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Date: June 2001			

THE RESOURCE CENTRE FOR BUILDING EXCELLENCE

CONFERENCE PAPER

No. 89 (2001)

Ventilation Effectiveness – Recognition in the Next Ventilation Standards

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Presented at the IRHACE Technical Conference,
Palmerston North, New Zealand, March 2001.

Funding for this research was provided by the Building Research Levy and the Public Good Science Fund of the Foundation for Research, Science and Technology.

ISSN: 0111-7505

VENTILATION EFFECTIVENESS - RECOGNITION IN THE NEXT VENTILATION STANDARDS

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ABSTRACT: Draft revisions of ventilation Standards ASHRAE 62 and AS 1668.2 appeared in 1996, written in terms of the effectiveness with which air is delivered to the zones where people breathe. By the end of 2000, neither of these revisions had successfully replaced existing Standards because of unrelated conflicts over the treatment of environmental tobacco smoke. When these issues are resolved, a new generation of ventilation Standards can be expected that treat the airflow path from the diffuser to the places where people breathe, as part of the fresh air delivery conduit. In draft form, the new Standards introduce terms such as "ventilation effectiveness", "ventilation efficiency" and "local mean age of air", and bring new considerations and calculations to ventilation design. This paper explains the ventilation effectiveness concept and how it is treated in the draft Standards.

Understanding the complex airflow processes which circulate air from diffusers to the breathing spaces below is a difficult task, requiring either detailed computational fluid dynamics modelling (CFD) or measurement using tracer gases. This paper describes measurements in office buildings in Wellington where tracer techniques were used to measure ventilation effectiveness parameters. These results, along with similar measurements in other countries, can often avoid the need for CFD modelling or further measurement. The measurements described here also give some insight into the consequences of non-ideal placement of fresh air delivery and exhaust points in relation to internal partitioning.

1. TRENDS IN STANDARDS

1.1 The ASHRAE 62 Standard and its linkage to NZS 4303

New Zealand Standard NZS 4303:1990 "Ventilation for Acceptable Indoor Air Quality" (SNZ 1990) is an adaptation of the ASHRAE 62 Standard (ASHRAE 1989) with amendments to suit local conditions. It provides the most commonly used compliance path for mechanical ventilation designs in New Zealand by providing fresh air supply rates that depend on the density of occupation and the application of the space (e.g. office space, smoking lounge etc). Further adjustments to the fresh air supply rate are possible when occupancy is intermittent or where recirculated air is cleaned. Adjustments for ventilation effectiveness are discussed but no specific advice or calculation method is provided. Accordingly, the process of delivering air from the diffusers to the breathing zones is rarely subject to calculation. A summary of ventilation effectiveness concepts and related terms is given in Appendix A of this paper, along with references to the formal development of the topic.

The first revision to Standard ASHRAE 62 (ASHRAE 1996) was released as a public draft in August 1996 but progress towards a consensus Standard was slowed by opposing opinions on the treatment of environmental tobacco smoke. To maintain some progress, the Standard was placed under continuous review, whereby addenda are added incrementally over time. ASHRAE also moved to separate the Standard into two parts (ASHRAE 1998): Standard 62.1:Ventilation and Acceptable Indoor Air Quality in Commercial, Institutional and High-Rise Residential Buildings (ASHRAE 1999a) and Standard 62.2:Ventilation and Acceptable Air Quality in Low-Rise Residential Buildings (ASHRAE 2000). Addendum 62n (ASHRAE 1999b) released for public comment in April 1999 retains the treatment of ventilation effectiveness in system design equations established in the first draft (ASHRAE 1996). A ventilation system design using the procedures proposed in addendum 62n would involve the following steps:

1 Calculate a design outdoor air supply rate V_{OA} from the sum of an occupancy rate V_P to dilute bioeffluents, and a building rate V_B to dilute contaminants introduced by the building and processes taking place within the space. This is expressed as:

$$V_{OA} = V_P + V_B \quad (1)$$

$$V_{OA} = R_P P + R_B A \quad (2)$$

The expansion of V_{OA} in equation (2) involves the following terms:

R_P The outdoor air requirement needed to dilute bioeffluents in L/s per person. These are listed in the draft for a wide range of building end uses.

P The design occupancy (persons). Allowances for population diversity are possible.

R_B The outdoor air requirement to dilute contaminants from building materials and processes within the building. These are listed in the draft for a wide range of building end uses in L/s m^2.

