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Measurement of Air Flow Between the Floors of Houses Using a Portable SF₆ System

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SUMMARY

This work is concerned with measuring air flows between the floors of houses. A simple measuring technique is described in which two portable SF_6 systems were employed. A comparison of air flow patterns in a superinsulated house and a standard house is made. The method has been also validated in the laboratory by measuring air flows between two small chambers using both the tracer systems and an independent flow device. The design, construction and calibration of the portable system are presented together with an analysis of the results. Results showed that the air flow between the upper and lower floors of the superinsulated house was about 20 m^3/h compared with 100 m^3/h in the standard house.

1. INTRODUCTION

The study of infiltration and interzonal air movement in houses is important for both energy conservation and indoor air quality control. The heat losses caused by air infiltration in standard houses can account for up to 40% of the heating or cooling energy requirements [1]. As a result a large number of superinsulated houses are being built in Scandinavia, North America and recently in the U.K. [2]. These houses are constructed in such a way that air leakage through cracks and openings in their envelopes no longer serves as a source of ventilation and so mechanical ventilation systems may be required. Inadequate air change rates give rise to an increase in indoor air contaminants (e.g., formaldehyde, nitrogen dioxide and moisture) which may influence the health and comfort of the building's occupants. Research is therefore required to evaluate the extent of air ventilation, interzone air movement and dispersion of interior contaminants, so that the optimum compromise between energy efficiency and sufficient air change to maintain a healthy environment is achieved.

Air flows between internal spaces in buildings are usually measured using tracer-gas techniques [3]. Several tracer gases have been used in the past but sulphur hexafluoride has been chosen for our work as it has desirable tracer-gas characteristics, in terms of detectability, safety, and cost, and has been used successfully in previous air infiltration studies [4, 5].

In the past, measurement of air movement in buildings has been accomplished using a single tracer-gas technique but recently multiple tracer-gas techniques have found increased application [6 - 8]. Although measurements can be made more quickly and accurately using a multiple tracer-gas method, the cost of the tracer gases and equipment is high.

The purpose of this work is to demonstrate the use of highly portable units fitted with electron capture detectors for measurement of air flow between floors of houses. A single tracer-gas method was employed in this work and the accuracy of this technique was assessed using a two-zone calibration rig. The design, construction and calibration of the SF_6 system are described in this paper along with an analysis of the experimental results obtained and an appraisal of the measurement technique.

2. TWO-ZONE MASS-BALANCE EQUATIONS

Figure 1 is a schematic diagram of a house in which the downstairs and upstairs are designated zone 1 and zone 2, respectively. Air can

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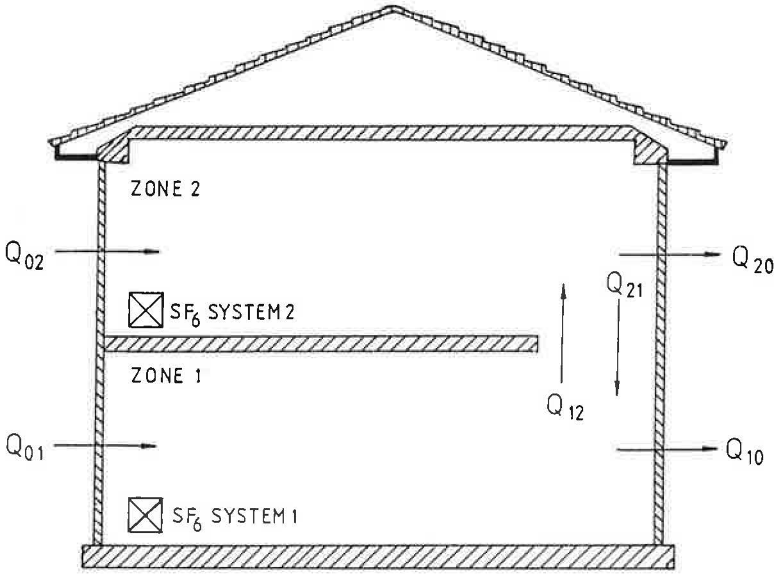

Fig. 1. Two-zone air flows in a house.

infiltrate from outside the house into each zone (Q_{01} and Q_{02}) and exfiltrate from each zone to the outside (Q_{10} and Q_{20}). In addition, air can exchange between the two zones in both directions (Q_{12} and Q_{21}).

