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A MULTI-TRACER GAS METHOD FOR FOLLOWING INTERZONAL AIR MOVEMENT AND ITS APPLICATION IN SOLAR HEATED BUILDINGS

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ABSTRACT

A multiple tracer gas method for following air movement in buildings has been developed and demonstrated at the Polytechnic of Central London. This paper describes the method and shows how it is being used to investigate: 1. the whole house infiltration rate of three experimental solar houses at Peterborough, U.K., 2. the transfer of warm air from passively heated conservatories to the living spaces, and 3. transfer between the ground and first floors.

The method allows up to four perfluorocarbon tracer gases to be released simultaneously in different parts of a building. The tracers are liquids at room temperature, and the release mechanism uses flash heaters operated remotely. An automatic sampling system, employing the principle of gas adsorption by a solid adsorbent is used to take spot samples of air containing the tracer gases. Sampling tubes packed with adsorbent, are arranged in groups of up to ten, at as many as five different sampling points. Samples are taken simultaneously at each sample point and in a timed sequence.

The tracer gases are quantitatively retrieved from the sampling tubes using an automatic thermal desorber, and analysed using a gas chromatograph fitted with a packed column and a flame ionisation detector. The analysis is controlled and data is collected by a low cost microcomputer.

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INTRODUCTION

Air Movement is a fundamental issue in building design and is essential for removing airborne contamination and maintaining the comfort and health of the occupants. However, excess infiltration rates result in unnecessarily high energy bills.

There has been particular interest in the control of air movement in buildings since the oil crisis of 1973. As soon as energy for heating buildings became expensive, great efforts were made to reduce energy usage by introducing better insulation standards. The point has now been reached where energy losses due to excessive air infiltration constitute a large fraction of the total heating load (1,2,3,4) in many buildings.

So far, most of the measurements of ventilation and air infiltration have treated buildings as single zones. Such measurements cannot take into account the airflow between internal rooms, which has a profound effect on both the local air quality and internal energy transfer.

The use of a multi-tracer-gas system instead of a conventional single gas method reduces the time required to make interzonal airflow measurements (5). Using more than one tracer gas reduces the errors in the experimental determination of interzonal flow rates.

The ventilation rate of a building is defined here as the rate at which air enters from outside. Air infiltration is that part of the total ventilation due to unintentional gaps and cracks in the building envelope. Airflow rates are generally expressed either in volume flow units of $m^3 s^{-1}$ or as ventilation rate units of air changes per hour (h^{-1}). The number of air changes per hour taking place in a given zone is equal to the total volume of air entering per hour divided by the volume of the zone.

This paper is divided into four main sections. The first describes the method, apparatus and mathematical analysis. The second shows whole solar house infiltration rates measured on three days in winter. The third illustrates the patterns of air flow which occur between the passively heated south facing conservatory and the living space of the solar house under both summer and winter conditions. The fourth describes the air flows between the floors we observed for a day in winter.

THE PCL MULTI-TRACER-GAS METHOD

The experimental method design was divided into several parts including

--Choice of tracer gases

--Tracer gas injection

--Sampling system

--Tracer gas separation and analysis

--Calculation of air flows from measured data

Choice of Tracer Gases

A detailed survey was carried out to find nontoxic, unreactive, odourless tracers with a zero background concentration, and which are not absorbed by room surfaces (6). A series of perfluorocarbons, similar to those used by Dietz and Cote (7), fit the requirements. The following have been used in this work:-

PP1 perfluoro-n-hexane
PP2 perfluoro-methyl-cyclohexane
PP3 perfluoro-dimethyl-cyclohexane
PP5 perfluoro-decalin

Tracer Gas Injection

In domestic spaces with volumes typically of the order of 30 m^3, about 1 ml of liquid tracer is flash evaporated by a 12 V, 55 W quartz-halogen car headlamp bulb, yielding an initial concentration of about 4 ppm. The injection system is energized by remote control using a microcomputer (8).

Sampling System

The sampling system (see Figure 1) operates on the principle of gas adsorption by a solid adsorbent. Each sampling point (see Figure 2) consists of a group of removable stainless steel tubes packed with a divinyl-benzene/styrene co-polymer adsorbent. Samples of room air are obtained by drawing a small fixed volume of air (about 100 ml) through the sample tubes, air being admitted by a solenoid valve controlled from a microcomputer.

Up to four perfluorocarbon tracer gases may be injected simultaneously in different parts of a building, and the change in concentration of each gas with time is measured at up to five points in space. The solenoid valves are operated so that tubes are exposed simultaneously at each sampler and in a timed sequence from one to ten. The sample tubes are then sealed and analysed later. Five sampling points and ten points in time have been chosen for convenience, although there is no restriction on either the number of groups or the number of tubes in each group that may be used.

A microcomputer was used to drive the gas injection and sampling system. The sampling system has been left running unattended for as long as a week.

