EFFECTIVE VENTILATION

9th AIVC Conference, Gent, Belgium
12-15 September, 1988

Poster 6

ZONE TO ZONE TRACER GAS MEASUREMENTS: LABORATORY CALIBRATION AND VALUES OF AIR FLOWS UP AND DOWN STAIRS IN HOUSES.

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ABSTRACT

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. The design and construction of the portable system are presented. A comparison of air flow patterns in a superinsulated house and a standard house is made. 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 traditionally built house. The method has also been validated in the laboratory by measuring air flows between two small chambers using both the tracer systems and an independent flow device.

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 traditionally built houses can account for up to 40% of the heating energy requirements[1]. As a result a large number of superinsulated houses are being built in Scandinavia, North America and more recently in the UK[2]. These houses are constructed in such a way that air leakage through cracks and openings in their envelopes no longer serve as a major source of ventilation and so mechanical ventilation systems may be employed. Inadequate air change rates give rise to an increase in concentration of 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 betwen internal spaces in buildings are usually measured using tracer gas techniques[3]. Several tracer gases have been used in the past but sulphur hexaflouride 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[6,7,8]. 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. We discuss the effect on air flow patterns of 1) using a ventilation system in the superinsulated houses and 2) using a kitchen extract fan in the traditionally built house. The design, and construction 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 infiltrate from outside the house into each zone (Q_{01} and Q_{02}). 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 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 rate of change of tracer concentration in zone 1 at time t is given by:

$$V_1 dC_1/dt = - C_1 (Q_{10} + Q_{12}) + C_2 Q_{21} \quad [1]$$

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 zone 1 and 2 respectively.

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

$$V_2 dC_2/dt = C_1 Q_{12} - C_2 (Q_{21} + Q_{20}) \quad [2]$$

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 zones can be expresed by a series of equations which can then be solved using matrices. A similar method was used in our work, modified by introduction 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 realise 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.

In order to improve the accuracy of the single tracer gas technique for measuring interzonal air flows, a refined experimental method was developed for use in our work. This involved releasing tracer gas first in zone 1 and monitoring the concentrations 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.

3 MEASUREMENT SYSTEM

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

(a) Sampling - 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, 6-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 length x 4.3 mm internal diameter 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 Ni-63 radioactive cell, was made by Pye Unicom Ltd. 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 reverse response from the detector cell is then displayed as peaks on the computer monitor. The system incorporates a BBC microcomputer with two $5^{1/4}$ 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 MEASUREMENT AND RESULTS

The tracer decay method has been used to measure interzonal air flows in two houses in Milton Keynes, UK. 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 are shown in Table 1.

Tests carried out in these occupied houses are detailed below.

4.1 Superinsulated House.

The superinsulated house is a 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 UK 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 provided by a gas boiler.

The downstairs floor, zone 1, has a volume of 73 m^3 and contains a living/dining room and 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 communicating 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 minutes, the sealing tape was removed and the communicating doors were opened. Samples were taken every 3 minutes for a total experimental time of about 90 minutes. 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 3 shows a schemetic 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 changes were found to be similar. Our experiments showed that the tracer decay curve (concentration/time variations) in zone 1 was not a simple expontential 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 measured after the house was built 18 months previously[12]. A blower door pressure test was also performed in this house and the test revealed an air change rate of 1.5 at 50Pa (i.e. approximately 1.5/20 = 2.075 ac/h under normal conditions). This value is within the performance range standards of Scandinavian houses.

Figure 4 shows schematic of the interzonal air flows with the ventilation system operating in low mode. The results show 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 ach (144 m^3/h) which is larger than the value calculated from duct flow measurements (130 m^3/h).

4.2. Traditionally Built House

In order to compare the pattern of air flows of a superinsulated house with a traditionally built house experiments were carried out in a three bedroomed, sem-detached house. In some of these tests all central heating radiators were switched off while in the others only the lower floor was heated. The total volume of the house was about 162 m^3 and that of the upper floor was about 95 m^3.

Figure 5 shows a plot of tracer gas concentration with time for both the upstairs and downstairs when SF_6 gas was released downstairs and Fig. 6 shows the same when the gas was released upstairs. Fig. 7 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/dining room and kitchen were heated to 20.5°C while the bedrooms were kept at 16.5°C. In this case air flowed into the ground floor and tended to flow upstairs under the stack effect as shown in Fig.8. The heat transfer rate for the ground floor to the first floor and external environment was -1.1 kW, and that from the first floor to ground floor and external environment was 0.24 kW.