A The net occupiable floor area in m^2.

2 Calculate the minimum air supply rate V_{MS} to reduce the transmission of infectious diseases. This will be the greater of a rate calculated from tables of R_{MS} and a calculated air supply rate:

$$V_{MS} \geq R_{MS} A \quad \text{and} \quad V_{MS} \geq V_{OA} / E_{AC}$$

E_{AC} Is the ventilation effectiveness (see Appendix A in this paper for an explanation). Default values provided in the draft Addendum 62n are reproduced in simplified form in Table 1.

R_{MS} Is the minimum supply rate, tabulated for certain spaces in the draft Addendum 62n.

Table 1: Default air change effectiveness values from draft Addendum 62n.

Application	**Default E_{AC}**
Supply of cool air at the ceiling.	1.0
Supply of warm air at the ceiling.	0.8
Supply of air from the floor with a velocity high enough to induce mixing of room air. Examples include most under-floor supply systems but exclude displacement ventilation systems.	1.0
Supply of cool air from the floor and return from the ceiling if nearly laminar flow and thermal stratification are achieved, eg displacement ventilation.	1.2
Supply of warm air from the ceiling and return from the floor.	1.0
Supply of warm air from the floor and return from ceiling.	0.7
Induced make-up air drawn in by exhaust where make-up air source and exhaust are widely separated.	0.8
Induced make-up air drawn in by exhaust where make-up air source is near the exhaust location.	0.5

The draft Addendum 62n also allows for the outdoor air supply rate to be adjusted for the efficiency with which the ventilation system distributes air to multiple occupied zones. This is expanded in more detail in Appendix H of the draft Addendum 62n.

1.2 The AS 1668.2 Standard

Australian Standard AS 1668.2 (AS 1991) is often used in New Zealand for ventilation designs complying with the Acceptable Solution G4/AS1 (BIA 1998) of the New Zealand Building Code. An early draft revision of this Standard (SA 1996) required ventilation effectiveness to be considered when calculating an amenity index. In more recent times, this draft has been split into two parts; one dealing with general contaminants (AS 1668.2.1-200X), (AS 2000a) and a related document (AS 1668.2.2-200X), (AS 2000b) dealing specifically with environmental tobacco smoke. Both draft Standards define a dilution index as a measure of ventilation amenity and allow for ventilation effectiveness in ventilation calculations. Although rather fewer standard values for ventilation effectiveness are given in Appendix D of the draft Standards than are offered in Table 1 above, a displacement ventilation design would achieve a higher dilution index than one based on mixing dilution of pollutants.

2. MEASURING VENTILATION EFFECTIVENESS

The effectiveness of ventilation systems can be measured by adding a tracer gas to incoming air or into the ventilated space. BRANZ has developed equipment and methods using SF_6 as a tracer, along with a computer-controlled gas chromatograph to measure the local mean age of air in the breathing zones of a ventilated space. Figure 1 shows the automated gas chromatograph, on a portable trolley, attached to a large number of small-bore plastic tubes for dosing the air with tracer gas, and for sampling air from different locations. The equipment and methods used have been described in detail (Bassett 1994 and 1997).