In a test example the tracer gas may be released first in zone 1 while all its doors and windows are closed. Following tracer-gas mixing the communication doors between the two zones are opened. Some tracer gas will be carried into zone 2 where it will mix with air and some will return to zone 1. If one applies the tracer-material balances in each zone, assuming that a steady state exists and that the concentration of tracer gas in the outside air is negligible, then the following equations will apply.

The rate of decrease of tracer concentration in zone 1 at time t is given by:

$$V_1(\mathrm{d}C_1/\mathrm{d}t) = -C_1(Q_{10} + Q_{12}) + C_2Q_{21} \quad (1)$$

where V_1 is the interior volume of zone 1, C_1 and C_2 are the concentrations of the tracer at time t in zones 1 and 2, respectively.

Similarly, the rate of decrease of tracer concentration in zone 2 at time t is given by:

$$V_2(\mathrm{d}C_2/\mathrm{d}t) = C_1Q_{12} - C_2(Q_{21} + Q_{20}) \quad (2)$$

where V_2 is the interior volume of zone 2.

The other two flow rates can be then determined using the continuity equations as follows:

$$Q_{01} = Q_{12} + Q_{10} - Q_{21} \quad (3)$$

$$Q_{02} = Q_{20} + Q_{21} - Q_{12} \quad (4)$$

Mass-balance equations may be solved using the theoretical technique described in ref. 9.

An alternative method to estimate air flows between internal spaces was used by Sinden [10]. The method assumes a multi-zone system may be represented by a series of cells of known and constant volumes which are all connected to a cell of infinitely large volume, i.e., the outside space. The mass balance for each zone can be expressed by a series of equations which can be then solved using matrices. A similar method was used in our work with the addition of the discrete time model as explained in detail in ref. 11. The estimated air flow rates for specific moments in time are usually incorrect and in some cases are negative values. However, it is important to realize that we are not concerned with air flow rates at specific times, but rather with mean flow rates over finite time intervals usually greater than one hour.

To improve the accuracy of the measurement technique, tracer gas was first released in zone 1 and the concentrations were monitored in the two zones.

The experiment was then repeated, this time releasing the tracer gas in zone 2 instead of zone 1. This method provides an alternative to the use of the two-tracer-gas technique, providing the weather conditions are stable during the measurements.

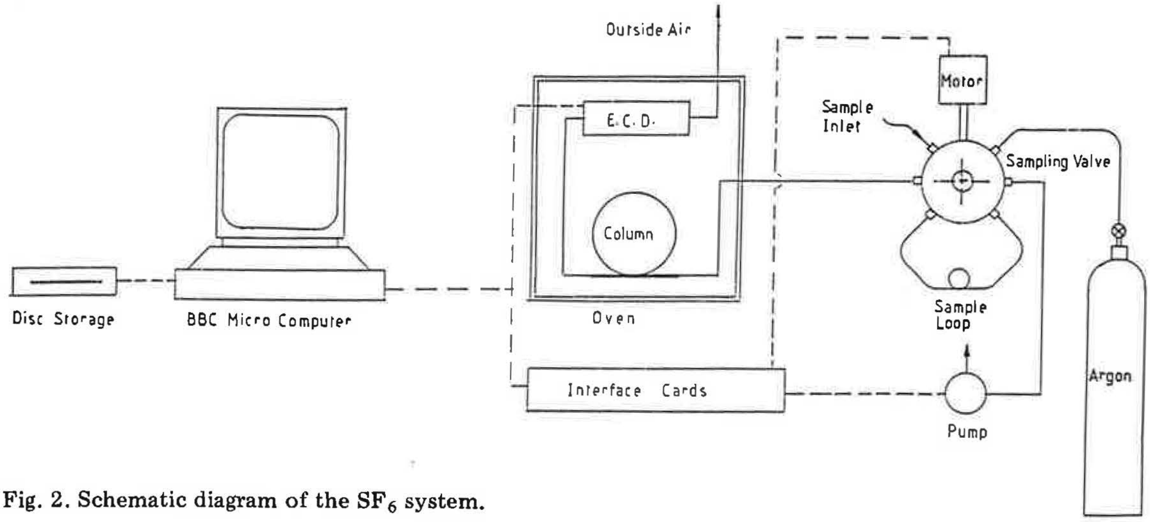

Fig. 2. Schematic diagram of the SF_6 system.

