# INNOVATIONS IN VENTILATION TECHNOLOGY

## 21st ANNUAL AIVC CONFERENCE
## THE HAGUE, NETHERLANDS, 26-29 SEPTEMBER 2000

# Pollutant dispersion simulated with tracer gas in a naturally ventilated test house

**M R Bassett**[1]

1 Building Research Association of New Zealand

## 1. Synopsis

The New Zealand Building Code has kept with tradition in allowing residential building ventilation designs based entirely on openable window areas. Working against this tradition, however, is a trend in New Zealand towards more airtight construction and declining reliance on open windows. Contributing to this trend are changing patterns of occupancy with fewer people at home during the working week, along with developing concerns for personal security. The research described in this paper is developing new ventilation strategies for single family residential buildings based on combinations of passive and simple mechanical systems. A series of measurements are described which used a tracer gas to simulate pollutant dispersion in a multi-room test house. The tracer was released at a constant rate in kitchen and bathroom locations with natural and mechanically assisted ventilation strategies in place. The building was operated in four modes reflecting two levels of building airtightness and with internal doors either open or closed. Results are expressed in terms of the mean age of air and the mean age of the pollutant averaged over periods of several days.

The first order effect of the different ventilation strategies was to control tracer concentrations about as effectively as a dilution ventilation system. While concentration differences were seen in the different rooms at breathing height, these were generally smaller than would have been expected to develop under static driving forces and with limited internal mixing, and are not overly significant in the context of limiting pollutant exposures within the building. Pollutant removal in the house is presented as a relative contaminant removal effectiveness averaging over the air volume and over time periods of at least a day. It is clear that the constantly changing driving forces of infiltration reduce some of the potential contaminant removal efficiencies that might be anticipated and that closed internal doors effectively partition the building into multiple zones. Although only one building has been examined, the results signal some simplifications in the way natural and single point mechanical ventilation systems are sized to meet ventilation requirements in code documents.

## 2. Background

New Zealand houses are traditionally naturally ventilated but it is increasingly common to find homeowners retrofitting small mechanical ventilation systems to combat internal dampness. The most common format is a supply-only ventilator that supplies air from the roof cavity and discharges at ceiling level into a central corridor or passage. Typically, these systems are thermostatically controlled to deliver air when the roof space temperature lies within a predetermined range. One of the questions often asked of natural and mixed mode ventilation systems concerns the relative efficiency of the approach in dealing with pollutants released in kitchen and bathroom areas. A central supply ventilator might conceivably sweep pollutants to leakage points in the perimeter and more effectively deal with pollutants than an array of window mounted passive ventilators that promote ventilation from one side of the building to the other. Targeted ventilators such as range hoods and bathroom extracts will dispose of cooking and bathroom moisture before they disperse throughout the building and measurements have confirmed that significant capture efficiencies are achievable [1]. This study investigates the relative effectiveness of two simple approaches to house wide ventilation (natural ventilation and natural ventilation assisted with a single point supply-only ventilator) by measuring the time averaged pollutant removal effectiveness in a test house with internal doors in open and closed positions.

## 3. Contaminant removal effectiveness in naturally ventilated buildings

The ventilation processes in buildings with natural and mixed mode systems vary continuously with changing wind and temperature conditions. This means that the purging flows that remove pollutants are constantly changing and therefore more complex than is the case where the entire ventilation process is driven mechanically. It also means that direct measurements of the contaminant removal effectiveness using conventional step, pulse or continuous tracer methods [2,3] can never be completed in steady conditions. Studies of natural ventilation by Walker [4] and Stymne [5] have used passive perfluorocarbon tracers to calculate the time averaged mean age of air $<\tau_p>$ at a point p, from the average local concentration of tracer $<C_p>$ resulting from tracers released continuously and homogeneously at a rate $S$ into the ventilated space of volume $V$.

$$<\tau_p> = V<C_p>/S \qquad 1$$

These mean age of air measurements have since been used extensively in surveys of natural and mechanical ventilation in buildings of many different types. Typically they are reported as a time and building averaged mean age of air $<\tau>$.

