(\frac{\partial\alpha_{\mu}}{\partial T}\Big|({}_{b}\tilde{\mu}-\tilde{\mu}) + \frac{\partial\alpha_{e}}{\partial T}\Big|({}_{b}T-T) + \frac{\partial\lambda_{\mu}}{\partial T}\Big|\frac{\partial\tilde{\mu}}{\partial n} + \frac{\partial\lambda_{e}}{\partial T}\Big|\frac{\partial T}{\partial n}\right)\cdot h_{T} \qquad (11)$$

Initial conditions are: at $t=0;\ h_{\mu}=0,\ h_{T}=0$ (12)

where $\tilde{\mu}$, T are the exact solution under boundary value of ${}_{b}\tilde{\mu}, {}_{b}T$. Solving the quasilinearized equations (6), (7) for dependent variables h_{μ}, h_{T} with quasilinearized boundary conditions Eqs.(10),(11) and initial condition Eq.(12), solutions h_{μ}, h_{T} are obtained.

The approximate solutions μ, T are: $\mu=\tilde{\mu}+h_{\mu}$, $\quad T=T+h_{T}$ (13)

CONDITIONS OF CALCULATIONS

Structure of Building Wall and Properties of Materials

Structure of building wall calculated is the internally insulated and externally hygric insulated wall as shown in FIGURE 1. Surface covers and thermal insulation layer are treated as having no thermal and moisture capacity. Physical values used in calculations are shown in TABLE 1.

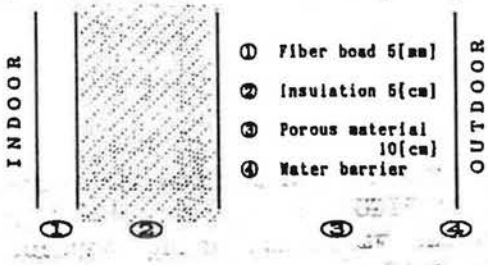

FIGURE 1. Structure of wall.

TABLE 1. Physical values.

Materials and air layers	Heat resistance [m²K/W]	Moisture resistance [m²sPa/Kg]
Indoor:		
Indoor air layer	0.108	8.00E+9
Fiber board	1.22	4.81E+8
Insulation	0.0538	3.42E+8
Outdoor:		
Outdoor air layer	0.0431	6.58E+8
Water barrier	———	8.00E+9

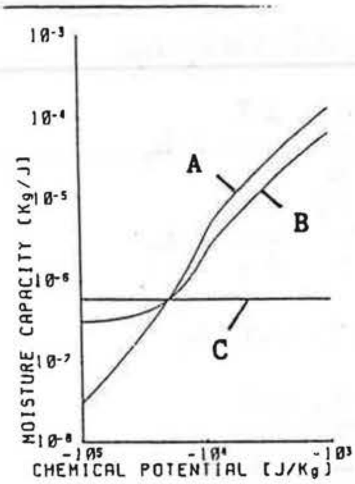

FIGURE 2. Moisture capacity $\partial\Phi/\partial\mu$.

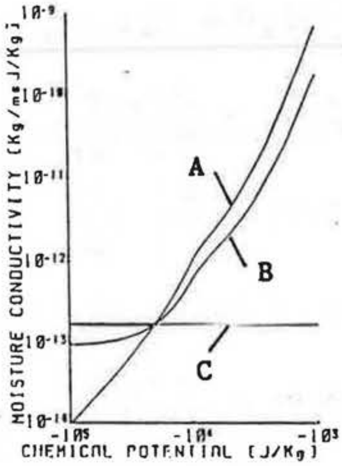

FIGURE 3. Moisture conductivity λ'_μ.

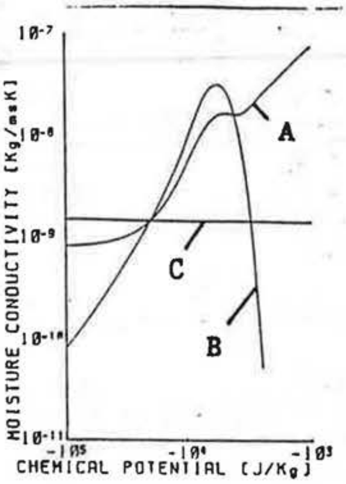

FIGURE 4. Moisture conductivity λ'_T.

Physical parameters ($\partial\Phi/\partial\mu$, λ'_μ, λ'_T) used in this study are shown in FIGURE 2-4. Curves of the largest dependency on water chemical potential in FIGURE 2-4 (curve A) are obtained by modifying the values of ALC for discussing the nonlinearity of the equations.

Boundary Conditions and Initial Condition

Boundary conditions for the reference solutions are as follows.
outdoor air:

$${_b\tilde{T}_0} = {_bT_{0,a}} + 11.3\cdot\sin(\omega t) \quad (14)$$

$${_b\tilde{\mu}_0} = R_v\cdot {_bT_0}\cdot\ln[{_bRH_{0,a}}] \quad (15)$$

where ${_bT_{0,a}}$=288.76 [K], ${_bRH_{0,a}}$=0.66, $\omega=2\pi/365\cdot24\cdot3600$ [s^{-1}].
indoor air:

$${_bT_i} = 293.16, \quad {_b\tilde{\mu}_i} = R_v\cdot{_bT_i}\cdot\ln(0.5) \quad (16)$$

Initial condition is: at $t=0$; $\mu=R_v\cdot T_0\cdot\ln(0.5)$, $T_0=293.16$ (17)

In this study, calculations under following boundary condition are shown. Variation of boundary value $\Delta\mu_i$ which is the most sensitive climatic function is a unit function ($\Delta\mu_0=\Delta T_0=\Delta T_i=0$). The amount of the unit function is 10^4 J/kg.

RESULTS

FIGURE 5 shows calculated results of which physical parameters are curve A. Deviations from the reference solutions in FIGURE 5, h_μ, are shown in FIGURE 6. FIGURE 7 is water chemical potential variation using physical parameters (curve B) that sensitiveness are half of the values of curve A. The amplitude of annual cycle and the error of approximation become smaller than that of FIGURE 5. On the case of parameter sensitiveness being zero (curve C), the approximated solution coincides with exact solution though there are dependency of λ'_μ and λ_T on temperature and dependency of α'_{μ} and α_T on temperature and moisture potential. The solutions of temperature show good agreement with the exact solutions.

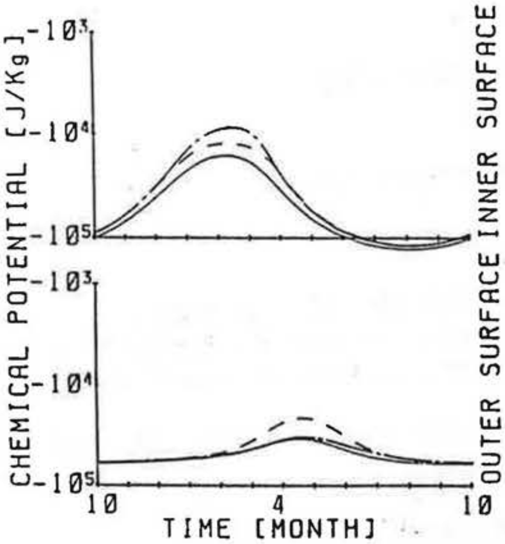

FIGURE 5. Fluctuations of μ (parameter values A).

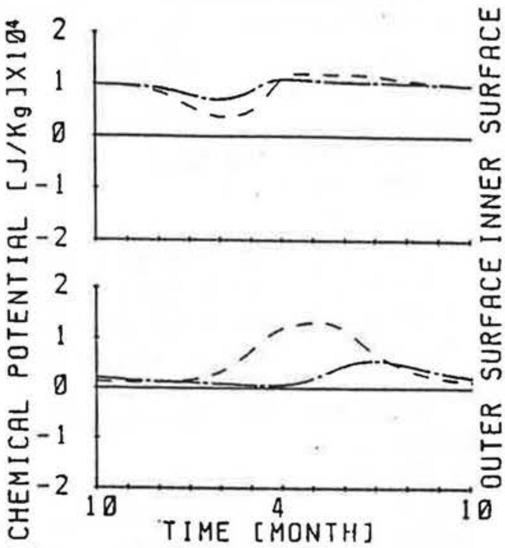

FIGURE 6. Fluctuations of h_{μ} (parameter values A).

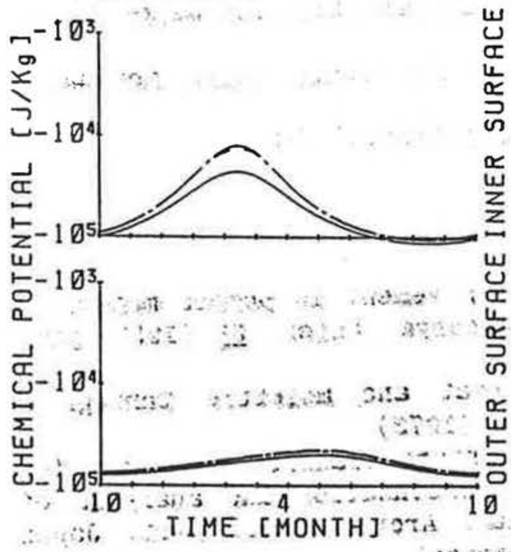

FIGURE 7. Fluctuations of μ (parameter values B).

CONCLUSION

1. Method of calculation of transient heat and moisture distribution in building wall by linearized equations are shown. The linearized equations by quasilinearization are obtained by expanding the exact solutions around the reference solutions. Those equations are linear and time variant.
2. Effects on accuracy of linear solutions of physical parameters dependency on dependent variables are discussed. Under usual condition and building construction, degree of approximation is fairly good. Linearized transient heat and moisture equations can give the useful solutions for evaluation of the hygric performance of building wall.
3. Nonlinearity due to temperature and transfer coefficients is relatively weak.

NOMENCLATURE

C $=c\cdot\rho$: heat capacity of wet material $J/m^3\cdot K$
c : specific heat of wet material J/Kg
h_T : variation of temperature K
h_μ : variation of water chemical potential J/Kg
RH : relative humidity
R_V : universal gas constant $J/Kg\cdot K$
r : the sensible heat of water vaporization J/Kg
T : temperature K
t : time s
α : thermal transfer coefficient $W/m^2\cdot K$
α_e $=\alpha+r\cdot\alpha'_T$: effective thermal transfer coefficient $W/m^2\cdot K$
α'_T : moisture transfer coefficient related to temperature $Kg/m^2\cdot s\cdot K$
α_μ $=r\cdot\alpha'_\mu$: thermal transfer coefficient related to water chemical potential $W/m^2\cdot J/Kg$
α'_μ : moisture transfer coefficient related to water chemical potential $Kg/m^2\cdot s\cdot J/Kg$
λ : thermal conductivity coefficient $W/m\cdot K$
λ_e $=\lambda+r\cdot\lambda'_{Tg}$: effective thermal conductivity $W/m\cdot K$
λ'_T $=\lambda'_{Tg}$: total moisture conductivity coefficient for temperature gradient $Kg/m\cdot s\cdot K$
λ'_μ $=\lambda'_{\mu g}+\lambda'_{\mu l}$:total moisture conductivity coefficient for water chemical potential gradient $Kg/m\cdot s\cdot J/Kg$
$\lambda'_{\mu g}$: moisture conductivity coefficient in gas phase for water chemical potential gradient $Kg/m\cdot s\cdot J/Kg$
$\lambda'_{\mu l}$: moisture conductivity coefficient in liquid phase for water chemical potential gradient $Kg/m\cdot s\cdot J/Kg$
μ $=R_V\cdot T\cdot\ln(P_V/P_{VS})$: water chemical potential J/Kg
ρ : density Kg/m^3
ϕ : water content %vol

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MOISTURE TRANSFER IN MATERIAL

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ABSTRACT

Calcium silicate board has recently been extensively used as an interior finish material for Japanese houses, in which the humidity needs to be controlled. The dependence of moisture diffusivity, due to both a moisture content gradient and a temperature gradient, and the thermal conductivity on the moisture content and the properties of the equilibrium moisture content curve in such calcium silicate board, were measured. Analysis showed that results were largely dependent upon levels of moisture content. The experiment on the condensation and re-evaporation process in interior finish materials, which are dampproofed on the vapor-barrier side, was carried out and the change of moisture content in materials over a period of time was measured. The results were compared with the analyzed value by simultaneous heat and moisture transfer equation. It was found that the equilibrium moisture content curve had a significant influence on the calculated value. It is proposed that the heat and moisture transfer equation is applicable in the case of the condensation and re-evaporation process.

1 INTRODUCTION

The analysis of moisture movement is very difficult and complex because vapor diffusion and liquid water movement, which occur at the same time, have an influence on each other, and the properties of the material change considerably depending on the moisture content and temperature of the given material. Studies dealing with quantitative analysis of the results of experiments on the condensation and re-evaporation process have been made by Kooi[1)], Matsumoto et al[2)], Mizuhata[3)](using cellular concrete),and Ikeda et al[4)](using soft fiber board). These studies suggest the validity of analysis of the condensation and re-evaporation by heat and moisture transfer equation. However, quantitative analyses of as many materials as possible are deemed necessary, since the thermal and moisture properties of building materials vary widely, even when they are of the same kind.

The purpose of this study is to obtain fundamental data on the design of condensation prevention methods, through theoretical analysis of and experiments on the moisture movement in the calcium silicate board, and through discussion of the validity of analysis using the simultaneous heat and moisture transfer equation.

2 THEORY AND CALCULATION

When the moisture content in materials is relatively low, then moisture diffusion depends almost entirely on the differences in moisture content, but when the moisture content is greater, moisture diffusion depends on differences not only in moisture content but also in temperature. Therefore in materials in which condensation occurs, moisture moves principally because of moisture content gradient and temperature gradient. Where there is no difference of pressure in a material and the influence of gravitation is negligible, then, for a one-dimensional flow the heat and moisture transfer equation can be expressed as; [5)]

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} D_\theta \frac{\partial \theta}{\partial x} + \frac{\partial}{\partial x} D_T \frac{\partial T}{\partial x} \quad (1)$$

$$c\gamma \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \lambda_\theta \frac{\partial T}{\partial x} + R \frac{\partial}{\partial x} \left(D_{\theta v} \frac{\partial \theta}{\partial x} + D_{Tv} \frac{\partial T}{\partial x} \right). \quad (2)$$

On the interior surfaces the boundary condition can be expressed as ;

$$\alpha'(p_i - p_s) = -D_\theta \frac{\partial \theta}{\partial x} - D_T \frac{\partial T}{\partial x}, \quad \alpha(T_i - T_s) = -\lambda_\theta \frac{\partial T}{\partial x}$$

in which the influence of adsorption heat on heat transfer is negligible.
On dampproofed surfaces the following equations apply ;

$$-D_\theta \frac{\partial \theta}{\partial x} - D_T \frac{\partial T}{\partial x} = 0, \quad T = T_d(t)$$

Numerical calculation is carried out using the Crank-Nicolson type explicit finite difference method. In numerical calculation time interval Δt is 1/10 hour and division interval Δx is 0.003 m (number of division 10). Stability of solution of this calculation has already been confirmed.

3 MEASUREMENTS OF MATERIAL PROPERTIES AND ITS RESULTS

3.1 Total moisture diffusivity due to moisture gradient[6)]

Method of measurement and measuring equipment used   For a one-dimensional flow, the Eq.(3) can be written thus for material that is isothermal and when the flow is in steady state ;

$$\frac{q_w}{\gamma} = -D_\theta \frac{\partial \theta}{\partial x}. \tag{3}$$

If moisture is provided at one end of the specimen and evaporates at the other end the moisture flow eventually becomes steady. After this the quantity of moisture flow q_w, and distribution of moisture content by dividing specimen and moisture content gradient $\partial\theta/\partial x$, are measured and D_θ is determined by Eq.(3).

The measuring equipment is shown in Fig.1. The specimen dimension is 3.0cm(l)×3.0cm(w)×4 cm(h). The specimen is thoroughly dried in an ovendryer at 105 ± 2 ℃ ,and its dry weight is measured. The side surface of the specimen is covered with aluminum tape to dampproof it, and the suction end of the specimen is covered with a cellophane semipermeable membrane. The membrane is installed to shield the air flow into the tank from the specimen, which is under constant suction pressure. Through control of the resistance of permeability of semipermeable membrane and control of the pressure by changing the vertical height of the tank from the mes-pipet to the top of the water tank, the evaporation and the average moisture content are controlled. As an acrylic acid resin vessel containing an NaCl-saturated water solution is mounted on the side on which evaporation occurs the humidity of the chamber is kept constant.

Measurement and the results   All the equipment was laid horizontally on the table in the room. The temperature of room air was kept at 20±0.5 ℃, and that of the chamber was kept at 20± 0.2 ℃. The inflow into the specimen was measured according to the distance moved by the meniscus of the water in the mes-pipet. Measuring was carried out daily, ensuring that there was always water in the mes-pipet. The experiment was continued until the change of the inflow became constant. Then, the specimen was removed from the equipment and the aluminum tape was removed. After measuring the weight of the specimen the width was cut with a multiband saw at approximately 5mm intervals. Using the same method as described previously all the pieces were then thoroughly dried and the dry weight and thickness of the pieces was measured. The achieved moisture content of each piece was regarded as the moisture content at the center of each piece. Measurement of 8 specimens was carried out. The moisture diffusivity D_θ which was obtained from stationary inflow and moisture content gradient of the specimen is shown in Fig.2.

3.2 Total moisture diffusivity due to temperature gradient[6)]

The method of measurement and measuring equipment   When there is no inflow the following equation can be written for a one-dimensional flow in a steady state ;

$$0 = -D_\theta \frac{\partial \theta}{\partial x} - D_T \frac{\partial T}{\partial x}. \tag{4}$$

Therefore, it follows that ;

$$\frac{D_T}{D_\theta} = -\frac{\nabla \theta}{\nabla T} \equiv \varepsilon. \tag{5}$$

where ε is the temperature gradient factor. Therefore, if the specimen is dampproofed on all surfaces, and a difference of temperature is maintained between both ends then a steady state will be achieved after a long while. Factor ε is determined by moisture content and temperature gradient at that time. Therefore, if ε and D_θ are known, the diffusivity due to temperature gradient D_T can be obtained thus ;

$$D_T = \varepsilon D_\theta. \tag{6}$$

The size of each specimen used was 45mm(l) × 45mm(w)× 30mm(h).To examine the dependence of temperature gradient coefficient on the average moisture content four kinds of specimens, of which the initial weight moisture contents was 9,20,30 and 40 % respectively, were used. For each kind of specimen, one for measurement of temperature distribution and seven for measurement of moisture content distribution, 32 specimens in all were used. As to the equipment of the experiment, the specimens, dampproofed on all surfaces with aluminum foil, were all put on copper plate on the same level and their side surfaces were insulated with foamed styrene so that heat flow might be one-dimensional as shown in Fig.3. Their upper surface was covered with a flat heating device, which was insulated with foamed styrene ,and on this a copper plate was placed so as to attach the heater and specimens. The entire equipment was put in the climate room.

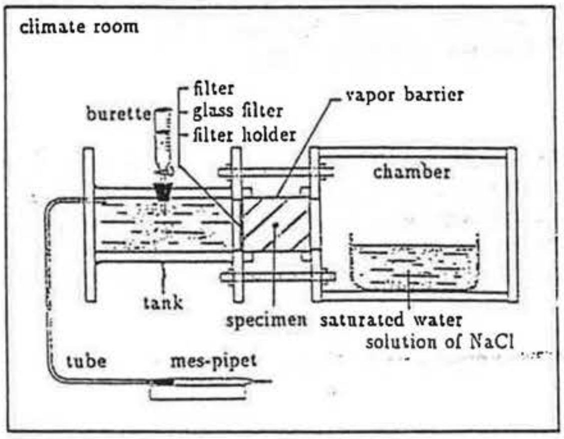

Fig.1 Experimental equipment on diffusivity due to moisture gradient

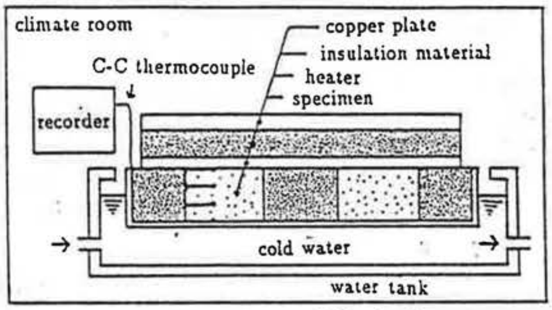

Fig.3 Experimental equipment on diffusivity due to temperature gradient

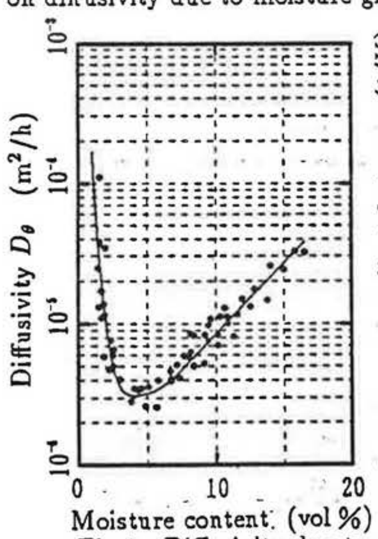

Fig.2 Diffusivity due to moisture content gradient

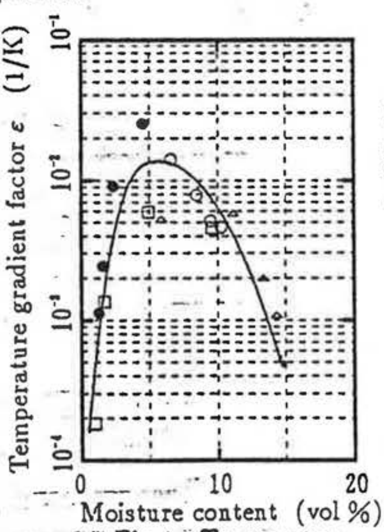

Fig.4 Temperature gradient factor

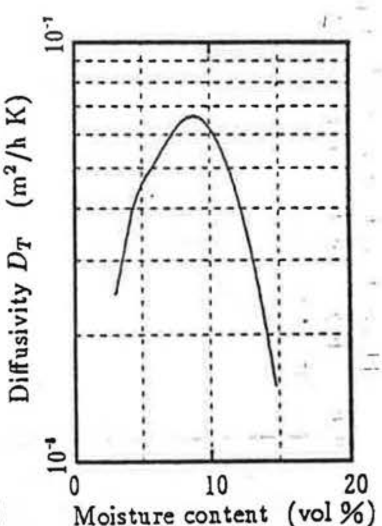

Fig.5 Diffusivity due to temperature gradient

Measurement and the results   After water was absorbed gradually to saturation from the end of the 4 kinds of specimens they were left in the climate room and dried until their moisture content achieved the specified level. Following this the initial average moisture content of each specimen was determined. Immediately after this the surface of each specimen was bound with aluminum foil three times and then fixed with cellophane tape in order to dampproof it. The specimens were left like this for about 2 weeks in the climate room, in which the constant temperature was 20±0.5 ℃.

The specimens were placed on the testing equipment, of which the tank water temperature was previously set at 10 ℃ and the temperature of the bottom surface of the flat heater was previously set at 70 ℃. After beginning the experiment each specimen was removed at an appropriate time, and divided into 5 pieces with a multiband saw at an average of 6 mm intervals. After the weight of each piece was measured it was then dried completely and its moisture content distribution was determined. The temperature gradient factor ε was obtained by calculation from the temperature gradient and the moisture content gradient as before. The calculated temperature gradient factor ε of 4 kinds of the specimens is shown in Fig.4. Fig.5 shows the diffusivity D_T obtained from D_θ in Fig.2 and ε in Fig.4.

3.3 Thermal conductivity

It is known that the thermal conductivity of humid material increases with the rise of moisture content. Measurement by the steady method is not suitable for long-term measuring or for measuring humid material because the moisture content changes while measurement is being carried out. Here, the measurement of humid calcium silicate board is carried out by the non-steady method which takes only about 5 minutes and is determined by the rate of the increase in temperature of the probe. The results are shown in Fig.6.

3.4 The equilibrium moisture content

In the glass vessels containing five kinds of saturated water solution of salts, such as LiCl, $MgCl_2 \cdot 6H_2O$, $Mg(NO_3)_2 \cdot 6H_2O$, NaCl, KNO_3, several small specimen pieces of calcium silicate board were set up for a long period, and when the weight change of each specimen became negligible, the equilibrium moisture content was calculated from that weight and the original dry weight. The results are shown in Fig.7. In the glass vessels the air temperature was maintained at 20 ℃.

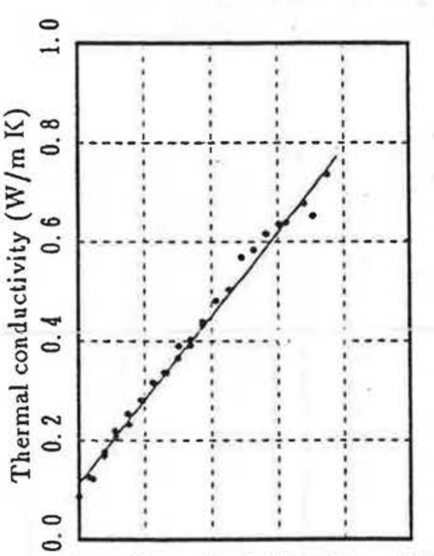

Fig.6 Thermal conductivity

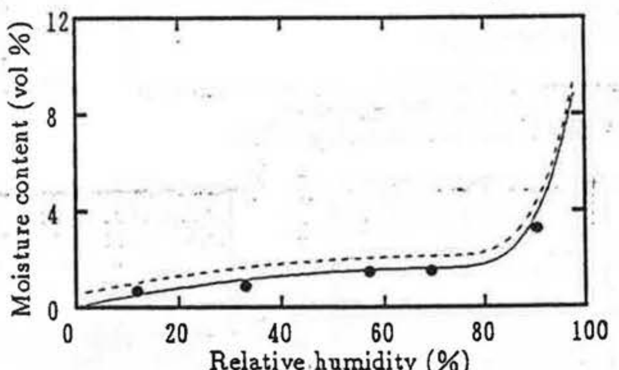

Fig.7 Equilibrium moisture content curve

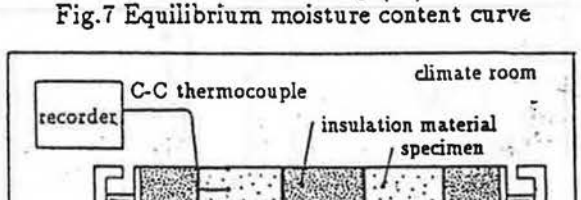

Fig.8 Experimental equipment on the condensation and re-evaporation process

4 EXPERIMENT ON AND ANALYSIS OF CONDENSATION AND RE-EVAPORATION

4.1 Summary of the experiment

As shown in Fig.8 the specimens made of calcium silicate board were put on a copper plate which was set up in the climate room. The bottom of the specimen was water-cooled and moisture was absorbed from the room air into the specimen. One specimen was used for measuring the distribution of temperature from top to bottom and three specimens used for measuring the average moisture content. All specimens measured 10 cm × 10 cm × 3 cm. The side and bottom of the specimens were dampproofed by covering them with aluminum tape and their sides were insulated from heat with foamed styrene so that heat and moisture flow would be in one direction. The room temperature and humidity were kept at 25 ℃, 68 % (21.5×10^2 Pa) during the condensation process, and the temperature of the bottom surface of the specimen was kept at 14 ℃ during the entire process. The weight of the specimens was measured for average moisture content every two days and then they were replaced on the copper plate. Once the weight change during the condensation process ceased, the room temperature and humidity were set at 25 ℃, 54 % (17.1×10^2 Pa), and the weight of the specimens was measured at irregular intervals.

4.2 Results and analysis of the experiment

The changes of the moisture content of the specimens, the temperature and humidity in the room and the temperature of the bottom surface of the specimen over a period of time are shown in Fig.9a and b. The condensation process is shown in Fig.9a and the re-evaporation process is shown in Fig.9b. In both figures the changes of measured moisture content in respect of the average values of three specimens are shown. In both cases the change of the moisture content is shown to be nearly steady after 50 days and the differences of their moisture content during the condensation process is approximately 1 vol %. In the re-evaporation process, however, no differences were noted. The value of properties used for calculation of moisture content are the measured value in §3 ,$\alpha = 7.8\mathrm{W}/(\mathrm{m}^2\cdot\mathrm{K})$ and $\alpha' = 0.18 \times 10^{-3}\mathrm{kg}/(\mathrm{m}^2\cdot\mathrm{h}\cdot\mathrm{Pa})$. The vapor pressure on the inside surface p_s is determined according to the temperature at the surface of the specimen T_s and the relative humidity, which corresponds to the moisture content of the specimen θ_s in the curve of equilibrium moisture content[1]. The curve changes over time, of calculated moisture content, are plotted in calculation value 1 in the figures. The calculated value agrees with the measured values in the condensation process ,but the former is smaller than the latter in the re-evaporation process.

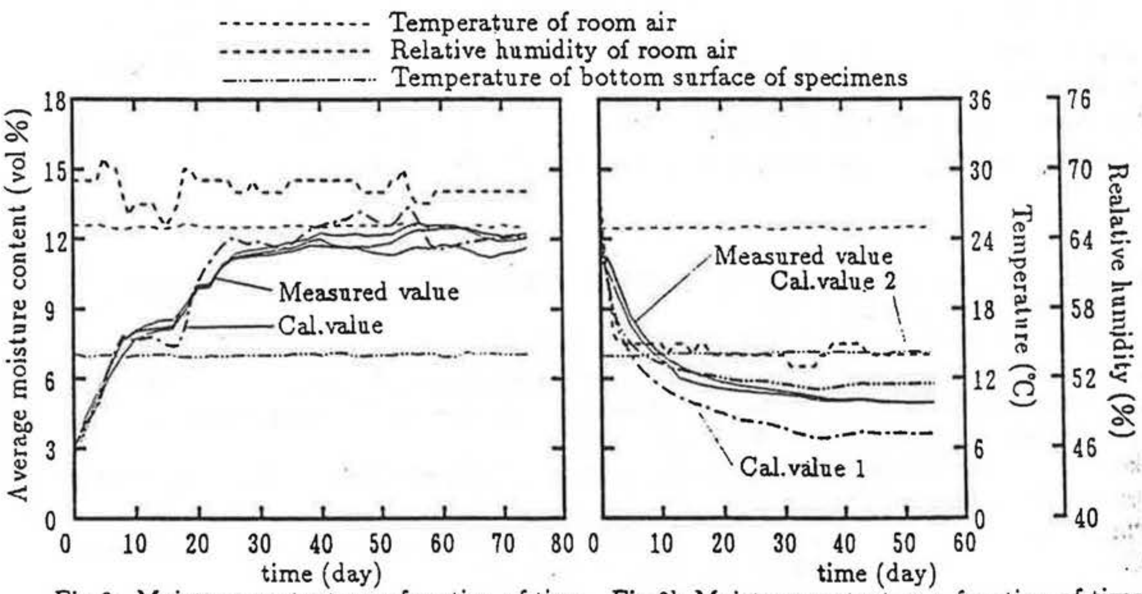

Fig.9a Moisture content as a function of time Fig.9b Moisture content as a function of time

It is thought that one of the causes of this is the difference of the applied value of the α, α',equilibrium moisture content curve and so on, used for calculating in both processes. Therefore another calculated value was established using the estimated values of the higher equilibrium moisture content curve of 0.5 % more than that of the absorption process in a solid line, as shown in Fig.7. The results are depicted as calculation value 2 in Fig.9b. Calculation value 2 is similar to the measured values compared with calculation value 1, but the values during the steady state are very different from those of calculation value 1. Results show that even a small difference of the equilibrium moisture content curve has a quite significant influence on the calculated values. This appears to be the reason why the moisture content increases so little while the relative humidity increases significantly, as seen in the equilibrium moisture content curve. In the future the influence of hysteresis will have to be examined.

5 CONCLUSION

The dependence of moisture diffusivity, due to both a moisture content gradient and a temperature gradient, and the thermal conductivity on the moisture content and the properties of the equilibrium moisture content curve in calcium silicate board, were measured. Analysis showed that results were largely dependent upon levels of moisture content. The experiment on the condensation and re-evaporation process was carried out using materials which were dampproofed on one side, and the change of moisture content in the materials over time was measured. The results were compared with the analyzed value by simultaneous heat and moisture transfer equation.

Results show that the calculated values are shown to correspond with the measured values during the condensation process, but do not correspond during the re-evaporation process. It is clear that the equilibrium moisture content curve has a great influence on the calculated value. Further examination of the influence of the hysteresis is left as a future problem. The validity of the application of the heat and moisture transfer equation to the case of the condensation and re-evaporation process is proposed.

Nomenclature

D_θ:total moisture diffusivity due to moisture gradient[m^2/h],
D_T:total moisture diffusivity due to temperature gradient[$m^2/(h \cdot K)$],
θ:volume moisture content[vol %], c:specific heat of material[J/(kg·K)],
γ:specific weight of material[kg/m^3], λ_θ:thermal conductivity of material[W/(m·K)],
α:heat transfer coefficient[$W/(m^2 \cdot K)$], α':moisture transfer coefficient[$kg/(m^2 \cdot h \cdot Pa)$],
T_i:room temperature[°C], T_s:surface temperature of the specimen[°C],
p_s:water vapor pressure at the surface of the specimen[Pa], x:length[m], t:time[h],
p_i:room water vapor pressure[Pa], q_w:quantity of moisture flow[$kg/(m^2 \cdot h)$],
T_d:temperature at the vapor barrier surface[°C], R:heat of adsorption[J/kg],
T:temperature[°C], ε:temperature gradient factor[1/K], subscript v:vapor

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TIME-OF-WETNESS MEASUREMENTS IN HIGH-HUMIDITY COMPARTMENTS OF DWELLINGS

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ABSTRACT

Measurements of the time-of-wetness (TOW) on the walls of a shower cabinet, a laundry and a bathroom of an occupied dwelling have been accomplished. Two types of miniature sensors, one electrolytic cell with Au grids and one commercial dew sensor, were used together with a specially developed instrument for monitoring of surface moisture conditions. Large differences in moisture time, or TOW, between various locations of the shower cabinet and the bathroom have been observed. Using the limit for mould growth (>70% RH, >0°C) as a criterion, moisture times approaching 75% of the total time have been observed close to the floor level. The conditions in the laundry, on the other hand, were not severe enough to exceed this limit. The measuring method employed has proved to be a valuable tool in the assessment of surface moisture conditions, indoors as well as outdoors.

1 INTRODUCTION

Bathrooms, shower-baths, and to some extent laundries and drying rooms are examples of compartments that are supposed to be designed to resist the moisture loads encountered during their normal utilization. Nevertheless, surface moisture conditions may develop which exceed critical levels for the onset of various forms of biological and physical degradation mechanisms.

Quantitatively, very little seems to be known about the characteristics of typical surface moisture loads in high-humidity compartments. The present paper deals with a pilot study (1) aimed at characterizing the surface moisture conditions prevailing in some high-humidity compartments of an occupied dwelling. The surface moisture was measured using miniature sensors mounted at various locations on the walls of a shower cabinet, a bathroom and a laundry. An electrochemical measuring technique based on the NILU WETCORR method (2) was applied to the moisture sensors. The moisture time or time-of-wetness (TOW) has been evaluated for all sensor locations.

2 EXPERIMENTAL

2.1 Instrumentation and Sensors

An instrument specially developed for surface moisture measurements was employed to continuously monitor the response of the various sensors (3).

The instrument is equipped with 16 channels which may be connected to sensors for surface moisture, temperature or relative humidity. Each moisture sensor is driven by a constant voltage of 100 mV, with polarity reversal every 30 seconds to avoid net polarization. The resulting current, which has a lowest resolution of 0.1 nA, is measured every second and the average over one minute, or longer if preferred, is stored on tape. The data are then transferred to a mini computer (VAX 6310) for data file editing, evaluation and plotting of the results.

Two types of moisture sensors were used throughout this study. One is a recently developed electrolytic cell equipped with impedance grids of Au (4). The other is a commercial dew sensor denoted HOS103 and made by Murata (5). The Au/Au-sensor measures 22 x 31 mm in total and has a thickness of 0.63 mm whereas the HOS103-sensor is only 6 x 7 x 0.7 mm in size. Both types of sensors were recently tried out in a climatic chamber under varying conditions (4). The current through the Au/Au-sensor can be described by the following empirical regression formula:

$$\log i_w = 3.439 + 3.409 * 10^{-4} * (RH)^2 - 1388/(T_s + 273.16) \qquad 1$$

where i_w, RH and T_s are, respectively, the cell current in nA, the relative humidity in % and the surface temperature in °C. The dew sensor HOS103 reacts only to relative humidities exceeding 90-95% and is virtually independent of temperature. In addition, this sensor responds with an increased resistance on exposure to high moisture loads, contrary to what is common for other similar sensors.

Air and surface temperatures were measured with copper-constantan thermocouples and the relative humidity with a Rotronic MP-100 probe.

2.2 Measuring Objects and Sensor Mounting

As was mentioned earlier, surface moisture measurements were carried out in a shower cabinet, a bathroom and a laundry, all belonging to a dwelling occupied by two adults and two infants. The measurements went on for 8 to 12 days per compartment. For the sake of conformity only the results of the first 7 days will be presented here.

The two types of sensors were mounted in pairs at four different locations situated on the walls of the compartments. In general, the sensors were placed so that the extremes with regard to moisture load would be represented. This meant e g that walls with different surface temperature were selected. As a rule, two pairs of sensors were placed 50-100 mm from the floor level and the other two pairs 100-200 mm from the ceiling.

In the bathroom one pair of sensors were mounted behind the bath tub near the floor. The distance between the wall and the the edge of the tub was about 50 mm, ensuring acceptable ventilation of this critical area. In all other locations the sensors were openly exposed.

In both the shower cabinet and in the bathroom the RH-probe was mounted close to the shower nozzle but away from the pouring water. The surface temperature of the coldest wall and also of the air was measured in all compartments.

The compartments were utilized in the normal way but a record was kept of all activities expected to influence the results, e g start and duration of showering, drying-up or not of floors using a scrape, open or closed doors to adjacent rooms, etc.

2.3 Evaluation Criteria

Surface moisture conditions that are considered critical have been translated into current criteria using Equation 1 for the Au/Au-sensors. Mould growth can take place at RH > 70% and temperatures > 0 °C although the optimum conditions for growth would involve higher relative humidities and temperatures. RH > 90% and T > 0 °C was mainly chosen to enable comparison with the dew sensor HOS103. For this sensor a relative humidity of 90% RH results in a current of approximately 10^5 nA (4).

After evaluation of the current with regard to the various criteria the results were expressed as the relative moisture time.

3 RESULTS

In order to make sure that at least the moisture sensors nearest to the RH-probe have been working well and in accordance with the preceding sensor evaluation (4) the moisture times for equivalent locations and various criteria are compared in TABLE 1. These results show that there is an acceptable correspondance between moisture times estimated for various criteria and different types of sensors.

TABLE 1. Comparison of Various Moisture Time Estimates for Locations Close to the RH-probe. Moisture Criteria According to Eq. 1.

Compartment	Moisture time (TOW), %			Showering time, %	Average air temp., °C
Moisture crit.	Au/Au	HOS103	RH-probe		
Shower cabinet					
70% RH, 20 °C	5.0	-	4.0		
80% RH, -"-	1.8	-	1.0		
90% RH, -"-	0.7	0.4*	0.6	0.47	20.6
Bathroom					
70% RH, 20 °C	3.8	-	3.3		
80% RH, -"-	3.1	-	2.2		
90% RH, -"-	2.7	2.4*	1.8	1.33	21.3

*For Murata HOS103 a current of 10^5 nA corresponds to 90% RH, 20 °C

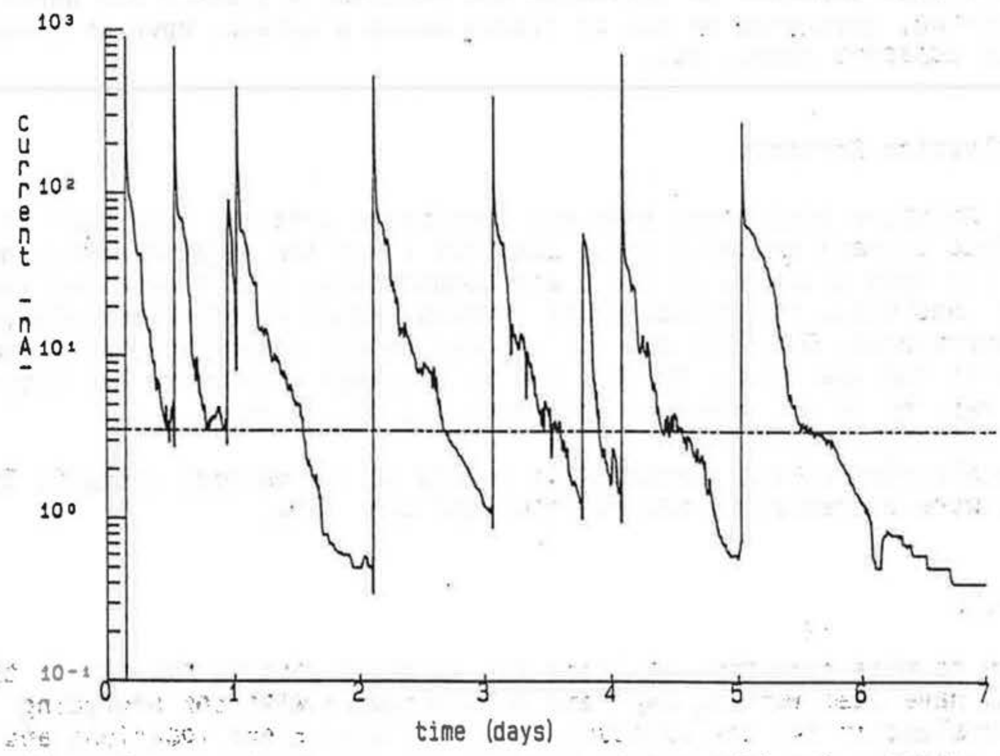

FIGURE 1. Current-time curve for Au/Au-sensor mounted close to the floor of a shower cabinet. The line represents 80% RH, $0^{\circ}C$.

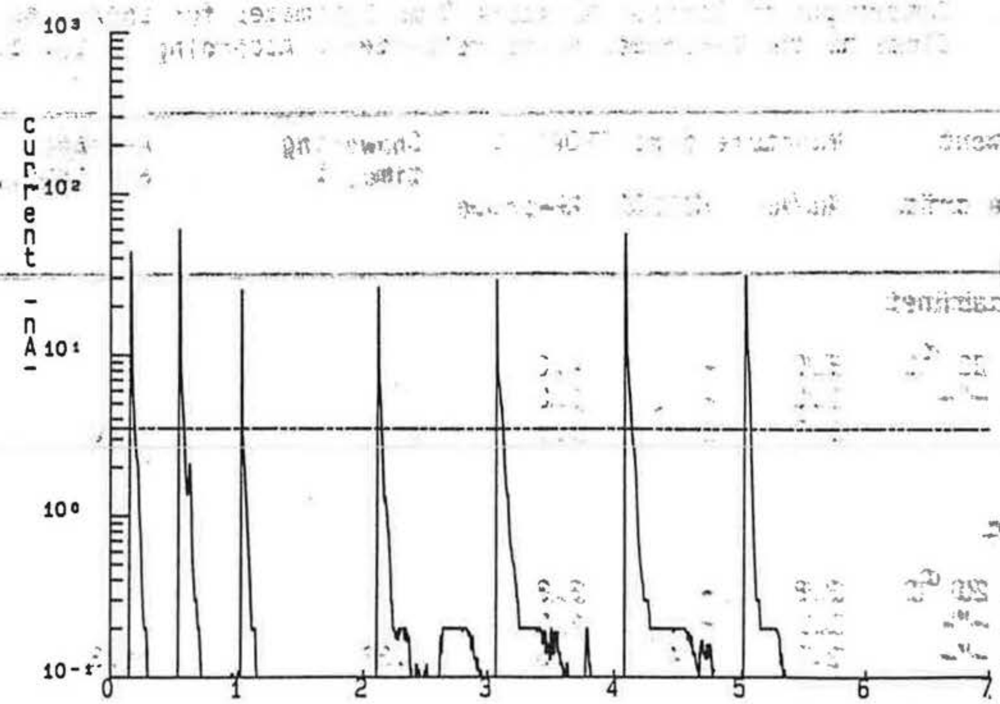

FIGURE 2. Current-time curve for Au/Au-sensor mounted close to the ceiling of a shower cabinet. The line represents 80% RH, $0^{\circ}C$.

Two examples of current-time curves for Au/Au-sensors mounted in the shower cabinet are shown in FIGURES 1 and 2. The first shows the result for a sensor placed close to the floor on the same side as the shower and the second the simultaneous response of a sensor mounted on the same wall but close to the ceiling. In both diagrams a current criterion of 3.5 nA is illustrated, which corresponds to a moisture level of 80% RH, 0°C. Every time the shower is being used a well defined peak can be identified.

TABLE 2. Moisture Times for Various Locations on the Walls of a Shower Cabinet. Total Showering Time = 0.47% of 7 Days.

	Moisture time (TOW), %			
	Au/Au-sensors			Murata HOS103
Sensor location	70%RH,0°C (=1.1 nA)	80%RH,0°C (=3.5 nA)	90%RH,0°C (=13.2 nA)	90%RH,0°C (=10^5 nA)
Close to floor, shower side	74.9	49.8	22.5	7.6
Close to ceiling, shower side	7.8	3.9	0.9	0.4
Close to floor, opposite shower	62.3	39.0	19.4	15.3
Close to ceiling, opposite shower	10.7	5.9	3.0	0.90

TABLE 3. Moisture Times for Various Locations on the Walls of a Bathroom. Total Showering Time = 1.33% of 7 Days.

	Moisture time (TOW), %			
	Au/Au-sensors			Murata HOS103
Sensor location	70%RH,0°C (=1.1 nA)	80%RH,0°C (=3.5 nA)	90%RH,0°C (=13.2 nA)	90%RH,0°C (=10^5 nA)
Close to floor, behind bath tub	44.6	30.9	5.4	7.7
Close to ceiling, above bath tub	5.1	3.4	2.9	2.4
Close to floor, opposite bath tub	5.1	3.8	2.1	2.6
Close to ceiling, window wall	2.8	2.5	2.3	1.8

The moisture times obtained for the shower cabinet are presented in TABLE 2 and for the bathroom in TABLE 3. In both compartments large differences in TOW can be observed depending on sensor location and choice of criterion. There is also a fair agreement in moisture time between the two types of sensors at 90% RH.

In the case of the laundry the relative humidity never exceeded 60% RH despite line drying of the clothes and closed door. This was not sufficient to generate any critical moisture levels on any of the walls of the compartment.

4 DISCUSSION AND CONCLUSIONS

This pilot study has demonstrated that large differences in surface moisture loads prevail in typical high-humidity compartments of a dwelling. Generally, the time-of-wetness observed close to the floor of the shower cabinet is in the order of 10 times longer than that close to the ceiling. For example, using the commonly accepted limit for mould growth (>70% RH,>0^{o}C) as criterion, the moisture time near the floor in this case was almost 75% of the total time but only 8% close to the ceiling. Similar figures were found for the bathroom but here the most critical location was behind the bath tub. The surface moisture measurements performed in the laundry, however, did not reveal any serious moisture loads. In the original report of this pilot study (1) more details are given about the importance of e g removing water that remains on the floor and of leaving doors open to minimize the moisture times.

The instrument with accompanying sensors has proved to be very useful and reliable in the present study. Characterization of surface moisture conditions in critical parts of buildings, indoors as well as outdoors, can be made in a short time and in a straightforward way using this technique. The results of such measurements could be of great value in the process of describing the interaction between the microclimate and the degradation of materials.

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DAMP-EXPERT
EXPERT SYSTEMS BASED DAMPNESS DIAGNOSIS

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ABSTRACT

The goal of DAMP-EXPERT is to assist trained staff members with less experience regarding building fysics, in diagnosing dampness in buildings. DAMP-EXPERT is specially aimed at technical personal of housing corporations, local authorities and maintenance and renovations construction companies.
After an initial phase which was based on 'if-then' rules, a frame-based approach was chosen. For this implementations the HT (Hypothesize-and-Test) module of the KES expert system shell was chosen. KES-HT is based on abductive reasoning and implemented as 'descriptions' of dampness problems in terms of characteristics. In general seven main categories of dampness problems are recognized, devided into 50 detailed dampness descriptions.
Early 1990 the final phase of DAMP-EXPERT has started. This phase largely focusses on the user interface, which should accomodate the end user in his normal working practice. Also a module will be developed to cope in detail with the complex relationship between damp production, ventilation and temperature. In addition full text and hypertext.modules will be developed for extended explanation, terminology and building defects.

1. INTRODUCTION

Dampness is one of the major problems of the indoor environment. The mechanism which causes dampness problems is rather complex. Technical staff of housing corporations and property owners have to cover a wide range of expertise concerning building maintenance. The necessary expertise to diagnose dampness problems correctly is not always available. Especially for the more compex cases this lack of expertise often results in an incomplete, if not wrong diagnosis.
Already in 1982 Lansdown (1) investigated the application of expert system in the building and construction industry. Following the general trend of computer science introductions in the construction industry, however, it would take many years before expert system research results emerged (2 – 6). One of the first examples was BREDAMP (7), which was developed in 1985 and 1986 for the British Building Research Establishment (BRE) by Loughborough University. During the development of DAMP-EXPERT, we also came across two other dampness expert systems: DAMP (8) from New Zealand and AIRDEX from America (9). With BREDAMP a general

trend was followed which emphasized the development of advisory and diagnostic systems as a major application area for expert systems.
Together with the demonstration project for an expert system for fire safety design (10), DAMP-EXPERT was one of the first expert systems project at TNO-IBBC, initiated in 1986.

2. EARLY STAGES OF DAMP-EXPERT

During the CIB World Congress in 1986 the idea emerged to investigate the possibilities for a Dutch version of the British BREDAMP. During the rest of 1986 and early 1987 a feasability study was carried out if such a 'translation' to the Dutch situation could be realised. The result of this study was that BREDAMP differs too much from the Dutch situation regarding both scope and use.
After the summer period of 1987, the actual research started. Although some experience was available on the artificial intelligence language Prolog, it was decided that experience with an expert system shell would also be of importance. After some consideration the expert system shell KES was chosen. It is important to realise that early 1987 most of the present expert system shells did not exist yet. One of the reasons for chosing KES was that, already in those days, KES was available on a wide range of machines, including DOS (end users) and UNIX (internal use). KES is still being marketed and with the new 2.6 version it will be one of the first to support X-windows. The PS-module of KES is based on 'if-then' rules in combination with frames and forward chaining.
In June 1988 the first prototype was finished, based on four phenomena: condensation, hygroscopicity, leakage and capillarity flow. This version recognizes a preliminary diagnosis and a detailed diagnosis. During the evaluation, the initial dampness diagnosis indication was quite satisfactory. The detailed diagnosis, however, proofed to be inadequate from as well the 'depth' of dampness knowledge as towards the operational conclusion for the user.

3. FRAME BASED APPROACH FOR DAMP-EXPERT.

To be more recognisable for the user the number of dampness problems was broadened to seven main phenomena: surface condensation; interstitual condensation; hygroscopicity; rain penetration; raising damp; initial moisture contents, capillarity flow and leakage. More important, however, was that a more 'knowledgeable' reasoning towards dampness would not only be difficult in implementing, but more important, would be extremely difficult to maintain. It would be necessary to broaden the reasoning by creating more if-then rules. Much more complicated, however, would it be to fine tune the diagnosis, i.e. exceptions should be implemented, which would require a fast increasing number of if-then rules. Although we did not pursue this effect in detail, effects of combinatory explosion were envisioned.
It was therefore decided to explore the possibilities of the KES-HT module. HT (Hypothesize-and-Test) is based on abductive reasoning (11). The HT approach is based on describing each possible conclusion as a hypothesis, i.e. a particular

diagnosis. These hypotheses consist of a number of charateristics which should (or should not) occur. KES-HT will start generating questions which will be most effective in pruning the number of hypotheses. If for one of the hypothesis the characteristics does not match the description, HT will skip that particular hypothesis and the group of possible hypotheses will become smaller. At the end HT will generate a set of matching hypotheses. Depending on how good the user input matches these hypotheses, the matching hypotheses will be ranked in order of matching with an certainty value of high, medium or low.
During the first few months of 1989 various methods of generating HT descriptions were investigated. Initially seperate tables were produced for the two characteristics location and outer appearance. Horizontal the seven dampness problems and vertical the various values for both location and outer appearance. In the various cells factors were given in terms of probability (++, +, 0, -, --) regarding the relation between a certain hypothesis, i.e. a dampness problem, and a specific location or outer appearance.
This approach, however, did not offer satisfactory results regarding the precision of the question inference. This precision problem especially occures where the probability of a certain hypothesis depended on the overall location of the dampness problem within the building, e.g. ground floor or top floor. To accomodate this distinction it would be necessary to differ the hypothesis also on the basis of general location. To achieve this the seven main dampness problems were differentiated into more then 50 detailed dampness hypotheses. The results of phase-2 are described in the final report for phase-2 (12). An example of an KES–HT description as is implemented at present might look like:

```
surface condensation massive.external wall [description:
      location = external wall <a>;
      outer appearance = stains, mold <h>, discoloring <l>;
      thermal bridges = true <n>;
      wall = concrete <h>, masonry <h>;
      isolated = false <a>;
      damp production = yes <h>, no <l>;
      operating ventilation system = yes <l>, no <h>;
      corners = true <h>;
      other locations = true <h>;
      ],
```

4. SPECIFIC SITUATIONS AND MULTI FUNCTIONALITY

During the development of phase-2 the idea emerged to high light a few specific dampness situations. These situations should be very distinct and well recognisable for the end user. If on the basis of a picture (fig.1) and an explanatory description such a situation was indeed indicated, it would not be necessary to start the detailed diagnoses process. However, if an additional detailed diagnosis was carried out the final diagnosis should include the specific situation, if only as one of more alternatives.

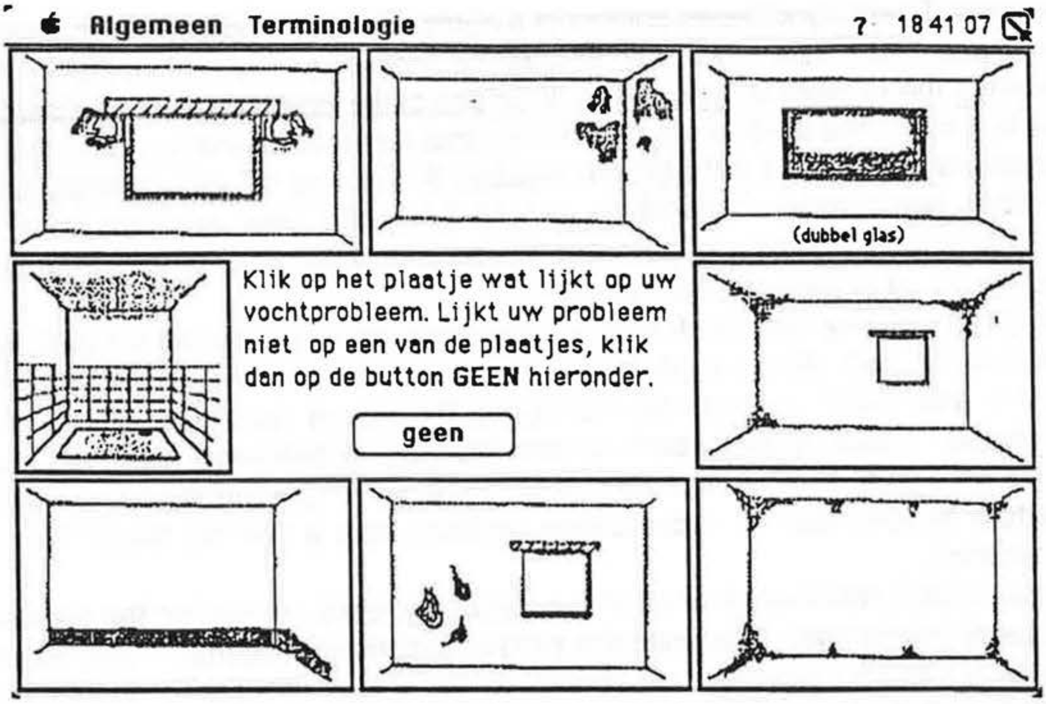

fig.1 Specific situations DAMP-EXPERT

Because dampness diagnosis is not an isolated process other views and considerations would be of importance for an acceptable DAMP-EXPERT system. Also in other expert system related projects at TNO-IBBC, this multi functionality proofed to be of importantce. For DAMP-EXPERT three added functionalities are being pursued:

- **Terminology.**
  Especially for less experienced users, it would be very helpfull if a quick reference mechanism would be available for checking the actual meaning of a term. During phase-2 a number of definitions were compiled and made accessible as a seperate module. In the final system these terminology definitions will be integrated in the system and may triggered at each opportunity. At present much attention is focused on terminology. The idea is that based on the international root thesaurus, Dutch translations will become operational. For specific applications, like DAMP-EXPERT, sub systems will be generated with the applicable terminology.
- **Extended explanation.**
  Regarding dampness much could and should be said about the various aspects of dampness. A publication which explains the topics covered in the DAMP-EXPERT system could very well be used as an independent supporting and/or explanatory document. During phase-2 the basis of such a document was implemented as a hypertext add-on, which could be consulted as a seperate module of the DAMP-EXPERT system. In phase-3 this module will be extended and integrated using a combination of full text retrieval and hypertext. At a number of questions the user may request '*extended explanation*', which will result in a jump to the appropriate page of the full-text/hypertext-module. Examples of publications which could be used for such an extended explanation are the new British Standards BS-8000 serie on workmanship (13), the SBR publication on energy concious construction (14) or the new version of the SBR 151 publication on dampness in buildings (15).

• **Building defects.**
The description of building defects is very common in the building industry. A good example are the *building defect action sheets* from the BRE. In a seperate feasability study (16) TNO-IBBC has implemented building defect descriptions in a full-text retrieval system. When dampness related 'defects' are compiled, it will be possible to access them from the DAMP-EXPERT system as is being finalised at present.

5. Diagnosis process DAMP-EXPERT

In December 1989 phase-2 has resulted in version–2 of DAMP-EXPERT, which recognises 5 steps (fig.2):

- Specific situations (A);
- Four initial questions regarding specific location, outer appearance, building type and general location (B);
- HT hypothesis inference, including the subsequent question generation (C);
- Additional reasoning concerning surface condensation. This part is directed towards the effects and influence of damp production, temperature and ventilation (D) ; and
- Detailed hypothesis explantion and possible solution startegies (E).