3. MEASUREMENT SYSTEM

The SF_6 system used in this study consisted of the following:

3.1. *The SF_6 release system*

The SF_6 release system consisted of a small SF_6 cylinder, a regulator and a solenoid valve. The solenoid valve is normally closed but is opened automatically using a BBC microcomputer. The volume of SF_6 gas released depends on the size of the building and is controlled by adjusting the length of time that the solenoid valve is open.

3.2. *The SF_6 measuring system*

The microcomputer measuring system is shown in Fig. 2. The system was made up from the following major components:

(a) sampling and injection unit;
(b) column;
(c) chromatographic oven;
(d) electron capture detector;
(e) microcomputer and interface.

Argon, used as the carrier gas, normally flows at a constant rate through the column via the sampling valve. The carrier gas then passes through the detection cell before being vented to the atmosphere. The sampling unit consists of a two-position, six-port valve, connected to a 0.5 cm^3 sampling loop. The valve can be easily rotated to position 1 or 2 using a small motor.

The column was made by packing a 1.5 m × 4.3 mm i.d. nylon tube with 60 - 80 mesh aluminium oxide. The tube was coiled three times and placed horizontally inside an electrically heated oven. The oven was maintained at a constant temperature using a temperature controller. The electron capture detector, which uses a Ni-63 radioactive cell, was made by Pye Unicom Ltd. This was also placed inside the oven as shown in Fig. 2. A pump was used to draw air from the test space to create a flow through the sample loop. By rotating the sample valve to position 2, air in the sample loop was injected into the argon flow which carried it into the column and finally to the detector for analysis. The amplified reversed response from the detector cell is then displayed as peaks on the computer monitor.

The system incorporates a BBC microcomputer with two 5¼-inch dual-sided floppy disc drives, a parallel printer and interfaces for both analogue and digital data. The interfacing of the gas chromatograph and the sampling and injection units was accomplished by specially designed interface cards. The system is very flexible and can be used for unattended operation.

4. SYSTEM CALIBRATION

Calibration of the two SF_6 systems was carried out using the test rig shown in Fig. 3. The rig consisted of a 215-litres metal chamber in which a small fan was used for mixing air and tracer gas. Air from a cylinder was line-fed to an opening in the chamber and its flow rate could be regulated between 10 - 150

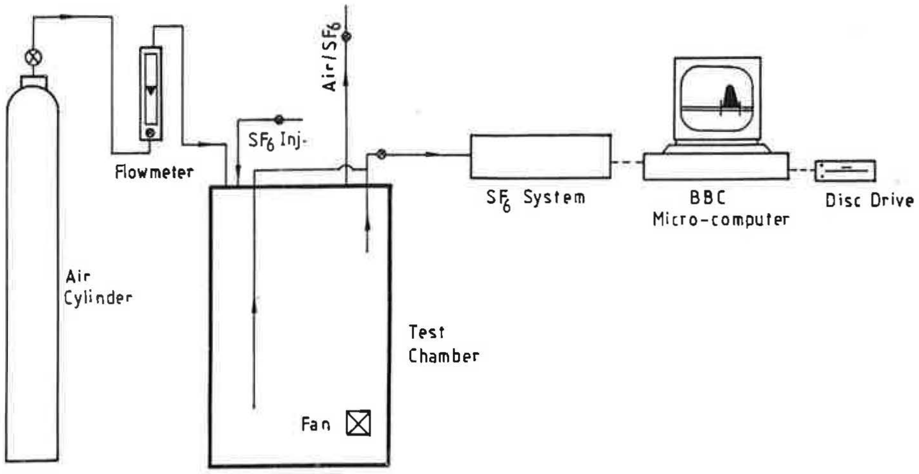

Fig. 3. Test rig for calibration of the SF$_6$ system.