Measuring a time averaged pollutant removal effectiveness in a naturally ventilated building is a similar problem to that of measuring the building averaged mean age of air. Haghighat [6] proposed a term "relative contaminant removal effectiveness" and defined this as the ratio of the average age of air in the building to the average age of a contaminant released within the building. Here the average age of the contaminant released at point c $<\tau_c>$ has been expressed as a function of the space averaged (steady state) concentration of tracer $<C_p>$ released continuously at rate $S$ to simulate an indoor contaminant.

$$<\tau_c> = V<C_p>/ S \qquad 2$$

and the relative contaminant removal effectiveness $\mu$ defined as:

$$\mu = <\tau>/<\tau_c> \qquad 3$$

The experimental approach used by Haghighat [6] involved two phases. In the first, a single continuous tracer source was released until reasonably steady concentrations were achieved, followed by a second phase where the tracer source was turned off and the measured decay rate used to calculate the mean age of air $<\tau>$. The mean age of the contaminant was determined from the space averaged concentration at the end of the tracer emission period.

## 4. Experimental method

This study has taken a different approach from Haghighat [6] to measuring the mean age of air. In this case pre-established relationships between wind speed, direction and ventilation rates measured using the method of continuous and uniform tracer emission have been developed and used to calculate the mean age of air during the period in which the mean age of the contaminant was measured. This avoided the need to conduct two measurements simultaneously, although it did have a downside of introducing some additional uncertainty into the relative contaminant removal effectiveness. The mean age of the contaminant in the building was determined using a single point source of sulphur hexafluoride and the same array of sample collection and analysis equipment used to measure the mean age of air.

The automated tracer dosing and detection system has been described in an earlier paper [7]. It consists of a gas chromatograph and electron-capture detector with a tracer delivery and sampling system automated to monitor tracer concentrations sequentially at 10 locations in a building. When the mean age of air was being measured, the breathing zones were dosed continuously with $SF_6$ through 10 equal length small-bore tubes supplied with tracer from a single-dosing manifold. Tracer released into the manifold was diluted with room air and pumped to all 10 dosing points. The floor plan was divided into equal area zones, coinciding with partitions where possible, and a dosing point was located in each zone about 1.5 m above floor level. When the mean age of the contaminant was being measured, the tracer was released continuously at a single point in either the kitchen or the bathroom. Air was sampled continuously from the mid points of the 10 equal volumes through small bore-tubes. The sensitivity of the gas chromatograph to $SF_6$ was checked every two to three days using certified reference gases at 5 ppb and 20 ppb, and the rate of emission of tracer from the dosing regulator was measured by positive displacement several times during the investigation. The individual sampling points were also checked to ensure that no cross-contamination occurred between samples. Wind speed and direction were measured 10 m above ground for the duration of the study.

## 5. Experimental building and ventilation system descriptions

The experimental house used in this study is maintained on the Building Research Association site at Judgeford. It is a timber framed single story building, clad in fibre-cement weatherboards and a lightweight galvanised steel roof. The north facing profile of the building along with the floor plan is shown in Figure 1. Also illustrated are the tracer sampling positions and the location of a ceiling mounted supply-only mechanical ventilator.

