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MEASUREMENT OF HEAT AND MASS TRANSFER BETWEEN THE LOWER AND UPPER FLOORS OF A HOUSE

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SUMMARY

The work is concerned with measuring heat and mass transfer between the lower and upper floors of a conventional house via a doorway. Air flows between the two floors were measured using a single tracer gas technique, and the temperatures at various points in each floor were measured using thermocouples. The lower floor of the house was heated to various temperatures in the range 18–35 °C using thermostatically controlled heaters. The upper floor was unheated. Two portable SF_6 systems fitted with electron capture detectors were employed for measurement of the interzonal air flow. The mass and heat flow rates between the two floors were calculated from the tracer gas concentrations, and temperature differences and results were compared with the values predicted by the existing algorithms for the two zone enclosures. The mass flow rate and coefficient of discharge for the doorway were found to be functions of the temperature difference between the floors of the house.

KEY WORDS Houses Interzone convection Doorway SF_6 tracer gas

INTRODUCTION

The study of interzonal natural convection in houses is important since it plays a significant role not only for the transfer of heat between various rooms but also for the indoor air quality and comfort of the occupants. Considerable attention has been given to interzone heat transfer in passive solar and conventional buildings so that algorithm energy models may be developed [1]. Experimental and theoretical work has been carried out by various researchers to study natural convection via doorways in small scale models and full size rooms [2, 3, 4]. These studies highlighted the significant heat losses via natural convection across the doorway. Interzone convection through a doorway was also found to be a major mechanism for distributing heat from a conservatory to the rest of a house [5].

In winter the lower and upper floors of houses are usually heated to different temperatures, e.g. the living or dining room is heated to 21 °C while the bedrooms are heated to 18 °C. During this period the air movement within the house via, for example, the doorway can create draughts and heat losses. As condensation in houses largely depends on air movement, it is important to monitor interzonal air flows if this problem is to be minimized. Although interzone convection studies have been carried out in passive solar buildings, it is remarkable that so little information has been published on heat and mass transfer between floors of conventional houses via doorways. To the author's knowledge the only published data available are due to Reynolds [6], who studied heat and mass flow in a scale model of a stairwell. Although correlations from scale models are useful, measurements in houses is essential in order to determine the exact nature of air movement and also estimate the infiltration rate which cannot be predicted easily in scale models. The objectives of this work are to study air movement between floors of a two-storey house and to compute the heat and mass transfer across a doorway opening.

Experimental studies were carried out in a three-bedroomed house in Milton Keynes, U.K. The interzonal mass and heat transfer were measured using sulphur hexafluoride tracer gas and thermocouples. This paper also describes the SF_6 system and measurement procedure and includes an analysis of the experimental results obtained. The results have been compared with those predicted by existing algorithms for two-zone enclosures.

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MASS AND HEAT TRANSFER EQUATIONS

Figure 1 shows 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 (F_{01} and F_{02}) and exfiltrate from each zone to the outside (F_{10} and F_{20}). In addition, air can exchange between the two zones through a doorway in both directions (F_{12} and F_{21}). The mean temperatures for zones 1 and 2 are T_1 and T_2, respectively. The air flow rate between the two zones may be varied by heating zone 1 at different temperatures. The volumetric flow rate through a doorway is given by Shaw [3] as follows:

$$F = (C\,W/3)\,(g\,\Delta\rho\,H^3/\rho)^{0.5} \tag{1}$$

Since the coefficient of thermal expansion $\beta = 1/T = \Delta\rho/(\rho\,\Delta T)$, equation 1 can be rewritten as follows:

$$F = (C\,W/3)\,(g\,\Delta T\,H^3/T)^{0.5} \tag{2}$$

The heat transfer rate Q, the heat transfer coefficient h, the Nusselt number Nu, the Prandtl number Pr and the Grashof number Gr may be given by [7]:

$$Q = F\,\rho C_p \Delta T = (C\rho W C_p/3)\,(g\,\Delta T\,H^3/T)^{0.5} \tag{3}$$

$$h = Q/(W H\,\Delta T) \tag{4}$$

$$\mathrm{Nu} = h\,H/k \tag{5}$$

$$\mathrm{Pr} = C_p\,\mu/k \tag{6}$$

$$\mathrm{Gr} = \rho^2 g\,\beta\,\Delta T\,H^3/\mu^2 \tag{7}$$

Equations (3)–(7) can be substituted in equation 2 to give:

$$\mathrm{Nu}/\mathrm{Pr} = (C/3)\,\mathrm{Gr}^{0.5} \tag{8}$$

In the above analysis it has been assumed that the flow of air is one-dimensional and the viscous effect has been neglected. The influence of viscosity, the temperature distribution in each zone and the shift of the neutral plane

