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Preliminary Ventilation Effectiveness Measurements by a Pulse Tracer Method

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Synopsis

Workers in 'white collar' jobs continue to complain about air-quality problems. Although there is a growing commercial interest in the measurement of gaseous and solid pollutants, there is no information on the effectiveness of New Zealand office ventilation systems. A set of baseline data is necessary to develop an understanding of the effectiveness with which air is provided in office spaces. This paper describes the results of preliminary ventilation effectiveness measurements made in mechanically ventilated spaces using a pulse tracer gas method.

Electron-capture tracer-detection equipment was modified to release a single pulse of sulphur hexafluoride (SF_6) into the fresh air supply duct and to monitor the concentration increase and decay in a matrix of breathing zone locations. A pulse approach was chosen on the basis of equipment suitability but it was found to have some drawbacks in terms of dependence on calibrations and long data-recording times.

The local mean age-of-air was determined at a matrix of locations in the largely un-partitioned zones of two unoccupied spaces of each of two large office buildings. A numerical approach was developed to allow the data acquisition to be truncated at a practical time and the remainder of the integration to infinity to be determined by extrapolation.

The paper discusses the practicalities of this approach to measuring air change efficiency and, in the course of discussing the results, makes recommendations for further work.

1. Experimental details

The tracer gas-detection system used in this study has been derived from equipment described [1] for multi-zone tracer studies in residential buildings. It consists of a gas chromatograph (GC) and electron-capture detector with a tracer delivery and sampling system automated to step through a sequence of eight independent local mean-age measurements. Air samples can be taken from eight points through small-bore PVC tubes through which sufficiently high air flows can be maintained to ensure that up-to-date tracer concentrations are seen by the GC. 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 from a small pressure vessel connected between two solenoid valves to a cylinder of pure SF_6. The solenoid valves were switched in a sequence that opened first the supply solenoid to charge the pressure vessel with SF_6 at 80 kPa. The supply solenoid was then closed and, thirdly, the pressure was allowed to relax to atmospheric pressure through the exhaust solenoid into the return air stream, where it was carried to the fresh air duct. The time taken to dose the inlet was typically 5 seconds and the volume of pure SF_6 delivered in each shot was 50cc.

For local mean age-of-air (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.

For pulse tracer measurements of the local mean age of air in mechanically ventilated buildings, the system configuration was as shown in Figure 1.

