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Efficiency of Ventilation in Office Buildings

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SYNOPSIS

Inadequate ventilation is often cited as the cause of unhealthy air quality within office buildings, whilst excessive ventilation is similarly assumed to be the cause of discomfort and energy waste. However, the reality is that very little data is available to assess the significance of these problems on any large scale. The perfuorocarbon tracer (PFT) technique offers the potential for overcoming the problems of applying conventional tracer gas techniques to large or multi-roomed buildings. Methodologies are described for its application to measure ventilation in a selection of different office building types, based on the concept of homogeneous tracer gas emission. Local ventilation rates are measured in a multicell office building, with both mechanical and natural ventilation. These illustrate the distribution of ventilation and highlight implications for air quality and energy-efficiency. A multicell computer model is used to validate the field protocol and to compare predictions with measured results. A simplified PFT measurement system based on standard commercial equipment is described, to encourage wider use of the method.

INTRODUCTION

Inadequate ventilation is often cited as the cause of unhealthy air quality within office buildings, whilst excessive ventilation is similarly assumed to be the cause of discomfort and energy waste. However, the reality is that very little data is available to assess the significance of these problems on any large scale. Part of the reason for this is the lack of any suitable measurement method which can be easily and cheaply applied in large or multi-roomed buildings. Conventional tracer gas techniques suffer from many inherent drawbacks when applied to such buildings, particularly where they are naturally ventilated.

The perfuorocarbon tracer (PFT) technique offers the potential for overcoming these problems. Measurement equipment has been developed independently in the US[1] and Sweden[2], although this has not been taken up widely in Europe mainly due to the specialist nature of the technology. The application to office buildings has not been well developed. To address these issues, we describe work carried out to develop such methodologies and a simplified PFT measurement system, based on standard commercial equipment, to encourage its wider use. Local ventilation rates are measured, which illustrate the distribution of ventilation and highlight implications for air quality and energy-efficiency. The work was carried out under the DOE Construction Sponsorship Directorate's Energy-Related Environmental Issues research programme.

METHODOLOGY

Sandberg[3] presented a theoretical method for measuring the mean age of air in a single room using a uniform distribution of tracer source strength, or homogeneous emission. BRE has been developing a practical application of the method to multi-roomed office buildings[4,5] as follows. Passive tracer gas permeation sources are placed in rooms and corridors throughout the building, with one or two in individual rooms and several along corridors, broadly in proportion to floor area. Diffusion-type air samplers are subsequently placed in a selection of typical rooms, to collect the average concentrations, C, over several days. The local mean age, τ_j, within a room of volume V_j is then calculated from the following:

$$(S / V_j) \,.\, 1/ C_j = 1 / \tau_j \qquad (1)$$

where S is the total emission rate, and S/V is the emission rate per unit volume, assumed equal in all rooms. We can regard $1/\tau_j$ as a local ventilation rate. The mean age of air for the building overall can be estimated by calculating a volume weighted average for groups of rooms represented by individual results.

The approach can be applied equally to buildings with natural ventilation or forced air systems. The technique can also be applied to large open areas. In this case sources are deployed evenly throughout the area, and air samples are subsequently taken at a representative number of locations or wherever a measurement is required.

MEASUREMENTS IN MULTI-ROOM BUILDING WITH NATURAL VENTILATION

Field trials were carried out using the homogeneous emission technique applied to measure ventilation rates in the three-storey BRE low-energy office building with natural ventilation, as currently operated. We placed sources in individual rooms approximately one week prior to the measurements (Figure 1). Pairs of diffusion samplers in 17 of the 70 or so rooms and the corridors collected time-averaged air samples over a one-week period. After analysis, the average concentrations were used to calculate time-averaged 'local' (ie room) ventilation rates using equation (1).

Results

Room air temperature were continuously recorded at six locations and used to adjust the source rates. Internal doors and windows were 'as used', i.e. a mixture of open and closed, with very few windows slightly open. External doors were normally closed. The wind was approximately 4.5m/s from 240° clockwise from north, and the average external air temperature approximately 7 °C, from a continuous on-site record.

