BRE Information Paper
IP 13/95
September 1995
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The passive gas tracer method for monitoring ventilation rates in buildings

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BRE has developed a new technique for measuring time-averaged ventilation rates in occupied buildings using a perfluorocarbon tracer gas. It was conceived as a way of solving the problems which arise when conventional tracer gas techniques are used in large or multi-roomed buildings. Potentially, the new technique will allow routine performance monitoring of both natural ventilation and forced air supply systems, thereby helping users to save energy and to meet the health, safety and comfort requirements of the building's occupants. This paper will be of interest to building consultants, operators and designers and to health and safety officers.

INTRODUCTION

When using conventional techniques for measuring ventilation rates with tracer gas, it is necessary to maintain an even mixture throughout the building and to take representative air samples. However, this is difficult to achieve in large or multi-roomed buildings, particularly when the building is in use or is naturally ventilated (because rates of natural ventilation are variable throughout the building and over time).

The Building Research Establishment (BRE) has developed a new tracer gas technique based on simple, unobtrusive 'passive' devices (see Figure 1). They are distributed around the building and used to take measurements while the building is occupied. The devices are filled with tracer liquid, which is released in tiny amounts as a perfluorocarbon tracer (PFT) gas at concentrations of a few parts in one hundred billion. The gas is totally inert, odourless and non-toxic. Separate sampler devices collect air samples by diffusion into an adsorbent material. These samplers are returned to the laboratory for analysis at the end of the measurement period (which varies from one day to several weeks, as required). The time-averaged ventilation rate is then determined from the mass of tracer adsorbed by the sampler and the known tracer emission rate in the building.

Measurement equipment using PFT gas was originally developed in the USA[1], but has not been widely taken up because of the specialist nature of the technology and because an application had not been developed to measure office ventilation. To remedy this situation, BRE has developed new methodologies and a simplified analysis system, based on standard commercial equipment. This paper describes trials carried out to assess the application of the technique in a variety of building types.

Figure 1 Passive devices for releasing the tracer gas (right) and for collecting air samples (left)

METHODOLOGY

Sandberg[2] devised 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 developed a practical application of this method for use in multi-roomed office buildings[3,4,5] (complementary work has also been carried out in Sweden[6]). Passive tracer gas 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 the floor area. Passive air samplers are subsequently placed in a selection of typical rooms. Care is needed in placing both samplers (eg away from sources, and in representative locations) and sources (eg not near local extracts). The average concentration C is determined from the mass collected over the measurement period (days or weeks) and the known diffusive sampling rate. The local mean age of air τ within a room of volume V is then calculated from the following equation:

$$(S/V)\,1/C = 1/\tau \qquad \text{...(1)}$$

where S is the total emission rate, and
S/V is the emission rate per unit volume, assumed equal in all rooms

In Equation 1, $1/\tau$ can be regarded as a 'local' ventilation rate; multiplying $1/\tau$ by V defines an 'equivalent flow rate' of fresh air directly from outside which would produce the same effect. The mean age of air for the building overall can be estimated by calculating a volume-weighted average from representative results for groups of rooms.

This technique can be applied to buildings with natural ventilation or forced air systems, and also to large spaces, eg open-plan offices, atria and factories. In large spaces 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).

Simplified analytical technique

BRE has collaborated with the University of Stockholm and Perkin Elmer (UK) Ltd — a manufacturer of gas chromatographic analysis equipment — to develop a simplified analytical technique. This technique uses an automated thermal desorber and compatible gas chromatograph with electron capture detector. Recent work in the Netherlands[7] reports success with a similar approach. The complete system has been validated against independent measurements of ventilation rates in a test chamber and a naturally ventilated room.

FIELD TRIALS IN VARIOUS BUILDING TYPES

Naturally ventilated office building

The methodology was tested with the assistance of the Danish Building Research Institute (SBI)[5], using their existing equipment from the USA to carry out trials in the three-storey BRE low-energy office building at Garston. Although designed for mechanical ventilation, this building is currently naturally ventilated. Tracer gas sources were placed in individual rooms (see Figure 2). Pairs of air samplers were then placed in 17 of the 70 or so rooms and corridors. These collected time-averaged air samples over six days, after which the samplers were removed for analysis to determine the time-averaged concentration of tracer gas in each room.

Room air temperature was continuously recorded at six locations and used to evaluate the source emission rates, which are temperature-dependent. Internal door positions were varied by the occupants; external doors were normally closed. A few windows were slightly open. The wind speed was approximately 4.5 m/s; the average air temperature was approximately 7 °C outside and 20 °C inside. The average concentration of tracer gas in each room, and the known source emission strength, were then used to calculate the time-averaged local ventilation rate from the local mean age, using Equation 1.

