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Ventilation Effectiveness Measurements in Selected New Zealand Office Buildings

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1. Synopsis

Office workers continue to complain about air quality problems, and a significant industry has developed to measure pollutants and environmental conditions such as temperatures and humidity. The effectiveness of the ventilation system is often ignored because it is a difficult measurement to carry out and interpret. The results contained in this paper make a start towards understanding the performance of mechanical ventilation in New Zealand office buildings.

A common ventilation approach in New Zealand office buildings involves supplying non-recirculated fresh air to the vicinity of unit air handlers in the plenum. This fresh air is mixed with exhaust air, and directed through ceiling registers to work stations below. Exhaust air returns through ceiling grills directly into the plenum and thence eventually to an in-plenum extract. In these cases some fresh air may be lost directly to the exhaust and the air change effectiveness of the system may fall short of the dilution ventilation description.

In this project the local mean age of the air was determined at a matrix of locations in four buildings in both open plan and partitioned working areas and in the plenums. Measurements were made using a pulse tracer approach with sulphur hexafluoride (SF_6) and a gas chromatograph with an electron capture detector.

The importance of planning the ventilation system around the floor layout has been illustrated by local mean age-of-air results. Air change effective results have shown that within a diverse range of air handling systems, most can be described by the dilution ventilation model.

2. Experimental approach

The tracer gas-detection system used in this study consists of a gas chromatograph (GC) and electron-capture detector with a tracer delivery and sampling system automated to step through a sequence of up to eight independent LMA (local mean age-of-air) measurements [1]. In the buildings examined in this study, dosing the fresh air inlet with tracer gas was achieved with a system that released discrete shots of tracer into the fresh air supply. The time taken to dose the inlet was typically 5 seconds and the volume of pure SF_6 delivered in each shot was 50cm^3.

For LMA measurements it is important that the calibration of the detection equipment is well established. For this electron-capture detector and peak-area integration software, it is known that the calibration depends on the carrier gas pressure but that the response is linear over the normal working range of 1 to 100ppb [1]. Certified reference tracer gases at 5 and 20 ppb were used to fit a linear relationship between the integrated output from the gas chromatograph and tracer concentration. This calibration process was carried out each time the equipment was moved.

The parameters measured in this study were the LMA and the air change effectiveness. The local mean age-of-air was determined by the pulse method with integration of local tracer concentrations and extrapolation to infinite time by fitting an exponential decay equation to the tail of the data [2]. The LMA was calculated from equation 1 as follows:

$$\bar{\tau}_p = \frac{\int_0^{t'} t\, C_p(t)\,dt + \frac{C_0}{n} e^{-nt'}\left[t' + \frac{1}{n}\right]}{\int_0^{t'} C_p(t)\,dt + \frac{C_0}{n} e^{-nt'}} \qquad (1)$$

Where $C_p(t)$ = The concentration of tracer gas at point p at time t (ppb).

$\bar{\tau}_p$ = The local mean age-of-air in units of t (hours).

n = The exponent in a fitted exponential decay curve.

C_0 = A constant in the fitted exponential equation (ppb).

t' = The time at which measurements terminated (hours).

A similar procedure can be used to compensate for data taking over a finite time when the room mean age-of-air is determined from tracer concentrations measured in the exhaust duct. This is described in more detail in [2] where it was concluded that truncation errors could be as high as 30%. Compensation for finite data taking times in local mean age-of-air measurements, in contrast, were mostly in the range 2% to 7% for measurement times between 2 and 4 hours.

3. Building and mechanical system descriptions

The ventilation performance measurements described here were carried out in four buildings (labelled A to D) located in the central business district of Wellington New Zealand. Buildings A and B are the same as A and B in an earlier paper [2] and buildings C and D provide new data. All were office buildings with varying degrees of internal partitioning ranging from open plan to individual offices.

Building A was originally designed and constructed in 1967 as the city base for a national airline. It consists of office spaces (the top floor) and freight handling areas (middle floor). The air handling systems for each floor are independent but in practice there was found to be some interaction between zones because the fresh air and exhaust air flow rates are not balanced.

Building B is a 7-floor office building constructed in the early 80's. Each floor is supplied with fresh air from a central duct and exhaust air is removed from the plenum area into a central extract shaft. Fresh air is delivered into the breathing zones by plenum-mounted fan coil units which are cooled by a central chilled water plant. Each unit recirculates a proportion of exhaust air from the plenum area but there is no significant mixing of air between floors. Floor 3 is mostly open plan but with about one third of the floor area partitioned into offices. Floor 2 is mostly open plan but does contain one small office.