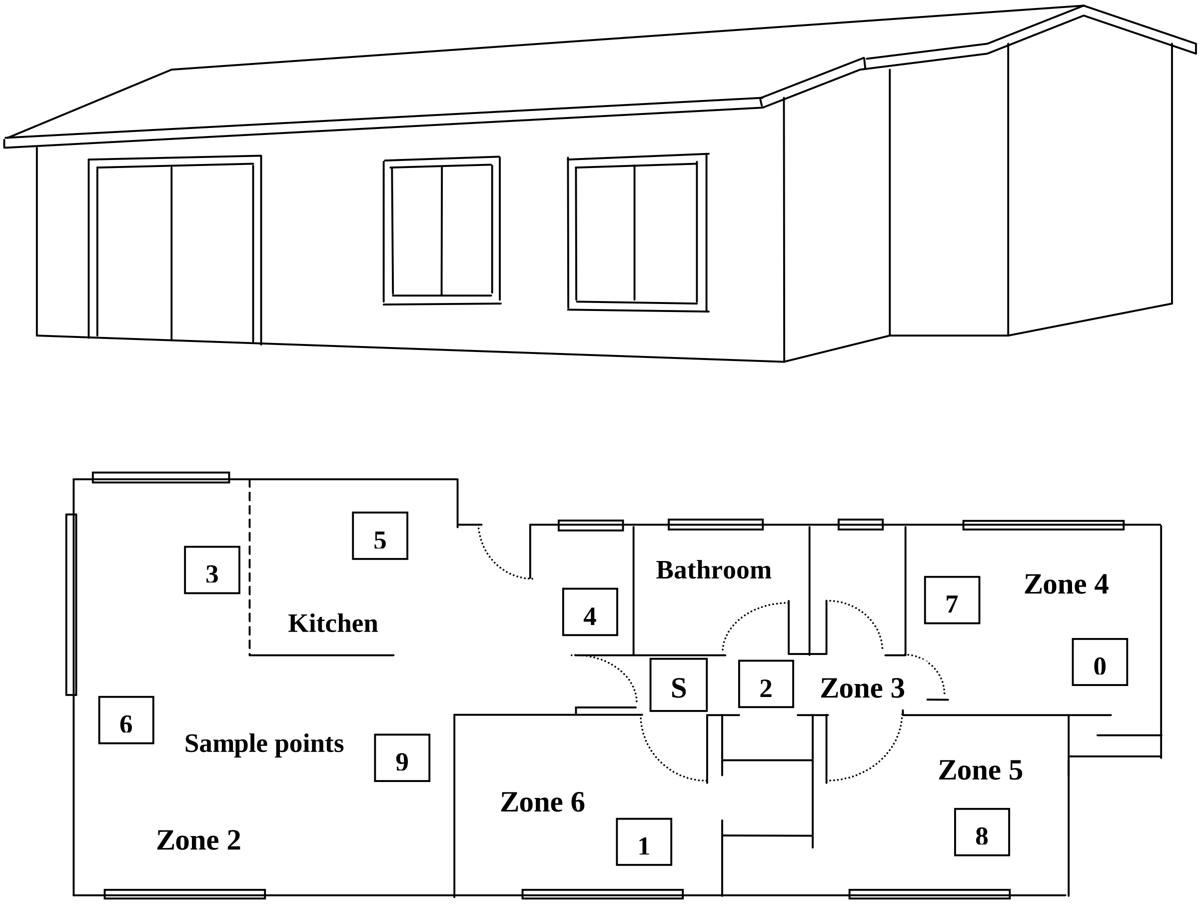

Figure 1: North elevation and floor plan of test house showing numbered tracer sampling positions and the mechanical ventilator supply point marked S.

The building was maintained at two levels of airtightness. In its initial state the building was not as airtight as would be expected of houses this age and type in New Zealand due to having been used for fire research purposes. The airtightness of the building was measured in this initial (airtightness A) state and later in (airtightness B) state after some remedial air tightening to reduce infiltration rates. This was achieved by taping over leakage openings in the interior lining. The airtightness characteristics are given below in Table 1.

A small mechanical ventilator was fitted to the building to move air from the roof cavity into the living area. It was located above the corridor, indicated as position S in Figure 1. The free air discharge rate is given in Table 1 along with the set point temperature, below which the ventilator was automatically turned off.

| | | |
|---|---|---|
| Building floor area | 69 $m^2$ | |
| Building internal volume | 166 $m^2$ | |
| Building airtightness characteristics | Airtightness level A | Airtightness level B |
| Airchanges at 50 Pa | 16.8 | 9.2 |
| Leakage exponent | 0.60 | 0.50 |
| Leakage coefficient | 0.0740 | 0.0601 |
| Mechanical ventilation rate | 28.6 l/s | |
| Temperature set point | Minimum 12 C | |

Table 1: Geometrical and leakage characteristics of test house.

## 6. Contaminant removal effectiveness

A series of tracer measurements were completed over a four-month period in 1999, in which the relative contaminant removal effectiveness was measured over 40 single-day periods. During this time several variables were changed which included: the location of the contaminant source (kitchen or bathroom), the position of internal doors (all open or all closed), the mechanical ventilator (on or off) and the airtightness of the building (airtightness level A or level B). The data gathered does not cover all combinations of these variables but it is sufficient to demonstrate the difference between the naturally and mechanically ventilated cases and the effect of closing internal doors.