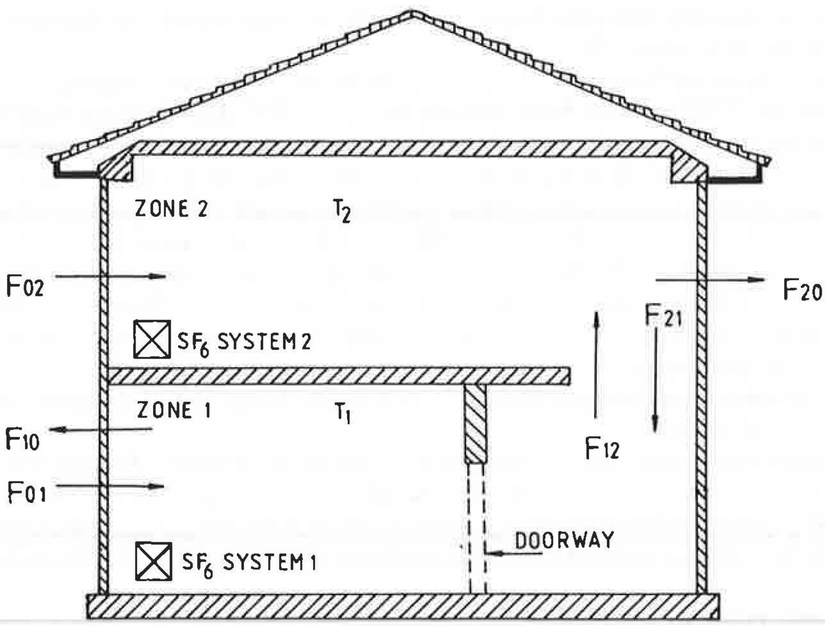

Figure 1. Interzone air flows in a house via a doorway

are given in Reference 8. The coefficient of discharge for a doorway in a vertical partition separating a two-zone enclosure is dependent on a number of parameters, such as the Reynolds number, opening size, zone geometries and experimental conditions. Various values have been measured in previous studies, but many researchers have assumed a value of 0·61.

EXPERIMENTAL TECHNIQUE

Air flow measurements were carried out using a single tracer gas technique [9]. Several tracer gases are available, but sulphur hexafluoride has been chosen for this work as it has desirable tracer gas characteristics in terms of detectability, safety, and cost and has been used successfully in previous air movement studies [10, 11].

The experimental procedure was as follows. A certain quality of tracer gas was released in zone 1 while all its doors and windows were closed. Following tracer gas mixing the communication door between the two zones was opened and the decay of tracer gas was then monitored. Some tracer gas was carried into zone 2 where it mixed with air and some returned to zone 1. If one then 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 decrease of tracer concentration in zone 1 at time t is given by:

$$V_1\, dC_1/dt = -C_1\,(F_{10}+F_{12})+C_2\,F_{21} \tag{9}$$

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

$$V_2\, dC_2/dt = C_1\,F_{12}-C_2\,(F_{21}+F_{20}) \tag{10}$$

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

$$F_{01} = F_{12}+F_{10}-F_{21} \tag{11}$$

$$F_{02} = F_{20}+F_{21}-F_{12} \tag{12}$$

Mass-balance equations may be solved using the theoretical technique described in Reference 12. An alternative method to estimate air flows between internal spaces was used by Sinden [13]. The method assumes a multizone 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 modification of introducing the discrete time model as explained in detail in Reference 14.

The tracer gas technique used in this work has been validated in the laboratory by measuring air flow between two small chambers and an independent flow meter. The agreement between the SF_6 tracer calculation of air flow and that measured with a calibrated flow meter was $\pm 5\%$.