Tracer Gas Separation and Analysis

A schematic diagram of the analysis system is shown in Figure 3. The tracer gases are desorbed from the sample tubes using an automatic thermal desorber and then separated and analysed on a gas chromatograph fitted with a flame ionisation detector and a 4m packed glass column (8).

The microcomputer was used to monitor the automatic thermal desorber and the gas chromatograph, so that peaks would only be written to disc when desorbed tracer gas samples were passed to the detector. Software allowed the screen to emulate a chart recorder, showing scalable peak heights and retention times at any point in the analysis. Very low signals activated an amplifier to avoid errors introduced by the analogue to digital convertor.

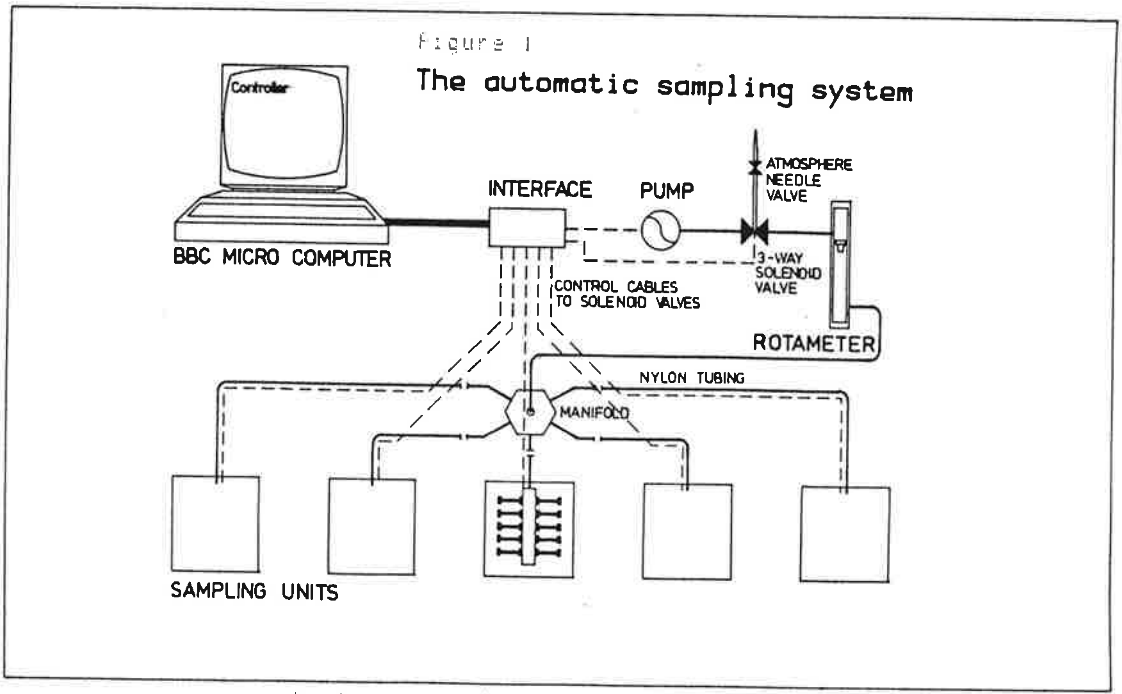


Figure 1 The automatic sampling system

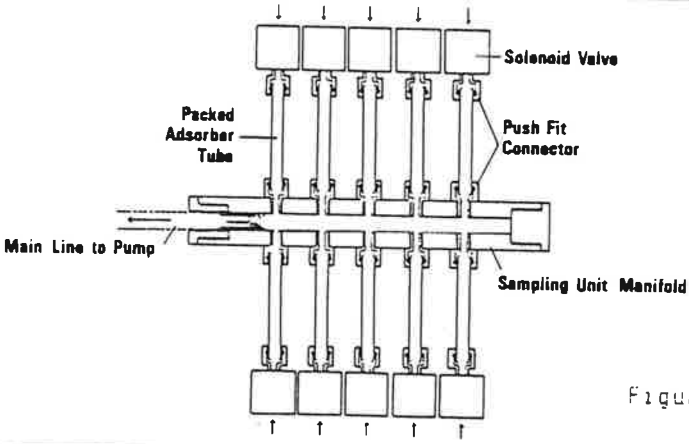


Figure 2 A sampling unit

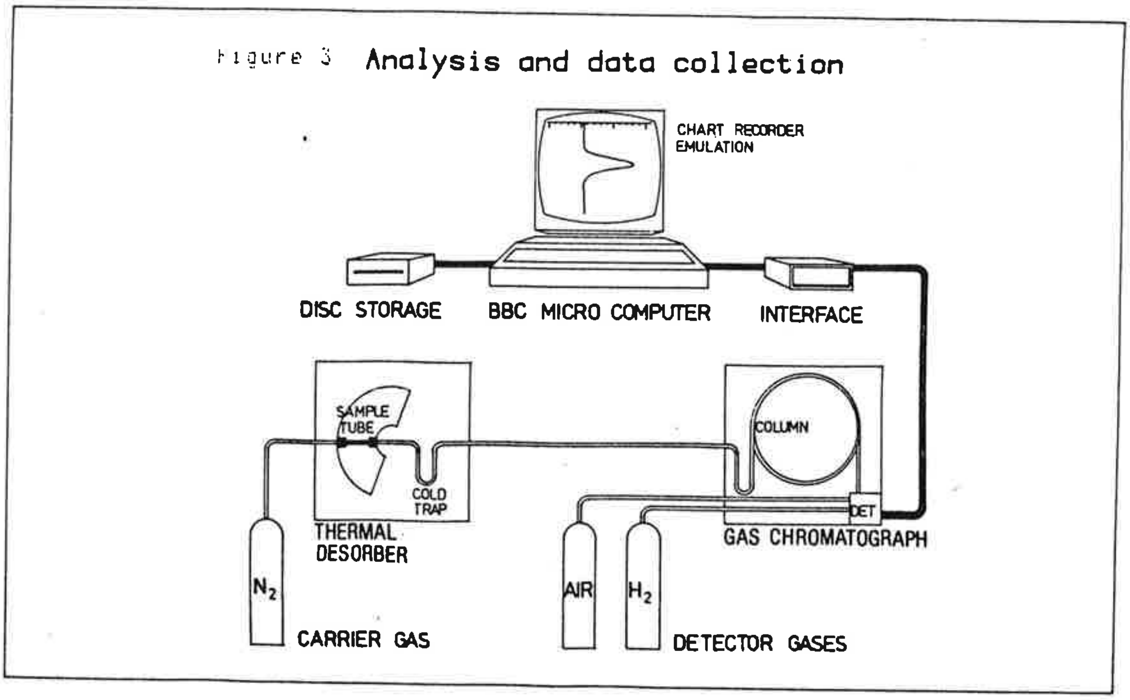


Figure 3 Analysis and data collection

Calculation of single-zone infiltration rates and multizonal airflows

A program was written to allow data from the floppy disc to be read. Each data file is loaded into computer memory, and peaks are reconstructed on the screen. As with a chart recorder plot, peaks are identified by their retention times. An average baseline may be constructed and then peak heights and integrated areas calculated.

The multizone system is modelled following Sinden (5) as a series of cells of constant and known volume, which are all connected to a cell of infinitely large volume corresponding to the outside. The net inflow and outflow from each zone are expressed by a series of equations (9) which are summarized below:

$$v_1 \dot{x}_1(t) = F_{1,1}\, x_1(t) + F_{2,1}x_2(t) + \ldots\ldots + F_{N,1}x_N(t)$$
$$v_2 \dot{x}_2(t) = F_{1,2}\, x_1(t) + F_{2,2}x_2(t) + \ldots\ldots + F_{N,2}x_N(t)$$
$$\vdots$$
$$v_N \dot{x}_N(t) = F_{1,N}\, x_1(t) + F_{2,N}x_2(t) + \ldots\ldots + F_{N,N}x_N(t)$$

where v_i = volume of zone i

$F_{i,j}$ = flow rate from zone i to j