The house infiltration rate was estimated to be about 0.6 ac/h (98 m^3/h) which is within the recommended ASHRAE standard.

TABLE 1

Experimental Conditions

House	Temperature difference between zones 1 & 2(°C)	Outside Temperature (°C)	Wind Speed (m/s)
Superinsulated			
Ventilation off	0.5	14.6	4
Ventilation on	0.7	20.0	3
Traditional			
Heating off	0.2	23.0	4
Heating on	4.0	8.5	6

5. 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. 9. This consisted simply of two chambers (215 litres each) connected in a closed loop by a small pump and a flow meter.

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 of 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 respectively, while those for experiment 2 were 232 and 244. This corresponds to a +9% error for experiment 1 and a -5% for experiment 2. Figure 10 shows a plot of tracer gas concentration with time for experiment 1. This is simlar to the accuracy obtained by Afonso *et al*[14] using N_2O tracer gas and a two-compartment laboratory model.

6. KITCHEN EXTRACT FANS

Installation of kitchen extract fans is widely recommended as a remedial measure to limit condensation in houses. The purpose of using a fan is to remove moisture laden air from the zone in which water vapour is generated and also to minimise the flow of warm moist air from the lower floor to the upper floor of the house where condensation normally occurs. Most houses nowadays are provided with extract fans and it is generally assumed that the use of a 150 mm fan (extract rate about 290 m^3/h) is effective in preventing migration of moisture from the kitchen to the rest of the house. There is lack of theoretical and experimental evidence to support this assumption, and the effectiveness of kitchen extract fans can only be determined by a more rigorous investigation.

To study the effect of a manually controlled kitchen extract fan on the air flows patterns in the house, two different tests were conducted. In the first test the central heating system was switched off, while in the second test only the lower floor was heated. Figure 11 displays a schematic of interzonal air flow for the first test. The use of an extract fan increases Q_{10} from 59 to 231 m^3/h but has only slight effect on interzone air flow. With the extract fan in operation Q_{12} and Q_{21} were 96 and 125 m^3 respectively compared to 105 and 97 m^3/h with extract fan switched off.

Figure 12 shows the interzonal air flow for the second test. The limit of the extract fan is clearly shown in this figure. For a temperature difference of about 5.6°C, Q_{12} was increased from 96 to 180 m^3/h while Q_{10} was reduced from 231 to 121 $^3/h$. The two tests indicate that the use of a 290 m^3/h capacity fan does not prevent moisture movement to other rooms. Calculations were carried out to establish the minimum extract rate which would limit condensation in the kitchen and prevent air flow from the lower floor to the upper floor of the house. Condensation may be avoided if the relative humidity in a zone does not exceed the range of 60-70% (ref.13). Using an RH of 60% and a total moisture release rate of 8 kg/day, the fan extraction rate should be about 600 m^3/h. This represents more than twice the rate which is recommended by the BS5250. The effectiveness of an extract fan depends on whether kitchen doors to the rest of the house are open or closed and also on the local wind speed and direction. The location of the fan in the kitchen is also important and ideally it should be positioned close to the cooker and at a high level.

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) 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 4m x 4m x 2m divided by a partition containing a doorway) under a variety of temperature differences using both portable SF_6 systems and our new PFC tracer systems developed at the Polytechnic of Central London.

(3) The air flow rate between the lower and upper floors of the traditionally built house was found to increase significantly with increasing temperature difference.

(4) The use of manually operated kitchen extract fans was found to be ineffective in reducing air flow from the lower floor to the upper floor of the traditionally built house. Further work is required to establish the optimum extract rate of a fan for prevention of condensation in the kitchen and reduction of moisture movement to the rest of the house.

(5) 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.

ACKNOWLEDGEMENTS

The authors wish to thank Directorate General XII of the Commission of the European Communities, and C J Martin of the Energy Monitoring Company Ltd.