Table 1 shows the local ventilation rates. A striking feature is the fall off in ventilation rates across the table, as you go from ground to second floor, over a range of 0.12 h^{-1} to 0.76 h^{-1} (a factor of six). This may be surprising in such a low rise, cellular office building. Note that these measurements take account of internal air exchanges from other rooms and floors and include only that portion which can be considered as the equivalent of 'fresh' air from outside ('purging' flow rate). The room (purging) flow rates were in some cases, on the second floor, less than half the minimum requirements as recommended by CIBSE[6], ie 5 l/s for single occupancy, with only a slight improvement on the first floor. Ventilation rates on the ground floor all exceeded this minimum requirement.

A previous study of controlled background ventilation for office buildings[7], based on the same building, predicted a range of ventilation rates between approximately 0.05 and 0.5 h^{-1}, and took the value exceeded 50% of the time, 0.12 h^{-1}, to represent acceptable ventilation. Clearly, however, on a significant number of occasions the ventilation rate will be lower than standard requirements. This suggests two issues to consider in drawing conclusions from these results. Firstly, we should bear in mind that occupants can open windows if they are dissatisfied with the indoor air quality. Secondly, we may need to reconsider how to interpret the ventilation guidelines; should they be an absolute minimum, or a time-average minimum in some sense - if so, over what length of time?

MODEL VALIDATION OF FIELD PROTOCOL USING MULTIZONE AIR MOVEMENT MODEL

The likely validity of the field protocol proposed above was assessed using a multi-zone computer model to simulate the bulk air exchanges between rooms and contaminant concentrations in a multi-room office building. The model was used to predict the sensitivity of the measured local ventilation rates to deviations from homogeneity of tracer gas source strength. This addressed a practical problem since, for field work, it would be convenient to use only a single source strength, with single sources placed in most rooms and small (integer) multiples in larger rooms. However, variations in room sizes will inevitably result in variations in source strength from room to room.

Multizone air flow and contaminant transport model

The model used, BREEZE, is commercially available and has been described elsewhere[8]. Briefly, the model takes input data on the distribution of external background leakage, and on connections between rooms and outside, ie openings, and their characteristic pressure and air flow relationships. External wind pressures are taken in the form of wind pressure coefficients and wind speed at a reference height, and stack pressure in the form of internal and external air temperatures. The model solves for the internal pressure consistent with air flow mass balance between the cells (rooms). Standard algorithms also estimate two-way air exchanges through large openings due to buoyancy and turbulence. In addition, contaminant source rates can be specified to calculate contaminant movement within the building.

Input data

The building modelled was the BRE Low Energy Office building at Garston. Wind pressure data were taken from previous physical model scale measurements[7] in a boundary layer wind tunnel. Calculations were carried out with different source strength distributions, and with internal doors open and closed in different combinations. All external doors and windows were closed. The background leakage for this building has previously been measured as ‘tight’ for UK office buildings[7,9]. In all cases the wind speed and direction were set at 5m/s from 240° clockwise from north, and air temperatures 18.5 °C internally and 7.3 °C externally. These correspond approximately to the average conditions of the full scale measurements described above. The interzone air exchanges and room (cell) concentrations were determined and, together with the local source strength, used to manually calculate local ventilation rates (from local mean ages of air) using equation (1).

Results

The reference condition was taken to be the case with rooms containing single or integral multiples of sources, ‘unity sources’, with all internal doors open. The results for all rooms in the centre section of the ground floor are shown in Table 2. A series of further cases were modelled in which the source strength per unit volume was set equal, or 'normalised', to that in an average sized room (cell 15) for increasing numbers of cells in the centre section. No significant change in the local mean age was observed. Similarly, no change was observed when the source strength was normalised in adjoining sections of building on the same floor level. Two further cases were modelled in which five of the doors to rooms in the centre section were closed, but allowing for a small crack area 1.5 cm x 75 cm, and then with perfectly sealed doors. Again, no significant difference in local rates was observed between unitary sources and uniformly distributed source strength although, as expected, the room ventilation rates themselves were significantly altered in each case.