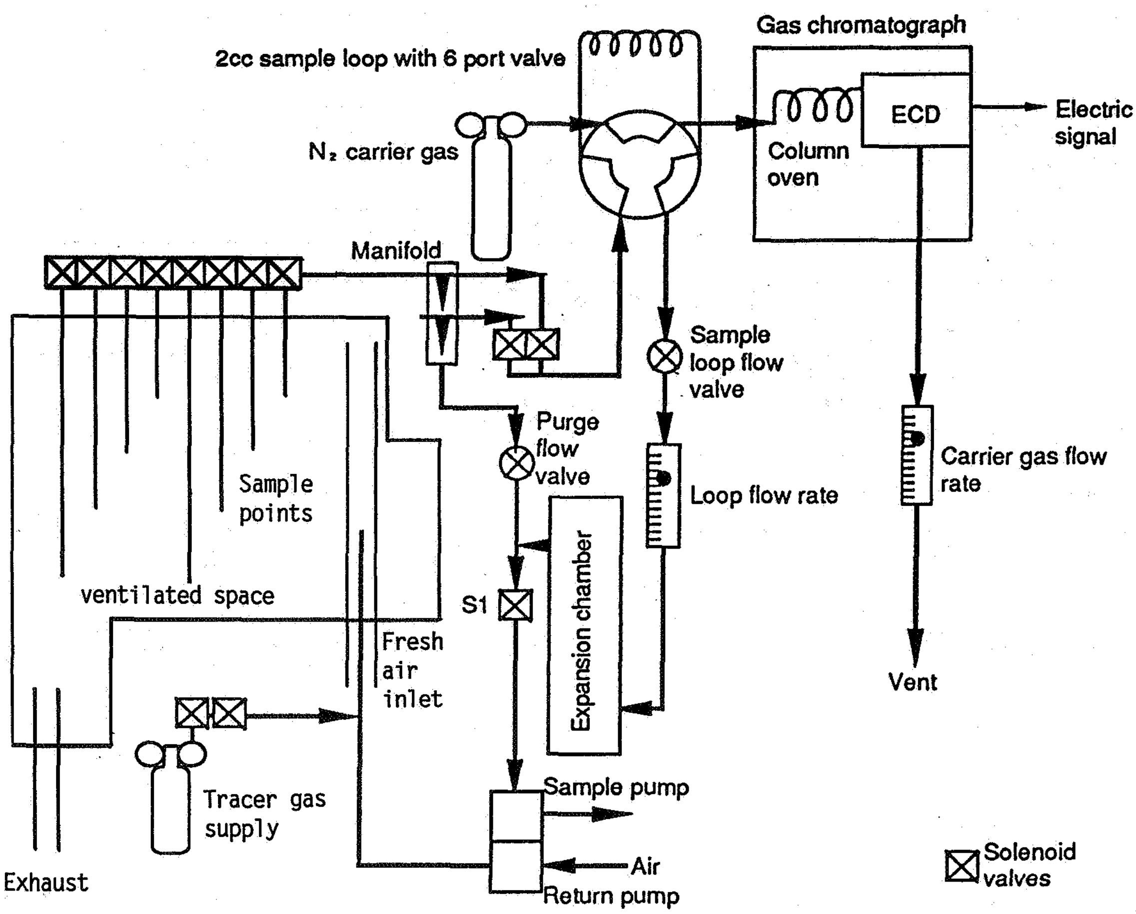

Figure 1: Tracer gas delivery and detection system for pulse local mean-age measurements.

2. Building descriptions

The two buildings examined in this study included both open-plan and partitioned zones. The important floor plan and air handling system details are presented in Table 1. Building A was originally designed as the city base for a national airline and consisted of office spaces (the top floor) and freight handling areas (middle floor). The air handling systems for each floor were independent but in practice there was some interaction between zones, because the fresh air and exhaust air flow rates were not balanced. Building B was a 7-level office building with each floor supplied with fresh air from a central duct. Exhaust air was removed through the plenum area into a central ventilation shaft. Fresh air was delivered into the breathing zones by plenum-mounted fan coil units cooled from a central chilled water plant. Each unit recirculated a proportion of exhaust air from the plenum area but there was no significant mixing of air between floors. Level 3 was mostly open plan but with about one third of the floor area partitioned into offices. Level 2 consisted of a single office with the remainder open plan.

Building A Top Floor	
Floor area (effective test space) 1,526 m²	**Volume** (including plenum) 4,731 m³
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 m²	**Volume** (including plenum) 2,553 m³
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 m³/h	**Exhaust air removal** - 3,219 m³/h
Building B Second Floor	
Floor area (effective test space) 454 m²	**Volume** (including plenum) 1,438 m³
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 - 1750 m³/h	**Exhaust air removal** - Not able to be measured
Building B Third Floor	
Floor area (effective test space) 469 m²	**Volume** (including plenum) 1,486 m³
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 - 1573 m³/h	**Exhaust air removal** - Not able to be measured

Table 1: Building descriptions and air handling system capacities.

3. Data analysis

The pulse method for determining the local mean age of air entering a room requires a shot of tracer gas to be injected into the airstream over a time period that is short compared to the nominal time constant of the room. It also requires that it be fully mixed in the ventilation duct before entering the room. When these conditions are satisfied, it has been shown [2] that the local mean age of the air at a point p can be determined from tracer concentration as follows:

$$\bar{\tau}_p = \frac{\int_0^\infty t\, C_p(t)\, dt}{\int_0^\infty C_p\, dt} \qquad (1)$$

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

$\bar{\tau}_p$ = The local mean age in units of t

This expression requires that the integration be continued to infinity but, in practice, the tracer concentration decays to low levels after 2 to 3 hours. A procedure developed here allows the data taking to be truncated to about two hours and a small (about 5%) correction term applied to approximate the required integration to infinity.

