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VENTILATION EFFECTIVENESS - WHAT IS IT AND HOW DO NEW ZEALAND BUILDINGS MEASURE UP?

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Ventilation effectiveness - What is it and how do New Zealand buildings measure up ?

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ABSTRACT: A new generation of Standards for building ventilation are being written in terms of the efficiency with which air is delivered to the zones where people breathe. In contrast to existing Standards, which define fresh air delivery rates from diffusers at ceiling level, the new Standards take a further step and consider air flows from the point where the ducted ventilation system ends to the places where people breathe. They introduce new terms such as "ventilation effectiveness", "ventilation efficiency" and "local mean age of air", and bring new considerations and calculations to ventilation design. This paper discusses these trends and summarises the terminology in as little detail as necessary to understand and apply the new Standards.

Accounting for the complex air-flow processes which circulate air from diffusers to the breathing spaces below is a difficult task, requiring either detailed computational fluid dynamics modelling 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 in many cases, be used to make useful generalisations that avoid the need for CFD modelling or measurement. Measurements with tracers have also given 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

The current New Zealand Standard for building ventilation, NZS 4303:1990 [1], is an adaptation of ASHRAE 62-1989 [2] with amendments to suit local conditions. The most commonly followed compliance path involves selecting the fresh air supply rates appropriate for the density of occupation and the application of the space (e.g. office space, smoking lounge etc). Further adjustments to the design fresh air supply rates are possible where occupancy is intermittent or where recirculated air is cleaned. No compensation is allowed for delivering air more effectively to the places where people breathe. However, the concept of ventilation effectiveness is discussed in Appendix F of ASHRAE 62-1989 in the context of a ventilation system which allows a fraction of the supplied fresh air to bypass the breathing zones. A summary of ventilation effectiveness concepts and terms is given in Appendix A of this paper, along with references to the formal development of the topic.

The public draft revision BRS/ASHRAE Standard 62-1989R [3], released in August 1996, takes more formal steps to include ventilation effectiveness considerations into system designs. Although progress with the draft has been stoped in its tracks, a detailed ventilation system design using the proposed procedures would involve the following steps:

1 Calculate a design ventilation rate *DVR* 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:

$$DVR = V_P + V_B \qquad (1)$$

$$= R_P P_D D + R_B A_B \qquad (2)$$

The expansion of *DRV* 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_D The design occupancy (persons).
- D A dimensionless diversity factor to allow for variability in the number of occupants.
- 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.
- A_B The occupiable floor area in m^2.

2 Calculate the minimum air supply rate *MSR* to reduce the transmission of infectious diseases. This will be the larger of the 7.5 L/s per person adjusted for design occupancy and ventilation effectiveness, and the design ventilation rate, adjusted for the ventilation effectiveness of the space:

$$\text{MSR} \geq \frac{DVR}{E_{ac}} \quad and \quad \geq \frac{7.5 P_D D}{E_{ac}}$$

E_{ac} The ventilation effectiveness (see Appendix A in this paper for an explanation).

3 Calculate the recirculated supply rate on the basis of filtration efficiency and account for differences in DVR and air change effectiveness between zones.

If the draft BRS/ASHRAE 62-1989R Standard is completed and adopted in New Zealand, with some modification for local conditions, it will add the consideration of air change effectiveness to routine ventilation system design. The draft Standard offers the following limited guide to air change effectiveness values (Table 1), which can be considered along with measurements made in New Zealand (Table 3).

TABLE 1: Default air change effectiveness values from the draft BRS/ASHRAE 62-1989R Standard.

Application	Default E_{ac}
Supply of cool air from ceiling.	1.0
Supply of warm air from ceiling provided temperature no greater than 8°C above indoor ambient temperature.	1.0
Supply of warm air from ceiling when the temperature of supply air exceeds 8°C above indoor ambient temperature.	0.8
Supply of air from the floor at a velocity high enough to induce substantial mixing of room air.	1.0
Supply of cool air from the floor and return from ceiling (displacement type systems).	1.2
Supply of warm air from the floor and return from ceiling.	0.7

1.2 The AS 1668 Standard

Australian Standard AS 1668.2-1991 [4] is often used in New Zealand for ventilation designs complying with the Acceptable Solution G4/AS1 [5] of the building code. A recent draft revision of this Standard, DR 96425 - 1996 [6], requires that ventilation effectiveness be considered when calculating an amenity index. This represents the outdoor air requirements for a particular enclosure, occupancy and ventilation system configuration. Similar ventilation effectiveness values are given in Appendix C of the draft Standard for a similar range of conditions to that contained in Table 1.