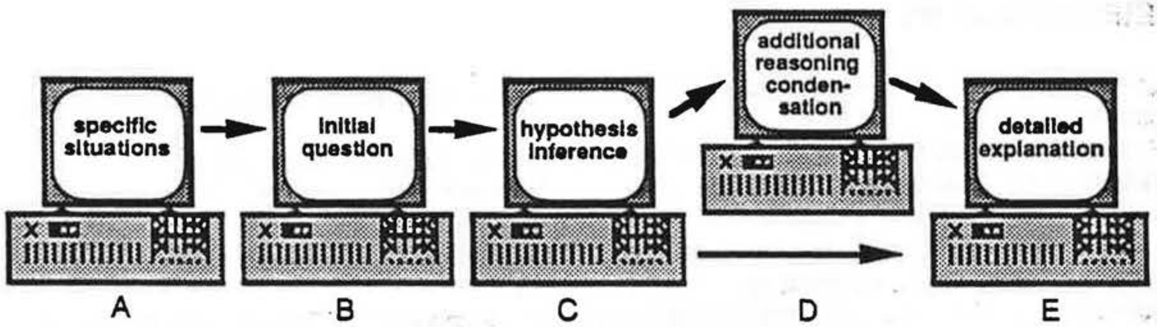

fig. 2 Diagnostic process DAMP-EXPERT

6. Final phase DAMP-EXPERT

Early 1990 the final phase-3 of DAMP-EXPERT has commenced. The aim of phase-3 is to implement the end user interface. This will done by creating an embedded C version of the KES-HT knowledge base together with the window package Vermont Views. During this phase workshops will be organised with potential end-users, to discuss the actual wording of the questions and the understandability of the answers. As part of phase-3 also an additional reasoning module will be developed to cope with the complex relationship between damp production, temperature and ventilation. This module will only be activated if surface condensation is part of the final diagnosis. Also the hypertext and full-text software for the modules for terminology, extended explanation and building defects will be implemented. For the end user a DOS version of DAMP-EXPERT will become available. For internal use and for online experiments, an UNIX core version will be implemented.

If the results of phase-3 are favourable it will be possible to have a beta version of DAMP-EXPERT available before the end of 1990. An actual commercial version will depend on an agreement regarding licence, support and maintenance.

6. Acknowledgement

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CONVECTION AND MOISTURE DRIVEN HEAT TRANSFER

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1. INTRODUCTION

The hygrothermal performance of a wall structure with air convection may considerably differ from that of a non-convective case. Convection may take place as a flow in macro-porous material layers or locally as a crack flow in material joints. Convection can be caused by temperature differences (natural convection), or pressure gradients in structures (wind, pressure differences over building envelope etc.), which may be present both separately or at the same time.

Phase changes between all the phases of water may occur, which may locally have a strong effect on the temperature field and also on the heat losses through the structure. The location and effect of phase changes may vary in time depending on, for example, the initial moisture distribution and the boundary conditions.

This paper presents numerically analyzed cases of air convection and phase changes in wall structures. Also the numerical study of dynamic insulation structures, which includes analysis of the potential effects of the heat recovery and risks for moisture accumulation are presented. The simulation model TCCC2D, which was used in the analysis, has been verified with several laboratory and field experiments (Kohonen et al. 1985, 1986 /1,2/).

2. NUMERICAL SIMULATION MODEL TCCC2D

TCCC2D (Transient Coupled Convection and Conduction in 2-Dimensions) solves the two-dimensional heat and moisture flow in multilayer building structures. Pressure, temperature, and partial vapor pressure are used as driving potentials. Darcy flow equation with Boussinesq approximation for incompressible fluid is used. Local thermodynamic equilibrium is assumed between stagnant and flowing phases. Phase changes may, however, occur.

The continuity, momentum, energy, and mass balance equations can be given in component form with Equations 1 through 4:

Mass balance:

$$\frac{\partial \rho_f}{\partial t} + \frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} = 0 \qquad (1)$$

Momentum:

$$v_{x,f} = -K_{v,x}/\eta_f \frac{\partial p_f}{\partial x} \qquad (2\ a)$$

$$v_{y,f} = -K_{v,y}/\eta_f \left(\frac{\partial p_f}{\partial y} - \rho_f g\right) \qquad (2\ b)$$

Energy balance:

$$C'' \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) - \frac{\partial}{\partial x}(\rho\, c_p\, v_x\, T)_f - \frac{\partial}{\partial y}(\rho\, c_p\, v_y\, T)_f + \sum_{\alpha} h_\alpha \sum_{\beta} q_{\alpha\beta} \qquad (3)$$

Moisture balance:

$$\frac{\partial (u\rho_0)}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{D,x} \frac{\partial p_v}{\partial x}\right) + \left(\lambda_{D,y} \frac{\partial p_v}{\partial y}\right) - \frac{\partial}{\partial x}(\rho_v v_x) - \frac{\partial}{\partial y}(\rho_v v_y) \qquad (4).$$

An ordinary finite-difference method is used in the numerical solution. Variables are calculated at the grid points and air velocities at the mid-point of grids. The upwind discretizing method is used in the solution of the convection terms. Moisture content of each material is coupled with vapor pressure and temperature by sorption isotherms.

3. THERMAL EFFECTS OF PHASE CHANGES OF WATER

Moisture transfer and phase changes in glass fibre thermal insulation may considerably increase the heat losses of a structure. The measurements by Kumaran /4/ with wet glass fibre thermal insulation under temperature gradient were analyzed numerically. Figure 1 shows the measured and calculated histories of heat flux through a glass fibre test specimen.

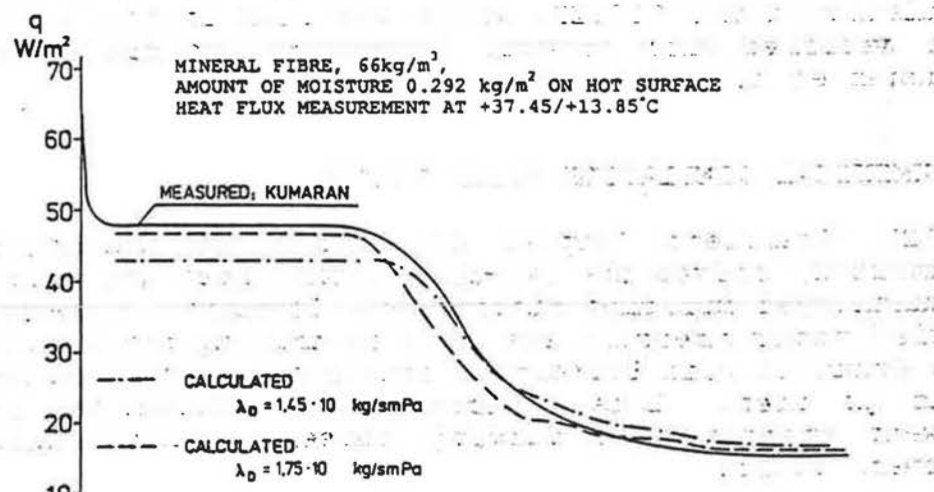


Fig. 1. Measured /4/ and calculated histories of heat flux through a wet glass-fibre insulation.

By changing the moisture transport properties given for the solution model, the measured heat flux distributions could be simulated relatively accurately. These results show that the latent heat is significant for the hygrothermal behaviour of wall structures and similar results are given in /3/.

4. HYGROTHERMAL EFFECTS OF AIR CONVECTION

4.1 Thermal Effects of Natural Convection

In numerical simulation, the structures are usually assumed to be ideal, so that different material layers are joined together without any extra surface resistances or local air leakage flows. Real structures are, however, non-ideal, which can be seen especially by increased local convection effects.

In an ideal, vertical wall structure with light weighted glass fibre thermal insulation covered with air impermeble material, natural convection can increase the heat losses with no more than 1 % according to calculations. Without any wind barrier, the calculated heat losses through a corresponding semi-open structure can be increased with about 8 % by natural convection. The experimentally measured increase of mean heat flow through a closed structure could be even from 10 to 15 % varying case by case /1,2,5/. This difference is due to the non-idealities of real multilayer structures, while the effects of convection are incresed with more material layers.

The difference between ideal and measured cases are most probably caused by locally increased air convection. These small air crack flows can be approximated by increasing the local permeability values in structural joints. Location and effect of these non-idealities varies case by case, so that they can not be accurately predicted. Calculations on ideal structures give the minimum limit for the influence of convection, which can be considered as a reference for the hygrothermal behavior of a structure. According to the numerical analysis and measurements, the structural air tightness is one of the main parameters which affect the hygrothermal behaviour of building structures.

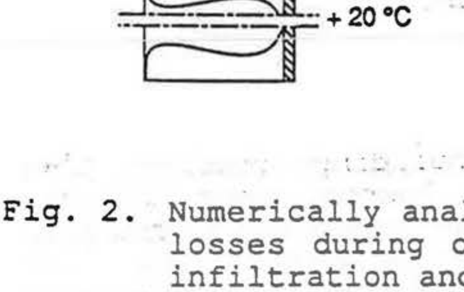
4.2 Air Infiltration / Exfiltration

When the air infiltrates through the building envelope, the heat recovery from transmission heat losses warms up the incoming air. Though the conductive heat losses are increased, the total heat losses reduce from those without any heat recovery. The total heat recovery effect of the structure (Nu^*) with a certain airflow rate from outside to inside air space can be given as the ratio between the total heat losses of the infiltration case (with heat recovery) and those of the reference case (without heat recovery) (Eq.5).

$$Nu^* = \frac{\sum q \text{ (heat recovery)}}{\sum q \text{ (no heat recovery)}} \quad (5).$$

The efficient use of a dynamic wall structure requires the airflow to be uniformly distributed over the structure. Nu^* has a minimum value, (about < 0.8), with a certain air flow rate typical for the U-value of the structure. This minimum value corresponds to the maximum relative heat recovery, and the airflow rate of this value can be considered as an optimum value for the structure. If the thickness of the thermal insulation layer increases, the optimum value decreases because the smaller transmission heat losses can be covered with smaller airflow rate.

Figure 2 shows a 2,5 m high dynamic wall structure with an air crack on the top of the inside covering board. Simulations using fixed infiltrating air flow rate (2,5 l/s) and weather data in Middle-Finland during one week in March were done. The outside temperature varied from about -17 to +2°C and the total radiation coming to the south facing facade was relatively high, about 3,2 kWh/m²d. Table in Fig. 2 shows the numerically solved heat losses. In the cases, when the air is taken directly to inside air space at outside temperature, and there is no radiation to the surface, the total heat losses are about 44.2 W per structural area. With air infiltration, the convective heat losses are reduced with about 43 %, but the total losses only with about 10 %. When also the radiation on the surface is taken into account, the total heat losses are reduced with about 26 % (Nu^*=0.74) during the one week simulation period.



CASE	SUN RAD.	HEAT RECOV. & INFILTR.	HEAT LOSSES q_{COND} W/Km²	q_{CONV} W/Km²	q_{TOT} W/Km²
REFER.	NO	NO	6.63	37.6	44.2
DYNAM.	NO	YES	18.5	21.4	39.9
DYNAM.	YES	YES	15.0	17.7	32.7

Fig. 2. Numerically analyzed dynamic wall structure and heat losses during one week period with and without air infiltration and radiation (3.2 kWh/m²day).

4.3 Moisture Accumulation due to Air Convection

Air exfiltration through the building envelope usually causes strong local moisture accumulation when continuing for a long time. Also any kind of inside air flow into the structure may cause similar moisture accumulation.

The next case represents numerically analyzed hygrothermal performance of a 2.5 m high structure with 150 mm thick mineral fiber thermal insulation (19 kg/m^3) covered from the inside with 12 mm wood chip board and from the outside with 12 mm wood fibre board (Figure 3). The inside covering board had cracks on the top and in the bottom of the structure so that air could flow between the thermal insulation layer and the inside air space through these cracks. The outside covering board was thus almost airtight when compared to the inside one. The temperature and vapor pressure conditions for the inside and outside air spaces were +20°C, 1400 Pa and -20°C, 70 Pa respectively. The temperature difference caused an air flow rate 0.033 l/sm from inside air into the structure and back again to inside air space.

These conditions were maintained constant throughout a 31 day simulation period. Figure 3 shows how the moisture has strongly been accumulated in the upper part of the structure even though the air flow rate was rather small. Thus any kind of continuous inside air flow into a structure may locally affect the hygrothermal behaviour of the structure.

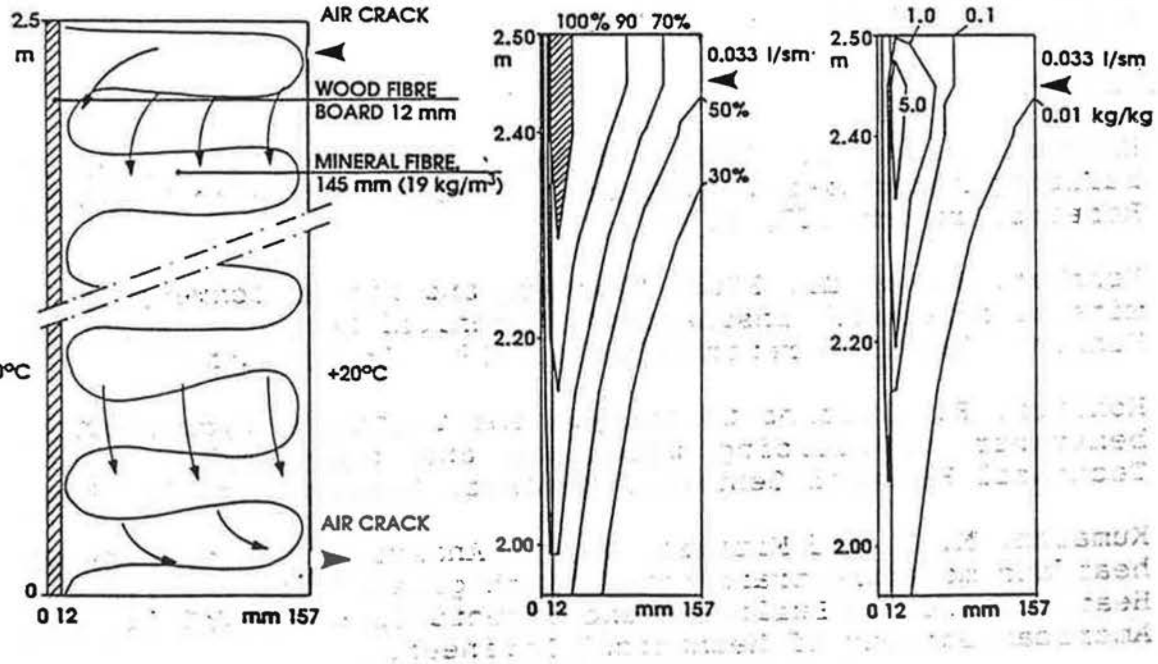


Fig. 3. Structure with air cracks at the inside covering board and numerically solved relative humidity and moisture content fields after 31 days of air convection.

CONCLUSIONS

Diffusive moisture transport can significantly increase the heat losses through a glass fibre insulation layer. The latent heat term must thus be taken into account in the hygrothermal simulation calculations when wet materials are concerned.

Convection caused effects on the thermal performance of building envelopes are highest with air infiltration or exfiltration, when the heat recovery effect decreases the total heat losses. With uniform air infiltration, the reduction of conductive and ventilation heat losses can be more than 20 %.

Long time air exfiltration or inside air flow into the structure may cause strong local moisture accumulation into the structure and thus affect its' hygrothermal performance.

NOMENCLATURE

c_p = specific heat capasity, J/kg K
g = gravitational pull, = 9.81 m^2/s
K_v = permeability, m^2
p = air pressure, Pa
p_v = partial vapor pressure, Pa
T = temperature, K or °C
v = airflow velocity, m/s

λ = thermal conductivity, W/K m
η = viscosity, kg/ms
ρ = density, kg/m^3

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HEAT, MOISTURE AND AIR TRANSPORT IN CRAWL SPACES

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INTRODUCTION

In the Netherlands it is common to build houses with a crawl space below the ground floor. Until now little attention has been paid to potential moisture problems associated with crawl spaces. Most houses are built at places where the ground water level is only few decimeters below the ground level and in general crawl spaces have a very humid climate. A relative air humidity of 95% and an excess water vapour concentration of 6 g/m3 with respect to outdoor air are quite normal. Up to now no special attention was paid to the air tightness of ground floors. The infiltration of moist air from the crawl space to the living areas have led to severe moisture problems in many cases. Another aspect, associated with potential moisture problems, is the presence of thermal bridges at the floor foundation. In recent years, the potential risks of humid crawl spaces have been recognized and since that time many remedial measures have been considered. At TNO several investigations were done with respect to crawl space problems. Research work was directed to investigations in the field as well to the development of models describing HMA (Heat, Moisture and Air) transport mechanisms in crawl spaces. In this paper a brief presentation will be given about work on modelling of crawl spaces.

A COMPLEX CRAWL SPACE MODEL

Below a description will be given of the thermal conduction model TH3DR. In this model some combined HMA features have been implemented, which makes it suitable for a crawl space model. The TH3DR program is an extended version of thermal model TH3D, which was originally developed as a general purpose thermal program to solve 3-D steady state and transient heat conduction problems. The purpose of the extended TH3DR model is to enable the combined modeling of the heat, moisture and ventilation phenomena in crawl spaces. To achieve this some subroutines were added to the TH3D program. Using these subroutines, an internal space is defined inside a 2-D or 3-D distributed solid structure. The internal space is confined by the surface elements of the thermal conduction model. The temperature and humidity of the internal air are considered to be uniform. A subroutine is added to calculate the heat, moisture and air balance of the internal space.

The heat balance includes:
- radiative heat exchange between surface elements
- convective heat exchange between each surface element and the internal air
- the heat loss by ventilation
- latent heat exchange by condensation or evaporation at the surface elements

The moisture balance incudes:
- moisture production
- condensation or evaporation on surface elements
- moisture removal by ventilation

To solve the combined HMA equations in the TH3DR model an iterative procedure of two nested iteration steps is followed. In the first iteration step the temperatures in the solid domain are computed. This yields estimated surface temperatures that are used in the second iteration step to solve the heat balance and moisture balance equations for the internal space. From these equations the internal air temperature and humidity are computed. The heat fluxes for surface elements are also computed and these are used as boundary conditions for the first iteration step. This process is repeated until the desired accuracy is achieved.
An example of a calculation result is given in figure 1.

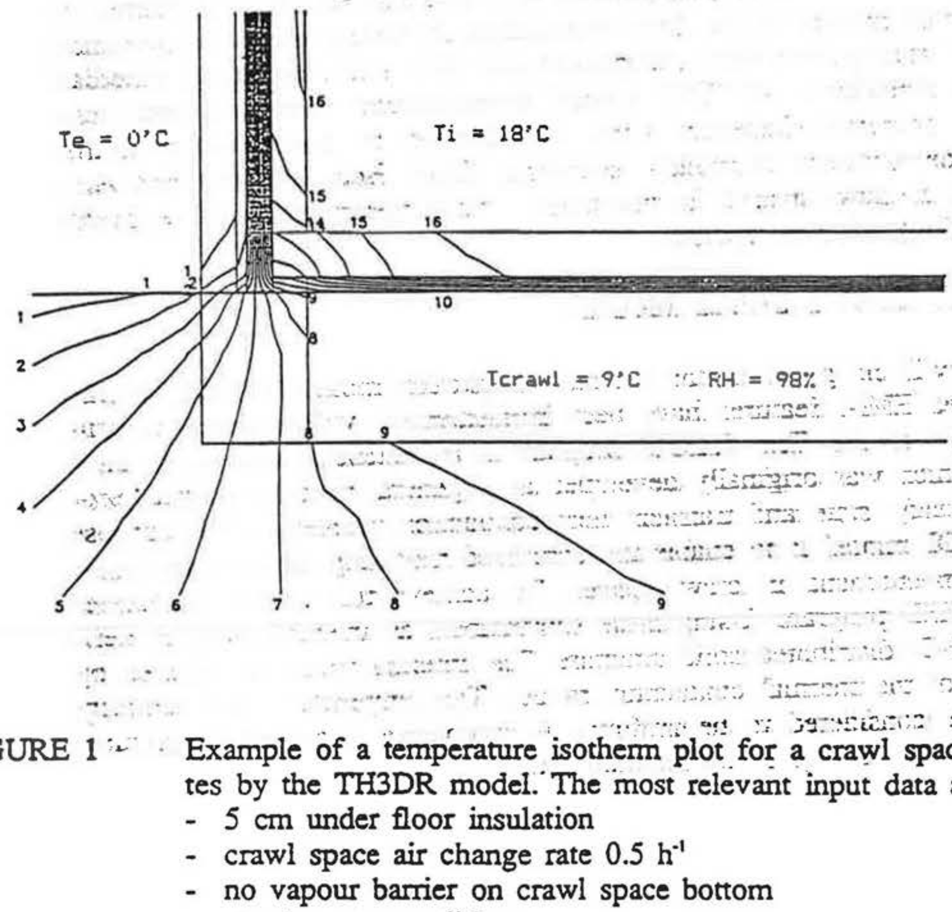

FIGURE 1 Example of a temperature isotherm plot for a crawl space as computes by the TH3DR model. The most relevant input data are:
- 5 cm under floor insulation
- crawl space air change rate 0.5 h^{-1}
- no vapour barrier on crawl space bottom
- steady state conditions
- external temperature Te = 0 °C.
- internal temperature Ti = 18 ° C.

The crawl space air temperature and air humidity are computed by the TH3DR model.

The TH3DR model has been used to study the dynamic thermo-hygric behaviour of different types of crawl spaces (1). The purpose of this study was to compare the energy and moisture performance for different concepts of crawl space configurations. Several technical options were taken into consideration, like floor insulation, insulation of the foundation elements and vapour retarders on the crawl space bottom. The aim was to evaluate three important aspects:

a. the air humidity in the crawl space
b. the heat loss through the floor
c. the thermal bridge effect near to the facade

The study resulted also in the development of a more simplified crawl space model as described in the next paragraphs.

SIMPLIFIED CRAWL SPACE MODEL

Simulation results from the complex TH3DR-model have been used to derive simplified equations for the heat, moisture and air balance of the crawl space. These equations are implemented as an utility for the spreadsheet program Lotus 123. The purpose of the spreadsheet model is to provide an easy to use tool to practitioners in evaluating different type of measures to solve crawl moisture problems. The spreadsheet model allows the evaluation of remedial measures like crawl space ventilation, insulation retrofitting, vapour retarders on the crawl space bottom and possible combinations of these measures. One of the critical aspects is the modeling of the heat loss to the ground. In the complex model the ground is divided into a large number of cells for which monthly temperatures and heat flows are computed, taking into account the large thermal inertia of the ground. In the simplified model the monthly heat flow through the bottom surface is computed by the equations

$$Q[t] = (Tk[t] - Tgr[t]) / Req$$
$$Tgr[t] = Tann + a \cdot (Tann - Te[t-t'])$$

where:

Q = averaged heat flux to the ground [W/m2]
Tk = crawl space air temperature [°C]
Tgr = equivalent ground temperature [°C]
Req = equivalent heat resistance of the ground [m2K/W]
Tann = annual mean outdoor temperature [°C]
Te(t)= monthly mean outdoor temperature [°C]
a = damping factor [-]
t = time [in months]
t' = time phase shift due to thermal inertia of the ground

In the simplified model the parameters Req,a, and t' are assumed to be constant. The values for these parameters are estimated from results of the detailed model using regression techniques. In figures 2 and 3 the some of the output is shown. These figures show the monthly temperature and humidity for three crawl space insulation options.

AIRBORNE MOISTURE TRANSPORT FROM CRAWL SPACES

Airborne moisture transport from the crawl space can lead to a severe moisture load for the living zones. Due to thermal stack effects the dwelling will have in general an underpressure with respect to the crawl space. Hence, humid air from the crawl space is easily transported through ground floor air leakages to the rooms on the ground floor. Influencing factors are

- crawl space ventilation
- air tightness of the ground floor
- air tightness of the building envelope
- (mechanical) ventilation systems
- wind pressures
- temperature differences

To study the influence of these factors a multi-zone ventilation and air infiltration model has been used (2). One of the conclusions is that the ratio (air leakage of ground floor) / (air leakage of the facades) is the an important factor. Or in other words: the more airtight the building facades the higher the risk of moisture penetration from crawl spaces, unless one pays a special attention to create airtight floor constructions. In principle there are two approaches to eliminate the moisture infiltration from the crawl space: a. improve he airtightness of the ground floor b. create a dry crawl space climate. The second option requires vapour barrier at crawl space bottom to prevent moisture penetration.

CONCLUDING REMARKS

In the Netherlands new building regulations, aiming at the elimination of crawl space associated moisture problems, are in preparation. Two basic requirements will play a role: an airtightness requirement for the ground floor construction and a thermal quality requirement for thermal bridges. Standard test and calculation methods for the evaluation of these aspects are also in preparation.

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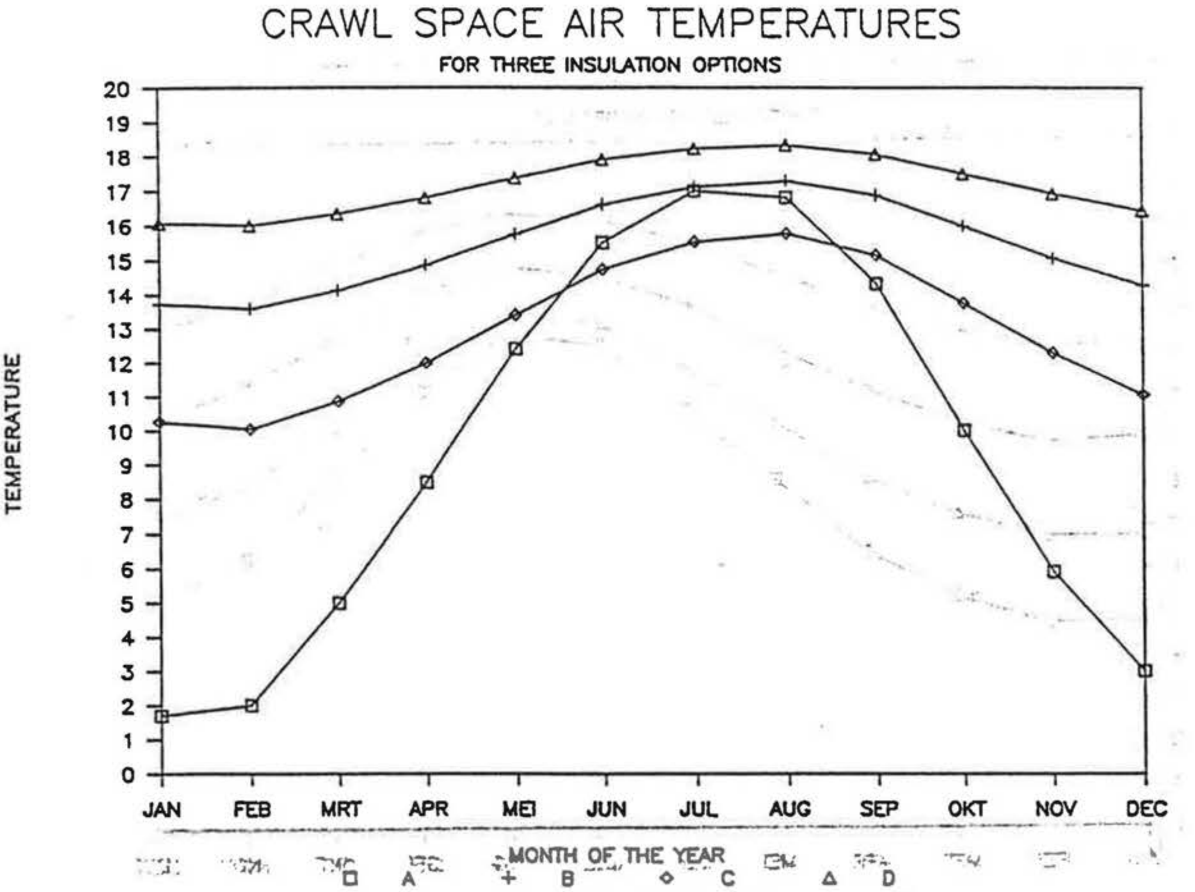

FIGURE 2 Crawl space temperatures as computed by the simplified spreadsheet model.
A: Monthly outdoor temperature.
Crawl space air temperatures are shown for three options:
B: no insulation
C: 5 cm insulation at the ground floor
D: 10 cm insulation including a vapour barrier on the crawl space bottom

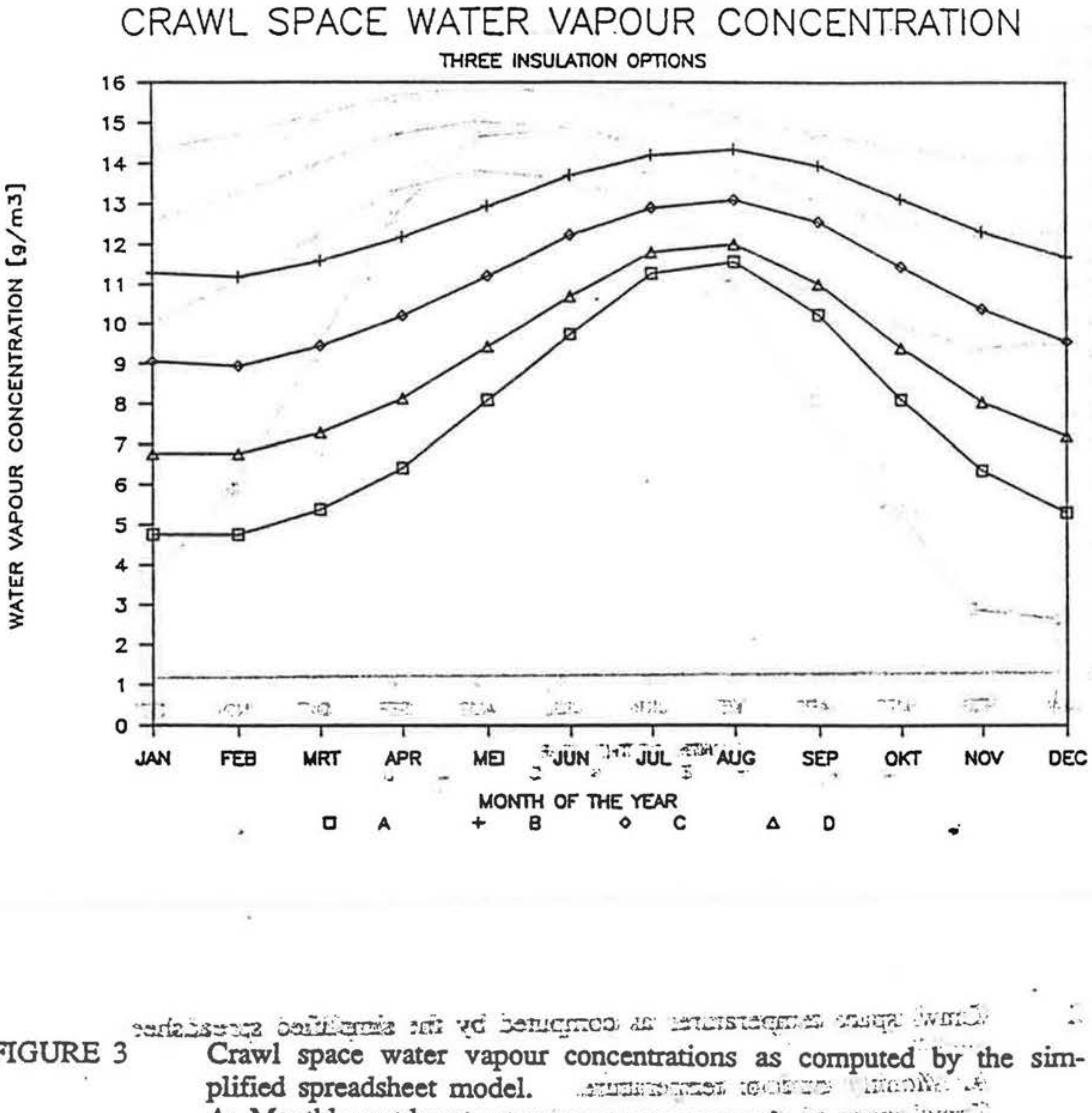

FIGURE 3 Crawl space water vapour concentrations as computed by the simplified spreadsheet model.
A: Monthly outdoor water vapour concentration.
Crawl space vapour concentrations are shown for three options:
B: no insulation
C: 5 cm insulation at the ground floor
D: 10 cm insulation including a vapour barrier on the crawl space bottom

HYGROTHERMAL BEHAVIOUR AND CONDENSATION CONTROL OF BUILDING ELEMENTS MADE OF PERLITE

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ABSTRACT

A number of building materials made of perlite were prepared. Their vapour diffusion resistivity coefficients and the thermal conductivities were measured. The results were statistically analysed. Various building constructions were designed with the use of these materials. They were checked to find the condensation risk for a number of winter design temperatures.

INTRODUCTION

Perlite, which is a siliceous volkanic rock, expands ten to thirty times its original volume when heated up to 700 - 1200 °C. Thus with its light-weight and porous structure it makes an excellent thermal and acoustic insulation material.

There has been many research work on the structural, acoustic, thermal and fire resistive qualities of building elements made of perlite. However, there hasn't been adequate research on their hygrothermal behaviour. Despite its many advantages perlite has an open porous structure and the prevention of condensation is necessary. The information on the hygrothermal behaviour of the building elements made of perlite is necessary for the evaluation of the condensation risk.

THEORY

Water vapour diffuses through a porous building element if there is a vapour pressure difference between the two sides of the element. (1) There are a number of terms used for the definition of water vapour diffusivity in building elements. One them is the vapour permeability(δ) measured in kg/m h (N/m^2) (or kg^m/m^2 h (N/m^2) and defined as the amount of vapour in kilogram passing through 1 m thickness and 1 m^2 area of the material with 1 N/m^2 pressure difference in 1 hour. Arithmetic reciprocal of vapour permeability is vapour resistivity ($\frac{1}{\delta}$). Another term is the vapour diffusion resistivity coefficent (μ) which is the ratio of the vapour resistivity of a material to the vapour resistivity of dry air of the same thickness. Either of these terms can be used as data for the prediction of condensation risk. The authors selected the vapour diffusion resistivity coefficient (μ) and the condensation control method which utilise it.

EXPERIMENTAL WORK

A number of building materials made of perlite were prepared. Some of these materials are commercially being produced, the others were proposed by the authors.The materials and their mix ratios were given in Table 1. Five specimens from each of the materials were taken and put into glass containers as shown in Figure 1. Calsium chloride in the container absorbs the humidity of the air and reduces the relative humidity 0 to 3 %. The containers with the specimen were put into a climatic chamber where the relative humidity and the temperature kept constant at 50% and 23 ^{0}C respectively.The containers were weighted by precise balances hourly to find the weight increase, which is due to the water vapour passing through the specimens and accumulating in the absorbent.The prodecure adopted is in accordance with DIN 52615 (2).

The equilibrium in hourly weight increase is reached aproximately in two to three hours. Only the values after the equilibrium point were used in evaluation. Water vapour diffusion coefficient is found according to the following equations:

$$\mu = \frac{1}{s} \left(\delta_L \cdot A \cdot \frac{p_1 - p_2}{I} - s_L \right)$$

$$\delta_L = \frac{0.083}{R_D \cdot T} \cdot \frac{p_o}{p} \left(\frac{T}{273}\right)^{1.81}$$

μ : Water vapour diffusion coefficient,
s : Average thickness of the model, m.
s_L : Average thickness of the air cavity in the container, m.
δ_L : Water vapour permeability in the air, kg/m h (N/m^2).
p_1 : Vapour pressure on the exterior side of the specimen, N/m^2
p_2 : Vapour pressure on the interior side of the specimen, N/m^2
I : The amount of water vapour passing through the specimen in one hour after the equilibrium point has been reached, kg/h .
R_D : Gas constant of water vapour, 462 Nm/(kg K)
T : Temperature of the climatic chamber, K
p : Average air pressure in the climatic chamber, N/m^2 .
p_o : Normal atmospheric pressure, 101 325 N/m^2 .

The thermal conductivities were measured by the hot plate method.

The results were statistically analysed by the computor program MICROSTAT. It was checked whether the number of samples were adequate to keep the standard error to be less then 5% . The 95% confidence intervals were also computed and given in Table 1. A number of constructions were designed.The condensation risk for these constructions and for a number of winter design temperatures were found by the use of the computer program based on Glaser's method.(3). The results were given in Table 2.

CONCLUSIONS

Expanded perlite has an open pore type structure.Thus, it is important to prevent moisture due either to condensation or to anexternal effect like rain.It is possible to prevent condensation by placing the layers of the building element appropriety.For the prevention of winter condensation, vapour resistances of the layers should be of descending order from inside to outside. At the same time, thermal resistances should be of descending order from outside to inside. It is is easier to prevent condensation in perlite insulated reinforced concrete roof constructions, because the above rule naturally applies. Present application of external perlite rendering is erroneous from the point of view of condensation and external moisture. The use of perlite mixed layer in sandwich building elements prevents condensation only up to a certain level. The use of loose fill perlite in the same construction is the weakest solution.

In this study hygrothermal quantities of building elements made of perlite was found to be used in condensation risk estimations. It was also planned to study the effect of temperature and vapour pressure difference on vapour diffusion resistivity coefficient.

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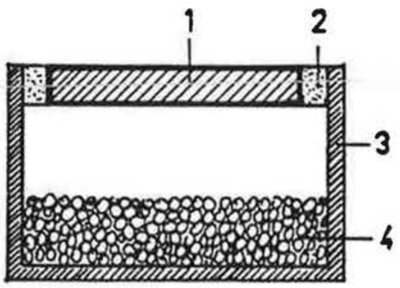
TABLE 1. The materials tested and the test results.

MATERIALS	MIXES	Average density d kg/m^3	Ave. vapour diffusion resistivity coefficient with 95% confidence int. μ –	Ave. thermal conductivity with 95% confidence interval λ W/mK
Perlite-cement-lime rendering	$1.4m^3$ expanded perlite 125kg cement 60kg lime 450lt water	402	7.3±0.06	0.14±0.011
Perlite concrete	$1.3m^3$ expanded perlite 150kg cement 300lt water	606	8.6±0.09	0.19±0.013
Surface silicated perlite concrete	Surface of perlite concrete silicated after curing. (Same as above)	606	58.7±2.0	0.19±0.014
Bitum coated perlite concrete	Surface of perlite concrete coated with bitum after curing. (Same as above)	606	563.0±9.8	0.19±0.014
Particle silicated perlite concrete	$1.3m^3$ expanded perlite 150kg cement 300lt water	960	85.4±2.4	0.14±0.012
Bitum-perlite-cement slab	$1.3m^3$ expanded perlite 150kg cement $0.3m^3$ bitum	1200	196.1±4.0	0.14±0.009
Loose fill expanded perlite	Expanded perlite of particle size 0 - 5 mm.	100	1.0±0.09	0.0395±0.002



1. Sample
2. Vapour proof sealant
3. Glass container
4. Absorbent (Calsium chloride)

FIGURE 1. The experimental set up.

TABLE 2. Condensation risks of various building elements made of perlite.

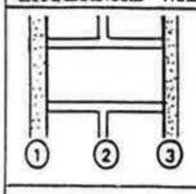
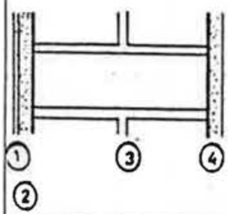
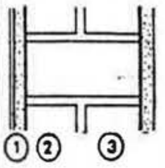
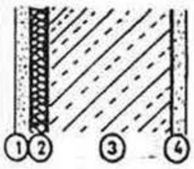
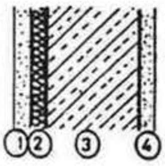
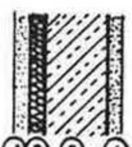
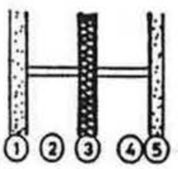
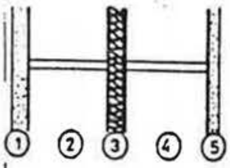
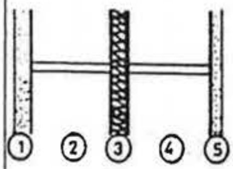
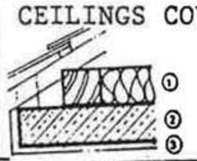
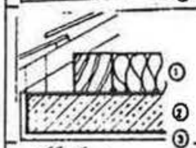
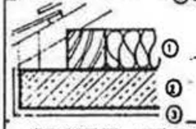
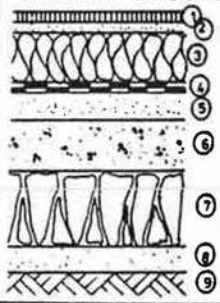
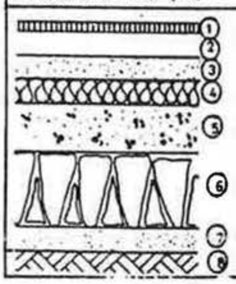
BUILDING ELEMENTS	(+)sign indicates the presence (−)sign indicates the absence of condensation risk for the winter design temperatures given below.										
EXTERNAL WALLS	+3	0	−3	−6	−9	−12	−15	−18	−21	−24	−27°C
 1.Cement-lime -sand rendering, 0.03 m 2.Solid brick,0.19m 3.Perlite-cement-lime internal rendering,0.022 m	+	+	+	+	−	−	−	−	−	−	−
 1.Cement-sand external rendering, 0.005 m 2.Perlite-cement-lime rendering, 0.025 m 3.Solid brick, 0.29 m 4.Perlite-cement-lime internal rendering,0.022 m	+	+	+	+	+	+	+	−	−	−	−
 1.Cement-sand external rendering 0.005 m 2.Perlite-cement-lime rendering, 0.025 m 3.Solid brick, 0.19 m 4.Perlite-cement-lime rendering, 0.022 m	+	+	+	+	−	−	−	−	−	−	−
 1.Cement-lime-sand external rendering, 0.03 m 2.Perlite concrete slab,0.03 3.Concrete wall, 0.20 m 4.Lime-sand internal rendering, 0.02 m	+	+	+	+	+	+	+	+	−	−	−
 1.Cement-lime-sand external rendering,0.03 m 2.Bitum-perlite-cement slab, 0.03 m 3.Concrete wall, 0.15 m 4.Lime-sand internal rendering, 0.02m	+	+	+	+	+	+	+	−	−	−	−
 1.Cement-lime-sand external rendering, 0.03 m 2.Bitum-perlite-cement slab, 0.03 m 3.Concrete wall, 0.10 m 4.Lime-sand internal rendering, 0.02 m	+	+	+	+	+	+	−	−	−	−	−
 1.Cement-lime-sand external rendering, 0.03 m 2.Hollow brick, 0.085 m 3.Bitum-perlite-cement slab, 0.05 m 4.Hollow brick,0.085 m 5.Lime-sand internal rendering, 0.02m	+	+	+	+	+	−	−	−	−	−	−

TABLE 2 (continued)

BUILDING ELEMENTS	(+)sign indicates the presence, (−)sign indicates the absence of condensation risk for the winter design temperatures given below.										
	+3	0	−3	−6	−9	−12	−15	−18	−21	−24	−27°C
 1.Cement-lime-sand external rendering, 0.03 m 2.Hollow brick, 0.135 m 3.Bitum-perlite-cement slab, 0.05 m 4.Hollow brick, 0.135 m 5.Lime-sand internal rendering, 0.02 m	+	+	+	+	+	−	−	−	−	−	−
 1.Cement-lime-sand external rendering, 0.03 m 2.Hollow brick, 0.135 m 3.Loose fill perlite,0.05 m 4.Hollow brick, 0.135 m 5.Lime-sand internal rendering, 0.02 m	−	−	−	−	−	−	−	−	−	−	−
CEILINGS COVERED WITH A ROOF											
 1.Perlite concrete, 0.10 m 2.Reinforced concrete,0.10m 3.Lime-sand rendering,0.01m	+	+	+	+	+	+	+	+	+	+	+
 1.Bitum-perlite-cement slab, 0.05 m 2.Reinforced concrete,0.10m 3.Lime-sand rendering,0.01m	+	+	+	+	+	+	+	+	+	+	+
 1.Loose fill perlite,0.05 m 2.Reinforced concrete,0.10m 3.Lime-sand rendering,0.01m	+	+	+	+	+	+	+	+	+	+	+
GROUND FLOORS											
 1.Precast terrazzo,0.02 m 2.Mortar, 0.025 m 3.Perlite concrete, 0.05 m 4.Damp proof layers,0.002m 5.Screed, 0.05 m 6.Coarse concrete, 0.10 m 7.Ground course, 0.15 m 8.Sand fill, 0.05 m 9.Compacted ground	+	+	+	+	+	+	+	+	+	+	+
 1.Timber flooring,0.022 m 2.Air cavity, 0.05 m 3.Cement screed, 0.05 m 4.Bitum-perlite-cement 0.05 5.Coarse concrete, 0.10 m 6.Ground course, 0.15 m 7.Sand fill 8.Compacted ground	+	+	+	+	+	+	+	+	+	+	+

IMPACT OF LATENT HEAT TRANSFER BY VAPOR DIFFUSION ON THE THERMAL BALANCE OF ROOFS

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ABSTRACT

The computer program MATCH is used to calculate the combined effects of heat and moisture migration through composite constructions such as low slope roofs. The program is a 1-D model that calculates transient distributions of temperature and moisture content resulting from the environmental conditions to which the construction is exposed. In this paper, the only moisture transport mechanism accounted for is vapor diffusion, which is calculated using vapor pressures as the driving potential. The coupling between moisture and temperature is treated by letting the thermal conductivities increase with moisture contents due to the enhanced heat conduction in wet materials and by accounting for the sources of enthalpy accompanying the evaporation or condensation of vapor within the control volumes.

During the diurnal variations of surface temperatures moisture is driven from one side of the construction to the other and back again. The uptake and release of latent heat at the points of evaporation and condensation tend to increase the overall heat transfer. Thereby, the heating and cooling loads on buildings are increased. The amount of moisture required to produce this process is small, just a little over-hygroscopic moisture is sufficient. Such moisture is easily obtained during the construction period.

The model has been validated by experiments in a Large Scale Climate Simulator, results of which are shown for dry as well as for wet conditions. Subsequently, it has been used to calculate both sensible and latent heat flows in a flat roof construction exposed to the Danish climate.

KEY WORDS: Moisture migration, latent heat, computer simulation.

INTRODUCTION

It has always been known that moist materials are not as good thermal insulators as if they were dry. The mechanisms whereby the moisture affects the thermal performance of a material are well known. Analytical and experimental investigations of the processes have been performed in (1, 2, 3 and 4). In (3) heat flow through a moist material is defined by three different mechanisms:

1. Heat flow caused by a temperature gradient.
   This heat flow is caused by heat conduction in the solid parts of a porous material, conduction in the air and still moisture (vapor, liquid and ice) in the pores, by radiation in the pores, by local convection in the pores and by evaporation and condensation on a microscopic level in the single pores.

Thermal conductivity caused by type 1 heat transfer may be somewhat higher for a moist material than for a dry. This is well described by increasing the thermal conductivity with moisture content.

2. Convective heat transfer.
   The air, vapor and liquid moisture carries sensible (non-latent) enthalpy when it migrates from either a colder or warmer region of the material.
   Moisture transfer is usually such a slow process that the convection with moisture gives negligible contributions compared to the conducted heat.

3. Heat transfer due to phase changes, latent heat transfer.
   When liquid moisture evaporates from one area of the material, migrates as vapor and condenses in another area, it involves a large amount of heat, even if the moisture transfer is limited, because the enthalpy of phase change vapor/liquid is considerable.
   The process becomes important compared to the conducted heat in permeable materials with a good insulation value even if there is only little moisture present.

The additional heat transfer in a moist material caused by type 3 heat flow is not described very well by simply increasing the thermal conductivity with moisture content. The vapor transport causing this type of heat flow increases with temperature in a non-linear way because the saturation vapor pressure varies non-linearly. Further, it is required that moisture is present in its liquid state for the process to become important, but it does not seem to matter how much extra moisture is present. Thus, in order to accurately predict the thermal performance of a construction having wet, permeable insulation it is required to simultaneously solve the transient transport equations for heat and moisture flow.

THE COMPUTER PROGRAM MATCH

MATCH, Moisture and Temperature Calculations for Constructions of Hygroscopic Materials, is a computer program that was developed as part of a recently finished Ph.D. study (5). Its main features are:

- A finite difference numerical method (FDM) is used.
- Moisture as well as temperature distributions are calculated transiently.
- Transport of moisture in vaporous as well as in liquid phase.
- Material properties are non-constant.
- Hysteresis in the moisture retention curves is accounted for.
- Phase conversion enthalpies are accounted for.

The transport equations used are the basic Fourier's, Fick's and Darcy's laws. Together with the continuity requirements of infinitely small control volumes, the governing transient transport equations are:

Thermal equation:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \Delta h_v \frac{\partial}{\partial x}\left(\delta\frac{\partial p_v}{\partial x}\right) \qquad (1)$$

Moisture equation:

$$\rho \xi \frac{\partial\left(\frac{p_v}{p_{v,s}}\right)}{\partial t} = \frac{\partial}{\partial x}\left(\delta\frac{\partial p_v}{\partial x}\right) \qquad (2)$$

where

ρ Dry density of the material $\left[\frac{kg}{m^3}\right]$ Δh_v Heat of evaporation $\left[\frac{J}{kg}\right]$

T	Temperature $[K]$	δ	Water vapor permeability $\left[\frac{kg}{Pa\,m\,s}\right]$
t	Time $[s]$	p_v	Partial pressure of vapor $[Pa]$
k	Thermal conductivity $\left[\frac{W}{m\,K}\right]$	$p_{v,s}$	Saturation vapor pressure $[Pa]$
x	One dimensional co-ordinate $[m]$	ξ	Moisture capacity $\left[\frac{kg}{kg}\right]$
c_p	Specific heat capacity referring to dry weight of the material $\left[\frac{J}{kg\,K}\right]$		

The specific heat capacity on the left side of equation 1 includes the heat capacity of the different phases of water in the material:

$$c_p = c_{p,dry} + \sum_{i = \substack{ice\\water\\vapor}} u_i c_{p,i} \tag{3}$$

Where

u Moisture content (in phase "i") $\left[\frac{kg}{kg}\right]$

Latent heat effects involved in ice formation are taken care of by increasing the heat capacity over the temperature range from $-\Delta T$ to 0°C:

$$\Delta c_p = \frac{u \cdot \Delta h_{ice}}{\Delta T} \tag{4}$$

where

Δh_{ice} Heat of formation $\left[\frac{J}{kg}\right]$

This resembles the actual phenomenon encountered in porous materials that ice formation takes place over a span of temperatures depending on the pore structure of the material.

The first term on the right of equation 1 is the regular conduction term from Fourier's law. The thermal conductivity should account for conduction in both the dry material and the moisture in the pore system, thereby making k an increasing function of moisture content (type 1 heat flux). The thermal conductivity is defined as a linearly increasing function of moisture content in MATCH. The second term on the right of equation 1 is the latent heat contribution from the evaporation-condensation process. The term represents the gain of moisture in the control volume entering as vapor, multiplied with the heat of evaporation. It is assumed that all of this gain will condense to form liquid or frozen water. A calculation of how much vapor, as a mass, there may be present in a control volume shows that this is a very good assumption.

The water vapor permeability of equation 2 is a somewhat varying function of the moisture content in the material. MATCH uses a simple equation to express this variation. The moisture capacity on the left of equation 2 is the slope of the sorption curve that gives the relation between moisture content and relative humidity. An analytical expression is used for the sorption curve (6).

It should be mentioned that the liquid flow is negligible for the calculations shown in this paper as moisture contents are too low to become important in the permeable insulation used. The equation describing this part of the moisture flow is therefore not shown.

VALIDATION OF MATCH

A flat roof construction of the cold deck type was tested in a Large Scale Climate Simulator (LSCS) belonging to the Roof Research Center of Oak Ridge National Laboratory, TN, USA. The Roof Research Center is operated as a national user facility under the U.S. Department of Energy (7). The LSCS, being the center-piece of equipment at the center, consists of two climate chambers on top of each other separated by one or more roof specimens in a test area measuring 3.9 x 3.9 m. The climate in the upper chamber may be varied according to a programmed scheme to simulate most outdoor conditions (for instance air temperatures in the range from -40 to 66°C), while the climatic conditions in the lower chamber may be varied within a slightly smaller range.

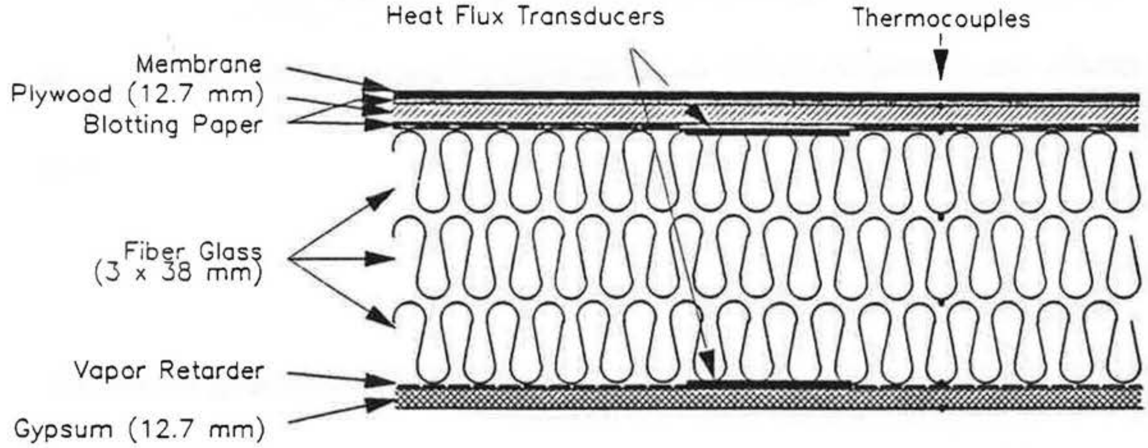

FIGURE 1. Experimental setup for measurement of heat flow in a wet flat roof construction in the Large Scale Climate Simulator.

A cross section of the roof specimen tested in the LSCS is shown in figure 1. It consisted of a 1.2 by 1.2 m test panel (out of nine) with, from the top: An EPDM roofing membrane, 12.7 mm plywood, 114 mm fiber glass, a polyethylene vapor retarder and a 12.7 mm gypsum plate as ceiling. Above and below the plywood were sheets of blotting paper that were wetted with a total of 1 kg moisture per square meter roof (less than 1% by volume of the insulation) after an initial determination of the dry thermal parameters of the construction. The roof specimen was instrumented with thermocouples in all material interfaces and with bakelite, thermopile heat flux transducers at the top and bottom of the insulation. The temperature in the upper chamber was varied in diurnal cycles between 10 and 66°C to resemble typical summer variations in the temperature of a black roof surface, while the lower chamber was kept at 24°C to simulate indoor conditions in a summer situation.

The measured temperatures at the boundaries were used as input to calculations with MATCH. The resulting measured and calculated heat fluxes are shown in figure 2.

The measured heat flux at the bottom of the insulation, next to the polyethylene, gave appreciably higher amplitudes than the flux measured at the top, next to the plywood. In the day, when vapor is driven down by the heat on the roof top, it condenses when it reaches either the vapor retarder or the top of the heat flux transducer, thus releasing the heat of condensation. This moisture re-evaporates in the following night when the temperature gradient is reversed, thus taking up an appreciable amount of heat. The heat flux measured by this transducer consists therefore of both the sensible (type 1) and the latent (type 3) heat.

A hypothesis was devised for why the reading of the top transducer gave smaller amplitudes: When vapor coming from the bottom condenses at the underside of this transducer its vapor pressure becomes equal to the saturation vapor pressure at its temperature. The plywood next to the transducer has almost the same temperature but absorbs the moisture hygroscopically, i.e. at a vapor pressure less than saturation. Any condensed moisture at

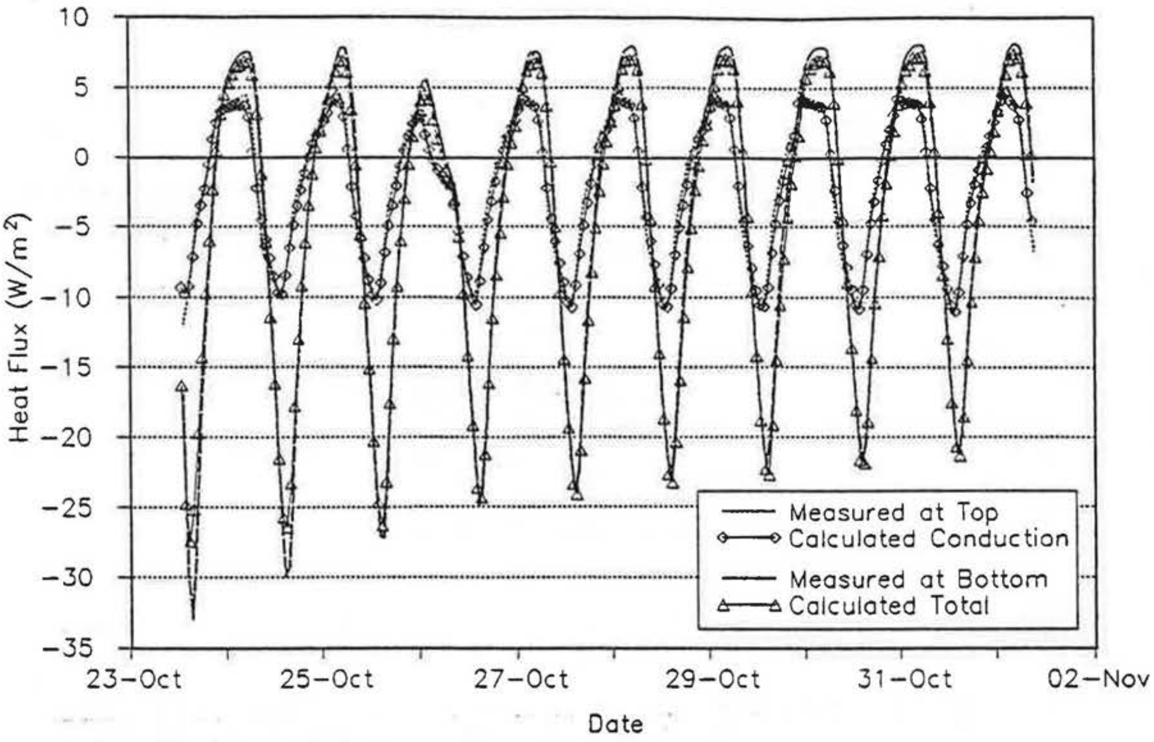

FIGURE 2. Measured and calculated heat flows at the top and the bottom of the insulation. Heat flows up are positive.

the underside of the transducer will therefore re-evaporate immediately, by-pass the transducer and become absorbed by the wood. Thus, only the sensible heat flow is read by this transducer.

The calculated heat flows are shown for the bottom of the insulation as total heat flows and for the top as sensible heat flow alone. Apart from some initial deviations the agreement is quite good. The values of positive and negative heat flows were added separately for the whole period except for the two first days. Comparing the calculated total heat flows with those measured at the bottom gives calculated downwards heat flow equal to 106% of the measured value, while the upwards heat flow is calculated to 83% of the measured value. Including the first two days in the sums actually improves the result.

Considering that the parameters describing the retention and transport of moisture had to be estimated the gained accuracy is quite satisfying.

In this example it was seen that the latent heat flow approximately doubled the heat flow obtained by conduction alone. The heat flows in a similar but dry construction were approximately 12% larger than the sensible heat flow with moisture. This is due to the smaller temperature gradients when moisture is present.

EXTRAPOLATION TO A CONSTRUCTION IN THE FIELD

A flat roof was calculated with MATCH using climate data from the Danish Test Reference Year (TRY). It consisted of, from the outside: A black, unprotected roofing membrane, 150 mm mineral wool, a vapor retarder and 25 mm of wood wool cement. The indoor temperature was held constant at 21 °C. Heat flows were calculated every hour and the downwards and upwards values were added daily for the sensible as well as the latent heat. Results are shown in figure 3.