Figure 2 is an example of the tracer concentration variation with time at one of the sample points in building B. It shows that the concentration has fallen from a maximum of 50 ppb to around 1ppb after 3 hours, suggesting that truncating the integration at this point might give a satisfactory estimate of the local mean age of air. Also indicated on Figure 2 is a running total of the mean age integral, which is clearly still increasing at the end of the data-taking period of 3 hours.

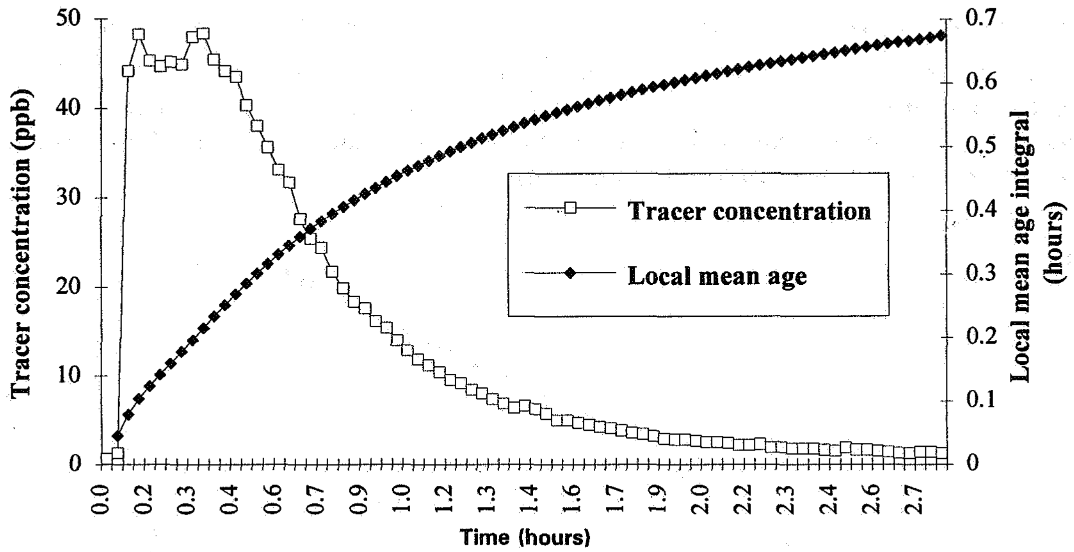

Figure 2: A typical tracer concentration record and developing local mean age of air integral.

One way of estimating the local mean age of air from data of this type is to assume that the concentration decay characteristics established in the last hour or so of results can be determined by curve fitting and extrapolation to infinity. The data gathered in this paper has been extrapolated using an exponential decay function of the following form:

$$C_p = C_0 e^{-nt} \qquad (2)$$

Where n = An exponent

C_0 = A constant (ppb)

There is no fundamental reason for expecting an exponential equation of this type to always be suitable (with displacement ventilation it would clearly not be suitable), but in the buildings investigated in this study the long tail decay has been found to approximate an exponential decay function. In these circumstances, equation 1 can be evaluated in two parts, the first determined from experimental data up to time t' and the second from values of C_0 and n determined from data recorded immediately prior to t'.

$$\overline{\tau}_p = \frac{\int_0^{t'} tC_p(t)dt + \left[\int_{t'}^{\infty} tC_0 e^{-nt} dt\right]}{\int_0^{t'} C_p dt + \left[\int_{t'}^{\infty} C_0 e^{-nt} dt\right]} \qquad (3)$$

This takes the following form

$$\bar{\tau}_p = \frac{\int_0^{t'} t\, C_p(t)\, dt + \frac{C_0}{n} e^{-nt'} \left[t' + \frac{1}{n} \right]}{\int_0^{t'} C_p\, dt + \frac{C_0}{n} e^{-nt'}} \quad (4)$$

A similar procedure can be used to compensate for data taken over a finite time when the room mean age of air is determined from tracer concentrations measured at the exhaust duct. In this case, the correction is rather more important because of the t^2 term in the numerator of equation 5. Figure 3 shows the tracer concentration measured at the exhaust of the middle floor of building A. The developing integral of the room mean age of air is plotted on the same time scale, where it is clearly seen to have not converged after 3 hours of data recording.