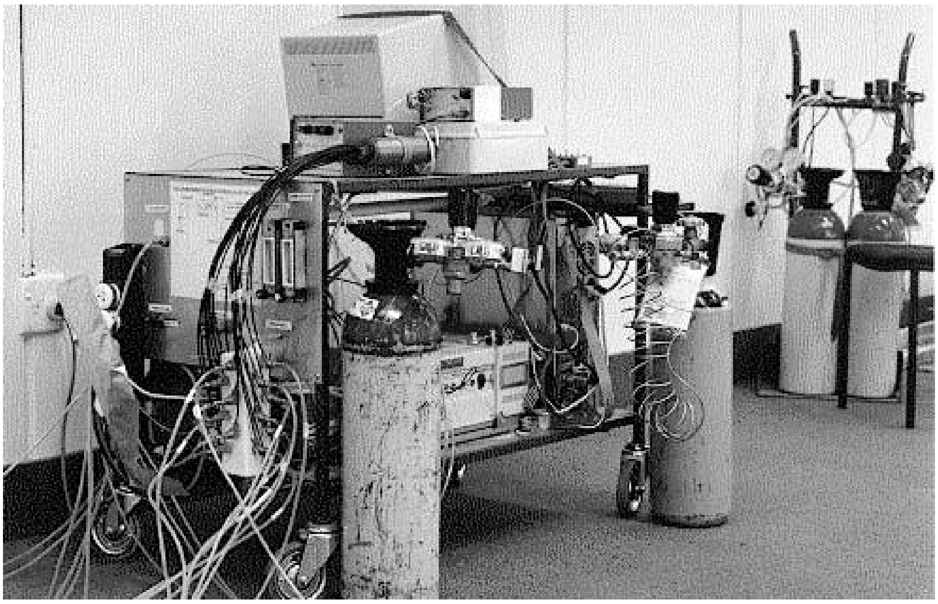

Figure 1: Automated tracer gas equipment for measuring ventilation effectiveness.

3. MEASUREMENTS IN WELLINGTON OFFICE BUILDINGS

Ventilation effectiveness measurements have been carried out in eight buildings (labelled A to H) located in the central business district of Wellington. Buildings A to D are described in earlier papers (Bassett 1994 and 1995) and buildings D (level 6) to H in a further paper (Bassett 1997). All were office buildings with varying degrees of internal partitioning, ranging from open plan to individual offices. Buildings A, B, C and D were provided with a constant air volume (CAV) air supply of 100% fresh air. In buildings B and C fresh air was supplied onto the floor from a central duct and ducted to the proximity of plenum-mounted fan coil units. The ventilation system in building G was similar except that fresh air was discharged into the plenum at only four points along one side of the building. The uniformity with which fresh air was distributed over the floor plan was the main point of interest in this building.

In buildings E, F and H air was supplied to core zones by a variable air volume (VAV) supply with recirculation. In buildings E and F an additional CAV system provided 100% fresh air around the glazed perimeter. During tracer measurements in buildings E, F and H, the VAV supply was held at maximum air delivery so that effective ventilation rates could be compared with a constant and known air supply rate. Recirculation was also at a minimum for cooling during the summer months when the tracer study was completed. The relevant floor plan and air handling system details are presented in Table 2.

Table 2: Building descriptions and air handling system capacities (n/d = not determined).

Building descriptions and air handling system capacities						
Building	**Level**	**Floor area m²**	**Volume m³**	**Ventilation system type**	**Air supply rate m³/h maximum**	**Mechanical exhaust rate m³/h**
A	3	1,526	4,731	CAV no recirculation	n/d	n/d
A	2	521	2,553	CAV no recirculation	1,826	3,219
B	2	454	1,438	CAV local recirculation	1,750	n/d
B	3	469	1,486	CAV local recirculation	1,573	n/d
C	5	1,476	4,723	CAV local recirculation	3,563	2,600
C	6	1,476	4,723	CAV local recirculation	4,183	2,540
D	7	499	1,536	CAV local recirculation	1,092	Nil
D	6	544	1,671	CAV local recirculation	1,730	Nil
E	6	532	1,430	VAV core CAV perimeter	4,745	n/d
F	27	864	2,324	VAV core CAV perimeter	4,778	n/d
G	4	368	1,114	CAV local recirculation	1,012	n/d
H	1	450	1,248	VAV non local recirculation	8,802	n/d

4. VENTILATION EFFECTIVENESS

Effective ventilation rates have been determined for the breathing zones on a total of 12 floors in eight buildings along with the air delivery rate for each floor. These effective ventilation rates are the inverse of the mean age of air in the breathing zone used later as average values to calculate the ventilation effectiveness for the zone. Contour maps of the effective ventilation rate at breathing height were prepared from a large number of spot measurements. Examples of effective ventilation rate distributions are given for building D level 6 with all internal doors open (Figure 2), and for the open plan space in building H (Figure 3). Contours of air discharge rate for building H are given in Figure 4 for direct comparison with effective ventilation rates in Figure 3.

The variation in effective ventilation rate over the floor plan of building D level 6 can be partly explained in terms of partitioning and the location of fresh air supply ducting. Lower than average effective ventilation rates in the northern corner of the building can be explained by full height partitioning preventing fresh air released in the plenum from reaching air handlers in this area. Much of the fresh air destined for this area has instead been discharged into the lift lobby area and adjacent rooms, where the effective ventilation rates are highest. Closing doors in the partitioned areas has further isolated the northern corner offices and further reduced the effective ventilation rates.