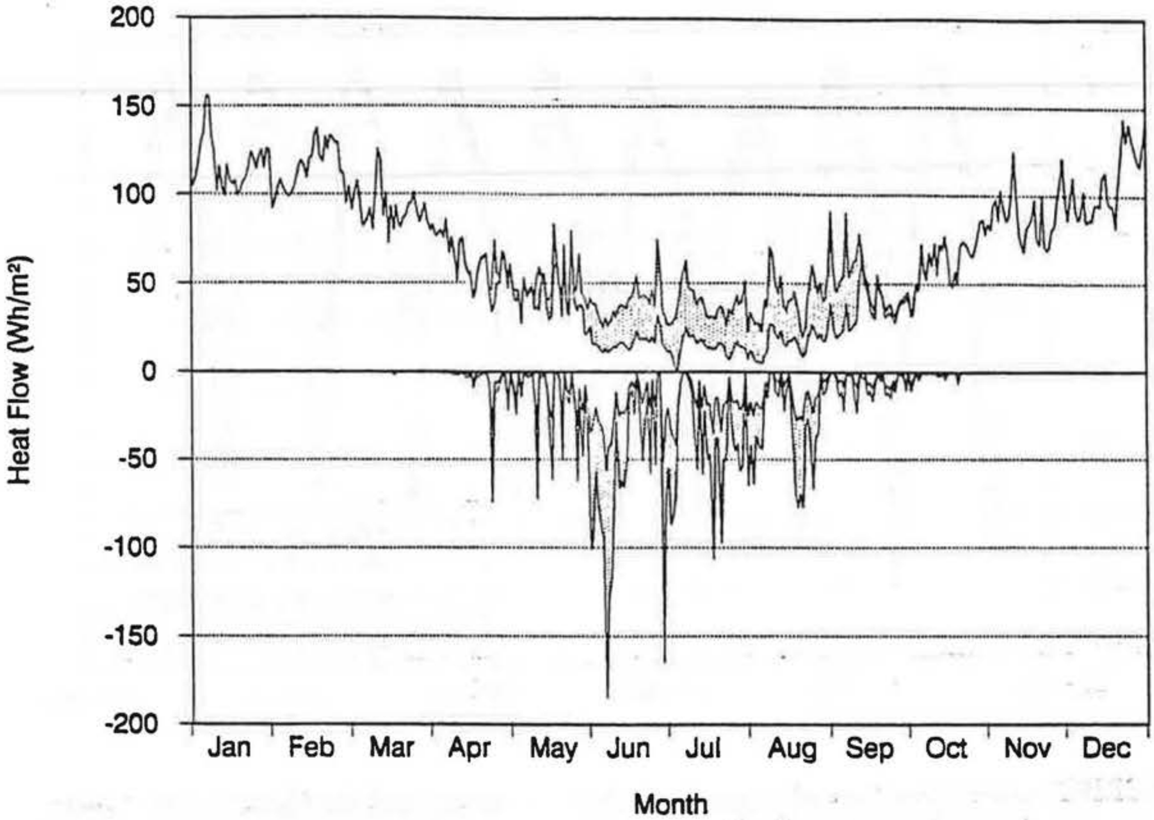

FIGURE 3. Calculated sensible and latent heat flows for a flat roof exposed to the Danish climate. Upwards (positive) and downwards heat flows have been added separately for each day in the year. The shaded area represents the additional heat flow due to latent heat.

There was no latent heat effect in the winter nor in the early spring and late fall. The moisture was deposited permanently at the top of the roof in these periods where the day-time roof temperature did not exceed the indoor temperature. In approximately one third of the year around the summer period did the roof surface temperature become sufficiently high in the day-time to drive some moisture down to the bottom of the roof where it condenses. Some of this moisture migrates back again in the night and in colder periods.

This cyclic process causes as well increased positive and negative heat loads on the building. Adding these values over the whole year the inwards heat flow is increased from 2.0 kWh/m2 by sensible heat flows to 5.1 kWh/m2 totally, i.e. an increase around 150%. The outwards heat flow is increased from 23.4 kWh/m2 sensibly to a total of 26.5 kWh/m2, i.e. 13%. The numerical value of the latent heat is in both cases 3.1 kWh/m2 because the same amount of moisture has migrated back and forth over the year.

The increased outwards heat flow will probably not cause any concern as the increase occurs out of the main heating season. In buildings with high internal heat loads the extra inwards heat flow in the summer may increase the cooling requirements considerably. The additional thermal loads occurs in the day-time and will therefore fall together with most activities in air-conditioned buildings.

CONCLUSION

A computer model is developed which simultaneously calculates heat and moisture flow. Advantage may be taken of such a model in accurately describing the heat flow through moist materials as it is able to better describe the impact of moisture on the thermal balance of constructions than simply increasing the thermal conductivity with moisture content. The transfer of latent heat by evaporation of moisture from a warm spot of the construction, migration as vapor and condensation at a colder spot may for permeable insulation materials more than double the heat transfer in certain periods when the temperature gradient changes direction cyclically. This process is possible as soon as over-hygroscopic moisture is present.

The additional transfer of heat will for whole year periods increase the heat flows in and out through the construction by appreciable amounts. The additional heating requirements are probably small as the increase occurs out of the heating season, while the additional inwards heat flow may cause important additional cooling requirements. This conclusion is valid throughout the majority of climates as most southern and northern climates have seasons where the outdoor temperature varies in diurnal cycles around the indoor temperature, thus causing the cyclic movements of moisture.

To thoroughly study the impact of moisture on building heating and cooling loads models for combined heat and moisture transfer should, in the future, be incorporated in models for simulation of whole building thermal loads.

ACKNOWLEDGMENT

The author wishes to express his gratitude towards the people at and the organization behind the Roof Research Center of Oak Ridge National Laboratory, TN, USA. Part of the experimental work in a recently finished study for the Ph.D. degree was carried out under ideal circumstances in Oak Ridge in the summer and fall of 1989.

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FIELD AND LABORATORY EVALUATION OF NEW DEVELOPMENTS IN GAS FIRED APPLIANCES TO PREVENT CONDENSATION IN DWELLINGS

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INTRODUCTION

Moisture is emitted into the atmosphere during cooking, clothes washing, personal hygiene and by breathing. A four person household produces between 5 and 10 litres of water vapour per day, rising to 12 litres where clothes drying indoors takes place[1]. This moisture can condense out onto cold surfaces within the dwelling, producing suitable conditions for mould spores to germinate. It is estimated[2] that of the UK housing stock of 17.5 million dwellings, 8.5 million are affected by some form of condensation with 2.8 million having serious problems, often accompanied by mould growth. Although condensation is more common in older, less well insulated dwellings, it can also occur in new dwellings having reduced ventilation heat losses to save energy. A recent survey[3] by BRE of 385 new small homes showed that 50% had pools of water on the window sills due to condensation.

To investigate the interaction between condensation, occupancy patterns and moisture production in well insulated dwellings, computer studies have been carried out for a two bedroom flat with walls having a 'U' value of 0.5 $W/m^2{}^\circ C$ and a heat loss of 2.6kW. The results for a two person household show that even where the moisture production is low (3.6 litres per day) condensation occurs when the house is unheated for long periods and relative humidities above 70%, the critical level for mould growth, will persist for over 5 hours per day. Where moisture emissions are greater, the periods of high humidity persist longer. These computer studies demonstrate that where houses are heated intermittently condensation can occur even though moisture emissions are low.

The mechanism of mould growth is well documented[4] as are the cures. These include decreasing the amount of water vapour being released into the house, increasing the fresh air ventilation rate, increasing the internal air temperature or removing water vapour either at source or with a dehumidifier. British Gas are investigating a range of novel approaches to the problem of condensation, especially in new well insulated dwellings.

COMBINED HEATING AND FRESH AIR SUPPLY

For anti-condensation measures to be effective and acceptable to the householders, it is essential that they do not adversely affect the thermal environment by, for example, promoting draughts. Consequently, where outside air is introduced mechanically it must first be heated before being distributed into the living space. This can be achieved in a number of ways.

Modular Approach

A novel approach is to use a specially developed water to air heat exchanger module supplied by hot water from a thermal store (that also provides domestic hot water) charged by a gas boiler. The Warm Air Module provides not only conditioned fresh air but also the heating requirements of the dwelling. It is specifically designed to be quiet, to ensure that it is used when required and is not turned off by the occupants because of noise. Extensive work in a reverberation chamber has confirmed that its noise level is less than 38dBA. The output is 2.75kW with a boost facility of over 3kW. The module can be supplied either as a basic unit or as a free standing cased room heater.

The Warm Air Module has been evaluated in a 3 bedroomed newly constructed end of terrace house having a heat loss of 4.7kW. Consequently two units, fed from the same thermal store, were installed. A schematic diagram of the installation is shown in figure 1. The upstairs unit was installed in a cupboard on the landing and supplied warm air to all three bedrooms through ducts laid in the loft. Fresh air was ducted into the return air inlet. Downstairs, the free standing room heater was installed in the main living room. It also supplied heat to the adjoining kitchen through a stub duct. The bathroom was heated by a radiator/towel rail connected directly to the thermal store. One advantage of using two modules was that it allowed independent control of the temperature upstairs and downstairs. The test house measurements, see

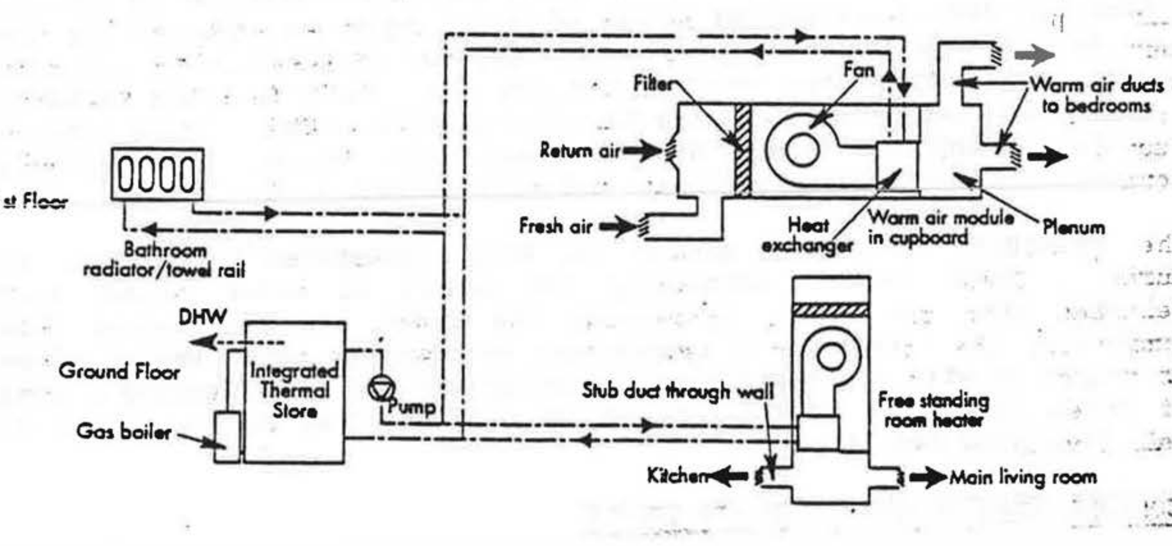

FIGURE 1. Installation of warm air module in test house

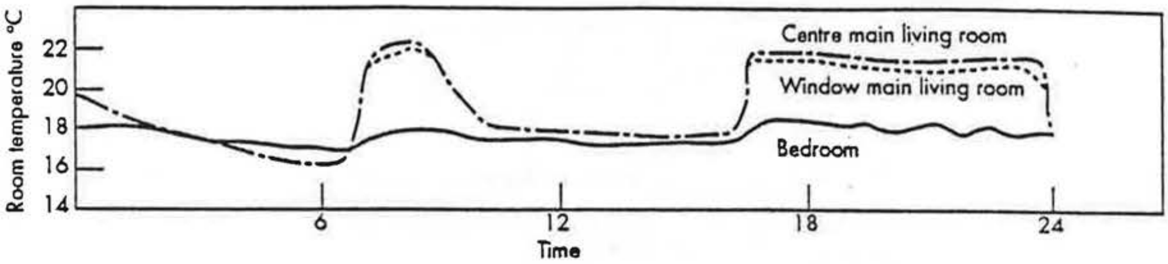

FIGURE 2. Test house evaluation of warm air module

figure 2, showed that the module provides a rapid warm up with a good distribution of warm air resulting in an even temperature throughout the room. Even in front of the window the temperature was within 0.3°C of that in the middle of the room. The satisfactory thermal and acoustic environments produced guarantees that sufficient fresh, pre-heated air is introduced, especially to the sensitive areas of the house, to prevent condensation.

Mechanical Ventilation with Heat Recovery

A more energy efficient method is to incorporate heat recovery with full mechanical ventilation. For highly insulated dwellings where the heating requirement is small, a water to air heat exchanger can be incorporated into the supply duct of a full mechanical ventilation with heat recovery system. This novel approach was used in a demonstration project funded by the European Community(5). Four superinsulated houses with heat recovery, and eight control houses without any form of mechanical ventilation, were built from components imported from Finland. The three bedroomed houses are identical except for the standard of insulation. The control houses have a heat loss of 4.5kW compared to only 2kW for the superinsulated ones.

The ventilation system is powered by a heat recovery and ventilation unit situated in the kitchen (Figure 3). The temperature of the fresh outside air, pre-heated in the heat recovery unit, is further raised by the water to air heat exchanger to compensate for the dwelling heat losses. With the average useful miscellaneous heat gains being of the order of 700W, there will be little heat demand for significant parts of the heating season. Consequently a crucial part of the design is the method of controlling the heat supplied by the water to air heat exchanger, as failure to control the small fluctuating heat requirements would inevitably result in wide fluctuations in supply air temperature. To ensure good control of the thermal environment, without excessive boiler cycling, the heat exchanger is fed from a thermal store, charged by a gas boiler. The temperature of the water flowing to the unit is then continuously modulated by a room thermostat operating on a 3-port valve in the water supply to provide the exact heat requirement.

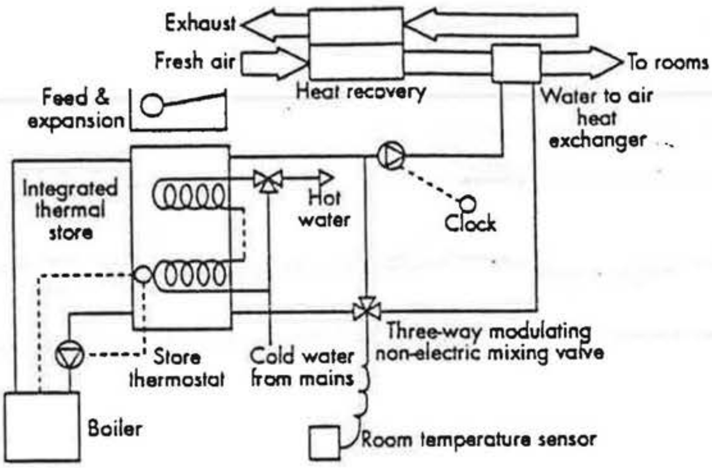

FIGURE 3. Heat recovery system for superinsulated homes

The performance of the houses has been extensively monitored. On average, the control houses used 56.2GJ per annum for heating and hot water compared to only 33.4GJ for the superinsulated homes. Of the energy savings approximately 8GJ could be attributed to the heat recovery system. Not only were fuel bills lower, but the occupants of the superinsulated houses had an enhanced thermal environment[6]. None of the superinsulated houses suffered from any form of condensation anywhere in the house. By contrast, all eight control houses suffered condensation on the windows even after slot ventilators had been added to the window frames.

Heat Recovery from Flue Products

British Gas are further increasing energy efficiency by developing a system that incorporates heat recovery from flue products[7]. The flue from a conventional gas boiler or air heater is connected into the extract system and the flue products pass through the heat recovery unit,

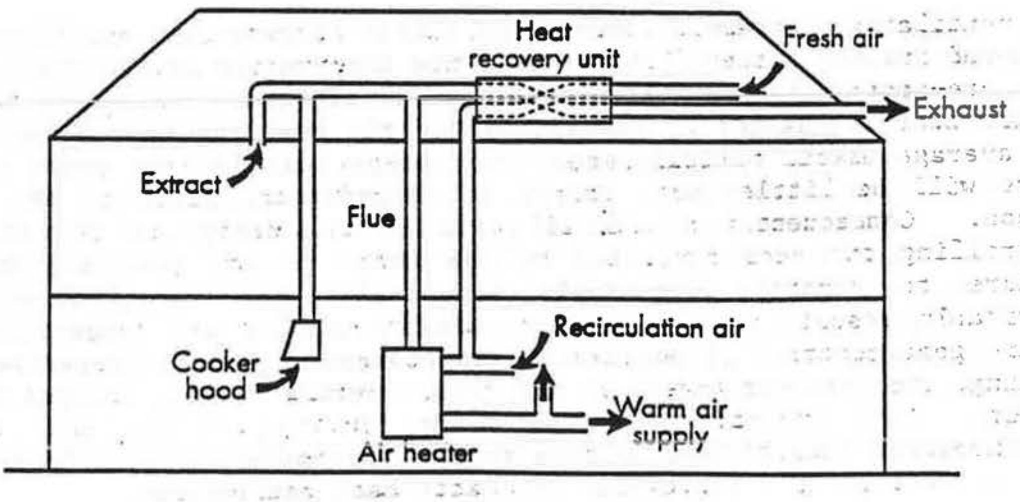

FIGURE 4. Warm air heating with heat recovery from flue products

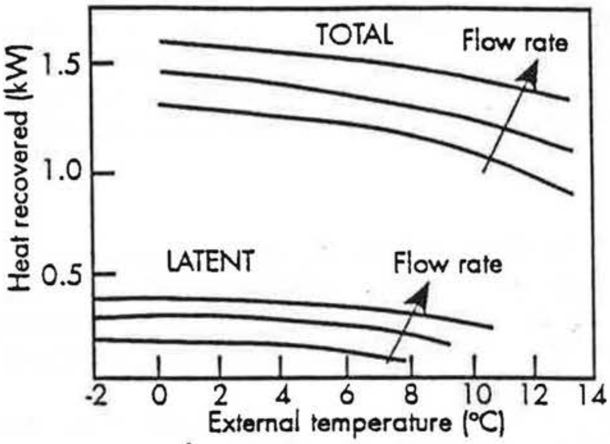

FIGURE 5. Variation of heat recovered with external temperature

so that the heat in the flue products as well as that in the extract ventilation air can be used to preheat the incoming fresh air. This heated air can either be used to provide background heating where a radiator system is installed or fed to the inlet duct of a warm air heater as shown in figure 4. The warm air version was tested in the same house used for the tests on the Warm Air Module and some of the results are shown in figure 5. The total heat recovery rate rises as the external temperature falls, reaching 1.5kW at 0°C. Since the latent heat of the water vapour in the flue products is also reclaimed, the heater becomes, in essence, a condensing appliance. Heat is also reclaimed from domestic activities with 1.2kW of the 3kW released by the cooker being recoverable.

A number of field installations are being monitored. Seven installations have a warm air heating system whilst two are based on radiator heating. Initial customer response has been very encouraging. The provision of a controlled supply of thermally conditioned air has almost completely eliminated condensation on even single glazed windows and there have been no adverse comments on draughts or of poor air distribution.

BACKGROUND HEATING

Local authority blocks of apartments are prone to condensation because they have inefficient heating systems which are not regularly used by the occupants. Consequently, the dwellings are cold and damp, a condition aggravated by the frequent use of unflued bottle gas heaters. Field trials carried out by the Building Research Establishment(4), have shown that installing a gas central heating system can, by providing a warmer internal environment, completely eliminate condensation problems. However, it is not always possible to install individual gas heating systems in high rise blocks of apartments. In these cases, communal systems can be installed whereby one central boiler supplies heat to each individual apartment. To meet this demand a new gas fired group heating system based on integrated thermal storage units that incorporates an element of continuous background heating under the control of the landlord has been developed[8]. The combination of landlord controlled background heating and a metered heating circuit ensures that heat is always available to combat condensation, but because the tenant pays directly for most of his energy, waste is minimised.

DEHUMIDIFIERS

An alternative method of reducing condensation is to remove the water vapour by a dehumidifer. Dehumidifiers are suitable for use where structural upgrading is not possible, increased heating is not economic and increased ventilation would be wasteful or difficult to achieve.

To date, all domestic dehumidifiers are electric, however a gas fired unit based on the absorption cycle, offers a number of advantages. A gas dehumidifier has no moving parts and therefore is quieter in operation and more reliable. It does not use CFC refrigerants and has lower running costs. Additionally, a gas dehumidifier provides background heating which helps to alleviate the problem. Watson House are currently carrying out feasibility studies on gas dehumidifiers.

CONCLUSIONS

Condensation and mould growth is a serious problem in 2.8 million homes in the United Kingdom. British Gas are actively pursuing energy efficient methods of combating it. The methods include mechanical ventilation with or without heat recovery, warm air ventilation modules supplied from thermal stores and communal heating systems with landlord controlled background heating. The development of a gas fired dehumidifier based on the gas absorption cycle is being considered.

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STRUGGLING WITH CONDENSATION PHENOMENA RISKS.FROM RESEARCH TO TECHNICAL CODES

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ABSTRACT

Starting from the research results,there was found the possibility to elaborate new experimental recommendations concerning the nuilding protection against harmful condesation phenomena risks in modern buildings,a problem of major importance in Romania.The utility of statistical studies on factors influencing this pathologic effect and also the need of adequate software concerning the heat and mass transfer process analysis in building elements are underlined.

1.INTRODUCTION

It is generally considered that water presence in building structures is not yet enough well-known /1/.Research studies are focused on condensation phenomena,the modern buildings being very sensitive to this kind of exceeding moisture.Therefore it was decided to establish new technical recommendations to be applied experimentally for future construction and rehabilitation works.

2.STATUS OF THE PREVIOUS TECHNICAL RECOMMENDATIONS

From the beginning,the aim of the technical codes in all the countries were to avoid:

-dew presence in areas at the surface of opaque walls or ceilings;
-excessive humidity levels of structural materials due to internal vapour condensation.

These technical codes were relied on Glaser method /2/. Some included approximations are considered responsible for the uncertain protection against condensation phenomena:

-non - hygroscopicity of building materials;
-negligence of the aleatory variability of the parameters influencing the heat and mass transfer conditions;
-steady - state unidirectional processes;
-the relative humidity inside the building is arbitrary considered at fixed levels.In fact it strongly depends on vapour sources and ventilation rate;
-vapour permeability independence from materials humidity;
-non - consideration of the capillary liquid water migration over critical moisture content levels.

3.RESEARCH CONTRIBUTIONS

(1) Field observations. The inhuman conditions imposed in Romania after the oil crisis aggravated the condensation phenomena,especially in multilevel blocks of flats with concrete walls and central heating.People prevented the heat losses by obstructing the windows and doors joints. They also permenently used kitchen gas machines in order to supplement the poor heating.The result was very bad increasing the air humidity and the condensation phenomena. Frequently,the high level of condensation could be a consequence of a "synergic" effect due to more than one single process (fig.1).

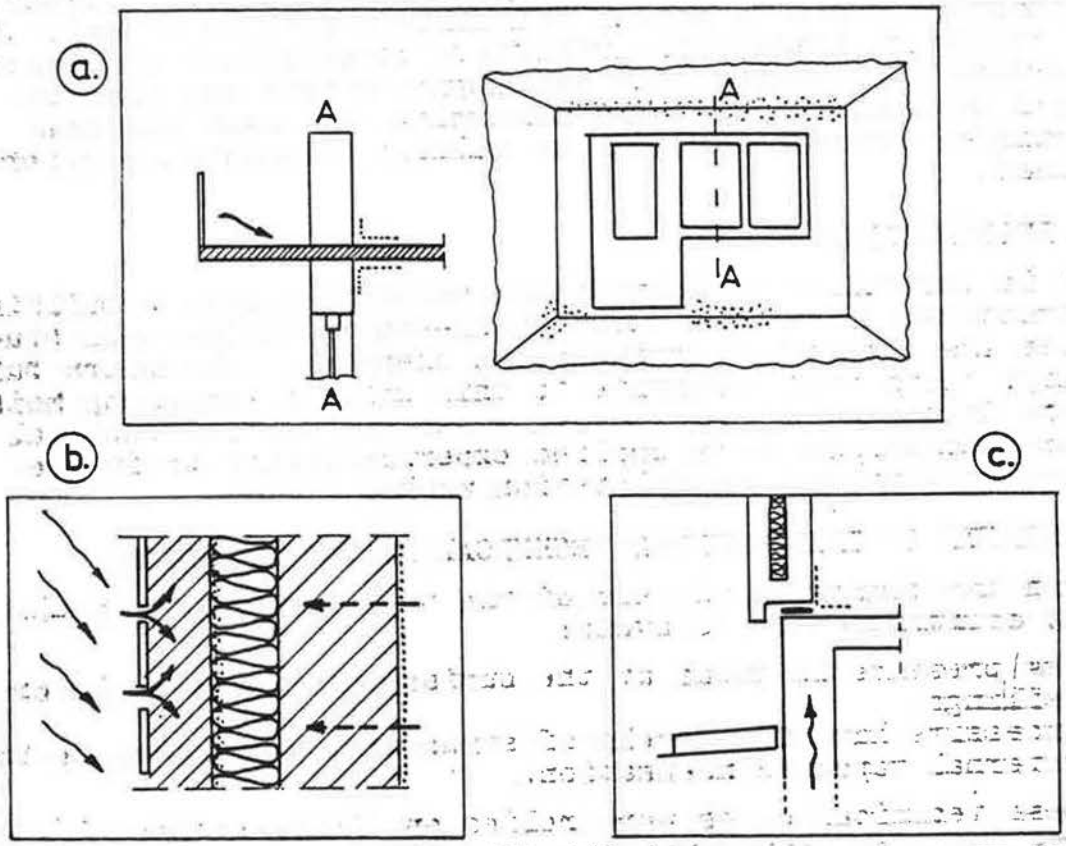

Fig.1 Condensation phenomena intensified by the superimposed effects: a-water infiltratio from balcony at lintel level; b-front wall covered with impermeable ceramic plates (rain infiltration through joints); c-basement wall (underground water ascent).

When adopting supplementary window glasses,the wet areas moved often to other points of the same room.As a result of the field investigations,the necessity of a carefully identification of all the humidity causes,a good ventilation and a competent information of the tenants become obvious.

(2) A better approach,preserving the Glaser fundamental elements,was obtained by considering the heat and mass flow as a plane problem using the mathematical model:

$$\nabla(\lambda\nabla T)=0 \qquad \nabla(\delta\nabla p)=0$$

In order to establish numerical solutions,electrical analogies and ordinators were used /3,4/.These contributions have led to a better understanding of the inner condensation in complex structures.

(3) Another progress was established calculating the true moisture content of the rooms air with the relation:

$$C_{vi}=C_{ve}+\left[G_i/n\cdot V\cdot\rho r\right]$$

To this aim,priority was given to systematic measurements of water vapour sources intensity in dwellings.Thus,in order to calculate the condensation risks inside the building elements it was considered possible to use daily mean values of the domestic sources (tab.1).Due to the considerable uncertainty in the assessment of the vapour sources,the G values are somewhat conservative.As for walls and ceiling surfaces,a realistic estimation is to be made in non steady state regime or,in any case,for short laps of time.The hygroscopic sorbtion of plaster and furniture surfaces are also important.Some results are presented by Glaser and Künzel /5,6/.The previous relation becomes:

$$C^{*}_{vi}=C_{ve}+\ G\left(n\cdot V\cdot\rho\cdot r\ \ +\sum A_i\cdot\gamma_i/C_{si}\right)^{-1}$$

Otherwise,the water vapour migration through opaque building elements are of little influence on the air humidity level.

(4) The ventilation rate must be carefully estimated taking into consideration the influence of various parameters, namely: storey level,prevailing winds,windows and doors joints permeability,ventilation channels,tenants usages,etc. A computing programm was created in order to allow a parametric analysis for the natural ventilation in blocks of flats and high level buildings.It was concluded:

- the useful thermal chimney effect becomes too small at the highest storey level;
- in order to prevent dew effects,the air trajectories must be alwys directed from the colder to the warmer points of the rooms.Therefore it is very important to avoid the penetration of the kitchens humid and warm air into living- and beedrooms;
- the staircase must be separately ventilated.

Obviously the ventilation needs,in order to avoid condensation phenomena,are the same as for the pollution control.

(5) The water vapour permeability of materials depends on their humidity,as evidenced by Anderson /7/ and Couasnet /8/.Due to the complexity of the mathematical model,suitable CAD methods are to be developed.

4.NEW TECHNICAL RECOMMENDATIONS

Starting from these research results it is now possible to consider new technical recommendations, in order to contribute to the reduction of the condensation risks in dwellings. Such a project is under experiment in Romania /9/. An auxiliary diagramm (annex I) has been conceived to check the dew occurence on building elements surfaces. A general flowchart for the assessment of the condensation risks in buildings is presented in fig.2.

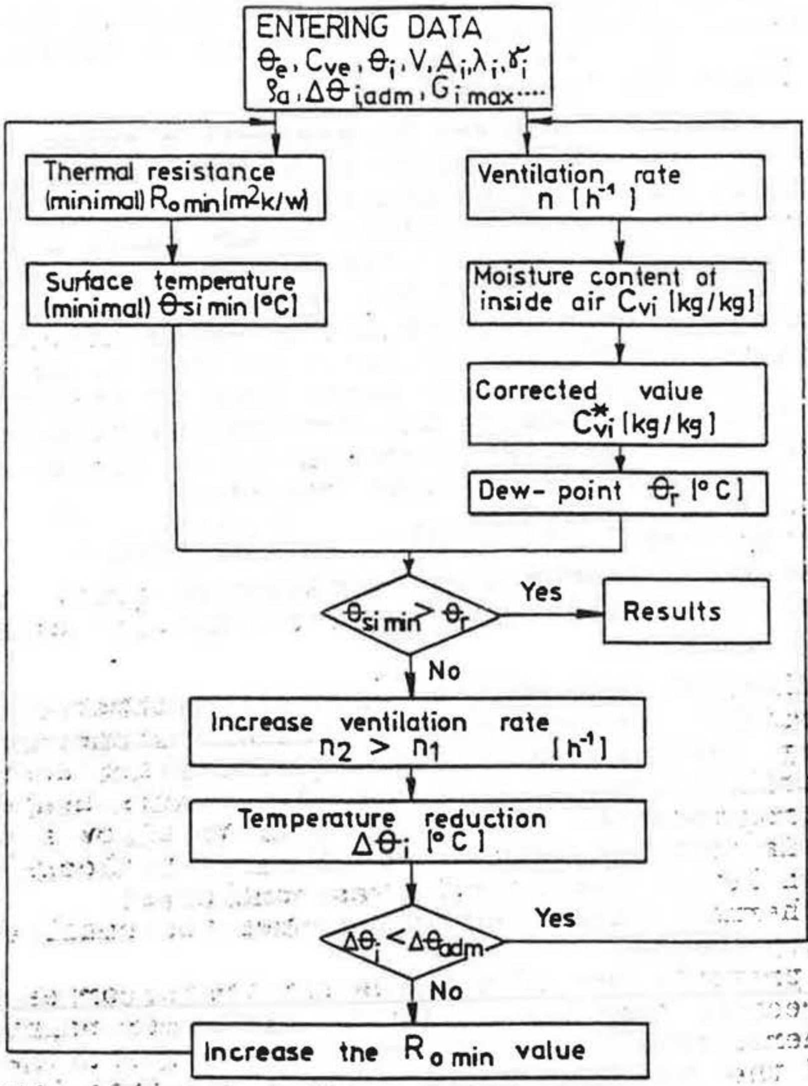

Fig.2 Flowchart for the assessment of the condensation risk and ventilation in buildings

5.CONCLUSIONS

The present status of the research concerning the condensation phenomenon in buildings allows for the improvement of the technical recommendations. Simultaneously, new research is to be developed referring to the statistical description of the aleatory parameters of influence on condensation risks and to the development of suitable CAD methods.

Table 1 Conventional values (G) of water vapour debits (g/h) in dwellings

Dwelling capacity		Kitchen	Living	Bedroom	Total
1 room	$\hat{G}$	650	125	-	700
	$\bar{G}$	85	50	-	140
2 rooms	$\hat{G}$	700	190	130	800
	$\bar{G}$	100	65	65	250
3 rooms	$\hat{G}$	750	250	130	900
	$\bar{G}$	125	85	65	325

Note : $\hat{G}$ - Peak hourly mean
$\bar{G}$ - Daily hourly mean

6.NOMENCLATURE

A - Area of wall / roof surface (m^2)
C_{vi} , C_{ve} - Vapour concentration (Kg_{vap}/Kg_{air}),indoor/outdoor
C_{si} - Saturated vapour concentration indoor (Kg_{vap}/Kg_{air})
G - Amount of vapour sources (Kg/h, g/h)
V - Volume (m^3)
p - Partial vapour pressure (Pa)
r - Coefficient of ventilation efficiency (-)
δ - Vapour permeability of building materials (Kg/m.h.Pa)
λ - Thermal conductivity of building materials (W/m.K)
γ - Amount of vapour absorbtion at materials surface (Kg/m^2h)
ρ - Density (Kg/m^3)
θ - Temperature (K , °C)
n - Ventilation rate (1/h)

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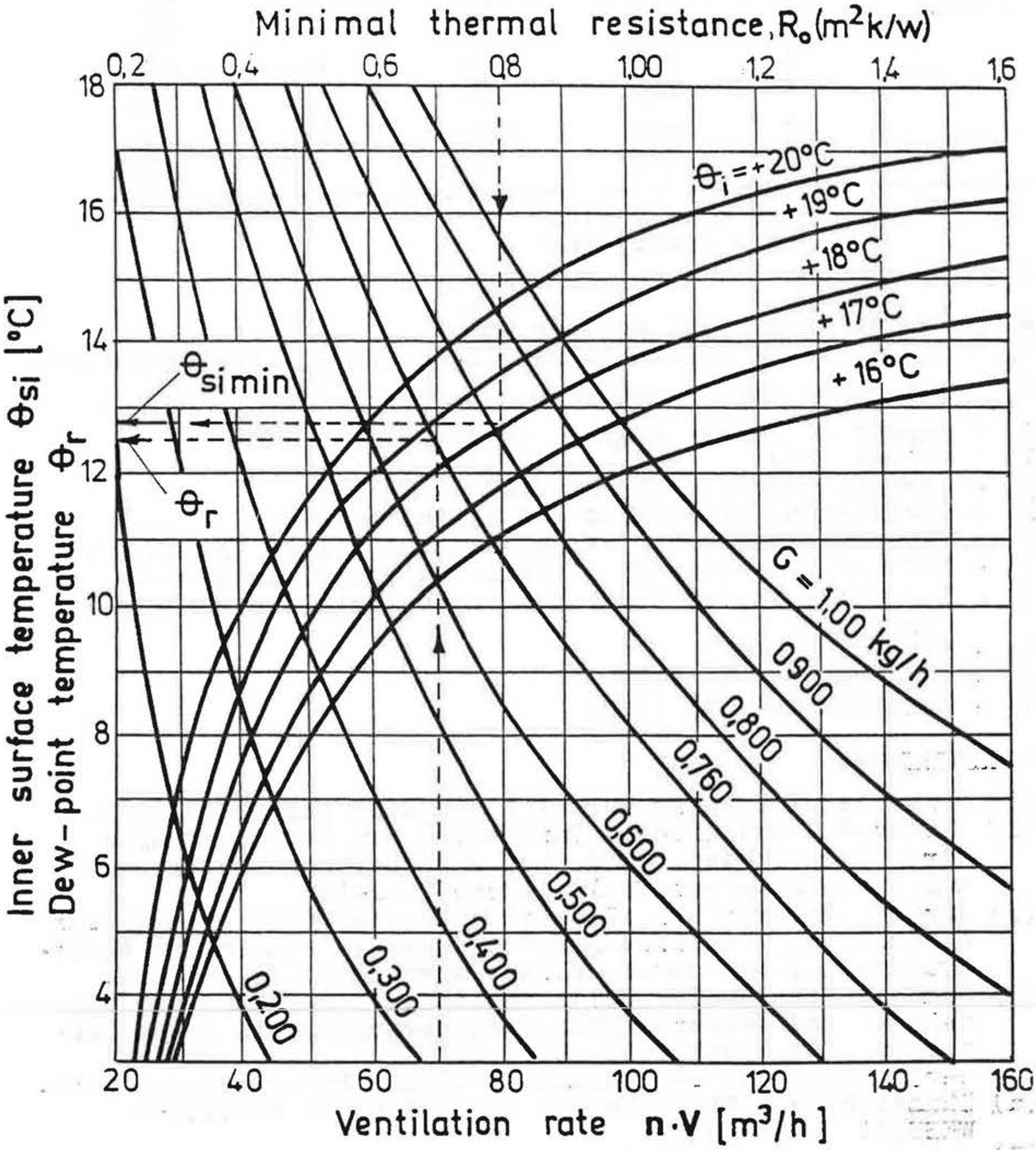
ANNEX I



Index lines for surface condensation identification.
Exemple: V=20 m^3 , G=0,700 Kg/h ; θ_i= 18°C ; n=3,5 h^{-1} ;
$R_{o,min}$= 0,8 m^2K/W ; θ_r =12,5°C 12,8°C =$\theta_{si,min}$
$R_{o,min}$ Thermal resistence wall/roof, minimal value.

CONDENSATION, HEATING AND VENTILATION IN SMALL HOMES

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BRE has investigated condensation in recently built 1-bedroom and bedsit homes in the UK. The study revealed significant condensation problems and gave an indication of the factors related to condensation: ventilation devices (particularly a passive ventilator in the bedroom, a mechanical ventilator in the kitchen and/or bathroom, or an air brick in any inner hall or landing); air movement (via stairs); heating (particularly the heating period and using bottled gas) and insulation. These factors were more important than occupant behaviour and "energy consciousness". It seems therefore that ventilation and heating facilities which depend on occupant behaviour are generally used effectively. The most important occupant characteristics were the number and age of occupants.

INTRODUCTION

Our study was concerned with owner occupied 1-bedroom and bedsit homes, built 1980-1985. Many such homes have been built, incorporating modern standards of insulation and ventilation and usually (though not always) a heating system. There had been anecdotal reports of condensation problems in such homes, which is surprising since the homes already have features proven in general to be effective measures against condensation. It was therefore of interest to investigate why such problems occur.

Condensation can occur in any type of dwelling, but there may be causes and solutions specific to small homes or the lifestyle and behaviour of their occupants. Condensation occurs when ventilation, insulation and heating are inadequate in the context of the moisture production in the dwelling. Even with adequate provision for these, full and proper use may not be made of them, and the design of the home may not promote full and proper use (e.g. ventilation and heating may conflict). Without better understanding of the interaction between building design and occupant behaviour, further application of standard solutions may be ineffective.

The main aim of the study was to identify the factors that contribute to condensation, thus providing the basis for suggesting remedies. We also investigated occupant perception of the seriousness of condensation and the correlation between subjective and objective measures.

METHOD

An interview was conducted at 383 homes (66% of valid contacts) in 5 regions of the UK (London, Havant, Leeds, Manchester, Dundee). All homes were over 1 year old, since newer homes may still be drying out from construction and the residents would not have experienced a full year in the dwelling. Sampling was based on information from Local Authorities in the 42 regions with the highest numbers of the required homes. 15 regions were chosen to represent a range of climates and a postal survey carried out to provide sampling data. The 5 regions were then chosen to represent a cross-section of dwelling types and climatic conditions.

A questionnaire provided data on condensation and mould, demographic details; pattern of home occupancy; dwelling size and structure; insulation; heating system and controls; heating behaviour and thermal comfort; fuel type and consumption; provision and use of ventilation; infiltration; air movement; knowledge of energy use and conservation; clothes drying and ratings of the home and home area. The following measures of condensation were used.

1. Respondents rated the seriousness of condensation on a scale from 1 (Not at all a problem) to 7 (A very serious problem), and rated how worried they were about condensation, on a 4-point scale: Very Much (1), Quite a Lot (2), A Little (3), and Not Worried (4).

2. MOULD. Interviewers rated (in each room) any mould which could be observed during the interview, from 1 (No mould) to 6 (Continuous areas of mould in cold spots and elsewhere). For most analyses, we defined a new variable, "MOULD" (the mean rating for all rooms).

3. COND. Respondents stated whether, during the winter, they had noticed any of a list of 8 signs of condensation (see Table 1). The sum of positive responses by each respondent (plus 1 to avoid zero scores) defines a new variable, "COND", a self-reported but relatively objective assessment of condensation problems, on a scale from 1 to 9.

RESULTS AND DISCUSSION: PREVALENCE OF CONDENSATION PROBLEMS

MOULD was the most objective measure of condensation problems, but it measured only one sign of condensation, and only problems which could be observed during the interview. We therefore used COND as the principal measure of condensation. COND correlates strongly with MOULD (accounting for 96% of the variance in MOULD, based on mean MOULD at each level of COND) and ratings of seriousness of condensation (80% of variance).

Table 1 shows the frequency of each sign of condensation. There does appear to be a problem which merits further attention. There were few homes with severe mould (only 4% had more than small patches), but the majority had condensation beyond windows steaming up. 32% of respondents

Table 1. Frequency of Various Condensation Problems.

	n	%
None	45	12
Misted mirrors/windows	327	85
Pools of water from windows	241	63
DAMP: Walls	63	16
Furniture and carpets	24	6
Clothes	14	4

	n	%
DAMAGE TO: Plaster	52	14
Woodwork	58	15
Mould	136	36

were worried very much or quite a lot by condensation and there was a significant correlation between COND and an overall rating of the home ($r=-0.314$, $p< 0.001$).

RESULTS AND DISCUSSION: FACTORS AFFECTING CONDENSATION

Statistical data are given separately at the end of this section.

Demographic Variables

MOULD was lower in pensioner households than other households. COND was also lowest for pensioners, followed by younger single-person households two-person households and households with a child. Presumably more people produce more moisture. This effect did not depend on the pattern of occupation of the home, suggesting that total moisture production is more important than the period during which the moisture is produced.

There was no evidence in our data on why pensioner households should have fewer condensation problems. COND was not significantly affected by social class, sex, keeping pets, previous housing experience, length of time in present home or expected duration of stay in that home.

Size of Dwelling

The size and type of dwelling were correlated, houses being the largest and bedsits the smallest, with flats having a wide intermediate range. Homes larger than $46.5m^2$ had significantly lower COND than smaller homes and this effect is in addition to the effect of dwelling type. The number of rooms in the dwelling did not affect COND.

Moisture Production

Bottled gas heating is dealt with under heating and insulation. There was no effect of cooking fuel. Drying clothes in the bathroom was associated with less mould in the bathroom. It may be that clothes are dried in the bathroom only if it is warm and well ventilated.

Ventilation, Infiltration and Air Movement

Passive or mechanical ventilators did not affect mould in individual rooms, except the bathroom where having a mechanical ventilator reduced mould. COND was lower if there was a passive ventilator in the bedroom, a mechanical ventilator in the kitchen or an air brick in an inner hallway or landing. Having any kind of ventilator in any other room, and the pattern of use of windows and ventilators, did not affect COND.

COND was higher where respondents said draughts made them feel uncomfortable. This was not related to indoor temperature. There was no effect on COND of having draught strip on doors or windows, or having a second external door. COND was lower for respondents who said the windows and ventilators provide enough cooling in summer and enough fresh air.

COND was highest if the stairs went from hall/landing to living room, lowest with the reverse arrangement, and intermediate if the stairs went from hall to landing or there were no stairs. This is probably due to heat transfer to bedrooms and is therefore another advantage of houses.

Heating and Insulation

The lowest COND was found with storage heaters in houses, followed by other electric heating, natural gas, storage heaters in flats/bedsits and bottled gas heating the highest COND. There was no difference in COND between homes with central heating and those with individual heaters. In larger homes this would be surprising, but in small homes there is relatively little advantage of central heating, so long as there is adequate heating in each room.

Homes heated all day had lower COND. There was no effect of the length of time the respondent typically spent out of the home before turning the heating down or off, the relative temperature of the bedroom and living room, the compass orientation of the main room or bedroom or the position of the heat source in each room. There was also no effect of room temperature or subjective ratings of temperature on COND or MOULD for the whole sample or for respondents who said that the temperature at the time of the interview was typical of the time of day and year.

COND was lower in homes with double glazed windows or external doors, filled cavity walls (or dry lining) or 100mm or more of loft insulation. There was no effect of floor type (suspended timber vs solid), but COND was lower in homes with carpet throughout than in homes with partial carpeting. The type of curtains had no significant effect on COND.

There was not a significant effect of total heat loss once floor area was taken into account. This suggests that, in the context of the type of homes studied, heat loss across individual components (which would affect surface temperature) is more important than total heat loss.

Occupant Knowledge, Expectation and Behaviour

There was a significant effect of having taken measures to reduce condensation: COND was higher if more measures had been taken. Thus, the greater the condensation problem, the more likely the occupants are to respond with remedial measures, but success is generally less than 100%. There was no effect of whether respondents said they would have expected to have had problems with condensation in a home like theirs. COND is not correlated with the thought the respondents put into energy conservation and heating costs when buying the home.

Statistics for Significant Effects

Mean values are given in square brackets, followed by t-test or analysis of variance statistics.

COND:

Household. Pensioner(s) [2.2] Younger single person [3.1] 2 persons [3.8, n=146] With a child [4.4] $F=5.45$, $df=5,375$, $p<0.01$

Over $46.5m^2$ [2.4] Smaller [3.6] $F=21.14$, $df=1,376$, $p<0.001$

Passive ventilator in bedroom? Yes [2.9] No [3.5] $F=6.40$, $df=1,381$, $p<0.02$

Mechanical ventilator in kitchen? Yes [3.1] No [3.5] $F=3.93$, $df=1,381$, $p<0.05$

Air brick in inner hallway or landing? Yes [2.6] No [3.4] $F=4.32$, $df=1,381$, $p<0.05$

Draughts cause discomfort? Yes [3.9] No [3.2] $t=3.56$, $df=381$, $p<0.01$

Windows and ventilators provide enough cooling in summer? Usually [3.3] Sometimes [3.2] No [4.2] $F=4.95$, $df=2,371$, $p<0.01$

Windows and ventilators provide enough fresh air? Usually [3.2] Sometimes [4.1] No [4.5] $F=11.86$, $df=2,377$, $p<0.001$

Stairs. Hall to living room [4.5] Living room to landing [2.8] Hall to landing [3.6] $F=12.64$, $df=2,168$, $p<0.001$ No stairs [3.5].

Heating. Storage (houses) [2.3], Other electric [2.9], Natural gas [3.7] Storage (flats/bedsits) [3.8] Bottled gas [4.7] $F=12.31$, $df=4,368$, $p<0.001$

Heating period. All day [2.8] Part of day [3.5] $F=5.47$, $df=3,361$, $p<0.01$

Glazing. Double [2.3] Single [3.7] $t=7.10$, $df=381$, $p<0.001$

External doors. Single glazed [3.4] Double glazed [1.7] Wood [3.5] $F=11.00$, $df=2,380$, $p<0.001$

Walls. Filled cavity walls or dry lining [3.0] Unfilled cavity [3.6] Insulation not known [3.2] Timber framed [3.7] $F=4.43$, $df=5,261$, $p<0.001$

Loft insulation. Over 100mm [3.1] 100mm [3.3] Under 100mm [4.6] $F=6.59$, $df=2,122$, $p<0.002$
Fitted carpet: throughout [3.1] partial [3.6] $F=7.22$, $df=1,336$, $p<0.01$
Measures taken to reduce condensation. 0 [2.9] 1 [3.7] 2 [4.6] 3+ [5.3] $F=33.18$, $df=3,379$, $p<0.001$
MOULD:
Pensioners [1.05] Other households [1.19] $t=2.01$, $df=380$, $p<0.05$
Clothes dried in bathroom [1.0] Elsewhere [1.2] $F=5.13$, $df=1,354$, $p<0.025$
Mechanical ventilator in the bathroom? Yes [1.1] No [1.3] $F=6.16$, $df=1,363$, $p<0.02$

In order to check the impact of atypical households on the results, all analyses which gave a significant effect were repeated with cases removed if the household included pensioners (n=23) or children (n=12), if there was any use of bottled gas for heating (n=29) and if the home was constructed prior to the 1982 improvement of insulation standards in Building Regulations (n=37). The same factors were correlated with COND.

CONCLUSIONS

There is clearly a problem to be addressed: nearly two thirds of the homes surveyed had condensation at least enough to cause pools of water on the window sill, and one in six homes had signs of damage caused by condensation. The problems are not necessarily severe in individual homes, but are likely to become worse over time if no action is taken.

The factors which contribute to condensation problems are related to the building, the occupants, and building factors which are only effective to the extent that they bring about appropriate behaviour (e.g. the heating system and ventilators which are controlled by the occupant). In fact, ventilation behaviour has little effect on condensation levels, once the provision of ventilation is taken into account. Similarly, variation in heating behaviour and attitudes to energy have relatively little effect (except use of bottled gas and all-day heating).

It therefore seems to be worthwhile providing facilities which depend on occupant behaviour since they are on the whole used effectively. The main areas in which behaviour seems to be of significance are moisture production and longer-term factors such as the number and age of occupants and modifications to the dwelling.

The findings of this study are based on a cross-sectional survey, not the assessment of individual cases, therefore the findings cannot be applied directly to individual cases. For example, it should not be concluded that advice about reducing condensation is of no value: we have only shown that variation in behaviour in this particular population is not a major contributor to variation in condensation. The results do even so provide guidelines for identifying the likely causes of condensation problems and for establishing design principles for small homes.

THE EFFECT OF INTERZONE AIRFLOW ON MOISTURE MOVEMENT IN HOUSES

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ABSTRACT

The work is concerned with measuring interzone air movement and investigates its effect on condensation in houses. Air flows through a doorway between the lower and upper floors of a house were measured using a microprocessor-controlled tracer gas system. Thermostatically controlled heaters were used to heat the lower floor of the house to various temperatures in the range 20-35 °C. The upper floor was unheated. The coefficient of discharge for the doorway was found to be a function of the temperature difference between the two floors of the house. We describe a two-zone moisture transfer model and investigate the effect of interzone air movement on condensation. The effect of using a kitchen extract fan on the air flow patterns in the house is also discussed.

1. INTRODUCTION

Condensation is a serious and a widespread problem in a large number of houses in the UK. An estimated 1.5 million houses suffer from dampness and mould growth (1). Considerable attention has been given to the study of factors influencing condensation in buildings in order to develop methods designed to minimise condensation risk (2). Although several computer-based models have been produced in an attempt to predict the risk of condensation and mould growth in buildings, these models cannot yet be used with confidence, as interzone moisture movements are often ignored and algorithms relating to migration of moisture between zones remain unverified. Our studies show that large errors can arise in the estimated relative humidity of various zones in a building if the mathematical models fail to consider interzone air movement. This paper describes measurements of air movement in a house with particular emphasis upon the removal of moisture via doorways and kitchen extract fans. A moisture transfer model based on the derived mass flow algorithms is presented.

2. INTERZONE AIR MOVEMENT THROUGH DOORWAYS

Figure 1 shows a schematic diagram of a house in which interzone air movement is assumed to occur between two zones, i.e., the downstairs and upstairs floors. Air can infiltrate from outside the house into each zone (F_{01} and F_{02}) and exfiltrate from each zone to the outside F_{10} and F_{20}). In addition, air can be exchanged between the two zones in both directions (F_{12} and F_{21}). The air exchange rate between the house and outside depends on wind speed and direction and also on the internal/external temperature difference between the two zones. Assuming the mean temperatures of zones 1 and 2 are T_1 and T_2, respectively and the pressure difference at the centre line (z=0) is zero, the pressure difference, ΔP, caused by stack effect, at height z is:

$$\Delta P = P_1 - P_2 = (\rho_1 - \rho_2)gz \qquad (1)$$

The volumetric flow rate through an infinitesimal area can be estimated by applying the orifice equation as follows:

$$dF = C_d W(dz)(2\Delta P/\rho)^{0.5} \qquad (2)$$

Substituting from eqn (1) into (2) and integrating gives the flow through the top half of the doorway:

$$F = \int_{z=0}^{z=H/2} dF = (C_d W/3)[gH^3 \Delta\rho/\rho]^{0.5} \qquad (3)$$

Because the coefficient of thermal expansion, $\beta = 1/T = -\Delta\rho/(\rho\Delta T)$, eqn (3) can be rewritten as follows:

$$F = (C_d W/3)[gH^3 \Delta T/T]^{0.5} \qquad (4)$$

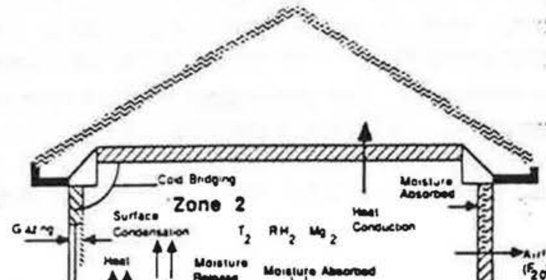

FIGURE 1. Interzone air flows in a house via a doorway.

To estimate the coefficient of discharge, C_d, the air flow through the doorway must be measured. Measurements of air flow through a doorway can be accomplished using tracer gas techniques. The fundamental equations of multi-zone air movement within a building are based upon Sinden's model (3). The model assumes that a building consists of a number of zones 0, 1, 2, ..., N, which are connected by air-flow passages. These passages are assumed to allow air flow in one direction only. The decay tracer gas technique involves injection of a known amount of tracer gas into each zone and it is assumed that there is no further generation of tracer gas in the zones after time zero. Applying tracer gas volumetric balance equations to zone j, we obtain:

$$V_j \, dC_j/dt = \sum_{i=0}^{N} F_{ij} C_j - \sum_{i=0}^{N} F_{ji} C_j \qquad \text{(for } 1 \leq j \geq N) \qquad (5)$$

The total flow into chamber j must equal the total flow out of the chamber and is given by the conservation equation:

$$\sum_{i=0}^{N} F_{ij} = \sum_{i=0}^{N} F_{ji} \qquad \text{(for } 1 \leq j \geq N)(F_{jj} = 0) \quad (6)$$

Zone 0 in the model represents the external air and is assumed to have an infinite volume. The concentration of tracer gas in this zone is assumed to be zero. The above equations for the two-zone situation can be solved using one of the analysis methods described by Riffat (4).

3. EXPERIMENTAL WORK

To estimate the air-flow rate through the doorway, measurements were carried out using a single tracer gas technique (4). Air flow measurements were carried out using two microprocessor-controlled tracer gas systems, Figure 2. In essence, the tracer gas sampling system incorporated solenoid valves, tracer gas sampling bags, a pulse pump, a microprocessor-based controller, a manifold and a by-pass valve. The portable chromatograph consisted of a 6-port valve connected to a 0.5 ml loop, a column, a chromatographic oven and an electron capture detector. The system incorporated a microcomputer, a parallel printer and interface cards for both analogue and digital data. It would be possible to use the system for sampling a range of tracer gases but chose to use sulphur hexafluoride (SF_6) as it has desirable characteristics in terms of detectability, safety and cost. Furthermore the suitability of this tracer gas has already been demonstrated by the successful use of SF_6 in previous air movement studies (5).

Temperature measurements were carried out at various points in each zone using copper-constant on thermocouples. The outside temperature and wind speed during the measurement period were also recorded.

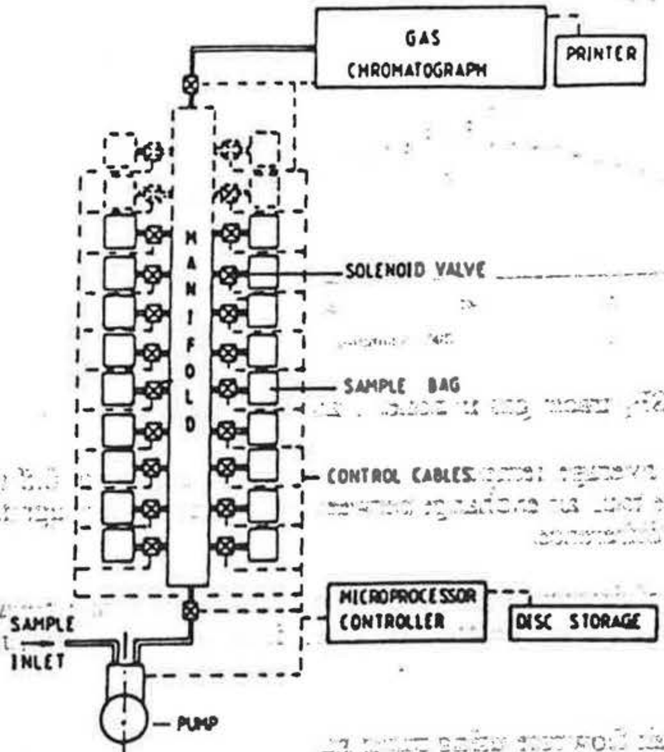

FIGURE 2. A microprocessor - controlled tracer gas system.

Measurements of interzone air movement were carried out in a house. The downstairs floor, zone 1, had a volume of $66m^3$ and upstairs, zone 2, had a volume of $92m^3$. The two zones were separated by a single doorway. In order to achieve high temperatures in zone 1, four thermostatically controlled electric heaters were used.

To estimate the air-flow rates between the two zones, two SF_6 systems were used. The first system was used to collect samples from zone 1, while the second was used to collect samples from zone 2. At the beginning of each test the communication door between the two zones was closed and gaps between the door and its frame were sealed with tape. This prevented tracer gas leakage prior to starting the test. A known volume of tracer gas was released from a syringe downstairs where it was mixed with air using an oscillating desk-fan. After a mixing period of about 30 min the sealing tape was removed and the communication door was opened. Samples were taken every 3 min for a total experimental time of 90 min. Several experiments were carried out in this house using a variety of temperature differences between the two zones.

4. SPECIMEN RESULTS

Figures 3 shows tracer gas concentration vs time for a temperature difference of 1.5°C. The smoothness of the tracer decay curve indicates that uniform mixing of tracer gas with air was achieved in both zones.

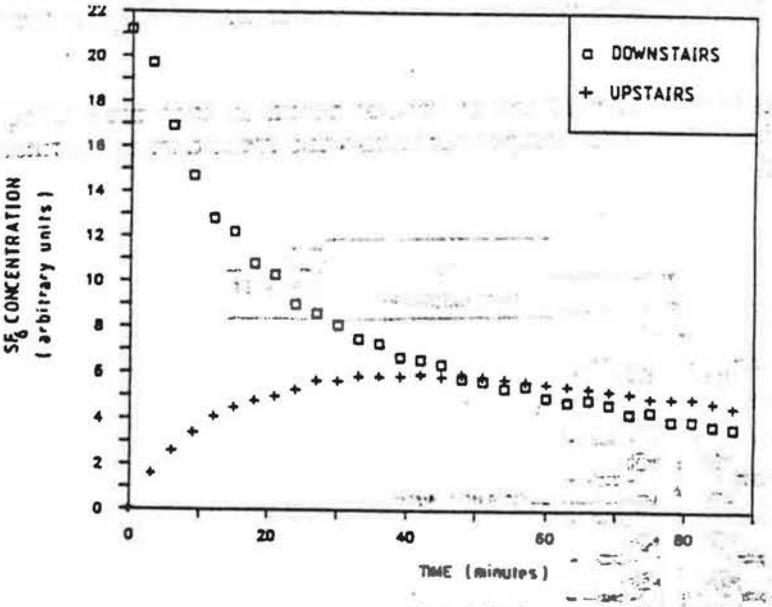

FIGURE 3. The decay of SF_6 tracer gas in zones 1 and 2; $\Delta T = 1.5°C$.

Tests were carried out for average temperature differences in the range 0.5 to 13K. These experiments showed that the total air exchange between the two zones through the doorway is a function of the temperature difference.