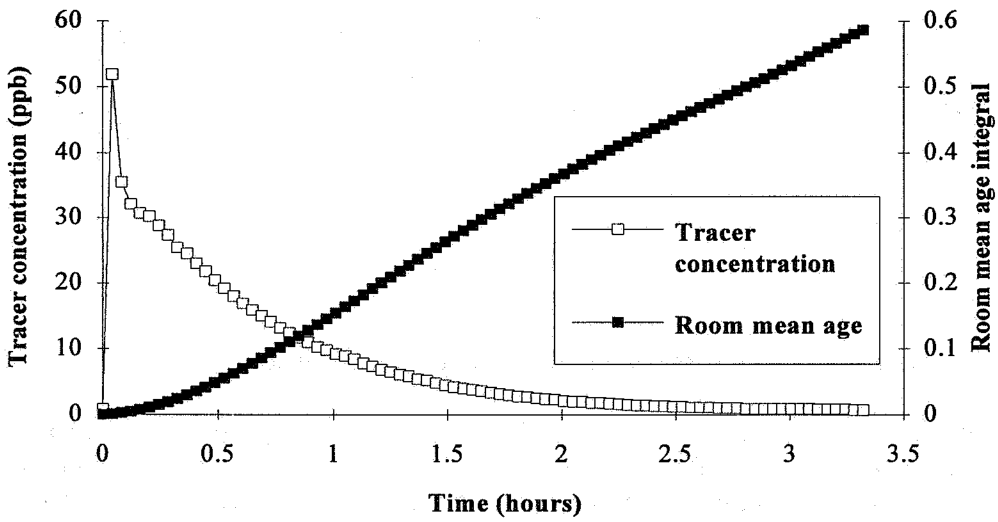

Figure 3: A typical tracer concentration record and developing room mean-age integral.

The equation for the room mean age determined from the exhaust [1] is shown expanded here into two parts:

$$\langle \bar{\tau} \rangle = \frac{Q}{2V} \frac{\int_0^{\infty} t^2 C_e(t)\, dt}{\int_0^{\infty} C_e(t)\, dt} = \frac{Q}{2V} \left[\frac{\int_0^{t'} t^2 C_e(t)\, dt + \frac{C_0 e^{-nt'}}{n} \left[t'^2 + \frac{2t'}{n} + \frac{2}{n^2} \right]}{\int_0^{t'} C_e(t)\, dt + \frac{C_0 e^{-nt'}}{n}} \right] \quad (5)$$

Where
$\langle \bar{\tau} \rangle$ = The room mean age of air
$C_e(t)$ = The tracer concentration at the exhaust duct at time t
Q = The airflow rate into the zone m³/h
V = The zone volume m³

Integrating the room mean age of air from extrapolated exhaust concentration measurements measured in this study has shown that the integration beyond 3 hours may add as much as 30% to the final result. The room mean age of air measured this way therefore rests heavily on assumptions made in extrapolating the data, as well as on the linearity of tracer detection equipment (in this case close to its detection limit). This reduces the practicality of pulse-method room mean age-of-air measurements by exhaust air tracer analysis.

4. Results

The local mean ages (in hours) measured in the four building floors are marked out on floor plans in Figures 4 to 7. Each local mean age of air has been determined using equation 3, which has compensated for the finite measurement period by adding between 2-7% to the result. 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 of interpretation that add further to the overall uncertainty. The systematic error has been estimated to be about 20%, which is similar to the 95% confidence interval suggested by Fisk [3] for breathing-level air-exchange effectiveness and air diffusion effectiveness measurements.