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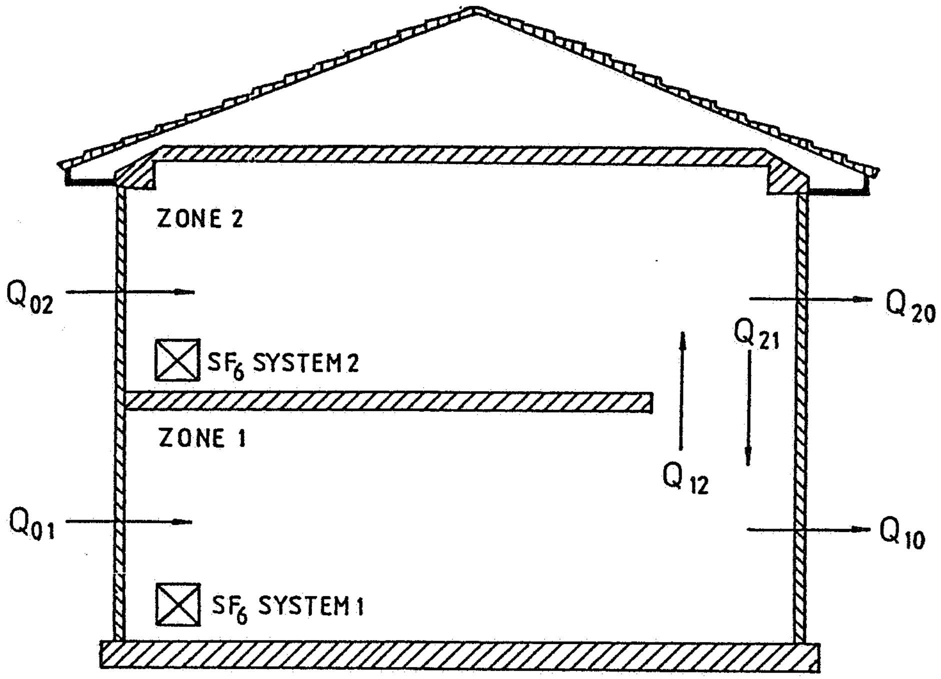

Figure 1.
Schematic of a Two-Zone House.