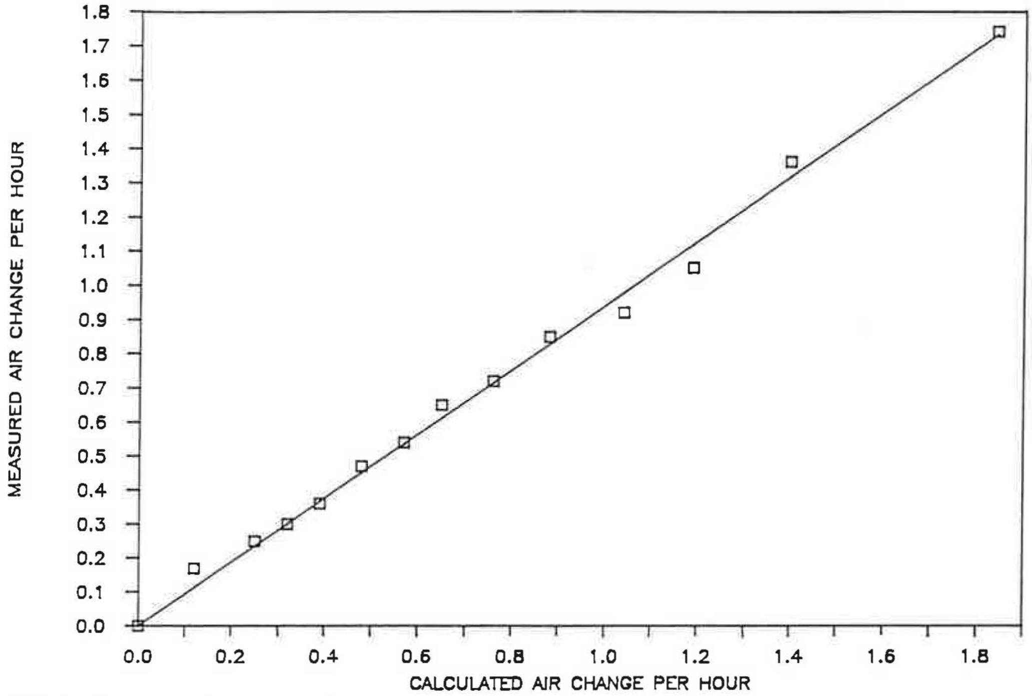

Fig. 4. Measured air change rate versus calculated values for system 1.

and 100 - 1250 l/h using Brooks Ltd. flowmeters. Provision was made for the injection of SF$_6$ tracer gas into the chamber and also for allowing the homogeneous SF$_6$/air mixture to leak out through a tube. Samples of SF$_6$/air mixture were drawn into tubes located at different levels in the chamber. These samples were then passed through the ECD gas chromatograph for analysis.

Experiments were conducted for infiltration rates in the range 0.1 - 2 air changes per hour (ach). Figure 4 shows the variation of measured air change rate versus calculated values for system 1. For system 1, the coefficient of correlation was found to be 0.9947 and the slope was 0.941 with an average error of 1.1%. The corresponding data for system 2 were 0.9873, 0.986 and 1.5%, respectively. This series of experiments showed that portable SF$_6$ systems provide reliable measurements.

5. MEASUREMENTS AND RESULTS

The tracer decay method has been used to measure interzonal air flows in two houses in

TABLE 1

Data recordings for the standard and superinsulated houses

House	Experimental conditions		
	Temp. diff. between zone 1 and 2 (°C)	Outside temp. (°C)	Wind speed (m/s)
Superinsulated			
Ventilation off	0.3	14.6	4
Ventilation on	0.7	20.0	3
Standard			
Heating off	0.2	23.0	4
Heating on	4.0	8.5	6

Milton Keynes, U.K. The two houses were sheltered by a number of adjacent houses. The temperature at various points on each floor, external temperature and wind speed during the measurement period were recorded, as given in Table 1. Tests were carried out in these occupied houses as described in the following paragraphs.