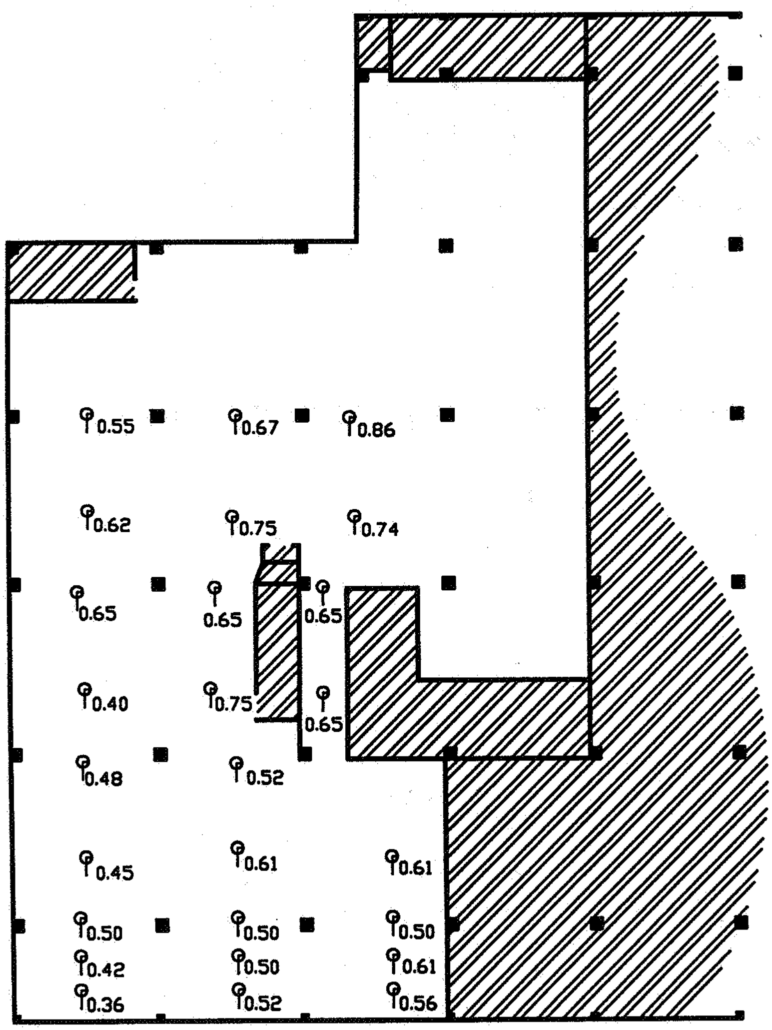

Figure 4: Local mean age-of-air data (in hours) for building A top floor

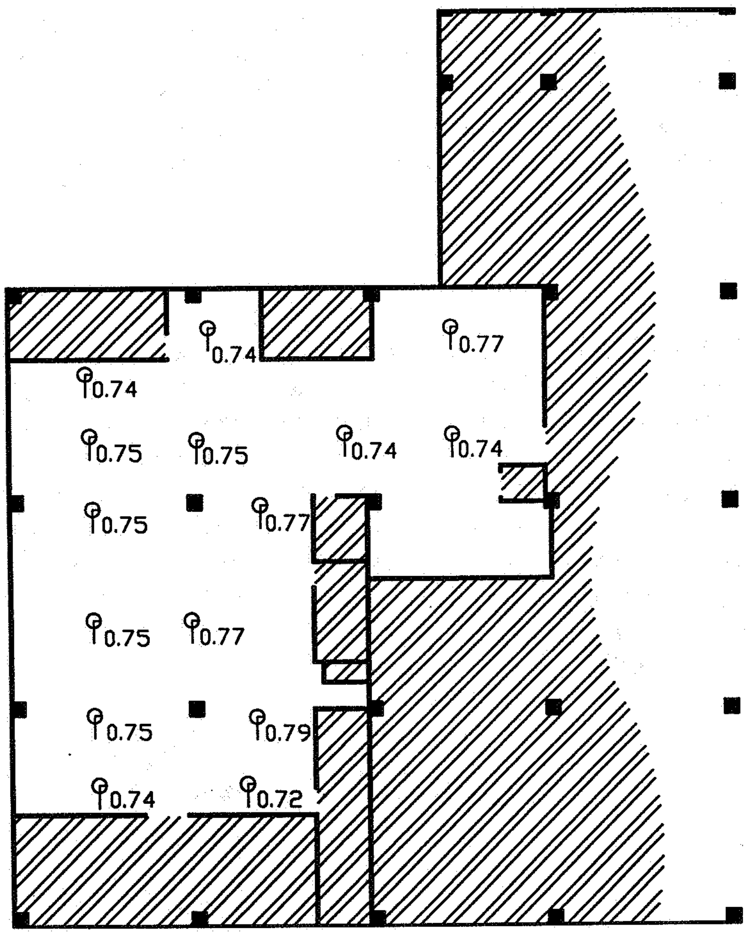

Figure 5: Local mean age-of-air data (in hours) for building A middle floor.