Building C was built in the early 80's but with significant expansion in the late 80's. It provides 7 floors of open plan office space with fresh air supplied to each floor. In common with building B, fresh air is delivered to the vicinity of plenum-mounted fan coil units which deliver air to the breathing zones below. There is a single exhaust point in the plenum as in building B, but in this case it serves a floor plan which is three times larger.

Building D was built in the commercial building boom of the mid 80's and therefore contains the most recently specified air handling system in the four buildings. In common with buildings B and C, fresh air is supplied to each floor and distributed to the breathing zones by plenum-mounted unit air handlers. The main differences in this buildings are the high level of internal partitioning and the reliance on exfiltration through the envelope and services shafts for exhaust losses.

The important floor plan and air handling system details are presented in Table 1.

Building A Top Floor	
Floor area (effective test space) 1,526 m^2	**Volume** (including plenum) 4,731 m^3
Air handling - Two roof air handlers delivering heated fresh air, return air ducted through the plenum.	
Fresh air delivery - Not able to be measured	**Exhaust air removal** - Not able to be measured
Building A Middle Floor	
Floor area (effective test space) 521 m^2	**Volume** (including plenum) 2,553 m^3
Air handling - Internal air handler with exposed duct running centrally at ceiling level. Internal extract from exposed duct following the external wall at ceiling level.	
Fresh air delivery - 1,826 m^3/h	**Exhaust air removal** - 3,219 m^3/h
Building B Second Floor	
Floor area (effective test space) 454 m^2	**Volume** (including plenum) 1,438 m^3
Air handling - Fresh air ducted to local heat pump air conditioners in the plenum area. Exhaust carried from plenum area into an extract shaft exhausting at roof top.	
Fresh air delivery - 1,750 m^3/h	**Exhaust air removal** - Not able to be measured
Building B Third Floor	
Floor area (effective test space) 469 m^2	**Volume** (including plenum) 1,486 m^3
Air handling - Fresh air ducted to local heat pump air conditioners in the plenum area. Exhaust carried from plenum area into an extract shaft exhausting at roof top.	
Fresh air delivery - 1,573 m^3/h	**Exhaust air removal** - Not able to be measured
Building C Fifth Floor	
Floor area (effective test space) 1,476 m^2	**Volume** (including plenum) 4,723 m^3
Air handling - Fresh air ducted to local heat pump air conditioners in the plenum area. Exhaust carried from a central point in the plenum into an extract shaft exhausting at roof top.	
Fresh air delivery - 3,563 m^3/h	**Exhaust air removal** - 2,600 m^3/h
Building C Sixth Floor	
Floor area (effective test space) 1,476 m^2	**Volume** (including plenum) 4,723 m^3
Air handling - Fresh air ducted to local heat pump air conditioners in the plenum area. Exhaust carried from a central point in the plenum into an extract shaft exhausting at roof top.	
Fresh air delivery - 4,183 m^3/h	**Exhaust air removal** - 2,540 m^3/h
Building D Seventh Floor	
Floor area (effective test space) 499 m^2	**Volume** (including plenum) 1,536 m^3
Air handling - Fresh air ducted to local heat pump air conditioners in the plenum area. No exhaust ducted from the floor. Exhaust by exfiltration through envelope.	
Fresh air delivery - 1,092 m^3/h	**Exhaust air removal** - No mechanical extract

Table 1: Building descriptions and air handling system capacities.

Fresh air delivery to occupied spaces

The approach to ventilating buildings B, C and D is common in New Zealand. It involves supplying fresh air to the vicinity of unit air handlers in the plenum which filter and condition the air as it is delivered to the breathing zones below. The extent to which this fresh air mixes with exhaust air in the plenum, and the extent to which fresh air is lost directly to exhaust, are the two main questions asked of this project. Within the buildings in this study there are significant differences in the approaches to ducting fresh air to the unit air handlers. Three approaches are illustrated in Figures 1,2 and 3. The approaches illustrated in these figures were considered by the design engineers to allow recirculated air from the plenum to be entrained and conditioned along with fresh air from the connected duct.