All the equations may be expressed in matrix form. Single and multi-zone infiltration rates are calculated from the measured data using a discrete time model which restricts the variable t to have only values of 1 2 ... S-1, where S is the number of samples taken in each zone. The discrete time model is described in detail elsewhere (9).

In use, problems have arisen with the sensitivity of the analysis to noise in the data. In some cases, the noise was such that the algorithm was unable to deduce air flows at all from the measured gas concentration data. In other cases, negative flow rates would result. This ties in with the experiences of other workers.

The high sensitivity to measurement error is a problem which has now been surmounted by the use of an iteritive parameter extractor programme written by Chris Martin (10). The parameter extractor creates a flow matrix from the measured concentration data and then recreates a set of concentrations to fit the flows. Each element of the calculated flow matrix is perturbed in turn as the search is made for the flow matrix which corresponds best to the measured data. The best flow matrix is the one which minimises the square of the error at each of the concentration points. Constraints are imposed on the flow matrix during the iteritive search, which prevent the generation of any negative flows. All the interzonal flow rates expressed in this work have been calculated using the iteritive parameter extractor.

INFILTRATION RATE MEASUREMENTS IN THE PETERBOROUGH EXPERIMENTAL HOUSE

Several tracer gas decay experiments have been carried out in the Peterborough solar house (12). The house is of timber frame construction and has been fitted with a vapour barrier which has been carefully sealed with tape wherever it has been pierced to make way for building services. The house has a volume of 251 m^3.

Several experiments were carried out to measure the whole house infiltration rate during the course of a week in December 1984.

Test 1 Infiltration measurement without any artificial mixing (11/12/84).

The sampling units were placed as shown on the house plans (Figure 4).

