

# A Study of Heat and Mass Transfer through a Doorway in a Traditionally Built House

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## ABSTRACT

The work was concerned with measuring heat and mass transfer through a doorway between the lower and upper floors of a traditionally built house. Airflow rates between the two floors were measured using a tracer gas decay technique, and the temperatures at various points on each floor were measured using thermocouples. The lower floor of the house was heated to various temperatures in the range of 18° to 35°C using thermostatically controlled heaters. The upper floor was unheated. Two portable SF<sub>6</sub> systems fitted with electron capture detectors were employed for measurement of the interzonal airflow. The heat and mass flow rates between the two floors were calculated from the tracer gas concentrations and temperature differences. Results were compared with values predicted by existing algorithms for 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.

## 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 (Barakat 1987). 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 (Brown and Solvason 1962; Shaw and Whyte 1979; Weber et al. 1979). 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 (Balcomb and Yamaguchi 1983).

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 drafts and heat losses. As condensation in houses largely depends on air movement, it is important to monitor interzonal airflows 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 (1986), who studied heat and mass flow in a scale model of a stairwell. Although correlations from scale models are useful, measurements in houses are essential in order to determine the exact nature of air movement and also to 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-story house and to compute the heat and mass transfer across a doorway opening.

Experimental studies were carried out in a three-bedroom house in Milton Keynes, U.K. The interzonal mass and heat transfer were measured using sulphur hexafluoride (SF<sub>6</sub>) tracer gas and thermocouples. This paper also describes the SF<sub>6</sub> 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.

## 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

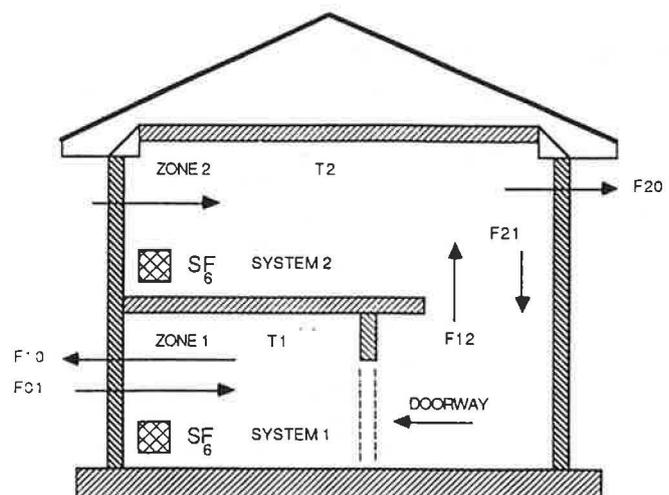


Figure 1 Interzone airflows in a house via a doorway

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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 airflow 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 and Whyte (1979) as follows:

$$F = (C_d W/3) (gH^3 \Delta\rho/\rho)^{0.5} \quad (1)$$

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

$$F = (C_d W/3) (gH^3 \Delta T/T)^{0.5} \quad (2)$$

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 Roger and Mayhew (1957).

$$Q = F_p C_p \Delta T = (C_d \rho W C_p/3) (gH^3 \Delta T/T)^{0.5} \quad (3)$$

$$h = Q/(WH\Delta T) \quad (4)$$

$$Nu = hH/k \quad (5)$$

$$Pr = C_p \mu/k \quad (6)$$

$$Gr = \rho^2 g \beta \Delta T H^3 / \mu^2 \quad (7)$$

Equations 3 through 7 can be substituted in Equation 2 to give:

$$Nu/Pr = (C_d/3) Gr^{0.5} \quad (8)$$

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 are given in Jones et al. (1985). 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

Airflow measurements were carried out using a single tracer gas technique (Harrje et al. 1985). Several tracer gases are available, but sulphur hexafluoride has been chosen for this work since it has desirable tracer gas characteristics in terms of detectability, safety, and cost and has been used successfully in previous air movement studies (Lagus and Persily 1985; Harrje et al. 1982).

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 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 change of tracer concentration in zone 1 at time  $t$  is given by:

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

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

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

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

$$F_{01} = F_{12} + F_{10} - F_{21} \quad (11)$$

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

Volumetric-balance equations may be solved using the theoretical technique described in Dick (1950). An alternative method to estimate airflows between internal spaces was used by Sinden (1978). 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 volumetric balance for each zone can be expressed by a series of equations which can then be 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 Littler et al. (1984).

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

## INSTRUMENTATION

### Airflow Measurements

The airflow measurements were carried out using two highly portable microcomputer systems (see Figure 2). The two systems are identical in construction and are described in detail by Riffat et al. (1987). 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 two-position, six-port valve connected to a  $0.5 \text{ cm}^3$  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  $\times$  4.3 mm internal diameter nylon tube with 60-80 mesh aluminum oxide. The column was held at  $35^\circ\text{C}$  in a thermostatically controlled electric oven. The electron capture detector uses a Ni-63 radioactive cell.