COMPARISON OF FIELD MEASUREMENTS WITH MODEL PREDICTIONS

The multicell model of the test building, described above, was used to compute mean ages from time averaged tracer concentrations over six days, to compare with the measured data. This was done by dividing up the six days into ten distinct sets according to wind speed. The average wind speed and external temperature were then determined for the duration of each of these sets. The wind direction remained approximately constant over the whole test. The model was then run for each of the ten 'weather' conditions, resulting in ten sets of local mean age for specified rooms, chosen to correspond to the field measurements. Time-weighted average values were calculated to compare with the measured results. Area weighted averages of these were computed to estimate of the mean age for each storey, and for the whole building, in the same way as for the field results.

Predicted and measured results are compared for each storey and the whole building in Table 3. The measured value of whole building ventilation rate (reciprocal of mean age), 0.26 h^{-1} compares reasonably well with the predicted value of 0.19 h^{-1}, based on the limited selection of rooms. The latter can be compared with the time-weighted nominal air change rate (inverse of nominal time constant) for the whole building, 0.16 h^{-1}, based on the predicted total inflow to all rooms. The values for individual stories do not compare so well. The reasons for this may be difficult to identify, with possibilities including differences in the model data and the real building regarding leakage between floors, pressure coefficients, internal door opening, and external door and window opening.

MEASUREMENTS IN A MULTI-ROOM OFFICE BUILDING WITH MECHANICAL VENTILATION

The above building was also equipped with a mechanical ventilation system supplying full fresh air, incorporating a cross-flow heat exchanger. With this operating, the local ventilation rates were measured in six rooms and the three corridors, using pumps to take air samples over a 30-minute period in each room.

Results

The internal doors and windows were in general as for the previous test. The wind was 4.5 m/s and the external air temperature was 8.5 °C. Table 4 shows that the ventilation rates were, on average, a factor of about two greater than for natural ventilation. Although the absolute values are greater, from 0.5 to 2.8 h^{-1}, they vary over a factor of six, coincidentally the same as with natural ventilation. However, as expected, the room rates do not vary with floor level. Local flow rates are just over one to under three times the CIBSE recommended value of 8 l/s per person. In this building, it is important that the installed cross-flow heat exchanger should be effective in offsetting some of the potential ventilation heat-losses which would result from these high supply rates.

By placing PFT sources in the supply duct and measuring the concentration downstream at the terminals in several rooms, the measurement technique was also successfully applied to measure the overall supply rate of 1.31 m^3/s and, including infiltration, 1.53 m^3/s, These results compared well with similar reference measurements of 1.26 and 1.45 m^3/s respectively, carried out using SF6 tracer gas. The build-up of SF6 tracer was also continuously monitored in the exhaust duct, and used to calculate the overall mean age $<\tau>$ and ventilation efficiency $<\varepsilon_a>$ of the ventilation system, using the following expressions[10,11]:

$$\langle \bar{\tau} \rangle = \frac{\int_0^\infty t.\,(1-\frac{c(t)}{C_e^\infty})\,dt}{\int_0^\infty (1-\frac{c(t)}{C_e^\infty})\,dt} = \frac{\mu^1}{\mu^0} \qquad (2)$$

$$\langle \epsilon_a \rangle = \frac{\tau_n}{2.\langle \bar{\tau} \rangle} = \frac{\tau_n}{2}.\frac{\mu^1}{\mu^0} \qquad (3)$$

where *C(t)* is the instantaneous concentration in the exhaust duct, and C_e^∞ is the final steady-state concentration. The numerator is defined as the 1st moment (μ^1) and the denominator the 0th moment (μ^0)about the origin[12]. τ_n is the nominal time constant, defined as the building volume divided by the ventilation supply rate.