PP1 (8.0 ml) and PP3 (8.0 ml) were released equally from heaters placed in the living room, the kitchen, the top of the stairs and the bathroom. Two tracer gases were used in order to give an estimate of measurement error. The total time allowed for tracer gas release and mixing was 15 minutes. Two people were present to aid mixing by walking round waving papers. After the mixing period ten air samples were collected at 20 minute intervals

For the duration of the test, the heating system was switched off. All the external doors and windows were closed and all internal doors (except to the cupboards) were open.

The average temperature difference between inside and outside was 14.5°C ± 1. The wind velocity was not measured.

Results Table 1 shows results calculated for each gas collected at each sampler and Figure 5 illustrates the concentration changes of each gas at sampler B.

TABLE 1 Whole house infiltration rate (11/12/84)

	PP1	PP3
Sampler B - Main bedroom	0.21	0.18
Sampler C - Kitchen	0.56	0.54
Sampler D - Living room	0.70	0.74
Sampler E - Upstairs data logging room	0.27	0.32

The mean calculated infiltration rate is $0.4\ h^{-1} \pm 0.2$.

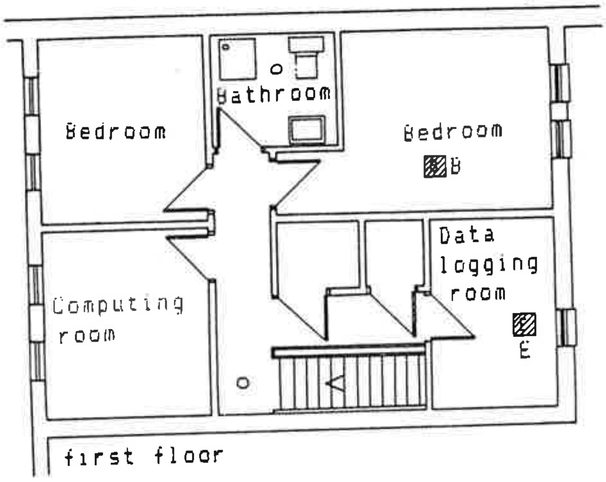
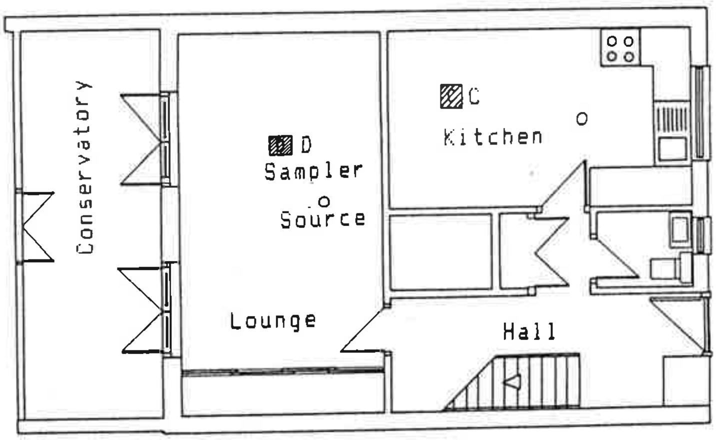