To evaluate the coefficient of discharge for the doorway, the air flow rate measured using the tracer gas technique was divided by the theoretical air flow rate, described in Section 1, as follows:

$$C_d = \frac{\text{measured air flow rate using tracer gas}}{(W/3)[gH_3 \Delta T/T]^{0.5}}$$

The coefficient of discharge was found to decrease from approximately 0.61 to 0.22 as the temperature difference between the two zones increased from 0.5 to 13K. These results showed close correlation with:

$$C_d = 0.0835[\Delta T/T]^{-0.313} \quad (7)$$

The decrease in coefficient of discharge may be due to an increase in interfacial mixing as a result of the direct transfer of some cold air from the upper floor into the inflowing warm air from downstairs. In addition, the increase in density difference could cause an increase in turbulence within the two zones which influences the coefficient of discharge.

By substituting from eqn (8) into eqn (4), the mass flow rate between the two zones can be given in the form:

$$M = 0.0278\rho W(gH^3)^{0.5}[\Delta T/T]^{0.187} \quad (8)$$

5. INTERZONE MOISTURE TRANSFERS

The occurrence of condensation in houses depends on the following parameters:

1. temperature and moisture content of the air in each room;
2. temperature and moisture content of the incoming air;
3. surface temperature and cold bridges in the room;
4. thermal resistance and permeability of the construction material; and
5. ventilation rate and interzone air movements.

Only the ventilation and interzone air movement factors are considered in this investigation, as separate studies of the effects of thermal insulation and cold bridges have been carried out by other researchers. The moisture content in the air within a house is raised above the moisture content of the external air by evaporation of moisture mainly from cooking, washing, drying and the metabolic processes of the occupants. The increase in the amount of water vapour within a warm zone raises the vapour pressure of the air and causes the moist air to convect to areas of lower vapour pressure, i.e. poorly heated bedrooms and the unheated roof space.

5.1 A two-zone moisture transfer model

A steady-state moisture transfer model is used to estimate internal vapour pressure. The model treats the house as two separate zones, as shown in Fig. 1. It is assumed that the moisture release rate in zone 1 is M_{g1} and in zone 2 is M_{g2}. The amount of moisture transfer in each zone can be calculated by applying equations describing the conservation of mass of water.

The rate of moisture increase in zone 1 is given by

$$d(d_{v1})/dt = F_{01}d_{vo} + F_{21}d_{v2} - F_{10}d_{v1} - F_{12}d_{v1} + M_{g1} \quad (9)$$

Similarly, the rate of moisture increase in zone 2 is given by

$$d(d_{v2})/dt = F_{02}d_{vo} + F_{12}d_{v1} - F_{20}d_{v2} - F_{21}d_{v2} + M_{g2} \quad (10)$$

Assuming a steady-state moisture transfer in the two zones, eqns (9) and (10) become respectively

$$F_{01}d_{vo} + F_{21}d_{v2} - F_{10}d_{v1} - F_{12}d_{v1} + M_{g1} = 0 \quad (11)$$

$$F_{02}d_{vo} + F_{12}d_{v2} - F_{20}d_{v2} - F_{21}d_{v2} + M_{g2} = 0 \quad (12)$$

Rearranging eqns (11) and (12) for d_{v1} and d_{v2}, substituting for d_{v2} from eqn (11) into eqn (12) and substituting for d_{v1} from eqn (12) into eqn (11), the following equations are obtained:

$$d_{v1} = d_{v0} + \frac{F_{21}M_{g2} + A_2V_2M_{g1}}{(A_1V_1A_2V_2 - F_{12}F_{21})} \quad (13)$$

$$d_{v2} = d_{v0} + \frac{F_{12}M_{g1} + A_1V_1M_{g2}}{(A_1V_1A_2V_2 - F_{12}F_{21})} \qquad (14)$$

where the air change rates in zones 1 and 2 are respectively:

$A_1 = (F_{10} + F_{12})V_1$

$A_2 = (F_{20} + F_{21})V_2$

The absolute humidities, d_{v1} and d_{v2}, are given by:

$$d_{v1} = 2.17P_{v1}/T_1 \qquad (15)$$

$$d_{v2} = 2.17P_{v2}/T_2 \qquad (16)$$

It is also assumed that

$$K_1 = \frac{F_{21}M_{g2} + A_2V_2M_{g1}}{(A_1V_1A_2V_2 - F_{12}F_{21})}$$

$$K_2 = \frac{F_{21}M_{g2} + A_2V_2M_{g1}}{(A_1V_1A_2V_2 - F_{12}F_{21})}$$

Substituting from eqns (15) and (16) into eqns (13) and (14), respectively and using K_1 and K_2 as defined above, eqns (13) and (14) become

$$P_{v1} = (T_1/T_0)P_{vo} + 0.461K_1T_1 \qquad (17)$$

$$P_{v2} = (T_2/T_0)P_{vo} + 0.461K_2T_2 \qquad (18)$$

5.2 Moisture movements between upstairs and downstairs

The mean internal vapour pressures for the lower and upper floors of the house were calculated using the moisture transfer model described previously. The external vapour pressure, at 5°C and 95% RH, was assumed to be 0.84 kPa using BS5250(Ref.7).

Moisture generation and distribution between the two zones are important in estimating the internal vapour pressure. It is estimated that between 4 and 12kg of moisture is generated within the home each day. For the purpose of this investigation, three levels of moisture release rate were assumed, namely 4, 8 or 10kg/day, and these were distributed between the two zones on the basis of occupancy and appliance use (e.g. cooker, tumble-drier and shower). Typical moisture-generation rates for various heating appliances and occupant activities are given by CIBSE(8).

Infiltration and interzone air movements in the house were measured and the algorithm described in Section 4, was used to determine the mass flow rate between the two zones. The following assumptions were made in the theoretical analysis:

a) The lower and upper floors of the house were assumed to be heated to different temperatures. The mean internal temperatures of the lower floor were 12.5, 14.5, 16.5, 18.5, 20.5, 22.5, 24.5, 26.5 and 28.5°C and the corresponding mean temperatures of the upper floor were 12, 13.5, 15, 16.5, 18, 19.5, 21, 22.5 and 24°C. The temperature differences between the two floors were therefore 0.5, 1, 1.5, 2, 2.5, 3. 3.5, 4 and 4.5°C.

b) The lower floor was heated to mean temperatures of 12.5, 14.5, 16.5, 18.5, 20.5, 22.5, 24.5, 26.5 and 28°C while the upper floor was kept at 12°C.

5.2.1 Analysis of results for case (a)

The internal vapour pressures were calculated using the mean internal temperatures, the amount of moisture generated in each zone, the air change rates and the interzone air flow. The mean internal vapour pressure and saturated vapour pressure were used to estimate the mean RH.

The RH difference between the upper and lower floors vs the temperature difference between the two floors is presented in Figure 4. The RH difference, RH_2 - RH_1, is found to increase from about 0.5% to about 9.5% (depending on the moisture release rate) as the temperature difference is increased from 0.5 to 4.5°C.

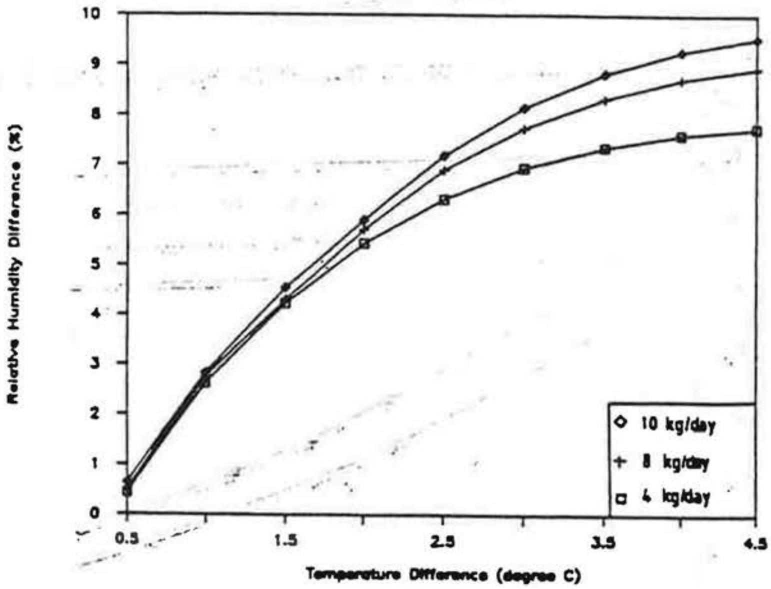

FIGURE 4. The variation of RH_2 - RH_1 with temperature; total moisture release rate of 4, 8 or 10kg/day (case a).

The effects of interzone air flows on the RH in the lower and upper zones are shown in Figures 5 and 6. These figures show that for zone 1, the condition including interzone air flow produces a RH about 8% lower than that for the condition with no interzone air flow. In the case of zone 2, the RH for the condition with interzone air flow is about 10% higher than that for the condition with no interzone air flow.

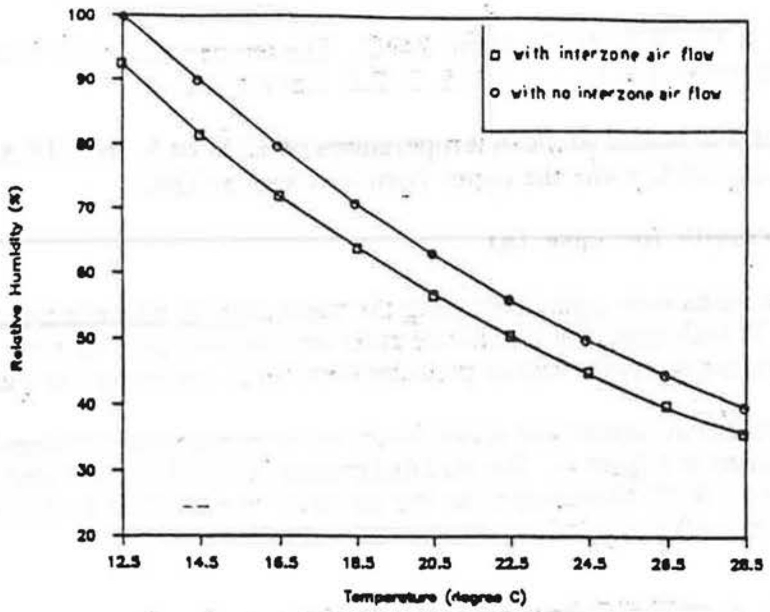

FIGURE 5. The effect of interzone air flow on the relative humidity in zone 1; total moisture release rate = 8kg/day (case a).

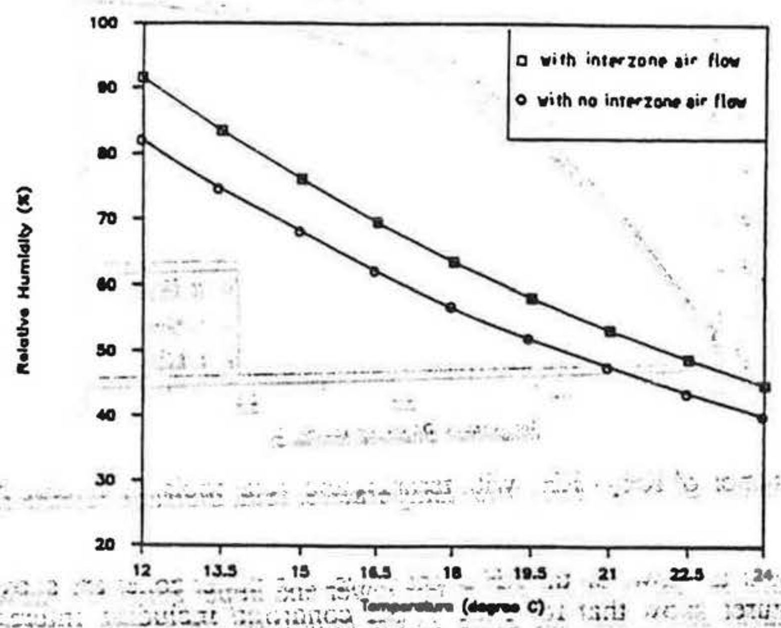

FIGURE 6. The effect of interzone air flow on the relative humidity in zone 2; total moisture release rate = 8kg/day (case a).

5.2.2 Analysis of results for case (b)

This assumption is valid when only the lower floor of the house is provided with heating. The estimated RH for the upper floor is about 92% for a mean internal temperature of 12^{0}C and a moisture release rate of 2.64kg/day. This high RH would lead to condensation and mould growth.

Relative humidity differences in the range 45-60% may be reached for a temperature difference of 16.5^{0}C. This situation is likely to occur when the kitchen reaches high temperatures during cooking periods. Even so, RH differences in the range 35-45% may exist if the lower floor is heated to about 22^{0}C while the upper floor is held at 12^{0}C.

The effect of interzonal air flow on the RH in zone 2 has been calculated. If the interzone air flows F12 and F_{21} are included, the calculated RH_2 is about 10% higher than for the condition with no interzone air flow.

6. KITCHEN EXTRACT FANS

Installation of a kitchen extract fan is widely recommended as a remedial measure to limit condensation in houses. The purpose of using a fan is to remove moisture-laden air from the zone in which water vapour is generated and also to minimise the flow of warm moist air from the lower floor to the upper floor of the house where condensation normally occurs. Most houses nowadays are provided with extract fans, and it is generally assumed that the use of a 150mm (extract rate about 290m³/h) fan is effective in preventing migration of moisture from the kitchen to the rest of the house. There is a lack of theoretical and experimental evidence to support this assumption and the effectiveness of kitchen extract fans can only be determined by a more rigorous investigation.

Two tests were conducted to study the effect of a manually controlled kitchen extract fan on the air flow patterns in the house. In the first test the central-heating system was switched off and in the second test the lower floor only was heated. Figure 7 is a schematic diagram of interzonal air flow for the first test. The use of an extract fan increases F_{10} from 59 to 231m³/h but has only a small effect on interzone air flow. With the extract fan in operation, F_{12} and F_{21} were found to be 96 and 125m³/h, compared with 105 and 97m³/h when the extract fan was switched off.

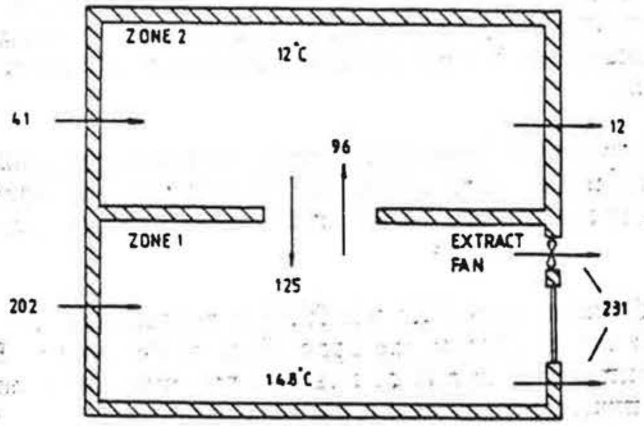

FIGURE 7. The effect of a kitchen extract fan on air flow patterns in the house, with central heating system switched off (units m³/h).

Figure 8 shows the interzonal air flow for the second test and clearly displays the limitations of the extract fan. For a temperature difference of about 5.6°C, F_{12} was increased from 96 to 180m³/h while F_{10} was reduced from 231 to 121 m³/h. The two tests indicated that the use of a 290m³/h capacity fan does not prevent moisture movement to other rooms. Calculations were carried out to establish the minimum extract rate which would limit condensation in the kitchen and prevent air flow from the lower floor to the upper floor of the house. Condensation should be avoided if the RH in a zone does not exceed 70% (Ref 9). Using an RH of 60% and a total moisture release rate of 8kg/day, the fan extraction rate should be about 600 m³/h. This represents more than twice the rate which is recommended by BS5250. However it should be remembered that the effectiveness of an extract fan depends on whether kitchen doors to the rest of the house are open or closed and also on the local wind speed and direction.

Our investigation showed that installation of manually controlled fans is often ineffective as a remedial measure to limit condensation, as these fans generally have inadequate extract rates and are under-used by the occupants.

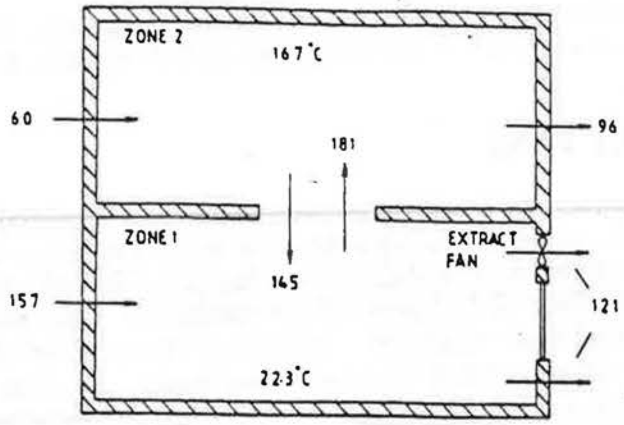

FIGURE 8. The effect of a kitchen extract fan on air flow patterns in the house, with central heating system in zone 1 switched on (units m^3/h).

CONCLUSIONS AND RECOMMENDATIONS

1. The experimental results indicate that the coefficient of discharge C_d is dependent on the temperature difference. Further experimental work is required to study the effects of the geometry of the house and the size of the doorway on the value of C_d

2. Tests are required to establish correlations for traditionally built houses under a variety of boundary conditions. Only limited studies of interzone heat and mass transfers under combined natural and forced convection have been carried out and the subject requires further investigation.

3. The mass flow rate between the lower and upper floors was found to increase significantly with increasing temperature difference. The effect of interzone air flows on moisture transfer was found to be significant and therefore should be included in condensation models.

4. The use of a standard kitchen extract fan was found to be ineffective in reducing air flows from the lower floor to the upper floor of the house. Further work is required to establish the optimal extract rate of a fan for prevention of condensation in the kitchen and for reduction of moisture movement to the rest of the house.

NOMENCLATURE

A_1, A_2	Air changes rates per hour in zones 1 and 2 respectively (h^{-1})
C_d	Coefficient of discharge (dimensionless)
C_1, C_2	Concentrations of the tracer at time t in zones 1 and 2, respectively (arbitrary units)
d_{vo}	Ambient absolute humidity (g/m^3)
d_{v1}, d_{v2}	Absolute humidities for zones 1 and 2, respectively (g/m^3)
F	Volumetric flow rate (m^3/s)
g	Acceleration due to gravity (m/s^2)
H	Height of the opening (m)
M_{g1},M_{g2}	Moisture release rates in zones 1 and 2, respectively (g/s)
P_{v1},P_{v2}	Vapour pressures in zones 1 and 2, respectively (N/m^2)
RH_1, RH_2	Relative humidities in zones 1 and 2, respectively
T	Mean absolute temperature of the two zones (°C or K as specified)
T_1,T_2	Average values of the air temperature in zones 1 and 2, respectively (°C or K as specified)

V_1, V_2	Volumes of zones 1 and 2, respectively (m^3)
W	Width of the opening (m)
β	Coefficient of thermal expansion (K^{-1})
ΔT	Average temperature difference between the two zones (°C or K)
$\Delta\rho$	Air density difference between the two zones (kg/m^3)
ρ	Average air density (kg/m^3)

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MOISTURE CHALLENGES IN CANADIAN ENERGY EFFICIENT HOUSING

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ABSTRACT

The rapid evolution of traditional wood-frame construction practices, in response to the need for energy conservation, has led to an increase in moisture problems in some new and retrofitted houses in certain parts of Canada. This has prompted Canada Mortgage and Housing Corporation (CMHC), the federal government's housing agency, to undertake a detailed program of research, which has involved field surveys, test hut monitoring and computer modelling. After almost a decade of such research, a better understanding of the principles of moisture, air and heat flow has been gained. This improved understanding is now being translated into practical applications for energy-efficient housing to prevent or remedy moisture problems.

INTRODUCTION: AN HISTORICAL BACKGROUND

Canadian low-rise housing has traditionally used wood-frame construction due to its advantages of economy, durability, speed of erection, flexibility of design, ease of renovation, and availability and renewability of materials. As a traditional form of building, various practices developed, based primarily on observation, which were passed from one generation of builders and trades to the next. Such practices recognized and enhanced the "forgiving" nature of wood framing - its ability to withstand repeated cycles of wetting and drying, of temperature extremes and of minor structural movements. Because the system had successfully withstood the rigours of the Canadian climate and was well understood by trades and laymen alike, little research was undertaken to determine the limits of its performance.

From World War II until the early 1970s, gradual changes in wood-frame construction took place which resulted in greater airtightness and reduced heat loss, while more affluent lifestyles increased internal moisture generation. Meanwhile, the primary exhaust device, the chimney flue, was being used less frequently as furnaces became more efficient, or disappeared altogether in the case of electrically heated homes. The combination of these three factors brought a certain percentage of Canadian homes close to the limits of "forgiveness". With the rise in world energy prices in the 1970s, wood-frame construction practices evolved rapidly to facilitate higher insulation values and increased levels of airtightness. However, these changes were so rapid that many aspects of traditional good building practice and building science were overlooked. The result was a higher incidence of moisture problems, both in new and energy-retrofitted homes, and an unfortunate association between energy efficiency and moisture troubles.

Since conventional assumptions about Canadian housing indicated that there shouldn't be moisture problems, there was clearly a need to re-examine these assumptions and to take a more detailed look at moisture loading, air change rates, local surface temperatures, effective insulation values, typical construction practices and building code requirements. Canada Mortgage and Housing Corporation (CMHC), the federal government's housing agency, became involved in recognition of the importance of moisture control to the durability of the housing stock and of the potential impact of various energy conservation programs. More recently, two additional factors - increasing epidemiological evidence linking respiratory disease to dampness, and a renewed interest in energy conservation due to concern over the global warming - have reinforced the significance of this issue.

CMHC'S MOISTURE RESEARCH PROGRAM

Preliminary studies in the Atlantic provinces confirmed anecdotal reports provided by CMHC inspectors of moisture deterioration. This led to a major national survey in 1982 of housing which CMHC had financed or mortgaged. The results were extrapolated to predict that approximately 1% of the Canadian stock had moisture-related structural damage, while approximately 10% had moisture problems of some degree, such as excessive condensation, damage to interior or exterior finishes, or mould growth. (1)

CMHC therefore initiated a comprehensive research program to determine the underlying causes of moisture problems and to develop solutions. This work has included the investigation of numerous housing units in various parts of Canada; the construction of test hut facilities in several climate zones to monitor the long-term performance of various wall assemblies; the development of computer models to simulate moisture, air and energy movement in walls (WALLDRY) and roofs (ROOFDRY); and the implementation and testing of remedial measures. The purpose of this paper will be to highlight the findings and implications for typical Canadian wood-frame housing.

FINDINGS

The past ten year's work has yielded many useful results. Theoretical modelling, supported by field and lab observations, has led to an improved understanding of the inter-related causes of moisture problems in exterior walls, attic spaces, basements and crawl spaces. Highlights include:

Climatic factors: The 1982 national survey indicated that the frequency of moisture problems was very dependent on climate. Cool, damp climates with insufficient sunny periods to promote drying, such as in the Atlantic provinces and to a lesser degree on the West Coast, had the highest incidence. Northerly areas, with extremely low temperatures and short drying seasons, were also susceptible. In other parts of Canada, moisture problems were rare. Clearly, the "forgiving" nature of wood frame construction could be challenged by long periods of moisture accumulation within the building envelope combined with insufficient drying periods.

Internal moisture sources: While it was previously believed that Canadian houses were "too dry" and required winter humidification, the 1982 survey found most troubled houses had high levels of indoor relative humidity (45-85%). The sources of these high RH levels were not immediately apparent. Further studies by CMHC and the National Research Council (NRC) revealed "hidden" moisture sources not previously considered: the drying of construction materials, especially concrete foundations (4-5 L/day during the first year); certain occupant practices, such as the drying of firewood indoors (up to 5 L/day); seasonal storage of moisture by the house and its contents during humid summers and subsequent release in the fall and winter (3-8 L/day); and ground-related sources (2-50 L/day). (2) The magnitude of these latter two was not fully appreciated until the results of two projects on "internal moisture source strength" were completed. These revealed that increased ventilation rates could actually draw more moisture into the house (up to 100 L/day), especially in relatively airtight houses with leaky basements or crawl spaces. (3) Related research on "soil gas" (primarily because of concern over radon and methane) confirmed that the infiltration of saturated air from below grade contributes several per cent of the "fresh air" entering Canadian houses. (4)

External moisture sources: Houses with problems on east walls were once thought to provide evidence that exfiltration of moisture-laden air was the primary mechanism for moisture deposition in wall cavities, since the prevailing winds are from the west. Upon further study, it was noted that many storms involve easterly, rather than westerly winds, especially on the east coast, and so wind-driven rain could not be discounted as a moisture source. It has also been found that condensation ("morning dew") behind the cladding can be evaporated and driven into walls under solar effects.

Poor selection of materials: The deliberate use of wet framing lumber in the Atlantic test huts drew objections from the housing industry, who claimed that this was not realistic. However, a subsequent survey of various building sites in the Atlantic provinces revealed that more than 90% of framing lumber exceeded the 19% moisture content specified by the National Building Code, and more than 50% exceeded the fibre saturation point. (5) In addition to retarding the drying process, the use of such green lumber leads to loss of airtightness when the wood shrinks and warps.

Inappropriateness of certain wall assemblies: Test hut monitoring has indicated that certain combinations of materials, such as low permeability exterior sheathing with wet framing lumber, could lead to prolonged conditions of elevated wood moisture contents, which in turn could lead to fungal growth. (6) However, the materials themselves may perform quite adequately under other conditions. An illustrative example is that of wet-sprayed cellulose insulation. In the Atlantic test hut project, framing members in panels with wet-sprayed cellulose took by far the longest time (18-24 months) to dry to moisture contents below 19%. On the other hand, a subsequent project in Edmonton, Alberta found that walls with wet-sprayed cellulose dried to 19% MC within only 2-3 months, with virtually no evidence of fungal growth. (7) A closer examination revealed certain advantages in Edmonton's environment and building practices: a much drier and sunnier climate which speeds the drying process; the use of typically drier framing lumber (15% MC); the use of plywood sheathing which is more resistent to moisture cycling than the composite sheathing products common on the East Coast; and the use of less water in the cellulose application. The dilemma presented by these two projects is how building codes and inspectors can allow a product under certain conditions and disallow its use under others.

Inadequate construction practices: Numerous field observations have provided anecdotal evidence of poor detailing. Wind-washed minimal insulation at exterior corners, convective currents around poorly-placed or missing insulation, and the lack of a continuous air barrier at electrical outlets or floor/wall intersections can reduce local thermal resistance values by an order of magnitude, thereby causing condensation to take place in homes with relatively low RH. In addition, poor siding and flashing practices can allow rain and snow to penetrate the envelope, while inadequate grading around the house perimeter can contribute to basement leakage. The use of exterior drainage-type insulation has been identified as a key to improving the performance of foundations with respect to moisture. (8) Test hut work has led to recommendations for assisting the drying process through the use of permeable sheathings and ventilated air spaces behind wood-based claddings. (9) Airtightness testing of various wall components and assemblies has demonstrated the need for air barriers and their joints to be structurally supported for durability under repeated pressure cycling, in order to reduce both the exfiltration of moisture-laden air and the infiltration of wind-driven rain and snow. (10)

Inadequate code interpretation: The requirements or enforcement of building codes may support accepted practices, while inadvertently violating building science principles. A study of basement condensation problems in new homes in Winnipeg, Manitoba provided a landmark example. The combination of typical overwatering and inadequate curing of concrete foundations, thermal lag in ground temperatures, and the placement of insulation on the interior of basement walls was found to make the occurence of summer condensation on foundation walls virtually inevitable in cold climates such as Winnipeg's. (11) Delaying the finishing of basement walls for approximately a year, to allow the concrete to dry, would permit any future condensation to be absorbed by the concrete, but represents a departure from code requirements. Similarly, a study of crawl space moisture problems in northern Manitoba identified the sill plate, which connects the floor framing to the foundation, as an "Achilles heel" in terms of inevitable condensation. (12)

Lack of general ventilation: In response to controversy over a proposed ventilation standard, a national airtightness survey of typical new homes in 1989 confirmed that Canadian housing had become 30% tighter since 1982-83, and that only 40% of new units had adequate ventilation systems. (13) While passive stacks have been demonstrated to be effective in certain situations for reducing excessive indoor RH levels, preliminary analysis (arising from separate work on combustion venting) has suggested that passive ventilation systems are too dependent upon wind to provide reliable moisture control. With respect to mechanical ventilation, in-situ testing of actual air flows has found that typical fans exhaust air at only half their rated performance, primarily due to poor installation of fans and ducting. (14)

Ventilation as a moisture source in attics and crawl spaces: The study of crawl spaces in northern Manitoba also revealed that the ventilation of crawl spaces, as required by codes, can actually increase the moisture content of framing lumber in the spring and summer, again because of thermal lag in ground temperatures. Similarly, the required ventilation of attic spaces may solve moisture problems in some cases, but worsen them in others. Protocols have been developed to determine attic airtightness and air change rates for a current survey of attics which is identifying the necessary conditions for attic ventilation to be effective. In summary, the use of ventilation for moisture control is only effective where sufficient drying potential exists.

Gaps in building science: The development of the WALLDRY model has exposed areas where the knowledge base is incomplete or inaccurate. There is a need for more accurate information on moisture movement through materials under thermal gradients, material properties under saturated conditions, wetting rates under surface-wet conditions, and surface drainage characteristics. (15) Initial validation of WALLDRY against field data has suggested that some property constants may need to be modified by factors as high as 4. Model development has also required the determination of time constants for air, moisture and heat flows, since data generated from test huts and simulations have confirmed that exterior walls never reach steady-state conditions, but continually demonstrate dynamic processes whose time constants may range from hundredths of seconds to several hours. Diurnal cycles were found to be particularly significant, with moisture cycling back and forth through the envelope under the alternating effects of solar and night sky radiation, analogous to a heat pipe. WALLDRY has successfully predicted the accumulation of moisture, as a result of such dynamic cycling, in a susceptible mid-height zone in single storey walls, a phenomenon which has often been noted in field observations, but not fully understood. (16)

MAJOR CONCLUSIONS AND DIRECTIONS FOR EFFECTING CHANGE

After 10 years of research, CMHC has developed an improved understanding of the complex relationships between energy and moisture in low-rise housing. The primary conclusion is that moisture problems can occur where the "threshold" limit of wood-frame construction is exceeded by the combination of three factors: high internal and/or external moisture sources, insufficient moisture removal through drying or ventilation, and cold local surface temperatures. While work continues on monitoring test huts in other climate zones, upgrading the moisture models and utilizing them to predict optimum moisture and energy performance, sufficient work has been completed to put forward some specific recommendations.

Moisture source control: The variable success of ventilation as a solution to moisture problems, combined with the associated energy penalty, leads to a preference for reducing moisture sources. Such source control is primarily an issue of homeowner and builder education. Code requirements can also assist; for example, CMHC recommended changes to the 1990 National Building Code regarding the sealing of basements to prevent soil gas entry.

Improved envelope detailing: The training of designers, builders and trades needs to focus on building practices which can reduce localized cold surfaces through more effective insulating techniques and through the minimization of air leakage paths. "Moisture Problems" has proved to be one of the most popular modules in the Builders' Workshop Series developed by CMHC.

"Intelligent" ventilation systems: The phenomenon of moisture storage within buildings, combined with the varying drying potential of outdoor air, suggests that ventilation, especially of attics and crawl spaces, be controlled by sensors which analyze both indoor and outdoor conditions.

Variability and the need for modelling: The great variability in climate, house design, building materials and construction techniques makes it difficult to predict moisture and energy performance. Since it is not feasible to build test huts of every possible configuration in every climate zone, computer modelling becomes an important tool to predict performance under a variey of conditions, to provide advice to industry and code officials, and to better target lab and field testing.

Regional application of building codes: Such variability also underscores the need for prescriptive building codes and standards to be modified or interpretted on a regional basis in a manner which is sensitive to local differences in climate, design, material selection and building practice.

The need for a "systems approach" to energy and moisture: Air sealing can reduce interstitial condensation, while increasing interior RH levels; higher levels of insulation can eliminate cold interior surfaces, while also reducing the drying potential of wall cavities and attics; exterior basement insulation can keep foundations dry, while interior basement insulation can make condensation inevitable. Clearly, energy conservation measures can be both a cause of, and a solution to, moisture problems. Individual manufacturers and trades are often unaware of the impact of their products or work on others. It is therefore necessary that research activities, information transfer programs and code development utilize a "systems approach" which considers the complex interactions among the building envelope, mechanical systems, ground conditions, exterior environment, interior environment and occupant lifestyle. It is only through such a systems approach that the "forgiving" nature of wood-frame construction can be enhanced, and the two objectives of energy conservation and building durability can be satisfactorily harmonized.

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STUDY ON A NEW HUMIDITY CONTROLLING MATERIAL

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Abstruct

The authors have been examining the method to use zeolite as solid absorbent for the building industry. Zeolite can be used as (1) humidity controlling material for building, (2) heat accumulating material and (3) passive cooling system. Development of (1) is now underway. Mortar is mixed with zeolite to substitute for sand and made into molded mortar panels or plastered walls. Exhibiting the physical properties equal to that of wood, zeolite-mixed mortar has more than three times as large moisture absorbing/discharging capacity as zeolite-free mortar. Such panels can be used not only for storage warehouses and art museums but houses and production facilities, and will be incorporated in a complex system as part of the technology for controlling indoor temperature/humidity environment.

Background

Excluding glass, metal plates, plastic plates, etc., all construction materials exhibit moisture absorbing/discharging property to some extent. Of various types of construction materials, those with especially great humidity controlling capacity are shown in Table-1. According to the grouping of building interior finishes in terms of moisture absorbing/discharging property, materials with higher rate of water vapor diffusion and large absorbing quantity are excellent in controlling humidity. Both wood and woody materials exhibit such tedency. Excellent characteristics of wood can be highly evaluated. However, wood is subject to aged deterioration due to its moisture absorbing/discharging property and lacks in fire resistance and dimensional stability. Fine-quality wood is difficult to obtain and offered at high prices. The above are the reasons why non-woody humidity controlling materials are being developed. It is reported that resin-oozing from Japanese cypress exercises adverse effect on works of art. Therefore, a substitute for woody material is desired for warehouses where works of art are stored. The performance expected as construction members is as follows:

— Humidity controlling performance maintains proper fluctuation width of the desired relative humidity in the interior space irrespective of disturbing humidity fluctuation in the outside environment. There are various types of construction space requiring humidity controlling performance, which is especially strongly needed for the space for storing works of art or industrial products part of which are susceptible to tempeature/humidity. The moisture absorbing/discharging performance is dependent on temperature, so control of temperature alone may possibly permit control of relative humidity.

— When room temperature drops, the rise of ralative humidity is stopped to prevent dew condensation. When dew forms outdoing the dew-condensation prevention performance, water-holding performance will prevent water droplets from falling. Two-stage dew-condensation prevention performance will be expected in such a way.

Zeolite stands for a "boiling stone" in Greek and, mineralogically speaking, belongs to the zeolite group. More than thirty types of natural zeolite are known today, of which mordenite and clinoptilolite are typical members. In Japan, zeolite is distributed widely in Tohoku, Hokuriku and San-in District. Synthetic zeolite is avaliable as well for industrial purposes. However, this paper discusses natural zeolite alone in view of cost performance. Major featuers of zeolite used as a desicating agent are as follows:

1. Absorbs water in preference to others.
2. Has greater absorbing capacity than silicagel or activated aluminum in a place with low water vapor pressure.
3. The moisture absorbing/discharging performance is highly temperature dependent, discharging moisture as temperature rises and absorbing moisture as temperature drops.

The feature 3. is especially desirable in view of controlling humidity and preventing dew condensation in buildings exposed to substantial change in temperature and fluctuation of relative humidity.

Table-1 Humidity Controlling Material

Group	Material
Used as chemicals	Aqueous solution of various salts Silicagel Zeolite Nickapellet
Used as construction material	Wood: Poulownia, cedar, Japanese cypress, spruce Cloth: Rayon Ceramic-type porous material Calcium silicate material ALC Gypsum board Roch wool Soft fiber board Cemented excelsior board Paper
Natural zeolite	Zeolite-mixed mortar panel


Natural zeolite

Experimintal

The authors prepared a zeolite-mixed mortar panel (zeolite panel) to be used as one of humidity controlling materials. The following are advantages of the zeolite-mixed mortar panel having features mentioned above. 1. Moldability 2. Fire and corrosion resistance 3. Strength 4. Low cost 5. Temperature dependency of moisture absorbing/discharging property 6. Dimensional stability 7. Durability.

Fig.1a-1f shows the dynamic characteristics obtained through experiments. The size of the test piece is $40\times40\times160$(mm). The zeolite mixture ratio stands for the ratio of zeolite substituted for sand during mortar preparation. The bending and compressive strength of zeolite mortar decreases as the zeolite mixture ratio increases. The mortar of 28 days of age with the zeolite mixture ratio of 100% will have the bending strength of about 50% lower and the compressive strength of about 45% lower than those of zeolite-free mortar. However, these values will not pose any meaningful problem when mortar is used as secondary members for building interior finish. In view of manufacture, transportation and installation of panels with high zeolite mixture ratio, vinylon fiber may be mixed, as a reinforcement, at a ratio of about 1% of the volume of mortar.

To understand the moisture absorbing/discharging property, $400\times400\times20$ (mm) test pieces of zeolite panels were put in and out of a conditioned chamber, and the weight variation was measured. Wood (spruce), calcium silicate board and ordinary mortar board of the same size were also tested for comparison. The result is shown in Fig.2. The moisture absorbing/discharging quantity of zeolite panels was equal to that of wood and about three times larger than that of ordinary mortar board. In about 5 weeks after placing, the discharge of excess water decreased, indicating almost the same cycle. When zeolite panels are made on an industrial basis, kiln-drying will permit them to exhibit specified moisture absorbing/discharging performacce at an early stage.

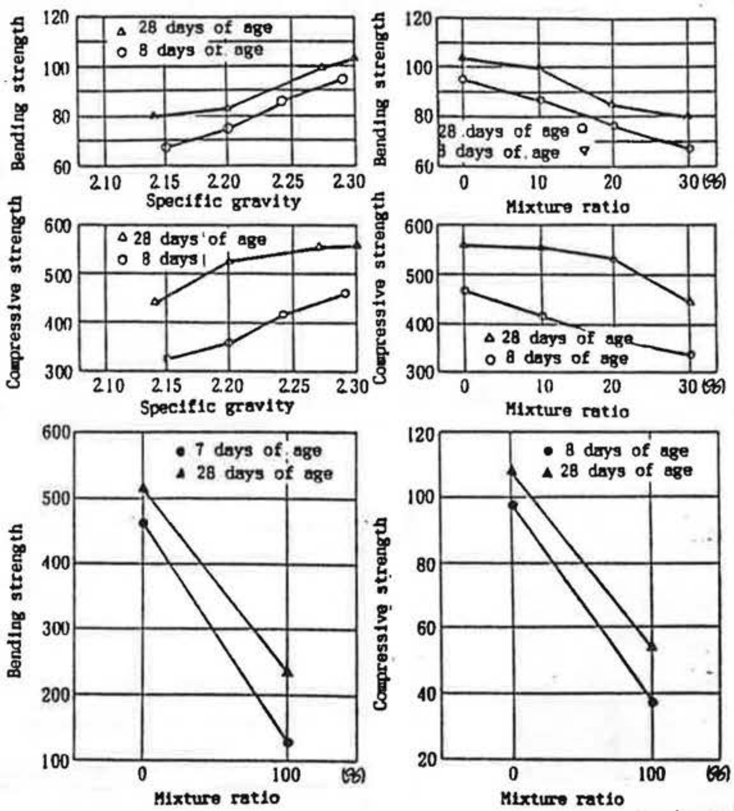


Fig.1a-1f Relation ship between Mixture Ratio and Bending Strength/Compresive Strength (kgf/cm^2)

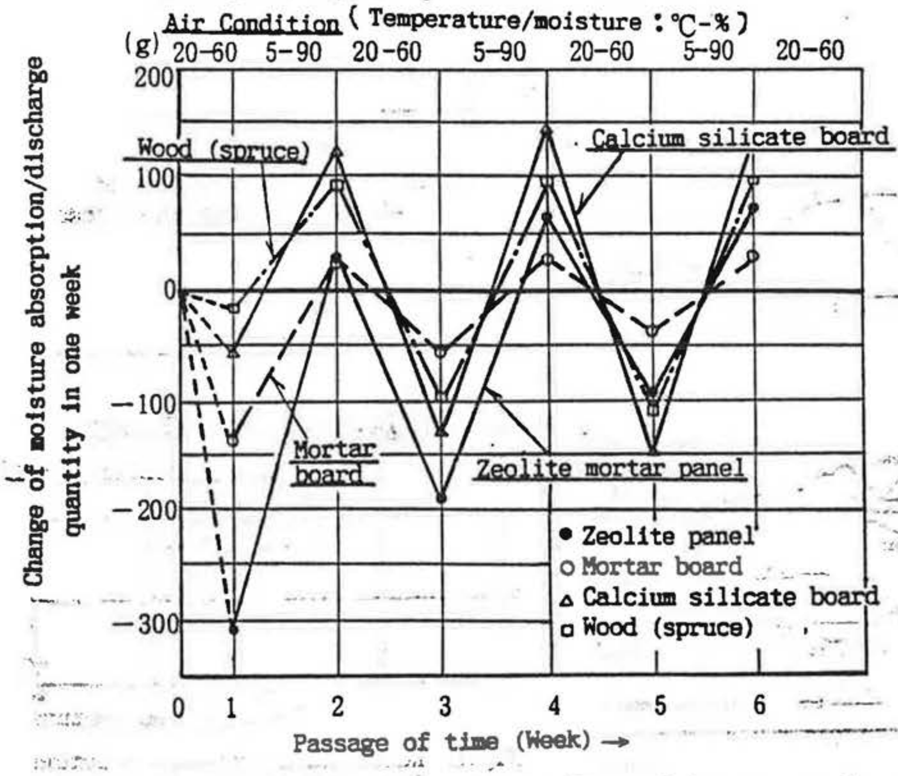


Fig.2 4 Materials Weight Change Value

In order to understand the moisture absorbing property of materials when they are cooled, a test piece measuring 150×150 ×20 (mm) with a mixture ratio of 50% was prepared and the weight change was measured while cooling only one side of the test piece. Fig.3 shows part of the measurement results. It is shown that zeolite has properties almost identical to those of wood in comparison with other materials.

The humidity controlling effect due to moisture absorbing/discharging was verified with the help of an experiment box. A steel box was prepared under the conditions where the space was 1m^3, the thickness of the roof board and baseplate was 3.2 mm and the thickness of the side panel mouting plate was 4.5 mm. The total size of zeolite panels on the north, south, east and west was 2.56m^2, accounting for 42% of the entire surface area. Box A with 16 zeolite panels 400× 400 ×20 (mm) and Box B with aluminum panels of 0.5 mm in thickness used for comparison purposes were installed outdoors. The dry-bulb temperature and the dew-point temperature were measured to compare the temperature/humidity fluctuation in boxes A and B, and The following facts were revealed as a result. The data on

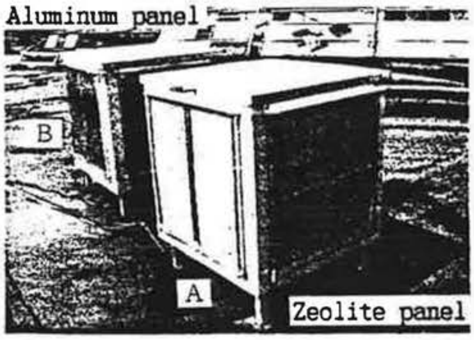
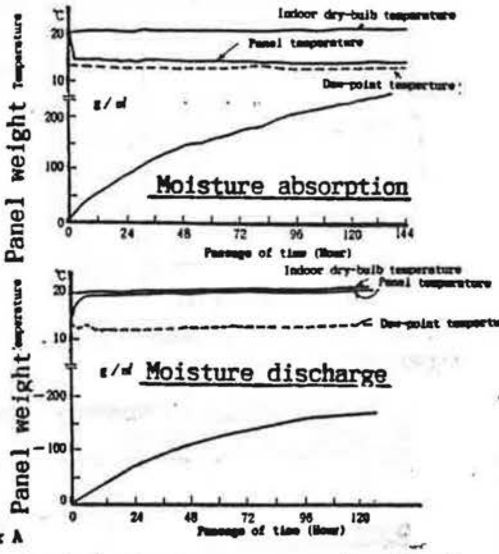


Photo-1 View of Experimental Box



Fif.3a-3b Measurement Result of Absorption/Discharge Speed

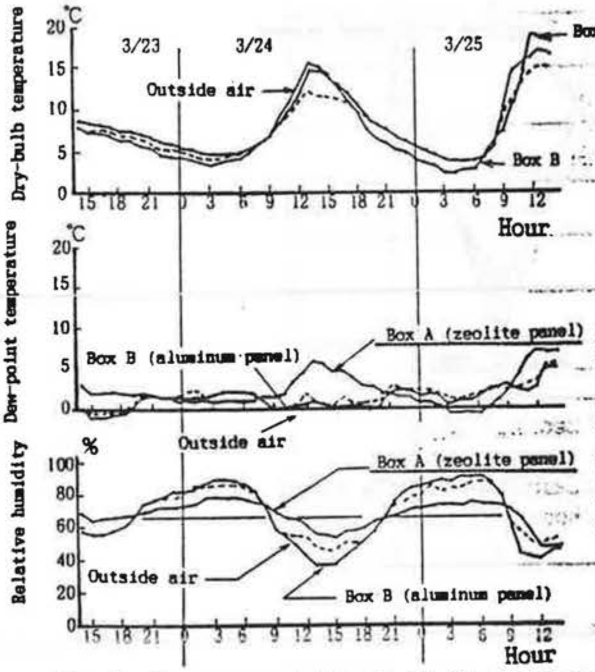


Fig.4 Measurement Result of Temperature and Humidity in Experimental Box

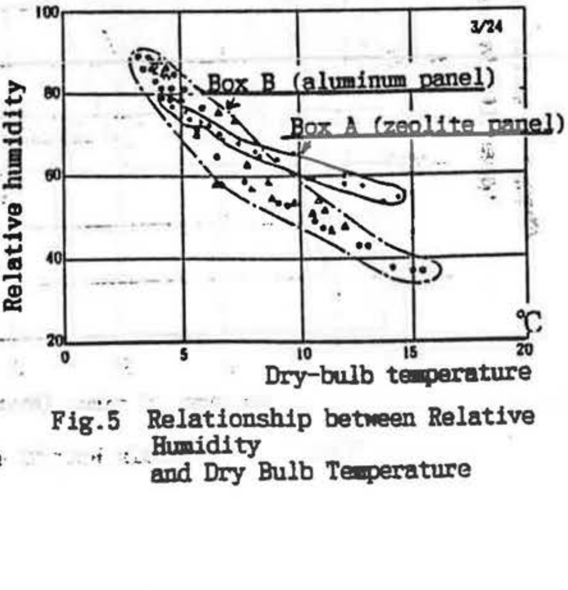


Fig.5 Relationship between Relative Humidity
and Dry Bulb Temperature

March 24 indicates that the dew-point temperature rose as the daytime temperature roses in Box A as shown in Fig.4, and zeolite panels discharged moisture to stop sudden drop in relative humidity. Fig.5 shows the combination of dry-bulb temperature and relative humidity for every measurement. In box B with aluminium panels, the relationship between dry-bulb temperature and relative humidity was almost the same as that in the outside air, while in Box A with zeolite panels, the humidity controlling effest was observed. When the situation is compared by using the standard deviation σ (%) of daily fluctuation of relative humidity, σ =15.19 in the outside air, σ=8.28 in the zeolite box, and σ=19.16 in the aluminum box. Fig.6 shows the difference of temperature and absolute humidity in and out of the boxes. In the seaked-up boxes, ventilation is considered to be zero. Therefore, the qrantitu of absorbed/discharged moisture observed in the experiment is considered to be that of the zeolite panels alone. After the above experiment, the aluminum panels were replaced by ordinary mortar panels without zeolite and subjected to a similar experment. As a result, the moisture absorption by the ordinary mortar panels was about 1/3 of that by the zeolite panels, and thus the result was almost identical to that obtained through the measurement of weight change in single test pieces.

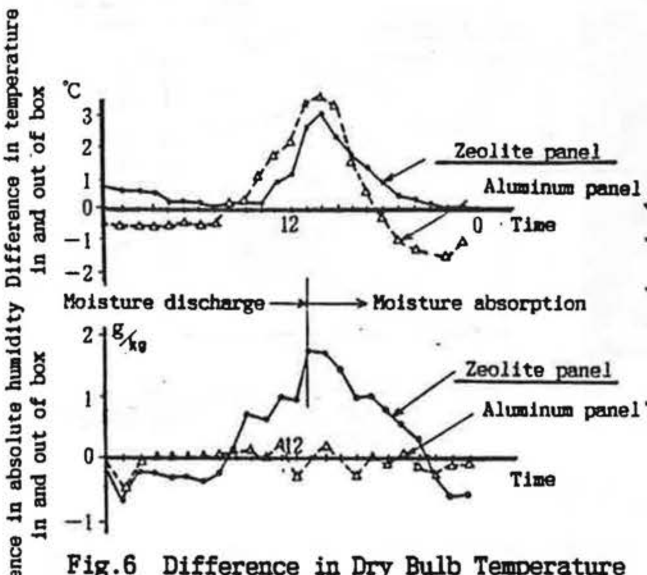


Fig.6 Difference in Dry Bulb Temperature and Absolute Humidity In and Out of Box

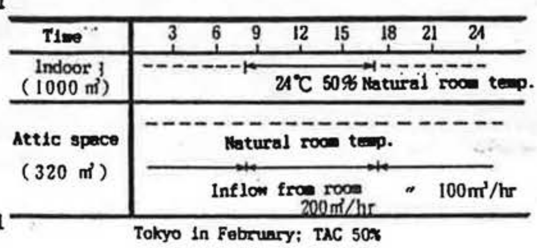


Fig.7 Air Condition for Simulation

Analysis

The behavior of zeolite panels against dew condensation in attic space was calculated by forming a space with zeolite panels. The extent of effect of zeolite panels on prevention of vapour condensation in attic space was checked with the help of vapour-condensation prevention performance judgement program (1) on the basis of the result shown in Fig.2. The quantity of moisture that one panel 400 $\times$400 $\times$20 (mm) measuring absorbs/discharges was assumed to be 54 g/day, which was avelaged per day to be used as the quantity of absorbed and discharged moisture. Fig.7 shows the calculated air condition for simulation, while Fig.8 shows the specification to model building. Fig.9 shows the calculation result of dew-condensation value in attic space without zeolite panels, indication dew formation on outer walls of attic space. Fig.10 shows the comparison of temperature/humidity between the case where 80 zeolite panels were installed in the attic space and the case where no panel was used. It is estimated that the humidity when zeolite panels were installed is 20 to 30% lower than that when no zeolite panels was used. In that case, there is no vapour condensation in the sttic space.

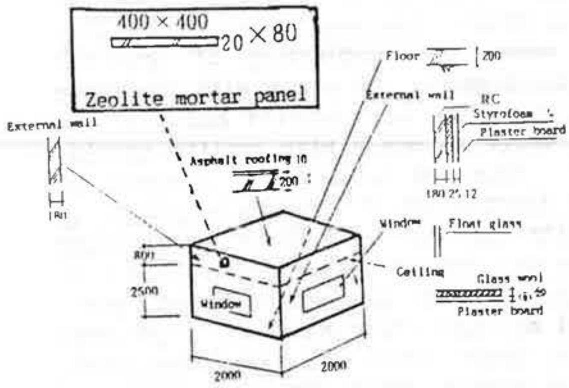


Fig.8 Specification of Model Building

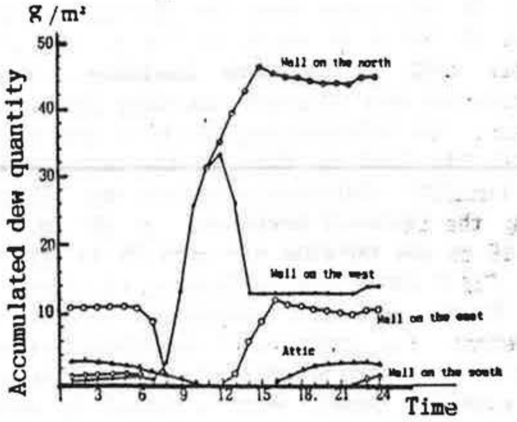


Fig.9 Calculation Result of Dew Condensation Value in Attic Space

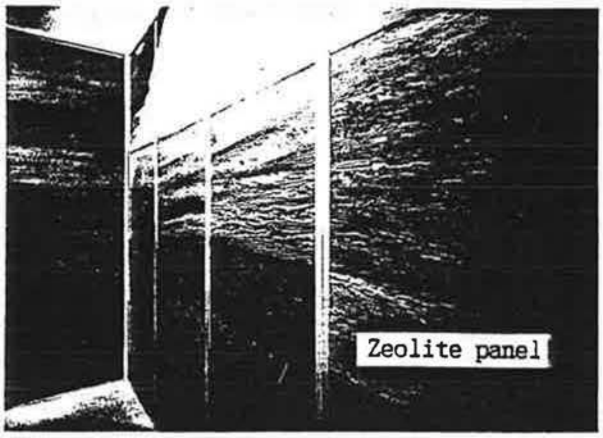


Photo-2 View of Zeolite Panels in Warehouses.

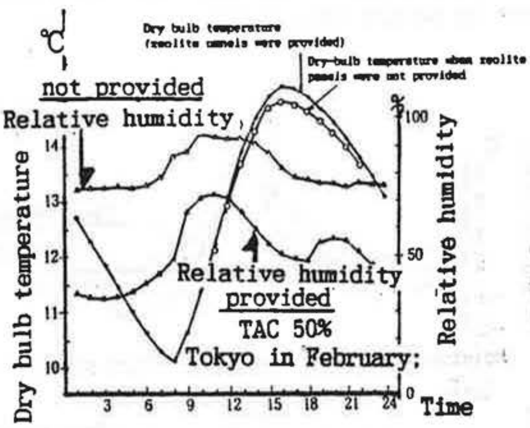


Fig.10 Calculation Result of Temperature/Humidity Change in Attic Space

Conclusion

Humidity controlling property is highly needed by art museums, storage warehouses and other types of buildings, which are also susceptible to excessive air conditioning. It is considered that the dew condensation problem results from imbalance between heat insulating performance and humidification/air conditioning in buildings. To solve such a problem, the building construction method and materials must be reviewed. When due attention is paid to interior finishes and stored objects, external walls and roofs themselves installed by the heat insulation construction method may be economical to prevent dew condensation. Zeolite panels are being examined for their application to the storage of paintings and other works of art in some buildings, and experiments for that purpose are underway (Photo-2). The number of humidity controlling materials to be developed will further increase in future.

Acknowledgements

The authors are grateful for the guidance and cooperation to Dr. Taku Kamazaki, Dr. Yasuhiro Kameda, Dr. Muneshige Nagatomo and Dr. Shumpei Ohara.

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DO ENERGY MEASURES CAUSE MOISTURE PROBLEMS?

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ABSTRACT

This paper describes the risks associated with application of retroactive energy conservation measures. Examples illustrate the potential for condensation and mildew damage caused by thoughtless or misguided application of measures without understanding of the underlying building physics aspects that need to be considered. Damage can also be caused, of course, by fundamentally incorrect design or faulty construction or installation.

HIGHER INSULATION LEVELS

Well-insulated buildings lose less heat than poorly-insulated buildings. As well as reducing the level of energy use, this results in an improved indoor climate in the form of more uniform temperatures on interior surfaces. All this is beneficial, but in some cases increased insulation can result in a greater risk of various forms of damage. Conditions on the inside of the insulation become warmer and drier, while on the outside they become colder and damper. Two examples can illustrate this.

Example 1 - Enhanced Insulation in Roof Spaces

Temperature and moisture conditions in roof spaces depend on the amount of insulation, the permeability of the joist structure from the rooms below, the insulating performance of the outer roof cladding and the ventilation in the roof space. After installation of additional insulation, the roof space will become somewhat colder than before. With all other conditions unaltered, the risk of damage then increases for two reasons:

- lower temperatures result in earlier formation of condensation, and
- lower temperatures result in poorer drying-out for the same degree of ventilation.

Assume that a ceiling/joist structure with a U-value of 0.50 is upgraded by application of additional loose-fill insulation to a U-value of 0.20. If the outer roof covering consists of concrete tiles and there is a mean ventilation rate of 3.0 air changes per hour, the temperature in the roof space will be reduced from -2.5 °C to -4.0 °C at an outdoor temperature of -5 °C and an indoor temperature of +20 °C.

If we assume that the ceiling/joist structure is totally impermeable, relative humidity in the roof space will be determined only by the ventilation. With an outdoor relative humidity of 90% at -5 °C, relative humidity in the roof space before the application of additional insulation was 74%, rising after upgrading to 83%.

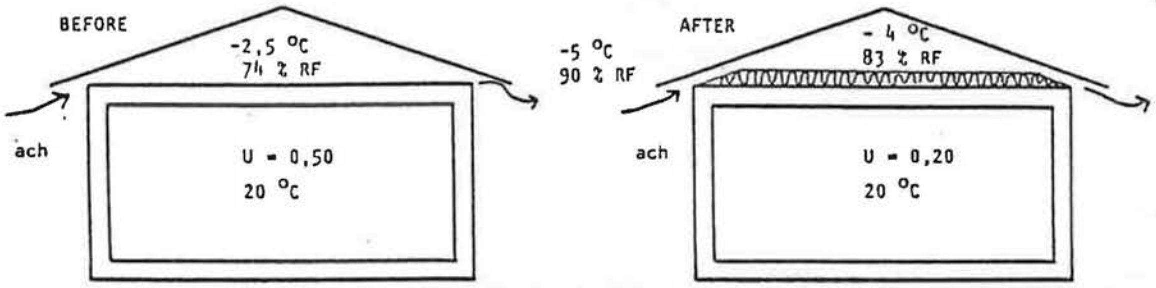

FIGURE 1. Moisture and temperature conditions in a roof space before and after application of additional insulation.

If we assume that moisture is to be removed from the roof space by ventilation, it will be necessary to double the ventilation rate if the same quantity of moisture is to be removed. However, the ventilation rate normally tends to fall after application of additional insulation, partly as a result of the lower temperature reducing the chimney effect, and partly as a result of blocking the ventilation gaps.

The conclusion to be drawn from this example is that additional insulation of roof spaces should be followed by inspection of the roof space during the next winter. If there are any signs of condensation, such as frost, damp or discoloured tiles etc., the causes should be ascertained and suitable counter-measures applied.

Example 2 - An Internally-insulated Basement Wall

If internal insulation is applied to an uninsulated basement wall, damage can be caused by the ensuing prevention of evaporation of moisture from the wall.

Moisture conditions in an uninsulated basement wall are determined by the amount of moisture input to the wall from the air outside and inside, the ground outside and the ground beneath. Inward diffusion of moisture need not cause any damage if it can evaporate off on the inside. However, insulating such a wall on the inside can result in the studding being exposed to such high moisture levels that rot and mildew can be caused. Internal insulation can be accepted only if either all inward migration of moisture from the air and the ground to the wall can be completely stopped by application of impermeable coatings, removed by ventilation or allowed to evaporate inwards through diffusion-permeable surfaces. This means that there must be no plastic film, no impermeable wallpapers and no impermeable paints on the inside of the wall. If these conditions are not fulfilled, internal insulation will involve an increased risk of moisture and mildew damage. The safest way of insulating basement walls is to apply the insulation to the outside.

