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A review and bibliography of ventilation effectiveness – definitions, measurement, design and calculation

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Annex V Air Infiltration and Ventilation Centre

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A Review and Bibliography of Ventilation Effectiveness – Definitions, Measurement, Design and Calculation

Martin W. Liddament

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PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Programme was formulated among a number of industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Programme, the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

As one element of the Energy Programme, the IEA encourages research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is encouraging various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programmes, building monitoring, comparison of calculation methods, as well as air quality and inhabitant behaviour studies.

The Executive Committee

Overall control of the R&D programme "Energy Conservation in Buildings and Community Systems" is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial. The Executive Committee ensures all projects fit into a predetermined strategy without unnecessary overlap or duplication but with effective liaison and communication.

Annex V Air Infiltration and Ventilation Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial groundwork the experts group recommended to their executive the formation of an Air Infiltration and Ventilation Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardisation of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and, based on a knowledge of work already done, to give direction and firm basis for future research in the Participating Countries.

The Participants in this task are Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States of America.

1. INTRODUCTION

Ventilation requirements are frequently expressed in terms of the overall "air change rate" necessary to fulfil ventilation needs. Implicit in this approach is the assumption that incoming air mixes uniformly with that already present in the building. In practice, the behaviour of internal air movement is not straightforward and much can happen to prevent the prescribed air change rate from providing the required level of ventilation. The degree to which a ventilation system fulfils ventilation requirements is variously described in terms of "ventilation effectiveness", "ventilation efficiency", "ventilation performance" and "local ventilation".

Laret [1] (in French) considers two aspects to ventilation efficiency; these are the need to maintain thermal comfort by avoiding excessive draughts and the need to achieve the maximum exhaust of contaminants from the occupied zone for any given ventilation rate. Similarly, Sandberg [2] defines ventilation efficiency in terms of the efficiency of controlling contamination. These ideas are, perhaps, universally accepted. The difficulty comes in representing these concepts in the form of a precise definition and in implementing an optimum ventilation approach. To achieve such objectives, many aspects must be considered. These include:

- an understanding of room air movement behaviour
- regard for thermal comfort requirements
- knowledge of the strength and location of pollution sources
- details of interzonal air movement and contamination characteristics
- occupancy details and definition of zone of occupancy
- building airtightness characteristics
- climatic data
- steady state and transient ventilation performance

Furthermore, the calculation of ventilation effectiveness or even the interpretation of experimental data can involve a high level of numerical complexity.

The objective of this report is to review the various definitions associated with ventilation efficiency studies and to outline the physical concepts, measurement methods and calculation techniques. It is not intended to present the mathematical detail since this is adequately covered by many of the articles referenced in the bibliography. Instead, the approach is one of outlining the background to ventilation effectiveness in terms of the need to provide both energy- and cost-efficient ventilation.

To assist in comparing the needs of different countries or climatic regions, the country of affiliation of authors referenced in the bibliography, combined with a brief subject index, is presented in Appendix 1.

2. CONCEPTS

2.1 Mixing and Air Movement

Ventilation effectiveness is related to the way in which fresh air and polluted air mix with the interior air mass within a defined zone or location. The pattern of room air movement is driven by a combination of the momentum of the incoming air and the convective currents created by the thermal heating (or cooling) effects of surfaces, heat emitters and occupants. There are three extremes of mixing condition. These are

(i) Displacement flow

This is also known as "piston flow" or "plug flow" and is normally regarded as the most "efficient" form of ventilation. Under these conditions, fresh air "displaces" contaminated air without actually mixing (Figure 1). In the industrial environment such ventilation is used to extract pollution at source by means of a fume hood and extractor fan. Make up air is supplied to the work space either by a separate mechanical supply system or by means of wall mounted passive vents. In the home, a similar objective is achieved by locating extractor points in the bathroom and kitchen and supplying fresh air to the living and bedrooms. Displacement ventilation in single rooms, such as offices, relies on thermal displacement in which fresh air at slightly below room air temperature is distributed at a low level and a very low speed (typically ∿ 0.1 m/s). This relatively dense air displaces the existing air mass which rises by convective heating and is extracted at ceiling level.

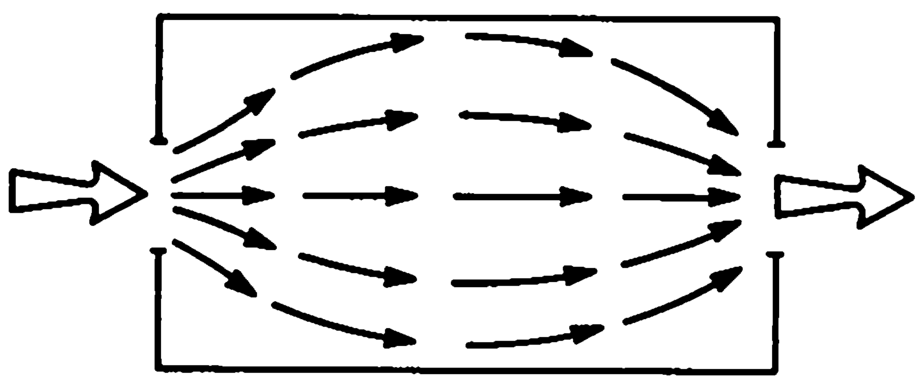

Figure 1: Displacement flow (reference 2)

(ii) Perfect mixing

Under conditions of perfect mixing, incoming air continuously and uniformly mixes with the interior air mass (Figure 2). This is the most common design intention for mechanically ventilated commercial buildings. Perfect mixing is frequently assumed to occur in individual rooms within buildings and is also normally assumed in numerical studies of ventilation and air infiltration.

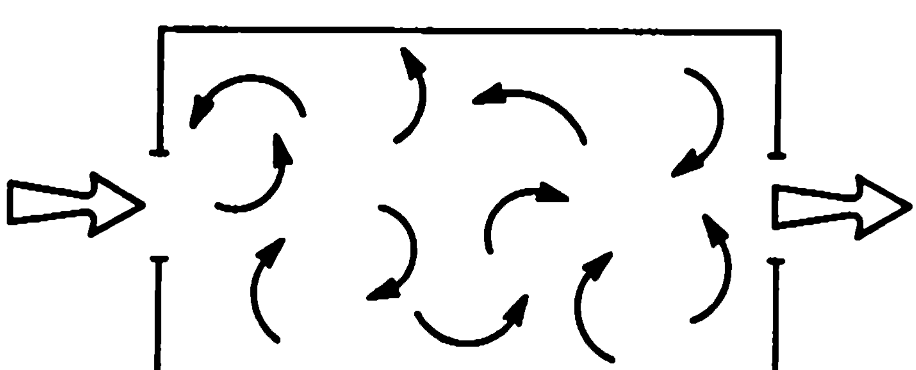

Figure 2: Perfect mixing (reference 2)

(iii) Short circuiting

This is the poorest ventilation condition in which fresh supply air is completely intercepted by the extract system without reaching the location at which ventilation is required (Figure 3).

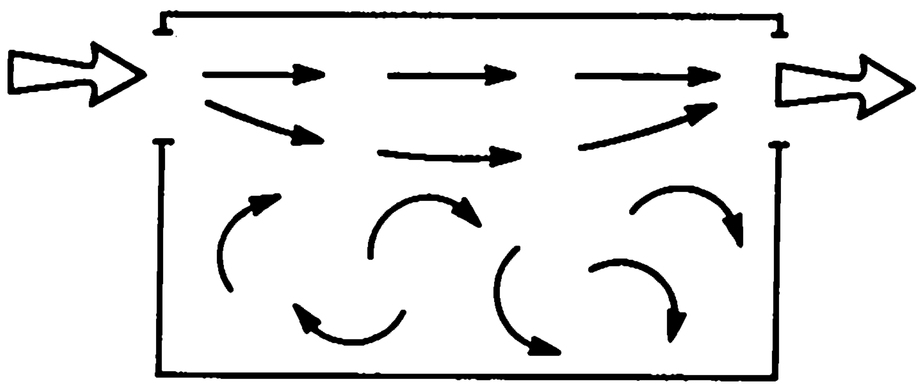

Figure 3: Short circuiting (reference 2)

In reality, a combination of these ventilation conditions will apply. Also conditions will be affected by occupancy and by the type and location of pollutants.

2.2 Comfort Conditions

In achieving optimum ventilation efficiency, the designer needs to be aware of comfort constraints. Of special consideration is the air temperature, velocity and thermal gradient within the area of occupancy. Comprehensive and detailed requirements for comfort conditions are covered in ASHRAE Standard 55-1981[3].

2.3 Zone of Occupancy

In some instances ventilation effectiveness relates to specific locations within a room or building, while in others it applies to the "occupied zone" or region in which ventilation is required. In the home or office this most probably coincides with the heated or air conditioned space. In industrial units it will be the zone in which the operative is located and therefore could be confined to a relatively small part of the total building volume. Also of importance is whether the zone itself is physically divided into further zones by means of internal walls. While many authors have applied the concepts of ventilation effectiveness to the confines of a single enclosed volume, some have applied these ideas to describe the differing rates of air and pollution exchange taking place in each room.

Ventilation effectiveness must thus be considered for the following conditions:

(i) A specific locality or localities within a zone.

(ii) Average conditions throughout a single zone.

(iii) Comparison of ventilation rates and pollution transfer between bounded zones or rooms.

2.4 Air Infiltration and Natural Ventilation

Excessive air infiltration will interfere with the design intentions of mechanical ventilation systems. In particular, air change rates and airflow patterns will become subject to the vagaries of climate. Similarly, under conditions of natural ventilation, air change is influenced entirely by the location and type of openings and by the driving forces of wind and temperature. This does not materially effect any definition of ventilation efficiency or any measurement approach but clearly the effectiveness should be expressed for the range of conditions to which the building is subjected.

2.5 Steady State and Transient Conditions

Sandberg[5] emphasises that, to fully characterise a system, its performance in both the transient and steady state phase must be considered. For example, in dwellings the longer term pollution level is most important but in industry, where perhaps there is a sudden release of toxic gas, the transient effect is important since it is necessary to know how rapidly the concentration can be brought below a required level. Sherman[5] shows how the behaviour of ventilation efficiency is strongly dependent in the time scale of interest. For long periods, e.g. weeks or months, the ventilation efficiency shows relatively little variation. On the other hand, for short periods, ventilation efficiency is very variable and correlates to the ventilation rate.

3. DEFINITIONS OF "VENTILATION EFFECTIVENESS"

Much progress has recently been made in defining ventilation effectiveness. Sandberg[4,6,7] suggests that ventilation efficiency should be used to express the ability of a system to evacuate pollution originating from a source in a room. He argues that it is not possible to make a single definition of ventilation efficiency that satisfies all requirements. The appropriate criteria of efficiency must be selected on a basis of what is regarded as the most desirable quality of the ventilation system.

To facilitate the determination of ventilation effectiveness, Sandberg defines a series of system parameters which satisfy the following criteria:

- They are general, in the sense that by using them the system performance can be assessed for different operating conditions.

- They can be measured with less effort than is required to simulate the actual operating conditions.

The following such parameters are defined

(i) Nominal air exchange rate.