Figure 4 Plans of the solar house



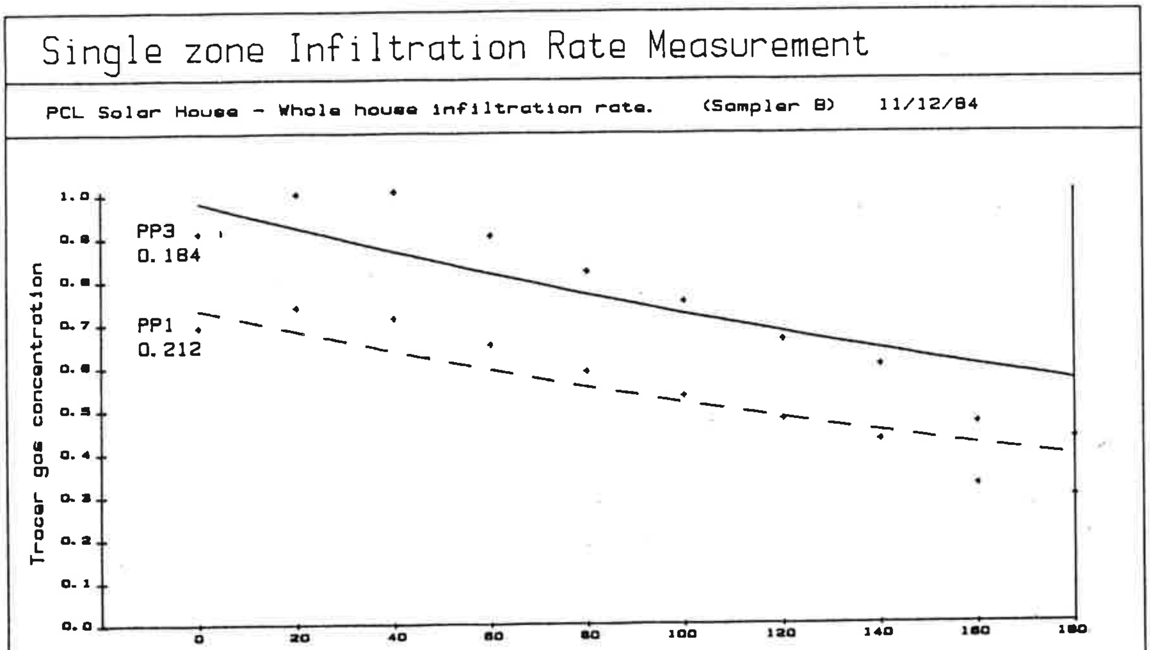


Figure 5

The spread of results is due to large local variations in infiltration rate throughout the house. The living room displays the largest value and this is probably due to fast exchange of air with the conservatory in addition to flow through the house to the upstairs. The kitchen has the next largest value, due to its proximity to the front door. The flow of air from the cooler ground floor up the stairs results in apparently lower decay rates in the two bedrooms measured. Sampler B was placed furthest from the stairs and shows not only the lowest decay, but also takes a considerable time to attain its maximum tracer gas concentration (Figure 5). It was considered that internal mixing throughout the experiment may have been inadequate and so during the following experiment the central heating fan was run for the duration of the test. One gas was released upstairs and the other downstairs, to gauge the quality of mixing.

Test 2 Whole house infiltration rate measurement with heating system fan on during the mixing period (20/12/84).

PP1 (6 ml) was released equally from two release heaters downstairs in the lounge and kitchen; and PP3 (6 ml) was released equally from heaters in the bathroom and at the top of the stairs. In this test, the house air circulation fan was run for the duration of the release and mixing period which had been increased to sixty minutes. After the mixing period, the fan was switched off and ten samples were collected at 40 minute intervals. The test was carried out overnight with the sampling units arranged as before.

The average temperature difference between inside and outside was 13.2°C ± 0.5. The average wind velocity was 1.84 m s^{-1} predominantly from the west.

Results Table 2 shows results calculated for each gas collected at each sampler.

TABLE 2 Whole house infiltration rate (20/12/84)

	PP1	PP3
Sampler B - Main bedroom	0.46	0.48
Sampler C - Kitchen	0.65	0.52
Sampler D - Living room	0.62	0.49
Sampler E - Upstairs data logging room	0.51	0.46

The mean calculated infiltration rate is 0.5 h^{-1} ± 0.1. It is clear from the pattern of results for each gas at each sampler that the two gases have each become better distributed about the house. However, the continued discrepancies imply that without forced mixing of air during the test, variations still exist in local infiltration rates. The living room has the largest exchange rate and the major bedroom the least. The fact that the largest differences in gas values occur for the living room and kitchen indicates a relatively fast exchange of air between the downstairs rooms and outside coupled with a flow of air from downstairs to upstairs.

INTERZONAL AIR FLOWS IN THE PETERBOROUGH SOLAR HOUSE

Air flows between living room and conservatory - summer operation

Several experiments have been carried out during the summer of 1984 to investigate the pattern of air flow between the south facing conservatory and the living room of the house (12).

Test 1 Air flow between living room and conservatory with communicating doors shut and living room/hall door open (11/6/84). Samplers A and B were placed in the living room and samplers C and D in the conservatory. It was a warm sunny day (see Figure 7) .

With all the internal and external doors shut, PP3 (0.7 ml) was released in the conservatory and PP1 (1.0 ml) in the living room. A total of 10 minutes was allowed for release and mixing of the gases in their respective zones before the door between lounge and hall was opened and the first air sample was collected. A further 9 air samples were collected at 10 minute intervals.

Results Plots of tracer gas concentration against time are shown for each gas in each zone in Figure 6. Figure 7 shows a schematic of the interzonal air flow rates. The calculated values have then been used to deduce the rate of transfer of energy between zones, with the aid of equation 1:

$$H = F / V * Cp * D \quad (1)$$

where H = Rate of heat transfer (kW)

F = Mass flow rate of air ($m^3\ s^{-1}$)

V = Specific volume of air at zone temperature ($kg\ m^3$)

Cp = Specific heat capacity of air at zone temperature ($kJ\ kg^{-1}\ K^{-1}$)

D = Temperature difference between zones

The overall trend is for air to flow from the conservatory into the house.

Test 2 Air flow between living room and conservatory with communicating doors shut and living room / hall door open (15/6/84). Samplers A and B were placed in the living room, and samplers C and D in the conservatory. It was a very hot sunny day (see Figure 8)

PP3 (2.0 ml) was released in the conservatory and PP1 (2.0 ml) in the living room, with all internal and external doors shut. A total of 10 minutes was allowed for the release and mixing of the two tracer gases in their respective zones. The doors between the living room and conservatory remained closed throughout the test, but just before collection of the first sample, the door between the living room and hall was opened. A further 9 samples were taken at 10 minute intervals.