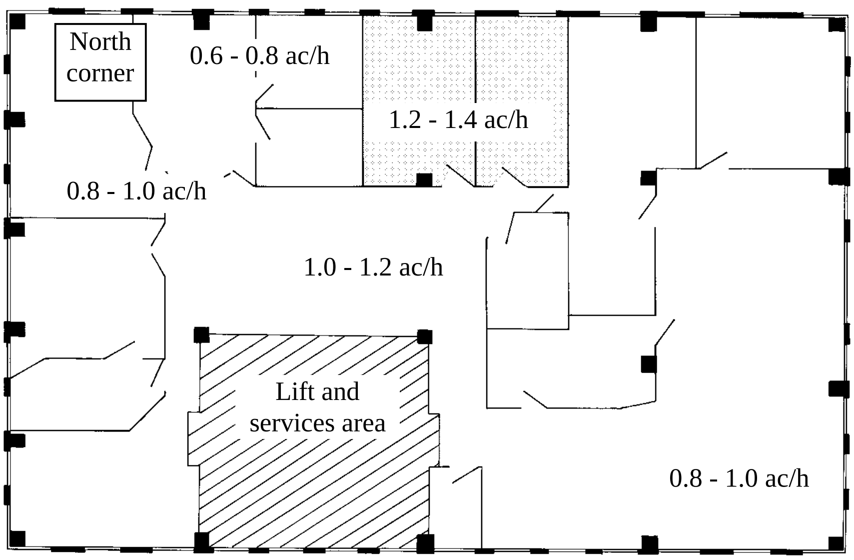

Figure 2: Contours of effective ventilation rate in the breathing zones of building D level 6.

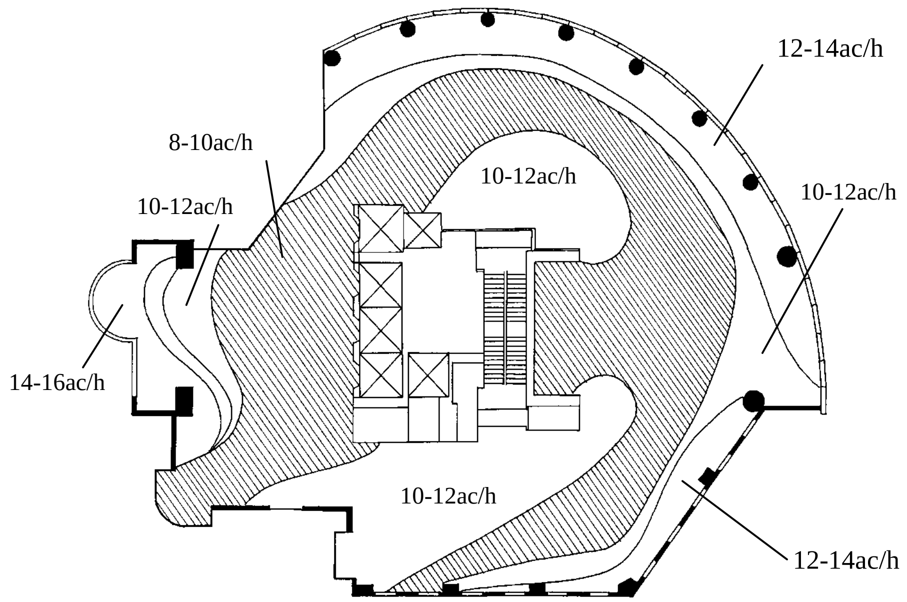

Figure 3: Approximate contours of effective ventilation rate in the breathing zones of building H.