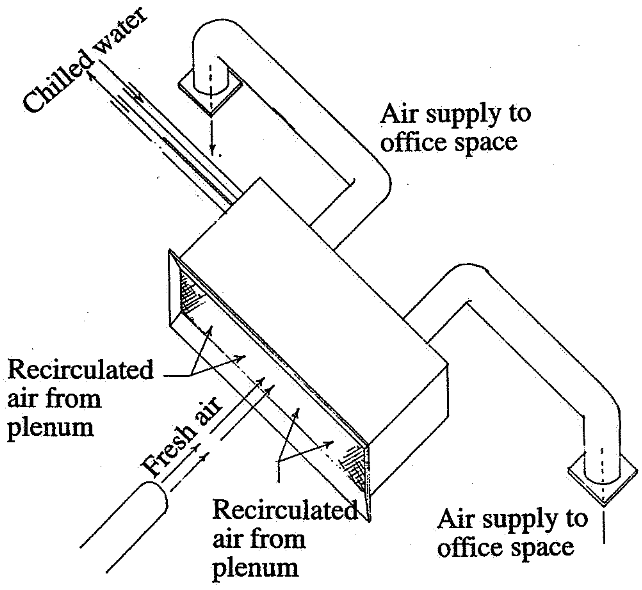

Figure 1: Air discharged in the general direction of the unit air handlers in buildings C and D, permitting recirculation of exhaust air from the plenum. In building D the distance between the closest fresh air delivery point and the unit air handler ranged between 0.5 and 10 meters.

On level 3 of building B there is a further development of the fresh air supply to unit air handler connection, as shown in Figure 2. In building B the fresh air was originally only released from the central air supply duct directly into the plenum. After an indoor air quality survey the approach shown in Figure 3 was adopted. This variation was also found on floor 5 of building C.

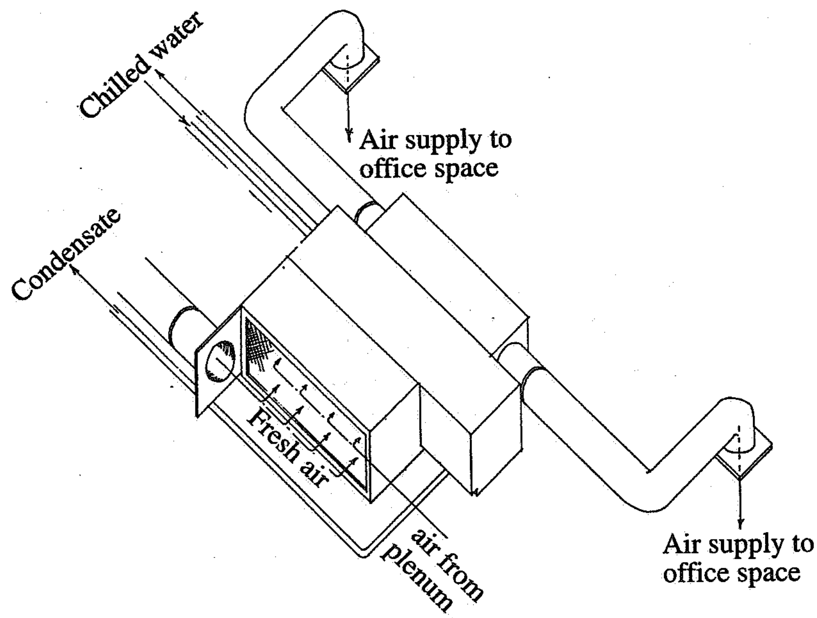

Figure 2: Direct ducting of fresh air to the face of the air handlers in building B.