The mean age of the contaminant was averaged over day-long periods from tracer concentrations continuously monitored at 10 locations in the building. Figure 2 shows a day of tracer concentration records where some records have been removed for clarity

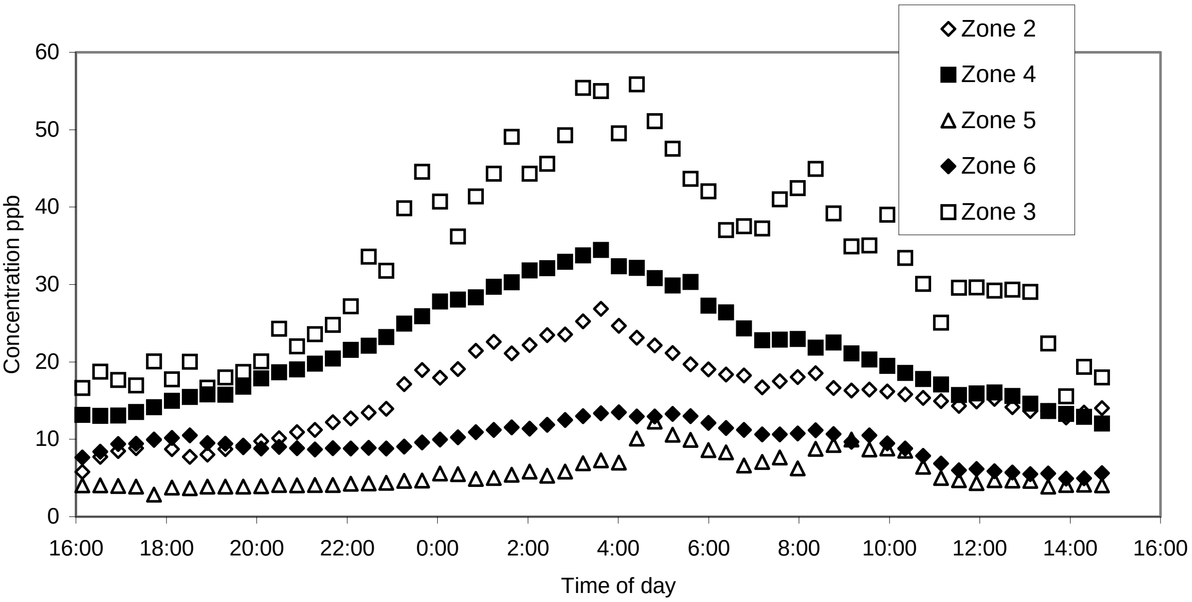

Figure 2: A one day record of tracer concentrations measured with a continuous tracer source in the bathroom. The house was at airtightness level B, ventilated naturally and with all internal doors closed.

Day averages for the mean age of air, mean age of the contaminant and the relative contaminant effectiveness are given in Table 2.