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 which use 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 tracer gas, and for sampling air from different locations.

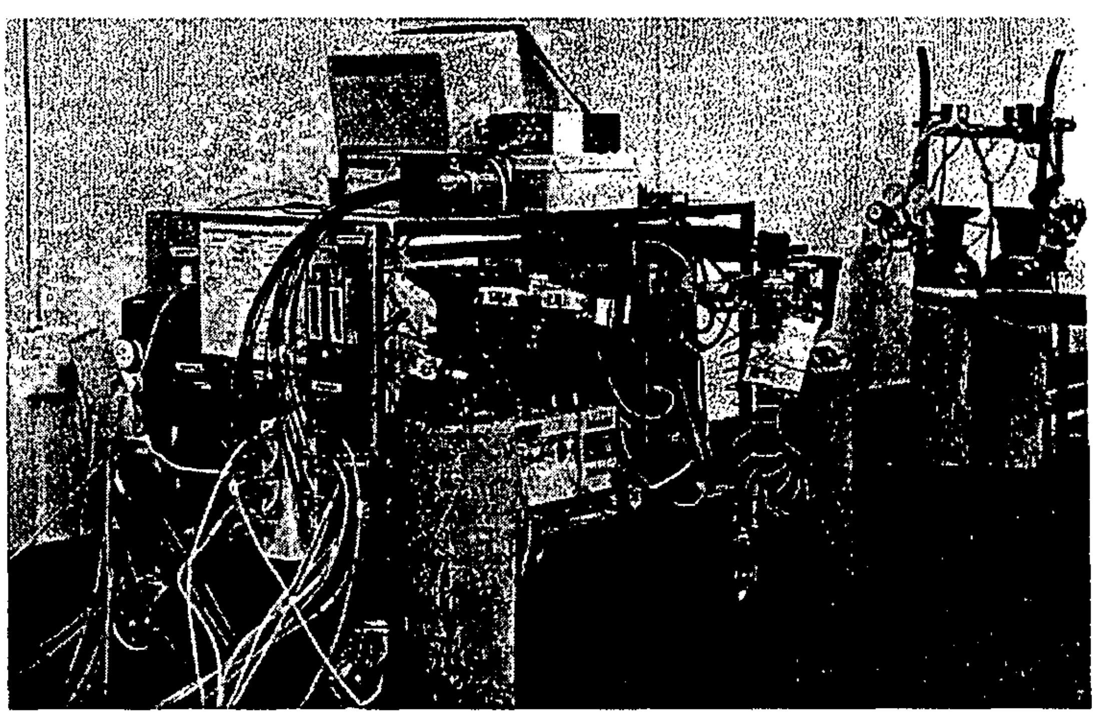

FIGURE 1: Automated tracer system for measuring ventilation effectiveness parameters.

The equipment and methods used have been described in detail [7, 8 and 9], along with the results of ventilation effectiveness measurements in eight office buildings in the Wellington area.

3. MEASUREMENTS IN WELLINGTON OFFICE BUILDINGS

The ventilation performance measurements described here were 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 [7 and 8] and buildings D (level 6) to H in a recent paper [9]. All were office buildings with varying degrees of internal partitioning, ranging from open plan to individual offices. Buildings A, B, C and G 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. Earlier studies [7 and 8] investigated the effectiveness with which fresh air was supplied to the breathing zones by mapping the mean age of air over the floor plan. 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. EFFECTIVENESS OF AIR DISTRIBUTION

Effective ventilation rates have been determined on a total of 12 floors in eight buildings. A contour map of the effective ventilation rate at breathing height was prepared from spot measurements. Averaging these measurements has given the data contained in Table 3, which includes the room mean age of air, the nominal time constant, the air change efficiency and the ventilation effectiveness calculated according to methods outlined in Appendix A. Examples of effective ventilation rate distributions are given for building D level 6 with all internal doors open (Figure 2), for the open plan space in building E (Figure 3), and the open plan spaces in building G (Figure 4).