The system incorporates a microcomputer, a parallel printer, and interfaces for both analog and digital data. The interfacing of the gas chromatograph and the sampling

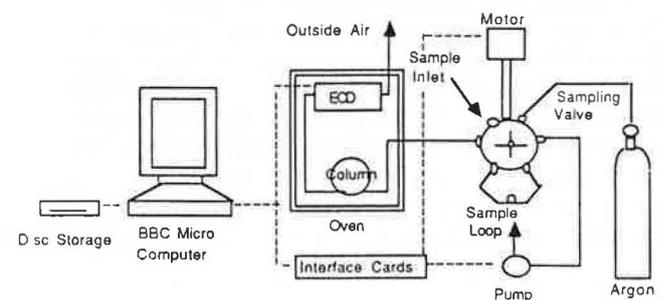


Figure 2 Portable  $SF_6$  system

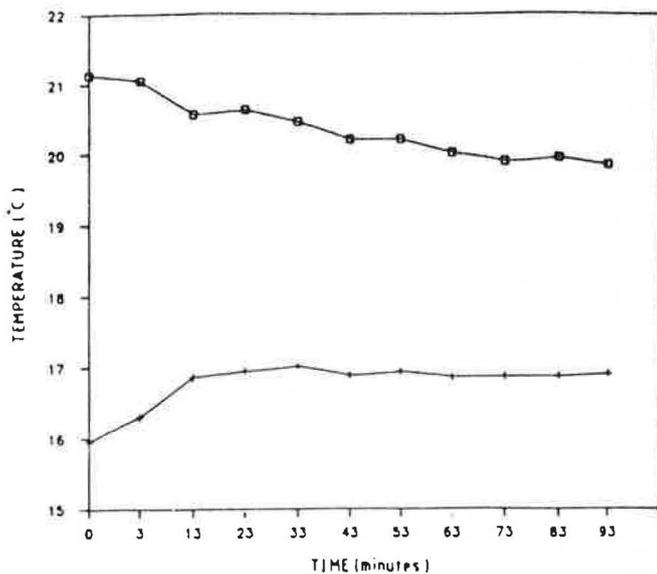


Figure 3 Air temperatures in zones 1 and 2 against time

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-constant thermocouples. The outside temperature and wind speed during the measurement period were also recorded. A data jogger 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 (1962) measured air temperatures as the average for vertical grids (floor to ceiling) located at a specific distance from the partition and the center of the opening. Shaw and Whyte (1979) 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 (Weber et al. 1979).

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 center of each room.

### MEASUREMENTS AND RESULTS

Measurements of interzone mass and heat transfer were carried out in a three-bedroom, semi-detached house. The downstairs floor, zone 1, had a volume of 65.5 m<sup>3</sup> and contained the living room, dining room, and the kitchen. The upstairs, zone 2, had a volume of 92 m<sup>3</sup> 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

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

temperatures in zone 1, four additional thermostatically controlled electric heaters were used.

To estimate the airflows between the two zones the two SF<sub>6</sub> 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<sub>6</sub> systems analyzed the samples in situ, thus providing instantaneous readings of gas concentration in each zone.

The airflows 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 affect the interzonal airflow, the induced flow was subtracted from the total airflow 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 other experiments only the lower floor was heated to temperatures in the range of 18° to 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 times during one experiment. The results indicate the temperature in zone 1 falls rapidly during the 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 stabilizes 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 ex-