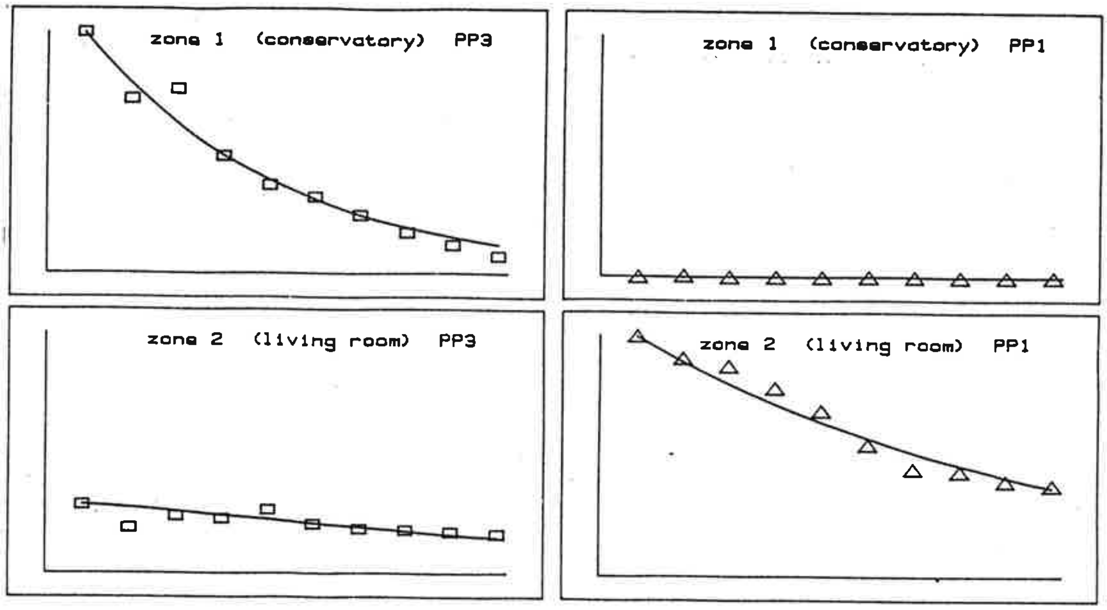


Figure 6 Plots of gas concentration against time.

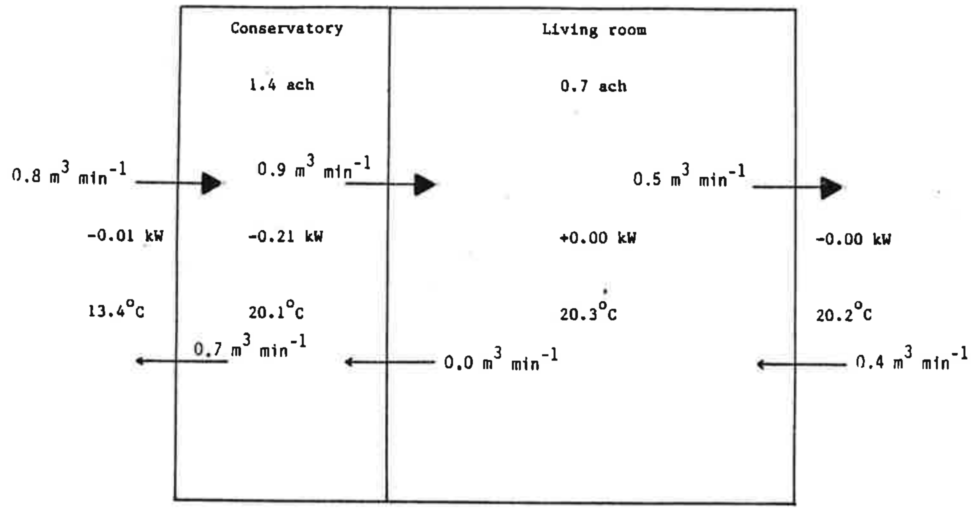


Figure 7 Calculated interzonal flow rates between conservatory and lounge 11/6/84

<u>Results</u> Figure 8 gives a schematic of the interzonal air flows calculated from the gas concentration data. The high conservatory temperature provides the potential for fairly fast air flow to and from the outside, and from the living room to the conservatory, in spite of the closed doors between

them. The overall flow is predominantly from the house to the conservatory. The energy balance calculated from equation 1 is shown in Figure 8.