5.1. *Superinsulated house*

The superinsulated house is a two-level, three-bedroomed, semi-detached unit, with a floor area of 75 m^2. The house was built to a superinsulated standard three times more stringent than the current U.K. building regulations. Vapour barriers were also installed for both the ceiling and walls of the house. A mechanical ventilation system with heat recovery is used to supply a controlled amount of ambient air. The system was manufactured by BAHCO of Sweden, and uses an aluminium cross-flow heat exchanger. The space and water heating are accomplished using a gas heating system.

The downstairs floor, zone 1, has a volume of 73 m^3 and contains the living room, dining room and the kitchen. The upstairs, zone 2, has a volume of 107 m^3 and contains the bathroom, three bedrooms, stairway and hall. Two identical SF_6 systems were used in these experiments. The first system was used to collect samples from zone 1 while the second was used to collect samples from zone 2. At the beginning of each test, the communication doors between the two zones were closed and gaps between each door and its frame were sealed with tape to prevent leakage of tracer gas during the initial mixing period. A known volume of tracer gas was released downstairs where it was mixed with air using an oscillating desk fan. To ensure that a uniform concentration had been achieved in zone 1, samples were taken at four sampling points. After a mixing period of about 30 min, the sealing tape was removed and communication doors were opened. Samples were taken every 3 min for a total experimental time of about 90 min. The SF_6 systems analysed the samples *in situ* so providing instantaneous readings of gas concentration in each zone.

A total of four experiments were performed in summer 1987 with the heating system switched off. In two of these experiments the ventilation system was switched off, while in the other two the ventilation system was operated at low fan speed. Figure 5 shows a schematic of the two-zone air flows with the ventilation system off. As the temperature difference between the two floors was about 0.3 °C, the air exchanges were found to be

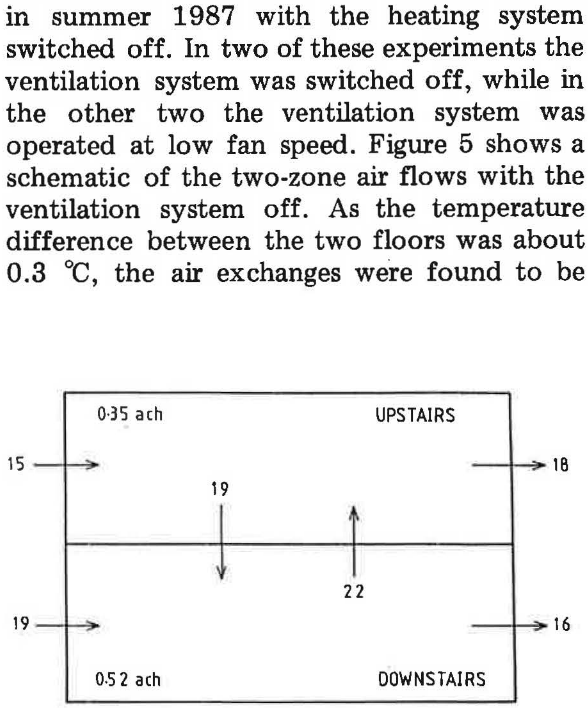

Fig. 5. Calculated interzonal flow rates for the superinsulated house with ventilation system switched off (m^3/h).

similar. Our experiments showed the tracer decay curve (concentration/time variations) in zone 1 was not a simple exponential function but the sum of two exponential functions. In another experiment the whole house was seeded with tracer gas and the background infiltration rate was measured using the decay method. The air change per hour was found to be about 0.1. This result agrees with that obtained soon after the house was built [12]. A blower door pressure test was also performed in this house and the test revealed an air change rate of 1.5 at 50 Pa (i.e., 1.5/20 = 0.075 ac/h). This value is within the performance range standards of Scandinavian houses.

Figure 6 shows a schematic of the interzonal air flows with the ventilation system operating in low mode. The results show that the ventilation system is effective in achieving the desired air change per hour in each floor of the house. The estimated whole-house air change rate per hour is 0.8 (144 m^3/h) which is larger than the value calculated from the duct flow measurements (130 m^3/h).