This applies to the conditions of "perfect" mixing and is given by

$$n = Q/V_r$$

where Q = ventilation air flow supply rate
V_r = total room volume

This is the classical ventilation rate and, subject to uniform mixing, both the transient change in pollution concentration and the steady state concentration can be completely described by this parameter under conditions of perfect mixing.

(ii) "Age" of air, internal age (τ, τ_i)

When mixing is not perfect, the air entering any part of the room is a mixture of recirculated and "fresh" air. The "freshness" of the air and its dilution capability at a particular point is characterised by its "age". The "age of air" at a point is defined as the time, τ, that has elapsed since the air entered the room. This has also been called "internal age".

(iii) Age distribution, $A_j(\tau)$

The age distribution indicates the fraction of air with an age less than or equal to a reference time (τ).

(iv) Average age or local residence time.

This indicates the age of air at a point. The younger the air the better its dilution capability.

(v) Residual lifetime, τ_{ri}

This is the time a fluid element will spend within a room before leaving it.

(vi) Residence time, τ_r

Residence time is the age of a fluid element when it leaves a room.

(vii) Nominal time constant, τ_n

This is the inverse of the nominal air exchange rate, i.e. $\tau_n = \frac{V}{Q}$

(viii) Time duration of discharge.

The period over which a pollutant discharge occurs. A "brief" discharge is less than the nominal time constant, whereas a prolonged discharge will be much greater.

The exposure of a brief discharge is characterised by its maximum concentration and the total time integrated exposure. The exposure from a prolonged discharge is totally characterised by its equilibrium concentration. In other words, a brief discharge may be diluted by the surrounding air volume while a prolonged discharge is only diluted by the flow rate of air.

(ix) Turnover time, τ_t

The turnover time is the steady state room content of contaminant (M_∞) divided by the continuous emission rate, $\dot{m}$.

Note: For a contaminant released within a room, the mean residence time is equal to the turnover time.

(x) Effective flow rate, Q_{eff}

This parameter is defined by the equation

$$Q_{eff} = \frac{V}{\tau_t}$$

The effective flow rate is not a physical flow rate. It can be either greater than or less than the nominal flow rate. When complete mixing occurs it is equal to the nominal flow rate.

(xi) Mean internal age of contaminant, $\mu_\Phi^{(1)}$

The average length of time that a contaminant remains in the enclosure.

(xii) Local "purging rate" or local "purging flow rate", V_p.

This term expresses the net rate at which a contaminant released from a point source flows towards the extracts and from the room.

Based on these concepts, Sandberg presents the following definitions of ventilation efficiency. These are:

(i) Relative ventilation efficiency.

The relative ventilation efficiency expresses how the system's ventilation ability varies between different parts of a room. Using values of the steady state condition, the relative ventilation efficiency, ε_j^r, in a given point, j, in the room is defined as

$$\varepsilon_j^r = \frac{C_\int^s - C_t}{C_j^s - C_t} \times 100\%$$

where $C_\int^s$ = the concentration in the exhaust air terminal

C_j^s = the concentration at point, j

C_t = the concentration in the supply air terminal

Thus the efficiency is expressed with reference to the difference in concentration between the exhaust and supply air.

The value of the relative ventilation efficiency is always positive and can be greater than 1. When $C_j = C_\int$, then $\varepsilon_j^r = 1$. The relative ventilation efficiency is a measure of dispersion and does not take into account absolute concentration levels or concentration changes from the original concentration level.

(ii) Overall relative ventilation efficiency.

An overall measure of the relative ventilation efficiency is provided by substituting the mean concentration in the whole room, $\bar{C}$ in the definition above, in place of the local contamination concentration, C_j.

$$\bar{\varepsilon}^r = \frac{C_f - C_t}{C^s - C_t} \times 100\%$$

In terms of system parameters

$$\bar{\varepsilon}^r = \tau_n/\tau_t \times 100\%$$

$$= Q_{eff}/Q \times 100\%$$

The overall relative ventilation efficiency therefore provides an "averaged" value for the entire enclosure rather than a point value.

Another definition of ventilation efficiency proposed by Sandberg[7] relates to the maximum level of concentration in the room, C_{max}. This is given by

$$\varepsilon_{max} = \frac{C_f^s - C_t}{C_{max} - C_t} \times 100\%$$

At perfect mixing the room concentration is the same as the exhaust concentration and $\varepsilon_{max} = 100\%$. The efficiency will never exceed this value, therefore no distinction is made between plug flow and complete mixing.

(iii) Absolute ventilation efficiency.

Absolute ventilation efficiency expresses the ability of the ventilation system to reduce a pollution concentration in relation to the feasible theoretical maximum, i.e. it shows by how much a pollutant concentration in a space can be reduced but it does not indicate the time it takes to reach this condition.

$$\varepsilon_j^a = \frac{C(0) - C_j^s}{\Delta C_{max}} \times 100\% = \frac{C(0) - C_j^s}{C(0) - C_t} \times 100$$

where $C(0)$ = initial pollution concentration

ΔC_{max} = difference between the initial pollution concentration within the room and that of the supply (outside) air

C_j^s = concentration at point

(iv) Transient relative ventilation efficiency.

Transient relative efficiency is the term used to describe the effect of transient or non-steady conditions, for example, the rate of removal of a pollutant following the cessation of emission, i.e. the supply concentration $C_t = 0$. At the time, τ, the transient relative efficiency, $\varepsilon_{tr}(\tau)$, is given by

$$\varepsilon_{tr}(\tau) = \frac{C_j(\tau)}{\bar{C}^s(\tau)} \times 100$$

(v) Relative air diffusion efficiency.

One of the most important factors determining air quality is the flow pattern of the supplied outdoor air within the room. As a mean measure of how efficient the air flow is, the room average of the internal age of the supplied air may be taken, $\mu_\phi^{(1)}$, (previously defined by Sandberg as the mean internal age or average internal age of the contaminant).

A relative air diffusion efficiency for the whole enclosure can be defined as

$$\varepsilon_a = \frac{\tau_n}{\mu_\phi^{(1)}}$$

where τ_n = the nominal time constant

The theoretical upper limit of this parameter is 200% corresponding to plug or displacement flow. For a homogenous contaminant the room concentration is quantified entirely by the air diffusion efficiency. For other contaminants it can be used as an air quality indicator.

Skaret[8] defines the objective of the ventilation process as maintaining air quality in the zone of occupation. In this respect adverse air temperature can also be treated as a contaminant. Contaminant levels are expressed as concentrations, e.g. for chemical substances ppm or mg/m^3, and for heat kJ/m^3. He also indicates that almost all ventilation processes are governed by turbulent diffusion and that the turbulent diffusion constants are approximately similar for both heat and respirable air particles. However the performance of a system depends on the location of the source of contamination and on the density of contamination compared to the density of room air.

Skaret[9] provides two definitions of ventilation efficiency. These are:

(i) The ratio between the pollutant (tracer) concentration in the working zone under normal conditions and the concentration under fully mixed conditions.

(ii) The ratio between the concentration in the exhaust air and the concentration in the working zone (cf Sandberg's overall relative ventilation efficiency).

Both these definitions can be applied to both the transient and steady state. They provide both information on the rate of removal of contamination and, under steady state conditions, a measure of the system's capacity to keep contamination at a low level in the working or occupied zone.

In a more recent publication, Skaret[10] introduces a clear distinction between "efficiency" which he reserves for describing air flow characteristics, and "effectiveness" which he relates to the mixing and dispersion of pollutants. In particular he points out that while some contaminant sources are more or less evenly distributed throughout the room and behave approximately as the ventilation air, other contaminants develop their own flow patterns which are superimposed on the ventilation air flow pattern.

"Time" parameters are used to quantify ventilation efficiency and effectiveness. These are given as follows:

(i) Transit time, τ_n

This corresponds to Sandberg's "nominal time constant" and is the inverse of the air exchange rate under conditions of perfect mixing (normal air exchange rate).

(ii) Residence time for the air in the room, τ_r

The residence time refers to the age of air when it leaves the room. Skaret shows that, for complete mixing, the average residence time for room air is twice the transit time. For "plug" or "displacement" flow the residence and transit times are identical.

(iii) Average transit time for contaminant flow, τ_t^c

This parameter is analogous to transit time for air flow, τ_n, but relates to the flow of contaminant.

(iv) Local mean age, τ_i

The mean age of air at a specific locality, e.g. within the occupied zone.

The resultant definitions of ventilation efficiency and effectiveness are as follows

(i) Average air exchange efficiency, ($\langle\eta_a\rangle$)

This is defined as the ratio between the transit time for the ventilation air flow and the average residence time for the room air., i.e.

$$\langle(\eta_a)\rangle = \frac{\tau_n}{\tau_r} \times 100\%$$

For:

Stagnant flow	=	$0 < \eta_a < 50\%$
Complete mixing	=	$\langle\eta_a\rangle = 50\%$
Displacement flow	=	$50\% < \langle\eta_a\rangle < 100\%$
Complete displacement	=	$\langle\eta_a\rangle = 100\%$

This expression only reflects the gross flow pattern for the entire enclosure.

(ii) Local air exchange indicator, ε_a

This term relates the average age of the total air mass to that within the zone of occupation. If the air arrives at the zone of occupation sooner than to other parts of the room, the mean age of the air within this zone is lower than the room average mean age. On the other hand, if it arrives later the age is higher than average. The average age of room air, $<\tau_i>$, is always half the residence time. The local air exchange indicator is the ratio between the average and local age which is therefore given by

$$\varepsilon_a = \frac{\tau_r}{2\tau_i} \times 100\%$$

(iii) Local efficiency,

The local efficiency indicates the ventilation efficiency within the occupied zone or zone of interest and is

$$<\eta_a>\varepsilon_a$$

(iv) Average ventilation effectiveness, $<\varepsilon_v^c>$

This term is concerned with pollutant concentration. It is the ratio between the steady state contaminant concentration in the exhaust air and the steady state average concentration of the contaminant in the room. It is also equivalent to the ratio between transit time for ventilation airflow and the transit time for contaminant flow, i.e.

$$<\varepsilon_v^c> = \frac{C_e^{(\infty)}}{<C_i(\infty)>} = \frac{\tau_n}{\tau_t^c}$$

where $C_e^{(\infty)}$ = steady state exhaust concentration
$<C_i(\infty)>$ = steady state average foom concentration

Note: Under conditions of complete mixing $<\varepsilon_v^c> = 1$.

(v) Contaminant removal efficiency, $<\eta_v^c>$

Under conditions of complete mixing, the probability of a contaminant staying in the room is equal to the probability of it leaving, i.e. the probability of leaving is 0.5. As the transit time for contaminant flow tends to zero, the average ventilation effectiveness tends to infinity and the probability of the contaminant to leave the room tends to 1, i.e. expressed as a percentage this probability can be expressed as a contaminant removal efficiency by the expression

$$\langle \eta_v^c \rangle = \frac{\langle \varepsilon_v^c \rangle}{1+\langle \varepsilon_v^c \rangle} \times 100\%$$

In which case, for complete mixing

$$\langle \eta_v^c \rangle = 50\%$$

(vi) Air quality index, ε_v

This term replaces the efficiency concept and is the ratio between the concentration of contaminants in the exhaust duct and the concentration in the zone of occupation, i.e.

$$\varepsilon_v = \frac{C_e(\infty)}{C_i(\infty)}$$

This parameter can be used as a design guideline in which efforts should be made to maximise its value.