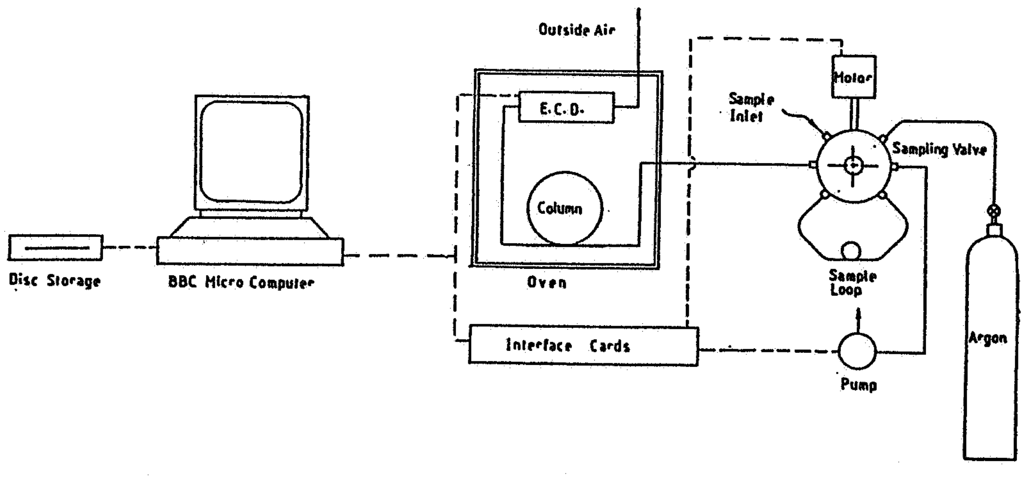

Figure 2.
Microcomputer measuring system for SF_6

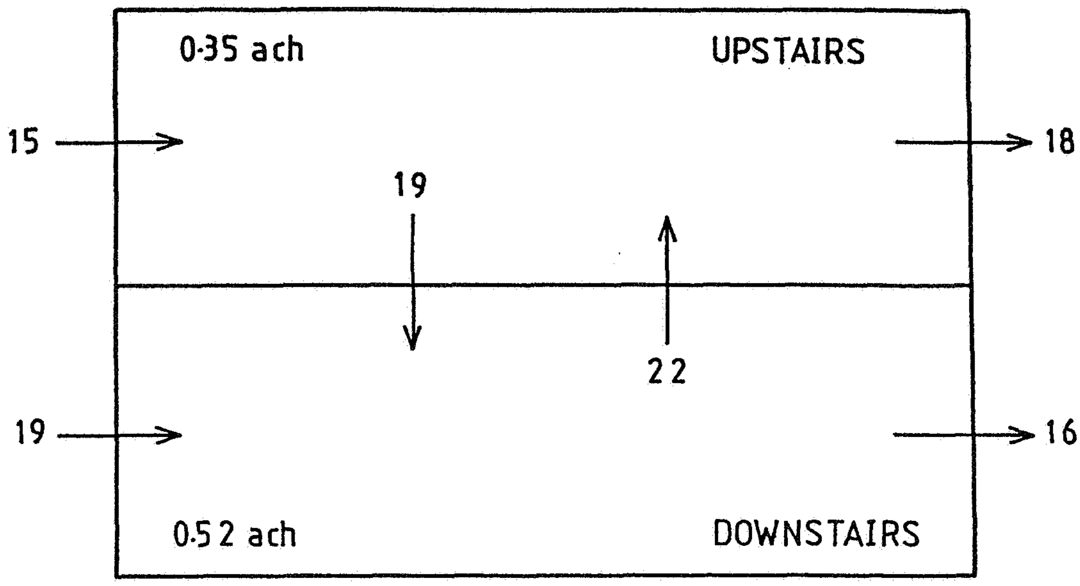

Figure 3.
Schematic of Airflows in Super-insulated House
- Ventilation System Off.

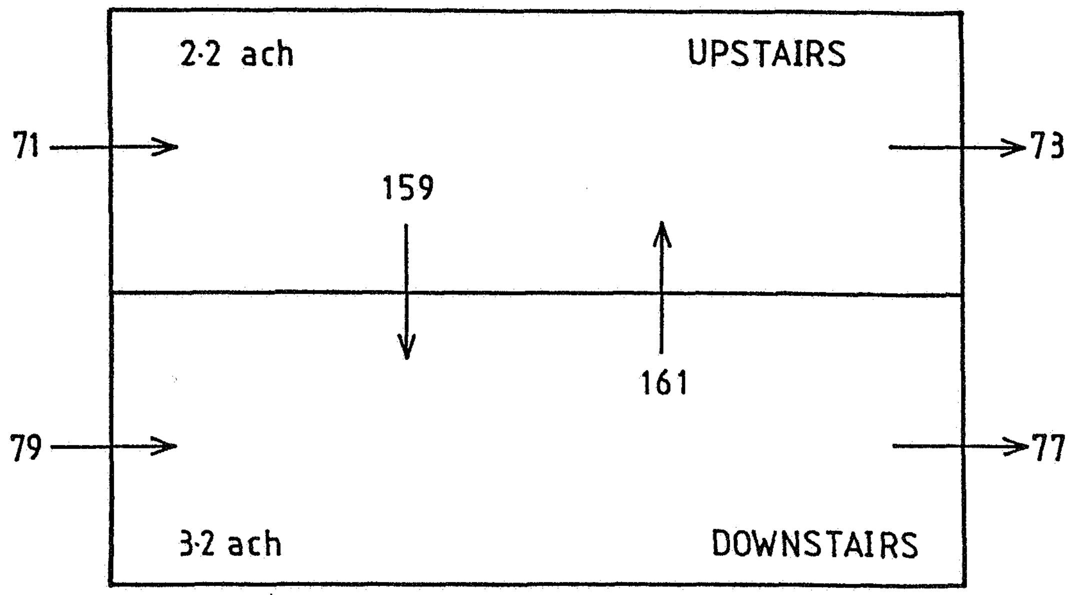

Figure 4.
Schematic of Airflows in Super-insulated House
- Ventilation System On.