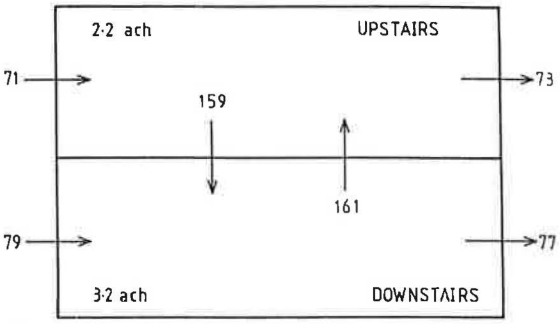

Fig. 6. Calculated interzonal flow rates for the superinsulated house with ventilation system on low mode (m^3/h).

5.2. *Standard house*

In order to compare the pattern of air flows of a superinsulated house with those of a standard house, experiments were carried out in another three-bedroomed, semi-detached house. In some of these tests the house central heating system (hot water radiators) was switched off, while in the other tests only the lower floor was heated. The total volume of the house was about 162 m^3 and that of the upper floor was 95 m^3.

Figure 7 shows a plot of tracer-gas concentration with time for both the upstairs and downstairs when SF_6 gas was released downstairs, and Fig. 8 shows the same when the gas was released upstairs. Figure 9 displays a schematic of interzonal air flows. This Figure shows that Q_{12} is slightly higher than Q_{21} due to a small temperature difference (about 0.2 °C) between the two floors. However, the situation was quite different when the living/

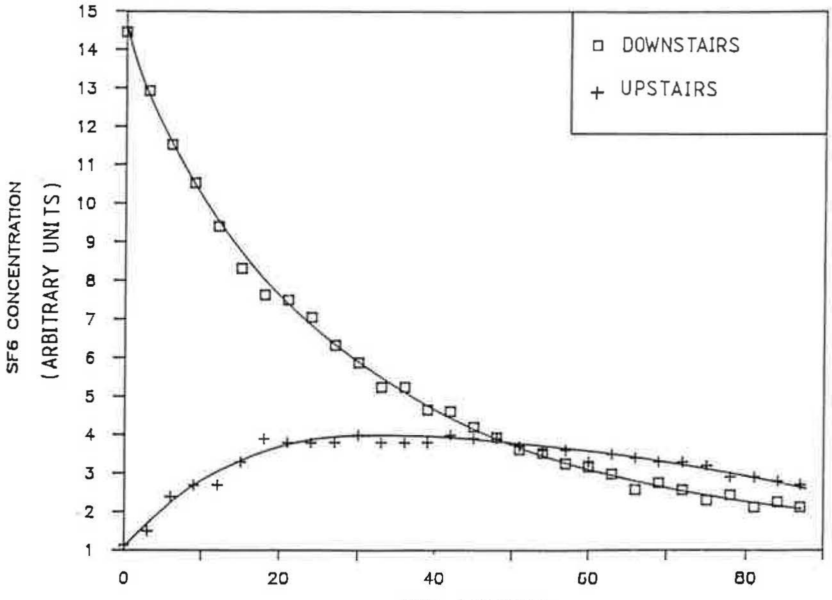

Fig. 7. The decay of SF_6 tracer gas for the standard house (gas released downstairs).