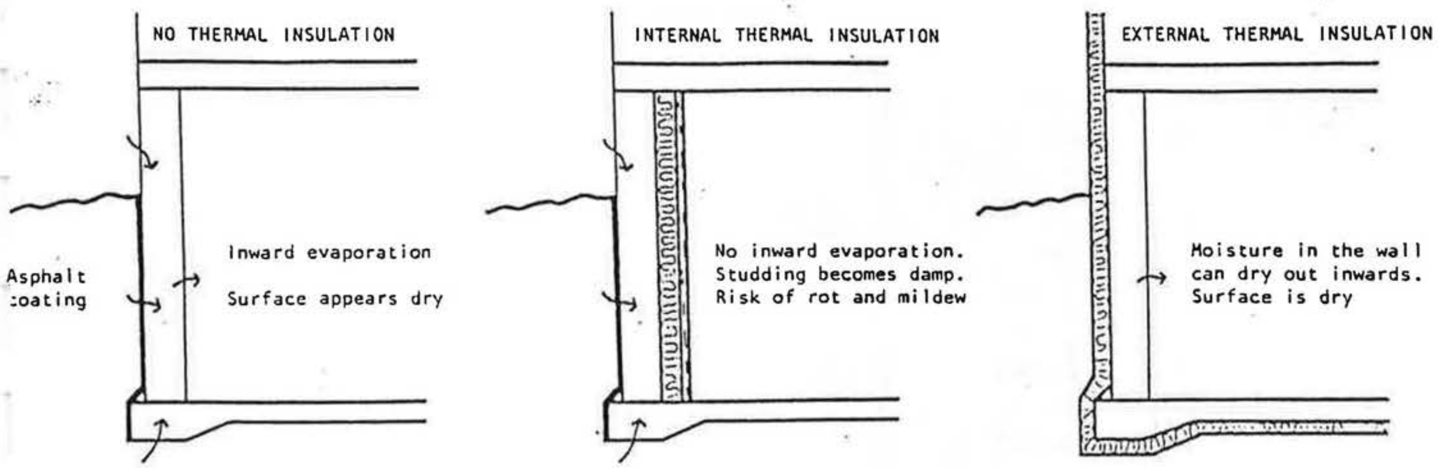

FIGURE 2. Moisture conditions in a basement wall with and without insulation

Greater Airtightness

Airtight structures reduce internal draughts and uncontrolled ventilation. Designing and building a house for high airtightness increases the scope for correct control of the ventilation. This is normally done by installation of a mechanical ventilation system, extracting air through ducts and supplying makeup air either directly from the outside through special inlet fittings or through inlet ducts. The correct balance between supply and exhaust air results in a slight negative pressure indoors, and is the necessary prerequisite for a good indoor climate and a dry house.

There is, however, also a considerable risk that an airtight house will be badly ventilated. If the ventilation system does not work correctly for any reason, the air change rate will be insufficient and problems are likely to arise. Higher indoor humidity levels, greater negative pressure indoors, changed inward air leakage paths and reverse air flows through extraction fittings are examples of problems that can arise in connection with more airtight structures and/or incorrectly operating ventilation systems.

Example 3 - Exterior Walls With and Without Internal Plastic Film

An airtight structure need not become damp. Moisture content on the inside of the sealing layer (plastic film, vapour barrier) is determined primarily by the relative humidity of the indoor air, while on the outside it is determined by the relative humidity of the outdoor air. Correctly created airtight conditions will result in the structure being dryer than if it is 'open'. (See Figure 3: next page.)

New Energy Systems and Energy-saving Building Services Systems

Certain building services systems can involve a risk of damage. A ventilation system that is working properly results in good ventilation throughout the house and a good indoor climate, while a system that is not working properly increases the risk of damage. An example of this could be a heat exchanger that allows both exhaust air and moisture to be recycled.

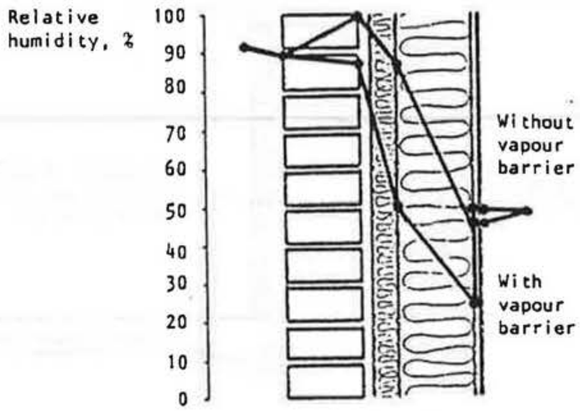

FIGURE 3. Moisture conditions (RH) in a brick-clad stud wall with and without an internal vapour barrier.

Example 4 - Rotating Heat Exchangers

In a residential area of 24 detached houses, twelve had been fitted with balanced ventilation systems (supply and exhaust fans) complemented by heat exchangers, and twelve with mechanical exhaust ventilation only. Indoor ventilation conditions in the first group were poor, with insufficient air change rates, recirculation of vitiated air by the ventilation system, high moisture inputs, frequent condensation on the insides of windows and serious condensation damage in roof spaces. Investigation found that exhaust air was leaking across to the fresh air supply in the heat exchangers, so that an estimated 60-70% of the supply air in the houses was recirculated, in systems that should have had no recirculated air at all.

The cause of the problem was partly poor sealing in the heat exchangers and partly incorrect arrangement of the fans, resulting in a high differential pressure between the supply and exhaust sides of the systems. Unfortunately, the occupants of the houses had to put up with substandard ventilation for ten years before improvements were made.

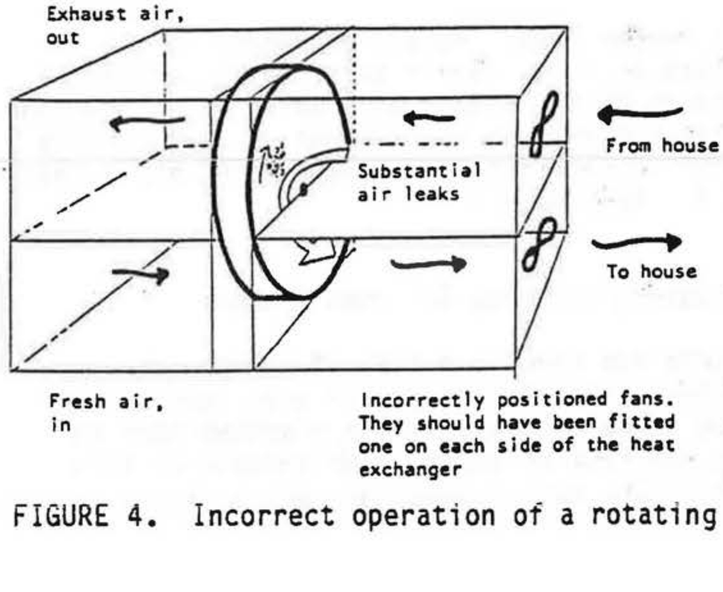

FIGURE 4. Incorrect operation of a rotating heat exchanger

Another example of a change that can cause problems can be found in the conversion from oil-fired heating to direct electric heating. The air drawn in by a boiler creates a negative pressure in the house. Changing to electric heating and eliminating the boiler reduces the negative pressure in the house, increasing the risk of condensation damage in the upper storey.

Negative pressure is high in a naturally-ventilated house in which the exhaust air ducts run in the warm chimney breast. Cooling of the chimney breast resulting from discontinuing use of the boiler when changing to electric heating reduces the air change rate and the negative pressure.

Changes in Occupants' Habits

Greater energy awareness on the part of the occupants is beneficial, but can result in a risk of damage. Substantial reductions in temperature should be avoided, as this can result in local condensation on cold surfaces. Unthinking sealing of all air leaks by weatherstripping can reduce ventilation air change rate to such an extent that the indoor relative humidity rises to levels at which condensation and mildew can form on internal surfaces. Another example of misguided energy saving is the use of drying cupboards and tumble dryers without arranging for them to discharge to the outside or to a ventilation exhaust system, so that the warm, moist air discharges instead to the inside of the house. Excessive use of the shower instead of the bath also increases the indoor moisture loading. Changes in cooking habits, too, can affect indoor moisture levels.

Reduction of indoor temperatures in parts of the house at times can also be risky. A constant indoor temperature throughout the year is a good way of avoiding damage.

SUMMARY

Energy conservation measures in buildings need not cause problems if they are applied correctly. A well-insulated, airtight house is normally an excellent house with low energy costs. However, if the measures are incorrectly applied, they can cause problems such as condensation or mildew.

The risk of moisture problems increases in cases such as the following:

- Placing thermal insulation on the wrong side of the structure. In a cold climate, thermal insulation should normally be on the outside.
- Producing an airtight envelope without mechanical ventilation.
- Placing vapour barriers on the outside of the structure.
- The use of energy-saving components, such as heat exchangers or heat pumps, in such a way as to lead to other problems.
- Applying measures with no understanding of the underlying energy-saving mechanisms or building physics principles.

It is our experience that damage caused by condensation or mildew occurs when energy-saving measures are implemented with no awareness or knowledge of either the potentials or the risks of problems. Any and every structural change in the building envelope is accompanied by a risk of problems. Energy-saving without knowledge of what can be involved should never be done.

TEMPERATURE AND MOISTURE CONDITIONS IN CAVITY WALLS

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ABSTRACT

There are many questions to be answered about the temperature and moisture conditions in a cavity wall and therefore measurements have been carried out in a test building.

The facades of the test building consist of 16 different sections, which can easily be changed. For example, the air gap between the outer masonry and the inner wall, the ventilation openings and the thickness of the insulation can vary.

The temperature and moisture conditions in the masonry, in the air gap and in the inner wall were measured. Furthermore the ventilation in the air gap was measured in different outdoor climate.

The measurements, which are not yet completed, preliminarily show that

- the masonry is dry in the summer and capillary saturated in the winter
- the air gap has a minor influence on the moisture conditions, both in the masonry and in the inner wall
- the thickness of the insulation has a minor influence on the temperature and the moisture content in the masonry.

1. INTRODUCTION

Moisture problems in cavity walls have become more common during latter years. Examples of problems that can be mentioned are mould and rot in the wooden framework and frost damage in the bricks.

It is evident that driving rain is one important cause of many problems. To avoid water coming into the framework and the insulation, the wall is constructed with an air space between the brick masonry and the inner part of the wall.

There are different opinions about this air space. Is the air space necessary? Lately it has become increasingly more common to fill the air space with heat insulation. But can this lead to problems in the future?

In order to study this, measurements have been carried out in a test building. The measurements started in 1987 and will be finished in 1990. In this paper the test building, the measurements and some preliminary results are described.

2. TEST BUILDING

The test building (FIGURE 1) is situated in a field adjacent to the Lund Institute of Technology. The facades facing south-west (SW) and north-east (NE) are changeable. The indoor temperature is +20°C.

The SW facade is exposed to quite heavy driving rain and sun radiation. The NE facade is exposed to little driving rain and little sun radiation.

Today there are 16 different test sections, 1.2 m long and 2.6 m high, in the facades. The test sections are all different types of cavity walls with an inner wooden framework (FIGURE 2). The test sections have

- different thickness of insulation, 100-300 mm
- different width of air space, 0-50 mm
- different openings for ventilation

Most sections have no surface treatment on the outer side. However, one section has undergone water repellant treatment and one section has been rendered with a LC-rendering.

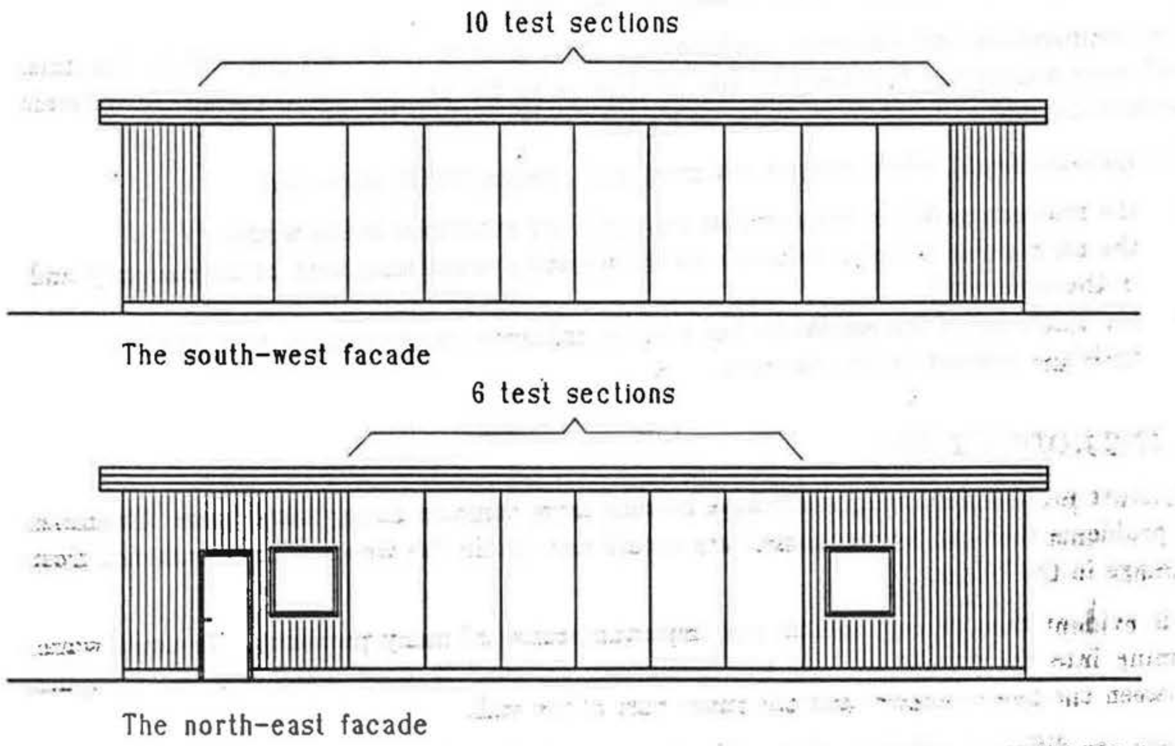

FIGURE 1. Test building.

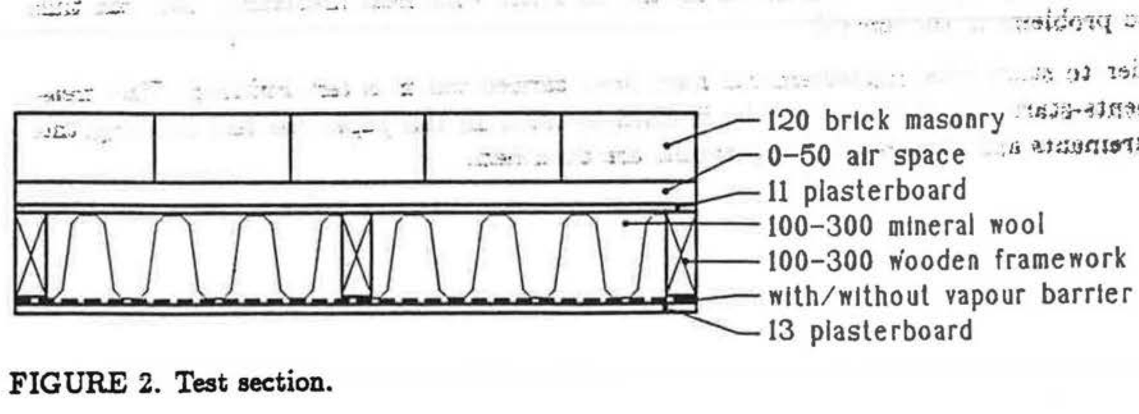

FIGURE 2. Test section.

3. MEASUREMENTS

3.1 General

The aim of the investigation is to clarify the building physics in the cavity wall. To fulfil this aim the following measurements are carried out

- outside climate (sun radiation, temperature, wind velocity and direction, humidity, rain and driving rain hitting the facades)
- ventilation in the air space
- moisture conditions in the bricks, in the air space, in the insulation and in the framework
- temperature in the bricks, in the air space and in the insulation

The measurements started in the winter 1986/87 and will continue at least until 1990.

Only a few examples of the results can be shown in this paper. A complete report will be published during 1990.

3.2 Ventilation in the air space

The ventilation rate of the air space has been measured using the tracer gas method, decreasing gas concentration. Measurements have been carried out in different climates and some results are shown in TABLE 1.

According to TABLE 1 the ventilation rate is highly dependant on the outdoor climate. With normal ventilation openings the ventilation rate is low. To achieve a high ventilation rate both the width of the air space and the ventilation openings must be very large.

3.3 Moisture content in the brick masonry

The moisture content in the bricks has been measured using the gravimetric method on whole bricks. Some results, on the SW facade, are shown in FIGURE 3.

The moisture content is always low during the summer and rises in the autumn. The bricks are very often capillary saturated during the winter. The different staples in FIGURE 3 represent different wall constructions. According to the figure there is no difference between the different walls with the exception of number 4. This wall has no insulation.

Measurements have also been carried out in walls with a LC-rendering and with a water repellant treatment respectively. These walls were quite dry while the other walls were capillary saturated.

TABLE 1. Air changes per hour in the air space.

Width of the air space (mm)	20	20	50
Ventilation openings at the bottom	no	one vertical joint	one brick changed for a lattice
sunny and windy	3	4	12
cloudy and calm	1	2	2

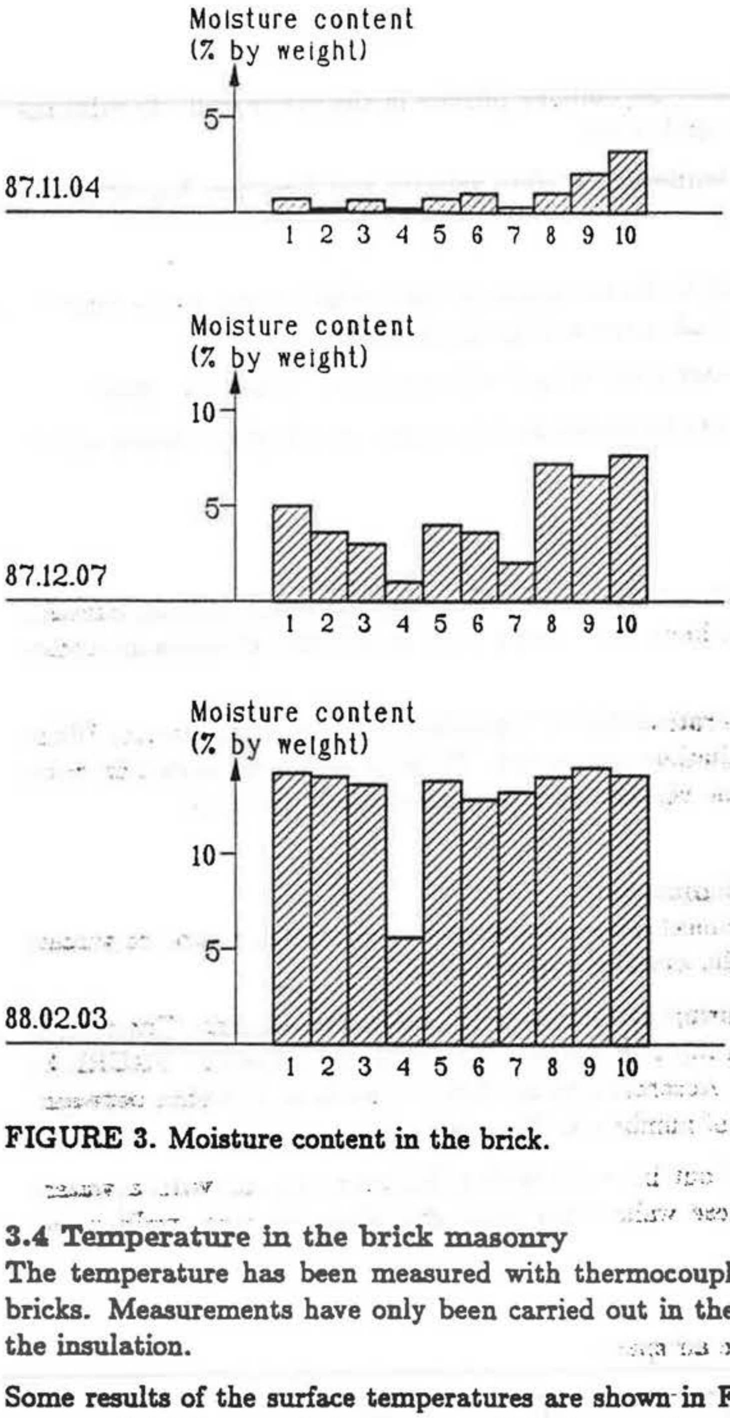

FIGURE 3. Moisture content in the brick.

3.4 Temperature in the brick masonry

The temperature has been measured with thermocouples fixed at different depths in the bricks. Measurements have only been carried out in the walls with different thicknesses of the insulation.

Some results of the surface temperatures are shown in FIGURE 4. As can be seen there is no essential difference between the walls facing south-west. Consequently the insulation has a minor influence on the temperature in the bricks. On the other hand the orientation of the walls has a great influence, depending on the different degrees of sun radiation. This can be seen clearly in FIGURE 5. The outdoor temperature is about -10°C. The sun radiation on the SW-facade causes a temperature rise to about +10°C.

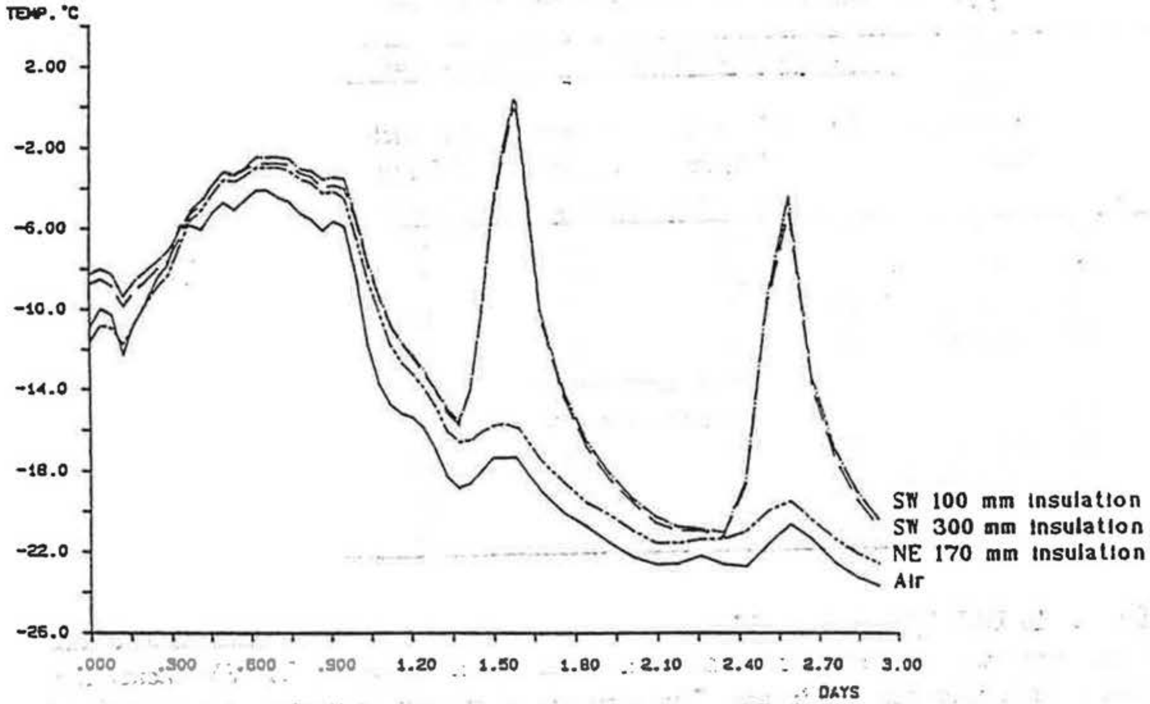

FIGURE 4. Surface temperature on the brick masonries with different insulation and different orientation.

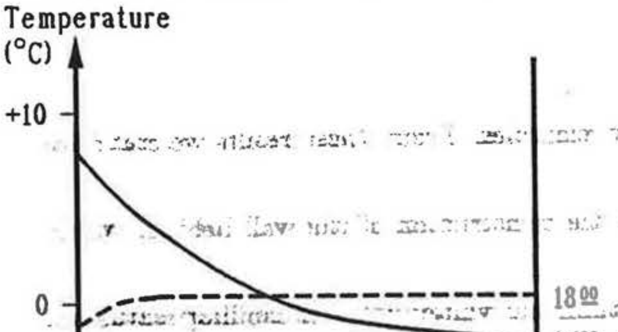

FIGURE 5. Temperature conditions in the brickwork facing SW during a day with sun radiation. Outdoor temperature is about -10°C.

3.5 Freezing - thawing cycles

The number of freezing - thawing cycles has been measured at different depths in the brick masonry. The results of these measurements on the outer surface are shown in TABLE 2.

TABLE 2. Freezing - thawing cycles in the surface and in the air.

Time		Monthly mean temperature	Number of freezing - thawing cycles			
			Air	SW with 100 mm insulation	SW with 300 mm insulation	NE with 170 mm insulation
Jan	-87	- 7.0°C	3	16	15	4
Feb	-87	- 2.2°C	5	19	19	7
Mar	-87	- 4.2°C	10	17	17	10
Nov	-87	+4.9°C	5	2	2	2
Dec	-87			no measurements		
Jan	-88			no measurements		
Feb	-88	+1.4°C	17	9	12	10
Mar	-88	- 0.1°C	14	11	11	11
Apr	-88	+3.9°C	9	6	6	8

According to TABLE 2 there is no difference between walls with different thicknesses of the insulation. However, the orientation of the facade has a great influence. The SW-facade has many more cycles than the NE-facade. This depends on the sun radiation. An example of this effect is shown in FIGURE 5. Despite an outdoor temperature of -10°C, the surface temperature rose to +10°C.

TABLE 2 also shows that the number of freezing - thawing cycles in the bricks is much higher than in the air when it is very cold outside.

4. DISCUSSION

The results shown in this paper are only a few examples. From these results we can draw some preliminary conclusions.

The outer brick masonry is barely affected by the construction of the wall behind, within reasonable limits.

The masonry absorbs driving rain during the autumn and winter until it is capillary saturated. The ventilation of the air space is not sufficiently efficient to affect the moisture content to a greater extent.

On the basis of TABLE 1 the maximum daily drying out through the air gap can be estimated at 0-0.1 kg/m^2. This figure should be compared with the driving rain that is absorbed. It is not unusual with monthly driving rain about 20-50 kg/m^2.

When the brickwork is capillary saturated it will be exposed to several freezing - thawing cycles. Consequently the masonry must have a very high frost resistance. You cannot solve any problems with frost damage by making more ventilation openings in an ordinary cavity wall.

The only way to lower the moisture content in the masonry is to apply some surface treatment.

ARE VAPOUR BARRIERS REALLY NECESSARY?

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1.0 Introduction

With the threat of fossil fuel shortage and the need for energy conservation, the desire to make buildings more airtight has heightened.

This reduction in ventilation will cause a larger than normal buildup of moisture in the internal climate unless it is removed by dehumidifiers or by controlled ventilation. If however, humidity control is not achieved events such as surface and interstitial condensation will become more prevalent especially during periods when the heating is switched off. This in turn will place a larger reliance on the operation of vapour and air barriers - which may be built into light weight structures such as the walls of mobile homes and temporary office accommodation.

It has been assumed previously that if these barriers fail to perform as designed, moisture caused by surface condensation could diffuse under thermal and vapour stresses as water or vapour into the structure. Such conditions exist during winter when the inside temperature could be 20°C and that outside 0°C.

The inclusion of condensed water vapour within such a structure may cause a variance in its thermal conductance. Thus the zone of condensation risk and the variation in thermal performance of a light weight insulated structure was studied in detail using a simple laboratory quasi-state method based on an airtight cube.

2.0 Thermal Test Cube

2.1 Theory

Assuming the existence of an airtight cubical box having one face removable the heat loss rate balance can be expressed by equation (1).

$$P_H + P_f = U.A_{Eff}.\ \Delta\ \Theta_{air} \qquad (1)$$

Where $A_{Eff} = \sqrt{A_i.A_o}$ effective planar surface area of cube

A_i = inside surface area m^2

A_o = external surface area m^2

P_f = fan heat output rate

P_H = heater energy output rate

$\Delta\Theta_{air} = \Theta_{in} - \Theta_{out}$ (air to air temperature difference)

Θ_{in} = steady temperature inside cube

Θ_{out} = steady temperature outside cube

$\Delta\Theta_{surf}$ = temperature difference across faces of the panel

Rearranging Equation (1)

$$\begin{aligned} P_H &= U.A_{Eff}.\ \Delta\Theta_{air} - P_f \\ &= G\ \Delta\Theta_{air} - P_f \end{aligned} \qquad (2)$$

Thus if a graph of P_H is drawn against $\Delta\ \Theta_{air}$ its slope, G, will yield $U.A_{eff}$ the heat loss rate per degree temperature difference. If the removable side is then replaced by a sample to be tested, the steady state heat loss rate for the cube arrangement can be expressed as follows:

$$P_H + P_f = U_s\ A_s \Delta\Theta_{air} + f\ G\ \Delta\Theta_{air} \qquad (3)$$

where: U_s = thermal transmittance of sample

A_s = surface area of sample

f = fraction of effective area occupied by 5 fixed sides of cube

r = fraction of effective area occupied by test sample

ie $r = \dfrac{A_s}{A_{Eff}} = \dfrac{A_i/6}{\sqrt{A_i A_o}} = 1/6 \times \sqrt{\dfrac{A_i}{A_o}}$

When equation (3) is rearranged equation (4) results.

$$P_H = (U_s A_s + fG)\ \Delta\Theta_{air} - P_f \qquad (4)$$

Therefore if P_H is plotted against $\Delta\ \Theta_{air}$ a straight line results the slope of which is $M = (U_s A_s + fG)$.
Rearranging, an expression for U_s results:

$$U_s = \frac{M - fG}{A_s} \qquad (5)$$

Thus if a cube can be constructed such that

(i) no ventilation losses occur
(ii) the sample area $A_s = A_i/6$
(iii) steady state conditions exist

then the thermal transmittance 'U' for a sample wall can be determined using Equation (5).

2.2 Design, Construction and Calibratrion

A test cube was constructed consisting of a wooden outer box fabricated from 10mm external grade plywood enclosing completely an inner cubical box made using 45mm thick slab insulation (polyisocyanurate aged foam reinforced with glass fibre strands). The physical dimensions of the cube arrangement are

External	(425 mm x 425 mm x 440 mm deep)
Internal	(305 mm x 305 mm x 345 mm deep)

The sixth removable side side was constructed such that it could be easily replaced by the sample lightweight insulated wall panels.

The internal steady state temperature environment of the cube was achieved using an electrical heater formed by two ceramic resistors in series fed by a stable DC power supply. A small mains fan was included to ensure that the internal air was thoroughly stirred to create an isothermal volume of air.

To provide an airtight cube while in operation and during calibration, a mastic compound which had been used in previous experiments and found suitable was used to seal all joints and where the test sample panel was attached to the test cube. (1)

To simulate winter conditions, the cube was located inside a large cabinet fridge which gave a constant external air temperature especially when a small fan was placed inside the fridge to eliminate stratified air layer formation. The temperature of the air inside and outside the test cube was determined using type K thermocouples embedded in 5 mm spheres. A differential type K thermocouple was also constructed to measure the external and internal surface temperatures of the panels during a test.

2.3 CALIBRATION RESULTS

From the results of the calibration test, a graph was drawn which yielded a slope, $G = 0.43\,WK^{-1}$, Fig. 1(a).

Using the dimensions of the cube the effective surface area $A_{Eff} = \sqrt{A_i A_o}$ was calculated.

ie $A_i = 0.56\ m^2$ $A_o = 1.08\ m^2$ which gives

$A_{Eff} = 0.78\ m^2$ and $r = 1/6 \times \sqrt{0.56/1.08} = 0.12$

giving $f = 1 - r = 0.88$

3.0 EVALUATION OF DRY WALL CONDUCTANCE

A sample model wall consisting of 10 mm thick plasterboard attached to a 12 mm wooden frame filled with fibrous rock wool and enclosed with a thin sheet of aluminium was fabricated. The wall sample was prepared such that it could be attached to the cubical arrangement using the

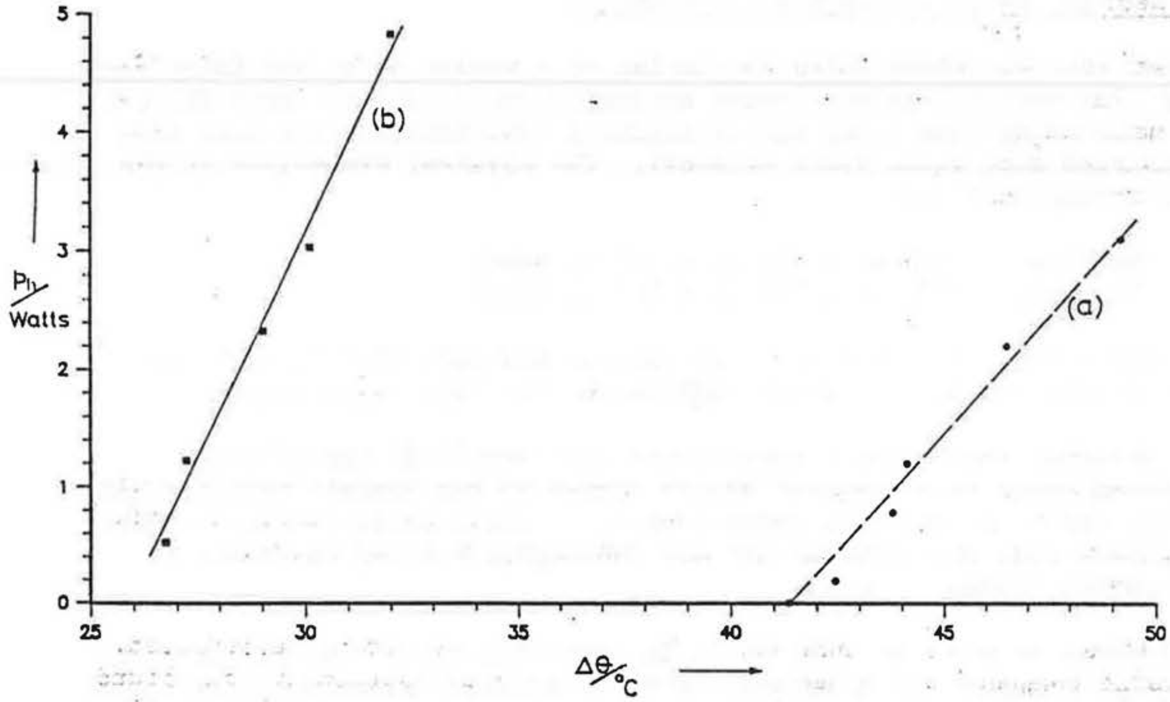

FIGURE 1. Graph of $P_H/\Delta\theta_{air}$ (a) calibration of cube (b) dry wall conductance evaluation

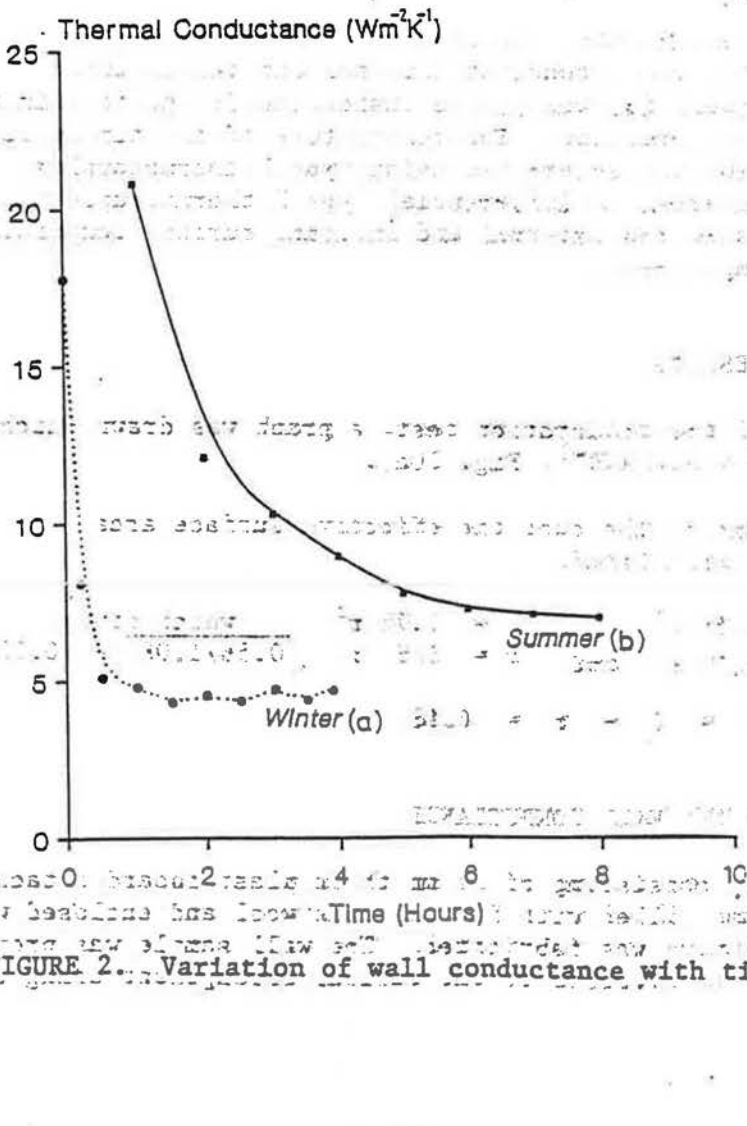

FIGURE 2. Variation of wall conductance with time

mastic compound and woodscrews. The cube was then placed carefully into the fridge. The heater was then turned on and varied over a period of time similar to the calibration sequence. The results obtained were then plotted using Equation (4) and the resulting slope, $M = 0.63\ W.K^{-1}$, Fig. 1(b) was used to evaluate U_s using equation (5) to give $U_s = 2.73\ W.M^{-2}K^{-1}$, where $A_s = 0.093m^2$.

Using this value and the expression

$$C_s = \frac{U_s\ \Delta\Theta_{air}}{\Delta\Theta_{surf}} \qquad (6)$$

the dry wall conductance $C_s = 2.85\ W.M^{-2}K^{-1}$ results.

4.0 PRELIMINARY WET WALL EXPERIMENTAL INVESTIGATIONS

To obtain a better understanding of the vapour and moisture movement process through the test panel, preliminary experiments were carried out. To simulate the effects of surface condensation a quantity of water was injected into the inside surface of the plasterboard and the panel set into the test cube which was then placed into the fridge. After several hours the temperature difference across the exposed surface of the test panel showed that it had returned to a similar value recorded during the dry wall calibration experiment.

The sheet on the panel was then removed to reveal condensed water droplets on its inside surface. The adjacent fibrous insulation was dry to touch and the plasterboard was also moisture free.

Another sample test wall was prepared as before with water being injected into the plasterboard and the experiment repeated until the temperature difference across the exposed faces had again reached a steady value. This time the sample panel was then removed, reversed and relocated in the cube which was then set in the laboratory. This arrangement was chosen to simulate summer conditions when metal surfaces can absorb solar enery causing the external surface temperatures to rise. After an eight hour period, the differential temperature across the exposed faces tended to slowly decrease with respect to time. Again the aluminium sheet was removed to reveal a dry internal metal surface adjacent to dry insulation then a slightly damp and slowly drying out plasterboard. Having an indication of the nature of the physical process occurring during the two proposed test regimes, the variation with time of the wall conductances was determined experimentally.

5.0 WET WALL CONDUCTANCE VARIATION EVALUATION

5.1 WINTER CONDITIONS

As previously described, approximately 0.15 kg of water was added to the plasterboard. After attaching the test panel to the cube the complete system was placed in the fridge. The temperatures Θ_{in}, Θ_{is}, Θ_{os} and Θ_{ext} were recorded simultaneously and recorded every ten minutes using a five channel recording thermometer. The power output from the fan was measured prior to the experiments and found to be 16.0 W. The conductance at various time intervals was calculated using the following expression derived using equations (3) and (6)

$$C_s = \frac{(P_H + p_f - f p_1)}{A_s \Delta\Theta_{surf}} \qquad (7)$$

The conductance of the panel was evaluated at 30 minute intervals and plotted against time as shown in Fig. 2(a). Where $P_1 = 17.9/41.7 \times \Theta_{air}$ and $f = 0.88$.

5.2 SUMMER CONDITIONS

To simulate summer conditions after winter conditions, the cube was removed from the fridge and the wall having suffered the winter simulation was removed and then reversed and fixed again to the thermal cube. Using the same heater and fan setting, the experiment was repeated and the corresponding conductance calculated using Equation 7. A graph of conductance against time was then drawn, Fig. 2(b).

6.0 ANALYSIS OF RESULTS

From the winter simulation it was found that the conductance of a wall having experienced the effects of condensation reverted quickly to a thermal performance similar to the dry wall case.

The summer simulation demonstrated that a wall having suffered the winter regime where water droplets had formed on the internal metal surface started to dry out and although slower to respond showed the same tendency to return to near dry wall thermal behaviour.

7.0 CONCLUSIONS

Taking account of the analysis of results and the short duration of both the winter and summer simulations, it may be concluded that the inclusion of a vapour or air barrier may not be absolutely essential in that during winter the thermal performance of such lightweight walls has not degraded even though water had condensed on the inside surface of the outer sheet. Thus with adequate drainage such a wall panel would remain thermally efficient for all of the winter. Towards summer when external conditions alter the water droplets will re-evaporate and diffuse towards the inside of the enclosure where if summer ventilation occurs the wall will dry out before the onset of another winter.

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SIMULATION OF TRANSIENT MOISTURE MOVEMENT IN LAYERED WALLS

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ABSTRACT

A one-dimensional, transient model of heat and moisture transport was developed and applied to a layered wall of typical residential construction, with wood siding, insulation, and gypsum board. Weather data was used to represent outdoor conditions while indoor conditions were held constant. A finite difference numerical solution produced the transient temperature and moisture profiles for each material. The model predicted that the wood layers offer substantial storage capacity for moisture, while gypsum board and fiberglass store very little moisture. Wood moisture at external surfaces varied more than at internal surfaces, responding to weather changes. Simulated air leakage through the wall produced substantially greater wood moisture in the region adjacent to the leak.

INTRODUCTION

The trend toward the construction of more energy efficient buildings in recent years has increased the concern about the presence of moisture in wall cavities. The addition of wall insulation lowers the temperature of those material layers external to the insulation during cold winter conditions. As moisture from within the house migrates outward, either by diffusion or leakage convection, it will condense on any surface whose temperature is below the dew point. If moisture were to accumulate at these sites, subsequent mold or wood decay could potentially occur.

Methods were developed to predict the occurance of moisture condensation within walls based on steady state moisture diffusion theory (1). However, under conditions whereby wall moisture was predicted to occur, it was not observed in field studies (2,3). The consensus seems to be that under such conditions, even though condensation may occur, it either does not accumulate at high enough levels to induce problems, or it evaporates during the warmer, drier summer months.

These findings point out the deficiency of a steady state model to usefully predict transient phenomenon such as the wetting and drying of wall materials. Transient models have subsequently emerged and are currently in various stages of development (4,5,6,7). These models, with adequately defined transport and material properties, would be capable of testing a wide range of constructions and exterior conditions in a relatively short time. The primary difficulty to date is measurement of the transport properties for these materials.

The purpose of this paper is to present the predictions of one of these transient models when subjected to actual weather data. While the critical need for accurate transport property data has not been circumvented here, the model relies on well established properties. The findings point out that structural effects are as important as the property data.

MODEL

The wall of a typical house in America consists of layers of materials (such as sheathing, siding, gypsum board, and insulation) which are hygroscopic to some degree. Each layer has the potential for conducting and storing heat, and for diffusing and storing moisture.

Heat and mass transport are driven by gradients in the temperature and moisture concentration, respectively, plus convection due to bulk flow when it is significant. Following arguments presented elsewhere (6,8), convection through construction materials is negligible, so the governing equations for heat and mass transport can be written as

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

$$\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial x^2} \qquad (2)$$

where α and D are the effective thermal and moisture diffusivities, respectively, for each material layer. Constant values for diffusion coefficients were used, although it was recognized that moisture diffusion coefficients are dependent on both moisture content and temperature.

The innermost and outermost layers were subjected to convective boundary conditions. The boundary condition for heat transfer is:

$$h\,(T_\infty - T_{surf}) + \dot{m}\,h_{fg} = -K \left.\frac{\partial T}{\partial x}\right]_{surf} \qquad (3)$$

Adsorption and desorption were assumed to occur only at these surfaces. Hence, the mass flux term was represented as:

$$\dot{m} = \rho D \frac{\partial M}{\partial x}\bigg]_{surf} \tag{4}$$

The convective mass transfer boundary condition was written in terms of the single dependent variable M as:

$$h_m(P_{wv,\infty} - P_{wv,surf}) = - \rho D \frac{\partial M}{\partial x}\bigg]_{surf} \tag{5}$$

The sorption isotherm was used to relate the moisture content at the surface to the water vapor partial pressure at the surface. The convective mass transfer coefficient was derived from the convective heat transfer coefficient by using the Lewis analogy.

At the interface between the layers, a diffusive boundary condition was assumed. A discontinuity in moisture content exists at the interface because of the definition of M. By assuming that the moisture content was in equilibrium with the water vapor pressure as predicted by the sorption isotherm, at each interface, then the moisture content discontinuity could be handled. This assumption was key to allow the use of a single dependent variable, namely moisture content, to be used for the mass continuity equation.

A fully implicit finite difference numerical method was used to solve the governing equations. The program was written in the Pascal programming language and employed the Crout Reduction Algorithm to solve the tridiagonal matrix. The computer program read data from an external file to incorporate a variety of materials and their properties. The finite difference sultion used a fixed time step of one hour and a variable spatial increment that utilized seven computational nodes per material layer.

The wall that was modeled for this study was a simple 3-layer wall as illustrated in Figure 1. This wall had a 2 cm. wood layer on the outside, a 9 cm. layer of fiber glass insulation, and a 1 cm. layer of gypsum board on the inside. The inside of the wall was exposed to a constant 22°C and 50% relative humidity. The outside of the wall was exposed to hourly data representing the Typical Meteorological Year for Portland, Oregon, USA. The convective coefficients for each surface were those recommended by ASHRAE (1).

Additional simulations were performed on a wall with an assumed leak, also shown in Figure 1. The leak extended through the gypsum board and insulation layers, but not through the wood. This type of leak is representative of the pathway around an electrical outlet, for example. For purposes of simultion, the heat transfer was assumed to be unaffected by the leak, implying that the convection was negligible and that the temperature distribution was the same as it would be for pure conduction. The moisture transfer, on the other hand, was assumed to be affected such that the leak imposed negligible resistance to the transfer of moisture. This combination of assumptions probably constituted the "worst case" conditions to investigate whether the presence of leaks are important in wall moisture transfer.

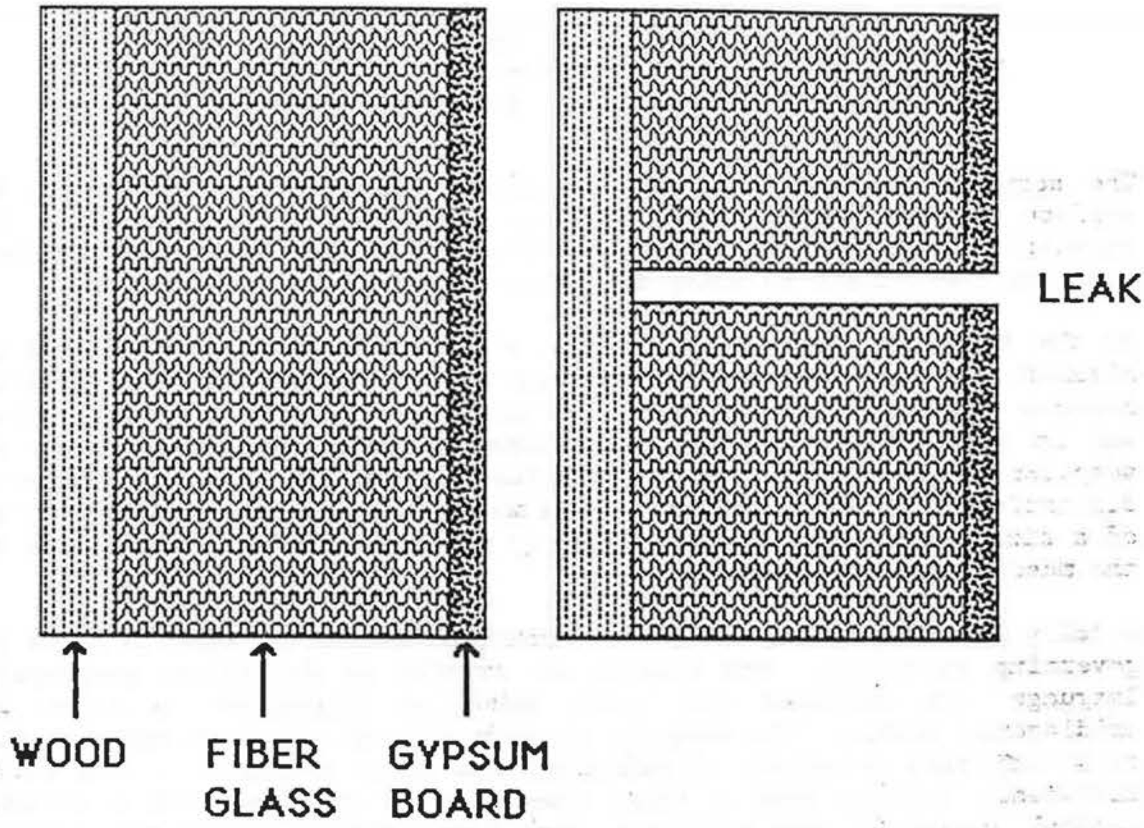

Figure 1. Model of a layered wall with and without a leak.

RESULTS

The computer simulation predicted the moisture and temperature distribution through each material for each hour for the entire year. As reported previously (6,8), the characteristic time constant for the redistribution of thermal energy is on the order of one day while that for moisture distribution is on the order of 50 days. To some extent, therefore, the energy and mass transfer equations are decoupled by the phenomena.

The wood layer of the wall is capable of storing significantly greater moisture than the insulation or gypsum board layers. The effective diffusion coefficient for wood is also much lower than those of the other materials. Hence, the wood layer acts as a moisture capacitor. This result is illustrated in Figure 2. The wood was assumed to have an initial moisture content of about 22%, but began to dry out immediately and had experienced significant drying during the first 11 weeks. During the remainder of the year, the wood's moisture fluctuated somewhat in response to the changing ambient conditions. The surface of the wood in direct contact with the outdoor climate showed wide swings in moisture content, varying from 7% to 26%. But the variation was reduced just slightly inside the wood, ranging from only 12% to 20%. At the inner wood surface, the fluctuation of moisture was negligible and remained at essentially 10% throughout the year. This moisture prediction reflects the constant indoor conditions and the high relative permeability of the other materials; actual walls would likely exhibit greater fluctuation due to indoor variations. The insulation and gypsum board layers showed little change.

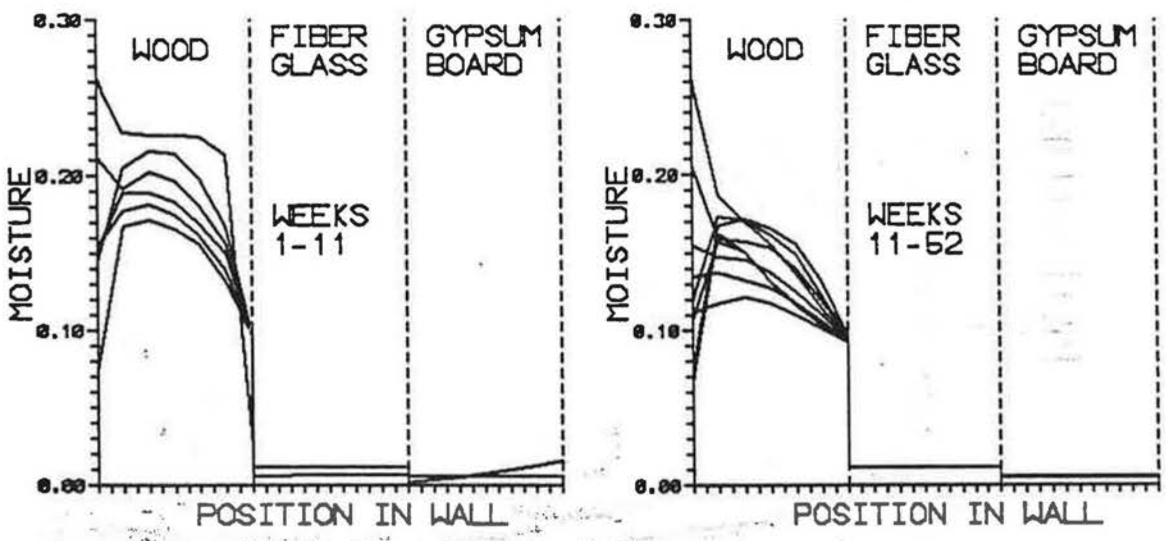

Figure 2. Moisture distribution in a layered wall for one year.

The predictions of the moisture history adjacent to a leak was quite interesting, as shown in Figure 3. As the warm, moist air was brought in direct contact with the inner surface of the wood, which became very cold in winter, the water vapor condensed on the wood and locally increased its moisture content. Local values were predicted to reach 50% - 60% in the neighborhood of the leak. These results are very similar to results obtained from measurements of wood moisture taken in actual houses during winter. Moisture in wood siding directly behind electrical outlets and other leak sites were measured in the range 40% - 60% (9). Measurements removed from the leaks were typically in the range of 15% - 20%; the model predicition was 10% for those sites. The model also predicts that the outside wood surface would be affected by the leak, but to a much lesser extent. As seen in Fgure 3, the outer woods surface for the two cases (leak and no leak) are quite similar. This implies that moisture problems may be hidden from outside inspection.

It must be noted that many simplifying assumptions have been employed to develop this simulation model. Some of these must next be examined to evaluate their impact on the results. Other wall configurations must also be tested, including such effects as paint and vapor retarders. But the model does appear to predict the correct trends observed by field studies, demonstrating the potential value of transient models.

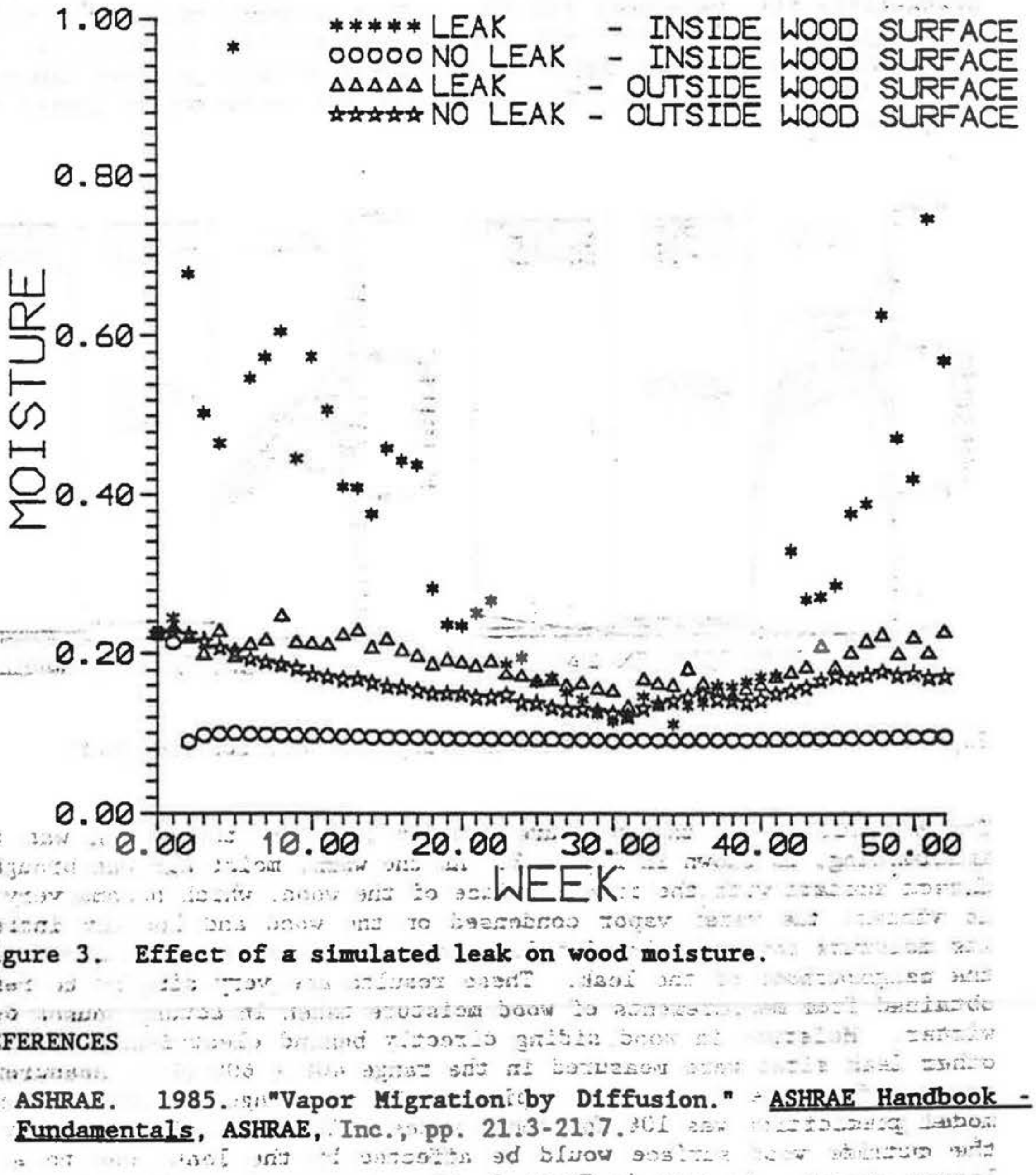

Figure 3. Effect of a simulated leak on wood moisture.

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NOMENCLATURE

D	effective mass diffusivity, m^2/s
h	thermal convection coefficient, W/m^2-K
h_m	effective mass convection coefficient, s/m
h_{fg}	enthalpy of phase change (fluid to vapor), J/kg
K	thermal conductivity, W/m-K
$\dot{m}$	moisture mass flux, kg/m^2s
M	moisture content, mass of water/mass of material
P_{wv}	water vapor pressure, Pa
T	temperature, Kelvin
t	time, s
x	spatial variable, m
α	effective thermal diffusivity, m^2/s
ρ	density, kg/m^3
∞	ambient conditions

RISING DAMPNESS PHENOMENA IN TRADITIONAL MASONRY

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1. INTRODUCTION.

There are several ways in which water may infiltrate through a building or its components, but in this paper we shall focus only on dampness rising by capillary flow from groundwater.

TABLE 1. Features recurring in pathologies from rising dampness.

HUMIDITY-INDUCED PATHOLOGIES IN TRADITIONAL WALL STRUCTURES (rising dampness from groundwater)		
Characteristics	Diffusion Intensivity Duration	Regular Constant Permanent
Findings	Same humidity values in all the walls (when built with the same materials)	
	The height dampness reaches remains constant in time: highest in poorly exposed (to the north) or ventilated faces, lowest in better exposed faces (to the south)	
	This phenomenon is present in adjacent buildings, if they are built with the same materials	

These humidity-induced pathologies are found quite frequently in old buildings while they are somewhat rare in the more recent ones where adequate geological surveys and waterproofing of foundation structures, of the outer underground walls ect. normally ensure perfect insulation.