| Date | Airtightness A/B | Internal doors O/C | Mechanical Vent On/Off | Contaminant Source Location | Mean age of contaminant (hours) | Mean age of air (hours) | Relative contaminant removal effectiveness |
|---|---|---|---|---|---|---|---|
| 1/July | A | Open | On | Kitchen | 0.28 | 0.30 | 1.08 |
| 2/July | A | Open | On | Kitchen | 0.22 | 0.24 | 1.07 |
| 3/July | A | Open | On | Kitchen | 0.59 | 0.54 | 0.93 |
| 4/July | A | Open | On | Kitchen | 1.06 | 1.00 | 0.94 |
| 15/July | A | Open | On | Kitchen | 0.51 | 0.54 | 1.05 |
| 16/July | A | Open | On | Kitchen | 0.43 | 0.51 | 1.20 |
| 17/July | A | Open | On | Kitchen | 0.33 | 0.42 | 1.28 |
| 18/July | A | Open | On | Kitchen | 0.69 | 0.74 | 1.06 |
| 19/July | A | Open | On | Kitchen | 0.58 | 0.52 | 0.90 |
| 20/July | A | Open | On | Kitchen | 0.56 | 0.54 | 0.96 |
| 21/July | A | Open | On | Kitchen | 0.45 | 0.47 | 1.04 |
| 22/July | A | Open | On | Kitchen | 0.70 | 0.74 | 1.05 |
| Relative contaminant removal effectiveness with internal doors open, the mechanical system running and the contaminant released in kitchen. | | | | | | | 1.05 average |
| 4/Sept | B | Closed | Off | Bathroom | 4.13 | 3.33 | 0.81 |
| 5/Sept | B | Closed | Off | Bathroom | 3.85 | 2.94 | 0.76 |
| 20/Sept | B | Closed | Off | Bathroom | 3.03 | 3.33 | 1.10 |
| 21/Sept | B | Closed | Off | Bathroom | 6.54 | 5.56 | 0.85 |
| 22/Sept | B | Closed | Off | Bathroom | 5.27 | 4.76 | 0.90 |
| 23/Sept | B | Closed | Off | Bathroom | 5.19 | 5.00 | 0.96 |
| 24/Sept | B | Closed | Off | Bathroom | 2.98 | 3.33 | 1.12 |
| 25/Sept | B | Closed | Off | Bathroom | 2.55 | 3.13 | 1.23 |
| 30/Sept | B | Closed | Off | Bathroom | 4.14 | 5.75 | 1.39 |
| 1/Oct | B | Closed | Off | Bathroom | 4.01 | 5.21 | 1.30 |
| 2/Oct | B | Closed | Off | Bathroom | 3.28 | 2.70 | 0.82 |
| 3/Oct | B | Closed | Off | Bathroom | 3.66 | 3.13 | 0.85 |
| Relative contaminant removal effectiveness with internal doors closed, the mechanical system off and the contaminant released in bathroom. | | | | | | | 1.01 average |
| 10/Sept | B | Closed | On | Bathroom | 1.78 | 1.39 | 0.76 |
| 27/Sept | B | Closed | On | Bathroom | 2.51 | 2.04 | 0.81 |
| 28/Sept | B | Closed | On | Bathroom | 2.08 | 1.72 | 0.83 |
| 29/Sept | B | Closed | On | Bathroom | 1.39 | 1.15 | 0.83 |
| 4/Oct | B | Closed | On | Bathroom | 0.84 | 0.83 | 0.99 |
| 5/Oct | B | Closed | On | Bathroom | 1.17 | 1.37 | 1.17 |
| 6/Oct | B | Closed | On | Bathroom | 1.44 | 1.61 | 1.12 |
| 7/Oct | B | Closed | On | Bathroom | 2.03 | 1.67 | 0.82 |
| Relative contaminant removal effectiveness with internal doors closed, the mechanical system on and the contaminant released in bathroom. | | | | | | | 0.92 average |
| 8/Sept | B | Closed | On | Kitchen | 3.70 | 2.50 | 0.67 |
| 9/Sept | B | Closed | On | Kitchen | 4.85 | 2.38 | 0.49 |
| 13/Oct | B | Closed | On | Kitchen | 1.31 | 1.49 | 1.14 |
| 14/Oct | B | Closed | On | Kitchen | 2.58 | 1.75 | 0.68 |
| 15/Oct | B | Closed | On | Kitchen | 3.22 | 1.69 | 0.53 |
| 16/Oct | B | Closed | On | Kitchen | 3.40 | 1.92 | 0.57 |
| 17/Oct | B | Closed | On | Kitchen | 2.62 | 1.27 | 0.48 |
| Relative contaminant removal effectiveness with internal doors closed, the mechanical system on and the contaminant released in kitchen. | | | | | | | 0.65 average |

Table 2: Day average values of the mean age of air, mean age of contaminant, relative contaminant removal effectiveness and building and ventilation system variables.

The mean age of air was calculated from weather records for the period and the mean age of contaminant determined from the day average tracer concentrations. These values were used to calculate the relative contaminant removal effectiveness for each day. At least seven days of data have been collected for each of four ventilation and building configurations. Some variation in the mean ages must be expected for each set of data because wind speed and direction changes influence the purging airflows that determine the contaminant concentrations in the rooms. Additional sources of error include the procedure for estimating the mean age of air for the day (standard deviation estimated at 10%) and other equipment calibration errors. The standard deviation of the relative contaminant removal effectiveness in each dataset is around 0.2 and this is considered to encompass all of the experimental uncertainties.