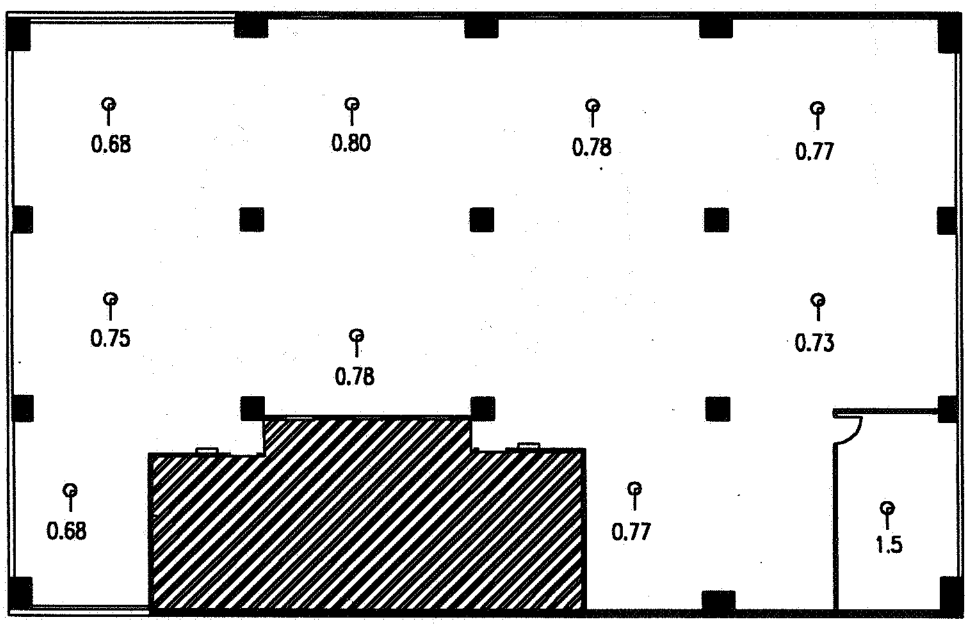

Figure 5: Local mean age-of-air data (in hours) for building B second floor

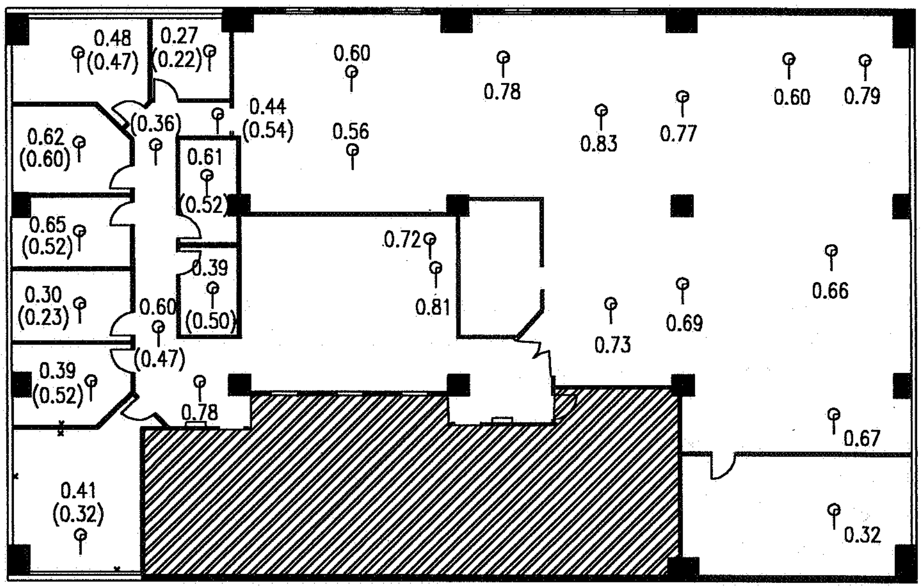

Figure 7: Local mean age-of-air data (in hours) for building B third floor (values shown in brackets measured with all doors closed).

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, are given in Table 2.

Ventilation parameter	Building A middle floor	Building A top floor	Building B floor 2	Building B floor 3
Room mean age of air (space averaged) in hours	0.75	0.60	0.76	0.64
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
Space averaged air change efficiency %	53%	-	54%	74%

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

Where it was possible to measure the nominal time constant, the air change efficiency measured in the breathing zones has fallen between 50%-75%, indicating a pattern of ventilation somewhere between uniform internal mixing and displacement flow. The short local mean ages in some of the partitioned areas may be attributed to the high density of inlet and exhaust registers leading to shorter nominal time constants in the rooms. Other workers, e.g. [3], have measured ventilation-effectiveness parameters in mechanically ventilated buildings and developed a picture of the effectiveness of systems in a range of buildings. It is too early to form similar conclusions about the effectiveness of ventilation systems in New Zealand office spaces, but further measurements are planned.

In the partitioned areas of the third floor of building B the local mean age of air was found to depend to some extent on whether the doors were open or closed. Data for doors open and closed is given in Figure 7 (doors closed in brackets). All of these spaces contained fresh air inlets and outlets, whereas the room isolated from the open-plan area on the second floor contained only an inlet. The LMA in this zone was difficult to measure but appeared to be at least twice that of adjacent open-plan areas.