This gave a ventilation efficiency of 54%, which is close to the theoretical value for a well-mixed system (50%). This indicates that the air supply is well distributed throughout the building, with no significant short-cuts. In this case, if we assume occupancy to be evenly spread, the required local ventilation supply rate per unit volume (ie local ventilation rate) is the same throughout the building, and equal to the overall building ventilation rate. Table 4 compares the local rates (h^{-1}) to the overall ventilation exhaust rate (1.2 h^{-1} assuming an internal volume of about 4500 m^3), as an indicator of efficiency. Values greater than 50% (perfect mixing) in many rooms indicate that more air is supplied than needed for uniform occupancy.

SIMPLIFIED 'PASSIVE TRACER' GAS ANALYSIS EQUIPMENT

For a few years now, technology has been available to measure ventilation rates using perfluorocarbon tracer gases (PFTs) emitted from small permeation sources, and collected using diffusion samplers. However, this has only been taken up in a few countries in Europe, in part due to the 'non-standard' nature and relative complexity of the laboratory-based analysis equipment. To overcome this problem BRE has collaborated with a manufacturer of gas chromatographic analysis equipment (Perkin Elmer (UK) Ltd), with guidance from Jan Krisstenssen of the University of Stockholm, to develop a simplified technique, based on commercially available equipment. This is based on the Perkin Elmer ATD50 thermal desorber and compatible gas chromatograph (gc) with ECD detector. Tracer separation on the gc is achieved with a silica PLOT column (25 m) at 120°C. Tracer gas samples are trapped in the samplers on an adsorbent bed of Carbopack B and desorbed at 200°C.

Validation tests

The passive tracer system has been used to measure the ventilation rates in both a test chamber and a naturally ventilated office room. In the case of the chamber, results compared well with reference measurements of the constant supply flow rate of 60 litres/sec. In the room reference measurement were made by monitoring the concentration of SF_6 tracer gas continuously introduced at a constant, metered, flow rate, in parallel with measurements made using the SBI passive tracer gas samplers and sources (PMCP - peflouromethylcyclopentane). Good agreement was found between the SBI and BRE analyses, for both pumped and passive sampling, but both over estimated the ventilation rate by 25% compared to the SF6 measurement. Further validation and inter-laboratory tests are planned to investigate this.

Field measurements

The equipment was used for measurements in five buildings, in parallel with work carried out as part of an EC collaborative programme on a 'European Audit Project to Optimise Air Quality and Energy Consumption In Office Buildings' [13]. All five buildings had forced air supply systems. In these situations it was considered necessary to use pumps to take air samples for a short period during the afternoon, to allow sufficient time for steady state tracer concentrations to be achieved following system start-up in the morning. Measurements in one of these buildings have been described in a previous paper[5]. The areas studied were all open plan, and in four of the buildings these received recirculated air from other parts of the building not tagged with tracer. This made it difficult to determine either the fresh-air supply or infiltration rates without additional measurements. Although such additional measurements were carried out, the analyses are rather complex and inappropriate for inclusion here. In the fifth building, two independent air supply systems supplied air only to the test area, but these switched on and off alternately at an interval of about 15 minutes, which may be expected to have affected the ability of the PFT tracer to reach steady state.

However, in four cases, results showed a relatively even distribution of tracer and, consequently, local ventilation rate. An uneven distribution was measured in the fifth building, part of which was confirmed to operate with full recirculation. This application to large open areas would benefit from some form of validation, particularly on source placement. A sensitivity analysis could usefully be carried out using computational fluid dynamics (CFD).

CONCLUSIONS

The perfuorocarbon tracer (PFT) technique offers the potential for overcoming the problems of applying conventional tracer gas techniques to large or multi-roomed buildings. Methodologies were described for its application to measure ventilation in a selection of different office building types, based on the concept of homogeneous tracer gas emission.