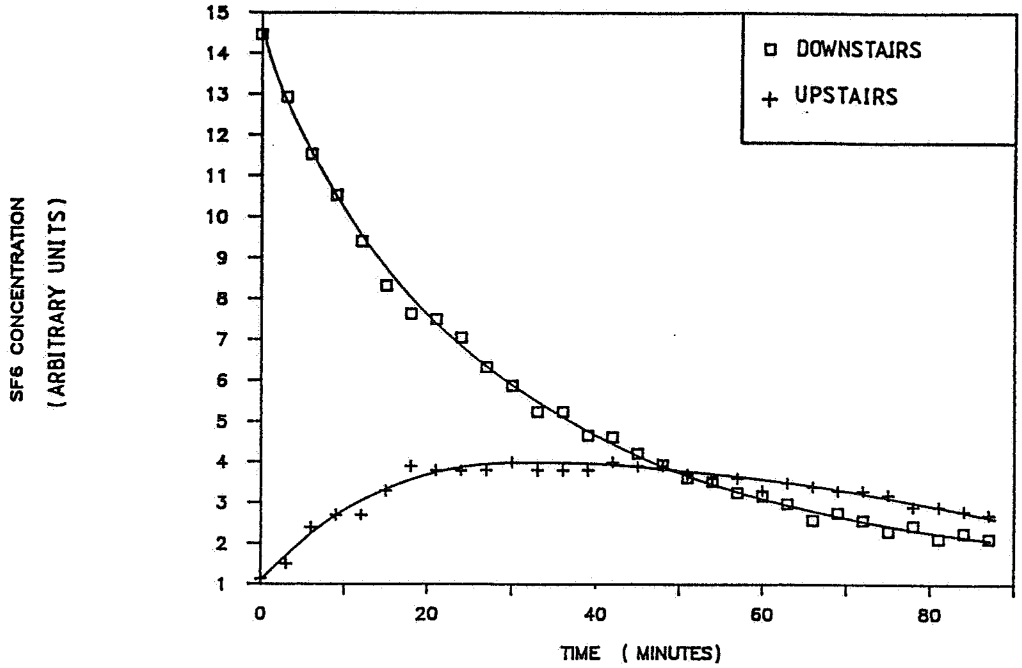

Figure 5.
Evolution of Tracer Gas Concentration in a Traditional House
- SF_6 Released Downstairs.

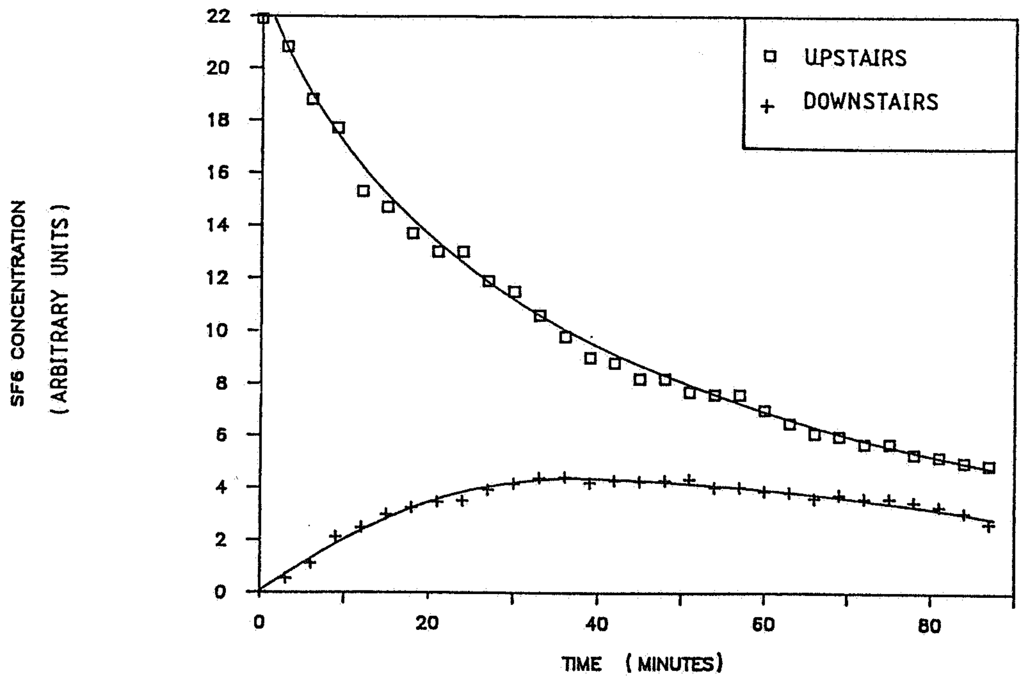

Figure 6.
Evolution of Tracer Gas Concentration in a Traditional House
- SF_6 Released Upstairs.