INSTRUMENTATION

Air flow measurements

The air flow measurements were carried out using two highly portable microcomputer systems, Figure 2. The two systems are identical in construction and are described in detail by Riffat *et al.* [15]. In essence, each consists of the following major components: a sampling and injection unit, a column, a chromatographic oven, an electron capture detector and a microcomputer and interface.

The sampling unit consists of a 2-position, 6-port valve, connected to a 0.5 cm^3 sampling loop. The valve can be easily rotated to positions 1 or 2 using a small motor. The separation column was made by packing a 1.5 m length × 4.3 mm internal diameter nylon tube with 60–80 mesh aluminium oxide. The column was held at 35°C in a thermostatically controlled electric oven. The electron capture detector, which uses Ni-63 radioactive cell, was made by Pye Unicom Ltd.

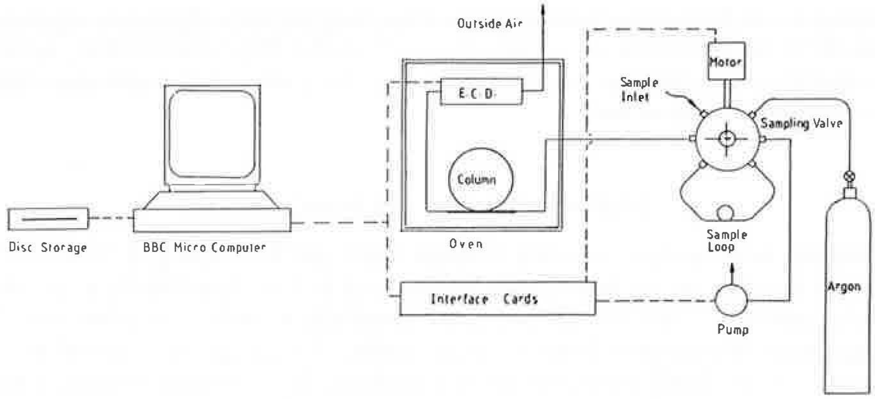

Figure 2. Portable SF_6 system

The system incorporates a BBC microcomputer, 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 compact and can be used for unattended operation.

Temperature and wind speed measurements

Temperature measurements were carried out at various points in each zone using copper-constantan thermocouples. The outside temperature and wind speed during the measurement period were also recorded. A data logger type MDL1000, with a built-in cold junction compensation network, was used for this purpose.

The location of thermocouples in each zone is important if the heat flow between the two zones is to be measured accurately. Various approaches have been used by previous researchers studying natural convection between two-zone enclosures. Brown and Solvason [2] measured air temperatures as the average for vertical grids (floor to ceiling) located at a specific distant from the partition and the centre of the opening. Shaw and Whyte [3] used thermocouple grids suspended either in the rooms or in the doorway openings themselves. Other studies on natural convection in small scale models have involved different techniques [4].

All these methods are useful in simple enclosures but are impractical if measurements are to be carried out in houses. In this situation it is important to employ a simple method of temperature measurement which would be relevant to building designers. In this study temperature measurements were made at the centre of each room.

MEASUREMENTS AND RESULTS

Measurement of interzone mass and heat transfer were carried out in a three-bedroomed, semi-detached house. The downstairs floor, zone 1, had a volume of 65·5 m^3 and contained the living room, dining room and the kitchen. The upstairs, zone 2, had a volume of 92 m^3 and contained the bathroom, three bedrooms, stairway and hall. The two zones were separated by a single doorway. The space heating in this house was accomplished using a hot-water radiator system. In order to achieve high temperatures in zone 1, four additional thermostatically controlled electric heaters were used.

To estimate the air flows between the two zones the two SF_6 systems were used. 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 door between the two zones was closed and gaps between the door and its frame were sealed with tape. This prevented heat and tracer gas leakage prior to starting the test. A known volume of tracer gas was released downstairs from a syringe 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 the communication door was opened.

Samples were taken every 3 min for a total experimental time of 90 min. The SF_6 systems analysed the samples *in-situ*, so providing instantaneous readings of gas concentration in each zone.