Janssen et al [11,12] used the concepts of ventilation efficiency to describe incomplete mixing within the occupied zone of a room ventilated by means of a typical supply/extract/recirculation system. A simple model representation was used in which the concepts of "stratification factor" and "recirculation factor" were introduced to describe ventilation efficiency in a mechanically ventilated office. These parameters are defined by the following:

(i) Stratification factor, s.

The stratification factor is the fraction of airflow that bypasses the occupied part of the room, thus the quantity (1-s) is mixed with room air.

(ii) Recirculation factor, r.

This is the fraction of the total return flow from the room that is recirculated.

(iii) Ventilation efficiency, η_v

In terms of stratification and recirculation factors, the ventilation efficiency is given by

$$\eta_v = \frac{1-s}{1-sr}$$

Offermann et al[13] relate ventilation efficiencies or local air exchange rates to the reference condition of perfect mixing. Three definitions of ventilation efficiency are considered. These are

(i) Nominal ventilation efficiency

This refers to the spatial increase in tracer gas decay rate with the operation of a "local" air-to-air heat recovery/ventilation systems compared with the increase that would occur in the reference case. This gives a global indication of the effectiveness of introducing a specific mechanical ventilation system but provides no spatial information on effectiveness.

(ii) Local ventilation efficiency

This is the relationship between the local air exchange rate observed at a sampling point with the ventilation system operating compared with the local air exchange rate measured at the same point when the ventilation system is not operating.

(iii) Relative ventilation efficiency

This is the relationship between contaminant or tracer concentration in the exhaust air stream compared with the concentration at an indoor location. In the reference case of perfect mixing, the resultant efficiency would be 100%. This definition compares with that of relative ventilation efficiency as used by Sandberg[4].

In addition to the above definitions of ventilation effectiveness and associated parameters, the following have been used by various authors in connection with this topic.

Skaret[14].
(i) Single room effectiveness.
(ii) Distribution effectiveness.

Skaret[15].
(i) Turnover time for contaminant flow.
(ii) Turnover time for ventilation airflow through the room.
(iii) Turnover time (average air exchange time) for the total volume of air in the room.

Dickson[16].
Median residence time or age, τ_S.
(The time taken for half the tracer gas or contaminant, following a pulsed discharge, to pass through the exhaust air terminal).

Sandberg[17].
Temperature efficiency.
(A measure of a system's capability to supply heat to the occupied zone).

Roussel et al[18].
Captive efficiency.
(This is defined as the fraction of airborne contaminants generated by a pollution source that is captured by a local exhaust ventilation system).

4. MEASUREMENT TECHNIQUES

4.1 Introduction

In many instances a "uniformly distributed" tracer gas is used to represent a homogeneous pollution source. Sometimes tracer gas is injected into the supply duct to trace the progression of "fresh air". Another alternative is for tracer gas to be injected at a specific point or zone within the building to represent a point source of pollution. Normally tests are conducted in the "transient" phase, i.e. the time varying behaviour of tracer gas over a period is monitored. These results may generally be used to analyse both the transient and steady state nature of ventilation effectiveness.

This section presents a general review of measurement techniques and is subdivided into sections covering general methods, measurements in large single zone buildings, multi zone buildings and naturally ventilated buildings.

4.2 General Methods

Sandberg[6,7] points to two methods for measuring ventilation effectiveness. These are direct measurements of air flow (anemometry) and tracer gas dilution. Of the first technique, Sandberg advises that the measurements themselves are extremely difficult and that advanced calculation techniques are required to determine the resultant distribution of pollutant in a room from such measurements. On the other hand, he states that the use of tracer gas is more attractive from a practical viewpoint and that this approach also enables a direct observation to be made of the system's capacity to "wash out" pollutant. Several tracer gas methods are considered and in each case the essence of the exercise is to measure the "transient relative ventilation efficiency" and the "steady state relative or absolute ventilation efficiency". The first technique proposed is the classical decay method in which tracer gas is uniformly mixed to an even concentration, C_o, the mixing fans are turned off, and the tracer gas decay is recorded at different locations. The second technique is the "source" method in which a constant concentration of tracer gas is monitored in the supply air and the increase in concentration in other parts of the room is monitored. The final technique is the "pulse" method in which a pulse of tracer gas is admitted to the supply air and the resultant rise and decay at points of interest is continuously recorded. In terms of numerical interpretation, the first two techniques are identical, although it is pointed out that a disadvantage of the "decay" technique is that the velocity field created by the ventilation system is affected by the mixing fans.

There are several ways of analysing the data. Where the decay (or rise) in tracer gas concentration is measured at several locations in an incompletely mixed system, Sandberg concludes that

- the decay rate varies initially both with location and time, but after a certain period of time it becomes constant and equal at each location.

- when the decay rate is constant and equal at every point, it reflects only the overall ventilation rate.

- no unique "local air change rate" can be defined for the whole process from the slope of the tracer gas curves.

- it takes a certain period before the differences in ventilation efficiencies have completely taken effect.

Although the decay rates themselves provide little information on ventilation efficiency, the differences in concentration at each location can be utilised since the ratio between the concentration in the exhaust duct and at any point within the room may be used as a measure of the "transient relative ventilation efficiency". Additionally, this ratio is shown to be proportional to the steady state efficiency.

Sandberg goes on to show that the transient ventilation efficiency may be represented by the areas under the dilution curves, i.e.

$$\varepsilon^{\tau r} \equiv \frac{\int_0^\infty C_f^{tr} d\tau}{\int_0^\infty C_j^{tr} d\tau}$$

where C_j^{tr} = the tracer gas concentration at an arbitrary point within the room at any given instant in time.

Assuming a "passive" pollution source, i.e. a pollutant that does not affect the velocity field created by the ventilation system, it is shown that from such data the residence time and steady state relative efficiency may be determined.

Not only do the results apply to a homogeneous passive pollution source but also to a point source within the room. In theory an infinite time must pass in order to execute an "under the curve" tracer gas analysis[3]. However, once the monitored decays are exponential, the remaining part of the decay curves may be readily calculated.

Sandberg concludes that the area of the dilution curve approach is a better defined measure of ventilation efficiency than either the slope of the decay curve or the ratio between decay curves at different locations. This is because all the information about the ventilation approach is taken into account and that the area represents a "smoothed" measure of the results.

Pederson[19] describes a measurement technique in which ventilation efficiency can be determined by measuring the tracer gas concentration at a single measurement point. The method is to measure the room air change rate during a cycle of complete mixing by measuring the tracer gas decay rate in the exhaust air duct. The measurement is then repeated with the mixing fans switched off. The ratio of the two air change rates is used as a measure of ventilation efficiency. Ventilation efficiency determined in this way is limited to expressing the average efficiency for the whole room without the possibility of indicating areas in the room of particularly high or low efficiencies.

4.3 Large, Single Zone Buildings

Dickson[16] describes the application of ventilation efficiency measurement techniques to large single zone enclosures with capacities varying from between 2650m^3 to 14000m^3. The ventilation efficiency at a specific location is measured by releasing a pulse of tracer gas at the chosen location and measuring the integrated concentration vs time at the exhaust terminal or duct, i.e. "area under the curve approach".

A "median" residence time or age, τ_S, is used to define the time taken for half the tracer gas to reach the exhaust air terminal. The ventilation efficiency can then be obtained by comparing τ_S with the median residence time which would occur if the air in the space was completely and uniformly mixed, τ_X. This latter value is inferred from the equation

$$\tau_X = 0.693/A$$

where A = average air change rate/unit time

Ventilation efficiency is equivalent to Sandberg's "relative air diffusion efficiency"[20], i.e.

$$\varepsilon = \frac{\tau_X}{\tau_S}$$

The air change rate, A, is determined from the tracer concentration decay rate during the latter part of the test.

Skaret[21] considers the solution of industrial ventilation problems by the use of small scale physical flow models in which water is used to represent air flow. The basis for scaling is the Archimedian Number, A_r, together with geometric scaling. An advantage of this approach is that velocities in water models are very low, thus the time scale is correspondingly increased with the result that "slow motion" visualisation of the flow pattern is possible. Secondly it is very easy to observe flow patterns with the use of dyes.

4.4 Multi Room Buildings

Skaret and Mathisen[14] emphasise the need to differentiate between single room effectiveness and distribution effectiveness (air flow between rooms) in multi-room buildings. The air flow rate between rooms can be determined by tracer decay starting from a condition of uniform mixing throughout the building. It is theoretically possible to calculate the flow of outside air to each room and the flow of air between rooms by solving the complete mass balance equation but, more generally, the flow of outside air to each room is determined by performing a constant concentration tracer gas test.

Sandberg and Blomqvist[22] describe multi-zone ventilation efficiency measurements in dwellings fitted with mechanical extract and with balanced ventilation system. The efficiency tests were undertaken by releasing nitrous oxide into each room and mixing with fans. A constant concentration was maintained to determine the flow rate of outdoor air into each room. The mixing fans and gas release were then stopped and the decay in tracer concentration used to determine the mean age of air in each room and the mean age of all the air present in the house. For the kitchen tests, 3.6 litres of tracer gas were released in the room and thoroughly mixed. The gas concentration in other rooms was then monitored to determine the degree of transfer. This test was repeated for the bedroom.

Janssen et al[11] present a series of tracer gas measurements which illustrate incomplete mixing in mechanically ventilated offices. Tracer gas was injected into the supply duct and the decay in concentration was measured in the return register in each room. A typical decay curve illustrated a distinct change in gradient after a period of time, indicating an apparent high initial air change rate followed by a lower steady state "equilibrium" rate. The apparent difference was attributed to the incomplete mixing of supply air. In other words, air from the supply registers circulated across the ceiling to the return registers without mixing in the occupied zone.

Harrje[23] describes a number of techniques suitable for measuring airflows and ventilation effectiveness in multizone buildings. He shows that dilution of single tracer is adequate for a well coupled two zone building whereas multiple tracers are needed to characterise flows among more zones. Particular attention is devoted to the description of the constant concentration technique using a single tracer. It is stressed that although this method does not fully characterise all interzonal airflows in the building, it can be useful in analysing the dilution of indoor pollutants and the ventilation efficiency.

Persily[24,25,26] describes in considerable detail problems associated with the measurement of ventilation effectiveness in large multi-zone office buildings. He especially addresses difficulties associated with air recirculation systems and the interaction of air infiltration with mechanical ventilation. The use of decay techniques and constant tracer injection are described. However, Persily states that techniques to measure ventilation effectiveness in buildings with ventilation systems operating with recirculation are not yet complete and only limited evaluation is possible.

Fisk et al[27] have developed a comprehensive automatic multi-tracer gas system for measuring ventilation rates and overall and local ventilation efficiencies in large buildings. The system includes a programmable tracer gas injector and a sampler which is capable of collecting up to thirty samples of air.

4.5 Natural Ventilation

So far measurements have been concerned with mechanically ventilated enclosures in which an extract and/or supply duct has been a paramount requirement. Freeman et al[28] discuss the theoretical concepts and measurement of ventilation efficiency in a naturally ventilated multi-zone dwelling. The purpose of the tests was to provide an insight into the relative ventilation efficiency of each room and to obtain an indication of the exposure to an airborne contaminant. Constant concentration measurements were made to determine (i) the overall fresh air change rate and (ii) the individual room fresh air change rate. Tracer gas decay tests were then performed without artificial mixing to determine the local ventilation rate. Comparisons of the two sets of results gave the ventilation efficiency of each cell and an idea of air quality in each room. Further details on air movement between rooms were obtained by injecting tracer gas in one room and following its progression to all the remaining rooms.