5. Conclusions

This study has developed pulse tracer equipment and analysis procedures for measuring the local mean age of air in the breathing zones of mechanically ventilated buildings in New Zealand. The following key points and limitations are identified:

- One problem often encountered was that of measuring all of the inlet and exhaust air flows. In the buildings studied here, there was either a significant imbalance between inlet and exhaust air flows leading to inter-zone air movement, or there were practical difficulties in measuring inlet or exhaust air flow rates using conventional velocity scanning methods. Tracer-dilution measurement methods will have to be used to measure air flows in further work.

- The limitation imposed by finite data-taking times has been addressed with a small correction (about 5%) applied to local mean age of air measurements made using the pulse method. The same problem arises with room mean age-of-air measurements determined from tracer concentrations measured at exhaust points. Unfortunately, the tracer concentration history that has to be determined by extrapolation forms a significant part (30%) of the mean age integral, and this limits the usefulness of room mean ages of air measured this way.

The air-change efficiencies reported in this paper lie in the range 50%-75%, indicating a pattern of ventilation somewhere between uniform internal mixing and displacement flow. In partitioned areas (building B third floor) the local mean ages were generally lower than in the open-plan areas. This was thought to be a result of the higher density of fresh air and exhaust registers in the partitioned areas, leading to shorter nominal time constants in the rooms. Further measurements are planned in order to develop an understanding of ventilation effectiveness achieved in New Zealand buildings.

6. Acknowledgements

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7. References

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