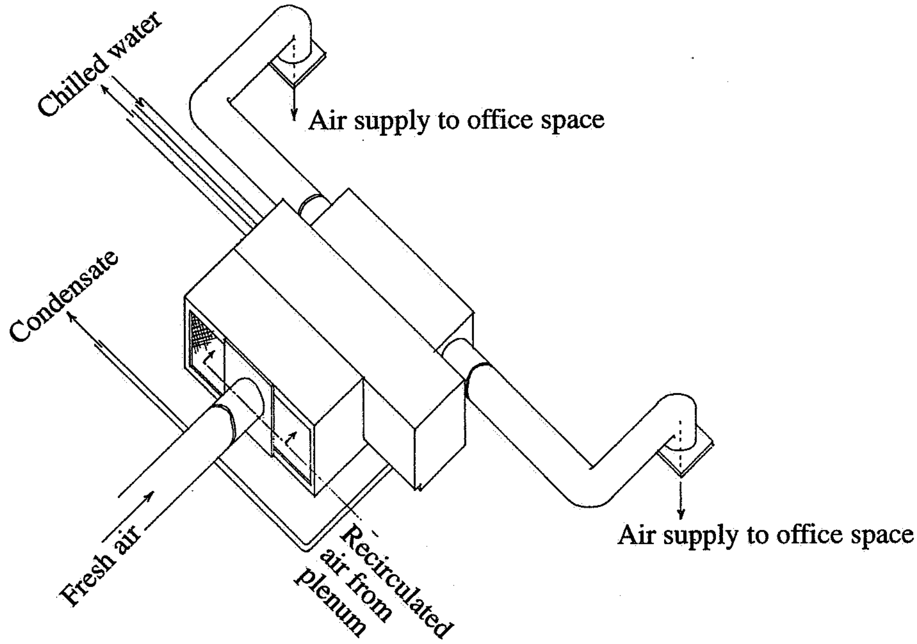

Figure 3: Direct ducting of fresh air to the air entry point of unit air handlers on floor 2 of building C.

4. Effectiveness of air distribution

The local mean age-of-air 1.5 m above floor level (in hours) has been measured and marked out on floor plans for all four buildings. Detailed data for buildings A and B can be found in [2] and local mean age data for buildings C and D are presented here in Figures 4, 5 and 6. A measure of the repeatability of these results has been determined from measurements carried out in five locations on the middle floor of building A. Lumped into this uncertainty will be experimental errors as well as the effect of infiltration changes and supply air temperature fluctuations. The pooled relative standard deviation of this data is 4%. There are, of course, systematic errors and errors in interpretation that add further to the overall uncertainty. The systematic error has been estimated to be 20%, which is similar to the 95% confidence interval suggested by Fisk [3] for breathing-level air-exchange effectiveness and air diffusion effectiveness measurements.

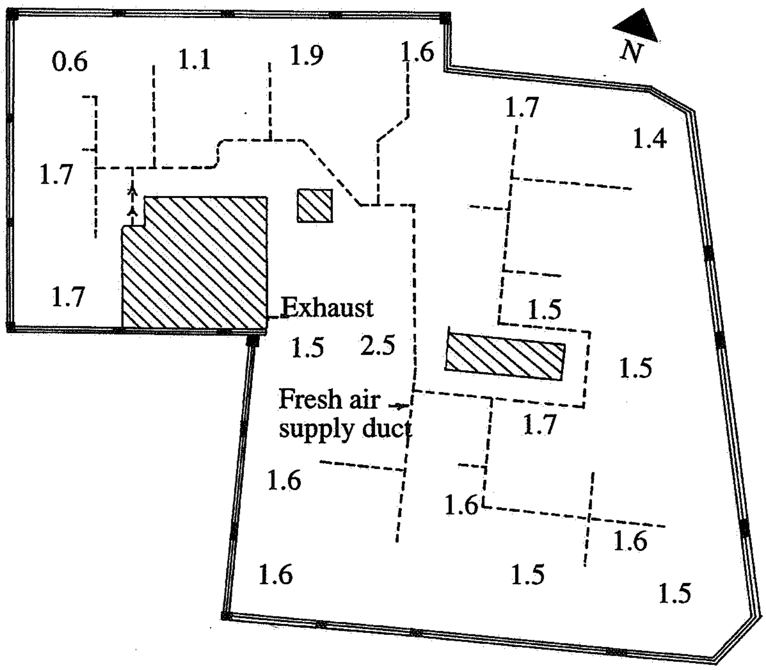

Figure 4: Local mean age-of-air (in hours) for floor 5 of building C in the breathing zone.