The decay commenced from a condition of uniform concentration C(0) throughout the house. The local ventilation rate in each room, r, was then determined by

$$r = \frac{C(0)}{A}$$

where A = the integrated exposure or area under the concentration vs time curve.

This local ventilation rate was compared with the fresh air exchange rate as determined by the constant concentration technique. A local ventilation rate comparable with the fresh air exchange rate corresponds to perfect mixing, while the larger the local ventilation rate, the greater the ventilation efficiency. Results of measurements for both "homogenous" pollution, i.e. starting from uniform pollutant concentration, and for point pollution showed that with internal doors open good mixing was achieved. Also it was shown that mixing between floors is better when the house is heated than when it is not heated.

Maldonado and Woods[29] also consider the measurement of ventilation efficiency in a naturally ventilated dwelling. Essentially the efficiency is measured in each room using the "area under the tracer gas curve" method of Sandberg[4]. A reference case is chosen which in this case relates to tracer gas decay in the living room. Thus the local ventilation efficiency in each room was compared to the living room value. Mixing fans were used to uniformly mix SF_6 tracer gas. Injection was then stopped, the air circulation system turned off and interconnecting doors closed. The concentration decay in each room was then measured using multi point sampling and a single gas sampler. Maldonado concludes that, even if the quantification of the ventilation efficiency is not immediate, ranking of the performance of the different zones is. This technique was subsequently used by Maldonado and Woods[30] as a procedure for field surveys of indoor air quality in energy efficient residences.

5. DESIGNING FOR AIR QUALITY AND THE REMOVAL OF CONTAMINANTS

The key requirement for ventilation is the need to remove contamination and to maintain adequate indoor air quality. Meyringer[31] suggests that a ventilation system claiming to be efficient must meet the following requirements:

(i) It must establish hazard-free air quality.
(ii) It must satisfy user comfort.
(iii) It should be energy efficient.
(iv) It must be cost effective.

While measurement techniques provide a method for observing the behaviour of ventilation systems for a specific set of conditions, they do not necessarily provide design information for replication elsewhere. This problem has been approached in a number of ways.

Sandberg[32] (in Swedish) notes that while there is no universally accepted term for describing the efficiency of ventilation in terms of pollution removal, there is now sufficient data to determine the difference in ability of different ventilation systems to evacuate pollution. He further argues that the most adequate single parameter, when assessing health effects, is the mean value of contaminant exposure, both with regard to time and space.

Skaret[33] has developed a set of design rules. These are:

(i) Air exchange efficiencies should be greater than 50% (perfect mixing) and the local age of air in the occupied zone should be greater than the average age.

(ii) Contaminant concentration in the occupied zone should be less than the room average. If conditions close to the contaminant source cannot be properly controlled by general ventilation, then local elimination techniques must be applied.

The most common approach to producing design guidelines has been to undertake systematic studies in which the behaviour of many combinations of ventilation strategy have been monitored under controlled conditions. This has enabled inferences to be made regarding the optimum approach to ventilation for a specific range of conditions.

Sandberg and Svensson[17] present the results of a series of ventilation efficiency measurements in which the following parameters are systematically varied:

(i) The position of supply and exhaust registers.

(ii) The ventilation air flow rate.

(iii) The temperature of the supply air relative to the mean temperature in the occupied zone.

The tests showed that the ventilation efficiencies vary considerably between different ventilation configurations depending on the supply temperature and the placing of registers. The best efficiencies were obtained with the supply and exhaust registers mounted far apart and when the air was supplied in a direction opposing the action of thermal forces.

In a subsequent publication Sandberg et al[34] report on the results of over 100 tests on 6 different warm air systems. The temperatures and the removal of tracer gas were monitored at several locations and the data used to determine both the temperature and ventilation efficiencies. For each system systematic adjustments were made to air flow rates and supply temperature.

Sandberg further outlines a series of experiments illustrating the performance of the following ventilation configurations:

(i) Supply and extract terminals located in the ceiling.

(ii) Supply terminal located in the ceiling and extract terminal located at floor level.

(iii) Supply terminal located at floor level and extract terminal located in the ceiling.

Contaminants of varying density were released for both unoccupied and simulated occupancy conditions. These tests showed that parallel flow systems, where the air and the contaminant moved in the same direction, gave rise to the lowest average room concentration. This implies that a "light" contaminant is best evacuated by a floor-to-ceiling system. However, Sandberg[35] emphasises the need to consider the effects of secondary flows, e.g. occupants. A system that works well as a parallel flow system in an empty room may, when occupied, change to a "counter flow" system.

Malmstrom and Ahlgren[36] also describe the results of systematic tracer gas tests involving occupancy. These showed that "displacement" ventilation, in which air was supplied at a low level and extract took place at ceiling height, gave the lowest concentration of contamination in the occupied zone.

In another series of tests, Boman[37] describes the results of measurements made on balanced supply/extract mechanical ventilation systems, in which the location of the supply registers and the temperature of incoming air was varied. In each case the exhaust terminal was located above the occupied zone. Highest ventilation efficiencies were obtained for the supply of air at low level, while the most common supply configuration in which air is supplied above the occupied zone was found to cause a certain amount of shortcircuiting. An improved measure of ventilation efficiency was obtained by supplying air at a slightly lower temperature than that of the ambient air within the room.

Skaret and Mathisen[38] describe a series of field measurements illustrating the benefits of displacement ventilation. Ventilation air is supplied to the occupied zone at low velocity and at slightly lower temperature than that of the room air. Paalanen[39] (in Finnish) also shows that "piston" or "displacement" ventilation is more efficient than "mixing" for removing impurities.

Martinsen[40](in Norwegian) reports on the results of measurements of ventilation efficiency in a full scale model of a small office and shows that higher air flow rates give lower pollution concentrations in the occupied zone. On the other hand, increased heat gains give higher concentrations of pollution.

Skaret[15] emphasises that air and contaminants distribute differently in a ventilated space. He outlines a series of experiments which were made partly to demonstrate the usefulness of age analysis to assess air quality and to describe the flow patterns in a ventilated space, and partly to examine how details like ventilation schemes, heat sources and types of contaminant sources influence the removal of pollutant. He shows that the average air exchange effectiveness alone does not account for air quality in the zone of occupation. The measurement of the "turnover time" for the contaminants improves the information and gives the correct "qualitative" information. On the other hand, measurements of the actual concentration of contaminants give the most accurate information.

Revzan[41] analyses the effectiveness of contaminant removal using range (cooker) hoods and window fans. Results tended to be highly dependent on environmental conditions while in all cases the results indicated the importance of free convection in pollutant transport. Maki and Woods[42] provide an analysis of the dynamic behaviour of pollutants generated by indoor combustion. They show that in non-steady conditions it is invalid to assume that pollutants from a local source disperse uniformly throughout the building. This has important implications in evaluating ventilation effectiveness. Sandberg[43] compares the performance of several ventilation configurations in minimising pollution concentration.

6. NUMERICAL CALCULATION TECHNIQUES

Multi-zone infiltration or interzonal airflow methods such as those outlined in the Air Infiltration and Ventilation Centre's Calculation Techniques Guide[44], provide the basis for predicting infiltration rates, exfiltration rates and the effects of air leakage on mechanical ventilation. They may also be used to estimate airflow patterns and airflow rates between interconnecting zones. In essence the assumption of perfect mixing within each zone is made and, subject to this condition being satisfied, the dilution and dispersion throughout a building of a homogenous contaminant or the time variant concentration within a single room may be predicted. Herrlin and Malmstrom[45] give examples of the use of this approach for simple combinations of two rooms. Calculations of local concentrations, ventilation efficiency and air exchange efficiency are presented for a variety of ventilation schemes. Railio[46] and Klobut[47] also describe the application of interzonal airflow models for ventilation efficiency calculations.

Where perfect mixing within a room or zone cannot be assumed, the numerical computation of air movement and convective heat transfer within each room must be considered. Such an approach involves a considerable degree of numerical complexity involving the simultaneous solution of either the 2- or 3-dimensional equations of Momentum, Energy and Mass. Whittle[48] presents a comprehensive review of this subject in which the fundamental conservation equations are described and a numerical procedure for solving the elliptic partial differential equations is outlined. An example of a room air movement study is presented and special attention is given to consideration of the appropriate boundary conditions. The evaluation of ventilation system performance by means of 3-dimensional numerical computation is also described by Ishizu[49]. He uses this method to determine the optimum positioning of an air inlet in relation to the outlet, whereby the most effective ventilation can be obtained. Commercial software is available from organisations listed in Appendix 3.

The application of 3-dimensional airflow calculation techniques to the problem of air movement in rooms is relatively new and presents a major research field in a subject which has important implications in the design of energy efficient ventilation.

7. VENTILATION EFFECTIVENESS STANDARDS

Standards covering the definition and measurement of ventilation effectiveness are under consideration.

The proposed IEA Annex "Optimisation of Air Flow Patterns" (Appendix 2) is intended as an international progression towards standards. National standards are mentioned in the literature by Nielsen[50] (in Danish) whonotes that ventilation efficiency is not referred to directly in current Danish (DIF) Standards since it is unclear how optimum ventilation efficiency can be achieved under different operating conditions. Blomqvist et al[51] (in Swedish) describe proposals for a Nordic Test Method for measuring ventilation effectiveness, while Skaret and Sandberg[52] (in Norwegian) describe more recent work on producing ventilation effectiveness guidelines for the Nordic Ventilation Group.

8. CONCLUSIONS

There is a diverse, confusing range of definitions associated with ventilation effectiveness. In some instances individual authors have not always been consistent with terminology while in other instances different authors may have used different expressions to represent the same parameter. Despite these difficulties the fundamental concepts behind the subject are fairly straightforward and it should not be too difficult to agree on a restricted and universally acceptable range of definitions to cover all aspects of the subject. It is hoped to cover this in a future AIVC report.

Ventilation effectiveness measurements have been made in many varieties of buildings. Calculation methods could provide valuable design information. However, such techniques are computationally very complex, and demand considerable detail regarding building detail.