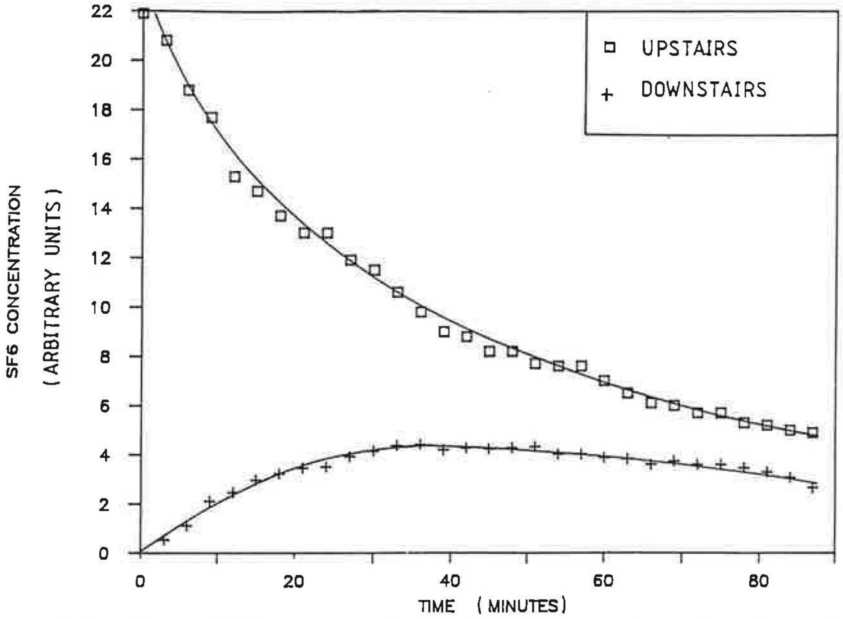

Fig. 8. The decay of SF_6 tracer gas for the standard house (gas released upstairs).

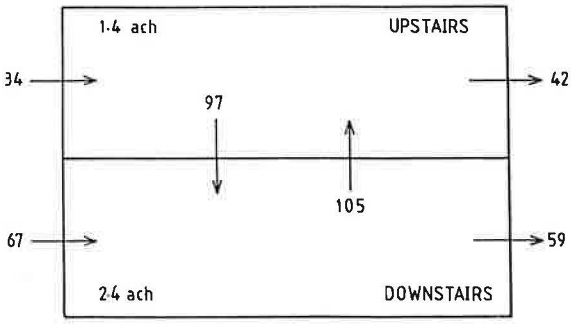

Fig. 9. Calculated interzonal flow rates for the standard house (m^3/h).

dining room and kitchen were heated to 20.5 °C while the bedrooms were kept at 16.5 °C. In this case, air flows into the ground floor and tends to flow upstairs under the stack effect. The flow rates Q_{12}, Q_{21}, Q_{01}, Q_{02}, Q_{10} and Q_{20} were found to be 180, 138, 107, 0, 71 and 55 m^3/h, respectively. From these flows and temperature differences, the rates of heat transfer were calculated. The heat transfer from the lower floor to the second floor and external environment was −1.1 kW, and that from the upper floor to the first floor and external environment was 0.24 kW.

The house infiltration rate was estimated to be about 0.6 ach (98 m^3/h) which is within the recommended ASHRAE Standard. Unlike the superinsulated house, the tracer decay curve was found to be a simple exponential curve. We believe this may be due to differ-

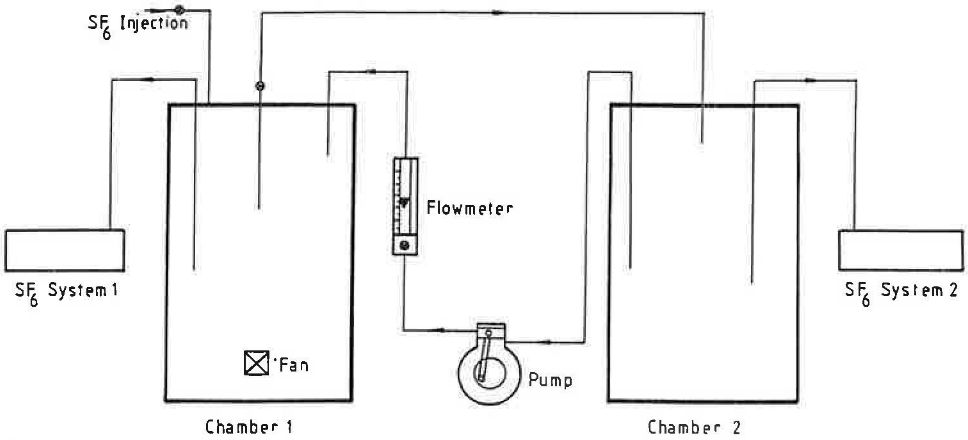

Fig. 10. Test rig for validation of the single tracer gas measuring technique.