**Case A** (Airtightness level A, mechanical ventilator running, all doors open and source in kitchen).
The mean age of air over the 12-day period was 0.55 hours. The average ventilation rate was therefore 1.8 ac/h and much higher than is normally seen in most residential buildings in New Zealand. The relative contaminant removal effectiveness during the period was 1.05, indicating that the combined infiltration and mechanical supply has been as effective at removing pollutant from the kitchen as a dilution ventilation system.

**Case B** (Airtightness level B, mechanical ventilator off, all doors closed and source in bathroom).
In this case with infiltration through the air-tightened envelope and no mechanical ventilation, the average ventilation rate was much lower than case A at 0.25 ac/h. Once again, the relative contaminant removal effectiveness over the 12-day period was 1.01 and equivalent in performance to dilution ventilation.

**Case C** (Airtightness level B, mechanical ventilator running, all doors closed and source in bathroom).
Here the average ventilation rate was 0.68 ac/h and the relative contaminant removal effectiveness 0.92. Once again, the approach is as effective at dealing with contaminant as a house wide dilution ventilation system.

**Case D** (Airtightness level B, mechanical ventilator running, all doors closed and source in kitchen).
This case is similar to case C except that the tracer source has been located in the kitchen and therefore more distant from the mechanical ventilation supply point. The relative contaminant removal effectiveness for the seven day period is 0.65 and is significantly different to cases A, B and C (as determined by the Spjotvoll/Stoline post-hoc test for an unequal number of cases). In this case, it appears that the mechanical ventilator (which provides most of the fresh air with the building at airtightness level B) has had relatively little influence over the contaminant released in the kitchen because it was isolated by the closed passage door.

## 7. Contaminant transfer index

While the relative contaminant removal effectiveness provides a house wide measure of the effectiveness of a ventilation system in dealing with a pollutant discharged at a given location, it provides little insight on how the personal exposure to a contaminant might vary from room to room. For this, the contaminant transfer index $T_{pm}$ is more useful. It has been defined in [3] as the steady concentration of contaminant $C_p(\infty)$ at point p divided by the source strength $S_n$ released at position n.

$$T_{pm} = C_p(\infty)/S_n$$

Here a time averaged contaminant transfer index has been calculated for each room and ventilation cases and presented in Figure 3. As expected, the contaminant transfer indices confirm that the highest tracer concentrations were in the rooms containing the source and that the tracer was uniformly dispersed throughout the house when either the internal doors were open or the tracer source was located close to the mechanical ventilator air outlet. Larger variations in the contaminant transfer index were seen when internal doors were closed and the building was ventilated naturally, or when the source was some distance from the mechanical supply point.