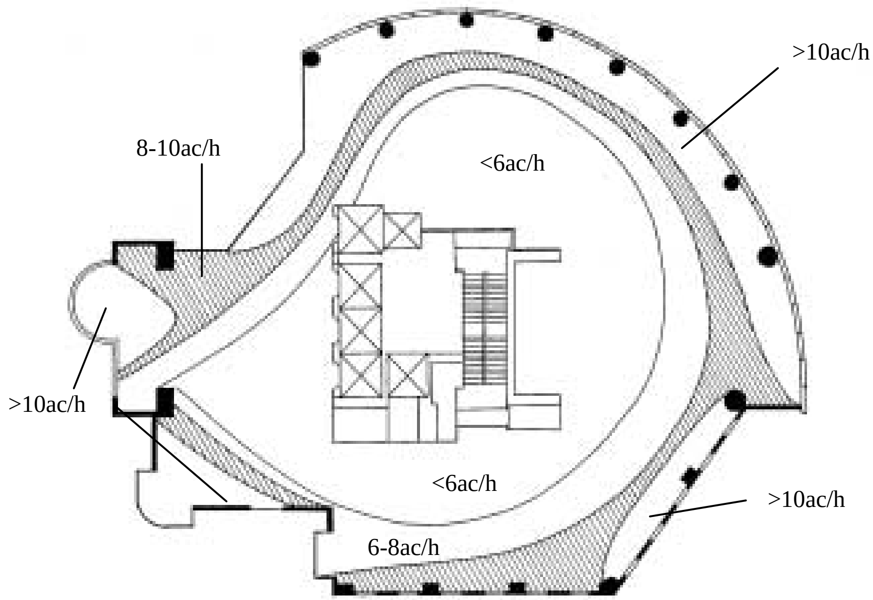

Figure 4: Approximate contours of airflow discharged through the ceiling of building H.

In the open plan areas of buildings B, E, F and G the effective ventilation rates have tended to be more uniform through the space than in partitioned spaces. The effective ventilation rates in the breathing zone of building H shown in Figure 3 have a similar pattern to the fresh air delivered at ceiling level in Figure 4, with highest values around the perimeter. In this case the effective ventilation rates tend to be higher than delivered fresh air rates, especially in the core areas close to the exhaust points, indicating that bulk air flows from the perimeter effectively sweep tracer gas or pollutants from the core breathing zones.

The ventilation effectiveness on 12 floors of eight buildings has been calculated as the ratio of the nominal time constant (the inverse of the fresh air delivery rate in ac/h) and the mean age of air in the breathing zones (the mean age of air is the inverse of the effective ventilation rate in the breathing zone). The mean age and nominal time constant are plotted in Figure 5 along with a line of equality (characterising dilution ventilation with a ventilation effectiveness of 1). Individual values ranged between 0.8 and 1.48, with a mean value of 1.1 and an experimental uncertainty of 20%. In all of these buildings, the ventilation process can best be described as dilution ventilation (see Appendix A). On floor 3 of building B, the air change efficiency was 1.48 and apparently closer to the displacement flow description. It must be remembered that effective ventilation rates were measured 1.5m above floor level and in highly partitioned areas this might not always be representative of the entire room volume. Other workers, (Fisk 1992), have measured ventilation-effectiveness parameters in a variety of mechanically ventilated buildings. Similar conclusions were reached concerning the description of mechanical ventilation in office buildings as being mostly dilution ventilation systems.

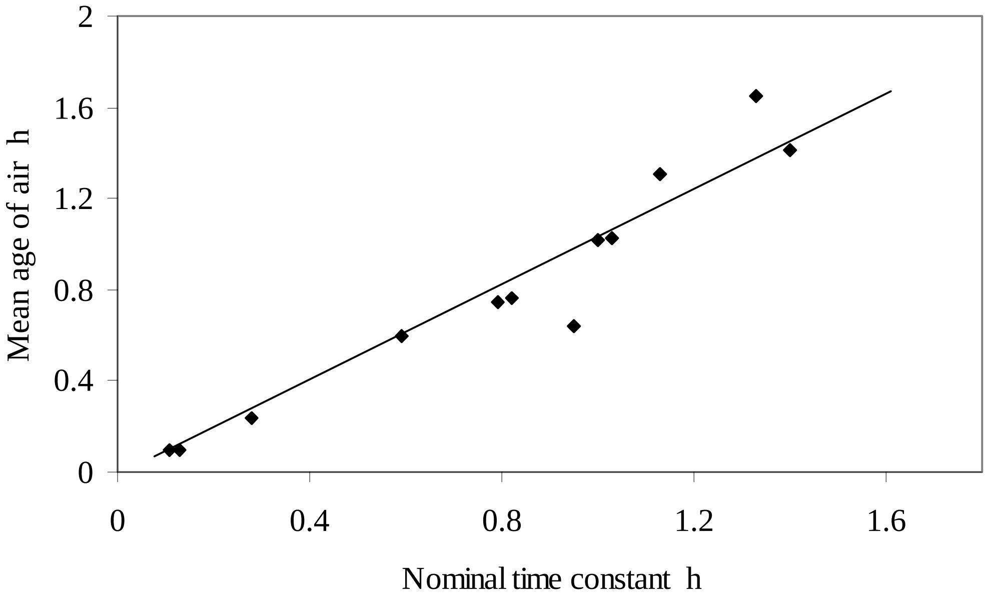

Figure 5: Measured ventilation characteristics in eight New Zealand office buildings.