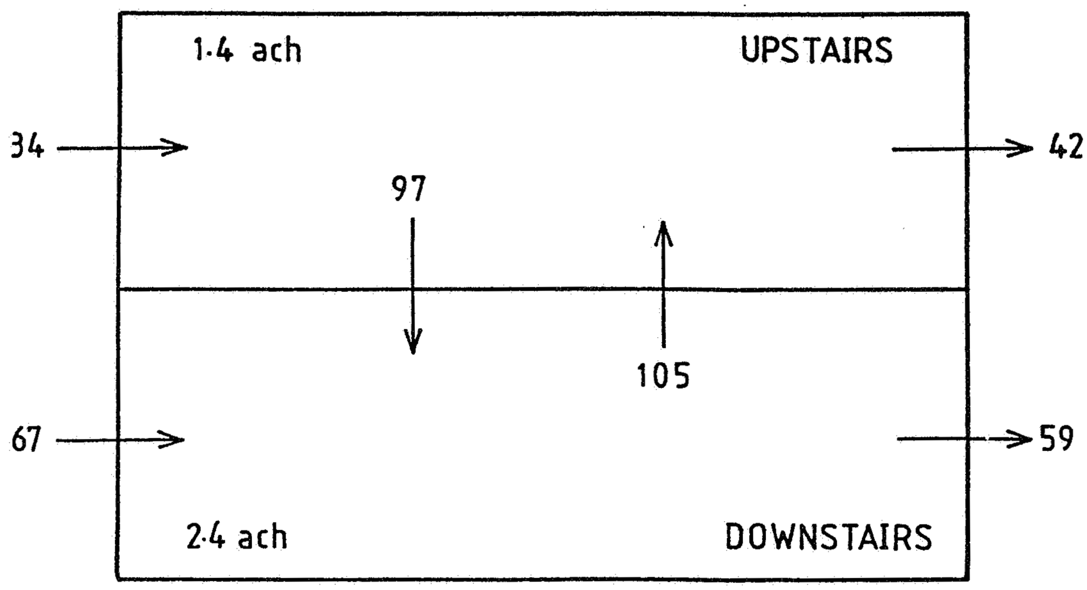

Figure 7.
Schematic of Airflows (m³/h) in Traditional House
- Temperature Difference 0.2 °C.

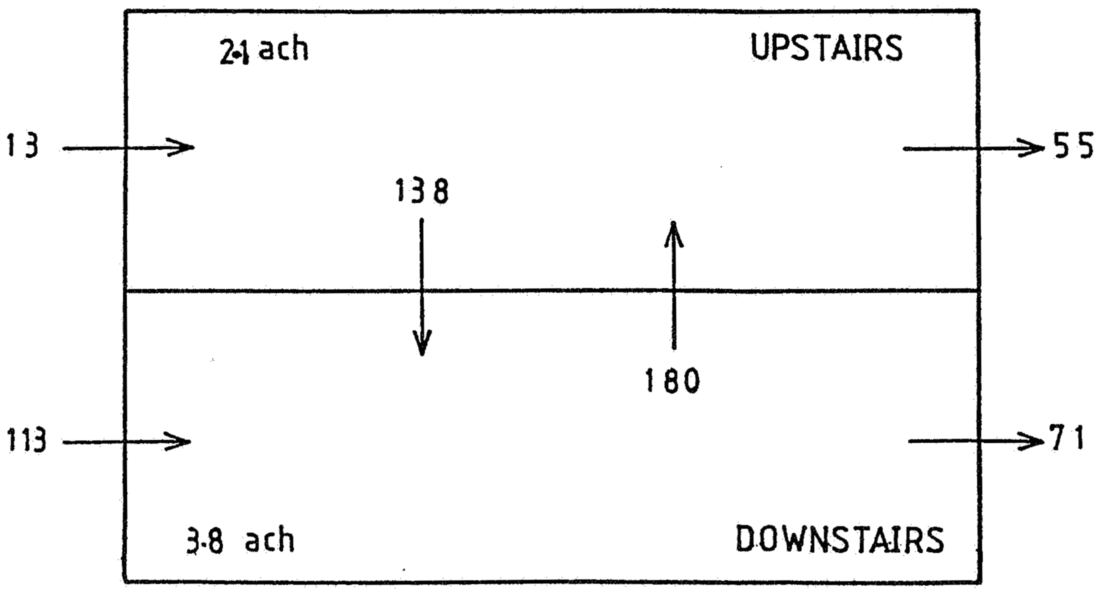

Figure 8.
Schematic of Airflows (m³/h) in Traditional House
- Temperature Difference 4.0 °C.