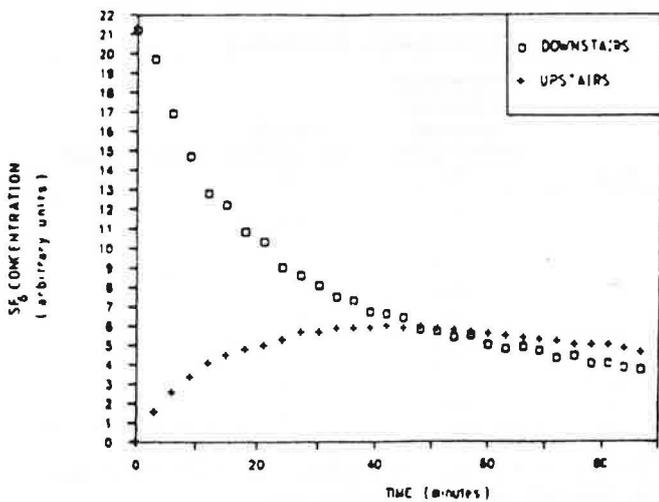


Figure 4 Decay of SF<sub>6</sub> tracer gas, ΔT = 1.6K

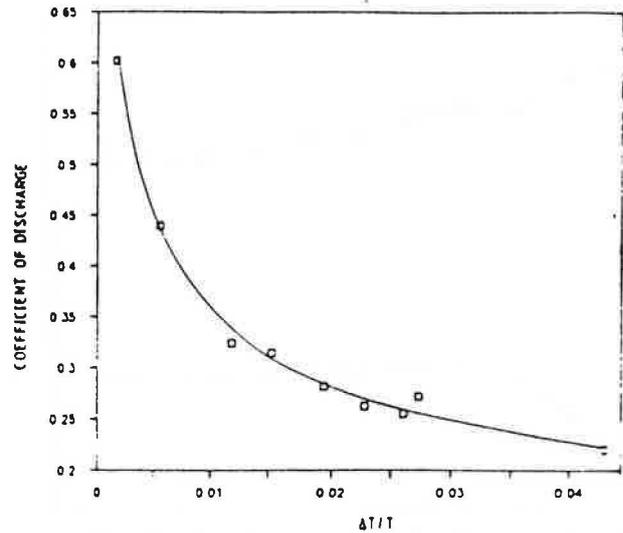


Figure 6 Variation of Cd with ΔT/T

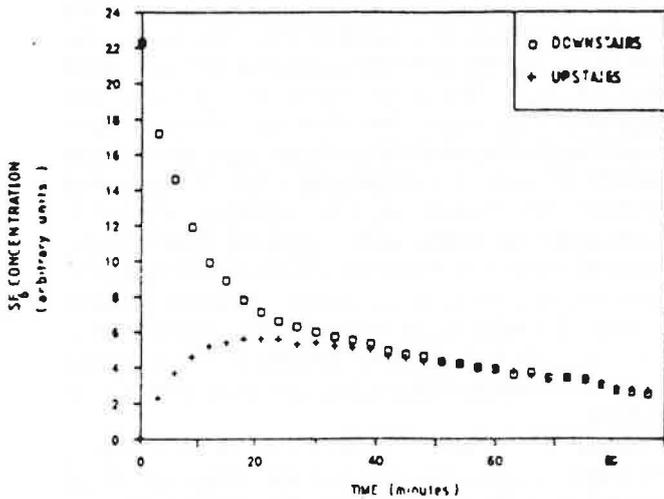


Figure 5 Decay of SF<sub>6</sub> tracer gas, ΔT = 13K

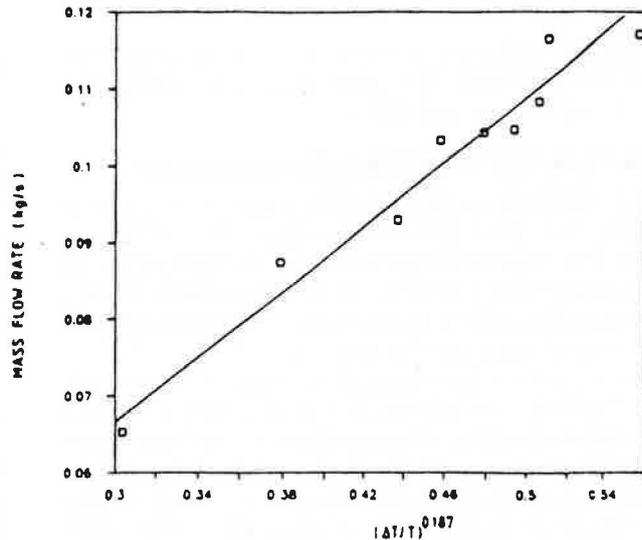


Figure 7 Mass flow rate against  $(\Delta T/T)^{0.187}$

change between the two zones was found to be 194 and 276 m<sup>3</sup>/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 airflow measured using the tracer gas technique was divided by the theoretical airflow described in Section 1 as follows:

$$C_d = \frac{\text{Measured air flow rate using tracer gas}}{(W/3) (gH^3 \Delta T/T)^{0.5}} \quad (13)$$