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ABSTRACT
Ventilation efficiency involves two aspects, to preserve thermal comfort, draughts should be avoided and yet one tries to obtain the best "sweeping out" which corresponds with a maximum exhaust of contaminants from the occupied zone for a given flow rate.
Reports study of 75 tests of ventilation efficiency made in a climatic room representing a heated living room. Thermal comfort was tested by measuring the air velocity both in the ventilation jet and in the occupied zone. Mixing of the ventilating air was measured by recording the concentration of a tracer gas at about 10 points inside the room.
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ABSTRACT
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KEYWORDS
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KEYWORDS
ventilation efficiency, air movement,

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KEYWORDS
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ABSTRACT
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KEYWORDS
air movement, tracer gas, rooms, nitrous oxide, decay rate, mechanical ventilation, ventilation efficiency

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1. Expressions for ventilation efficiency
2. Methods for measuring ventilation efficiency
3. Rules for acheiving efficient ventilation.
Derives expressions for ventilation efficiency in a room by using two-box theoretical model, assuming thermal stratification occurs. Measures ventilation efficiency by the tracer gas steady state method, using N2O and an infra red ga analyzer. Uses a series of probes placed in a vertical column and put in different positions in the room for gas detection. Sampling, analyzing and movement of the column are done automatically using a microprocessor. Tests show that the efficiency varies considerably between different ventilating systems. Finds that the best system for warm air ventilation is with the air supply located just below the ceiling and the air exhaust near the floor, and vice-versa for cool air ventilation. Therefore "diagonal schemes" seemm to be the most efficient, and more efficient then complete mixing.
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ventilation efficiency, air change rate

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ABSTRACT
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The paper shows that age analysing techniques are an excellent tool to assess ventilation effectiveness. It is important to differentiate between air exchange effectiveness and contaminant removal effectiveness, having continuous generation of contaminants. Only when a source is homogeneous and passive, are the age of the air and the contaminants in the room equal. However, the air exchange effectiveness accounts for the removal effectiveness of the contaminant left in the room when the generation stops. Tests reported

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KEYWORDS
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Gives measurements of the ventilation as well as the temperature efficiency of mechanical supply and exhaust systems (balanced systems). The ventilation efficiency is a measure of the performance of providing air in the occupied zone and is also an indicator of the air quality. The temperature efficiency is a measure of the system's capability of supplying heat in the occupied zone. Monitors ventilation efficiencies by adopting tracer decay techniques and the temperature efficiencies by measuring the stationary temperatures. In experiments, the following quantities are varied systematically.
1. The positioning of supply and exhaust registers.
2. The ventilation air flow rate.
3. The temeperature of the supply air relative to the mean temperature in the occupied zone.
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KEYWORDS
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AIC bk, AIC 1842
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KEYWORDS
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KEYWORDS
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ABSTRACT
A comprehensive theoretical framework is presented, based on the use of moments of concentration histories ie multiplying concentration readings by time of reading and then integrating with regard to time. The concept can be used to characterize either the diffusion of the supplied air or a contaminant released within the room. Results are presentd from about 50 measurements demonstrating the usefulness and practical applicability of the approach for assessing air quality in ventilated buildings. Different experimental

procedures have been explored and are discussed.
KEYWORDS
air quality, pollutant,measurement technique, tracer gas,

21.
Skaret E
NO 2213 Industrial ventilation - model tests and general development in Norway and Scandinavia.
BIBINF
Ventilation '85. (Chemical Engineering Monographs 24). Amsterdam, Elsevier, 1986. Edited by Howard D Goodfellow. p19-31. 6 figs, 10 refs. DATE 00:00:1986 in English AIC bk, AIC 1916
ABSTRACT
Ventilation studies using small-scale water models have, especially in Norway gained new and important knowledge in industrial ventilation the last 15 years. The outcome has been twofold. First of all it has resulted in important experience in making small-scale model tests for ventilation studies. Secondly, it has increased the knowledge in where to apply and how to design efficient displacement ventilation systems. In most industries the displacement principle is outstanding compared to other principles for general ventilation. The displacement direction is generally vertical-up, providing for supply of fresh air directly to the workspace. In most cases thermal stratification can be utilized to optimize the effectiveness for the systems. Effective- ness is sensitive to the diffuser design for the supply air. It is also necessary to avoid using the ventilation system for space heating (cov- ering the transmission losses). Research results and practical applications have developed hand in hand and have also resulted in new understanding and practical definitions of the ventilation effectiveness as well as calculation methods, the two-zone model, and design guidelines for displacement ventilation systems.
KEYWORDS
industrial building, modelling

22.
Sandberg M, Blomqvist C
NO 1788 Exploration of ventilation strategies in domestic housing. Theory and experimental results.
BIBINF
6th AIC Conference "Ventilation Strategies and Measurement Techniques", Het Meerdal Park, Netherlands, 16-19 September 1985. Bracknell, UK: Air Infiltration Centre, 1985. p15.1-15.22. 5 figs, 1 tab, 3 refs. DATE 00:09:1985 in English AIC bk
ABSTRACT
The performance of whole-house mechanical ventilation systems was explored in a full-scale indoor test house (volume 176 m3). A range of parameters were monitored: 1, the pressure distribution 2, the inflow of outdoor air to each room, the mean age of air in each room and the air exchange effectiveness 3, the spread of a contaminant released respectively in the kitchen and in the bedroom. The tests were undertaken both with the internal doors closed and with the internal doors open. Both a mechanical extract system and balanced (combined) systems were tested. The tests were undertaken for a specific flow rate equal to 0.5 house volumes/hour (total flow rate 88 m3/h). The fundamental concepts used are defined at the beginning of the paper. The concepts are in accordance with those currently proposed in Scandinavia. In particular the relevant meaning of the concept air exchange rate is discussed. Then follows a short description of the test house and the measuring procedures adopted. Finally the results obtained are given.
KEYWORDS
house, ventilation strategy, air change rate, ventilation efficiency, tracer gas, nitrous oxide, measurement technique

23.
Harrje D T, Dutt G S, Bohac D L, et al.
NO 1862 Documenting air movements and infiltration in multicell buildings using various tracer-gas techniques.
BIBINF
Preprint. ASHRAE Transactions 1985, Vol 91, Pt 2. HI-85-40 No 3. 15p. 11 figs, 18 refs. DATE 00:00:1985 in English AIC 1267
ABSTRACT
Tracer gas techniques for measuring airflows in buildings fall into three categories - dilution, constant injection, and constant concentration. Dilution of a single tracer works well in buildings with a single zone and also in some two-zone buildings. Multiple tracer gas measurements, necessary to characterize flows among more zones, are best conducted using the constant injection approach. The constant concentration method uses a single tracer gas to determine the air flow rates from the outside into each of as many as ten building zones. The paper outlines the different tracer techniques for making airflow measurements in multicell buildings and describes the operation of a constant concentration system. This system measures tracer gas concentration in different zones and injects accordingly to maintain a constant concentration in each zone. The system was tested in a single zone structure and successfully applied to a small three-zone house. Sensitivity analyses and calibration procedures described in this paper define the capabilities and limitations of this technique. Although this method does not fully characterize all interzone airflows in the building, it can be useful in analyzing the energy balance of multizone buildings. Additionally, these measurements can be used to evaluate the dilution of indoor air pollutants and the ventilation efficiency of buildings.
KEYWORDS
multi-chamber, tracer gas, measurement technique, decay rate, constant concentration, constant emission, air movement, air infiltration

24.
Persily A K, Grot R A
NO 1810 Ventilation system performance evaluation using tracer gas techniques.
BIBINF
6th AIC Conference "Ventilation Strategies and Measurement Techniques", Het Meerdal Park, Netherlands, 16-19 September 1985. Bracknell, UK: Air Infiltration Centre, 1985. p26.1-26.16. 2 figs, 3 tabs, 12 refs. DATE 00:09:1985 in English AIC bk
ABSTRACT
This paper discusses existing and recently developed tracer gas techniques for the in situ evaluation of ventilation system performance. Past work on whole building infiltration and ventilation measurement is discussed and the major findings reviewed. The use of tracer gas to measure ventilation effectiveness in mechanically ventilated buildings is also discussed. While techniques exist for such measurements under conditions of 100% outside air intake, the evaluation of systems operating with recirculation is more difficult. Techniques appropriate to this latter situation are not yet available, but some limited evaluation is possible. Measurement procedures are also described to separately measure the intentional outside air intake through the air handlers and the amount of uncontrolled air leakage through the building shell. The results of the application of these techniques in a three-storey office building are presented and discussed.
KEYWORDS
office, high rise building, measurement technique, tracer gas, sulphur hexafluoride, ventilation efficiency, mechanical ventilation, air infiltration, decay rate, air change rate

25.
Persily A K
NO 1877 Ventilation effectiveness in mechanically ventilated office buildings.
BIBINF
Gaithersburg,USA: Department of Commerce, National Bureau of Standards, 1985. NBSIR 85-3208. 39p. 9 figs, 2 tabs, 27 refs. DATE 00:08:1985 in English AIC 1282
ABSTRACT
Mechanical ventilation systems in large office buildings are designed to meet space conditioning loads and to maintain acceptable indoor air quality. In order to achieve acceptable air quality, the ventilation systems are designed to bring in a minimum amount of outside air whenever the building is occupied. In addition to minimum outside air intake levels, there must also be adequate distribution of this air within the building. Although the net ventilation rate of a building or room may be sufficient, poor air distribution may lead to some areas within the space being inadequately ventilated. The concept of ventilation effectiveness has been developed to quantify the air distribution characteristics of a ventilated space. This paper examines several definitions of ventilation effectiveness and associated tracer gas measurement techniques. Techniques for making ventilation effectiveness measurements in mechanically ventilated office buildings are discussed with reference to building and mechanical equipment design and tracer gas instrumentation. Specific strategies are proposed for measuring ventilation effectiveness on different scales ranging from individual rooms to whole buildings.
KEYWORDS
ventilation efficiency, measurement technique, tracer gas, mechanical ventilation, office

26.
Persily A K, Grot R A.
NO 2155 Measurements of ventilation rates and ventilation effectiveness
BIBINF
Recent Advances in Control and Operation of Building HVAC Systems, CIB, Trondhei m, Trondheim, Norway, 22-23 May 1985, 53-63, 3 figs, 1 tab, 12 refs. DATE 00:05:1985 in English AIC 1539.
ABSTRACT
Describes how multizone tracer gas analysis techniques can provide a complete description of office ventilation. Treats the concept of ventilation effectiveness to characterise internal air distribution. Discusses the measurement of whole building ventilation rates and ventilation effectiveness in mechanically ventilated office buildings.
KEYWORDS
air change rate, measurement technique, tracer gas, office, multi-chamber, ventilation efficiency

27.
Fisk W J, Binenboym J, Kaboli H, et al.
NO 1977 A multi-tracer system for measuring ventilation rates and ventilation efficiencies in large mechanically-ventilated buildings.
BIBINF
6th AIC Conference "Ventilation Strategies and Measurement Techniques", Het Meerdal Park, Netherlands, 16-19 September 1985. Bracknell, UK: Air Infiltration Centre, 1985. Supplement. p69-92. 5 figs, 4 tabs, 18 refs. DATE 00:09:1985 in English AIC bk
ABSTRACT
Measurement of ventilation rates and overall and local ventilation efficiencies in large buildings is often complicated by the building size and compartmentalization, and by the presence of multiple ventilation systems. To allow characterization of the ventilation process in such buildings, a unique

experimental system that employs multiple tracer gases is being developed at Lawrence Berkeley Laboratory. The tracer gases include sulphur hexafluoride and several halocarbons. The system is designed to be non-obtrusive, highly automated, and relatively easy to install in buildings. Included in the system is a programmable tracer-gas injector that automatically initiates and terminates the process of tracer injection and regulates the injection rate. One injector will be used for each tracer gas. Another component of the system is a programmable sampler that collects up to thirty small samples of air in containers that can be mailed to the laboratory for analysis. One sampler will be placed near each sampling location. Because each tracer gas injector and sampler is a stand-alone device, long runs of tubing are not required to inject tracer or take samples. The concentrations of tracer gas in the air samples are determined using a gas chromatograph with an electron capture detector. An overview of the experimental system is given and a description of the tests undertaken to validate its performance. Various methods of using the system to assess ventilation performance will also be discussed briefly.
KEYWORDS
mechanical ventilation, ventilation efficiency, tracer gas measurement technique, automatic equipment

