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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:

$$F = (C_d W/3)[gH^3\ \Delta T/T]^{0.5} \qquad (4)$$

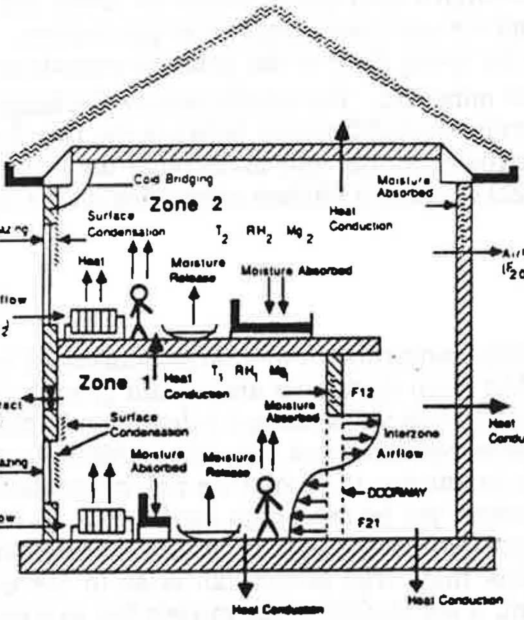

FIGURE 1. Interzone air flows in a house via a doorway.

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:

$$\sum_{i=0}^{N} F_{ij} = \sum_{i=0}^{N} F_{ji} \qquad (\text{for } 1 \leq j \geq N)(Fjj = 0) \qquad (6)$$

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.

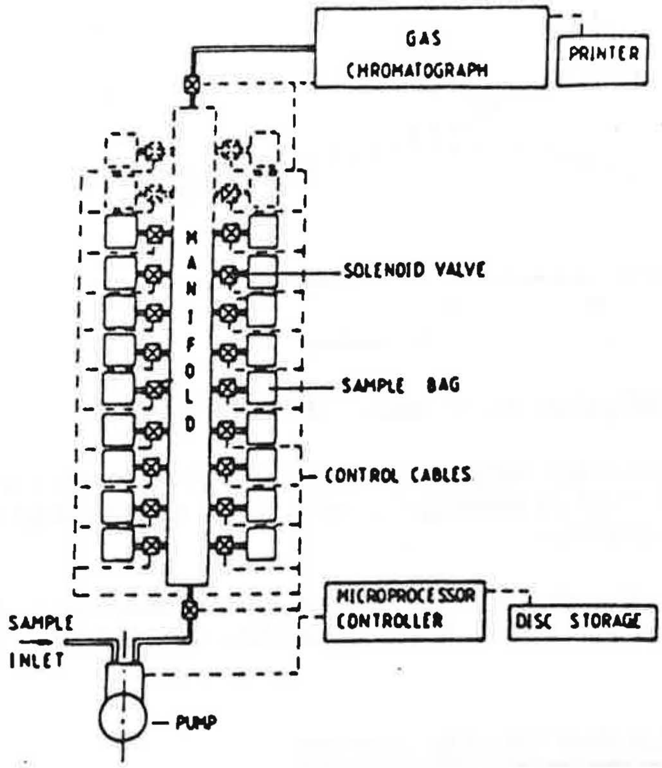

FIGURE 2. A microprocessor - controlled tracer gas system.

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.

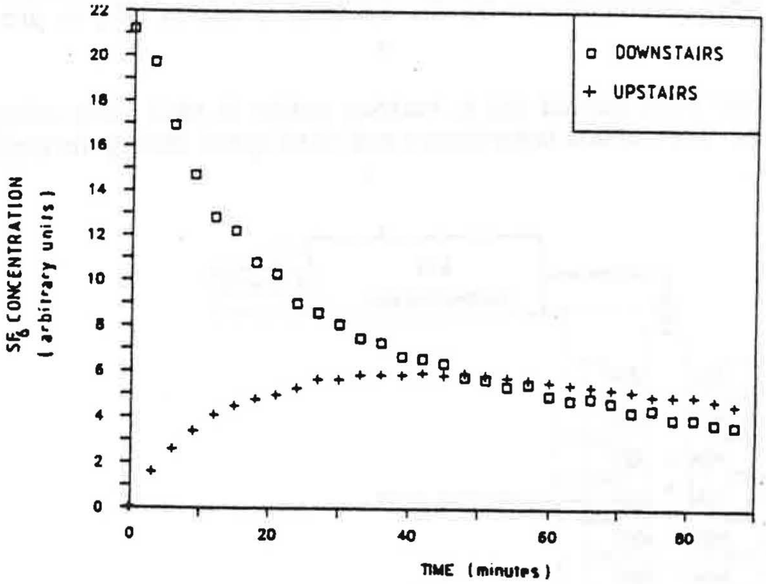

FIGURE 3. The decay of SF_6 tracer gas in zones 1 and 2; $\Delta T = 1.5^{\circ}C$.