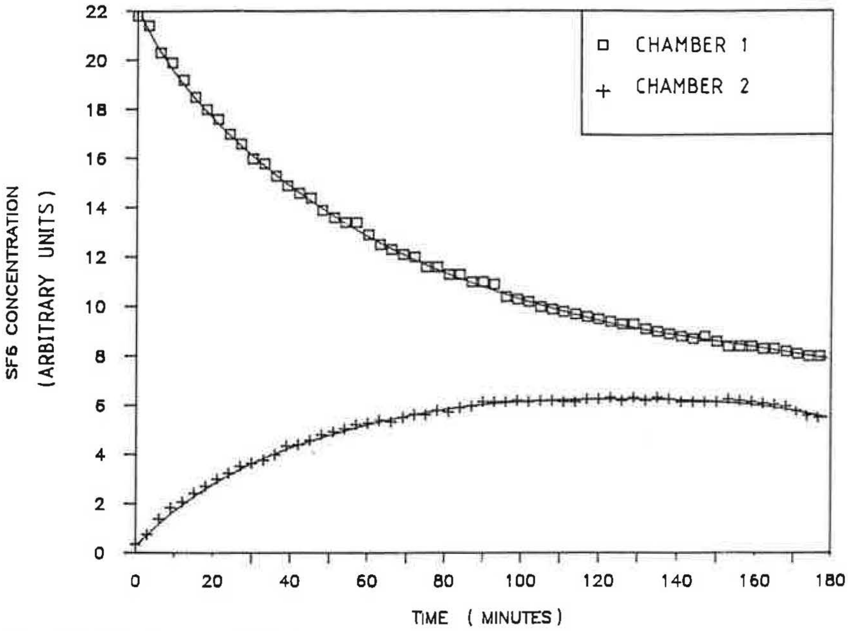

Fig. 11. The decay of SF_6 tracer gas in chambers 1 and 2.

ences in both the geometries of the houses and the number of communication doors connecting the two zones.

6. VALIDATION OF THE TWO-ZONE AIR FLOW MEASUREMENTS

To validate the tracer-gas technique used in this work some experiments were carried out under controlled conditions. For this purpose a small-scale test rig was built, Fig. 10. This simply consisted of two chambers (215 litres each) connected in a closed loop by a small pump and a flowmeter.

The experimental procedure was as follows. At the beginning of each experiment, SF_6 tracer gas was injected into chamber 1 in which a small fan was used for mixing the tracer and air. Following the initial mixing, the pump was turned on and the two chambers were connected. SF_6/air samples were drawn from the two chambers using nylon tubing. These samples were then passed to the two SF_6 systems for analysis.

Experiments were carried out for two different values of air flow rates. The calculated and measured (using the flowmeter) flow rates for experiment 1 were 124 and 114 l/h while those for experiment 2 were 232 and 244 l/h. Figure 11 shows a plot of tracer-gas concentration with time for experiment 1. The errors between calculated and measured air flow rates were found to be +9% and −5%, respectively. The accuracy of our measurements is similar to that obtained by Afonso *et al.* [13] using N_2O tracer gas and a two-compartment laboratory model.

7. CONCLUSIONS AND RECOMMENDATIONS

(1) The use of the compact, microcomputer SF_6 system has proved to be a reliable and practical approach for measuring air movement in houses.

(2) The air flow between the upper and lower floors of the superinsulated house was found to be considerably lower than that of the standard house. The air flow between the floors of the standard house was found to increase from 105 to 180 m^3/h when the temperature difference increased from 0.2 to 4 ℃.

(3) We have found that the use of the portable SF_6 system is an inexpensive and simple way of estimating the two-zone air flows in houses. However, for multi-zone measurement in large buildings, the use of multiple tracer gases is preferable as it reduces the time required to make these measurements. To compare the measurement accuracy of single and multiple tracer-gas techniques we intend to

examine air flow between two zones (a room 4 m × 4 m × 3 m divided by a partition containing a doorway) under a variety of temperature differences using both portable SF_6 systems and our new perfluorocarbon tracer systems developed at the Polytechnic of Central London.

(4) To study the interzone convection heat transfer, further experiments are needed to estimate the air movement between, for example, the conservatory and living room, where a higher temperature difference usually occurs.

(5) More tests are also required to evaluate the air flows between the house and its roof-space as well as between the kitchen and bedrooms. These experiments would be useful in determining the extent of condensation which might occur in the roof-space or in the bedrooms as a result of the transfer of warm humid air from the bathroom and kitchen.

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