28.
Freeman J. Gale R. Sandberg M.
NO 1068 The efficiency of ventilation in a detached house.
BIBINF
3rd AIC Conference "Energy efficient domestic ventilation systems for achieving acceptable indoor air quality" September 20-23 1982 UK p.15.1-15.22 9 figs. 2 tabs. 3 refs. DATE 20:09:1982 in English AIC
ABSTRACT
Uses the SEGAS "Autovent" constant concentration apparatus to measure the fresh air entering and the local ventilation rate in each cell of a multi-celled dwelling with both natural and mechanical extract ventilation. Measures fresh air entry into each cell using tracer gas constant concentration and decay techniques. Conducts decay tests without artificial mixing, and interprets them by computing the area under the decay curve to obtain local ventilation rates. Compares the 2 measurements, giving the ventilation efficiency of each cell and an idea of air quality in each room of the house. Traces the pathways of air movement around the house by injecting an amount of tracer gas into one room and following the transfer to all other rooms of the house.
KEYWORDS
tracer gas, decay rate, constant concentration, ventilation efficiency, natural ventilation, mechanical ventilation,

29.
Maldonado E.A.B. Woods J.E.
NO 1189 Ventilation efficiency as a means of characterizing air distribution in a building for indoor air quality evaluation.
BIBINF
Preprint Ashrae Transactions 1983 vol.89 pt.2A and B 9pp. 4 figs. 3 tabs. 12 refs. DATE 01:01:1983 in English AIC 745
ABSTRACT
Air change rate is often reported as a single number, with no attention paid to different values of air change rate in different zones of a building. This may affect air quality evaluation as there may be undetected zones where air change rate is too small, resulting in localized pollutant concentrations. Describes a multi-point tracer gas technique used to quantify air change rate in different zones of various residential buildings. Defines and calculates zonal ventilation efficiency terms, and proposes a criterion for analysis of the results for indoor air quality evaluation.
KEYWORDS

ventilation efficiency, air change rate, tracer gas, measurement technique, air quality,

30.
Maldonado E.A.B. Woods J.E.
NO 1237 A procedure for field surveys of indoor air quality in energy efficient residences.
BIBINF
Proceedings of the 2nd International Congress on Building Energy Management 30 May-3 June 1983 Iowa USA 10pp. 1 tab. 9 figs. DATE 30:05:1983 in English AIC 785
ABSTRACT
Describes a field method for surveying residences for indoor air quality. The method requires 2 days of field testing for each residence - a day to perform a multipoint tracer gas study to characterize the ventilation efficiency of the various spaces in the house and to determine the overall air change rate; and a day to measure contaminant concentrations in locations selected according to the results of the tracer gas study and contaminant generation locations. Describes and discusses results obtained by this surveying procedure in 3 energy efficient residences.
KEYWORDS
air quality, tracer gas, ventilation efficiency, tight house, pollutant,

31.
Meyringer V
NO 2125 Ventilation systems in residential buildings: requirements to the design of systems and equipment.
BIBINF
Proceedings of the CLIMA 2000 World Congress on Heating, Ventilating and Air-Conditioning, Copenhagen, 25-30 August 1985. Edited by P O Fanger. Vol 6. Heating, ventilating and air-conditioning systems. p287-293. 6 figs, 7 refs. DATE 00:08:1985 in English AIC 1510
ABSTRACT
Evaluates results of the 'Ventilation in Residential Buildings' research programme of the German Federal Ministry for Research and Technology. It was found that conventional ventilation methods based on infiltration and window opening cannot secure proper air quality and at the same time provide energy conservation and user comfort, nor can intelligent ventilation habits be expected of the average user, for subjective and objective reasons. All ventilation systems evaluated had shortcomings. Soft displacement ventilation techniques taking advantage of natural buoyancy forces instead of contaminant dilution can be expected to provide major improvements in ventilation efficiency and user comfort in future.
KEYWORDS
ventilation efficiency, air quality, ventilation strategy, occupancy effects

32.
Sandberg M.
NO 1159 What is an efficient ventilation system?
Vad ar ett effektivt ventilationssystem?
BIBINF
VVS no.1 1983 p.69-72 3 figs. 1 tab. 9 refs. DATE 01:01:1983 in Swedish AIC 715
ABSTRACT
Notes that there is currently no generally accepted term for the efficiency of a system in terms of pollution removal. Different proposals have been suggested. There is now sufficient factual data to determine the difference in ability of different systems to evacuate pollution. This is despite the fact that the requirement for minimum flow is the same for all fan-assisted ventilation. The requirement is also unrelated to whether the system is an

extract or push-pull system and where the ventilation devices are positioned.
KEYWORDS
ventilation efficiency, pollution, mechanical ventilation,

33.
Skaret E
NO 2121 Effective ventilating systems. Characterization and design implications.
BIBINF
Proceedings of the CLIMA 2000 World Congress on Heating, Ventilating and Air-Conditioning, Copenhagen, 25-30 August 1985. Edited by P O Fanger. Vol 6. Heating, ventilating and air-conditioning systems. p205-213. 6 figs, 8 refs.
DATE 00:08:1985 in English AIC 1506
ABSTRACT
Displacement flow has been found to be the best flow principle for ventilation, with ventilating air being supplied to the occupied zone. The design procedure should, amongst other things, contain an analysis of contaminant source in order to design the ventilating system to create the most favourable flow pattern for the contaminants. This paper deals with design principles and problems related to displacement ventilating systems.
KEYWORDS
ventilation efficiency, ventilation strategy, air movement

34.
Sandberg M. Blomquvist C. Sjoberg M.
NO 1098 Warm air systems.Part 1 - temperatures and temperature efficiencies. Part 2 - tracer gas measurement and ventilation efficiency.
BIBINF
Swedish Building Research Institute Bulletins M82:22 and 23 1982 119pp and 153pp. DATE 01:10:1982 in English AICR SE20
ABSTRACT
Reports the results of over 100 tests of 6 different warm air schemes. The temperatures and the removal of a tracer gas were monitored at several points and the data used to determine the temperature efficiency and ventilation efficiency. For each ventilation the following values were varied systematically - the location of the supply and extract registers, the total ventilation rate, the supply-extract air temperature difference. In 1) presents the temperatures measured in two cross-sections of the room. The isotherms in each cross section are also presented plus the average room temperature efficiency and the average efficiency in the occupied zone. In 2) presents the tracer gas measurements. The concentrations were measured at 4 levels within the room and in the supply and extract duct. Presents concentration versus time graphs for all measuring points together with their statistical signatures, mean and standard deviation. Supplies in addition the local ventilation rate at the 4 levels and the average ventilation efficiency in the occupied zone.
KEYWORDS
ventilation efficiency, mechanical ventilation, tracer gas,

35.
Sandberg M., Sjoberg M.
NO 1626 A comparative study of the performance of general ventilation systems in evacuating contaminants
BIBINF
Indoor Air. Vol.5. Buildings, Ventilation and Thermal Climate. Edited by B Berglund, T Lindvall, J Sundell. Swedish Council for Building Research, 1984. 59-64, 4 figs, 8 refs. DATE 00:00:1984 in English AIC bk
ABSTRACT
Based on the age concept, the performance of the following three principle ventilation schemes have been monitored (supply air terminal - extract air

terminal), ceiling-ceiling, ceiling-floor, floor-ceiling. All systems used only air for both heating and cooling. Contaminants with both greater, less and approximately the same density as air were released at a point source. The tests were both carried out in an empty room and with a person (heated mannekin) in the room.
KEYWORDS
ventilation efficiency, air quality, nitrous oxide, helium, air flow, air movement

36.
Malmstrom T G, Ahlgren A
NO 1801 Efficient ventilation in office rooms.
BIBINF
Environment International, 1982, Vol 8, p401-408. 11 figs, 1 tab, 4 refs.
DATE 00:00:1982 in English AIC 1175
ABSTRACT
Results from a two-box model for calculation of tracer gas concentrations in rooms are given and consequences of different definitions of ventilation efficiency are discussed. Results from three different series of experiments are presented. The first two series were dilution experiments: examples of the results are given and discussed. The third series of tests was performed with one person working at a desk in the test room. Above the person's head, a tracer gas (N2O) was injected into the convection plume, with as low a momentum as possible. Starting with zero concentration, a test continued until steady-state conditions were established for the concentration levels in the different parts of the room. The tests included simulation of summer, autumn/spring and winter daytime conditions. The results indicate a tendency towards lower tracer gas concentrations in the "breathing zone" when the supply air (typical flow rate equivalent to two air changes per hour) is brought into the room at a low level as compared to a high level close to the ceiling. The exhaust air terminal device in all tests was situated high in the "corridor" wall.
KEYWORDS
tracer gas, ventilation efficiency, office, simulation, constant emission, multi-chamber, nitrous oxide

37.
Boman C.A.
NO 1069 Field trials of ventilation efficiency in buildings equipped with mechanical ventilation systems.
BIBINF
3rd AIC Conference "Energy efficient domestic ventilation systems for achieving acceptable indoor air quality" September 20-23 1982 UK p.14.1-14.12
7 figs. 2 refs. DATE 20:09:1982 in English AIC
ABSTRACT
Gives results from fiel trials of the performance of various mechanical ventilation systems. Carries out measurements in buildings built during the seventies, using the tracer gas decay technique with N2O. Tests 3 cases:
1. Air supplied only through register above door
2. Air supplied both through register and the slot under the door
3. Air supplied only through slot undr the door
Concludes that the slot under the door gives the highest ventilation efficiency. In another case, varies the temperature of the supply air to measure the effect on ventilation efficiency.
KEYWORDS
mechanical ventilation, ventilation efficiency, tracer gas, decay rate,

38.
Skaret E, Mathisen H M
NO 2054 Test procedures for ventilation effectiveness. Field measurements.

BIBINF
Recent Advances in Control and Operation of Building HVAC Systems, CIB, Trondheim, Norway, 22-23 May 1985, p64-75. 8 figs, 1 tab, 9 refs. DATE 00:05:1985 in English AIC 1420
ABSTRACT
Substantial work on ventilation effectiveness has been carried out in Norway and Sweden using tracer gas techniques based on fundamental physical and mathematical concepts. The nature of, and how to characterize by using tracer gas techniques, the flow of ventilation air and contaminants through a ventilated room is known. Displacement flow has been proved to be the best flow principle for ventilation, and in general ventilation air should be supplied to the occupied zone. Results of a field test of ventilation effectiveness are presented, showing how the experimental technique can be applied.
KEYWORDS
ventilation efficiency, air movement