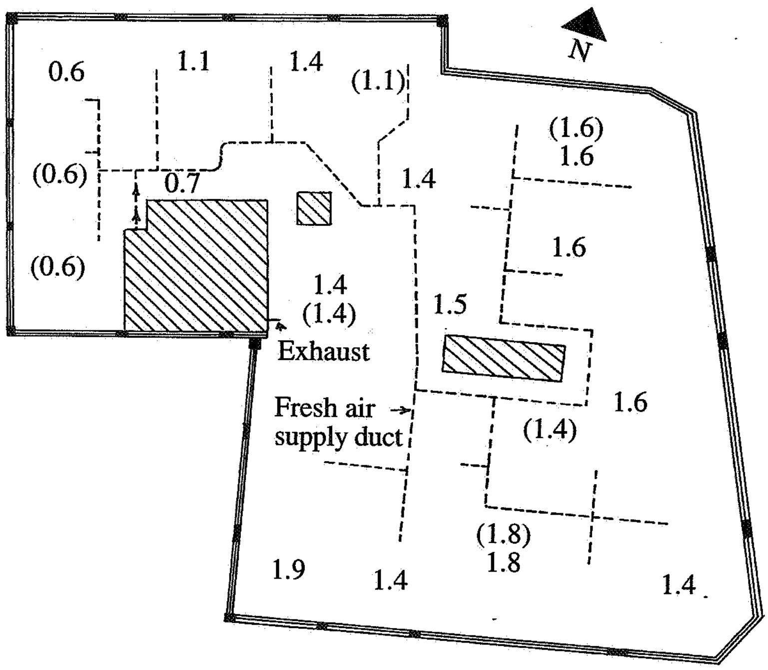

Figure 5: Local mean age-of-air (in hours) for floor 6 of building C in the breathing zone and [in brackets] measured in the plenum.

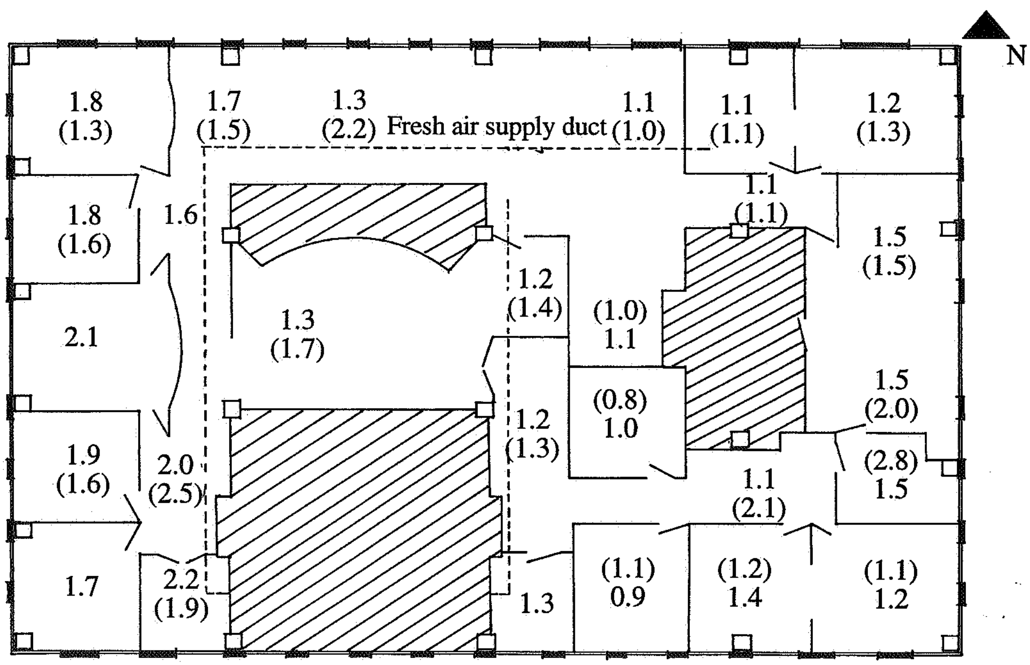

Figure 6: Local mean age-of-air (in hours) for floor 7 of building D in the breathing zone with all doors open and (in brackets) measured with all doors closed.

The nominal time constants for the fresh air supplied by the ventilation systems were measured using an electronic air velocity probe and a pitot static tube, and found to exceed or come close to the fresh air deliveries specified by NZS 4303 [3] for office buildings. In all cases they exceed the ventilation requirements in force when the buildings were constructed.

Variations in the LMA over the floor plan give an insight into the effectiveness of air distribution systems. In buildings C and D, in particular, there are clearly defined areas of the building with relatively long mean ages. In building D the mean age-of-air is 1.2h along the north-south axis of the building following the fresh air ducting path and at the east and west ends of the building the mean age-of-air is appreciably longer at 1.7h. This difference can be attributed to relative isolation from the fresh air supply of unit air handlers in the east and west ends of the building.

A similar lengthening of local mean age with distance from fresh air supply points was noted on the top floor of building A [2]. In the open plan areas of buildings B, C and D the local mean age-of-air is generally more uniform throughout the space than is the case for partitioned areas in these buildings. The only exception to this is one end of building C floor 6 where air-handling commissioning notes show fresh air delivery rates to exceed design requirements even with the dampers fully closed. Here the LMA is 0.6h where in the remainder of the floor it is 1.5h.