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 which has prevented fresh air released in the plenum from reaching air handlers providing conditioned air to the rooms below. 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, further reducing effective ventilation rates.

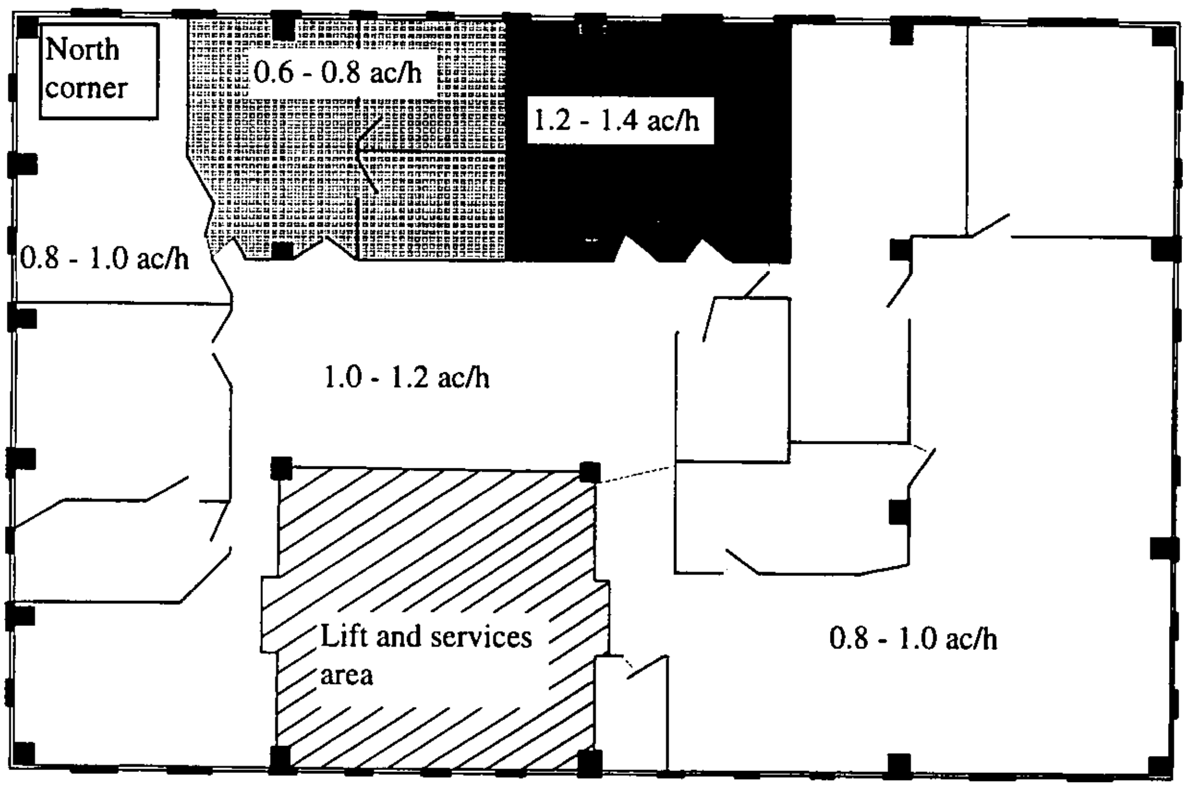

FIGURE 2: Approximate contours of effective ventilation rate in the breathing zones of building D level 6.