The air flows between the two zones were estimated from the tracer gas concentration data using the method described above. Since infiltration and exfiltration of air, i.e. $(F_{01} - F_{10})$ and $(F_{02} - F_{20})$, due to the temperature difference between the inside and outside of the house and the wind speed can effect the interzonal air flow, the induced flow was subtracted from the total air flow between the two zones.

Several experiments were carried out in this house under a variety of temperature differences between the two zones. In some experiments the house central heating system and electric heaters were switched off. In others experiments only the lower floor was heated to temperatures in the range 18–35 °C. The heaters in zone 1 were switched on about 5 hours before the beginning of a test to enable the heaters and air in the zone to reach a steady temperature. Figure 3 shows the temperature in zones 1 and 2 for various elapsed time during one experiment. The results indicate the temperature in zone 1 falls rapidly during first 13 min and then decreases at a much slower rate. The temperature in zone 2 increases rapidly in the first 13 min and then stabilises at an almost constant value. The temperature difference between the two zones, the outside temperature and wind speed for various tests are given in Table 1.

Figures 4 and 5 show tracer gas concentration against time for two temperature differences. The total air exchange between the two zones was found to be 194 and 276 m^3/h for temperature differences of 0.5 and 3.5 K, respectively. Tests were carried out for average temperature differences between 0.5 and 13 K. These experiments showed that the total air exchange between the two zones through the doorway is a function of the temperature difference.

To evaluate the coefficient of discharge for the doorway, the air flow measured using the tracer gas technique was divided by the theoretical air flow described in Section 1 as follows:

$$C = \frac{\text{Measured air flow using tracer gas}}{(WH/3)\,(g\,\Delta T H^3/T)^{0.5}} \tag{13}$$

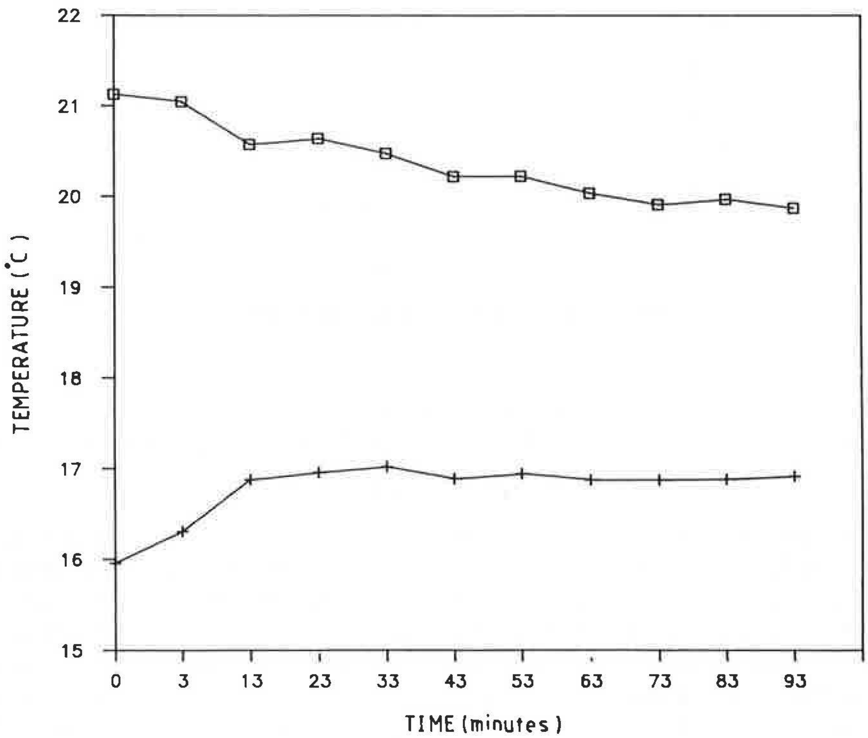

Figure 3. Air temperatures in zones 1 and 2 against time

Table 1. Experimental conditions

Run.	Temperature difference between zones 1 and 2 °C	Outside temperature °C	Wind speed m/s
1	0·5	9·5	4·0
2	1·6	7·7	2·0
3	3·4	8·4	4·1
4	4·4	1·7	4·5
5	5·6	8·5	3·4
6	6·6	1·8	3·7
7	7·6	5·9	2·0
8	8·1	5·3	2·0
9	13·0	4·6	2·6