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:

$C_d = 0.0835[\Delta T/T]^{-0.313}$ (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:

$M = 0.0278\rho W(gH^3)^{0.5}[\Delta T/T]^{0.187}$ (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

$d(d_{v1})/dt = F_{01}d_{vo} + F_{21}d_{v2} - F_{10}d_{v1} - F_{12}d_{v1} + M_{g1}$ (9)

Similarly, the rate of moisture increase in zone 2 is given by

$d(d_{v2})/dt = F_{02}d_{vo} + F_{12}d_{v1} - F_{20}d_{v2} - F_{21}d_{v2} + M_{g2}$ (10)

Assuming a steady-state moisture transfer in the two zones, eqns (9) and (10) become respectively

$F_{01}d_{vo} + F_{21}d_{v2} - F_{10}d_{v1} - F_{12}d_{v1} + M_{g1} = 0$ (11)

$F_{02}d_{vo} + F_{12}d_{v2} - F_{20}d_{v2} - F_{21}d_{v2} + M_{g2} = 0$ (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:

$$d_{v1} = d_{v0} + \frac{F_{21}M_{g2} + A_2V_2M_{g1}}{(A_1V_1A_2V_2 - F_{12}F_{21})} \qquad (13)$$

$$d_{v2} = d_{v0} + \frac{F_{12}M_{g1} + A_1V_1M_{g2}}{(A_1V_1A_2V_2 - F_{12}F_{21})} \qquad (14)$$

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.

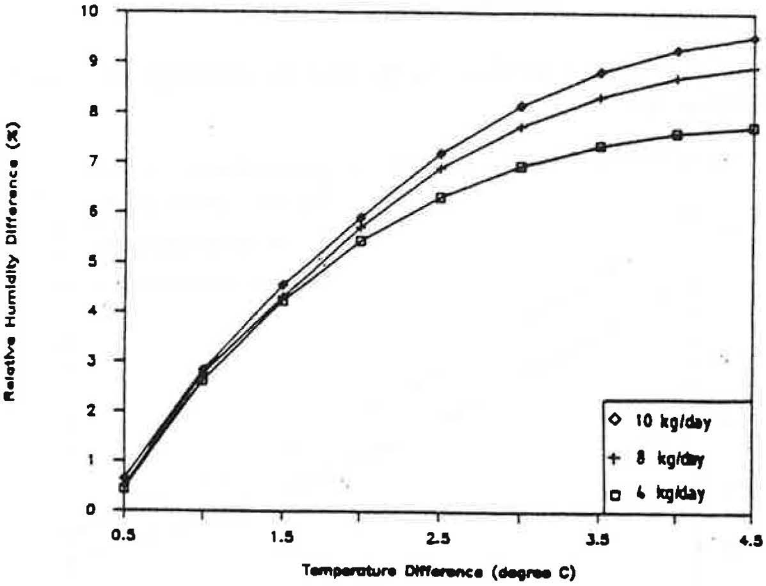

FIGURE 4. The variation of $RH_2 - RH_1$ with temperature; total moisture release rate of 4, 8 or 10kg/day (case a).

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.

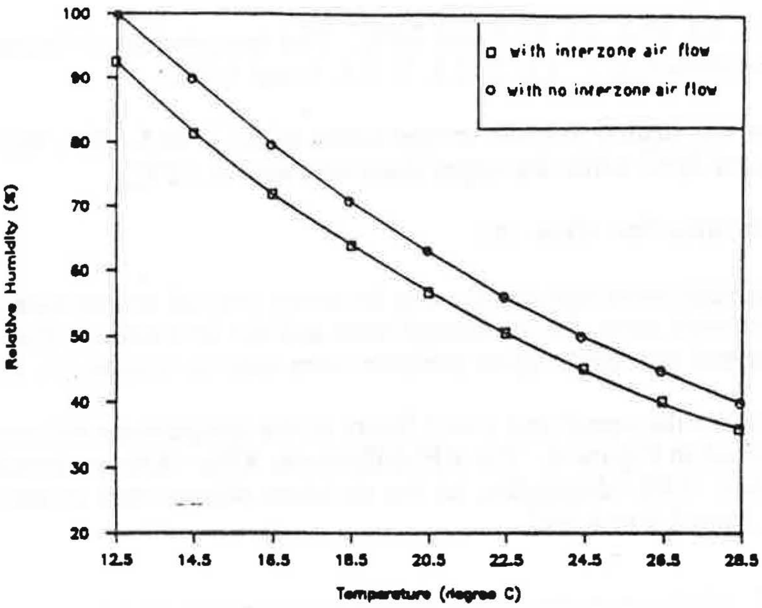

FIGURE 5. The effect of interzone air flow on the relative humidity in zone 1; total moisture release rate = 8kg/day (case a).