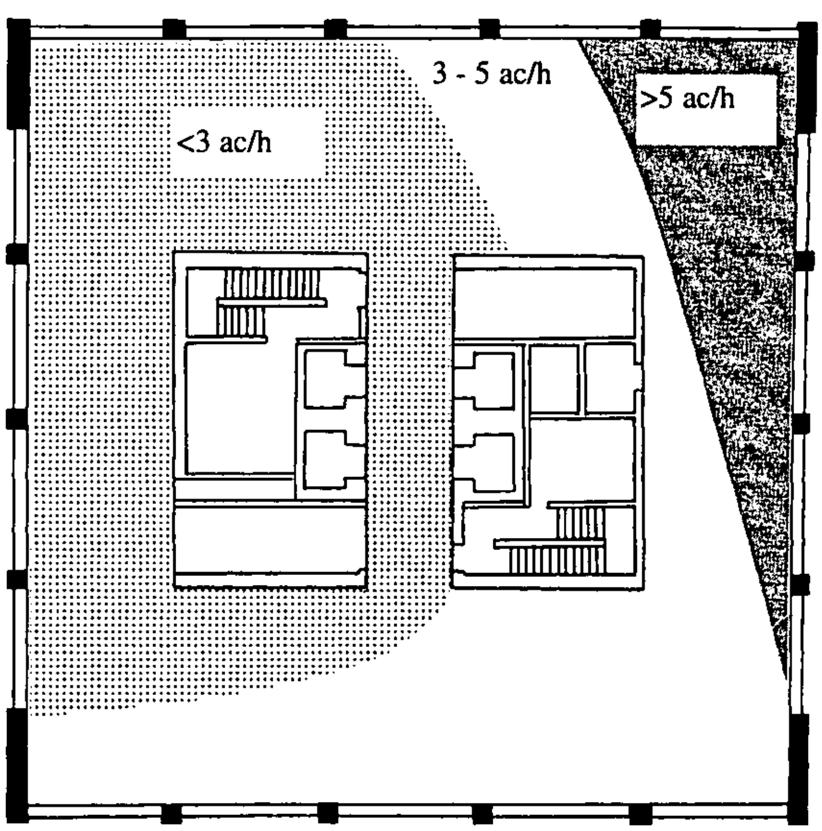

FIGURE 3: Approximate contours of effective ventilation rate in the breathing zones of building E.

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 for partitioned spaces. The effective ventilation rates in the breathing zone of building H have been shown [9] to form a similar pattern to the fresh air delivered at ceiling level, with highest values around the perimeter. 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.