2. REHABILITATION OF TRADITIONAL MASONRY.

In spite of the great many products now available for pathologies induced by dampness rise and of adequate know-how about intervention techniques, the last few years have witnessed quite a few failures in the field of rehabilitation. The manifold reasons for this may be sinthesized and adequately represented by the following motivations (considered to be the most frequent):
2.1) the inefficacy of some products;
2.2) inadequate application of other products believed to be valid;
2.3) misinterpretation or neglect of diagnostic aspects;

2.4) poor knowledge of the physical and chemical phenomena related to humidity and scanty knowledge of the building technologies used for the object being examined.

With respect to this last point, it has long been asserted that knowledge solely of the physical phenomena involved in a humidity-induced pathology is insufficient. It should be accompanied by an in-depth knowledge of building materials and technologies, and of how the phenomena differ according to the materials or technology used.

Indeed, damp phenomena in masonry may be related to a host of factors like:

a) absorption of the materials the masonry is constructed of (bricks, mortar, plaster);
b) microcrimatlic conditions which may or may not favour evaporation (temperature, relative humidity of the air, ventilation);
c) salt concentrations contained in and transported by water;
d) geometric characteristics of the part of the building where dampness is present.

One may easily forget that the water contained in a wall becomes pathological not so much because the material is capable of absorbing water but because it tends to eliminate it by means of evaporation at varying rates. This is why "critical water contents" in a wall differ according to the materials used. Normally, 2.5-3% water/weight are considered to be critical values for brickwork while for masonry in tufa (*), sandstone, etc. such values are 5-6%.

Some of the above-mentioned causes of failure in resolving humidity pathologies may be considered to be objective and cannot be ascribed to errors or misestimation on the part of the operator. They undoubtedly include the wrong measures recorded by some of the instruments utilized for determining water contents and the scarcely adequate technical requirements of some products and intervention techniques.

Furthermore, there is no doubt that some of the measuring instruments used are quite unreliable (water content values for the same wall differed greatly when tests were performed with different devices) and that the same applies for certain rehabilitation techniques as they have turned out to have only a limited durability in the long run (either because of the limitations of the product or because it was misapplied).

3. RESEARCH AND EXPERIMENTS.

These problems are dealt with in the research programme: "Comparative Analysis of the Hygrometric Rehabilitation Techniques Used in Buildings with Rising Dampness Problems, with Particular Reference to the Techniques Involving "Chemical Cutting" (performatory assessments and tests procedures)" (*).

After assessing the reliability of the main instruments on the market by means of laboratory tests and calibrations, the aim of the research was to carry out a comparative study on the

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*) The term "tufa" indicates those poorly-resistant calcareous rocks of clastic origin which -in Apulia and other regions of Southern Italy- can easily be cut into parallelepipedal blocks and used as building material, mainly in masonry (outside and inside, structural and non-structural masonry)

rehabilitation technologies used on masonry with rising damp phenomena (with an in-depth analysis of the techniques involving "chemical cutting" of the masonry). Subsequently, the research focussed on standardizing the procedures and tests for a reliable evaluation of the quality and durability of the rehabilitation interventions.

3.1. Problems Faced During the Initial Phase of the Research.

The first problem we tackled was to define the geometric characteristics of the walls to be built and immersed in tanks which were subsequently filled with water.
Thickness -T- was considered an objective value as it is a function of the different masonry and materials used (bricks, tufa, tiles, etc.). The relevant thicknesses were determined by defining certain samples of masonry. The other two geometric characteristics (L=2.00 mt; H=2.50 mt) were determined considering the experiences and findings reported in the literature on the maximum height water rises to in masonry in conditions of "maximum wettability" (*).
After defining the samples and the geometric characteristics of the walls, the tank prototype was designed. The tank was made of sheet metal and has a special locking system (which shuts once the wall is built and the tank is filled with water) to minimize any extremely important evaporation phenomena or accidents during the experimental phases.
The tanks were designed by the author of this paper and are joined together in pairs by means of a special connecting system. The tanks
in each pair maintain the same water level (principle of communicating vessels). Each tank contains a device which integrates the quantity of water evaporated without upsetting the system and a spillway which conveys any overflowing water into a graduate once the water has been integrated to reach a previously established height.
Right after this, the size of the standard tank to be fit in the IRIS-CNR test-lab was defined and the number of tanks and walls to be built was computed. Following upon the first results 21 tanks were evisioned. In defining the room to be taken up by each tank, the distance between the tanks was also taken into account as it was necessary to leave enough space for the instruments to be utilized in the various steps of our research.
The main instruments and equipment used were:

1) a "wall-cutter" (a machine used for cutting the masonry and for rehabilitation interventions);
2) IR AGA THERMOVISION 720 equipment (for thermographic visualisation -equipment owned by IRIS-);

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*) Teachers and researchers from the Dipartimento di Termofluidodinamica Applicata e Condizionamenti Ambientali (DETEC) of the University of Naples; from the Istituto per la Residenza e le Infrastrutture Sociali of the Consiglio Nazionale delle Ricerche (National Research Council) of Bari; from the Dipartimento di Energetica of the Polytechnic of Turin; from the Istituto di Fisica Tecnica ed Impianti Termotecnici of the University of Bari, contributed to the research which is part of the CNR Dedicated Project on Building (Subproject 3., Objective 3.2, Theme 3.2.1.).

3) HASSELBLAD equipment (to photograph the masonry before and after the intervention -equipment owned by IRIS-);
4) different humidity measuring devices (including Digital Diagnostic MKIII belonging to IRIS);
5) ANADATA Microclima equipment (to measure environmental parameters -equipment owned by IRIS-).

The distances between the tanks was thus reckoned to be 3 mt., which left enough space to test and sample the masonry and determine its water content with the "dry and weigh" method. This rigorous method will make it possible to determine reference values to be compared with the values obtained with the various "field" instruments.

3.2. How "Environmental" Parameters Affect Experimentation.

The most delicate aspect of laboratory experimentation concerns the effect of "environmental" conditions. Should over twenty tanks be built, the evaporation of the water contained in the tanks would greatly increase the relative humidity of the air inside the laboratory. How could we make a correct evaluation of rising water phenomena and assess the quality of rehabilitation without taking into account the overall effects of the water the wall absorbs directly from the air?
Two methods were proposed to solve this problem, the former more rigorous than the latter:

a) to air-condition the whole area (3,000 cu.m.);
b) to implement an "on-off" air-exhauster regulated according to the partial pressure of the vapour.

Both methods were rejected for economic reasons (considering the scheduled budget and the funds for the research). The author then proposed the following solution: to build two walls -identical as to building technology, material, thickness, etc.- and use then as follows. Both walls were to be immersed into water, but only one would undergo rehabilitation and tests to assess its water content, leaving the other "undisturbed" so as to make the relevant comparisons and evaluations. Practically speaking, both walls would show the same degree of alteration in the water content for the high humidity of the air due to the evaporation phenomena, but only a comparative analysis would be able to adequately appreciate the efficacy of the intervention and zero the water content results. Hence, the need to connect the tanks in pairs.

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*) Jurin's law, which correlates the physical phenomena occurring in rising dampness and estimates its maximum height, has great limitations.
Jurin's law (simplified for water)

$$H(mt) = \frac{15 \times 10^{-6} \cos\theta}{r\ (mt)}$$

$\cos\theta$ accounts for the priming conditions of water;
r (mt) is the average radius of the pores.
The application of this law demonstrates that for a brick wall (average radius of pores = 1 μm) in conditions of maximum wettability (completely immersed in water) the height dampness rises to -which should amount to 15 mt- is only about 2.5 mt in the most unfavourable cases and under particular conditions (buildings in Venice).

4. LABORATORY ACTIVITY.

The first two pairs of walls, both made of tufa (a calcareous rock used as building material) have already been erected. This building technique is still widely used in many regions of Southern Italy, despite the poor performance of the material.
In order to include other technologies in the research, however, we have thought of building brick walls, and as this is a dedicated investigation on "experimental and innovative rehabilitation technologies", we have thought of using bricks produced in an old kiln near Matera (Basilicata -Southern Italy). This kiln can reproduce a manufacturing process for baking ashlar very similar to the processes used in the past.
When adopting this working hypothesis, i.e. the laboratory reconstruction of old-fashioned masonry, the need obviously arises to face the problem in a comprehensive fashion and therefore reproduce "historical" mortars and plasters as well. An IRIS-CNR research programme has already started working on this.

TABLE 2. Physical parameters and resistance features of the tufa used for the first pair of walls.

specific weight	2,63 (gr/cm)
total specific weight	1,43 "
porosity	0,46
compressive strength	23,6 (Kg/cm)
imbibition coefficient	24 (%) as referred to weight
Wall geometry (in centimetres)	35 x 198 x 234

Stretcher wall

Masonry mortar (produced with the products and in the proportions indicated)
Law reference: Ministerial Decree: D.M. 20.1.87 "spurious mortar" type M3

Class compression	concrete	hydraulic lime	lime	compr.strength
M3	1	1	5	50 (kg/cmq.)

The dose of sand (equal to 5) was further divided as follows:
2.5 parts of "tufina"
2.5 parts of sand.
"Tufina" is the product of "calcarenite tufa" pulverization; it can be obtained during tufa processing or prepared on-the-spot during block grinding. Mortar mixed with "tufina" as an aggregate is widely used in the Apulian building industry.

Plaster.
The compositions and proportions indicated in building contract terms were used as a guideline for plastering the walls, although a few variables were introduced due to the use of "tufina".
Three different types of plaster were applied to each wall, in order to observe their effect on moisture phenomena, which may or may not be heightened by the use of different plasters. The main faces of the walls were divided into three parts, each separated from the other by a removable strip of wood (plaster was not

applied to the sides of the wall). A type of plaster containing 100% tufina was used on the first part, another containing 50% tufina was used on the second, whereas a type of tufina-free plaster was applied to the third.

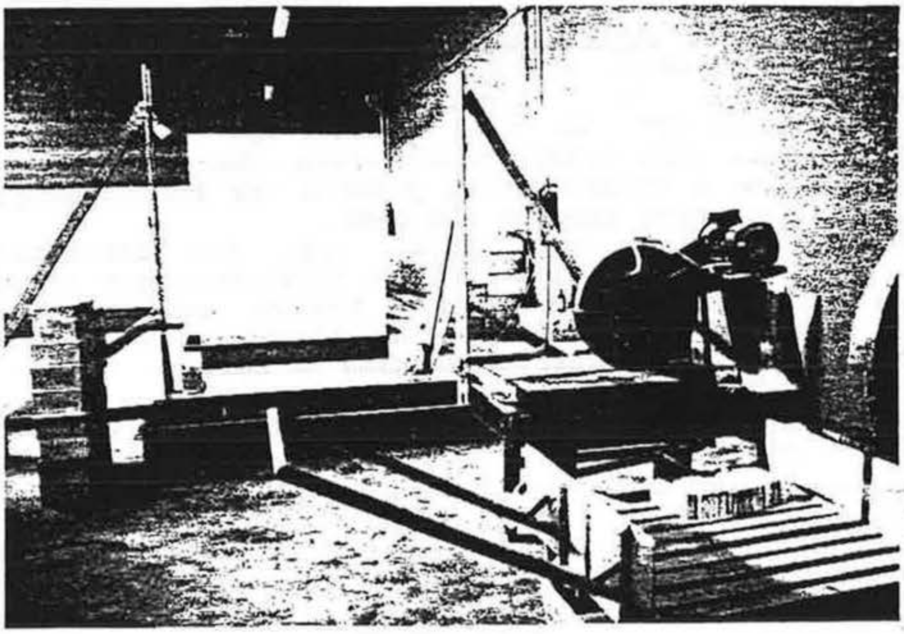

Figure 1. First pairs of walls made of calcareous tufa.

Second pair of tufa walls.
(all, blocks from the same quarry)

wall geometry	(in cm.)	55 x 196 x 248
"quarry bed" masonry		

(mortars for masonry and plasters were made in the same way).

"Quarry-bed" masonry - which differs from the previous walls for the way the ashlar is assembled (the biggest face being placed along the bearing surface) is typical of outer bearing walls. This building typology was used in order to verify the theoretical hypothesis that the rising water phenomena occurring in this type of masonry, owing to its more irregular "capillary routes", was different (less evident) from the phenomena occurring in stretcher walls. This is also what the lithogenesis of the rock itself seems to suggest. Indeed, calcarenite is a sedimentary rock formed by the overlapping of consecutive layers.
Pores are thus unlikely to line up with one another as in a "quarry-bed" stratigraphic section, contrarily to what happens in stretcher walls where capillaries might easily form along the "layers of sedimentation" of debris.

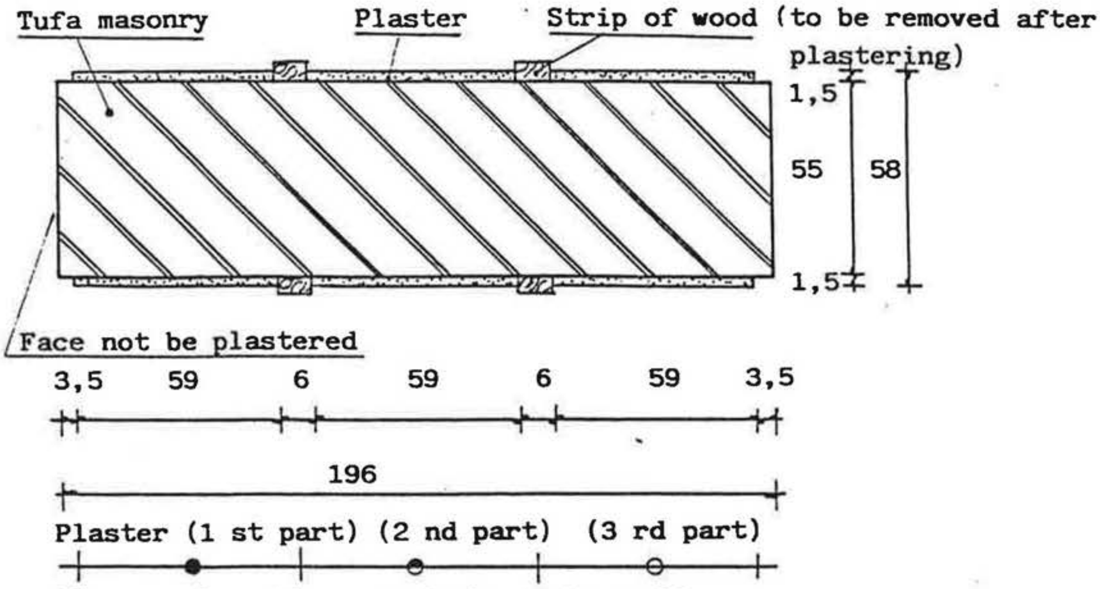

Figure 2. "Quarry-bed" tufa wall.

5. CONCLUSION.

After plastering the various parts following the above-mentioned methods, the tanks have recently been filled. Hopefully, we shall be able to report the first major results at the symposium.

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INNOVATIVE RETROFITS FOR FIGHTING MOULD IN RESIDENTIAL BUILDINGS

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INTRODUCTION

As a consequence of measures necessary for reducing the heating energy consumption in residential buildings, there have been more and more complaints in the last few years concerning the contamination of dwellings by mould, in particular in retrofitted old buildings. Mould growth is frequently the result of a marked reduction in the natural air change in old buildings caused by the installation of airtight windows and by unchanged user habits. In dwellings, an average quantity of humidity of 8 - 15 l/day is produced which is usually released through window joints. However, airthight windows and insufficient ventilation cause indoor air humidity to rise, something which may lead to surface humidity on cold external walls, e.g. at thermal bridges, thus providing ideal conditions for mould growth. The process can only be mitigated by increasing the surface temperature of the exposed areas, i.e. by improving the level of thermal insulation at the same time. Some examples of how to prevent or limit mould growth in housing will be presented below.

MEASURES FOR PREVENTING MOULD GROWTH

Paints

To prevent conditions favourable for growth, it is necessary to develop and utilise paints with alkaline pH values. Such paints are already on the market. However, their efficiency is limited. Since mould merely needs a layer of dust to germinate and grow, it is doubtful whether alkaline paint covered with dust will prevent their growth. Besides, it is not clear, whether the alkalinity, i.e. the inhibiting effect, does not vanish with time. In addition, the chemicals which alkalise the paint must not present any health hazards. These problems are particularly serious for fungicidal additives, which may lead to an increased level of chemical substances indoors. Chemicals represent a restricted possibility of fighting mould in residential buildings.

Electrical Strip Heating for Problem Areas

Due to missing or insufficient thermal insulation, low surface temperatures may result in critical relative humidities ranging above 80 %. Through heating these areas by way of electrical strip heating, surface temperatures may be increased such that the equilibrium relative humidity at the wall surface does not exceed critical values. However, heating also requires electric energy. To offset defects in the building structure by additional heating can only provide a temporary solution.

Ventilation

Missing or insufficient thermal and humidity insulation as well as insufficiently-insulated thermal bridges are related to the building construction. In comparison, the production and release of humidity are user-related. Surveys conducted in the Ruhr (FRG) [2], where modernized rental flats were examined, have shown that about one third of the damage is a result not of flaws in the building fabric, but of insufficient ventilation. If a building is constructed in accordance with the rules and regulations (thorough thermal and humidity insulation!), it is the difference between the quantity of humidity generated indoors and released that becomes the major cause for mould damage. As humidity is in general released through ventilation, a few ventilation methods for regulating the level of indoor air humidity will be discussed in the following.

The most common method is free ventilation by way of opening windows and through window joints. While the basic air change formerly took place through window joints, the installation of new, airtight windows now often results in mould contamination. To increase the air change by window ventilation is often insufficient as in many cases the windows are neither opened frequently nor long enough. Continuous ventilation results in increased heat losses during the heating period, and in cooled down window reveals (often with mould contamination of the reveal). To satisfy energetic and hygric requirements, a short period of intensive ventilation seems to be the best solution here. As the ventilation is actively influenced by the user - he assesses the air quality - this may nevertheless result in air change rates either being too high (energy losses!) or too low (risk of mould!). Several systems have been developed in order to adapt ventilation to requirements.

Free Ventilation Adapted to Actual Parameters

Based on the principle of free ventilation, a humidity-controlled ventilation unit has been developed at the Fraunhofer Institute of Building Physics (see Fig. 1).

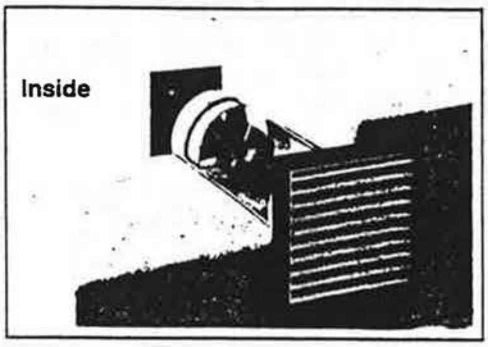

FIGURE 1. Automatic, humidity-controlled ventilation unit developed at the Fraunhofer Institute of Building Physics. It functions based on the principle of a hair hygrometer and reacts without electric energy. The air change is the result of pressure differences between indoor and outdoor air.

The unit is installed in the external wall of the building, thus providing a connection between indoor and outdoor air. Its sensor-regulated opening functions according to actual parameters (see Fig. 2).

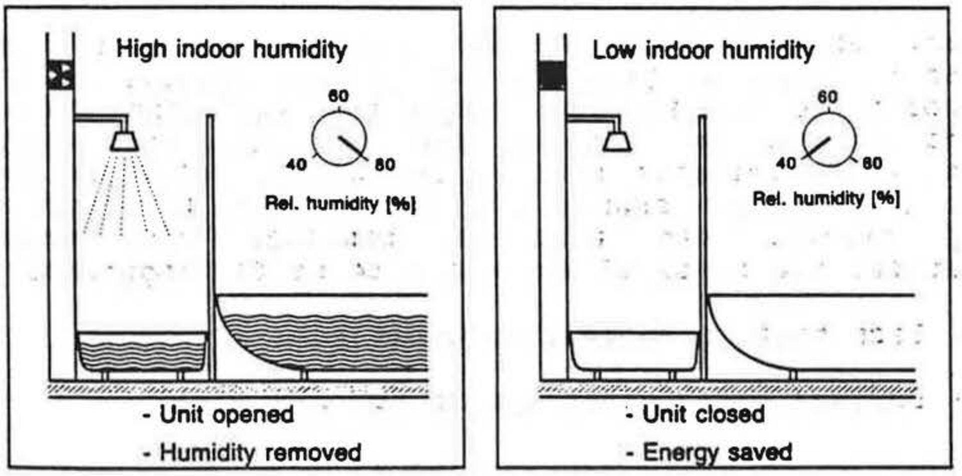

FIGURE 2. Principle of the ventilation unit: the unit automatically opens at high indoor air humidities and closes at low values.

At high indoor air humidities, the valve opens and an air infiltration starts, dependent on the difference of pressure between indoor and outdoor air (see Fig. 3). Several such units, which function dependent on wind pressure, are required to provide openings for supply and exhaust air. The unit is opened and closed by way of sensors working without auxiliary energy. The longitudinal dilatibility of adequate natural or chemical filaments due to the relative humidity of the surrounding air is used directly for adjusting the valve. For this reason, no auxiliary energy is necessary, and the unit works self-sufficiently for years. The air change is reduced by the unit when the indoor air humidity decreases below the critical value of relative humidity; at the same time, substantial ventilation heat losses are avoided, too.

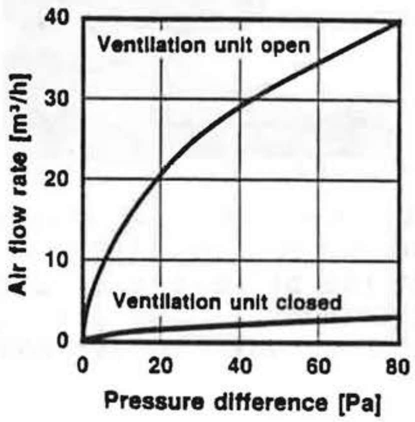

FIGURE 3. Air flow through the ventilation unit (above: open, below: closed), dependent on the pressure difference between the air of the room considered and the outdoor air.

Mechanic Ventilation Adapted to Actual Parameters

An exact determination of the air change rate can be achieved by means of mechanic ventilation systems which are independent of temperature conditions and wind pressure. Mechanic systems can also be combined with heat recovery systems, which transfer part of the energy contained in the exhaust air to the supply air via a heat exchanger. Air heating systems can also be combined with mechanic ventilation, two kinds of which are to be distinguished:

- Each room is ventilated individually
- Central ventilation system for all rooms

A switched-on mechanic ventilation results in a continuous air flow which, if it is sufficient, keeps the values of indoor air humidity in an uncritical range . If mechanic ventilation is not adapted to actual parameters, there will be unnecessary heat losses. By way of example, two such systems will be presented below.

Single room ventilators Single room ventilators are mostly installed in bathrooms and toilets. They are switched on together with e.g. the lighting system each time the room is being used. The ventilators frequently go on working for a certain time after the light has been switched off, in order to release a specified quantity of exhaust air and desorpt humidity. Hereby, it is not taken into account whether this is actually required for reasons of humidity production or hygiene. The device is provided with a ventilator powered by electricity.

<u>Central mechanic ventilation adapted to actual parameters</u>
Values of indoor air humidity are also kept in an uncritical range by way of humidity-controlled supply air and central mechanic exhaust air systems. In this context, a supply air valve is mounted between indoor and outdoor air, which automatically regulates the opening. A mechanic exhaust air system is mounted in the centre of the dwelling, permanently removing exhaust air with a suction pump. As the flow of supply air is controlled by the level of indoor air humidity, the supply air is in particular released from rooms where high values of humidity prevail. If all supply air valves are closed, the exhaust air suction pump is running against the joints of the windows and doors of the dwelling, thus leading to increased heat losses. It has to be mentioned that mechanic systems permanently consume electricity because of the suction pump.

CONCLUSION

In order to successfully fight moulds in housing, the interior of dwellings has to be such that the conditions for mould growth are eliminated. The first step at the occurrence of mould consists in investigating the building fabric to detect flaws in thermal and humidity insulation. If there are no such defects, it is often due to interior conditions that mould occurs. The most effective measure for improving the indoor climate consists in one of various ventilation systems based on free or mechanic ventilation. Mould prevention through paints is advisable only under certain conditions.

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FUNDAMENTAL STUDY ON THE INDOOR HUMIDITY REGULATION CHARACTERISTICS OF POROUS BUILDING MATERIALS

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ABSTRACT

The effects of the dynamic characteristics of porous building materials on the natural humidity regulation of an indoor space were investigated with a series of moisture transfer experiment and simulation. Putting plywood and calcium silicate board as test pieces in the box where controlled air specified temperature and humidity was delivered, the experiment was carried out. Plywood was found more efficient than calcium silicate board in their humidity regulation characteristics. The procedure for calculation based on the inhomogeneous diffusion simultaneous equations of heat and moisture transfer within the hygrocsopic region and thermal network method is used. A good agreement between measured and calculated values in the experiment was observed. A series of computer simulations were performed to identify the influence of moisture absorption and desorption on the hour-by-hour heating/cooling load. The results of simulations showed large discrepancies in latent load of space heating/cooling and humidity between in the cases of considering and neglecting moisture absorption and desorption.

INTRODUCTION

It is well known that moisture absorption and desorption in building surface materials are accompanied by latent heat load of a space and that porous building materials have natural humidity regulation characteristics. But present energy calculation and indoor environmental simulation programs are not capable of taking moisture absorption and desorption into account. By analogy, disregarding moisture absorption and desorption in the latent heating/cooling load is comparable to disregarding heat capacity of slabs and walls in sensible heating/cooling load. Therefore, the values of indoor latent heating/cooling load and humidity calculated by conventional method are considered different from actual values. The purpose of this study is to identify these differences between in the cases of considering and neglecting moisture absorption and desorption both in the building materials themselves and in the sensible and latent loads of space heating and cooling.

THERMAL AND MOISTURE CHARACTERISTICS OF TWO MATERIALS

To obtain the moisture characteristics of two materials a preliminary experiment in conformity to the method proposed by Nakao[1] was conducted. The thermal and moisture properties of two materials were summarized in Table 1. Moisture

Table 1. Thermal and moisture characteristics of two materials.

	calcium silicate board	plywood
thickness [mm]	10	12
emissivity [ND]	0.9	0.9
thermal conductivity [W/m°C]	0.10	0.17
specific heat [kJ/kg°C]	1.51	1.30
specific weight [kg/m³]	525	550
porosity [m³/m³]	0.79	0.80
moisture conductivity [kg/mh(kg/kg')]	0.053	0.039
κ [kg/m³ (kg/kg')]	422	910
ν [kg/m³°C]	0.53	1.38

conductivity of plywood is less than that of calcium silicate board, and κ and ν of plywood are greater than those of calcium silicate board, where κ is moisture absorption per unit volume of material for humidity ratio rise [kg/m^3(kg/kg)] and ν is moisture desorption per unit volume of material for temperature rise [kg/m^3°C] as proposed by Maeda and Matumoto(2) in heat and moisture simultaneous transfer equations. These indicate that plywood has more efficient humidity regulation characteristic than calcium silicate board.

As shown in Figure 1 and Figure 2, two boxes (experiment box and air conditioning box) made by polystylene were installed within the environmental test chamber at Waseda University, whose temperature and humidity could be precisely controlled. As a test piece, either calcium silicate board or plywood board was put on one of the inside walls of the experiment box. In the air conditioning box a heater of 800 W and a humidifier of 200 cc/h were installed, then heated and humidified air was supplied to the experiment box through a flexible duct from the air conditioning box. First, for 5 minutes the supply air from the air conditioning box to the experiment box was kept 25 °C, 50 %rh to be equal to the values of the environmental test chamber. After 5 minutes, step changed hot and humidified air was given to the experiment box so that heat and moisture transfer might occur at the surface of a test piece . Both a heater and humidifier were switched off after 305 minutes from the start of the experiment.

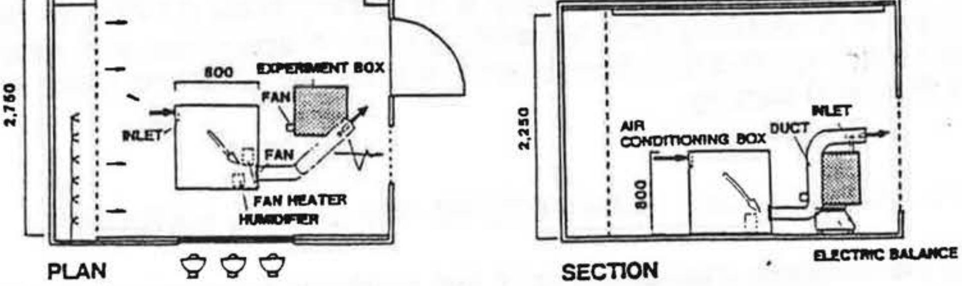

Figure 1. Locations of the experimental equipments in the environmental test chamber.

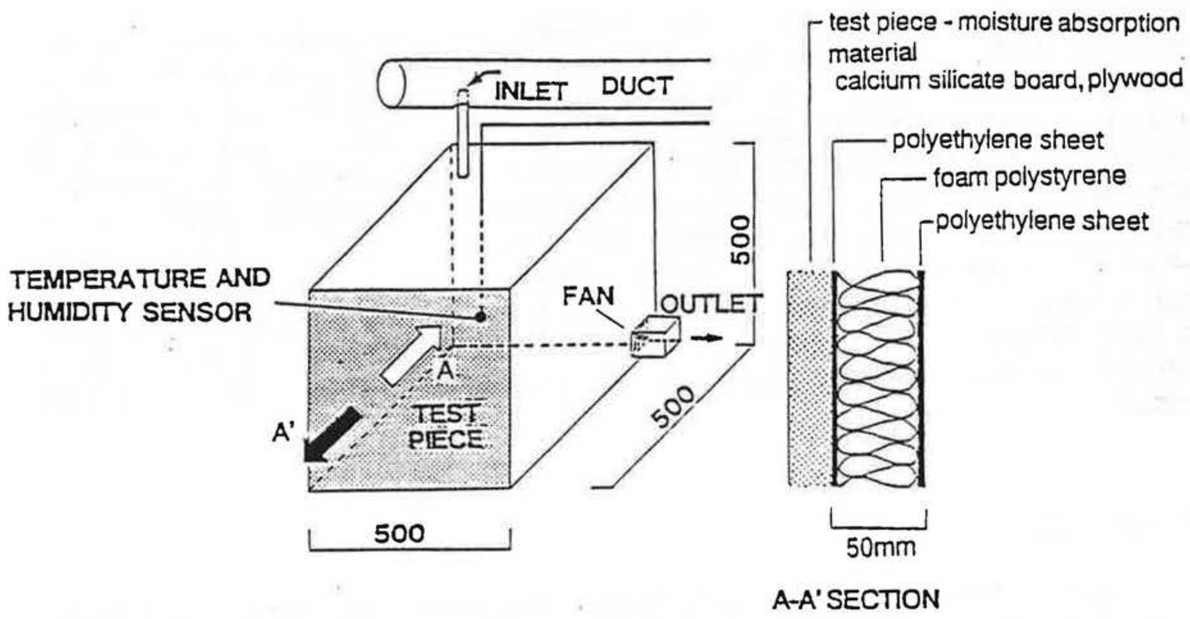

Figure 2. The experiment box.

Figure 3 and Figure 4 show the comparisons of the calculated and measured temperatures and humidity ratios in the cases of plywood and calcium silicate board as test pieces attached on the surfaces of the experiment box respectively. The calculation procedure of heat and moisture transfer within the materials developed by the authors, on the basis of simultaneous equations presented by Maeda and Matsumoto[2] and vector-matrix equation described by the thermal network method[3], was used to calculate temperature and humidity variations in

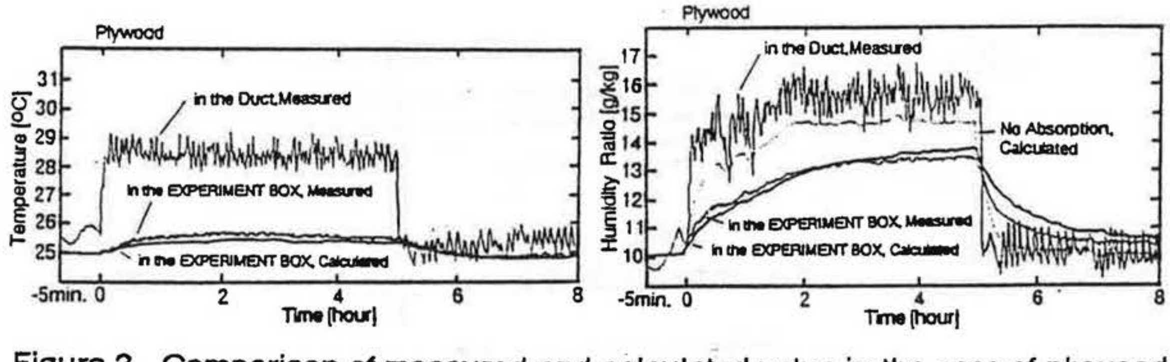

Figure 3. Comparison of measured and calculated value in the case of plywood.

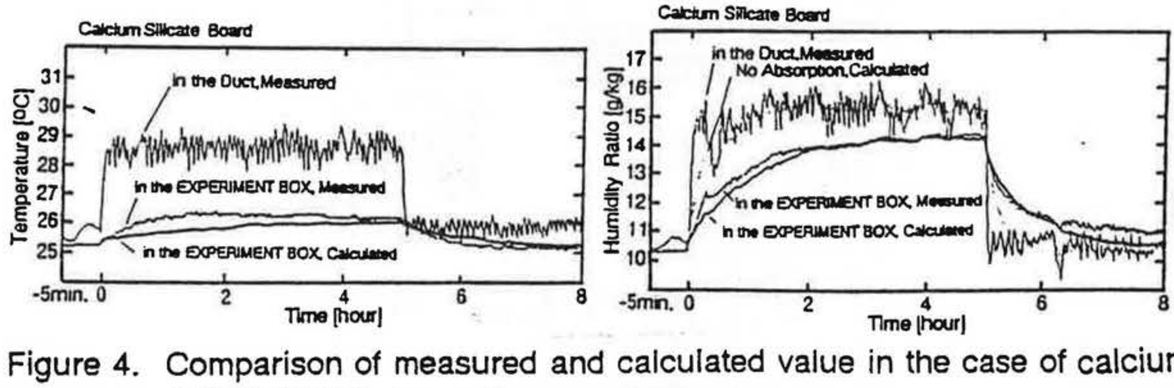

Figure 4. Comparison of measured and calculated value in the case of calcium silicate board.

the experiment box. The differences between the broken and solid lines of humidity ratios in the experiment box are considered equal to the amount of absorbed moisture within the test piece, corresponding to the natural humidity regulation characteristics. Comparing the results in Figure 3 and Figure 4, it seems that plywood is a little greater than calcium silicate board in absorbing and desorbing moisture. The calculated temperatures and humidity ratios in the experiment box are in good agreement with the measured values in both cases. Although there are some differences between measured and calculated humidity ratios in Figure 3 and Figure 4, they are regarded to be within the error of hygrometers, i.e. +3%. Based on the results of this experiment, it is possible to simulate indoor humidity using above mentioned method with a certain accuracy.

SIMULATION

To determine the influence of moisture absorption and desorption on the hour-by-hour heating/cooling load, a series of computer simulations were carried out. The object room for simulation is shown in Figure 5. It is assumed that the air conditioning system of the object room is operated from 8 a.m. to 7 p.m., air change rate of the room is 0.3 1/h, and pulling down or warming up periods are 1 hour. Heat generation from equipment of 2900 W and occupants of 0.013 person/m^2 during period from 9 a.m. to 6 p.m. were assumed. In this computer simulation, calcium silicate board of 1 cm thickness was used as a material to absorb and desorb moisture. Implicit type of finite difference method was used

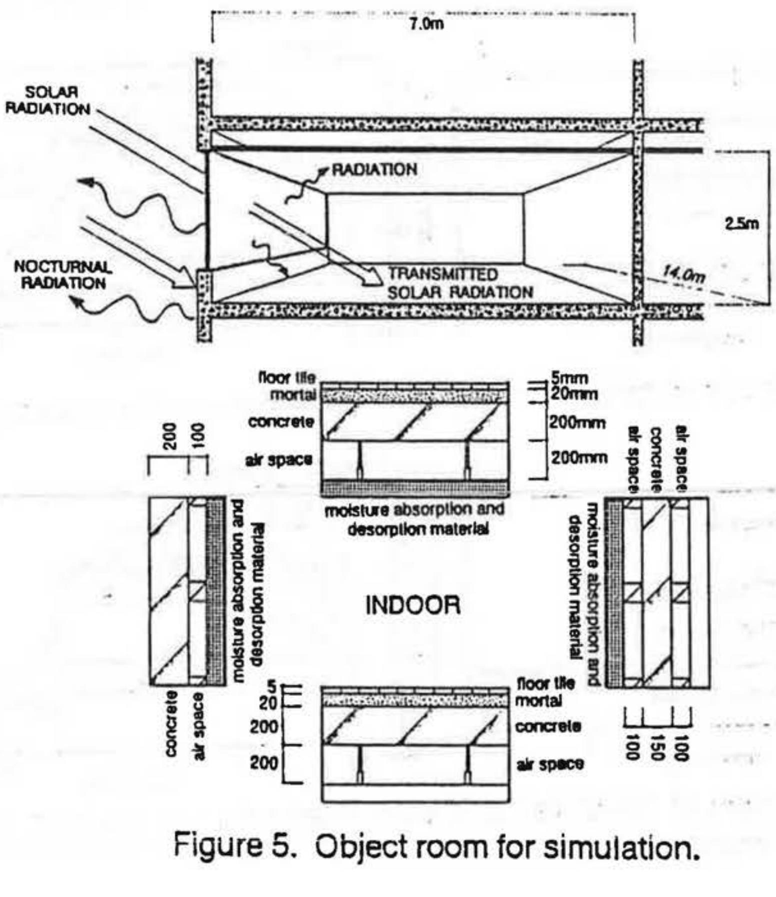

Figure 5. Object room for simulation.

as the time discretization in the calculation procedure. The time increment of 1 hour was used to be coincided with that of the available meteorological data.

Simulation results of January 30 and July 31 with Tokyo data are shown in Figure 6 and Figure 7. As can be observed from these results, the latent heating/cooling load in the case of considering moisture absorption and desorption is greater than in the case of neglecting them. This is due to the fact that in winter the amount of absorbed moisture within the walls must be supplied to the room and in summer released moisture from the walls must be removed from the room. The differences between the two cases of considering and neglecting moisture transfer are too significant to be disregarded.

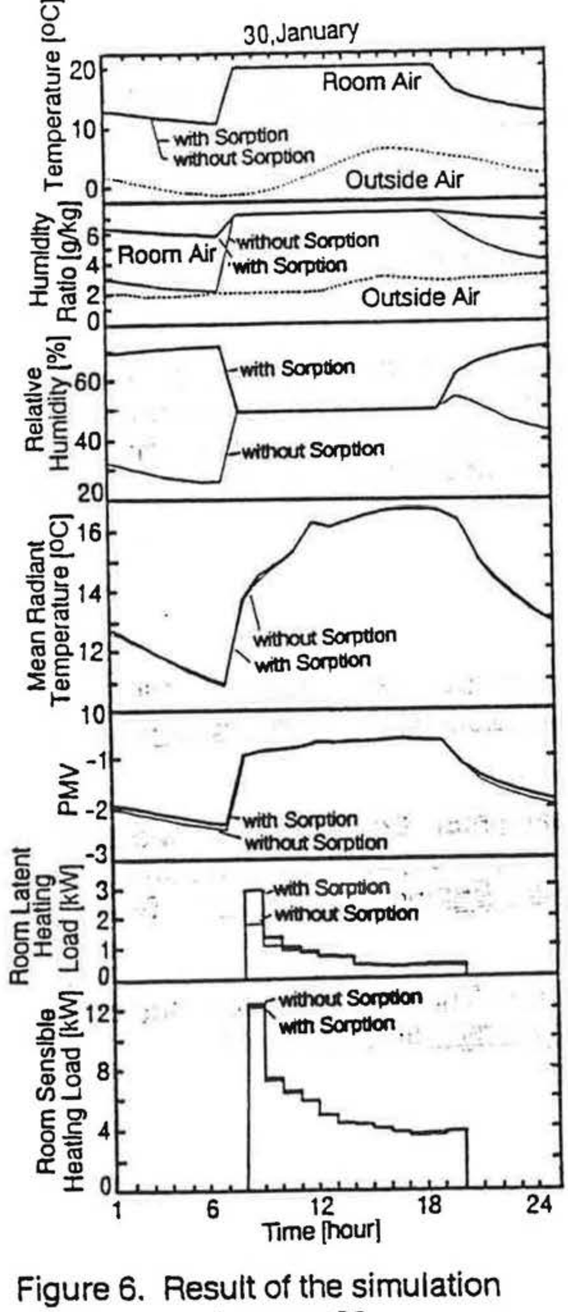

Figure 6. Result of the simulation on January 30.

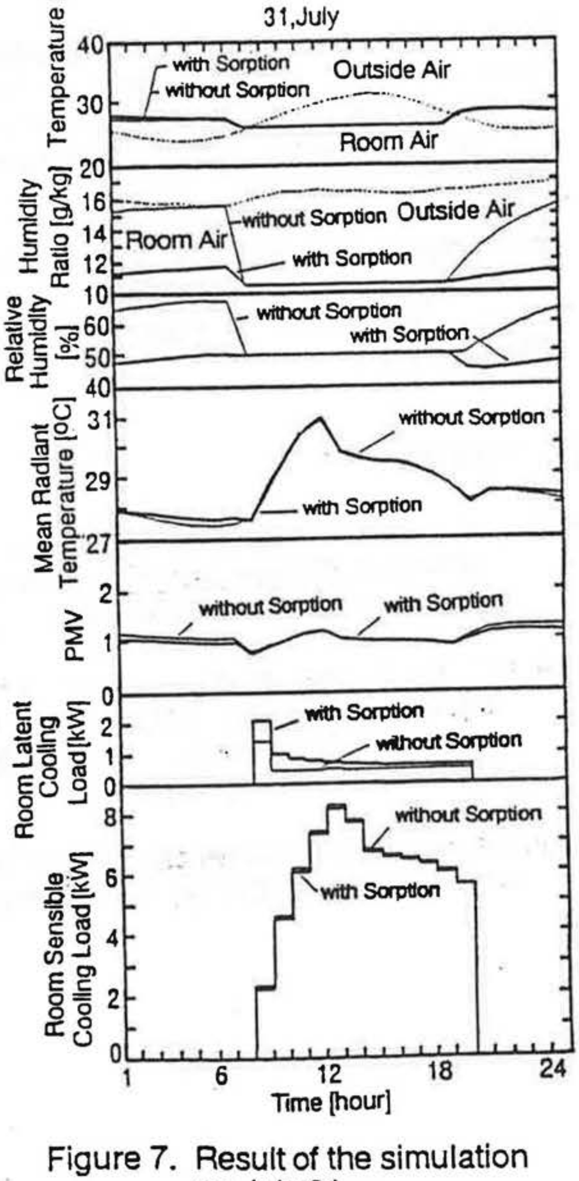

Figure 7. Result of the simulation on July 31.

In winter, when the moisture absorption occurs at the surface of the walls during heating period, the latent heat accompanied by vapor condensation makes the wall surface temperatures rise. Thus the mean radiant temperature rise brings sensible heating load to be slightly lower than in the case of neglecting moisture absorption, as shown in Figure 6. On the contrary, in summer, mean radiant temperature falls down because of removal of the latent heat accompanied by evaporation. Then sensible cooling load decreases as shown in Figure 7. However, the differences of sensible heating/cooling load between the two cases of considering and neglecting moisture absorption and desorption are much less than those of latent heating/cooling load.

CONCLUSIONS

1. Results of the experiment showed that the humidity regulation characteristics of plywood was found more efficient than calcium silicate board.

2. Temperature and humidity measured in the experiment agreed well with those calculated by the procedure of heat and moisture transfer developed by the authors based on the fundamental equations of Maeda and Mstsumoto and thermal network method of Okuyama.

3. The results of computer simulation indicated a dramatic difference on the latent heating/cooling load between in the two cases of considering and neglecting moisture absorption and desorption. Consequently, moisture transfer cannot be disregarded in indoor environmental simulation and energy analysis.

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COUNTER-MEASURES AND BETTER SOLUTIONS AGAINST MOISTURE AND MILDEW IN GROUND CONSTRUCTIONS

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ABSTRACT

During the last 10-20 years, many Swedish buildings have suffered from various forms of moisture damages. The underlying causes have varied widely, and corrective measures have been expensive in many cases. This has resulted in the development of alternative, cheaper methods of treatment. There has, however, been no comprehensive feedback of experience of the results of different methods.

We have evaluated some of the methods used today. Out of thirteen methods investigated, four can be regarded as successful, by eliminating moisture and mildew problems. The other projects have more or less failed depending on:
- not knowing the real reason of the damage;
- unsuitable method of treatment ;
- not knowing details about the design and/or the materials used.

In order to avoid moisture problems in new built houses, other safer constructions are developed. One method using ventilation under the base slab was evaluated. The result was very succssful.

SOME GENERAL NOTES ON MOISTURE IN BUILDINGS

If only the humidity of the surrounding air needs to be considered, present-day methods of theoretical design and analysis allow the moisture states likely to be encountered in a building to be estimated relatively accurately. From the known physical characteristics of the materials, and from the thermal and moisture conditions in the air, the moisture contents of the parts of the structure can be calculated.

Problems arise when moisture reaches the structure in the form of driving rain, water leaks, rising damp from the ground, residual building moisture or condensation, subjecting structures to higher moisture loadings than they were designed to withstand.

FORMS OF MOISTURE DAMAGES

The forms of damage that can be caused to damp foundation structures can be roughly divided into the following categories:

Mildew and Rot

The following conditions must be fulfilled if mildew is to be able to grow:

- spores must be present
- suitable organic material (e.g. wood or wood-based materials) must be available
- oxygen must be available
- the temperature must be above 0 °C
- relative humidity must exceed about 70 %, equivalent to a moisture ratio of about 17 % in wood.

The same conditions as above must be fulfilled if rot is to occur in wood, except that the relative humidity must be 100 % (=moisture ratio of 28 % or above).

Mildew occurs on external surfaces, such as painted wooden panels, on internal surfaces, and in the structure of the material itself. It is particularly the last one that gives rise to an unpleasant smell.

The presence of mildew causes primarily an odour problem, and possibly also health problems. At higher moisture levels, rot presents a threat to the structural integrity of wood-based materials. It has not been possible to prove any connection between the smell of mildew and an increased spore number in indoor air. However, intensive work is in progress to attempt to find relationships between the growth of mildew and the presence of an unpleasant odour.

Mildew in parts of buildings often gives rise to odour problems:

- in joisted floors resting directly on a concrete floor slab;
- from sill plates of internal and external walls;
- on wooden studding in internally insulated basement walls.

Self-levelling Flooring Compounds

An unpleasant smell can occur in buildings having floor structures finished with self-levelling floor compound. This applies to certain caseine-containing compounds that, in Sweden, were used between 1977 and 1983. When the relative humidity of the air in the structure exceeds about 75-85 %, a chemical process occurs that can result in the emission of ammonia. Besides an unpleasant smell, this can also affect surrounding materials, e.g. by discoloration of oak parquet or cork floors, smell from PVC floor coverings and saponification of adhesives.

PVS Floor Coverings

Excessive moisture content in concrete slabs covered by PVC flooring can give rise to an unpleasant smell from emitted octanoles. This may occur if the relative humidity of the concrete exceeds 95 %. The smell, which is sweet and acidic, is caused by disintegration of the plasticiser in the PVC sheet.

Where a caseine-containing self-levelling compound, which can emit ammonia, has been used under the PVC sheet, relative humidities of about 75-85 % are enough for the process to start. At high relative humidity levels, considerable displacements can occur in the floor covering: loss of the plasticiser means that it also becomes brittle.

Floor Adhesives

It is not uncommon for adhesives to saponify if used under plastic floor coverings on concrete and if the moisture content is high. Older solvent-based adhesives resisted higher moisture loadings (sometimes up to 100 % RH), while present-day water-based adhesives can saponify at relative humidities of 85-95 %.

Formaldehyde

Problems with formaldehyde emission from chipboard materials occurred during the 1960s and 1970s, due to an excessive phenol content in the adhesive at that time. Formaldehyde emission is accelerated by increased moisture contents. In high concentrations, formaldehyde has an unpleasant pungent smell.

CAUSES OF DAMAGE

The counter-measures used in buildings suffering from moisture damages are not always successful. One of the reasons may simply be that the cause of the damage has not been determined, or that one does not know how the proposed counter-measure is intended to work.

When dealing with existing buildings, it may be necessary to modify parts of the strucutre that cannot be entirely replaced. It is therefore important to know how new designed structures or elements work. A given counter-measure is seldom applicable to all types of damages.

COUNTER-MEASURES

The effects of the following counter-measue principles have been followed up:

1. Drainage/deep drainage.
2. Drying out floor joist structures with electric osmosis.
3. Impregnation of concrete surfaces of cast-on-ground floor slabs.
4. Supply and exhaust air ventilation under floor slabs.
5. Negative pressure ventilation under floor slabs.
6. Positive pressure ventilation under floor slabs.
7. Maintenance of negative pressure under suspended floors.
8. Negative pressure ventilation under suspended floors.
9. Maintenance of negative pressure in under-floor crawl spaces.
10. Maintenance of negative pressure behind stud walls against basement ground walls.
11. Injection of lower part of basement walls.
12. Drying out of sill plates with electric heating cables.
13. Negative pressure ventilation of exterior wall sill zones.

RESULTS

Table 1 gives a general summary of the results from the various methods of counter-measures.

TABLE 1. Results from the Various Methods of Counter-measure

No	Method Description	Problem	Our assessment	Result
1.	Drainage Deep drainage	Moisture in floor joists, odour	–	1
2.	Drying-out floor joists by electric osmosis	Moisture in floor joists, odour	–	1
3.	Impregnation of concrete surfaces of cast floor slabs	Moisture in floor joists, loosening of floor covering, odour	(+)	1
4.	Supply and exhaust ventilation under the floor slabs	Moisture in floor joists, loosening of floor covering	(+)	4–5
5.	Negative pressure ventilation under floor slabs	Moisture in floor joists, odour	(+)	1
6.	Positive pressure ventilation under floor slabs	Moisture in floor joists, odour	(+)	2–4
7.	Maintenance of negative pressure under suspended floors	Moisture in floor joists, odour	(+)	3–4
8.	Negative pressure ventilation under suspended floors	Moisture in floor joists, odour	(+)	4–5
9.	Maintenance of negative pressure in the under-floor crawl space	Odour in the crawl space	(+)	1–4
10.	Maintenance of negative pressure behind stud walls against basement ground walls	Odour from outer basement walls	(+)	4–5
11.	Injection of lower part of basement walls	Capillary attraction of moisture from below to basement walls	(+)	1
12.	Drying out of sill plates with electric heating cables	Moisture in sill plates, odour	(+)	2–4
13.	Negative pressure ventilation of exterior wall sill zones	Moisture in sill plates, odour	(+)	4–5

Our assessment of the efficacy of the method relates to its relevance to the problem to be dealt with:

+ = relevant method
- = not relevant mehtod
( ) = possible reservations

The results are evaluated on a scale from 1-5 as follows:

1. No measurable result - problems remain

2. Measurable change, although not sufficient - problems remain.

3. Measurable change - problems have been lessened, but not sufficiently.

4. Measurable change of expected extent - problems almost cured.

5. Measurable change of expected extent - problems completely cured.

A SAFER GROUND CONSTRUCTION REGARDING MOISTURE AND MOULD

Most damages in ground constructions are caused by high moisture content. By creating a dry construction with a minimum period of residual building moisture the risk for problems is almost eliminated.

The structure shown in figure 1 consists of a ventilated base slab with underlying heat insulation. The slab is ventilated with exhaust air from the dwelling (except from kitchen and lavatories).

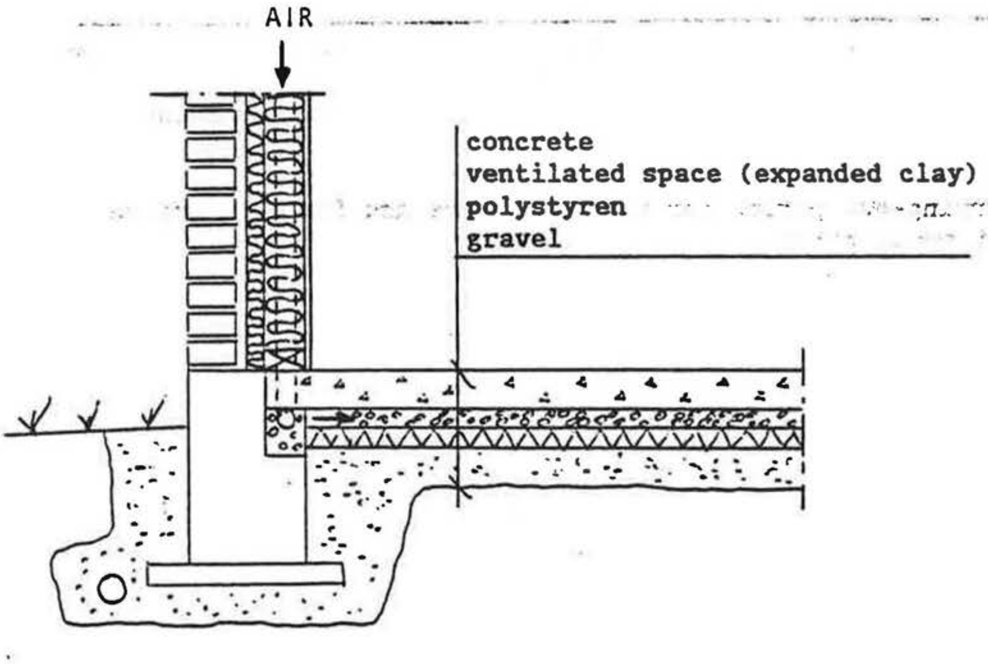

FIGURE 1. The principle of a ventilated base slab with underlying heat insulation.

In figure 2 the drying-out period is shown for the test house and for a reference house without ventilation.

Conclusion:

- The residual moisture in the slab dries out during much shorter time than in the reference house.
- The slab is a little warmer than the slab in the reference house depending on the ventilation.
- The method eliminates the main risks for moisture damages in a conventional structure.

By using experiences from damages and different counter-measures in existing houses much better and safer solutions can be created for new houses, as the last exemple shows.

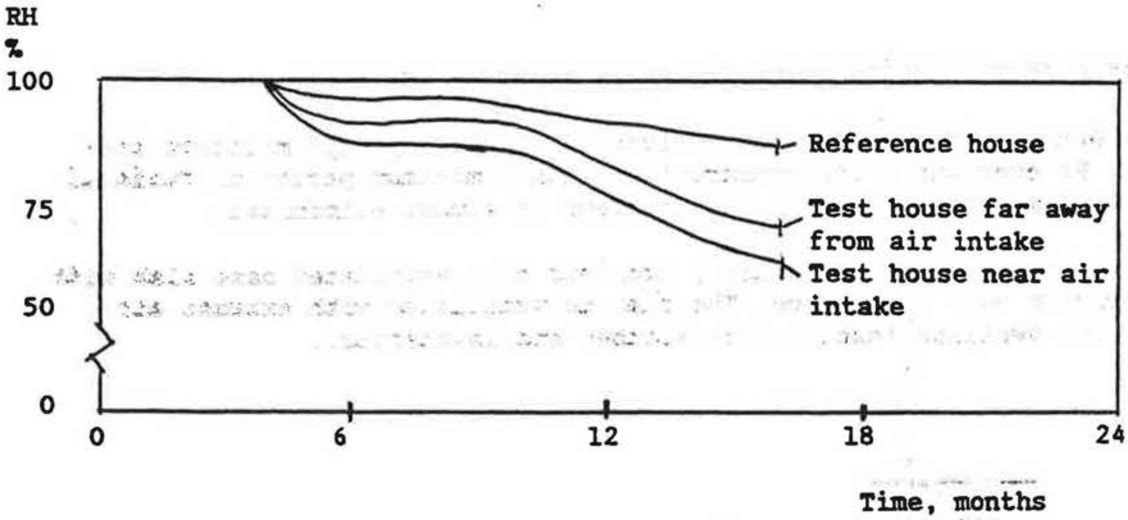

FIGURE 2. Drying-out period for the test house and for a reference house without ventilation.

A FIELD STUDY OF EXCESS MOISTURE IN THE WALLS OF NEW NORTHWEST USA HOMES

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ABSTRACT

The exterior walls of 86 new houses in the Pacific Northwest of the USA were cut open to determine if building them with more insulation (at least R-3.3) and an air-vapor retarder causes unacceptably high levels of moisture or moisture damage within walls. Measurements of the moisture content of wood within the wall cavities were first made between January and March 1987. Over half of the test homes had at least one wall wood member with over 20% moisture content. The 28 homes with the wettest walls were reopened during July and August 1988 to check for drying. Some of the homes still had elevated wall moisture levels. The 16 homes with the highest summer moisture contents were reopened during March 1989. Elevated moisture contents were again measured. Some specific causes of the elevated wall moisture levels were discovered. While no wood decay was observed, the study was not able to determine whether sufficient wall drying would occur to avoid long-term structural damage.

PROJECT DESCRIPTION AND PURPOSE

Background

Concern about moisture damage in conventional 2x4 walls retrofitted with insulation without a vapor retarder led to two separate field studies to measure the moisture levels within such walls (1,2). Approximately 100 houses were examined in each of Portland, Oregon and Spokane, Washington during the winter months when moisture accumulation was expected to be greatest. In neither study was wall moisture concluded to pose a problem to the structural integrity of the houses. It was assumed that comparably insulated walls with a vapor retarder would be even more immune to moisture problems.

To promote energy conservation in new houses in the Pacific Northwest, the Model Conservation Standards (MCS) were developed as an energy-efficient building code. Electrically-heated houses built to the MCS are required to have walls insulated to at least R-3.3 and have a vapor retarder. Although the studies previously mentioned (1,2) implied the MCS houses might not experience wall moisture problems, some researchers and builders expressed concern that the results of those studies should not be extrapolated to the more heavily-insulated MCS walls. Thus a field study to determine the potential for wall moisture problems due to these construction techniques was undertaken. Additional details of this study are described in a report to the sponsor (3) and two papers (4,5).

Project Objectives

The purpose of this project was to cut open actual MCS walls and measure the in-situ moisture inside them under the worst expected conditions and inspect for moisture damage. Such measurements would determine whether building the exterior walls of new homes to Model Conservation Standards causes unacceptably high levels of moisture or related problems within the walls.