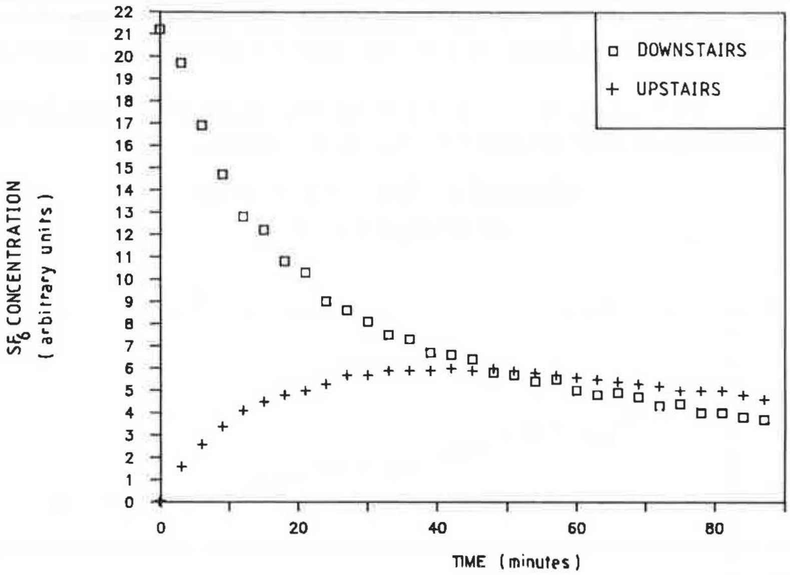

Figure 4. Decay of SF_6 tracer gas, $\Delta T = 1{\cdot}6$ K

The coefficient of discharge was found to decrease from about 0.61 to 0.22 as the temperature difference between the two zones increased from 0.5 to 13 K, in Figure 6. These results were correlated well with:

$$C = 0.0835\,[\Delta T/T]^{-0.313} \tag{14}$$

We believe that the decrease in the coefficient of discharge may be due to an increase in interfacial mixing as a result of the direct transfer of some cold air from the upper floor into the inflowing warm air from downstairs. In addition, the increase in density difference can cause an increase in turbulence within the two zones which will affect the coefficient of discharge. The mean velocity of air through the doorway was calculated by dividing the measured flow rate by the area of the doorway multiplied by the coefficient of discharge. The mean velocities were varied between 0.06 and 0.3 m/s. The Reynolds numbers based on the hydraulic diameter Dh of the opening were found to be in the range 4410–21110. The values of C and Re_{Dh} were correlated in the form:

$$C = 268\,\mathrm{Re}_{Dh}^{-0.639} \tag{15}$$

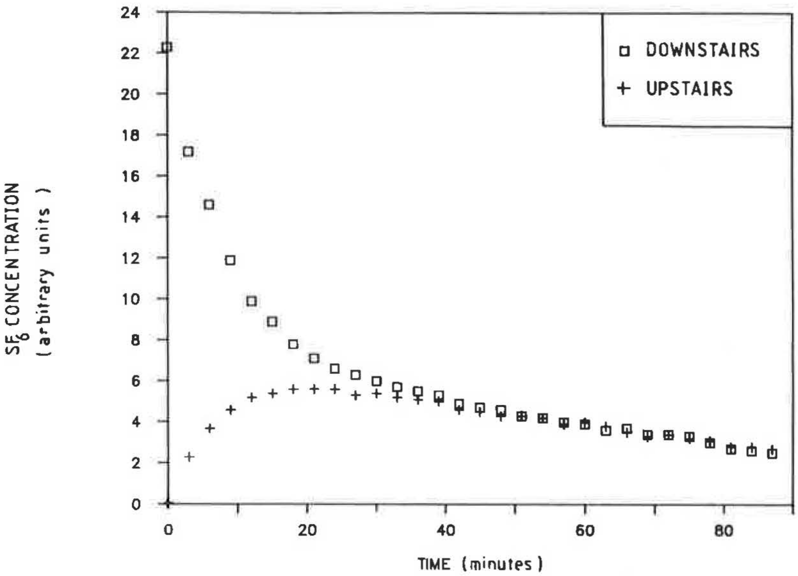

Figure 5. Decay of SF_6 tracer gas, $\Delta T = 13$ K

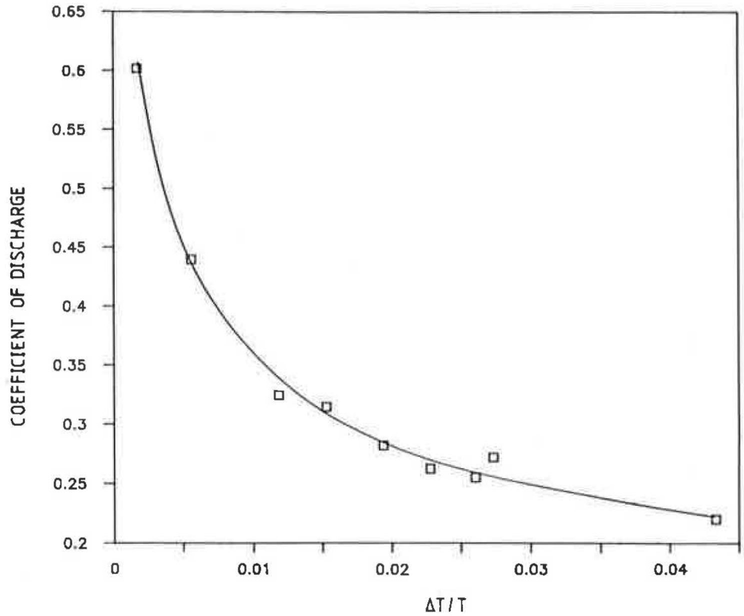

Figure 6. Variation of coefficient of discharge with $\Delta T/T$

On substituting equation 14 into equation 2, the mass flow rate between the two zones can be given in the form:

$$M = 0.0278\, \rho\, W\, (g\, H^3)^{0.5} [\Delta T/T]^{0.137} \tag{16}$$

A plot of the mass flow rate against $[\Delta T/T]^{0.187}$ is shown in Figure 7. It is clear from this Figure that the mass flow rate increases linearly with the temperature difference.