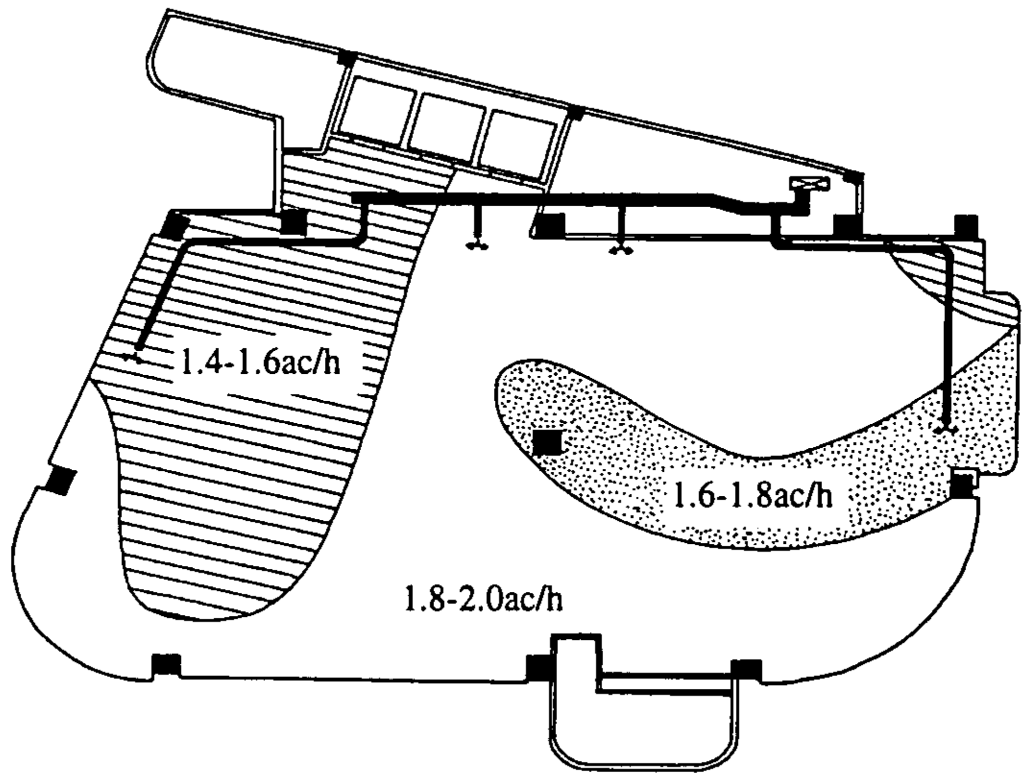

FIGURE 4: Approximate contours of effective ventilation rate in the breathing zones of building G.

It has been possible to measure effective mechanical ventilation rates during office hours, and infiltration rates at nights and during weekends. In building G the infiltration rate on level 4 was almost half the fresh air supply rate during office hours, and this is thought to have contributed to variations in the effective ventilation rate shown in Figure 4. It is likely that most of the measured infiltration was driven vertically in the building by stack pressure differences. In this case the effective infiltration rate for the whole building will be less than the infiltration rate in Table 3 because much of the infiltration measured will be common to all floors. Infiltration and its interaction with mechanical ventilation systems is still poorly understood in office buildings in New Zealand.

TABLE 3: Measured ventilation characteristics in eight New Zealand office buildings.

Measured ventilation characteristics in eight New Zealand office buildings							
Building	Level	Tracer method ref[7,8,9]	Nominal time constant (h)	Mean age of air (infiltration) (h)	Mean age of air (ventilation) (h)	Air change efficiency %	Ventilation effectiveness
A	3	Pulse	0.79	n/d	0.75	53%	1.06
A	2	Pulse	-	n/d	0.60	-	-
B	2	Pulse	0.82	n/d	0.76	54%	1.08
B	3	Pulse	0.95	n/d	0.64	74%	1.48
C	5	Pulse	1.33	n/d	1.65	40%	0.80
C	6	Pulse	1.13	n/d	1.31	43%	0.86
D	7	Pulse	1.40	n/d	1.41	50%	1.00
D	6	Constant	1.03	n/d	1.03	50%	1.00
D	6	Pulse	1.03	n/d	1.02	50%	1.00
E	6	Constant	0.28	3.8	0.24	59%	1.18
F	27	Constant	0.13	2.7	0.10	62%	1.24
G	4	Constant	0.59	1.3	0.60	49%	0.98
H	1	Constant	0.12	1.0	0.098	63%	1.26

The ventilation effectiveness on 12 floors of eight buildings has ranged between 0.8 and 1.48, with a mean value of 1.1 and an experimental uncertainty of 20%. This indicates that ventilation in these buildings can best be described as dilution ventilation (see Appendix A). In 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, e.g. Fisk and Faulkner [10], 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 mostly dilution ventilation systems.

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 4. Here the normalised standard deviation of effective ventilation rates expressed as a percentage tends to be higher in partitioned areas, illustrating the importance of floor space design considerations in the planning of air conditioning system layout.

TABLE 4: 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 in Table 1, within the 20% uncertainty considered to apply 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 expressed as a percentage of the room average mean age was higher in partitioned areas than within large open-plan areas. In ventilation designs, however, this effect can be minimised. Far more important were two rooms missing either a fresh air supply or an exhaust return to the plenum. Here the effective ventilation rates were half that of adjacent areas.

- Infiltration rates were measured in four buildings and were found to be significant enough to recommend more detailed investigation in New Zealand buildings. More detailed data would allow infiltration to be either accounted for in ventilation system design, or appropriate changes made to building designs to minimise air leakage.