39.
Paalanen K.
NO 1363 The efficiency of ventilation.
BIBINF
LVI no.3 1984 p.17-20 6 figs. 4 refs. DATE 01:01:1984 in Finnish AIC 877 AND IN Teknillinen Korkeakoulu LVI Laboratorio Sisailmastoprojekti. Report C2. Espoo. 1984. 106pp.in Finnish. AICR FI1
ABSTRACT
Discusses different ways of defining and comparing ventilation efficiency. It can be defined in absolute values ie the ability of the system to decrease the concentration of impurities in proportion to the maximum concentration. A time constant can also be used ie the time elapsed from the moment a determined flow of contaminant is started till the concentration of the contaminant in the air extracted has reached a constant value. An effective ventilation system will thus have a low time constant value. The principle of air distribution in a room is a determining factor in the ventilation efficiency. The "piston" method, where the supply air flow is pushing the impurities and no mixing takes place is the most efficient. The mixing method is the most common way of air distribution - where the concentration of impurities is the same in the whole room. Lab tests show that the piston method of air distribution renders efficiency up to 1.45x the efficiencies obtained with complete mixing.
KEYWORDS
ventilation efficiency, pollutant, air flow,

40.
Martinsen H.M.
NO 1300 Ventilation efficiency and diffuse air supply in small offices. Ventilasjonseffektivitet og diffus lufttilforsel i cellekontor.
BIBINF
Norsk VVS 1983 vol.26 no.11 p.862-866,870,885 8 refs. DATE 01:11:1983 in Norwegian AIC 822
ABSTRACT
Reports the results of measurement of ventilation efficiency in a full scale model of a small office with a diffuse air supply, which can be used to improve ventilation efficiency and therefore reduce air supply rates. Steady state and transient definitions of ventilation efficiency are given. Finds that ventilation efficiency depends on air flow rate and heat gain in the office. Higher air flow rates give lower pollutant concentration in the ocupied zone but also more mixing between the occupied and under-ceiling zones. Increasing heat gains give higher pollutant concentrations in the occupied zone and clearer demarcation between cool and warm zones (clean and polluted zones). A comparison is also made between diffuse air supply and

conventional diffusers.
KEYWORDS
ventilation efficiency, pollutant, air flow, office building,

41.
Revzan K L.
NO 1627 Effectiveness of local ventilation in removing simulated pollution from point sources
BIBINF
Indoor Air. Vol.5. Buildings, Ventilation and Thermal Climate. Edited by B Berglund, T Lindvall, J Sundell. Swedish Council for Building Research, 1984. 65-71, 4 figs, 1 tab. DATE 00:00:1984 in English AIC bk
ABSTRACT
The effectiveness of range hoods and window fans in removing indoor pollutants is considered. Tests were conducted in a two-room test space with an infiltration rate less than 0.1 hr-1 using sulphur hexafluoride as a tracer gas. Range hood tests were carried out with heated and unheated tracer gas. In the former case, ventilation efficiency was roughly linear over a range of flow rates from 10.3 to 60.0 l/sec., the highest measured efficiency being 0.77. With unheated tracer gas, effectiveness was highly dependent on environmental conditions. Window fan tests were conducted with the source of tracer gas in each of the two rooms, the fan itself remaining fixed. With the source in the room without the fan, fairly good agreement with a mass-balance model was obtained. With the source in the same room as the fan, agreement with the model was poor. In all cases, the results suggest the importance of free convection in pollutant transport.
KEYWORDS
ventilation, tracer gas, sulphur hexafluoride, pollutant

42.
Maki H T., Woods J E.
NO 1628 Dynamic behaviour of pollutants generated by indoor combustion
BIBINF
Indoor Air. Vol.5. Buildings, Ventilation and Thermal Climate. Edited by B Berglund, T Lindvall, J Sundell. Swedish Council for Building Research, 1984. 73-78, 1 tab, 6 refs. DATE 00:00:1984 in English AIC bk
ABSTRACT
When indoor air concentrations from indoor combustion processes are estimated, source strengths and ventilation rates are usually considered. Recent studies, conducted in the Energy Research House at Iowa State University, indicate that several other factors also have a significant effect on indoor air concentrations. In one of these studies, a ventless kerosene heater served as the source of pollutants. Resultant concentrations of NOx, CO2, H2O and air temperatures were monitored throughout the house. A tracer gas, SF6, was released in the house and at the same points as the pollutant concentrations. It is concluded that, in non-steady conditions, it is invalid to assume that pollutants from a local source disperse uniformly throughout a house. To the contrary, various pollutants are dispersed at various rates and additional research should be directed to these dynamic behavioural characteristics.
KEYWORDS
ventilation efficiency, air movement, pollutant, nitrogen oxides, carbon dioxide, water vapour, tracer gas, sulphur hexafluoride, air quality

43.
Sandberg M, Blomqvist C, Sjoberg M
NO 2221 Efficiency of general ventilation in residential and office buildings - concepts and measurements.
BIBINF
Ventilation '85. (Chemical Engineering Monographs 24). Edited by H D Goodfellow. Amsterdam, Elsevier,1986. p323-332. 2 figs, 4 refs. DATE

00:00:1986 in English AIC bk, AIC 1912
ABSTRACT
This paper gives a presentation of the current research being carried out at NSIB with the aim of exploring the effectiveness of ventilation systems in controlling contaminant levels. The key concepts used for quantifying the performance are; the age distribution of both air and contaminants. The air exchange effective- ness and the average ventilation efficiency are derived from the age distributions. Measurements of the performance of different ventilation s systems are given, expressed in terms of the key concepts above. Results from both single room applications and whole houses or buildings are reported.
KEYWORDS
office building, residential building, ventilation efficiency

44.
Liddament M W
Air infiltration calculation techniques - an application guide.
BIBINF
UK, Bracknell, AIVC, 1986. DATE 00:00:1986 in English

45.
Herrlin M, Malmstrom T-G.
NO 1589 Air leakage or controlled ventilation?
BIBINF
5th AIC Conference 'The implementation and effectiveness of air infiltration standards in buildings' Reno, Nevada, 1-4 October 1984, pp9.1-9.18, 12 figs, 1 tab, 2 refs. DATE 00:10:1984 in English AIC bk
ABSTRACT
This paper compares the conventional exhaust system with a supply-exhaust system with regard to the possible degree of control of the air exchange in the individual rooms. Ventilation efficiency and air exchange efficiency are defined and some examples show the local concentration, mean ventilation efficiency and mean air exchange efficiency for some simple ventilation schemes. Exhaust systems require a very tight building with small make up air openings. The ability of the different systems to avoid leakage out from the building of indoor air is also compared. The calculations indicate that the exhaust system can give small duration of indoor air. The supply-exhaust system gives a greater duration, but the flow can be considerably reduced if the supply air flow rate is reduced. An extremely low velocity exhaust system will also reduce the unwanted outflow.
KEYWORDS
controlled ventilation, air infiltration, air leakage, ventilation efficiency, air change rate, mechanical ventilation, natural ventilation

46.
Railio J, Saarnio P.
NO 1698 Air infiltration - modelling and practical results.
BIBINF
Unpublished paper, Technical Research Centre of Finland, 1985, 11 figs, 4 tabs, 5 refs. DATE 00:00:1985 in English AIC 1057
ABSTRACT
A steady state multi-cell calculation model has been developed in order to predict the interconnection between airtightness and ventilation rates. The model has been tested with measured leakage data of a detached house. It is applicable also for other types of buildings provided with natural ventilation systems. The model is being used - combined with field measurements on airtightness, air flows, pressure conditions and air change rates - to help to solve various practical problems on ventilation. Some examples of calculation results are presented. The airtightness of various leakage paths is measured with the collector chamber method. To measure local air change rates and

ventilation efficiency in various rooms, a ten-point measurement equipment with N2O tracer gas is used. For practical purposes, methods for airtightness measurements in larger buildings have been developed. Results from measurements in residential buildings are presented. Observed comfort or air quality problems are less related to air infiltration than to insufficient total or local air change rates, which occur in airtight buildings without supply air arrangements, with natural ventilation or mechanical exhaust.
KEYWORDS
mathematical modelling, air tightness, air change rate, multi-chamber, detached house, natural ventilation, tracer gas, nitrous oxide, residential building, ventilation efficiency

47.
Klobut K.
NO 2161 Model tests of ventilation effectiveness and air distribution - literature survey.
BIBINF
Report C:13, Espoo, Finland:Helsinki University of Technology, Laboratory of Heating, Ventilation and Air-Conditioning, Indoor Climate Project, 1985. 114p, 34 figs, 8 tabs, 84 refs. DATE 00:00:1985 in English AIC 1545.
ABSTRACT
A survey of mathematical models of air flow and of ventilation efficiency. Measuring equipment for laboratory experiments is described and the limitations and potential uses of the models are discussed.
KEYWORDS
mathematical modelling, air flow, ventilation efficiency

48.
Whittle G E
NO 2525 Computation of air movement and convective heat transfer within buildings.
BIBINF
Int J Amb Energy, Vol 7, No 3, July 1986, p151-163, 9 figs, 36 refs.
DATE 00:07:1986 in English AIC 2024
ABSTRACT
A review has been undertaken of the numerical computation of the air movement and convective heat transfer within buildings. The fundamental conservation equations together with a turbulence model are described, and a numerical procedure for solving the elliptic partial differential equations is outlined. The literature on the subject, spanning the past twelve years, is reviewed. Attention is briefly drawn to examples of the use of numerical air movement codes.
KEYWORDS
calculation techniques, air movement, heat transfer, turbulence, model, review, computer, prediction

49..
Isuizu Y
NO 2145 Evaluation of ventilation systems through three dimensional numerical computation.
BIBINF
Trans SHASE, No.30, February 1986, p1-7, 15 figs, 3 refs. DATE 00:02:1986 in English AIC 1529.
ABSTRACT
To make an evaluation of ventilation systems, numerical computation was carried out for three dimensional, isothermal, and turbulent flow schemes. It was found that there exists an optimum position for an inlet in relation to an outlet whereby the most effective ventilation can be attained. In addition, similar to the results for the two dimensional computation, the slope of the concentration decay is virtually constant and independent of the position in

the room, so the mixing factor derived from this slope can be used as an index of the ventilation efficiency. Further, three dimensional computation seems to be necessary for a quantitative estimation of the mixing factor.
KEYWORDS
mathematical modelling, ventilation strategy, ventilation efficiency.

50.
Nielsen O.
NO 1163 Ventilation efficiency.
Ventilationseffektivitet.
BIBINF
VVS vol.18 no.12 p.43-46 vol.19 no.1 p.27-39 6 figs. 1 tab. DATE 01:12:1982 in Danish AIC 719
ABSTRACT
Notes that ventilation efficiency is not referred to directly in the new DIF standards for ventilation effciency. Reasons for this are that there are no clear definitions for the term or instructions on how optimum ventilation efficiency can be achieved under different operating conditions. Describes some measurements carried out on ventilation efficiency in non-industrial premises.
KEYWORDS
ventilation efficiency, standard,

51.
Blomqvist C. et al
NO 883 Measuring ventilation efficiency at SIB.
Matning av ventilationseffektivet vid SIB.
BIBINF
In ½Seminar on tracer gas and ventilation efficiency' Swedish National Institute for Building Research memorandum M81:16 March 1981 p.69-75 DATE 01:03:1981 in Swedish AICR SE11, AIC 1826
ABSTRACT
Reviews the development of methods and results achieved. The methods have resulted in a proposal for a Nordic test method for measuring ventilation efficiency (local air change frequency) using tracer gas techniques and measurements carried out for two different ventilation systems.
KEYWORDS
ventilation efficiency, tracer gas, measurement technique, air change rate

52.
Skaret E, Sandberg M.
NO 2139 Air change rate and ventilation efficiency. A new aid for the ventilation industry.
Luftvekslings- og ventilasjonseffektivitet - nytt hjelpemiddel for ventilasjonsbransjen.
BIBINF
Norsk VVS. 1985, Vol.28, No.7, p527-534. 13 figs, 1 tab. DATE 00:07:1985 in Norwegian AIC 1524
ABSTRACT
Discusses guidelines produced for the Nordic Ventilation Group. Explains how the designer can select an effective ventilation system on the basis of information on ventilation rates and ventilation efficiency.
KEYWORDS
Ventilation strategy, ventilation efficiency.