An indication of the variation in LMA has been given in Table 2 in the form of the standard deviation of the mean age-of-air measured 1.5m above floor level divided by the average mean age-of-air. The normalised standard deviation in LMA is shown to more than double in partitioned areas, illustrating the importance of floor space design considerations in the planning of air conditioning systems.

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

Table 2: The normalised standard deviation in local mean age-of-air measured in buildings B, C and D.

In some individual rooms on floor 3 of building B and floor 7 of building D the local mean age-of-air was found to change when doors were opened or closed, but over many rooms the average mean age-of-air remained unaffected. The average mean age in the partitioned areas of floor 7 of building D was 1.5 hours with the doors closed and 1.4 hours with the doors open. In the partitioned part of floor 3, building B, the average mean age with doors closed was 0.44 hours and with doors open 0.49 hours. These differences are considered to be insignificant.

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 LMA with doors closed was about twice that of adjacent areas.

5. Ventilation effectiveness

The breathing-zone local mean age-of-air data has been averaged to give an estimate of the room mean age of air. These averages, along with the nominal time constants and the room mean age of air determined using exhaust air analysis where possible, are given in Table 3.

Building/floor Ventilation parameter	A/2	A/3	B/2	B/3	C/5	C/6	D/7
Room mean age of air (space averaged) in hours	0.75	0.60	0.76	0.64	1.65	1.31	1.41
Room mean age of air (analysed at exhaust duct) in hours	0.76	-	0.79	0.60	-	-	-
Nominal time constant (hours)	0.79	-	0.82	0.95	1.33	1.13	1.40
Space averaged air change efficiency %	53%	-	54%	74%	40%	43%	50%

Table 2: Ventilation effectiveness parameters measured in seven building ventilation zones.

Where it was possible to measure the nominal time constant, the air change efficiency measured in the breathing zones was between 40% and 75%. There was no obvious link between these results and the connection between fresh air supply and the unit air handlers. Indeed, local mean age-of-air measurements in the plenum of building C showed that, in this case, the plenum and the occupied areas were effectively one zone.

In five cases the air change efficiency ranged between 40% and 53%, indicating that the ducted fresh air performed a dilution ventilation role. In floor 3 of building B, the air change efficiency was 75% and apparently closer to the displacement flow description. It must be remembered that the LMA was 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 [4], have measured ventilation-effectiveness parameters in mechanically ventilated buildings and developed a picture of the effectiveness of systems in a range of buildings. In their data, similar conclusions are reached concerning the description of mechanical ventilation in office buildings as dilution ventilation systems. It is too early to form secure conclusions about the effectiveness of ventilation systems in New Zealand office spaces, but further measurements are planned.

6. Conclusions

This study has measured the local mean age-of-air in the breathing zones of four mechanically ventilated buildings in New Zealand. Three of the buildings used a common approach, of ducting fresh air to unit air handlers in the plenum space where it is directed to the occupied spaces below. In some cases the fresh air supply was tightly coupled to the unit air handler while, in others, fresh air was discharged more generally into the plenum. The following key points concerning the performance of these ventilation systems were established:

- The floor-averaged nominal time constants for the ventilation systems studied in four buildings ranged between 0.79 to 1.4 hours. These exceed or come close to the fresh air deliveries specified by NZS 4303 [3] for office buildings, and in all cases exceed the requirements in force when the buildings were constructed. The floor-averaged mean age-of-air in the breathing zones of the four buildings ranged between 0.6 and 1.65 hours, which in most cases came close to the nominal time constant for the space.

- The air change effectiveness in three buildings employing unit air handlers fell in the range of 40% to 54%, with a further result at 74%. There was no obvious link between these results and the connection between fresh air supply and the unit air handlers. Indeed, measured local mean age-of-air measurements in the plenum of building C showed that the plenum and the occupied areas were effectively one zone.

- Variation in the local mean age-of-air in the breathing zones of the four buildings has depended 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 about twice as high in partitioned areas as it was within large open plan areas. In ventilation performance terms, however, this was not considered to be significant. Far more important were two cases of rooms missing either a fresh air supply or an exhaust return to the plenum. Here the local mean age-of-air was twice that of adjacent areas.

Further measurements are planned in order to develop a wider understanding of ventilation effectiveness achieved in New Zealand buildings.

7. Acknowledgments

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8. References

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