7. ACKNOWLEDGMENTS

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8. REFERENCES

1. Standards New Zealand. NZS 4303:1990. *Ventilation for Acceptable Indoor Air Quality.* Wellington.
2. American Society of Heating, Refrigeration and Air-conditioning Engineers, Inc. 1989. *"ASHRAE Standard 62-1989"*. Atlanta.
3. American Society of Heating, Refrigeration and Air-conditioning Engineers, Inc. 1996. *"BSR/ASHRAE Standard 62-1989R"*. Public review draft standard. Atlanta.
4. Standards Australia. 1991 AS 1668.2-1991. *The Use of Mechanical Ventilation and Airconditioning in Buildings Part 2: Mechanical Ventilation for Acceptable Indoor-Air Quality.* Sydney.
5. Building Industry Authority. 1992. *New Zealand Building Code, Approved Document G4, Ventilation.* Wellington.
6. Standards Australia. 1996. DR 96425. *The Use of Mechanical Ventilation and Airconditioning in Buildings Part 2: Ventilation of buildings.* Sydney.
7. Bassett, M.R. and Isaacs, N. 1994. *Preliminary ventilation effectiveness measurements by a pulse tracer method.* Proceedings of the 15th AIVC Conference, Buxton, England.
8. Bassett, M.R. and Isaacs, N. 1995. *Ventilation effectiveness measurements in selected New Zealand office buildings.* Proceedings of the 16th AIVC Conference, Palm Springs, USA.
9. Bassett, M.R. 1997. *Ventilation efficiency measurements by the method of homogeneous emission in real time.* Proceedings of the 18th AIVC Conference, Athens, Greece.
10. Fisk, W. J. and Faulkner, D. 1992. *Air change effectiveness in office buildings: Measurement techniques and results.* Proceedings of the International Symposium on Room Air Convection and Ventilation Effectiveness, pp282-294. Tokyo.

APPENDIX A: VENTILATION EFFECTIVENESS - WHAT IS IT ?

The ventilation efficiency parameters describe the mixing behaviour of air in the breathing zones, and the processes by which pollutants are diluted or displaced by the ventilation process. 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 concepts of ventilation efficiency allow the performance of 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 [1] and Skåret [2], and in summary form from Sutcliffe [3], and Brouns and Waters [4].

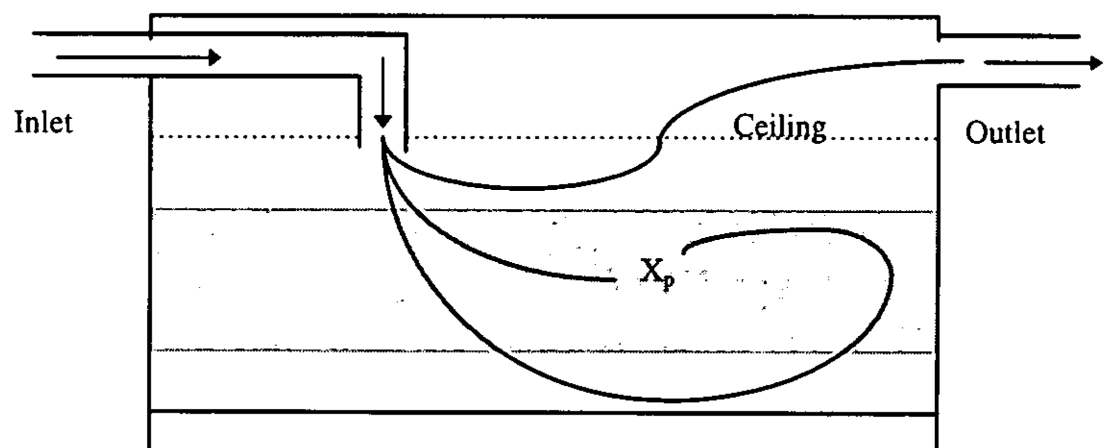

FIGURE A1: Representation of a mechanically ventilated room.

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.