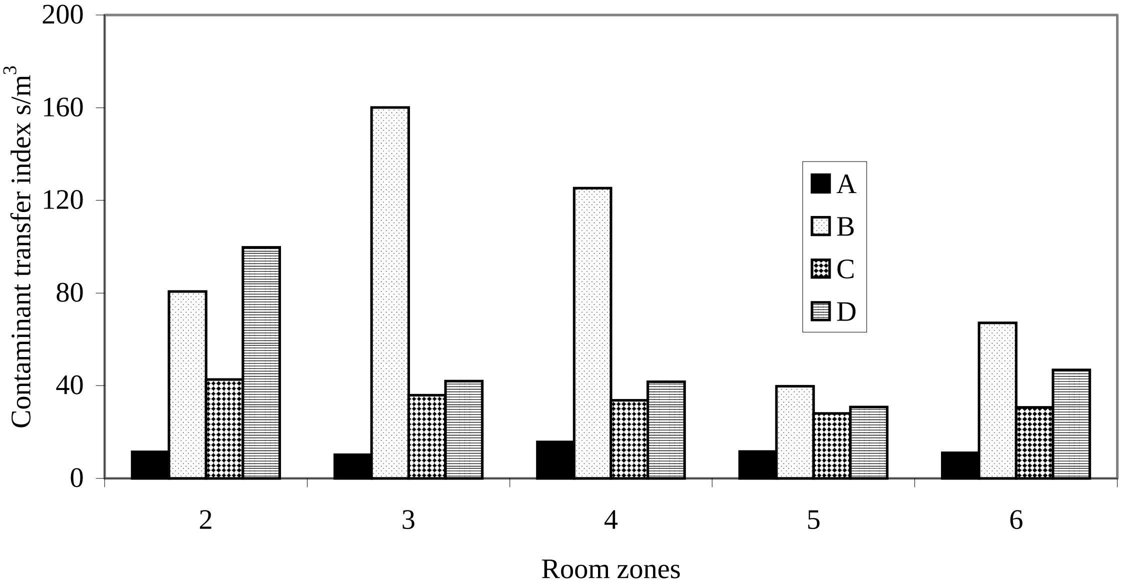

Figure 3: Average contaminant transfer indices for four ventilation cases (A,B,C,D) and five building room zones (2 to 6).

## 8. Conclusions

Tracer gas methods have been used to measure the contaminant removal effectiveness of a simple ventilation system consisting of infiltration and a supply-only mechanical ventilator in a single-story, light timber framed house. The mean age of air and mean age of the contaminant were used to calculate relative contaminant removal effectiveness results and these, along with contaminant transfer indices, were used to form the following conclusions:

- The overview of the contaminant dispersion measurements in a single building is that ventilation provided from infiltration and a single supply point mechanical ventilator achieved relative contaminant removal effectiveness performance similar to the dilution ventilation model.

- In detail, the ventilation processes were clearly more complex than the simple dilution ventilation model. With all internal doors open, the building acted as a single zone with relatively uniform pollutant transfer indices calculated for each room zone. The relative contaminant removal effectiveness for the building was 1.0.

- Closing internal doors and ventilating through infiltration alone increased the range of zonal pollutant transfer indices (maximum 4 to 1) but the relative contaminant removal effectiveness for the building remained at 1.0 within experimental error. Turning on the mechanical ventilator did not change the relative contaminant removal effectiveness but reduced the variation in zonal transfer index. Its main effect was to reduce the average concentration of contaminant present. Moving the pollutant source from close to the mechanical ventilation supply point (the bathroom) to a more distant point in the kitchen has given a significantly lower relative contaminant removal effectiveness result.

## 9. Acknowledgments

This work was funded by the Building Research Levy and the Foundation for Research, Science and Technology. The assistance of Roger Stanford from BRANZ and Barbara Baird from Queens University Belfast are gratefully acknowledged.

## 10. References

1 Li, Y., Delsante, A. and Symons, J., 1997. *Residential kitchen range hoods – buoyancy-capture principle and capture efficiency revisited.* Indoor Air, No. 7, pp 151 – 157.

2 Sutcliffe, H., 1990. *A guide to air change efficiency.* Air Infiltration and Ventilation Centre, Technical Note 28. Coventry.

3 Brouns, C and Waters, B., 1991. *A guide to contaminant removal effectiveness*. Air Infiltration and Ventilation Centre, Technical Note 28.2. Coventry.

4 Walker, R., White, M.K. and Bergsøe, N., 1994. *Application of new strategies for measuring ventilation rates in office buildings as part of an assessment of indoor air quality and energy use.* Healthy Buildings 94, Proceedings of the 3rd International Conference, Vol. 1, pp319-324, Budapest, Hungary.

5 Stymne, H and Boman, C.A., 1996. *Application of a passive tracer technique in naturally and mechanically ventilated school buildings.* Proceedings of 17th AIVC Conference, Vol. 1 pp284-291, Gothenburg. Sweden.

6 Haghighat, F., Fazio, P. and Rao, J., 1990. *A procedure for measurement of ventilation effectiveness in residential buildings*. Building and Environment, Vol 25, No. 2, pp 163-172.

7 Bassett, M.R., 1997. *Ventilation effectiveness measurements in real time using the method of homogeneous tracer emission*. Proceedings of the 18th AIVC Conference, pp 641-650, Athens, Greece.