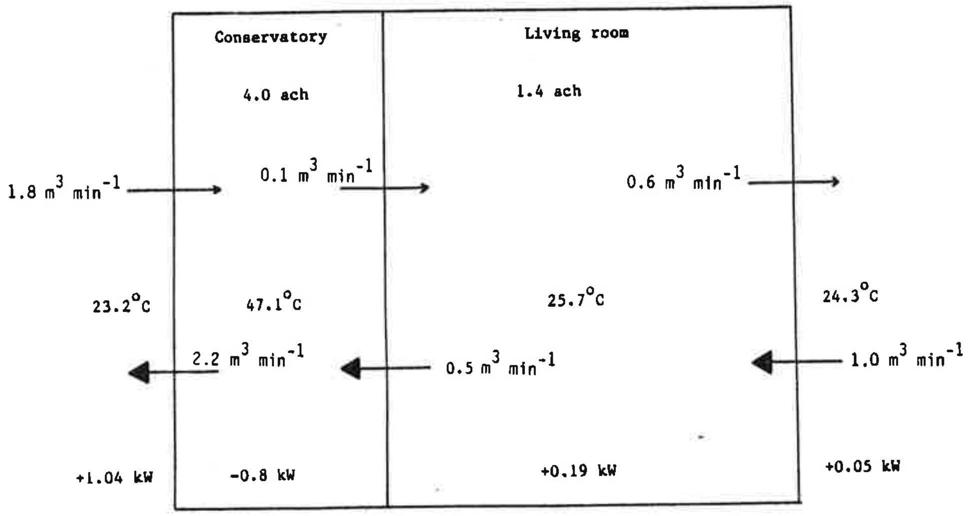


Figure 8 Calculated interzonal flow rates between conservatory and lounge 15/6/84

Air flows between living room and conservatory - winter operation

Subsequently, measurements have been carried out during the heating season, with the conservatory ventilator and external doors and windows closed, and the house air heating system switched off.

Test 3 Air exchange between the conservatory and living room with all doors shut 10/9/84. Sampler A was placed in the conservatory and sampler B in the living room.

PP3 (1.0 ml) was released in the living room and PP5 (2.0 ml) in the conservatory. All doors and windows were closed for the duration of the test. A total of ten minutes was allowed for release and mixing of the tracer gases before the first sample was taken. A further nine samples were collected at ten minute intervals.

Results Figure 9 shows a schematic of the interzonal flows. Air flow is almost unidirectional, from the living room to the conservatory with no recirculation. The energy balance has been calculated from equation 1.

Test 4 Air exchange between the conservatory and living room with the communicating doors open 10/12/84. Sampler A was placed in the living room and sampler D in the conservatory. It was a sunny day.

With all the internal and external doors shut, PP3 (2.0 ml) was released in the conservatory and PP1 (2.0 ml) in the living room. A total of 6 minutes was allowed for release and mixing of the gases in their respective zones before the first sample was taken. The eastern most set of communicating doors was then opened and a further 9 air samples were collected at 2 minute intervals.

<u>Results</u> Figure 10 shows a schematic of the calculated air flows and energy exchanges. The trend was for air to flow from the warm conservatory into the house.

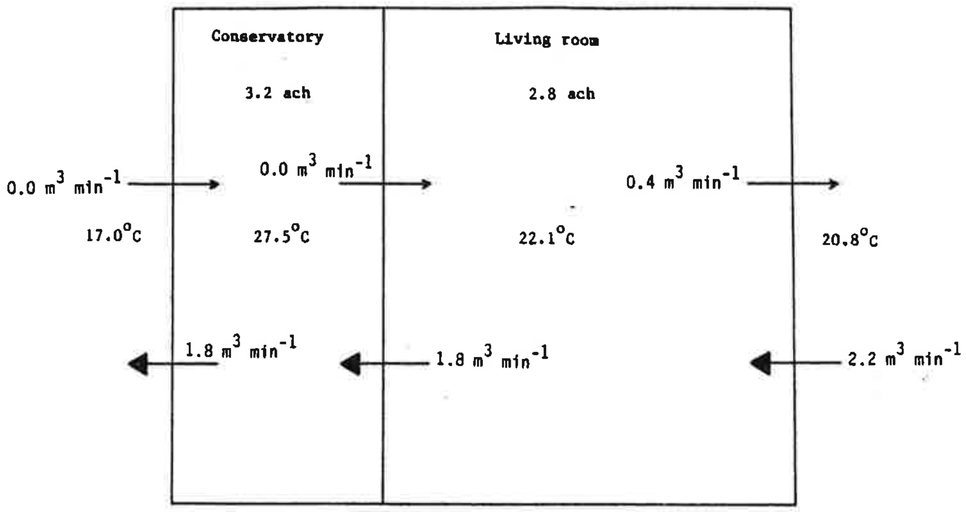


Figure 9 Calculated interzonal flow rates between conservatory and lounge 10/9/84