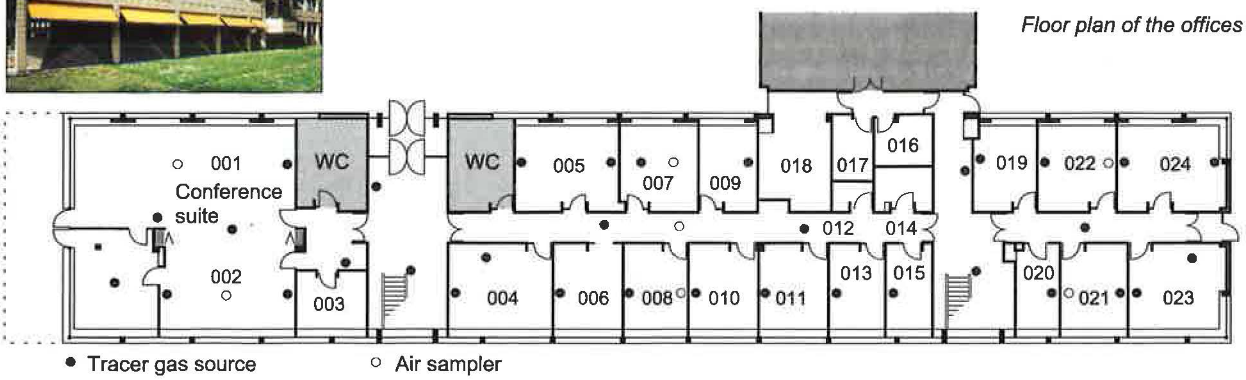
Local ventilation and equivalent flow rates varied throughout the building (see Table 1). The equivalent flow rate, for example, ranged from 10.3 l/s to 1.8 l/s; the current minimum recommended level is 5 l/s per person[8].

Validating the field protocol using a computer model

When carrying out measurements in a building, it is convenient to use as few source types as possible, with given emission rates. However, there is a risk that variations in room sizes will result in variations in source strength (ie per unit volume) from room to room. This risk was assessed[5] for the trial at Garston using a multi-zone computer model[9] of the air exchanges and contaminant concentrations in the low-energy building.

Calculations were carried out with different source strength distributions, and with internal doors open and closed in different combinations. Weather and internal conditions were set to be similar to those which prevailed during the trial, which were typical of winter. The interzone air exchanges and room concentrations were determined and, together with the local source strength, used to calculate local ventilation rates from the local mean age using Equation 1.

The low-energy office at BRE, Garston



Floor plan of the offices

Figure 2 Location of tracer gas sources and air samplers in the multi-roomed low-energy office building at Garston (see inset picture)

Table 1 Ventilation rates in the naturally ventilated offices

Location	Volume (m^3)	τ (h)	$1/\tau$ (l/h)	Q_{eq} (l/s)
021	49	1.3	0.76	10.3
022	52	2.8	0.36	5.2
008	49	1.4	0.70	9.5
001/2	300	3.6	0.28	23.3
007	54	1.7	0.58	8.7
C0	111	2.6	0.39	12.0
122	40	3.7	0.27	3.0
123	48	6.3	0.16	2.1
113	42	4.2	0.24	2.8
112	47	6.7	0.15	2.0
105	65	5.9	0.17	3.1
106	63	6.3	0.16	2.8
C1	112	3.4	0.29	9.0
224	41	6.3	0.16	1.8
225	166	7.1	0.14	6.5
213	48	4.3	0.23	3.1
212	53	5.9	0.17	2.5
204	77	8.3	0.12	2.6
205	65	8.3	0.12	2.2
C2	133	3.7	0.27	10.0

Q_{eq} = equivalent local ventilation flow rate
$1/\tau$ = local ventilation rate
τ = local mean age
Cn = corridor level n

The reference condition was taken to be the case with rooms containing one or more unit sources, with all internal doors open. In subsequent cases, the source strength per unit volume in selected rooms nearby was then set equal to the source strength in an average sized room. The local mean age was calculated, and found to be unchanged regardless of the number of rooms selected. A similar result was found when the measurement was repeated with internal doors set closed, both with and without a perfect seal.

A multi-room office building with mechanical ventilation

The BRE low-energy building is also equipped with a mechanical ventilation system supplying full fresh air, which incorporates a cross-flow heat exchanger. With this system operating, the local ventilation rates were measured in six rooms and in the corridors on each storey. The procedure was the same as for the naturally ventilated office, but with one change: pumps were used to take air samples over only a 30-minute period in each room, since the total ventilation rate was expected to remain relatively constant.

Weather and internal conditions were similar to those noted during measurements with natural ventilation. Table 2 shows that the ventilation rates were, on average, a factor of about two greater than for natural ventilation. In this trial, equivalent local flow rates varied from just over one to under three times the recommended value[10] of 8 l/s per person.