Field trials were carried out using the homogeneous emission technique applied to measure ventilation rates in a three-storey, naturally ventilated office building. The local ventilation rates in some rooms were less than half the minimum recommended rate of 5 l/s for single occupancy. It was noted that occupants can open windows if they are dissatisfied with the indoor air quality. However, since the occupants are satisfied, this suggests the possible need to reconsider how to interpret the ventilation guidelines; should they be an absolute minimum, or a time-average minimum over some specified time period?

A multi-cell prediction model was used to validate the field procedure, which indicated that local mean ages calculated from tracer concentrations were not significantly insensitive to uniformity of tracer source placement (homogeneity). The model was also used to compute ventilation rates from tracer concentrations in a limited selection of rooms, for conditions corresponding to field measurements over a six day period. The measured whole building ventilation rate (reciprocal of mean age), 0.26 h^{-1}, compared reasonably well with the predicted value of 0.19 h^{-1}.

The technique was also applied to measure local ventilation rates in a multi-room office building with mechanical ventilation. Room ventilation rates were found to be just over one to under three times the recommended value of 8 l/s per person, which emphasises the need for the installed cross-flow heat exchanger to be effective in offsetting some of the potential ventilation heat-losses which would result from these high supply rates. The measurement technique was also successfully applied to measure the overall supply rates. A separate tracer gas showed the ventilation efficiency to be close to the theoretical value for a well-mixed system.

To underpin the wider use of the method, a simplified PFT technique, based on commercially available equipment was also described, along with some limited validation work. This was applied in five buildings, with forced air supply systems and open plan layouts. As expected, results generally showed a relatively even distribution of tracer, and consequently local ventilation rate. An exception to this was identified, which corresponded to a building with a malfunctioning supply system.

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Location:	021	022	008	001/2	007	C0	122	123	113	112	105	106	C1	224	225	213	212	204	205	C2
Vol m3	49	52	49	300	54	111	40	48	42	47	65	63	112	41	166	48	53	77	65	133
Up (l/s)	10.3	5.2	9.5	23.3	8.7	12.0	3.0	2.1	2.8	2.0	3.1	2.8	9.0	1.8	6.5	3.1	2.5	2.6	2.2	10.0
τ (h)	1.3	2.8	1.4	3.6	1.7	2.6	3.7	6.3	4.2	6.7	5.9	6.3	3.4	6.3	7.1	4.3	5.9	8.3	8.3	3.7
$1/\tau$ (1/h)	0.76	0.36	0.70	0.28	0.58	0.39	0.27	0.16	0.24	0.15	0.17	0.16	0.29	0.16	0.14	0.23	0.17	0.12	0.12	0.27

Key: Up = room purging flow rate; τ = local mean age; $1/\tau$ = local ventilation rate; Cn = corridor level n

Table 1 . Ventilation rates in the naturally ventilated office building

Cell number	Room number	Volume V (m^3)	Conc (pl/l)	S/V [1] (nl/h)/m^3	Infiltration (l/s)	age τ (h)	rate $1/\tau$ (h^{-1})
10	4	70	199	52	317	3.85	0.26
11	corridor	96	165	38	0	4.39	0.23
13	6	47	279	39	117	7.23	0.14
14	5	71	155	51	417	3.03	0.33
15	8	47	201	39	167	5.21	0.19
16	7	55	90	33	367	2.72	0.37
17	10	47	896	39	0	23.03	0.04
18	9	39	115	46	283	2.48	0.40
19	11	47	169	39	183	4.39	0.23
20	18	68	3,423	27	0	128.2	0.01

[1] S/V = 39 nl/h per m^3 for uniform homogeneous emission

Table 2. BREEZE prediction for centre section of ground floor, with 'unity' sources.