Test Homes and Study Locations

The houses eligible for inclusion in this study were those built to the MCS. The age of the homes during the winter of 1987 openings ranged from a few months to a few years old. Tests were to be concentrated in two regions of the Pacific Northwest that experience climatic extremes to ensure that there would be the best chance of finding moisture damage, if it exists. In addition, a region with a major population concentration was included. Houses were selected in the following regions:

1. Coastal Region (16 homes). This region is characterized by relatively mild winters with very high relative humidity, accompanied by frequent wind-driven rains. The summers tend to be temperate with continuing high relative humidity, reducing the potential to dry moist wood. Central western Washington had the only concentration of MCS homes large enough to obtain the required number of coastal homes.
2. Cold Region (20 homes). The mountains and interior basins of the Northwest experience extremely cold winters. This climate condition leads to much greater condensation potential, even though the warm dry summers may cause substantial redrying. Homes in several Montana cities were solicited.
3. Metro Region (50 homes). Most people in the Northwest live in regions that are generally mild and humid in the fall, winter and spring, with high annual rainfall. Since most of the new houses are built in these regions, and because the potential for moisture accumulation exists, a population center was studied. The test sample was selected from MCS homes in the Seattle-Olympia area.

Study Work Plan and Schedule

The study was conducted in three sequential phases. The first part of the first phase involved identifying the pool of eligible MCS houses during the fall of 1986. In each region an attempt was made to obtain a mix of vapor retarder types, including polyethylene (poly), interior foam, airtight drywall, and no vapor retarder as a control. Furthermore, it was planned to open as many as possible of those homes whose occupants had reported moisture problems such as window condensation or mold and mildew. The houses were then screened to select the specific houses to be included in the test sample. An effort was made to select worst case MCS houses from a moisture point of view.

The second part of the first phase of the study was undertaken during the winter of 1987. It included an interview with an occupant of each proposed test house to determine pertinent lifestyle characteristics, a detailed inspection of each house, including assessment of indoor moisture problems, and location of the wall opening sites. Shortly thereafter, the selected homes were revisited, the walls were cut open in three locations, and the moisture contents of selected wood members in the wall cavities were measured using a temperature-compensating electric resistance moisture meter. After completing the field tests, the moisture content results were compiled, analyzed, and correlated to local climate and a variety of house and occupant characteristics.

Because very elevated moisture contents of wall wood members were measured in a majority of the homes during the winter 1987 wall openings, the 28 homes with very wet walls were selected to be reopened during the summer of 1988. The purpose of this second phase was to see if the same previously wet walls had dried out sufficiently to prevent wood decay. Because some of the walls were still wet during summer weather, the third phase took place during the winter of 1989 and involved reopening the same walls of the 16 worst case homes that were still too wet. The subsequent period was used to perform statistical analysis of the data.

MAJOR FINDINGS AND CONCLUSIONS

Excess Moisture in Walls

Unacceptably high moisture levels were measured during the 1987 winter in the walls of a large percentage of the test homes. The criterion for unacceptably high levels was chosen to be any wood moisture content greater than 20% because any time wood members are over 20% moisture content the wood is considered wet and there is a possibility of wood decay occurring, although decay only occurs during warmer weather (6). Actual decay does not start until about 30% moisture content (6), but when 20% is measured other parts of the structure may be wetter. Hence when moisture levels are greater than 30% the wood is considered very wet and there is major cause for concern.

The overall mean moisture content of all 1244 temperature-compensated readings was 16.2%. The means for the sheathing, sill (mud) plates, and subflooring were significantly higher, with the mean moisture content of 21.2% for the sill plates being the highest. Moreover, the maximum values measured for those three wood members were all over 50%. About one-fifth of all the measured readings were equal to or above 20%. Almost half of the readings in the coastal region were equal to or greater than 20%.

The number of test homes with high moisture contents is shown in Table 1. Over half the test homes had at least one wall member with a moisture content over 20%. All but one of the coastal homes had a moisture content of 20% or greater in at least one wall wood member. Over 16% of the homes had one wall member with a moisture content greater than 30%.

On average the highest readings occurred in sheathing (SH) and sill (mud) plates (MP). More than one-third of all the sheathing measured had moisture contents over 20%, while more than one-half of all the sill plates were over 20%. The highest moisture content measured was approximately 55%. There were significant differences between regions, with the homes in the mild and humid Washington coastal area being the wettest and those in the cold Montana region being the driest. However, the cold region homes were often still very wet.

Table 1
Number of Homes With Any One Wood Member With High Moisture Content

Region	No. Test Homes	Moisture Content Range (%) ≥20	≥30	≥40
Coastal	16	15	3	1
Metro	50	29	8	5
Cold	20	8	3	2
All	86	52	14	8

The 28 homes with the wettest walls were reopened during the 1988 summer to see if the walls dried out enough to avoid wood decay. The wall cavity wood members of the cold region homes had thoroughly dried out, as shown in Table 2. Thus there is no reasonable likelihood of wood decay, except in the case of leaks. On the other hand, many of the walls in the coastal and metro (Seattle-Olympia) homes had not dried sufficiently to rule out the possibility of wood decay and subsequent structural damage occurring in the future. How long it takes for wood decay to develop is unknown, although many of the walls are wet enough to decay during warm weather. While there were no cases of wood decay observed in any of the wall cavities during any part of this study, sometimes it takes many years for decay to develop and be noticed, as for example in the Tri-States Homes case (7). In those homes severe structural damage occurred due to wood decay, but the homes were about a decade old before the damage was discovered. Incidently, in this study there were no cases of condensed moisture or liquid water accumulation observed within any of the insulated wall cavities.

Table 2
Summer Wall Moisture Content Results

Region	No. Homes	≥20% MC Readings	Max Moisture Content(%) SH	MP	Other
Cold	0/2	0	7.5	----	7.5
Metro	3/14	5	17.0	25.0	16.5
Coastal	6/12	10	23.0	20.0	29.0

The walls of the 16 coastal and metro test homes that were still wet during the summer were again reopened during the 1989 winter. While the walls were generally drier, they were still wet enough to be of concern. The drying that occurred between the 1987 and 1989 winters appears to be the result of a record-setting two-three week period of abnormally cold, dry, and windy weather just before the 1989 wall openings. Thus the question of whether the high moisture contents will lead to wood decay and subsequent structural damage is still unresolved. The walls of a few of the worst test homes should be regularly opened and checked for a few years to see if they are in fact slowly drying or if any decay occurs.

Statistical data analysis Statistical analysis of the field data was undertaken to try to find out what caused the high wall moisture contents. Wet walls were strongly associated with high indoor relative humidities. The wettest walls and highest indoor relative humidities were in the humid coastal region. Many homes had indoor relative humidities that were clearly too high. Thus one of the major factors contributing to high wall moisture levels was the lack of indoor moisture control. Reducing indoor relative humidities with improved moisture control systems that are presently available but seldom used should reduce wall moisture levels. One of the main conclusions of this study is that better indoor moisture control is a major programmatic need in MCS housing and probably in most new housing.

Most of the wettest walls were in homes with T1-11 plywood panel siding and shingle siding. These siding types are especially prone to what is called "splashback" because their lower edges and back sides are often not satisfactorily painted or sealed. They readily absorb rain water or melted snow that splashes up from the ground, and that moisture is transmitted into the wall cavity wood members. Walls with insufficient clearance between the bottom of the siding and the ground were especially prone to splashback. Walls also were significantly wetter if they did not have an exterior air or moisture barrier behind the siding, such as Tyvek or building paper. These findings point out that while moisture is generally believed to enter wall cavities from the inside, significant amounts of moisture leading to elevated wall moisture levels also can enter from the outside. Thus control of exterior moisture may be at least as important as interior moisture.

To avoid high wall cavity moisture levels when T1-11 and shingle siding materials are used, the lower edges need to be protected, the ground-to-siding clearances need to be maintained above some minimum level, such as about one half meter, and an exterior moisture barrier needs to be installed. Adding exterior insulating sheathing also would be wise.

In addition, high sheathing moisture contents often were found at sites where moist indoor air leaked through the wall cavity, such as through electrical outlets and a variety of penetrations in the poly air-vapor retarder, indicating the need for better sealing on the inside of the wall. The high sill plate moisture levels were likely caused in part by moisture from the wet ground wicking up by capillary action through the crawl space or basement concrete foundation walls into the adjacent sill plates and in part by the effects of splashback wetting.

It also was found that building walls with more cavity insulation leads to increased moisture levels in them. Fortunately that adverse finding is balanced by the positive finding that walls with exterior insulating sheathing are significantly drier than walls without it. Almost none of the wettest walls had such sheathing, and half of the driest had it. These walls are drier because the insulating sheathing keeps the wall cavity wood warmer and also because the sheathing is an excellent exterior moisture barrier that keeps wet siding from transmitting moisture into the wall cavity better than other moisture barriers.

While the walls of homes with a poly air-vapor retarder were slightly drier than those without or with poly only on the walls and not on the ceiling, the differences were not statistically significant. However, there were almost no homes with wet or very wet walls that had both a poly air-vapor retarder and external insulating sheathing. Furthermore, the airtightness of the home was not signicant.

Statistical analysis was undertaken to see if the high wall moisture values were caused by using wet construction materials in the relatively airtight walls that are slow to dry out. There were no indications that this was a factor. However, the initial material wetness may still be an important factor. Continuous field monitoring of wall moisture levels is needed to find out.

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MEASUREMENT OF LOCAL VAPOR TRANSFER FROM THE VERTICAL WETTED SURFACE

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ABSTRACT

The experimental design for measuring the rate of water vapor transfer from the surface of a vertical wetted model is described. The original wall model, 1.8m high and 1m wide, consists of sixteen wetted surfaces and is set up in climate chamber. In result, the vertical distributions of local vapor transfer coefficients in natural convection are obtained. The distributions are characterized by surface air flows which is induced by the combined force of thermal and humid buoyancy.
Furthermore, the experimental values agree with computed values by the Navier-Stokes equations in natural convection.

1. INTRODUCTION

The problems of water vapor transfer for air-conditioning or equipments, in general, can be analyzed by the Lewis relation (ref.1) which has developed the relation between heat and mass transfer. For the surface condensation problems in buildings, however, there is no experimental study to measure directly the rate of water vapor transfer from a actual wetted building wall or a surface with condensation to its atmosphere.

The purpose of this study is to obtain experimentally local vapor transfer coefficients and their vertical distribution from the surface of a wetted wall model with actual size under the steady-state condition and to compare with the experimental data and numerical solution by the Navier-Stokes equations for the wall model.

2. THE EXPERIMENTAL SYSTEM AND METHOD

Figure 1 shows the front, the side view and the cross sectional detail of the original experimental model. The vertical surface model, approximately 1.8m in height and 1m in width, consists of sixteen pieces of oblong aluminum plate with a reservoir below. Each plate is covered with a sheet of filter paper as wick, which bottom edge hangs down in the reservoir. Pure water continuously flows up the filter paper by capillary action and saturates the paper completely. Temperature of the plate surfaces can be controlled by heaters on the back of the plates.

A thermo-couple is set between the paper and the center of each plate. The experimental cases and their conditions of the surface temperature are listed in **TABLE 1.**

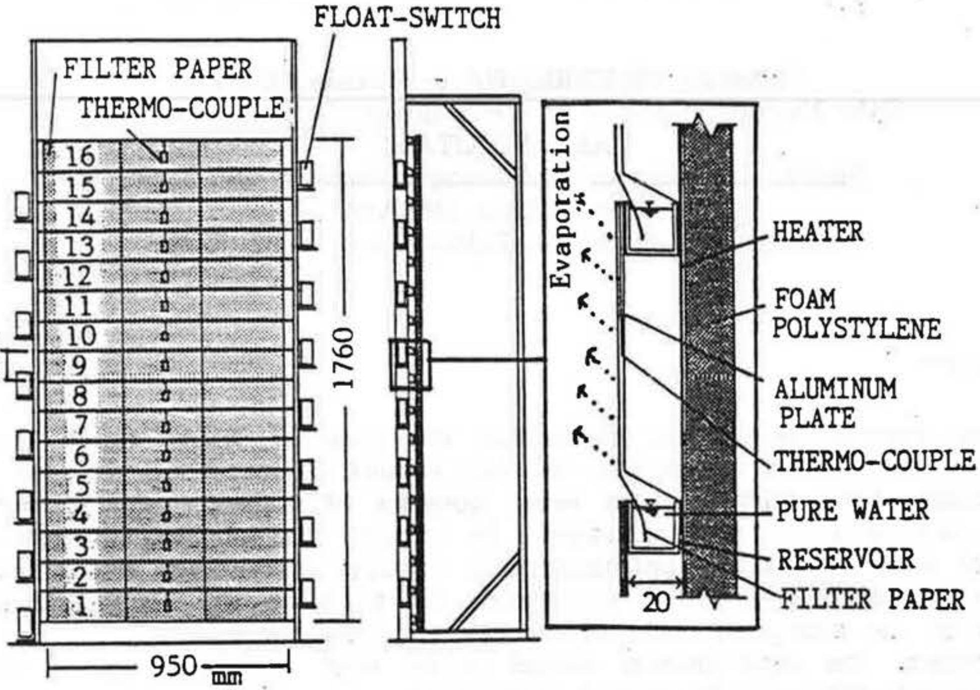

FIGURE 1 The Vertical Wetted Surface Model

TABLE 1 Experimental Conditions

	surface's temp.(Ts)		air temp.(Ta)	RH	air velocity
CASE 1	Ts=Ta	20 °C			
CASE 2	Ts=Ta-5	15	20 °C	35%rh	<0.1m/s
CASE 3	Ts=Ta+5	25	const.	const.	const.
CASE 4	Ts=Ta+10	30			

As shown in **Figure 2**, water level in each reservoir is kept just under full by means of the original float-switch, a magnetic valve and an electric relay. Under this system the rate of water evaporation from the filter paper at each plate equals the decrease in weight of each measuring cylinder which supplies water to the reservoir.

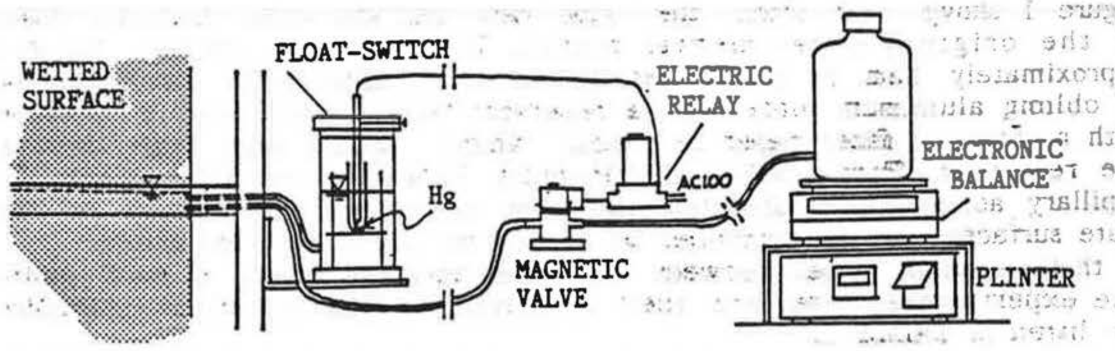

FIGURE 2 Water Supplying and Controlling System

In order to neglect the radiation exchange between the wetted surface and surrounding surfaces and to avoid the effect of free convection in the climate chamber, the guard box is prepared as illustrated in **Figure 3.**
Under the steady-state condition in the climate chamber, temperatures of sixteen plate surfaces, an ambient air and a relative humidity at the center of the guard box are recorded once every 30 minutes by a digital data-recorder. Three electronic balances and printers indicate the weights of three measuring cylinders, No.1, No.9, No.16, once every 60 minutes. For another cylinders, the heights of water level are measured accurately with a ruler and are recorded.

For the design of a wetted surface model, it is assumed that evaporation from the surface is unaffected by thermal radiation and by heat conduction within the wall model. The rate of evaporation from each wetted area in the steady-state condition can be represented by following simple equation.

$$W = h_m(Fs - Fa)A \qquad \text{Eq.(1)}$$

where
W = the rate of water evaporation (kg/h)
h_m = local vapor transfer coefficient (kg/m^{2}hmmHg)
Fs = saturated vapor pressure at each wetted surface temperature (mmHg)
Fa = vapor pressure of ambient air (mmHg)
A = area of a wetted surface (m^2)

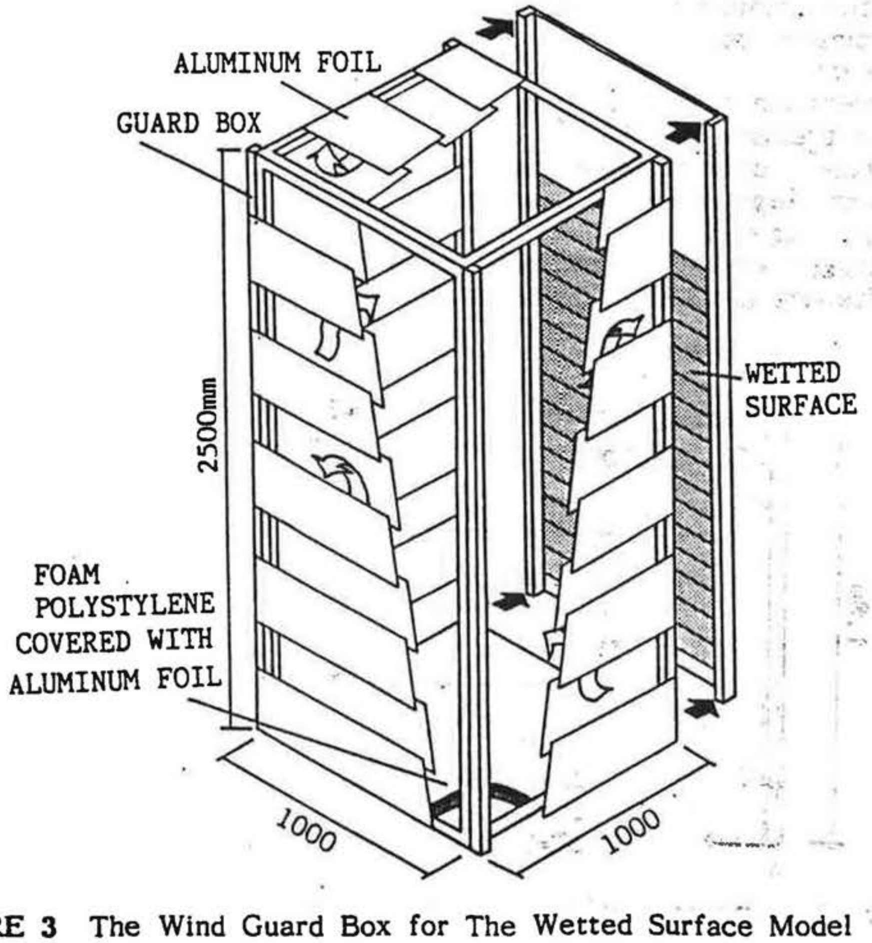

FIGURE 3 The Wind Guard Box for The Wetted Surface Model

3. NUMERICAL ANALYSIS

Local water vapor transfer coefficients and their distributions are calculated by a two-dimensional laminar flow model and its boundary conditions which governed by the Navier-Stokes equations as shown in **Figure 4.** The equations for the model disregard the terms concerned with pressure.

continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad \text{Eq.(2)}$$

momentum equation

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-g\frac{\rho-\rho_\infty}{\rho_\infty} \qquad \text{Eq.(3)}$$

concentration equation

$$\frac{\partial f}{\partial t}+u\frac{\partial f}{\partial x}+v\frac{\partial f}{\partial y}=D\left(\frac{\partial^2 f}{\partial x^2}+\frac{\partial^2 f}{\partial y^2}\right) \qquad \text{Eq.(4)}$$

boundary conditions

$\overline{AB}$	$\overline{AC}$	$\overline{CD}$	$\overline{BD}$
$u=0$	$\frac{\delta u}{\delta x}=0$	$\frac{\delta u}{\delta y}=0$	$\frac{\delta u}{\delta x}=0$
$v=0$	$v=0$	$v=0$	$v=0$
$f=fs$	$f=fa$	$f=fa$	$\frac{\delta f}{\delta x}=0$

where

- u, v : velocity components (m/s)
- x, y : coordinates (m)
- t : time (s)
- g : acceleration of gravity (9.8 m/s^2)
- f : vapor pressure (mmHg)
- fs : saturated vapor pressure (mmHg)
- fa : ambient vapor pressure (mmHg)
- ρ : density (kg/m^3)
- ν : kinematic viscosity (15.01×10^{-6} m^2/s at 20°c)
- D : diffusivity (24.90×10^{-6} m^2/s at 20°c)

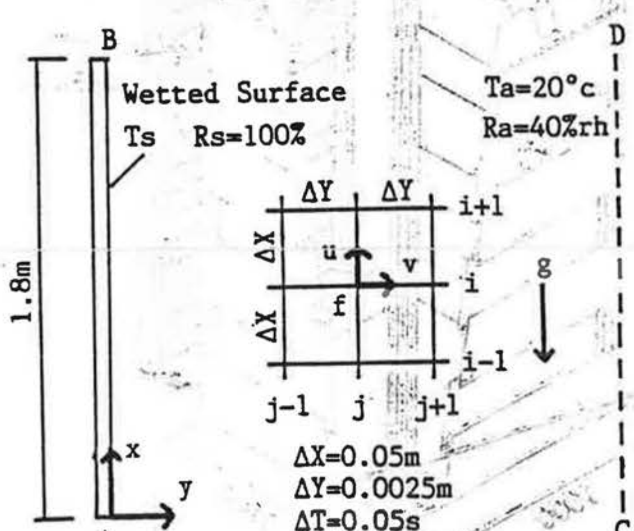

FIGURE 4 The Two-Dimensional Laminar Flow Model

4. RESULTS AND DISCUSSIONS

As shown in **Figure 5**, The weights of supplied water from three cylinders (No.1, No.9, No.16) to each reservoir increase linearly with time. This result suggests that evaporation at each wetted surface is continuously and uniformly during the experiment.

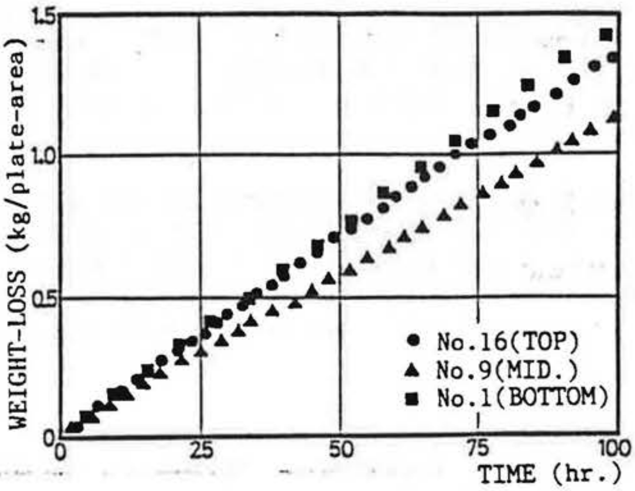

FIGURE 5 Weight Loss of Water with Time (Ts=Ta+5)

The distributions of local vapor transfer coefficients with respect to the height from the bottom of the model by experiments are shown in **Figure 6**. In the case of Ts=Ta-5, values of the coefficient on the top part is considerably larger than those on the middle and lower parts.
Apparently, this phenomenon is caused by the influence of air flow from the top to the bottom along the surface.
On the other hand, the air flow from the bottom to the top causes the larger values of the coefficient on the lower parts in the case of Ts=Ta+10.

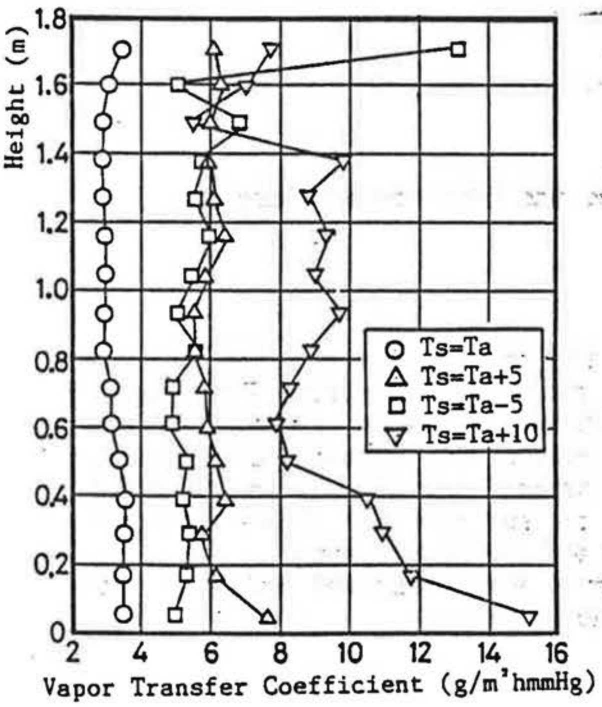

FIGURE 6 Experimental Results

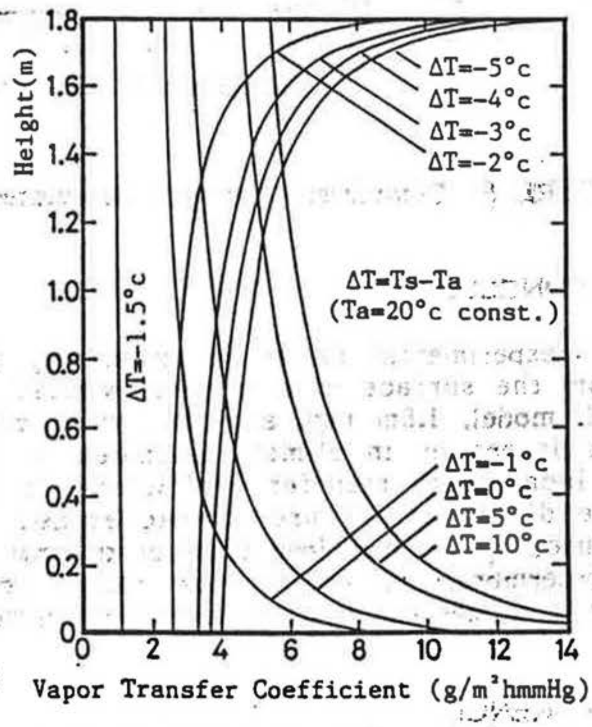

FIGURE 7 Calculated Results

Figure 7 shows the profiles of vapor transfer coefficient calculated by the Navier-Stokes equations. It is clear that temperature difference between the wetted surface and its atmosphere affects the distribution of vapor transfer coefficient. At the temperature difference dT=-1.5 °C, the downward air flow by the thermal buoyancy counterbalances the upward flow by the humid buoyancy. This phenomenon suggests that the water vapor of the wetted surface is transferred to its atmosphere by diffusion only.

Figure 8 shows the comparison of the average values with respect to the height between calculations and experiments. The agreement between calculated and experimental values within -5 to 5 °C is good. For the deviating experimental value at 10 °C, it appears that the result has the influence of the turbulent air flow nearby the surface of the model.

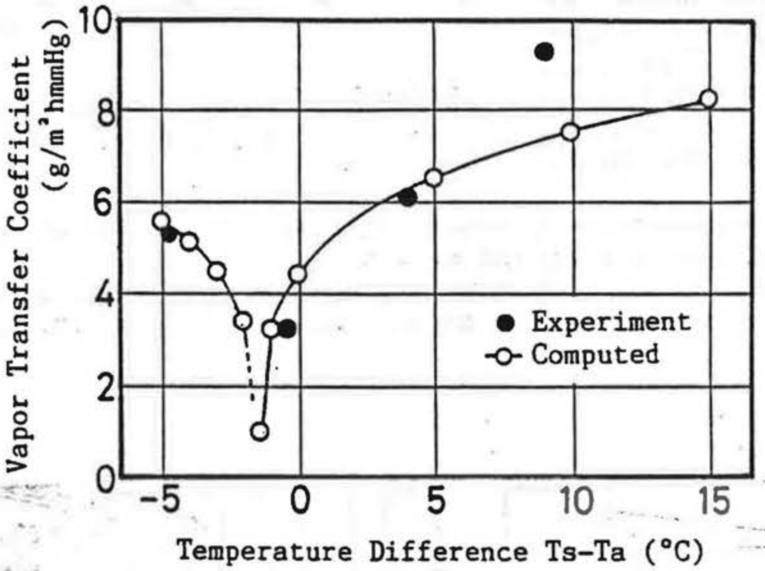

FIGURE 8 Comparison between Calculated and Experimental Results

5. CONCLUSIONS

The experimental design for measuring the rate of water-vapor transfer from the surface of a vertical wetted model is described. The original wall model, 1.8m high and 1m wide, consists of sixteen wetted-surfaces and is set up in climate chamber. In result, the vertical distributions of local vapor transfer coefficients in natural convection are obtained. The distributions are characterized by surface air flows which is induced by the combined force of thermal and humid buoyancy. Furthermore, the experimental values agree with computed values by the Navier-Stokes equations in natural convection.

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CALCULATION OF MOISTURE DISTRIBUTION

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1. INTRODUCTION

From the point of wiew of vapour diffusion walls are chacked in the design praxis usually on the basis of the well-known Glaser-method. According to this traditional method the distribution of temperature, of saturation pressure and that of the calculated partial pressure are to be determined; the construction is considered as acceptable, if $p > p_s$, where p - the calculated partial pressure, p_s - that of the saturation.

It has been proved by experiences, that sometimes moulding or "condensation" problems occur, although the construction seemed to be acceptable, and contrary, in case of some construction, independing on the $p > p_s$ ratio there is no moisture problem.

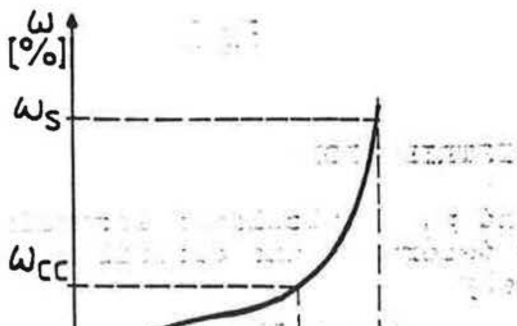


Fig.1

The risk of damages can be reduced, considering

- not only the partial pressure, but the moisture content of the materials
- the non-steady state character of the vapour transfer.

Analysis of conditions, developing on the innere surface of wall must be separated from the checking of moisture distribution in the cross-section of the construction.

Moisture content of materials / ω / is determined by sorption isotherms /Fig.1./ as a function of the relative humidity of air /RH/. Point "CC" represents the capillary condensation starting in generally at RH=7o-8o%, point "S": the saturation.

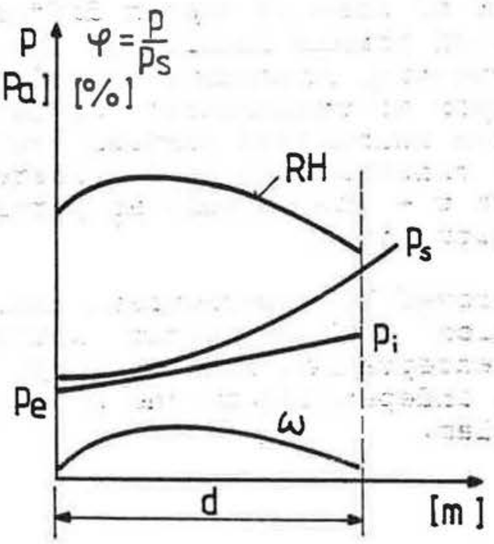


Fig.2.

2. MOISTURE DISTRIBUTION

Curves of p and p_s, calculated according to the classic Glaser-method determine the distribution of the relative humidity, namely

$$\frac{p}{p_s} = RH \qquad /1/$$

Moisture distribution / ω / is determined by RH and sorption isotherm /Fig.2./. For some materials /wood, mineral wool/ $\omega > \omega_{CC}$ is not acceptable from the point of wiew of rot, heat conductivity, corrosion, in these cases the construction must be changed or improved although $p < p_s$!

3. DEVELOPING TIME

Fig.2. shows a steady-state situation. The real process is

periodic. Developing of the partial pressure - and moisture distribution begans with the heating season, at a distribution, belonging to the end of the summer-period. The area between the ω_{ss} and ω_o curves is in direct proportion with the mass of the water /M_w/, "filling up" the construction to the steady state niveau /Fig.3./. Here ω_o- moisture distribution at the end of the summer period /usually to RH=60%/, ω_{ss} -moisture distribution, calculated on the basis of steady state transfer. The time necessary to the developing of the steady-state distribution can be calculated aproximatively

$$T = \frac{M_w}{g}$$

where g is the vapour flow, at steady-state conditions.

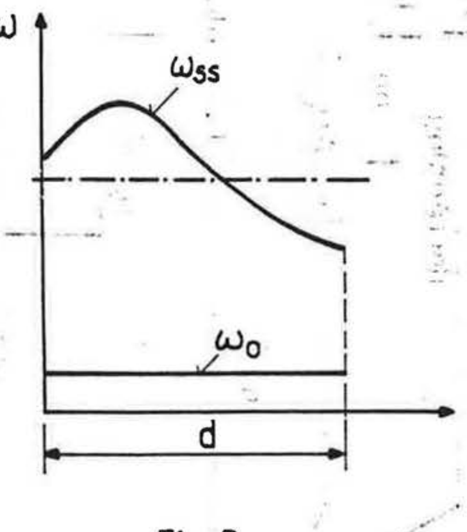
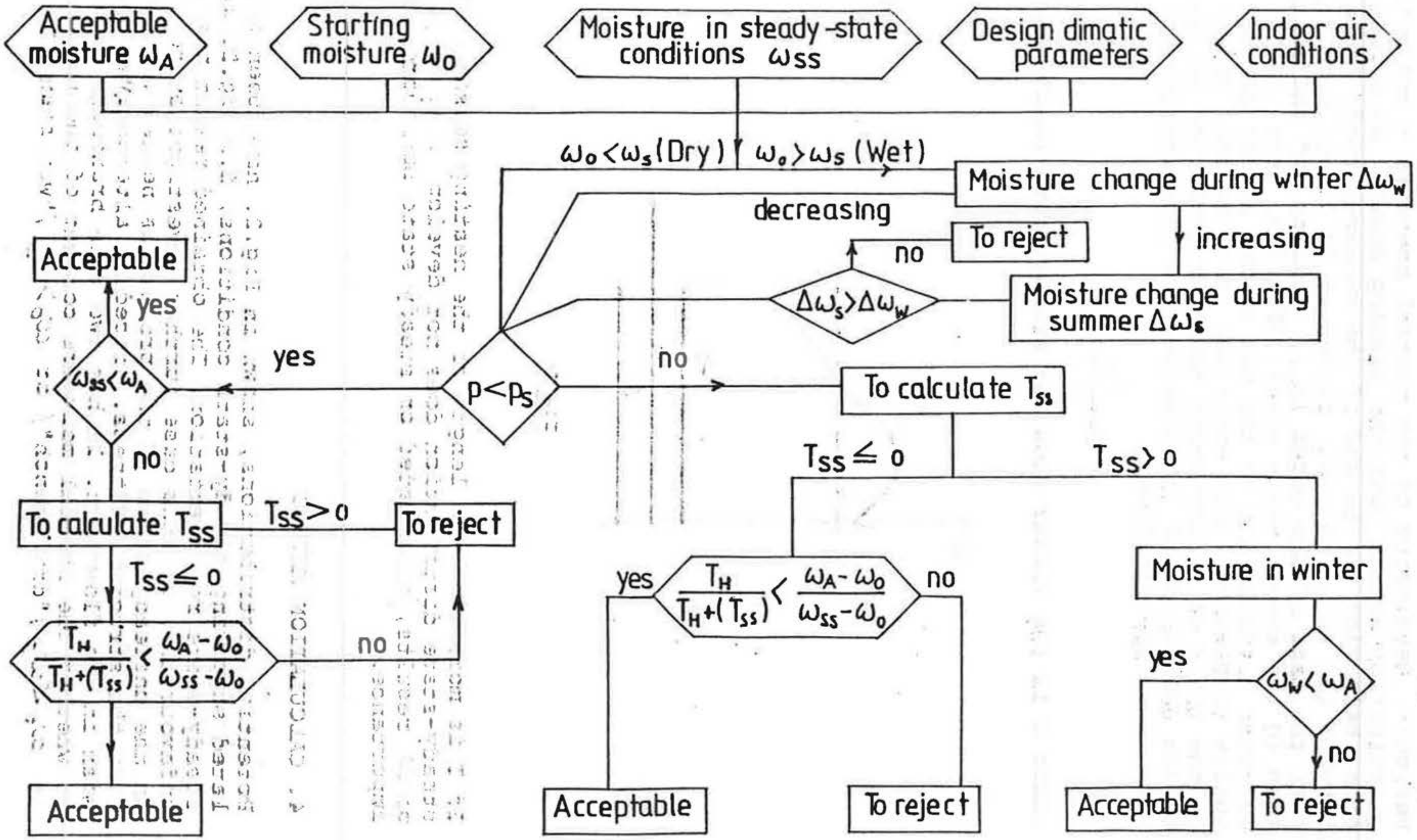


Fig. 3.

If T is more then the length of the heating season, the steady-state distribution does not develop, i.e. no p, RH or ω results,(calculated on steady state basis)are of importance.

4. CALCULATION METHOD

Potential distributions, shown in Fig.2. have been calculated supposing steady-state conditions, i.e.Fig.2. is a steady-state representation. The obtained result may seem unfavourable, in this case further investigation relying on the unsteady state of the process is needed to decide over the structure fitness. Procedure alternatives are seen in the flowchart. It has two main branches, depending on whether the initial moisture content of the structure is $\omega_o < \omega_s$ /"dry branch"/ or $\omega_o > \omega_s$ /"wet branch"/.



Acceptable moisture ω_A
Starting moisture, ω_0
Moisture in steady-state conditions ω_{SS}
Design dimatic parameters
Indoor air-conditions
$\omega_0 < \omega_s$ (Dry)
$\omega_0 > \omega_s$ (Wet)
Moisture change during winter $\Delta\omega_w$
decreasing
increasing
To reject
no
$\Delta\omega_s > \Delta\omega_w$
Moisture change during summer $\Delta\omega_s$
Acceptable
yes
yes
$\omega_{ss} < \omega_A$
$p < p_s$
no
To calculate T_{ss}
no
$T_{SS} \leq 0$
$T_{SS} > 0$
To calculate T_{SS}
$T_{SS} > 0$
To reject
$T_{SS} \leq 0$
yes
$\frac{T_H}{T_H + (T_{ss})} < \frac{\omega_A - \omega_0}{\omega_{ss} - \omega_0}$
no
Moisture in winter
$\frac{T_H}{T_H + (T_{ss})} < \frac{\omega_A - \omega_0}{\omega_{ss} - \omega_0}$
no
yes
$\omega_W < \omega_A$
no
Acceptable
Acceptable
To reject
Acceptable
To reject

where ω_s means the state of sorptional saturation.
Remarks on the algorithm:

"Dry Branch"

It comprises two other bifurcations, depending on the partial distribution of vapour pressure resulting from the steady-state calculation.

$p < p_s$

If condition ω_{ss} and ω_A are simultaneously met, the structure is suitable.
For $\omega_{ss} > \omega_A$, it, has to be checked what time is needed for the steady-state pressure and moisture distribution to develop. To that, the initial moisture content ω_o at the beginning of the heating season has to grow to ω_{ss}. Water quantity may be obtained from the sorption isotherm /Fig.1./, vapour flow is approximated by that at steady state. Quotient of the two quantities is the time needed for moisture $\omega_{ss} - \omega_o$ $_D$ to be absorbed. Deducing this time from the heating season $/T_H/$ yields the time of steady state to subsist. For $T_{ss} > 0$, the structure is unsuitable. For $T_{ss} < 0$, the question is whether the heating season is sufficient for the absorption of moisture $\omega_A - \omega_o$ or not. In the negative case, the structure is suitable, equivalent to the fulfilment of inequality for the proportions:

$$\frac{T_H}{T_H + |T_{ss}|} < \frac{\omega_A - \omega_o}{\omega_{ss} - \omega_o}$$

$p \geq p_s$

The T_{ss} value has to be determined as before.
For $T_{ss} < 0$, then for every layer with $\omega_A < \omega_s$, last condition in the preceding branch has to be met.
For $T_{ss} > 0$, then moisture penetrating the structure has to be distributed between layers according to differences $\omega_{ss} - \omega_o$ characteristic of the layers.
Thereby the rate of moistening in winter $\Delta\omega_W$ may be determined.

If moistening in winter $\Delta\omega_W$ exceeds the permissible value ω_A, the structure has "FAILED", if it is lower, the structure has "PASSED".

Moist Branch

As seen from the flowchart of computation/decision algorithm, first the winter moisture variation has to be determined. If winter moisture variation means drying out, then the presented branch of the flowchart has been arrived at. If winter moisture variation means moistening, then summer moisture variation has to be examined. For a drying in summer less than the winter moistening, the structure has to be qualified as "FAILED". Provided summer drying exceeds winter moistening, the already examined branch of the flowchart has been arrived at.

5. CONCLUSIONS

Analysis of moisture conditions in the cross-section must be separated from those of the surface.

Conditions in the cross-section are to be checked considering the moisture distribution, comparing it with the acceptable moisture content of each layer.

Contrary to the traditional Glaser-model, in some cases, although the calculated vapour pressure less, then the saturation value the construction is to be rejected, because the moisture content of one or more layer is over the acceptable niveau.

Contrary to the traditional Glaser-model, a lot of construction can be accepted and realized, although the calculated vapour pressure shows an interstitial condensation. Considering the non-steady state character of the process, the possibility of developping of the steady-state distribution is to be checked. If the length of the heating season is not enough to "fill up" the construction with water and to achieve the steady-state moisture distribution or the acceptable moisture content, the construction is to be accepted.

Constructions with free water /moisture content over the saturation/ are to be checked in a separate way, comparing the increasing of moisture content during the winter and the decreasing of it during the summer.

The presented method decreases the risk of damages, facilitates to avoid some sophisticated and expensive solutions. In order to use the proposed method the sorption-isotherms of different building and insulation materials must be available and the acceptable moisture content of some sensible materials is to be determined. For the majority of building materials the saturation value can be considered as acceptable. Increasing of heat conductivity due to the moisture content is to be taken into account.

MOISTURE PROBLEMS IN BUILDINGS AND BUILDING COMPONENTS
TECHNICAL SESSION #1

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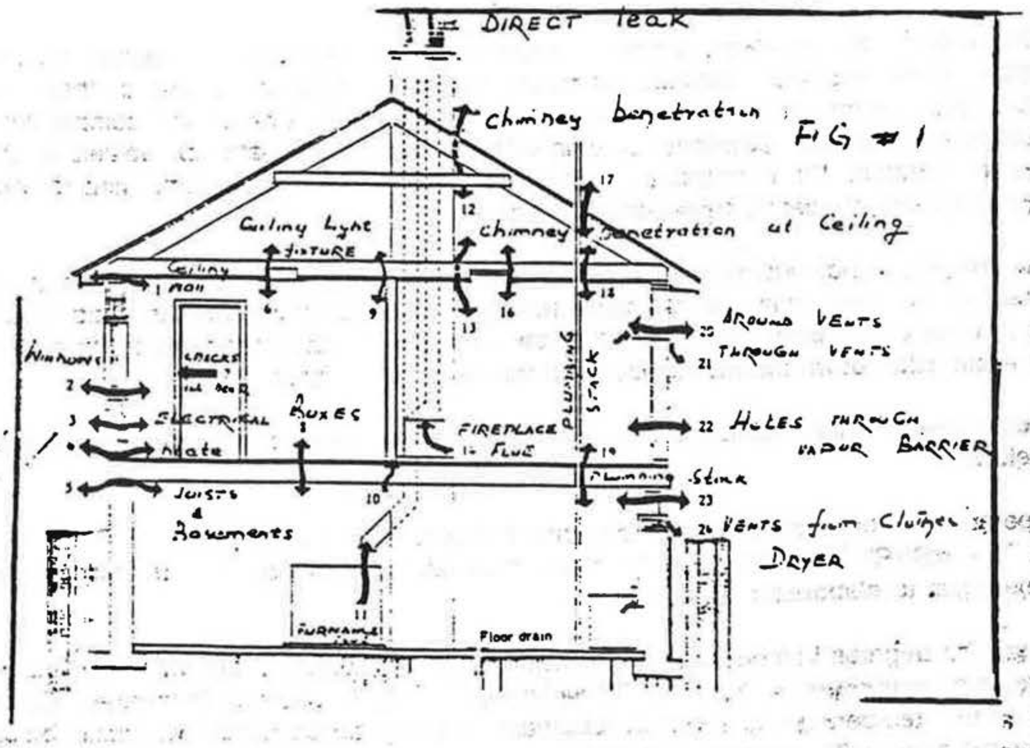
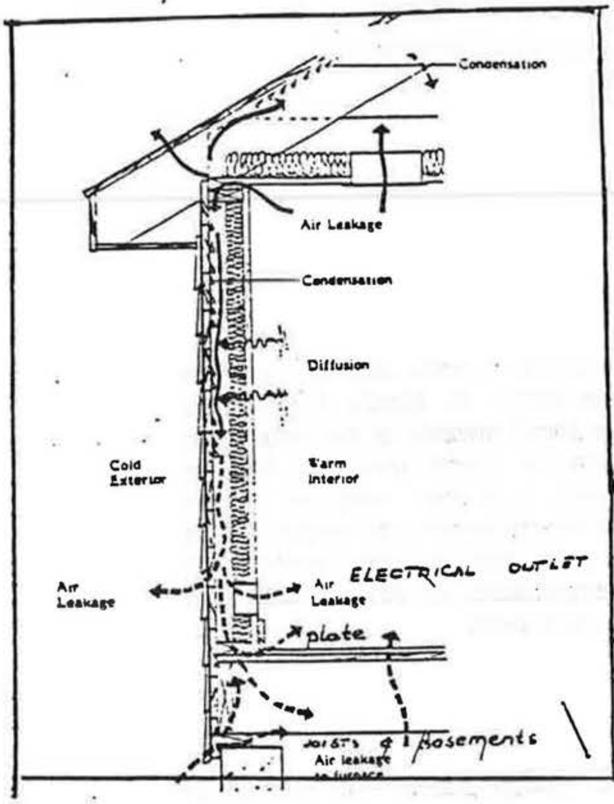
Moisture problems are rampant in almost all new constructions in cold regions, moisture migration is somewhat higher than temperature climate owing to higher temperature gradients and vapor pressures. Before we embark on the basic physics of the underlying principles defining migration of moisture, it would be safer to touch base with Relative Humidity and its sister Absolute Humidity. Relative humidity is a mere indication of the amount of water vapor present in the air compared to the maximum amount available at a given temperature. Going further, an RH of 50% that air is able to carry one-half the amount of water vapor it is capable of holding at that temperature. An RH of 100% then would mean that air is fully saturated and has reached its dew point.

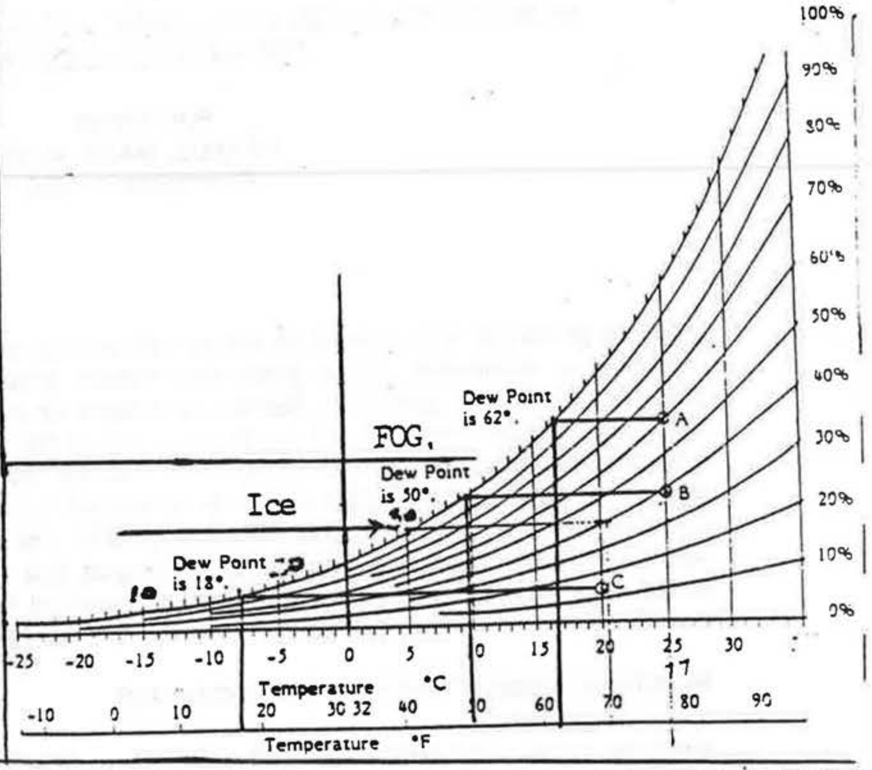
MOISTURE TRAVEL THROUGH WALL CAVITIES

Moisture travels and enters the wall cavities by different leakage paths. The amount of moisture carried by air leakage paths is ten times more than the moisture travelling by diffusion. As this hot humid air travels by leakage/diffusion and hits cold surfaces outside, it begins to condense in the form of water droplets or even ice crystals depending upon the temperature. The figures below show all possible leakage paths in addition to showing actual travel of moisture through leakage and diffusion. Also shown is a psychrometric chart indicating dew points for various RH and temperature.





MOISTURE TRAVEL
WALL SECTION.



THE PSYCHROMETRIC CHART.

POINT A DEW POINT 6
B DEW POINT 5
C DEW POINT 1

Having shown the diagrams above, it would be worth the effort to identify hidden air leakage routes and their possible locations helping in eventual sealing of these leaks. These hidden paths are around bathtubs, cabinets, with the exterior wall component and all possible joints and partitions. It is imperative that these paths be sealed to check moisture migration. If it is possible, it would be much easier to use some kind of thermal imaging systems to identify these leakage areas.

Do we need a vapor retarder and can we evaluate any emperical basis to justify its use? Further, if it is used, what are the perm ratings of the materials used as vapor retarders both in walls and ceilings. First, we would take the use of vapor retarders in the roofs and then would slide down the roof to look into the walls of the structure.

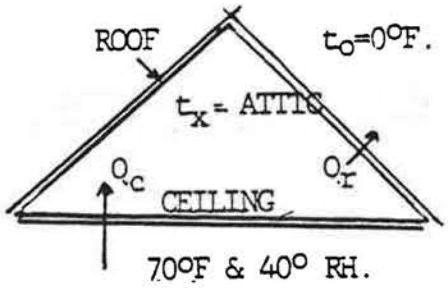
There is a very familiar relation known to all dealing with temperatures and insulation given as below:

Temperature at the desired point at any part of the roofing system.
$T = T - (\Sigma R/\Sigma R)\ T$ where symbols have their usual meanings. Let us plug in some numbers just to elaborate on the relation.

T = say 70 degrees Fahrenheit; R = 14 at the desired location under the roof; Total R of the roofing component = 16. T = 70 we have T = 8.75 degrees Fahrenheit. The dew point at this temperature is some 36 degrees, meaning condensation will occur because the temperature 8.75 degrees Fahrenheit is less than 36 degrees Fahrenheit, the dew point.

Let us now go to some other location in the roof component. Say at the air space where total R at that point is 0.65, let us see what happens now, plugging numbers in the same equation. We have the desired temperature as 68.15 which is above the dew point temperature of 36 F. meaning that dew condensation will not occur because the temperature 68.15 F. is greater than 36 F., the dew point. All this was just an example to show how best we can evaluate the critical temperatures to avoid condensation. A thing to remember is some condensation will always occur, it is just how effectively we can dry it away through ventilation or other means given at the end of this paper that would be the main source of concern. Before leaving the emperical relations, it would be worth looking into a residential attic and see if our relation holds for a typical attic construction in the U.S.

Q. A pitched roof construction of shingles on roofing felt plus sheathing has an over-all coefficient of 0.60 Btu/(hr)(sq ft)(F). The roof area is 1,000 square feet. The ceiling, with an area of 500 square feet, is made up of 1 inch of gypsum lath and plaster having a conductance of 1.50 Btu/(hr)(sq ft)(F) for thickness stated



plus 3 inches of mineral wool having a conductivity of 0.27 Btu/(hr)(sq ft)(F) for 1 inch thickness. Inside and outside film conductances are 1.65 and 6.0, respectively. Outdoor temperature is plus 0 F. Indoor air is at 70 F. and 40 percent relative humidity. Attic space is not ventilated. Will condensation form on the attic side of the wood sheathing?

SOLUTION →

Heat gain through ceiling into attic:

$$QC = Uc\ Ac\ (ti - tx)$$

Heat loss through roof to outside:

$$QR - Ur\ Ar\ (tx - to)$$

$$Uc = \frac{1}{\frac{1}{1.65} + \frac{1}{1.50} + \frac{3}{0.27} + \frac{1}{1.65}} = 0.76 \text{ Btu/(hr)(sq ft)}$$

Solution: Heat through roof (Qr) = Heat through ceiling (Qc)
Heat loss = Heat gained

$$0.076 \times 500\ (70 - tx) = 0.60 \times 1000\ (tx - 0)$$
$$tx = 4.2 \text{ F.}$$

This temperature is below the dew point temperature based on 70 F. and 40% humidity conditions of room; dew point is at 30 F. and the calculated temperature is approximately 5 F. which indicates condensation will occur without vapor retarder.

Let us take an example if condensation will occur in a wood frame wall exposed to 70 F. and 50% RH with a vapor pressure of 0.37 in Hg and outdoor conditions of 0 F. and 80% RH with a vapor pressure of 0.03 in Hg. The wall is gypsum and painted on the inside with mineral wool insulation bet studs. The outside is one inch wood siding with wood exterior sheathing and paper.

In modern structures with well insulated walls, condensation will not occur until outside sheathing is reached. We can always calculate temperature at some point by the general equation
$Tx = T - (\Sigma Rx/\Sigma Rt)\ T$, where Rx, Rt, To, Ti, and Tx have their usual meanings. Plugging the numbers in the equation - Tx = 10 F. calculate the saturation vapor pressure at the temperature of 10 F. from the steam/water tables. To check for condensation, let us check vapor flow to some point (x) at which we calculated temperature and vapor flow from x to outdoors. If the vapor flow to x is greater than vapor flow from x to outdoors, condensation will occur. To avoid condensation, resistance of the inside of the wall needs to be increased by an amount

$$\frac{\text{vapor pressure diff.}}{\text{saturation vapor pressure}}$$

In the example we took 70 F. and 50% RH = vapor pressure 0.37 Hg saturation vapor pressure at section x at the temperature calculated = 0.06 Hg resistance required to avoid condensation =

$$\frac{0.37 - 0.06}{0.06} = 5.2 \text{ rep.}$$

A more resistant film or heavy coat of paint could accomplish this by increasing the resistance to condensation to 5.2 rep.

REFERENCES:

(1) ASHRAE HANDBOOK OF FUNDAMENTALS.

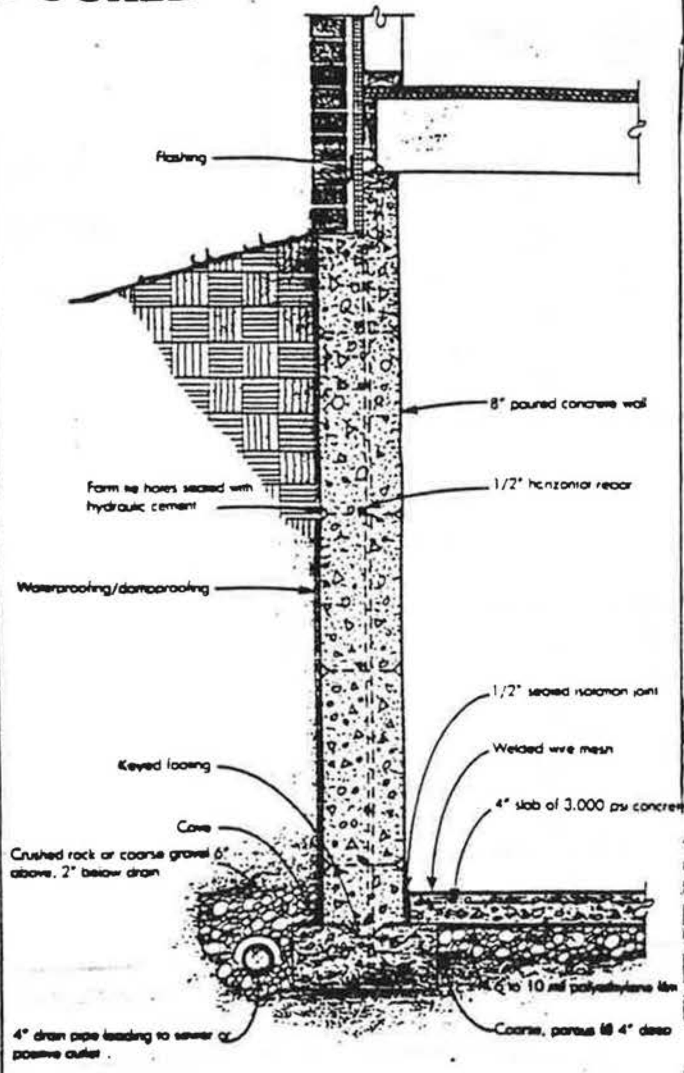
(2) DIDAK Corporation. Washington. DC.

(3) RK VARMA's Seminars.

mer poured or block, ...rete foundations should ...w some basic principles: ...e Place footings on un-...urbed soil below the frost ...If the soil below the ...ngs is loose or filled with ...ockets, the foundation ...settle excessively, caus-...g basement walls to crack. ...a Place welded wire ...sh ... top third of the ...to ...o control shrinkage ...ing. In order to allow for ...movement and prevent ...akage where slab meets ...all, build in a ½-inch isola-...on (expansion) joint filled ...flexible sealant. ... To balance backfill ...ure, backfill only after ...e basement wall has been ...raced or the first floor has ...een placed. Backfill material ...d be free of large boul-... frozen earth and mate-...at will rot. Place it in ...mped layers, not all at ...nce, and keep heavy equip-...ent away from the newly ...a...lled wall.

Divert surface water away from the house by (A) dis-charging downspouts farther tha... 24 inches away from ...the ...all onto a splash block; (B) ...ding backfill at a ½ to 1-inch slope per foot away from the wall (regrading may be needed after settling); and (C) ...dscaping with plants ...ha... ...ave a dense, moisture-...ra...ing root structure.

POURED



Note: check designs against local code requirements.

Sketch adapted from Basement Water Leakage: Causes, Prevention and Correction, by permission of the NAHB Research Foundation, Inc.

FIG. BASIC PRINCIPLES FOR AVOIDING MOISTURE PROBLEMS.

IMPROPER INSTALLATIONS.