5. FRESH AIR DELIVERY AND EXHAUST POINTS IN RELATION TO PARTITIONING

The location of fresh air diffusers and exhaust return paths in relation to internal partitioning is known to be critical to delivering effective ventilation. An indication of the effect of partitioning on effective ventilation rates has been given in Table 3. Here the normalised standard deviation of measured effective ventilation rates tends to be higher in partitioned areas. This wider variation is indicative of the importance of ventilation system planning in relation to floor planning.

Table 3: Normalised standard deviations of effective ventilation rates in buildings B, C and D.

Building /floor	**B/2**	**B/3**	**C/5**	**C/6**	**D/6**	**D/7**
Entire floor	6%	27%	10%	12%	16%	34%
Partitioned areas	-	31%	-	-	16%	34%
Open plan areas	6%	12%	10%	12%		-

In some individual rooms on floor 3 of building B and floor 7 of building D the effective ventilation rate was found to depend on whether doors were opened or closed, but over many rooms the average effective ventilation rate remained unaffected. The average effective ventilation rate in the partitioned areas of floor 7 of building D was 0.66 ac/h with the doors closed and 0.70 ac/h with the doors open. In the partitioned part of floor 3, building B, the average effective ventilation rate with doors closed was 2.3 ac/h and with doors open 2.0 ac/h.

Most rooms in the partitioned areas of buildings B and D contained both fresh air diffusers and an exhaust path to the plenum. There were two exceptions to this. One room on the east side of building D lacked a fresh air supply and the only separate room on the second floor of building B lacked an exhaust return to the plenum. In these two cases, the effective ventilation rate with doors closed was less than half that in adjacent areas.

6. CONCLUSIONS

Consideration of ventilation effectiveness looks certain to be required by the next generation of building ventilation standards. This paper has outlined the development of ventilation effectiveness concepts and parameters. It has also reported results of ventilation effectiveness on 12 floors of eight Wellington office buildings. This was achieved using tracer gas methods, with the following conclusions:

- The ventilation effectiveness in the breathing zones of 12 floors in eight New Zealand office buildings ranged from 0.8 to 1.48, with a mean value of 1.1, indicating the dilution ventilation model closely describes the ability of common ventilation configurations to deal with pollutants in the breathing zones. The results are consistent with those proposed for inclusion in the ASHRAE 62 Standard within the 20% uncertainty applying to the tracer measurements.

- Variation in the effective ventilation rate in the breathing zones depends on the coverage of the fresh air distribution system, as well as on the extent of internal partitioning. The normalised standard deviation of the local mean age-of-air was higher in partitioned areas than within large open-plan areas. This effect can easily be minimised in ventilation designs. Far more important were two rooms missing a fresh air supply and an exhaust return to the plenum. Here the effective ventilation rates were half that of adjacent areas.

7. ACKNOWLEDGMENTS

This work was funded by the Building Research Levy and the Foundation for Research, Science and Technology. The assistance of the building owners for access to the buildings, Roger Stanford from BRANZ, Ron Conders from Advanced Building Services Ltd and Mark Sinclair from Colliers Jardine is also gratefully acknowledged. Andrew Persily and Vincent Aherne are also acknowledged for providing review documentation on ASHRAE 62 and AS 1668.2 respectively.

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APPENDIX A: VENTILATION EFFECTIVENESS - WHAT IS IT ?

Ventilation effectiveness parameters describe the mixing behaviour of air in the breathing zones of buildings, and the processes by which pollutants are diluted or displaced by the ventilation system. Traditional measures of ventilation performance include fresh air delivery rates and recirculation rates. On their own, these parameters are properties of the ventilation system and relate more to air flows in ducts than to fresh air delivered to the zones where people breathe. The concept of ventilation effectiveness allows the performance of a ventilation systems to be quantified in terms of the delivery of air to occupants and the dilution and removal of pollutants. The detailed mathematical background to these parameters can be obtained by reference to (Sandberg 1981) and (Skåret 1984), and in summary form to (Sutcliffe 1990), and (Brouns 1991).