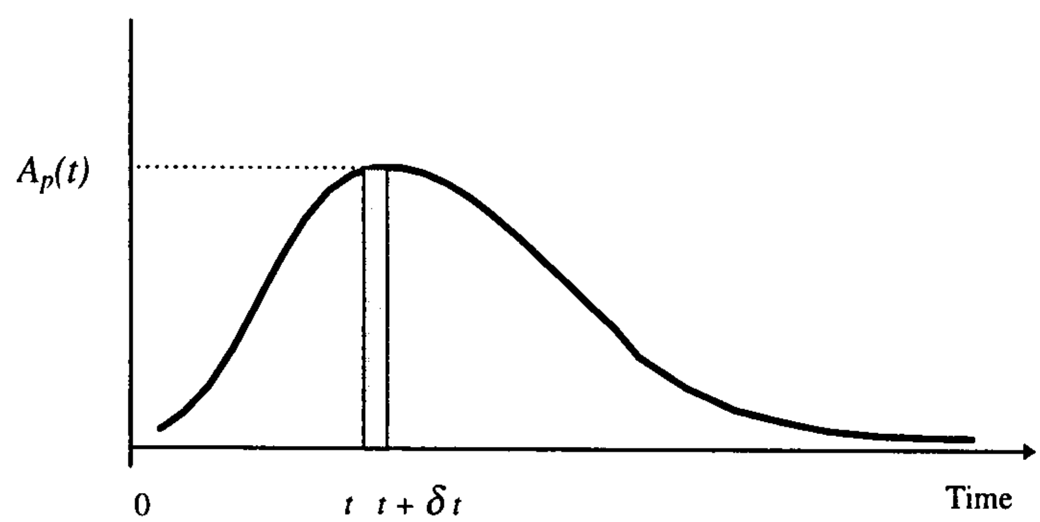

FIGURE A2: A possible frequency curve for air arriving at point P.

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:

Number of molecules arriving at

$$Xp = \int_0^\infty A_p(t)dt = 1 \qquad (1)$$

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:

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

From equation 1 this can be expressed as:

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

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:

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

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:

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

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

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

It can alternatively be expressed as a coefficient of air change performance E_{ac} as defined in the ASHRAE draft Standard 62-1989R [5] as the ventilation effectiveness, as follows:

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

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 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	$\tau_n/2$	100 %	2