10. APPENDICES

10.1 Appendix 1

Key Subject Index and Author Affiliation

Country	Author	Ref.No.	Definition	Measurement	Calculation	Other
Belgium	Laret	1	*			
Fed.Rep.Ger.	Meyringer	31	*			
Finland	Paalonen	39		*		
	Railio	46			*	
	Klobut	47			*	
Japan	Ishizu	49			*	
Norway	Skaret	8	*			
	Skaret	9	*			
	Skaret	10	*			
	Skaret	14	*	*		
	Skaret	15	*	*		
	Skaret	21		*		
	Skaret	33				Design rules
	Skaret	38		*		
	Martinsen	40		*		
Sweden	Sandberg	2	*			
	Sandberg	4	*			
	Sandberg	6	*	*		
	Sandberg	7	*	*		
	Sandberg	17	*	*		
	Pederson	19		*		
	Sandberg	20	*			
	Sandberg	22		*		
	Sandberg	32		*		
	Sandberg	34		*		
	Sandberg	35				Influence of occupants
	Malmstrom	36		*		
	Boman	37		*		
	Sandberg	43		*		
	Herrlin	45			*	
Switzerland	Roussel	18	*			
United Kingdom	Dickson	16	*	*		
	Freeman	28		*		
	Liddament	44			*	
	Whittle	48			*	

continued/...

10.1 Appendix 1 (continued)

Country	Author	Ref. No.	Definition	Measurement	Calculation	Other
United States of America	ASHRAE	3				Comfort requirements
	Sherman	5	*	*	*	
	Janssen	11	*			
	Janssen	12	*			
	Offerman	13	*			
	Harrje	23		*		
	Persily	24		*		
	Persily	25		*		
	Persily	26		*		
	Fisk	27		*		
	Maldeno	29		*		
	Maldeno	30		*		
	Rerzan	41		*		
	Maki	42		*		

10.2 Appendix 2

IEA Annex Proposal "Optimisation of Air Flow Patterns

1. Background

Until recently air change rates have been used to define both the requirement for and the performance of ventilation systems. This is no longer an adequate parameter, because maximum energy economy can ony be achieved with optimum ventilation effectiveness. Hence more research attention has recently been given to the patterns of air circulation within rooms and through buildings, to ensure that fresh air supply and pollutant removal requirements are effectively attained without undue use of energy resources.

2. Objectives

To study the physical phenomena which drive air, indoor pollutants, and energy transport within and between building zones to produce information necessary to design and operate ventilation systems to maintain indoor air quality and comfort conditions in an energy efficient manner. This work is also relevant to the use of ventilation to transport energy in response to individual building zone requirements.

3. Means

The Participants will undertake a task sharing project involving data acquisition, mathematical prediction, specific experimentation and analytical studies. The work being carried under Annex V, the Air Infiltration and Ventilation Centre, will be complementary with this proposed annex. In particular, AIVC will, as part of its on-going work plan, carry out assessments of existing knowledge in the field, highlight gaps in the knowledge, and act as a vehicle for disseminating the results of this particular annex.

4. Responsibilities of Participants

The Participants shall contribute to all of the following sub-tasks:-

a) Study the physical phenomena which drive air, indoor pollutant, and energy transport within and between building zones, and conduct a detailed technical assessment of existing models which address these phenomena for ventilation flows. This will develop on from the review to be carried out by AIVC, which will identify various available models and their data requirements. The new annex will assess the applicability of these models to various air flow problems. Of particular importance will be to analyse the role of simpler design procedures as compared to complex three dimensional simulation codes.

b) Conduct controlled experiments to measure ventilation effectiveness in single and multizone applications using test-chambers (and scale models if applicable) for different ventilation configurations. The first stage of this task is to develop a standard reporting format to assist information exchange between various research groups working worldwide, and to enable a more effective consolidation of the results. These controlled and co-ordinated experiments will provide quality data for the validation of the various models. The detailed measurements of the performance of different ventilation systems under varying operating regimes will also form the basis of a document summarising the merits and disadvantages of alternative ventilation strategies. This will provide an important contribution to the achieving of installed ventilation systems providing an adequate level of indoor air quality with a minimum non-renewable energy input. The dissemination of these conclusions will be an area where the AIVC should play a key role.

c) Based on the experimental work described above, it should be possible to identify areas of weakness in the currently available models. These can then be improved to make them suitable for assessing ventilation flow problems. The task should then should address the problems of simplifying the model to enhance usability for practitioners without sacrificing desired accuracy. Such an exercise will need to carefully qualify the areas where these simpler models can be validly applied. Again, the development of this work into a summary guide for practitioners is an area where AIVC should be involved. The final document is a natural follow on from the AIVC's current Calculation Techniques Guide.

5. Responsibilities of Operating Agent

The Operating Agent will:-

a) Coordinate the work amongst the various Participants.

b) Finalise the detailed work plans for each Subtask in collaboration with its Participants and submit an annual programme of work to the Executive Committee not later than two months before the end of each year.

c) Ensure that duplication of reasearch effort is avoided or minimised. In particular, to ensure that the information and results of the project are submitted to the AIVC so that the results can be consolidated and disseminated effectively to both researchers and practitioners. This will involve the collation of information and the preparation of comprehensive guidance documents on both calculation techniques and system design. These documents will form the final output of this Annex.

d) Co-ordinate the exchange of information through publications, reports, meetings and conferences.

e) Report the progress of work under the Task to the Executive Committee at least semi-anually.

f) Submit a final report to the Executive Committee within three months after the completion of all the work under this Task, and submit such other reports as the Executive Committee may request.

6. Results

a) Reporting format for describing the experimental methods and results of air flow measurements in both test rooms and real buildings.

b) Data sets for the verification of prediction techniques used in the analysis of ventilation systems.

c) A manual giving summary guidance on the merits and problems associated with various ventilation schemes as an aid to good practice in system design.

d) Manual on calculation techniques providing information to enable building designers and operators to maximise ventilation effectiveness and thus maintain comfort and indoor air quality in an energy efficient manner.

7. Funding

Each Participant shall individually bear the costs associated with the execution of activities defined in section 3. Participation in the Annex is subject to a minimum overall commitment of 36 man-months over the 3 year duration of the annex, plus the cost of using the necessary test facilities.

In addition to the technical input to the task, the Operating Agents will committ a further 3 man months per year to the task.

8. Time Schedule

This Annex will come into force on 1st ???? 1987 and will remain in force for a period of three years. It may be extended by agreement of any Participants desiring to continue this Task beyond its expiration date. The extension of this Annex shall be binding only on those Participants notifying the IEA Secretariat of their intention to so continue the Annex. It shall be binding on those Participants who withdraw from the Annex in accordance with Article 10(g) of the Agreement.

9. Operating Agent

To be defined

10. Information and Intellectual Property

a) Executive Committee's Powers. The publication, distribution, handling protection and ownership of information and intellecutal property arising from this Annex shall be determined by the Executive Committee, acting by unanimity, in conformity with the Agreement.

b) Right to Publish. Subject only to copyright restrictions, the Annex Participants (referred to in this Annex as the "Participants") shall have the right to publish all information provided to the Annex, except proprietary information and all information arising from the Annex.

c) Proprietary Information. The Participants and the Operating Agent shall take all necessary measures in accordance with this paragraph, the laws of their respective countries and international law to protect proprietary information provided to the Annex. For the purposes of this Annex, proprietary information shall mean information of a confidential nature such as trade secrets and know-how (for example, computer programmes, or design procedures and techniques, chemical composition of materials, or manufacturing methods, processes, or treatments) which is appropriately marked, provided such information:

1) It is not generally known or publicly available from other sources
2) Has not previously been made available by the owner to others without obligation concerning its confidentiality and
3) Is not already in the possession of the recipient Participant without obligation concerning its confidentiality.

It shall be the responsibility of each Participant supplying proprietary information to a Lead Country or to the Operating Agent, to identify the information as such and to ensure that it is appropriately marked.

d) Production of Relevant Information by Governments. The Operating Agent should encourage the governments of all Agency Participating Countries to make available or to identify to the Operating Agent all published or otherwise freely available information known to them that is relevant to the Task.

e) Production of Available Information by Participants. Each Participant agrees to provide to a Lead Country or to the Operating Agent all previously existing information, and information developed independently of the Task, which is needed by a Lead Country or by the Operating Agent to carry out its functions in this Task and which is freely at the disposal of the Participant and the transmission of which is not subject to any contractual and/or legal limitations:

1) If no substantial cost is incurred by the Participant in

making such information available, at no charge to the Task
2) If substantial costs must be incurred by the Participant to make such information available, at such charges to the Task as shall be agreed between the Operating Agent and the Participant with the approval of the Executive Committee.

f) Use of Confidential Information. If a Participant has access to confidential information which would be useful to a Lead Country or to the Operating Agent in conducting studies, assessments, analyses, or evaluations such information may be communicated to a Lead Country or to the Operating Agent but shall not become part of the reports, handbooks, or other documentation, nor be communicated to the other Participants except as may be agreed, between the Operating Agent and the Participant which supplies such information.

g) Reports on Work Performed under the Task. The Operating Agent shall, in accordance with paragraph 5 above, provide reports of all work performed under the Task and the results thereof, including studies, assessments, analyses, evaluations and other documentation, but excluding proprietary information.

h) Copyright. The Operating Agent or a Lead Country may take appropriate measures to protect copyrightable material generated under this Task. Copyrights obtained shall be the property of the Operating Agent, for the benefit of the Participants, provided, however, that the Participants may reproduce and distribute such material, but shall not publish it with a view to profit, except as otherwise directed by the Executive Committee.

i) Authors. Each participant will, without prejudice to any rights of authors under its national laws, take necessary steps to provide the co-operation from its authors required to carry out the provisions of this paragraph. Each Participant will assume the responsiblity to pay awards or compensation required to be paid to its employees according to the laws of its country.

11. Participants

To be defined

10.3 Appendix 3

Sources of Commercial Air Movement Software

1. Program "PHOENIX"

   Cham Ltd
   Bakery House
   40 High Street
   Wimbledon
   London
   SW19 5AU
   United Kingdom

   Telephone: 01 947 7651

2. Program "FLUENT"

   Flow Simulation Limited
   Thermofluids Engineering Consultants
   Red Brick House
   Toppet Lane
   Sheffield
   S1 4EL
   United Kingdom

   Telephone: 0742 701595

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Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and United States of America.

The Air Infiltration and Ventilation Centre provides technical support to those engaged in the study and prediction of air leakage and the consequential losses of energy in buildings. The aim is to promote the understanding of the complex air infiltration processes and to advance the effective application of energy saving measures in both the design of new buildings and the improvement of existing building stock.

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