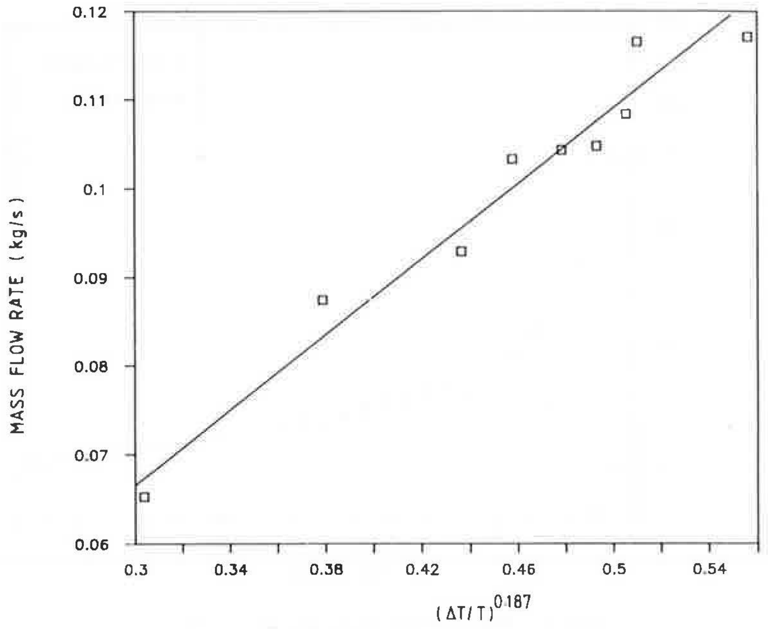

Figure 7. Mass flow rate against $(\Delta T/T)^{0.187}$

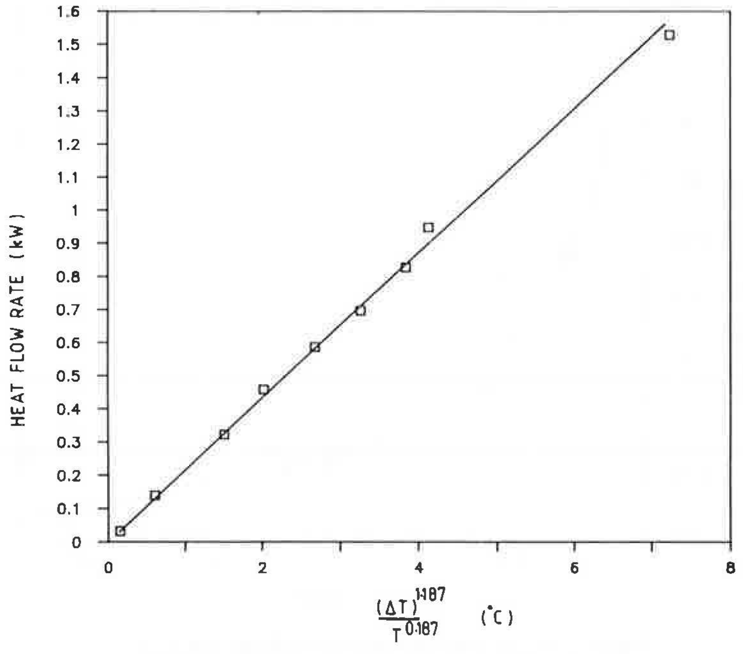

Figure 8. Heat flow rate against $\Delta T^{1.187}/T^{0.187}$

The heat flow rate between the two zones through the doorway is given by:

$$Q = 0.0278\, \rho\, C_p\, W (g\, H^3)^{0.5}\, (\Delta T^{1.187}/T^{0.187}) \tag{17}$$

The variation of heat flow rate with $\Delta T^{1.187}/T^{0.187}$ is shown in Figure 8. The heat losses from the lower floor through the doorway were found to be significant and temperatures up to 21 °C were achieved in the upper floor with the heating system switched off on this floor.

Equation (18) describes convection through the doorway in terms of the Nusselt number, Grashof number and Prandtl number:

$$\mathrm{Nu/Pr} = 130{\cdot}83\,\mathrm{Gr}^{0.18} \tag{18}$$

or, in different form

$$\mathrm{Nu/Pr} = 0.0278\,[\Delta T/T]^{-0.313}\,\mathrm{Gr}^{0.5} \tag{19}$$

Figure 9 shows this correlation together with a number of previous correlations [2, 3, 4] describing flow through openings between two-zone enclosures. The difference between the present case and examples based on convection between two adjacent zones is apparent. The mean interzone heat transfer coefficient may be calculated using the average experimental values of Pr, ρ, μ and k as follows:

$$h = 47{\cdot}22\,W\,[\Delta T H^3]^{0.187} \tag{20}$$

Alternative formulations may be used to determine the heat and mass transfer. These formulae may be based on the area of the doorway and the vertical distance between the upper and lower floors (i.e. $L = 2{\cdot}55$ m). The Froude number, Fr, and Stanton number, St, which characterise the force and energy balances, respectively, may be defined as follows:

$$\mathrm{Fr} = F/\{A\,(g\,L)^{0.5}\} \tag{21}$$

$$\mathrm{St} = Q/\{\rho\,C_p T A\,(g\,L)^{0.5}\} \tag{22}$$

The Grashof and Reynolds numbers are given by:

$$\mathrm{Gr}_{AL} = \rho^2 g\,\beta \Delta T\,A\,L/\mu^2 \tag{23}$$

$$\mathrm{Re}_A = \rho\,F/(\mu\,A^{0.5}) \tag{24}$$

The dependencies of Fr on St, Re_A on Gr_{AL} and Gr_{AL} on St were found to conform to the following relationships:

$$\mathrm{Fr} = 0{\cdot}0282\,St^{0.159} \tag{25}$$

$$\mathrm{Re}_A = 91{\cdot}42\,\mathrm{Gr}_{AL}^{0.18} \tag{26}$$

$$\mathrm{Gr}_{AL} = 2{\cdot}02 \times 10^{14}\,St^{0.822} \tag{27}$$

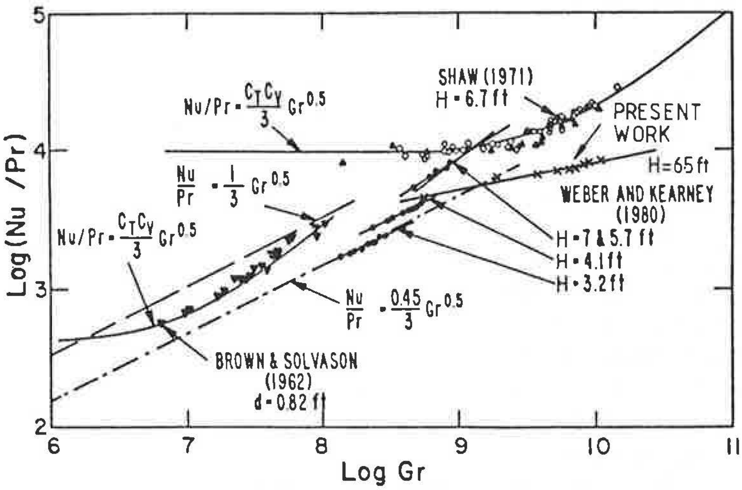

Figure 9. Comparison between convection flows in the house and flows in two-zone enclosures

CONCLUSIONS AND RECOMMENDATIONS

The experimental results indicate that the coefficient C is dependent on the temperature difference. Further experimental work is required to study the effects of geometry of the house and size of the doorway on the value of C.

The use of the SF_6 systems and thermocouples to measure temperatures at the centre of each room has proved to be a simple and practical approach for measuring heat and mass transfer between the two floors of the house.

The mass flow rate between the lower and upper floors was found to increase significantly with increasing temperature difference. The measurement of interzone air movement can be used to determine the extent of condensation which might occur in the bedrooms or in the roof space of the house as a result of the transfer of moisture from the kitchen and bathroom.

Although we have used a single tracer gas technique for estimating interzonal air flows, the accuracy of measurement could be improved by using multiple tracer gases techniques [15, 16].

Tests are also required to establish correlations for conventional houses and under a variety of boundary conditions. The study of interzone heat and mass transfer under combined natural and forced convection is limited and requires further investigation.

ACKNOWLEDGEMENTS

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NOMENCLATURE

C = Coefficient of discharge (dimensionless)
W = Width of the opening, m
H = Height of the opening, m
A = Area of the doorway, m^2
L = Vertical distance between upper and lower floors, m
g = Acceleration due to gravity, m/s^2
T_1 = Average air temperature in zone 1, °C or K
T_2 = Average air temperature in zone 2, °C or K
T = Mean absolute temperature of the two zones, °C or K
ΔT = Average temperature difference between the two zones, °C or K
F = The volumetric flow rate, m^3/s
M = Mass flow rate, kg/s
Q = Heat transfer rate, kW
h = Heat transfer coefficient, W/m^2 K
Nu = Nusselt number (dimensionless)
Pr = Prandtl number (dimensionless)
Gr = Grashof number (dimensionless)
Gr_{AL} = Grashof number based on A and L (dimensionless)
Re_{Dh} = Reynolds number based on the hydraulic diameter (dimensionless)
Re_A = Reynolds number based on A (dimensionless)
Fr = Froude number (dimensionless)
St = Stanton number (dimensionless)
Dh = Hydraulic diameter of the opening = $2WH/(W+H)$, m
V_1 = Interior volume of zone 1, m^3
V_2 = Interior volume of zone 2, m^3
C_1 = Concentrations of the tracer at time t in zone 1, arbitrary units
C_2 = Concentration of the tracer at time t in zone 2, arbitrary units

C_p = Specific heat of air, KJ/kg K
μ = Dynamic viscosity, kg/m s
k = Thermal conductivity, kW/m K
ρ = Average air density, kg/m^3
$\Delta\rho$ = Air density difference between the two zones
β = Coefficient of thermal expansion, K^{-1}

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