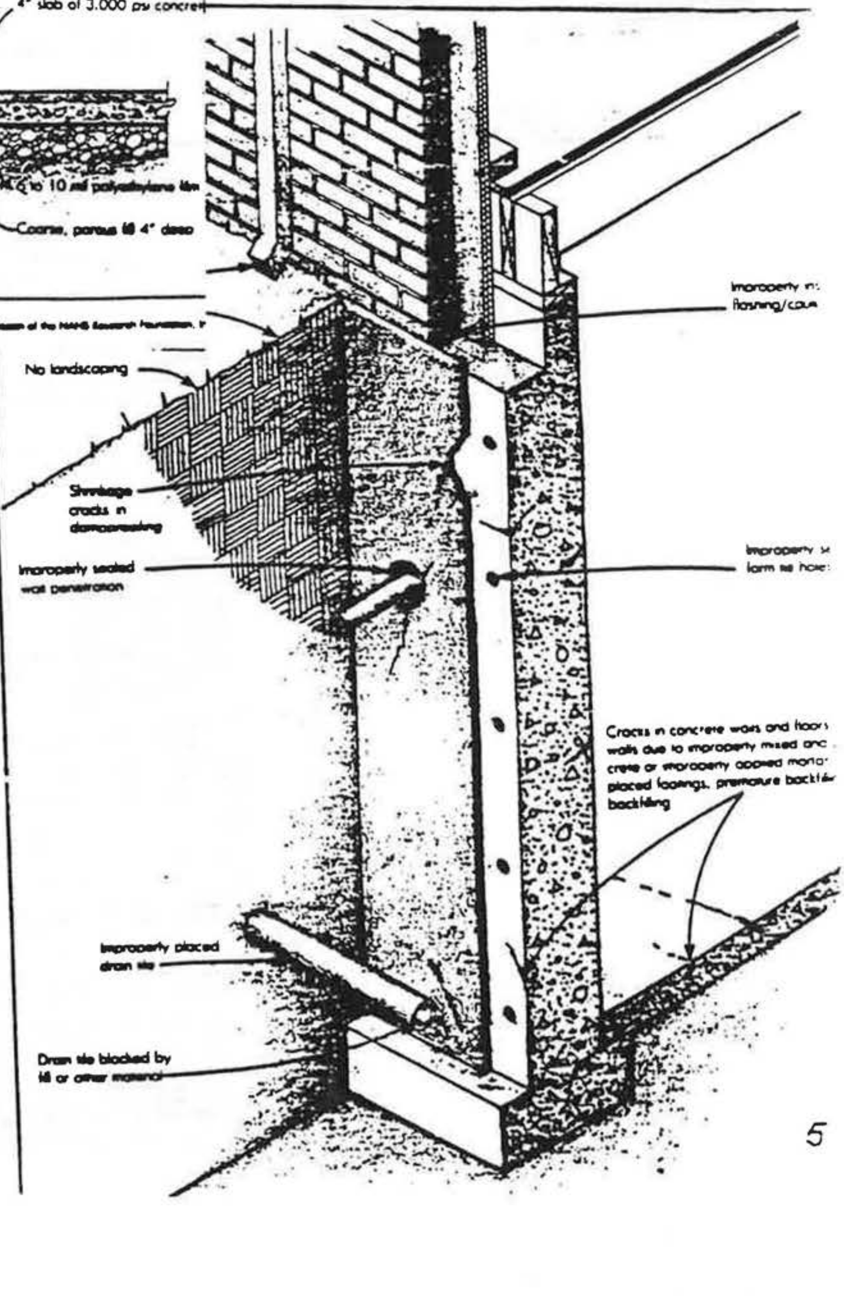


Table 2 Permeance and Permeability of Materials to Water Vapor[a,b]

Material	Thickness (in.)	Permeance (Perm)	Resistance[j] (Rep)	Permeability (Perm-in.)	Resistance/in.[j] (Rep/in.)
Materials used in construction					
Concrete (1:2:4 mix)				3.2	0.31
Brick masonry	4	0.8[f]	1.3		
Concrete block (cored, limestone aggregate)	8	2.4[f]	0.4		
Tile masonry, glazed	4	0.12[f]	8.3		
Asbestos cement board	0.12	4-8[e]	0.1-0.2		
With oil base finishes		0.3-0.5[e]	2-3		
Plaster on metal lath	0.75	15[f]	0.067		
Plaster on wood lath		11[e]	0.091		
Plaster on plain gypsum lath (with studs)		20[f]	0.050		
Gypsum wall board (plain)	0.375	50[f]	0.020		
Gypsum sheathing (asphalt impreg.)	0.5			20[e]	0.050
Structural insulating board (sheathing qual.)				20-50[f]	0.050-0.020
Structural insulating board (interior, uncoated)	0.5	50-90[f]	0.020-0.011		
Hardboard (standard)	0.125	11[f]	0.091		
Hardboard (tempered)	0.125	5[f]	0.2		
Built-up roofing (hot mopped)		0.0			
Wood, sugar pine				0.4-5.4[f,e]	2.5-0.19
Plywood (douglas fir, exterior glue)	0.25	0.7[f]	1.4		
Plywood (douglas fir, interior glue)	0.25	1.9[f]	0.53		
Acrylic, glass fiber reinforced sheet	0.056	0.12[e]	8.3		
Polyester, glass fiber reinforced sheet	0.048	0.05[e]	20		
Thermal insulations					
Air (still)				120[f]	0.0083
Cellular glass				0.0[d]	∞
Corkboard				2.1-2.6[e]	0.48-0.38
				9.5[f]	0.11
Mineral wool (unprotected)				116[e]	0.0086
Expanded polyurethane (R-11 blown) board stock				0.4-1.6[e]	2.5-0.62
Expanded polystyrene—extruded				1.2[e]	0.83
Expanded polystyrene—bead				2.0-5.8[e]	0.50-0.17
Phenolic foam (covering removed)				26	0.038
Unicellular synthetic flexible rubber foam				0.02-0.15[e]	50-6.7
Plastic and metal foils and films[c]					
Aluminum foil	0.001	0.0[e]			
Aluminum foil	0.00035	0.05[e]	20		
Polyethylene	0.002	0.16[e]	6.3		3100
Polyethylene	0.004	0.08[e]	12.5		3100
Polyethylene	0.006	0.06[e]	17		3100
Polyethylene	0.008	0.04[e]	25		3100
Polyethylene	0.010	0.03[e]	33		3100
Polyvinylchloride, unplasticized	0.002	0.68[e]	1.5		
Polyvinylchloride plasticized	0.004	0.8-1.4[e]	1.3-0.72		
Polyester	0.001	0.73[e]	1.4		
Polyester	0.0032	0.23[e]	4.3		
Polyester	0.0076	0.08[e]	12.5		
Cellulose acetate	0.01	4.6[e]	0.2		
Cellulose acetate	0.125	0.32[e]	3.1		

NOTE: Values have been taken

ASHRAE HANDBOOK OF

FUNDAMENTALS (USA.)

PERM RATINGS

(ASHRAE HANDBOOK OF FUNDAMENTALS)

Table 2 Permeance and Permeability of Materials to Water Vapor[a] (Concluded)

Material	Weight[i]	Permeance (Perms) Dry-Cup	Permeance (Perms) Wet-Cup	Permeance (Perms) Other	Resistance[j] (Rep) Dry-Cup	Resistance[j] (Rep) Wet-Cup	Resistance[j] (Rep) Other
Building paper, felts, roofing papers[h]							
Duplex sheet, asphalt laminated, aluminum foil one side	8.6	0.002	0.176		500	5.8	
Saturated and coated roll roofing	65	0.05	0.24		20	4.2	
Kraft paper and asphalt laminated, reinforced 30-120-30	6.8	0.3	1.8		3.3	0.55	
Blanket thermal insulation back up paper, asphalt coated	6.2	0.4	0.6-4.2		2.5	1.7-0.24	
Asphalt-saturated and coated vapor retarder paper	8.6	0.2-0.3	0.6		5.0-3.3	1.7	
Asphalt-saturated but not coated sheathing paper	4.4	3.3	20.2		0.3	0.05	
15-lb asphalt felt	14	1.0	5.6		1.0	0.18	
15-lb tar felt	14	4.0	18.2		0.25	0.055	
Single-kraft, double	3.2	31	42		0.032	0.024	
Liquid-applied coating materials	**Inches**						
Commercial latex paints (dry film thickness)[k]							
Vapor retarder paint	0.0031			0.45			2.22
Primer-sealer	0.0012			6.28			0.16
Vinyl acetate-acrylic primer	0.002			7.42			0.13
Vinyl-acrylic primer	0.0016			8.62			0.12
Semi-gloss vinyl-acrylic enamel	0.0024			6.61			0.15
Exterior acrylic house and trim	0.0017			5.47			0.18
Paint-2 coats							
Asphalt paint on plywood			0.4			2.5	
Aluminum varnish on wood		0.3-0.5			3.3-2.0		
Enamels on smooth plaster				0.5-1.5			2.0-0.66
Primers and sealers on interior insulation board				0.9-2.1			1.1-0.48
Various primers plus 1 coat flat oil paint on plaster				1.6-3.0			0.63-0.33
Flat paint on interior insulation board				4			0.25
Water emulsion on interior insulation board				30-85			0.03-0.01
Paint-3 coats	Oz/ft²						
Exterior paint, white lead and oil on wood siding		0.3-1.0			3.3-1.0		
Exterior paint, white lead-zinc oxide and oil on wood		0.9			1.1		
Styrene-butadiene latex coating	2	11			0.09		
Polyvinyl acetate latex coating	4	5.5			0.18		
Chloro-sulfonated polyethylene mastic	3.5	1.7			0.59		
	7.0	0.06			16		
Asphalt cut-back mastic, 1/16 in., dry		0.14			7.2		
3/16 in., dry		0.0			—		
Hot melt asphalt	2	0.5			2		
	3.5	0.1			10		

[a]In this chapter the permeance, resistance, permeability and resistance per unit thickness values are given in the following units.

Permeance	Perm	= gr/h·ft²·in. Hg
Resistance	Rep	= in. Hg·ft²·h/gr
Permeability	Perm-in.	= gr/h·ft²·(in. Hg/in.)
Resistance/unit thickness	Rep/in	= (in. Hg·ft²·h/gr)/in.

[b]Table 2 gives the water vapor transmission rates of some representative materials. The data are provided to permit comparisons of materials; but in the selection of vapor retarder materials, exact values for permeance or permeability should be obtained from the manufacturer of the materials under consideration or secured as a result of laboratory tests. A range of values shown in the table indicates variations among mean values for materials that are similar but of different density, orientation, lot or source. The values are intended for design guidance and should not be used as design or specification data. The compilation is from a number of sources; values from dry-cup and wet-cup methods were usually obtained from investigations using ASTM E96 and C355; values shown under others were obtained from investigations using such techniques as two-temperature, special cell, and air-velocity. Values included were obtained from Ref. 16 to 29 and other sources. Some values were obtained from unpublished tests conducted by Pennsylvania State University and the Building Research Div., National Research Council of Canada.

[c]Depending on construction and direction of vapor flow.

[d]Usually installed as vapor retarders, although sometimes used as exterior finish and elsewhere near cold side where special considerations are then required for warm side barrier effectiveness.

[e]Dry-cup method

[f]Wet-cup method

[g]Other than dry- or wet-cup method

[h]Low permeance sheets used as vapor retarders. High permeance used elsewhere in construction.

[i]Basic weight in lb per 100 ft² (lb per square ft)

[j]Resistance and resistance-in. values have been calculated as the reciprocal of the permeance and permeability values.

[k]Cast at 10 mils wet film thickness.[31]

A DESIGN METHOD OF BUILDING COMPONENTS WITH VAPOUR RESPIRATORY MATERIAL

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JAPAN

SUMMARY

It is actually recommended to apply a vapour barrier to the external building components in order to reduce the problems due to the condensation at the inside of components that occurs when the temperature gradient throughout the component is important. But in Japan where it is very humid in summer, owing to the application of vapour barrier the risk of the internal condensation rises importantly when the people uses cooling equipment in the room. This fact conducts us to search for another solution: how to reduce the risk of hot season condensation due to the vapour barrier. Using the heat and moisture simultaneous transfer model developped by Prof. Makoto MATSUMOTO, we can obtain the water content distribution, the temperature distribution, the vapour pressure distribution and the relative humidity distribution in the component under the standardized variable climate conditions. With such model we can find solutions applicable to such a severe climate condition by using the vapour respiratory material which can reduce the amplitude of relative humidity change though permits the vapour transfer through it.
This report presents a series of charts which show the conditions for the application of vapour respiratory materials to the building components under the climate conditions of Tokyo. This study implies the possibility of improving the design flexibility of building components under such climate conditions as is hot and humid in summer whereas cold and dry in winter by introducing the vapour respiratory material.

1. OBJECT

In Japan where it is very hot and humid in summer though cold in winter, the vapour barrier placed at the room side of building components increases the relative humidity at the inside of components on the point just behind the vapour barrier when the room is cooled with equipments. Of course if you put the vapour barrier at the external side of components, the relative humidity at the inside of component increases importantly in winter. If you put the vapour barrier at the both sides of component, the problems can occur when some members used for the component contains certain humidity; they cannot dry themselves and are risky to be decayed. The object of our work is to find a solution to such contradictory conditions and for this object, taking into consideration the climate conditions that vary from time to time, we tried to utilize some vapour respiratory materials which permit certain vapour transfer but can serve as a retarder of transfer and reduce the amplitude of relative humidity variation.

2. BASE OF CONSIDERATION

1) TWO MODELS OF EXTERNAL WALL COMPOSITION: OBJECTIVES OF STUDY

In order to study the possibility of above mentioned use of materials, the two models of wall composition are chosen. One is a wall composition in which a vapour respiratory material is placed at the room side and another is that in which the vapour respiratory material is placed at the external side. The choice of materials and the decision of their thickness are the practice of design and for this practice some useful design charts are requested to be prepared.

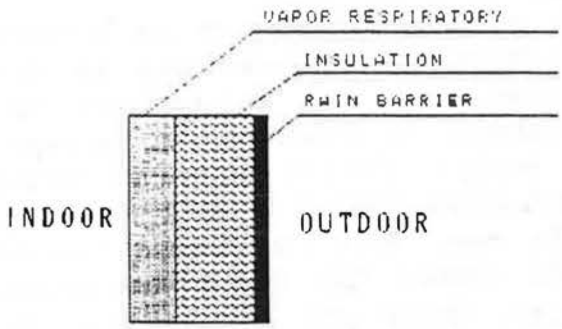


FIG-1

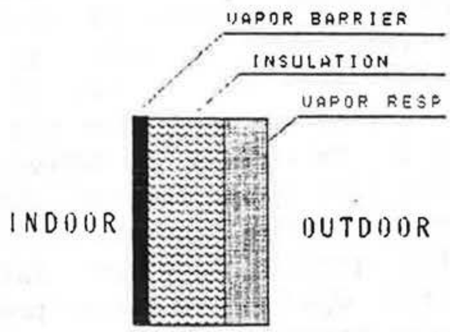


FIG-2

MODEL1: VAPOUR RESPIRATORY MATERIAL PLACED AT THE ROOM SIDE.

MODEL2: VAPOUR RESPIRATORY MATERIAL PLACED AT THE EXTERNAL SIDE

2) INTERNAL AND EXTERNAL CLIMATE CONDITIONS

(i) ROOM CONDITIONS

In order to simplify the problem, the room temperature T_r and room humidity h_r are settled constant throughout a year.

$T_r = 23℃$: ROOM TEMPERATURE

$h_r = 50\%$: ROOM RELATIVE HUMIDITY

(ii) OUTDOOR CONDITIONS

The outdoor conditions are also simplified; the outdoor air temperature T_a and relative humidity h_a are given as follow:

$$T_a = \theta_a \cos \frac{2\pi}{\tau} t + \theta_m$$

$$h_a = H_a \cos \frac{2\pi}{\tau} t + H_m$$

τ = term of a cycle = one year

Here the climate data of Tokyo are introduced and the amplitude of temperature θ_a, the mean year temperature θ_m, the amplitude of relative humidity H_a and the mean year relative humidity H_m are given as follows:

$\theta_a = (T_{maug} - T_{mjan})/2 = (26.4-3.7)/2 = 11.35℃$

$\theta_m = (T_{maug} + T_{mjan})/2 = (26.4+3.7)/2 = 15.05℃$

$H_a = (h_{maug} - h_{mjan})/2 = (79-60)/2 = 9.5\%$

$H_m = (h_{maug} + h_{mjan})/2 = (79+60)/2 = 69.5\%$

Here "maug" signifies the mean of august and "mjan" signifies the mean of january.

3) OTHER SUPPOSITIONS

In order to simplify the calculations, the following suppositions are introduced:

(i) The surface transmission resistances for both heat and humidity are ignorable for a long term transfer.

(ii) The humidity transfer resistance of the thermal insulation layer supposed to be composed of mineral wool is ignorable. $r'_2 = 0$

(iii) The thermal conduction resistance is ignorable for the vapour barrier supposed to be composed of thin film. $r_3 = 0$

(iv) The heat capacity of the vapour respiratory layer supposed to be composed of materials of rather low density is ignorable. So the heat transfer at every part of the layer becomes steady momentarily and the temperature distribution can be supposed to be linear.

(v) The equilibrium moisture content of the vapour respiratory layer can be supposed to show a curve quite linear in the expected range of relative humidity in this study.

(vi) The dominant mode of water diffusion in the vapour respiratory layer can be supposed to be the vapour diffusion mode. The range of the calculation is hygroscopic, the realtive humdity is less or equal to 95% and the moisture conductivity is constant.

3. BASIC FORMULATION FOR THIS STUDY

The basic model used in this study is that of MATSUMOTO described as follows:

$$\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x}\left[\frac{D\phi_g}{\rho_w}\frac{\partial \phi}{\partial x}\right] + \frac{\partial}{\partial x}\left[\frac{D_{Tg}}{\rho_w}\frac{\partial T}{\partial x}\right] \cdots (1)$$

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\frac{\lambda + \gamma D_{Tg}}{\rho c}\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial x}\left[\frac{\gamma D\phi_g}{\rho c}\frac{\partial \phi}{\partial x}\right] \cdots (2)$$

$$\phi = \phi(h) \quad mh + n \cdots (3)$$

Here the symbols signify as follows:

ϕ : moisture content
t : time
x : distance
ρ_w : density of water
$D\phi_g$: gas phase moisture diffusivity due to moisture content gradient
D_{Tg} : gas phase moisture diffusivity due to temperature gradient
T : temperature
λ : thermal conductivity
γ : heat of phase change
ρ : density of material
c : specific heat of material
h : relative humidity
m : slope of linealized isothermal sorption curve
n : constant for material

The formulation can be simplified according to the above-mentioned suppositions. In this study the following equations are used.

The equation (3) can be expressed as $\phi = m\frac{P_v}{P_{vs}(T)} + n$ and the coeffient $D\phi_g, D_{Tg}$ can also be replaced by following equations:

$$D\phi_g = \lambda' \frac{\partial P_v}{\partial \phi}, \quad D_{Tg} = \lambda' \frac{P_v}{P_{vs}}\frac{dP_{vs}}{dT}$$

Then the expression of the equation (1) can be transformed as follows:

$$\frac{m}{P_{vs}}\frac{\partial P_v}{\partial t} = \frac{\lambda'}{\rho_w}\frac{\partial^2 P_v}{\partial x^2} + \frac{m P_v}{P_{vs}^2}\frac{dP_{vs}}{dT}\frac{\partial T}{\partial t} \cdots (4)$$

According to the supposition (iv), the temperature of every point at every moment can be obtained as follows:

$$T(x,t) = \left(\theta_e \cos \frac{2\pi}{\tau} + \theta_f\right) \frac{x}{L} + \theta_g \cos \frac{2\pi}{T_o} t + \theta_h \cdots (5)$$

Here the symbols signify as follows in case of MODEL1:

$$\theta_e = \frac{r_1}{R}\theta_s, \quad \theta_f = \frac{r_1}{R}(\theta_m - T_r), \quad \theta_g = 0, \quad \theta_h = T_r$$

$R = r_1 + r_2$, $r_1 = L / \lambda$,

L : thickness of vapour respiratory material

λ : thermal conductivity of vapour respiratory material

r_2: thermal resistance of thermal insulation

The boundary condition for the equation (4) is described as follows:

$$\left.\begin{array}{ll} \text{for MODEL1:} & -\lambda' \dfrac{\partial P_v}{\partial x} = (P_{va} - P_v) / r_3' \quad \text{at } x = L \\ \text{for MODEL2:} & -\lambda' \dfrac{\partial P_v}{\partial x} = (P_v - P_{vr}) / r_3' \quad \text{at } x = 0 \end{array}\right] \cdots (6)$$

Here the symbols signify as follows:

P_{va} : outdoor vapour pressure

P_{vr} : indoor vapour pressure

r_3' : vapour transfer resistance of vapour barrier

These 3 equations (4),(5),(6) can be non-dimensionalized as decribed below:

$$\frac{\partial P*_v}{\partial t*} = A P*_{vs} \frac{\partial^2 P*_v}{\partial x*^2} + B P*_v \cdots (7)$$

Here the symbols signify as follows:

$A = \dfrac{\lambda' \tau P_{vo}}{\rho_w L^2 m'}$, P_{vo} : representative vapour pressure in this study $P_{vo} = P_{vr} = 10.6$mmHg

$$B = \frac{1}{P_{vs}} \frac{dP_{vs}}{dT} \tau \frac{\partial T}{\partial t} = -2\pi \frac{d}{dT*}(\ln P*_{vs})(\theta*_e x* + \theta*_g)\sin 2\pi t*$$

$$T* = (\theta*_e \cos 2\pi t* + \theta*_f) x* + \theta*_g \cos 2\pi t* + \theta*_h \cdots (8)$$

In case of the MODEL1, $\theta*_e$, $\theta*_f$, $\theta*_g$, $\theta*_h$ are replaced as follows:

$$\theta*_e = \frac{\xi}{\xi+1}\theta*_s, \quad \theta*_f = \frac{\xi}{\xi+1}(\theta*_m - 1), \quad \theta*_g = 0, \quad \theta*_h = 1$$

when $\xi = \dfrac{L/\lambda}{r_2} = \dfrac{r_1}{r_2}$

$\theta*_s = \theta_s / T_r$

$\theta*_m = \theta_m / T_r$

The boundary condition for the equation:

$$\left.\begin{array}{ll} \text{for MODEL1:} & -\dfrac{\partial P*_v}{\partial x*} = \eta \, (P*_{va} - P*_v) \quad \text{at } x = 1 \\ \text{for MODEL2:} & -\dfrac{\partial P*_v}{\partial x*} = \eta \, (P*_v - P*_{vr}) \quad \text{at } x = 0 \end{array}\right] \cdots (9)$$

when $\eta = \dfrac{L/\lambda'}{r_3'} = \dfrac{r_1'}{r_3'}$

The equations are transformed into rather simple differential equations composed by only 3 parameters: A, ξ, η.
The value of A varies conversely to the value of m, the slope of the isothermal sorption curve of the used vaour respiratory material.
The values of ξ and η vary in accordance with the thermal resistance and vapour resistance of the vapour respiratory material respectively.

4. VERIFICATION OF THE SIMPLIFIED MODEL

The results of simulation executed with the simplified model are compared with those obtained with the complete model and this comparison shows a good agreement between the two.

The figures 3, 4 and 5 show an example of simulation executed with two models for a component whose pattern can be considered to be MODEL2. As for the vapour respiratory material in order to check the effect of the heat capacity, a neglected parameter in the simplified model, a concrete panel is chosen for this verification simulation.

FIG-3
VARIATION OF TEMPERATURE COMPARISON OF COMPLETE AND SIMPLIFIED MODELS

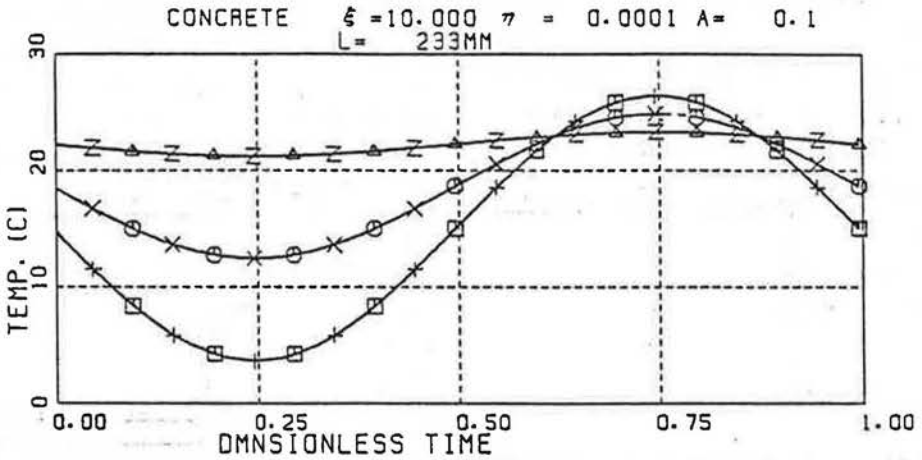


FIG-4
VARIATION OF VAPOR PRESSURE COMPARISON OF COMPLETE AND SIMPLIFIED MODELS

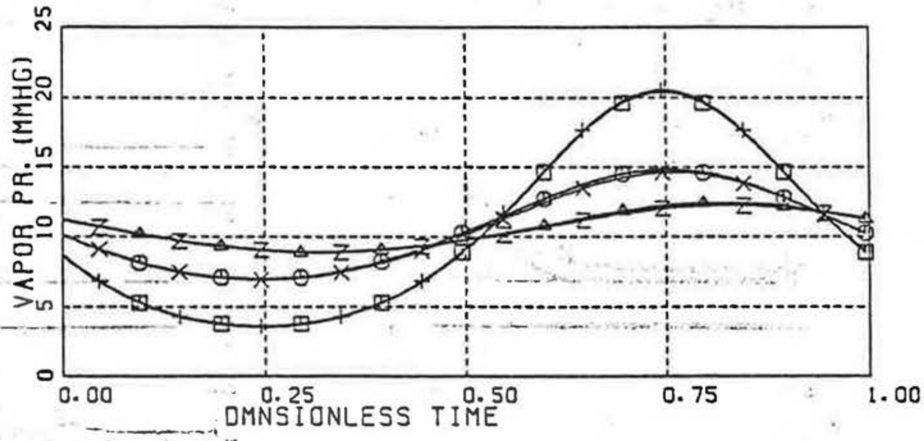
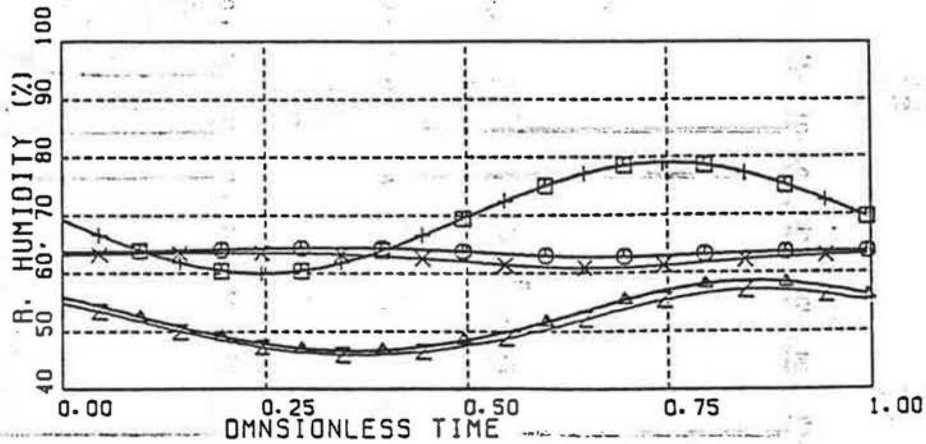


FIG-5
VARIATION OF RELATIVE HUMIDITY COMPARISON OF COMPLETE AND SIMPLIFIED MODELS



5. DESIGN CHART FOR COMPONENTS USING VAPOUR RESPIRATORY MATERIALS

The two series of figures shows the results of simulation conducted with the simplified model. These figures show the change of applicable range of material characteristics according to the variation of the value of "A". The first series(figures 6) concerns the components categorized as MODEL1 and the second series(figures 7) concerns the components categorized as MODEL2. In this study as the room condition is settled constant through a year, the effect of the use of vapour respiratory material is not sufficiently clear. But in the figures for the MODEL2, because the vapour respiratory material is applied at the side exposed to the variable condition, the effect of the vapour respiratory material is important. So if the risk of condensation is important because of the variation of the indoor climate, it can be supposed that the application of the vapour respiratory material can show a more visible effect.

REFERENCE: WATANABE Kazumasa, SAKAMOTO Yuzo "VERS UNE SOLUTION AUX PROBLEMES DE CONDENSATION DANS LA CONSTRUCTION" XI[th] Congress CIB 89

FIG-6 DESIGN CHART FOR COMPONENT MODEL1

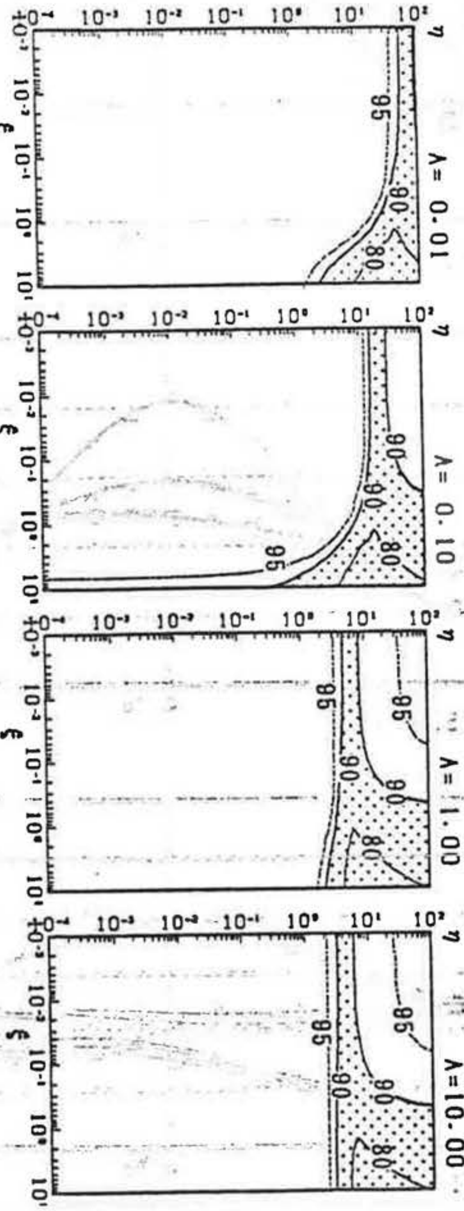


FIG-6.1 A=0.01
FIG-6.2 A=0.10
FIG-6.3 A=1.00
FIG-6.4 A=10.00

FIG-7 DESIGN CHART FOR COMPONENT MODEL2

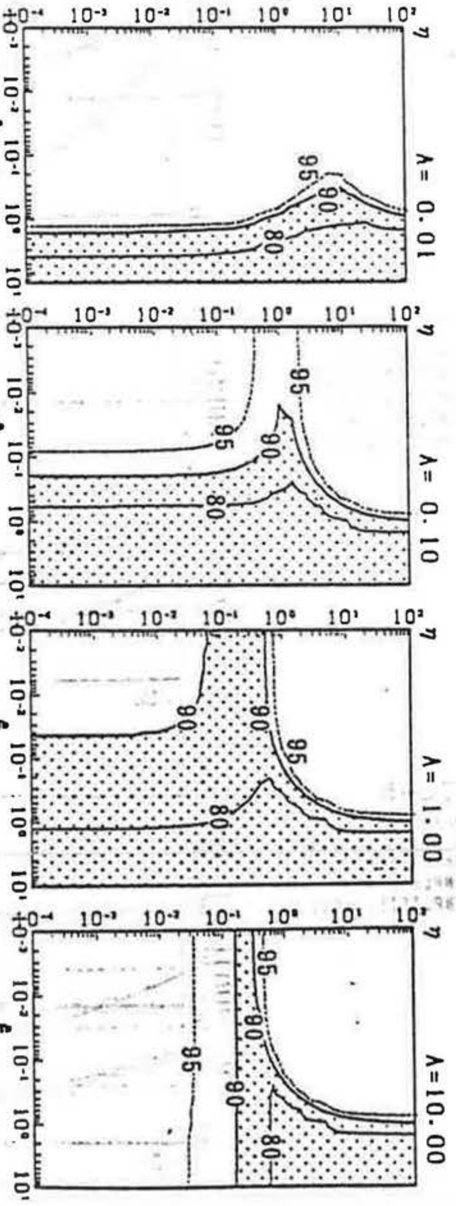


FIG-7.1 A=0.01
FIG-7.2 A=0.10
FIG-7.3 A=1.00
FIG-7.4 A=10.00

DISTRIBUTION OF WATER VAPOUR IN A ROOM; EXPERIMENTAL RESEARCH IN A CLIMATE ROOM

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INTRODUCTION

In building practice the water vapour pressure in every point in one room is often considered to be the same. One of the premises in the present moisture models is the ideal mixture of the air-vapour compound.

In order to verify this, indicative measurements are taken of the water vapour distribution in a room. One needs to gain an insight into water vapour distribution in order to interpret measurement data in problem situations and to study mould problems in building practice.

The research is executed by the FAGO Department (Physical Aspects of the Urban Environment) of the Faculty of Building Science and Architecture of Eindhoven University of Technology in the scope of the research "Damp Economy of Buildings".

EXPERIMENTS

During half an hour water vapour was produced in a climate room (LxBxH = 10x5x3.5 m^3) by boiling water on an electric cooker. The development of the vapour pressure (p) was determined by recording the relative humidity and temperature at various distances from this vapour source and at various heights.
In the measurement set up the position of the vapour source and the surface temperature of space boundaries, among other things, were varied.

RESULTS

In this abstract the results of one of the measurement-series are discussed.

Measurement set up of the main-serie, which will be discussed:
- the vapour source is placed in the middle of the climate room, at a height of 0.8 m above the floor;
- surface temperature of the walls: 293 K;
- surface temperature of the floor: 293 K.
- several positions of 4 temperature/humidity sensors and 4 air-velocity sensors. The sensors are all projected in a straight line (horizontal or vertical), see figures 1 and 2. The positions of the sensors are given by co-ordinates (x,y,x)
  x = horizontal distance from the vapour source to the probes (facing the short axis) [m];
  y = horizontal distance from the vapour source to the probes (facing the long axis) [m];
  z = vertical distance from the probe to the floor [m].
  Also, the position of the vapour source, in the experiment described below, can be given as (x;y;z)=(0;0;0.8);

Serie A1
Measurement set up: The horizontal distance from the vapour source to the points of measurement is 1m. Distances from the floor to the points of measurement (z-values) vary.

Right from the start of the water vapour production the vapour pressure near the ceiling (z=3m - z=3.5m) increases dramatically. The increase of vapour pressure is a lot less at z=0.05 and z=0.8m.
Vapour pressure gradients were built up over the vertical section during the vapour production ($\Delta p = p_{z=0.8m} - p_{z=2.9m} = 750$ Pa).

At t=30 min, when the vapour production is stopped, the vapour pressure against the surface of the ceiling first drops by leaps and bounds and then exponentially. At 30 cm below the ceiling the vapour pressure decreases more gradually. In contrast with these points, the local vapour pressure still continues to rise for some time at z=0.8 and z=1.6m.

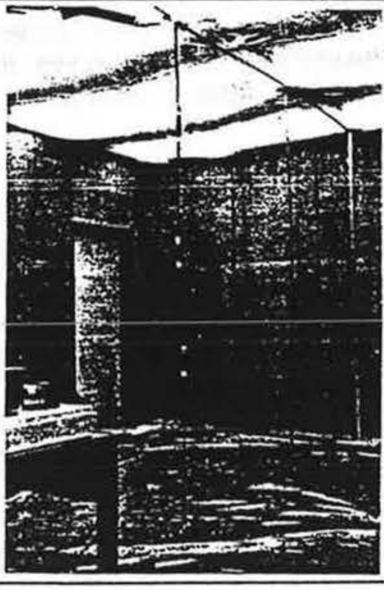

FIGURE 1: Vertical projection of the sensors

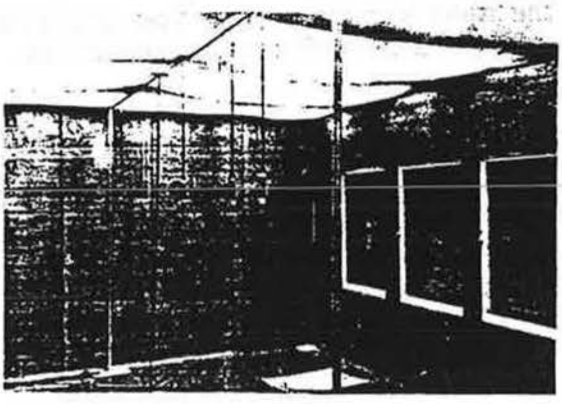

FIGURE 2: Horizontal projection of the sensors

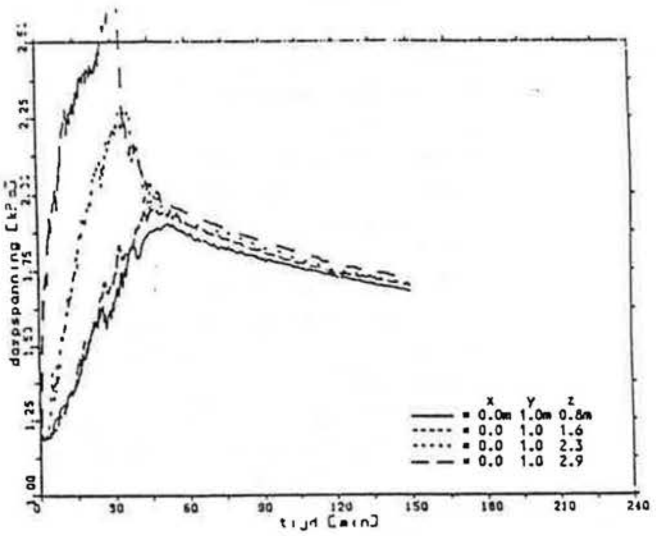

FIGURE 3: Results serie A1

About 20 minutes after removing the vapour source, the vapour pressure over the section is equal (see figure 3). This is called the "vapour pressure balancing period".

Serie A2
Measurement set up: The horizontal distance from the vapour source to the points of measurement is 2m. The distance from the floor to the points of measurement vary (see co-ordinates in figure 4).

At a height of z=1.6m, p_{max} is reached at t=45 min. After t=45 min, the pressure increases gradually. When z=0.8m and y=2m, the vapour pressure rises gradually from t=0 up to t≈60 min. The vapour pressure remains at a lower level in comparison to the other points of measurement. At t=90 minutes, the vapour pressures at the points of measurement in the vertical section are equal (i.e. the balancing period lastst about 60 minutes!).
At a height of z=2.9m, the maximum vapour pressure (p_{max}) at t=30 minutes is at y=2m much <u>lower</u> compared to p_{max} at t=30 minutes at y=1m. In contrast with this, at the hight of z=2.3m, p_{max} at t=30 minutes is <u>higher</u> at a distance of y=2m than p_{max} at a distance of y=1m;

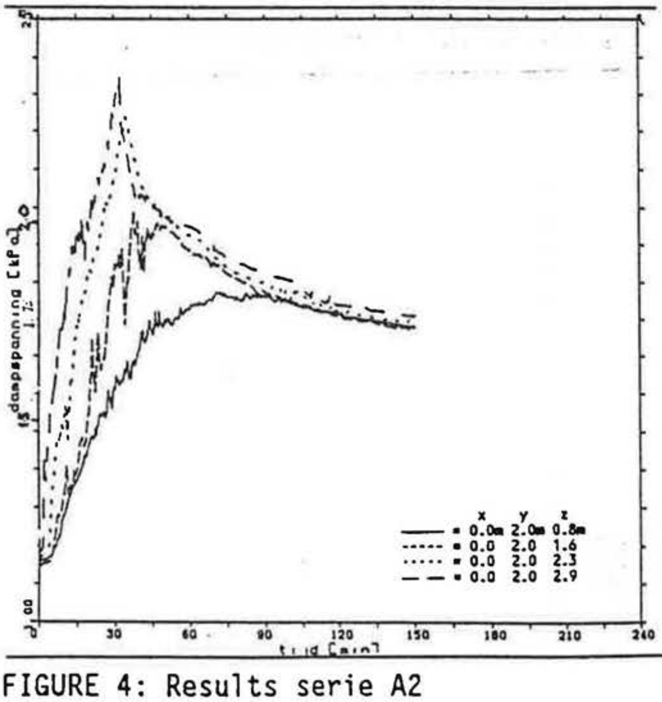

FIGURE 4: Results serie A2

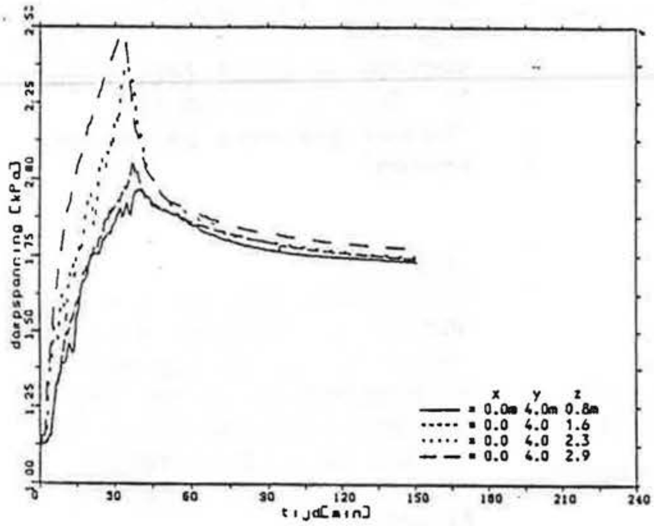

FIGURE 5: Results serie A3

Serie A3

Set up: y=4m, z-values vary.

There is hardly any difference in the course of the vapour pressure at y=3m and y=4m. However, at y=4m distance from the vapour source, the vapour pressure gradients that are built up in the period lasting from t=0 to t=30 minutes are not as big. The balancing period lasts about 10 minutes.
Near the wall (y=5m), the vapour pressure gradients are <u>smaller</u> than at a distance of y=4m.
The balancing period for both the distances y=4m and y=5m counts just a few minutes.

Serie A4

Measurement set up: Sensors are positioned at a height of z=2.9m. Y-values vary.

The gradients of the vapour pressures in horizontal sections is a lot less in comparison to the vapour pressure gradients that were built up in vertical sections.
It appears that after starting the vapour production the excess of the water vapour pressure is enormously at z=2.9m (i.e. near the surface of the ceiling) at all points of measurement varying from y=0.5 to y=5m (see figure 6). The shorter the horizontal distance to the vapour source the higher the vapour pressure during the vapour production.

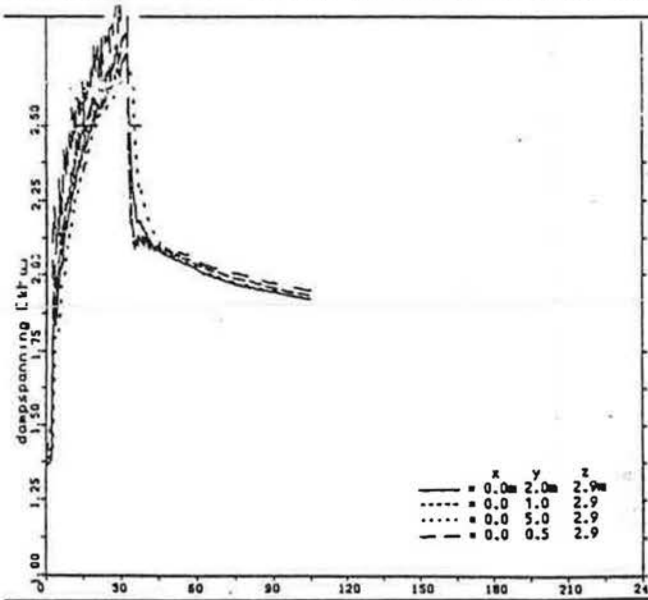

FIGURE 6: Results serie A4

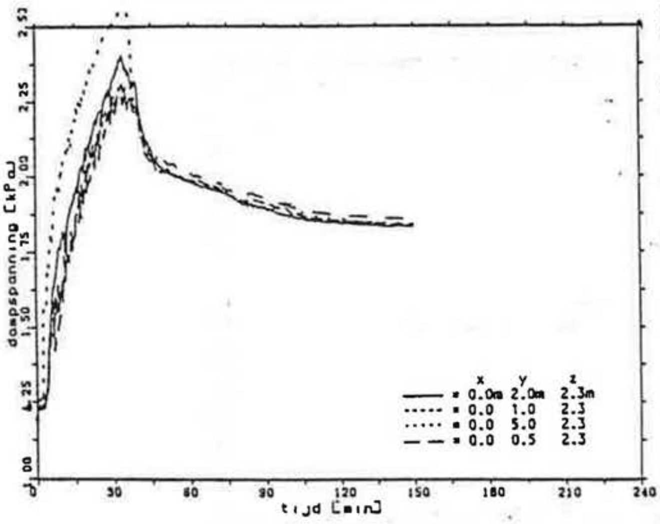

FIGURE 7: Results serie A5

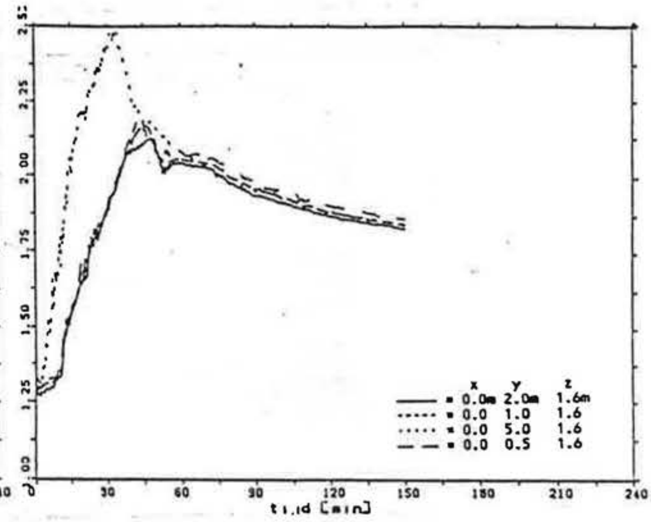

FIGURE 8: Results serie A6

The vapour pressure decreases during the vapour production when the horizontal distance to the vapour source is increased. The vapour presure gradient at location (x;y;z)=(0;0.5;2.9) and (x;y;z)=(0;5;2.9) is about 250 Pa.

After the vapour source is removed, the vapour pressure drops by leaps and bounds. There remains no significant vapour pressure gradient after t=30min.

Series A5 and A6

Set up: z=2.3m (serie A5)/z=1.6 (serie A6); y-values vary.

At horizontal distances of y=0.5, 1, 2 and 5m, and at the heigths of z=0.8, 1.6 and 2.3m, the course of the vapour pressures are more or less the same (see figure 7 and 8).

However, it is remarkable that the vapour pressure near the wall (y=5m) is much higher compared to the other points of measurement. This is caused by the air flow patterns.

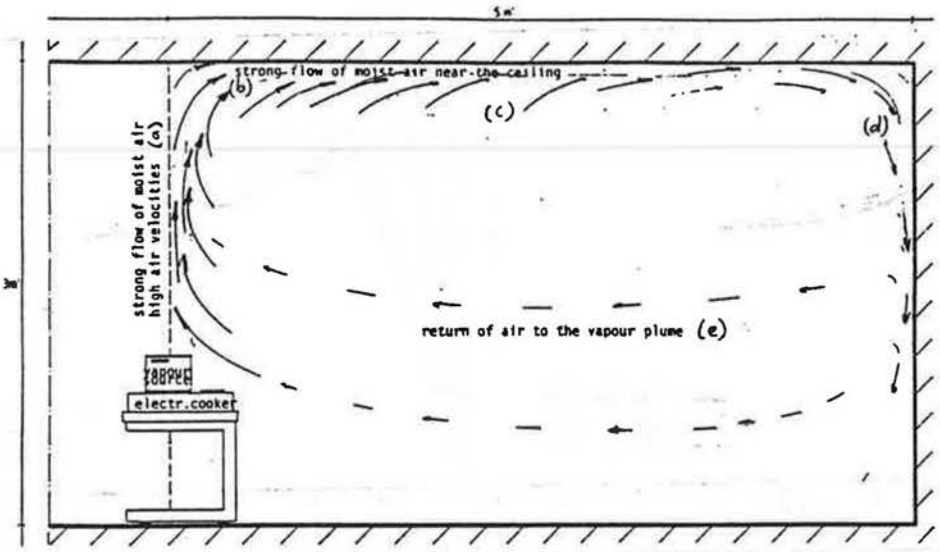

FIGURE 9: Pattern of air movements in the climate room during vapour production (cross section)

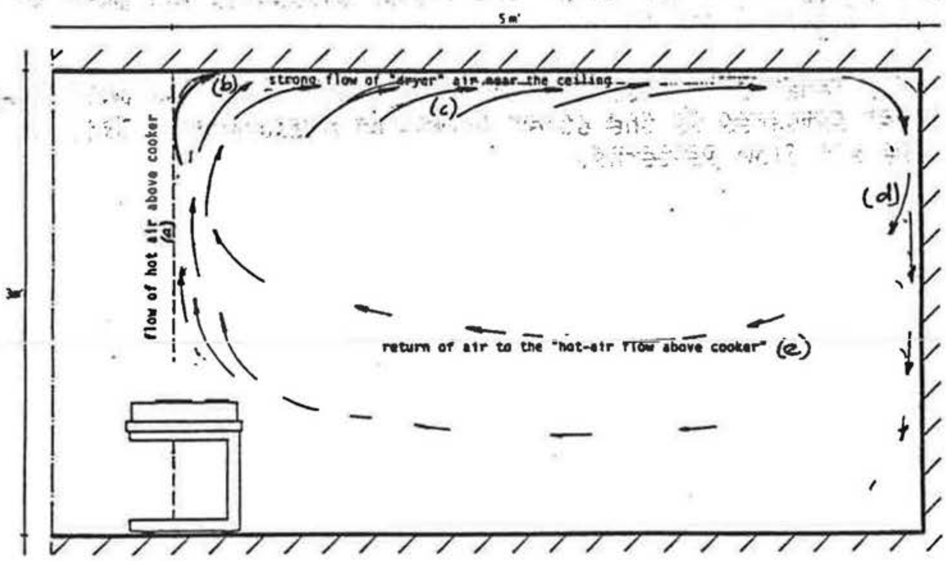

FIGURE 10: Pattern of air movements in the climate room immediately after stopping the vapour production (cross section)

Figures 9 and 10 show that the air flows and the air velocities determine both the development of the local vapour pressures and the balancing period:

During water vapour production (1):
1a- a strong flow of moist air rises from the vapour source to the ceiling, which causes exponential increase of the vapour pressure;
1b- moist air flows near the surface of the ceiling. The airvelocity is high. This causes a strong increase of the vapour pressure;
1c- mixture of moist air (near the ceiling) and "dry air" (in lower layers, the increase of the vapour pressure is less);
1d- moistened air bends near the walls;
1e- return of moistened air to the "vapour plume" above the vapour source (air velocities <5 cm/s). Mixing of air continues. Also, the vapour pressure in these lower laying areas rise gradually.

After stopping the water vapour production (2):
2a- a flow of hot air, mixed up with "dry air", rises from the electric cooker in the direction of the ceiling. The air velocities are high. This causes exponential decrease of the vapour pressure;
2b- flow of relatively dry air flows against the surface of the ceiling (high air velocities). This causes a strong drop of the local vapour pressure near the whole ceiling, because of the high air velocities at its surface;
2c- the aircirculation causes equalisation of the vapour pressure in the room, i.e. decrease of the vapour pressure in higher areas ($z > 1m$), increase of the vapour presser in lower areas ($z < 1m$);
2d- air with lower humidity bends near the walls (drop of water vapour pressure near the wall);
2e- return of the air to the "hot-air flow" above the electric coker ("recirculation").

CONCLUSIONS

During the production of water vapour, large vapour pressure gradients are built up, especially in vertical direction. These vapour pressure gradients can be explained by analysis of air flow patterns in the climate room.
The vapour pressure balancing period in the climate room in areas with $z \geq 0.8m$ lasts about 60 minutes.

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MOULDING AND GEOMETRY OF BUILDING SHELL

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1. WALL MOULDING AS AN ECOLOGY PHENOMENON

Ecesis of a microbe on a surface has two essential factors: accessibility and proper living conditions for elements of the microbe able to grow. In the case of fungi, viable elements are, on one hand, germinative reproductive elements /spores, conidia/, on the other hand, threads able to grow/hyphae/. These fungus bodies occur in air more or less profusely. Proper living conditions mean both availability of nutrients, and tolerance to surrounding /physical, chemical and biological/ conditions. Both aspects involve complex groups of interrelated factors. Availability of nutrients means harmonizing occurrence of nutrient components, subject to Liebig's law of minimum principle, stating that the chance of survival, growth or proliferation depends on the quantity of minimum nutrient. Though, Shelford's rule of tolerance to surrounding conditions states that any of surrounding conditions /temperature, atmosphere, reaction, etc./ has to be within the tolerance limits of the given being - different between species of fungi. These factors have a complex action, "interacting" with the former group.

The wealth of fungi comprises hundreds of thousands of species, decomposing organic matter of other beings or of artificial origin, absorbing a part in their bodies, while they absorb nutrients only in aqueous solution.

With a view on the presence of germinable elements, nutrients, living conditions involving temperature, light, atmosphere, it can be stated that because of the rather different tolerances between fungi, no real surrounding comprising the factors above can be created such as to exclude some types of mould. The only factor to be influenced by building structure and user's behaviour is moisture.

2. THE IMPORTANCE OF WATER

Water in fluid state is a material indispensable for living beings; living processes are biochemical reactions taking place in a moist medium. Therefore any living organism is only viable with a definite water content in its body. Water loss, drying out is "dangerous to life", survived by certain beings alone, but only at the cost of suspending their vital functions /anabiosis/, and continuing to live only after being in possession of the needed water quantity.

Accordingly, all the living beings, hence also fungi, need given, different quantities of water in their surroundings, closer, in their substrata. Part of surrounding water is needed to maintain the water content in their bodies,hence also atmospheric moisture reducing their evaporation is of importance, partly supplemented by water of fluid state absorbed from the surroundings. Though, chilotrophic nutrient absorption by fungi always required fluid water in the surroundings, namely they can only absorb nutrients in aqueous solution. Remind, however, that fluid water from outside is not only required for nutrient absorption, but in case of macromolecular nutriens also for digestion beginning outside the cell - since partly these are in no solution, and partly they are larger them to pass the cell membrane. Namely in this case so-called primary decomposing enzymes have to leave the cell again requiring fluid water in the surroundings, while water is both medium, and one reagent of reactions /hydrolysis/. All these point to the complexity of the "water problem", still aggravated by that of the water quantity a fungus is able to absorb from some surroundings. In this respect, water content in the surroundings or substratum is not critical alone. Vital processes being biochemical reactions involving solutions, obviously, also physico-chemical effects prevail. Thereby so-called free - rather than overall - water content of solutions is what counts. Molecules or ions of the dissolved material reduce not only water evaporation but also the quantity of "free" water to be absorbed by a living being, actually, a fungus. As a matter of fact, the numerical ratio between particles in solution, and water molecules is what counts. This is normally indicated by water activity /WA/ of solutions and aqueous substrata. Water activity is namely relative humidity percentage of air space to be kept in balance by the aqueous solution or the object with a water content.

Micro-organisms, hence also mould fungi, as aqueous systems, have a water potential or water activity. At the same time, also surroundings of the mould fungi /atmospheric humidity, fluid or solid matter/ have definite water potentials, water activities. Provided moulds have a lower water potential, water activity than that of the surroundings, the microorganism takes water from its environment, and if this is sufficient to start vital functions, the microorganism starts growing. In the oppo - site case, if water potential, water activity of the medium is lower, the microba looses water to its surrounding, its growth stops, at a marked exsiccation mould micelia may perish.

Fungi decisive in house moulding have several defense mechanisms preventing them to perish if the surroundings get dried out.

3. MACRO- AND MICROGEOMETRY OF THE BUILDING SHELL

Geometry conditions of the building shell affect moisture distribution in the structure.

If not with this very wording, but this is essentially the problem in examining parts of the building shell constituted by other than plane parallel slabs /corners, joints, thermal bridges/. Without omitting at all the importance of this paramount problem another, not less important microgeometric problem has to be pointed out, namely, pore structure of the inner surface layer.

According to traditional conception, moulding is due to surface condensation. In theoretical and laboratory investigations /1,2/ as well as in monitoring inhabited buildings /3,4/, it has become clear that capillary condensation in inner surface layers is a sufficient moisture condition of moulding. /According to later information by K. Gertis and Zs. Herbach, the same results are expected from actual tests actually made in the Institut für Bauphysik Laboratory./ These observations impose a new approach to mould tests.

Capillary condensation proceeds in dependence of air R.H. and of the material - surface layer - porosity. Material characteristics appear from the sorption isotherm, exhibiting monomolecular and polymolecular water absorption, and intervals of capillary condensation, and that is related to the distribution function of pore diameters.

As concerns accessible water affecting fungus growth, it is still of interest, how much surface materials, that is, the capillary walls, are hydrophilous, how they bind the thin - maybe monomolecular - water film, how this is helped, or just hampered, by materials dissolved from them.

These materials create micro-environments with different pH values and pH buffer capacities, that may definitely forward or prevent vital functions of fungi.

An important part of room linings are based on lime, hence contain calcium. In these materials, different calcium compounds get chemically transformed and the material hardens. This transformation is, however, incomplete, the process is not complete even after years. Its consequence is that the condensate water penetrating the material dissolves the alkaline calcium compound i.e. calcium hydroxide.

Alkalinization may affect living conditions of fungi, namely alkali neutralized acid metabolites, pointing out the high importance, in addition of the pH value, of the buffer capacity of the arising solution, that is, its neutralizing ability.

Another problem of importance is the capilary size distribution of the surfacing materials, whether they grant hyphae steric access to the contained water or not. In addition to the capillary size distribution, it also requires the knowledge of size distribution of hyphae of potential fungi /meeting other environmental conditions/. Since, however, this problem did not yet emerge from other aspects, and in identifying fungi, dimensions are of importance only for the formulae of proliferation, little else than some sparse data are found in the literature, referring to laboratory culture media rather than to natural substrata.

From the available scarce data it can, however, be stated that hyphae sizes range from some tenths of μm to some μm enabling them to penetrate such and wider capillaries, where water in fluid state is available. This latter may result from capillary condensation in the permeated capillary, or from capillaries anastomosing to the permeated cavity. Presence of hyphae in the cavities modifies, of course, geometry conditions - in the "constricted" space left between hypha and cavity wall, conditions of capillary condensation are altered, condensation comes about at a lower R.H.

Also capillaries impenetrable to hyphae are of importance. Namely, these "harmless" capillaries are able to bind and discharge much water on inner wall surfaces, of importance for taking up and discharging timely variable moisture loads, for its buffering action relieving outer walls.

4. ANTIMICROBIAL AGENTS

Presence of some materials in the surface layer may inhibit fungi from settling there. Namely, there are several natural or artificial materials /compounds, molecules/, able to inhibit vital function or some process of it of one or more representants of some groups /metabolism, growth, proliferation/ or to destroy them. In this respect there are significant differences between groups or species of living beings, the knowledge of which is of interest for the actual scope, since, on one hand, by incorporating antifungi in the surfaces, moulding may be prevented for a while, on the other hand, in reconstructing already moulded surfaces, the fungi in ecesis have to be destroyed. This requires, however, two aspects to be reckoned with: tolerance of fungi, and of man!

Remind that fungicides are of timely effect, since if they do not dissolve in water, then they don't act on fungi either, but if they do, then they get leached out of the surface by moistening, main cause of moulding /let alone decomposition/, while residua of some decontaminants may just act as nutrients.

5. CONCLUSIONS

Moulding does not require surface condensation, water present in capillaries in fluid state is sufficient.

Presence of water is determined by microgeometry, porosity of the inner surface layer. Inner walls and furniture should be such that have possible small-size capillaries safe from moulding are able to absorb and discharge much of water, enabling them to buffer timely variable moisture development.

In case of outer walls - because of lower surface temperature and higher R.H. - cavities still penetrable to hyphae, and water accumulating in them, are of importance. Because of the scarcity of data available, stil lengthy investigations are needed to establish distribution functions of pore and hypha diameters, underlying selection or even development of surfacings of the proper microgeometry. To then, relying on this qualitative description, supporting data, and practical poofs, to prevent moulding, air at 75% R.H. and at the same temperature as that of the surface has to be provided for by way of proper design and user's behaviour.

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