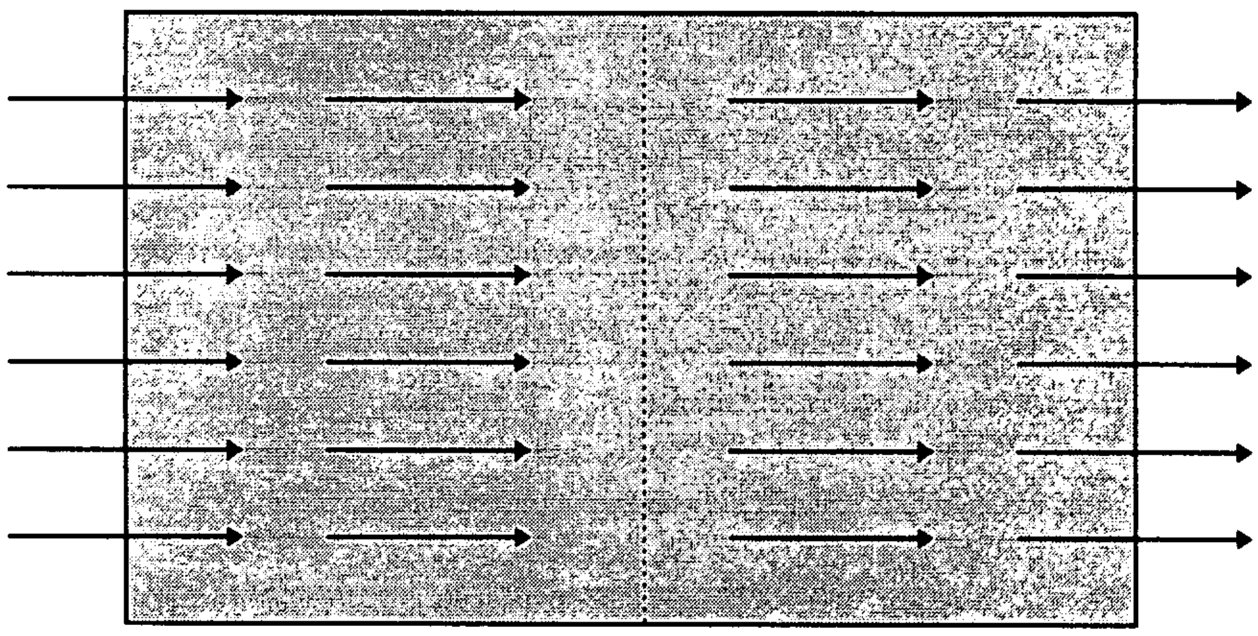

FIGURE A3: Displacement flow of air through a ventilated space.

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.

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

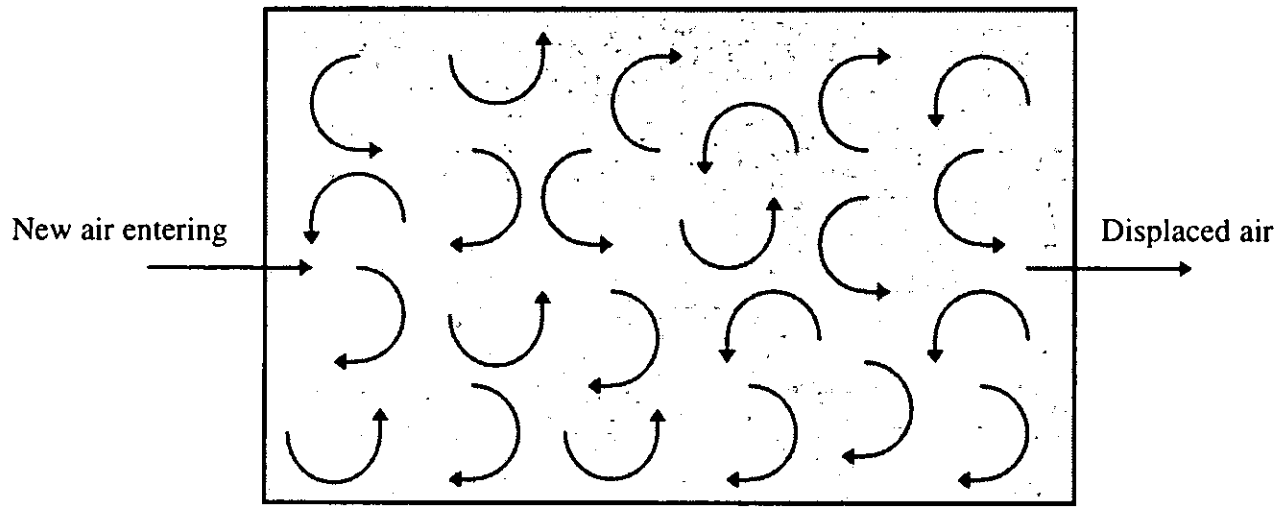

FIGURE A4: Fully mixed air in a space representing dilution ventilation.

In practice, the local mean age of air or the effective ventilation rate will vary with location in a ventilated space in a way which will depend on the location of fresh air entry and exhaust points in relation to internal partitioning and other physical conditions. The ventilation indices can either be measured with tracer gas methods or calculated with computational fluid dynamics methods.

8. References

1 Sandberg, M. 1981. *What is ventilation efficiency.* Building and Environment, Vol. 16. 1981.

2 Skåret, E. 1984. *Ventilation efficiency - A survey of concepts of ventilation efficiency - new aids for designers.* SINTEF report STF15 A84057, Trondheim, Norway, 1984.

3 Sutcliffe, H. 1990. *A guide to air change efficiency.* Technical Note AIVC 28. Air infiltration and Ventilation Centre. Warwick, UK.

4 Brouns, C. and Waters, R. *A guide to contaminant removal effectiveness.* Technical Note AIVC 28.2. Air Infiltration and Ventilation Centre. Warwick, UK.

5 American Society of Heating, Refrigeration and Air-conditioning Engineers, Inc. 1996. *"BSR/ASHRAE Standard 62-1989R".* Public review draft standard. Atlanta.

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