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

$$C_d = 0.0835 [\Delta T/T]^{-0.313} \quad (14)$$

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 of 4410 to 21,110. The values of Cd and Re<sub>Dh</sub> were correlated in the form:

$$C_d = 268 \text{Re}_{Dh}^{-0.639} \quad (15)$$

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

$$M = 0.0278 \rho W (gH^3)^{0.5} [\Delta T/T]^{0.187} \quad (16)$$

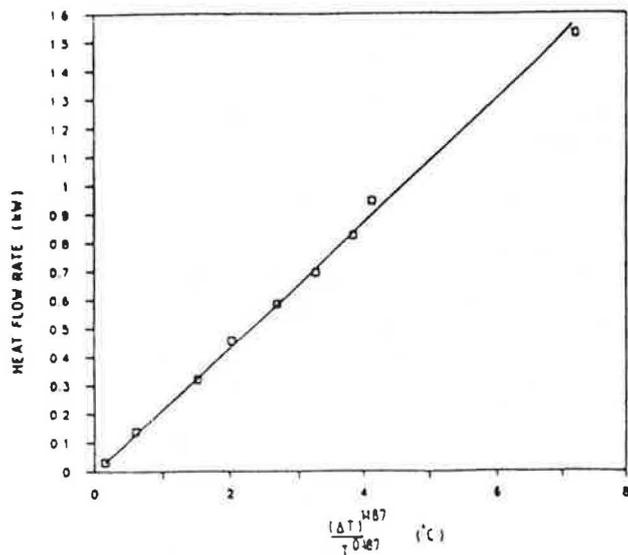


Figure 8 Heat flow rate against  $\Delta T^{0.187}/T^{0.187}$

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  $[\Delta T/T]^{0.187}$ .

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

$$Q = 0.0178 \rho C_p W (g H^3)^{0.5} (\Delta T^{1.187}/T^{0.187}) \quad (17)$$

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:

$$Nu/Pr = 130.83 Gr^{0.18} \quad (18)$$

or, in different form,

$$Nu/Pr = 0.0278 [\Delta T/T]^{-0.313} Gr^{0.5} \quad (19)$$

Figure 9 shows this correlation together with a number of previous correlations (Brown and Solvason 1962; Shaw and Whyte 1979; Weber et al. 1979) 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  $Pr$ ,  $\rho$ ,  $\mu$ , and  $k$  as follows:

$$h = 47.22 W [\Delta TH^3]^{0.187} \quad (20)$$

## CONCLUSIONS AND RECOMMENDATIONS

1. 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  $C$ .

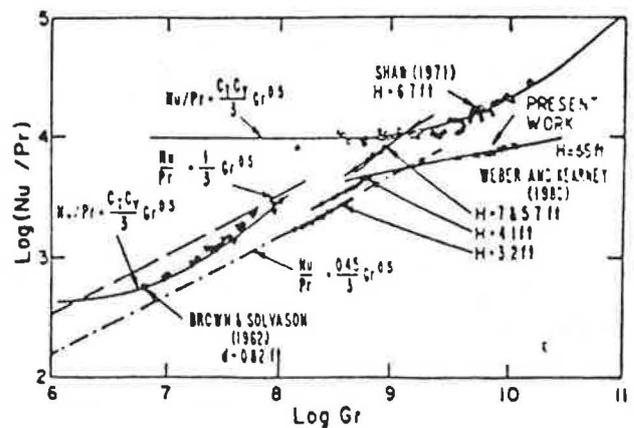


Figure 9 Comparison between convection flows in the house and flows in two-zone enclosures.

2. The use of the SF<sub>6</sub> systems and thermocouples to measure temperatures at the center 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.

3. 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 that 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.

4. Although we have used a single tracer gas technique for estimating interzonal airflows, the accuracy of measurement could be improved by using multiple tracer gases techniques (Riffat et al. 1987; Dietz and Crote 1982).

5. 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.

## NOMENCLATURE

$C_d$	= coefficient of discharge (dimensionless)
$W$	= width of the opening, m
$H$	= height of the opening, m
$g$	= acceleration due to gravity, m/s <sup>2</sup>
$T_1$	= 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
$\Delta T$	= average temperature difference between the two zones, °C or K
$F$	= volumetric flow rate, m <sup>3</sup> /s
$M$	= mass flow rate, kg/s
$Q$	= heat transfer rate, kW
$h$	= heat transfer coefficient, W/m <sup>2</sup> K
$Nu$	= Nusselt number (dimensionless)
$Pr$	= Prandtl number (dimensionless)
$Gr$	= Grashof number (dimensionless)
$Re_{Dh}$	= Reynolds number based on the hydraulic diameter (dimensionless)
$Dh$	= hydraulic diameter of the opening = $WH/2(W+H)$ , m
$V_1$	= interior volume of zone 1, m <sup>3</sup>

$V_2$	= interior volume of zone 2, $m^3$
$C_1$	= concentration 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, $kJ/kg\ K$
$\mu$	= dynamic viscosity, $kg/m\ s$
$k$	= thermal conductivity, $kW/m\ K$
$\rho$	= average air density, $kg/m^3$
$\Delta\rho$	= air density difference between the two zones
$\beta$	= coefficient of thermal expansion, $K^{-1}$

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