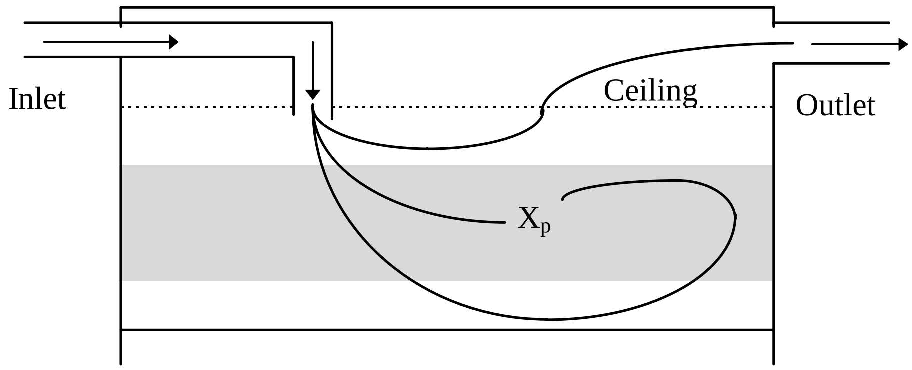

Figure A1: Representation of a mechanically ventilated room.

Figure A1 illustrates some of the possible passages of air molecules from inlet to outlet in a mechanically ventilated room. Of the molecules that leave the inlet at time t = 0 some will pass through point Xp. Because they travel by different routes, the number arriving at Xp will vary with time, according to a frequency distribution curve that might resemble that in Figure A2.

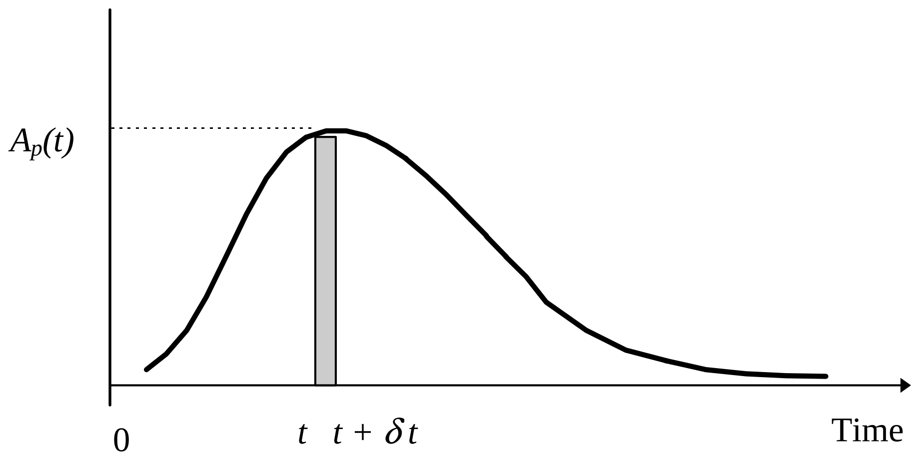

Figure A2: A possible frequency curve for air arriving at point P.

The number of molecules arriving at Xp is equal to the area under the frequency distribution curve which can be normalised and expressed as follows:

The number of molecules arriving at $$\text{Xp} = \int_0^\infty A_p(t)\,dt \qquad (1)$$

The central parameter to air efficiency considerations is the local mean age of air $\bar{\tau}_p$. This is the average time it takes air entering through the ventilation system to reach an arbitrary point Xp. This can be expressed as follows:

$$\overline{\tau}_p = \frac{\int_0^\infty t.A_p(t)dt}{\int_0^\infty A_p(t)dt} \quad (2)$$

If the frequency distribution is expressed in terms of the fraction of the total number of molecules arriving at Xp, then the area under the curve (equation 1) can be normalised and the mean age expressed as follows:

$$\overline{\tau}_p = \int_0^\infty t.A_p(t)dt \quad (3)$$

The local mean age of air has units of hours and it can be expressed as an effective ventilation rate *Vp* in units of air changes per hour as follows:

$$V_p = 1 / \overline{\tau}_p \quad (4)$$

The local mean age will generally vary with location within a ventilated space and it is possible, using tracer gas methods, to map out the local mean age of air at breathing height. The room mean age $< \overline{\tau} >$ is the mean age of air averaged over the entire room volume. An equivalent time constant for the air delivered by the ventilation system is τ_n which is called the nominal time constant. This can be expressed in terms of the room volume V and the volumetric ventilation air flow rate Q as:

$$\tau_n = V / Q \quad (5)$$

Finally, the efficiency of the ventilation system can be expressed as a percentage air change efficiency ε_a as follows:

$$\varepsilon_a = 100. \tau_n / 2.< \overline{\tau} > \quad (6)$$

It can alternatively be expressed as a coefficient of air change performance E_{ac} defined in the ASHRAE draft Standard 62 1989R (ASHRAE 1996) as the ventilation effectiveness, as follows:

$$E_{ac} = \tau_n /< \overline{\tau} > \quad (7)$$

Table A1: Ventilation indices for displacement flow illustrated in Figure A3.

Ventilation indices for displacement flow			
Nominal time constant τ_n (hours)	Room mean age of air $< \overline{\tau} >$ (hours)	Air change efficiency ε_a %	Ventilation effectiveness E_{ac}
V/Q	τ_n/2	100 %	2

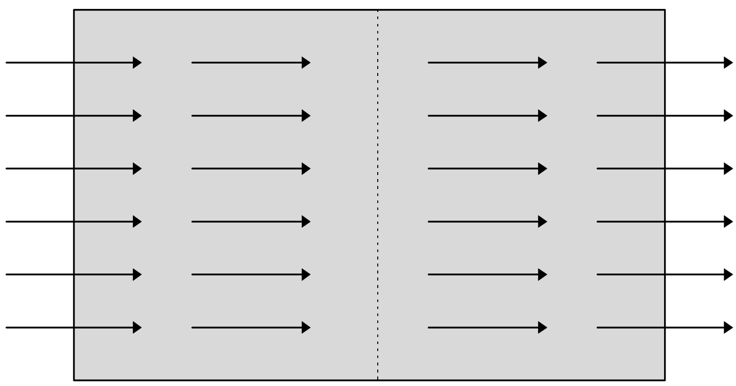

Figure A3: Displacement flow of air through a ventilated space.

The room mean age of air, air change efficiency and ventilation effectiveness have been calculated [3] for two reference cases, described as displacement flow and ideal mixing. Displacement flow is represented in Figure A3 as a steady non-mixing volumetric flow *Q* of air through the space of volume *V*. It is a particularly efficient form of ventilation as is indicated by the air change efficiency and ventilation effectiveness indices summarised in Table A1.

Table A2: Ventilation indices for dilution ventilation illustrated in Figure A4.

Ventilation indices for dilution ventilation			
Nominal time constant τ_n (hours)	Room mean age of air $<\bar{\tau}>$ (hours)	Air change efficiency ε_a %	Ventilation effectiveness E_{ac}
V/Q	τ_n	50 %	1

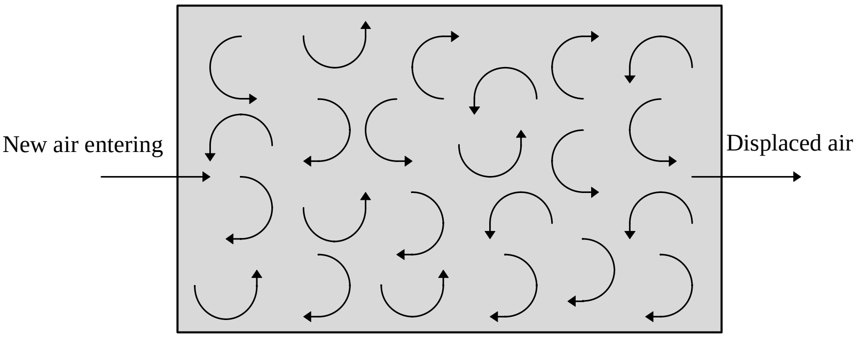

Figure A4: Fully mixed air in a space representing dilution ventilation.

An alternative to displacement flow is the model of complete mixing. In this case air entering the room is assumed to mix uniformly with the room air, along with any pollutants present. Air leaving the room will have the same mean age as at any point in the room. Figure A4 illustrates the internal mixing process and Table A2 gives the ventilation indices for ideal mixing. In practice, the local mean age of air or the effective ventilation rate will vary throughout a ventilated space depending on the location of fresh air entry and exhaust points in relation to internal partitioning. These ventilation indices can either be measured with tracer gas methods or calculated with computational fluid dynamics methods.

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