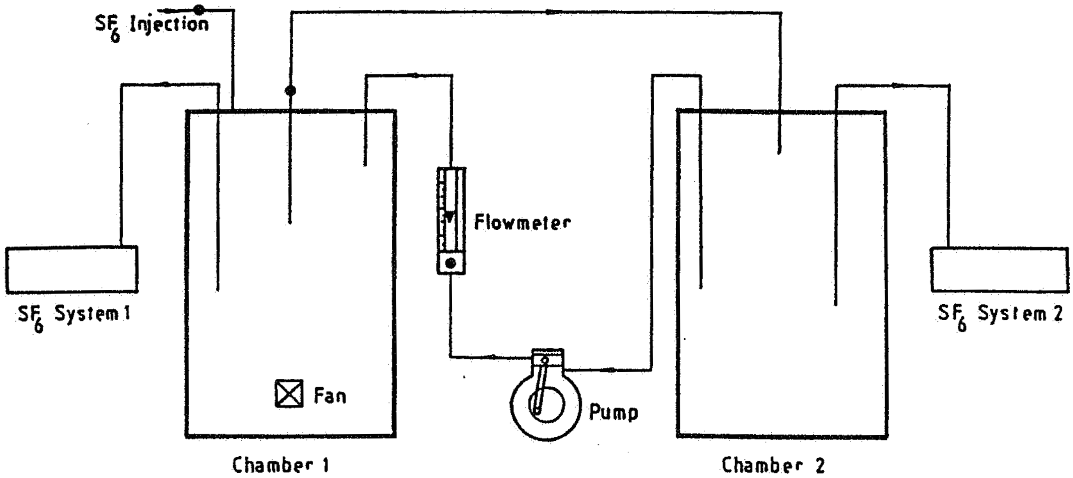

Figure 9.
Test Rig Used for Multizone Method Validation.

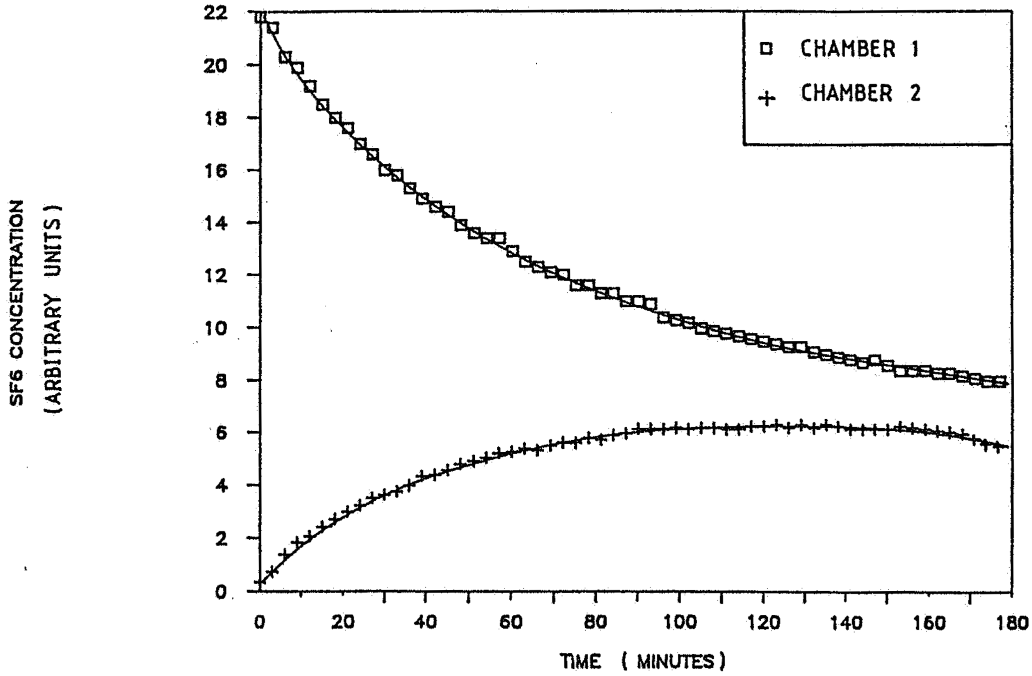

Figure 10.
Tracer Gas Concentration for Validation Experiment 1
- Calculated Flowrate, 124 l/h.