In a separate test, the forced air supply rates were measured using a tracer gas dilution method[11], in which several PFT sources were placed in the supply duct and the resulting concentration measured downstream at the inlet terminals in selected rooms. Dividing the emission rate by the average terminal concentration gave a supply rate of 1.3 m^3/s. Measurements in the return duct gave an overall ventilation rate of 1.5 m^3/s (which includes infiltration). These results compared well with measurements of 1.3 m^3/s and 1.4 m^3/s respectively, carried out subsequently using SF_6 tracer gas continuously monitored with an infra-red analyser.

Table 2 Ventilation rates in the mechanically ventilated offices

Location	Volume (m^3)	τ (h)	$1/\tau$ (l/h)	Q_{eq} (l/s)
001	300	1.6	0.62	51.7
008	40	0.5	1.82	20.2
C0	110	1.6	0.64	19.6
113	40	1.1	0.94	10.4
112	45	1.1	0.90	11.3
122	27	0.4	2.80	21.0
C1	112	2.0	0.50	15.6
213	40	0.7	1.53	17.0
C2	133	1.5	0.67	24.8
Inlet	4500 in total	1.0	0.95	1309.0
Exhaust		1.2	0.84	1480.0

Q_{eq} = equivalent local ventilation flow rate
$1/\tau$ = local ventilation rate
τ = local mean age
Cn = corridor level n

Open-plan building with air-conditioning

Measurements were also carried out to detect and measure infiltration in a mainly open-plan two-storey office building, built in 1989. The building was square in plan, with a total floor area of 1200 m^2. An air-conditioning system supplied air to four zones on each storey, providing both heating and cooling. Ventilation was designed to provide 6 to 8 air changes per hour, and at least 5 l/s of outside air per person.

It was necessary to correct for air recirculated from zones which did not contain tracer sources: this can be done by measuring the concentration at the inlet terminals[4]. A reference measure of the system supply rate was independently obtained by the method of dilution of SF_6 tracer gas in the supply air duct[11]. The infiltration rate was then obtained by subtracting the supply rate from the total ventilation rate, measured using the PFT technique, and was found to be negligible.

Naturally ventilated classroom in summer

The passive tracer gas technique has also been used to measure natural ventilation rates on a daily basis in a classroom in the Cable and Wireless Training College at Coventry[12] (see Figure 3).

By a special arrangement of interlinking teaching blocks and a raised, waveform-shaped roof, natural ventilation was achieved over an effective depth of approximately 47.5 m. The design intention — tested using a 'salt bath' physical scale modelling technique[12] — was that there would be a form of displacement ventilation through high-level windows in opposite faces. The passive tracer gas technique was applied to test how well the ventilation worked in practice, and to check the validity of the design prediction procedures.

Courtesy of Ove Arup

Figure 3 Naturally ventilated classroom blocks in Coventry

Groups of PFT sources were attached to several workbenches spread throughout the classroom, and air samples were taken at four heights at a location near one wall and approximately midway between the window walls. Air samples were taken over a 30-minute period, using a pump to draw the air through the samplers. In this way it was possible to measure the ventilation rate at mid-afternoon; this was necessary to assess the risk of summertime overheating.

Typical ventilation rates measured on hot days in two weeks during July were in the range 4.0 to 9.0 air changes per hour. This was consistent with the design predictions.

Cruise ship passenger cabins
The PFT technique has also been used to measure ventilation system supply rates in passenger cabins on cruise ships. The whole test had to be completed in one day.

Sources were conditioned to temperature in advance and installed at the start of the day in various cabins of interest. A pre-set, time-controlled pump automatically took samples over a 30-minute period in the afternoon; in some cases, passive 'diffusive' samples were taken over a 24-hour period. Results enabled the operators to check that ventilation met current recommended minimum levels for health and safety[8].

Houses
The PFT technique can easily be used to measure ventilation rates in houses. The equipment is simple to use, and the measurement procedures are straightforward. It is therefore possible to carry out large-scale surveys without using specialist operators.

For example, a small survey has been carried out in four houses on Orkney[13], two of which were naturally ventilated, and the other two mechanically ventilated. In this trial, sources were placed in each room of each house, and diffusive samples were taken in the lounge and bedroom for a period of three months in winter. In general, it is possible to measure the overall ventilation rate by using just one or two sources in each house.

CONCLUSIONS
Using the passive tracer gas technique, it is now possible to monitor time-averaged ventilation rates in a wide range of building types while the buildings are still occupied. These buildings can be large, multi-roomed and naturally ventilated, in which it is impractical to apply conventional tracer gas techniques. The passive method is also simple to use, which makes it ideal for application on a wide scale.

ACKNOWLEDGEMENT
The authors wish to acknowledge Don Dickson and his team at EA Technology for their valuable partnership in carrying out the measurements in the open-plan office building.

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ISBN 1 86081 025 X
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