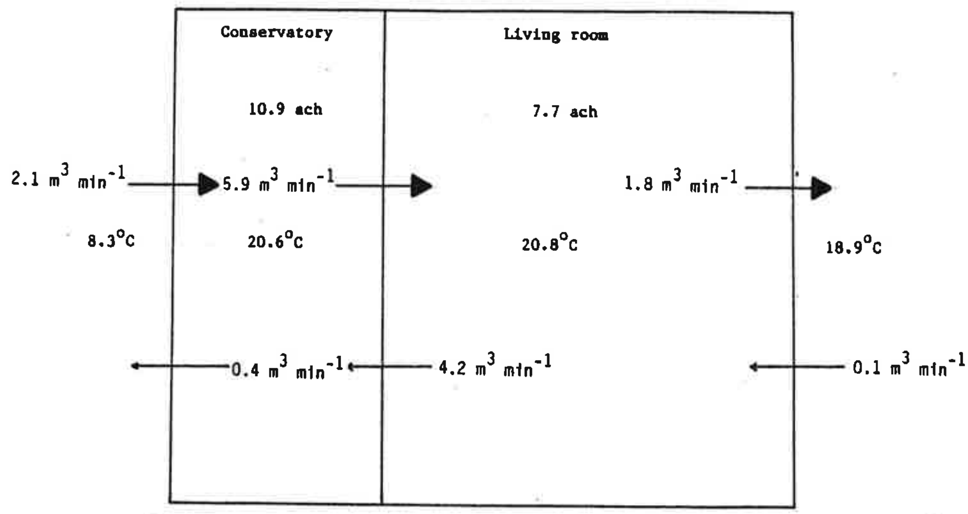


Figure 10 Calculated interzonal flow rates between conservatory and lounge 10/12/84

AIR FLOWS BETWEEN UPSTAIRS AND DOWNSTAIRS 12/12/84.

An experiment was carried out in which the air flow rate between floors of the solar house was measured. The sampling units were placed as shown in Figure 4.

PP1 (6.0 ml) was released equally from heaters placed in the living room and kitchen, and PP3 (6.0 ml) was released equally from heaters placed at the top of the stairs and in the bathroom. The total time allowed for tracer gas release and mixing was 15 minutes. Two people were present to aid mixing by walking round waving papers. One mixed the air upstairs, and the other remained downstairs.

For the duration of the test, the heating system was switched off. All the external doors and windows were closed and all internal doors (except to the cupboards) were open.

The average temperature difference between the inside of the house and outside was 16.8°C ± 0.5.

Results Figure 11 shows a schematic of the interzonal air flows and energy exchange. Air flows into the house at the ground floor and tends to flow upstairs under the stack effect. There is much recirculation between the floors and air leaves the building from points both upstairs and downstairs.

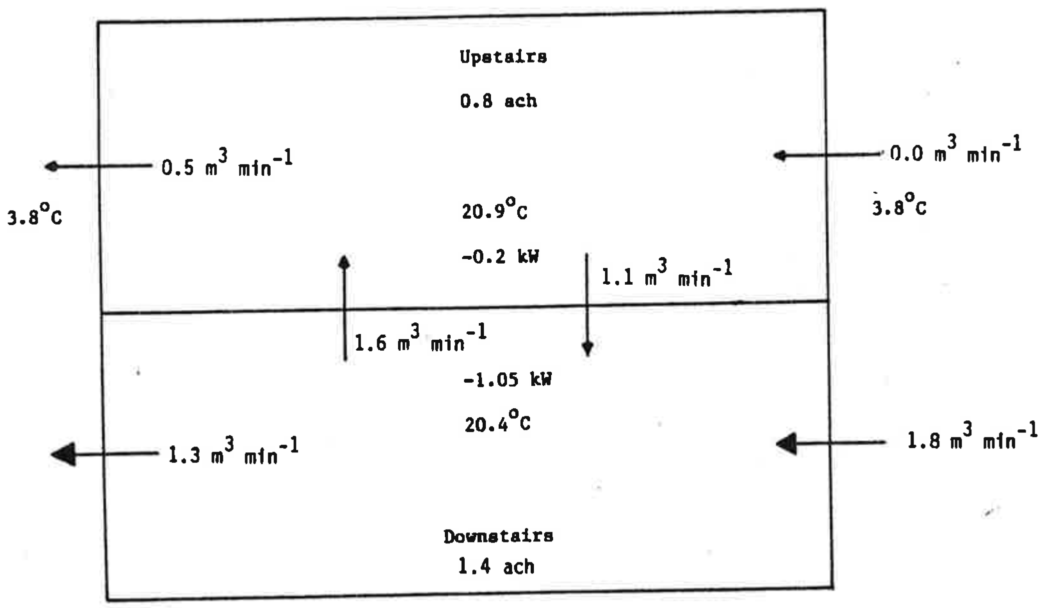


Figure 11 Calculated interzonal flow rates between upstairs and downstairs: 12/12/84

CONCLUSION

A method has been successfully established for the automatic measurement and analysis of interzonal air flows using a multi-tracer gas technique.

The automated system has been used to make a variety of single zone infiltration and interzonal air flow measurements in a new solar heated house in Peterborough U.K. The single zone measurements indicate that compared to most British houses the Peterborough solar house is very airtight. The interzonal measurements between the conservatory and living room show that in the winter, the conservatory acts as a buffer space between the house and outside, and on a sunny day it acts as a passive heater. In the summer with the vent open and communicating doors to the living room closed, the conservatory maintains comfortable temperatures inside the house.

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