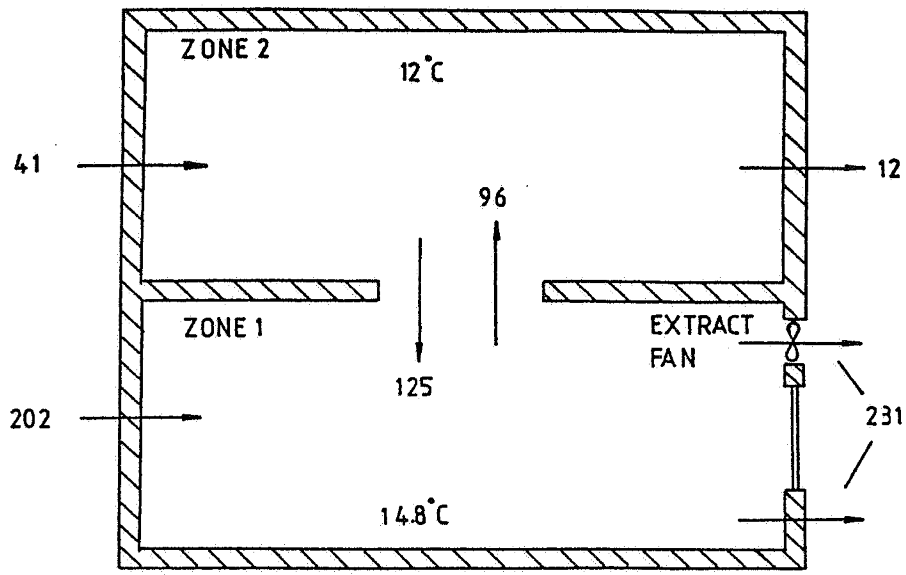

Figure 11.
Airflows with Extract Fan On and 2.8 °C Temp. Difference
- Small Change in Interzonal Airflows Compared to Figure 7.

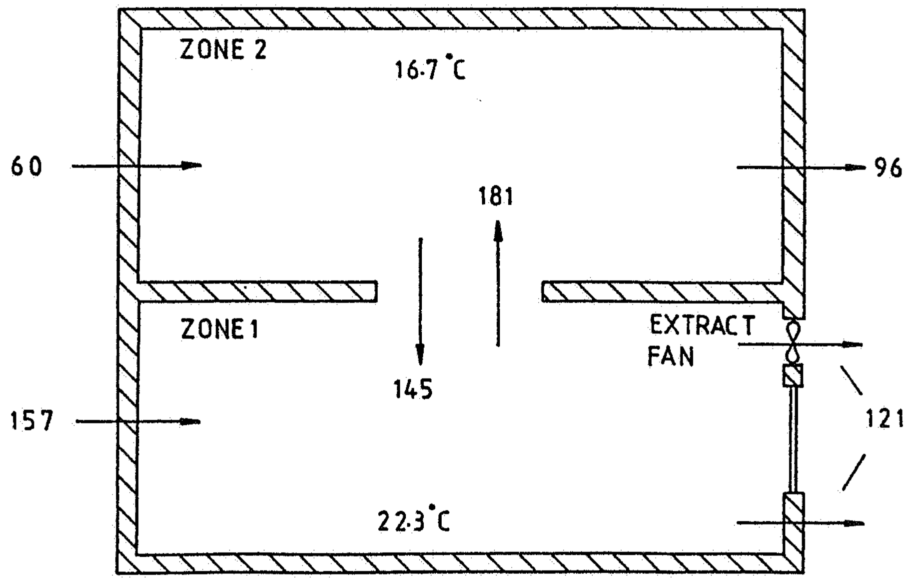

Figure 12.
Airflows at 5.6 °C Temperature Difference
- Reduced Effectiveness of Extract Fan at High Temp Difference