	$r = 1 / \tau_{avg}$ (h^{-1})	
	Measured	Predicted
Second floor	0.20 (0.05)	0.22
First floor	0.22 (0.05)	0.13
Ground floor	0.47 (0.2)	0.28
	( ) = approx std dev.	
Whole building	0.26 (0.05)	0.19

Table 3. Predicted and measured ventilation rates calculated from concentrations in selected rooms

Location:	001	008	C0	113	112	122	C1	213	C2	inlet	exhaust
Vol m3	300	40	110	40	45	27	112	40	133	(4500)	
Up (l/s)	51.7	20.2	19.6	10.4	11.3	21.0	15.6	17.0	24.8	1309	1480
τ (h)	1.6	0.5	1.6	1.1	1.1	0.4	2.0	0.7	1.5	1.0	1.2
1/τ (1/h)	0.62	1.82	0.64	0.94	0.90	2.80	0.50	1.53	0.67	0.95	0.84
Effic (%)	26	77	27	40	38	118	21	65	28		
Key: as Table 1; Effic = 100 * τ (exhaust) / 2.τ (room)											

Table 4 . Measurements with mechanical ventilation

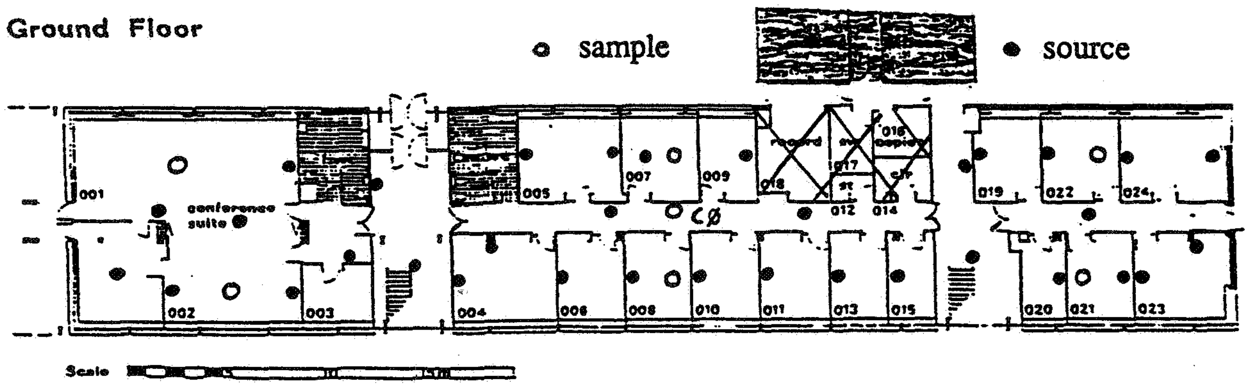

Figure 1. Multi-roomed office building; typical source and sample locations

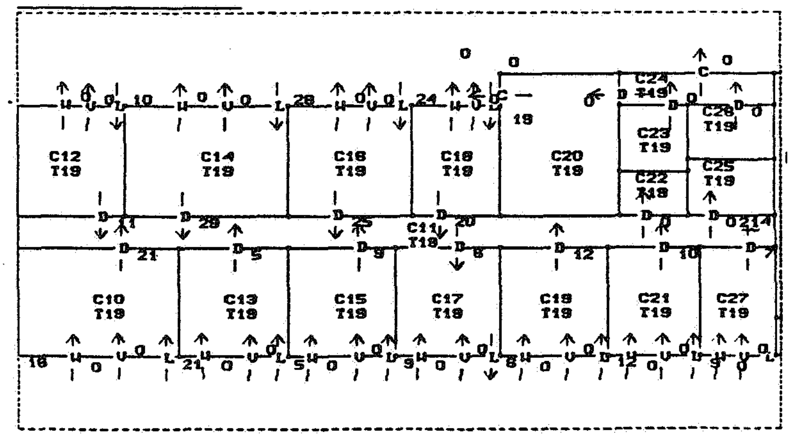

Figure 2. BREEZE coding of centre section of ground floor, showing air flows (m^3/h) through fabric leakage (L). No flow through windows (W) and vents (V).