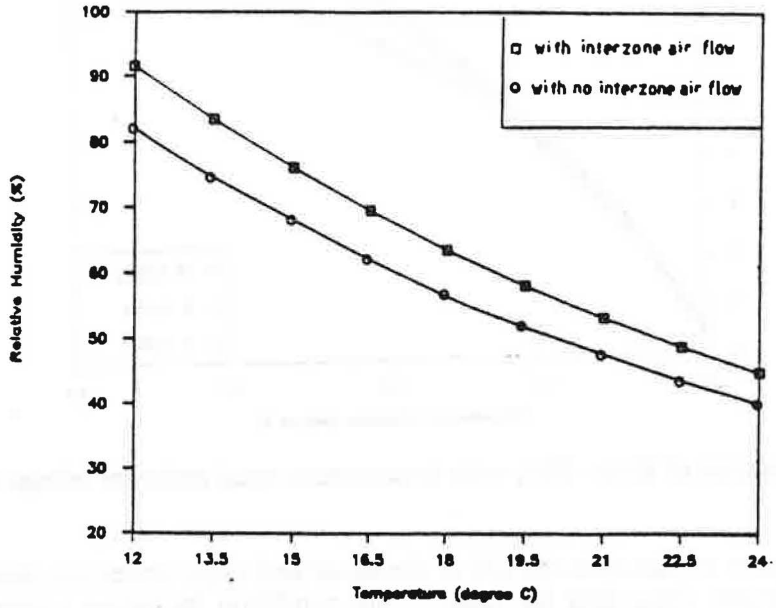

FIGURE 6. The effect of interzone air flow on the relative humidity in zone 2; total moisture release rate = 8kg/day (case a).

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 290m^3/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 231m^3/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 125m^3/h, compared with 105 and 97m^3/h when the extract fan was switched off.

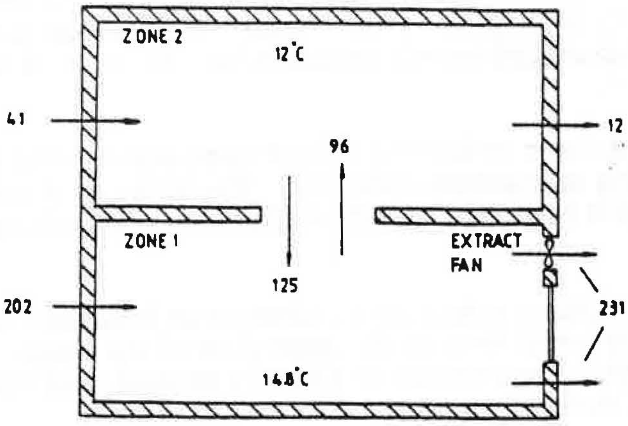

FIGURE 7. The effect of a kitchen extract fan on air flow patterns in the house, with central heating system switched off (units m^3/h).

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 180m^3/h while F_{10} was reduced from 231 to 121 m^3/h. The two tests indicated that the use of a 290m^3/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 m^3/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.

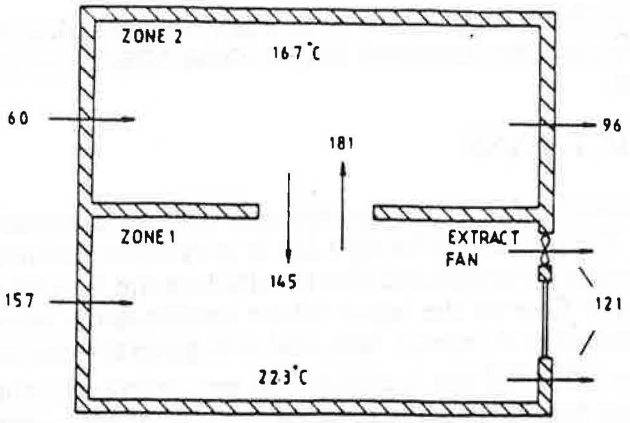

FIGURE 8. The effect of a kitchen extract fan on air flow patterns in the house, with central heating system in zone 1 switched on (units m^3/h).

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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