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An Experimental and Theoretical Investigation of Airflow Through Large Horizontal Openings

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Synopsis

The work was concerned with measuring natural convection through a large horizontal opening of different sizes and shapes located between two rooms in a building. Airflow rates between the two rooms were measured using a tracer-gas decay technique. Room 1 was heated to various temperatures in the range 18°C to 33°C using thermostatically-controlled heaters; room 2 was unheated. A multi-point sampling unit was used to collect tracer-gas samples from each room. The concentration of SF_6 tracer was measured using an infra-red gas analyser. The heat and mass flow rates between the two rooms were calculated from the tracer-gas concentrations and temperature differences. The coefficient of discharge of the opening was found to be a function of the temperature difference between the two rooms. The mass flow rate was increased by increasing the area of the opening. The mass flow rate of a circular opening was in most cases higher than that of a square opening.

The work also describes CFD modelling of natural convection through horizontal openings. Results were compared with values obtained from experiment.

List of symbols

A	= Cross-sectional area of the opening, (m^2)
A_i	= The area perpendicular to U_i of individual cells within the opening, (m^2)
C_1	= Concentration of the tracer at time t in room 1, (ppm)
C_2	= Concentration of the tracer at time t in room 2, (ppm)
C_p	= Specific heat of air, (J/kgK)
F	= Volumetric flow rate, (m^3/s)
g	= Acceleration due to gravity, (m/s^2)
H	= Thickness of the partition containing the opening, (m)
M	= Mass flow rate, (kg/s)
M_C	= Mass flow rate of circular opening, (kg/s)
M_S	= Mass flow rate of square opening, (kg/s)
q	= Heat transfer rate, (W)
T	= Mean absolute temperature of the two rooms, (°C or K)
T_1	= Average air temperature in room 1, (°C or K)
T_2	= Average air temperature in room 2, (°C or K)
ΔT	= Average temperature difference between the two rooms, (°C or K)
U_i	= The vertical component of air velocity at individual grid points within the opening, (m/s)
V_1	= Interior volume of room 1, (m^3)
V_2	= Interior volume of room 2, (m^3)
ρ	= Average air density, (kg/m^3)
K	= Coefficient of discharge
n	= The number of grid points (or cells) within the span of the horizontal opening

1. Introduction

In recent years use of natural ventilation has become more widespread in order to minimise air conditioning and resulting emissions of greenhouse gases. Building services designers and architects require design tools for accurate prediction of air movement in buildings. Several advanced computer models such as ESP , BREEZE and COMIS have been developed for prediction of ventilation and interzone air movement in buildings. However, these models lack suitable algorithms for estimation of airflow through large horizontal openings, such as ventilation shafts and stairwells. Airflow through this type of opening has serious implications on energy saving, moisture and pollutant transfer, thermal comfort and control of fire and smoke.

A review of airflow through large openings carried out by Riffat (1) showed that little work has been published on interzonal convection through large horizontal openings. Brown and Solvason (2) have investigated airflow through small square openings in horizontal partitions. Riffat (3) has studied buoyancy-driven flow through a staircase in a house and Reynolds et. al (4) have developed a model for buoyancy driven flow in a stairwell. Advancements in tracer-gas technology allow scope for conducting extensive measurements to investigate airflow through openings. The results could be used to develop accurate algorithms for inclusion in existing mathematical models. The present paper provides the foundations for development of such algorithms.

2. Theory

2.1. Interzone airflows

Airflows in a two-zone system are shown in Fig. 1a. Air can infiltrate from outside the building into each room (F_{01} and F_{02}) and exfiltrate from each room to the outside (F_{10} and F_{20}). In addition, air can exchange between the rooms through a large horizontal opening (communication opening) in both directions (F_{12} and F_{21}). If one applies the tracer-gas material balances in each room, assuming that a steady state exists, the rate of change of tracer concentration in room 1 at time t is given by:

$$V_1 \frac{dC_1}{dt} = C_2 F_{21} - C_1 (F_{10} + F_{12}) \qquad (1)$$

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

$$V_2 \frac{dC_2}{dt} = C_1 F_{12} - C_2 (F_{21} + F_{20}) \qquad (2)$$

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

$$F_{01} + F_{21} = F_{10} + F_{12} \qquad (3)$$

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

The volumetric-balance equations can be solved using the theoretical technique based on the Sinden method (5). The method assumes that a multizone system may be represented by a series of cells of known and constant volume which are all connected to a cell of infinitely large volume, i.e., the outside space. The volumetric balance for each room can be expressed by a series of equations which can then be solved using matrices.

2.2 Interzone heat and mass transfer

Applying Bernoulli's equation, the mass flow rate through the opening is:

$$M = \rho\, A\, K \sqrt{\frac{\Delta T\, gH}{T}} \quad (5)$$

The heat transfer flow between zone 1 and zone 2 through the opening is:

$$q = \rho\, A\, K\, C_p \sqrt{\frac{(\Delta T)^3\, gH}{T}} \quad (6)$$

3. Material and method

Experiments were carried out using two rooms as shown in Fig. 1b. Room 1 is located downstairs and has dimensions 3.6m × 6m × 3.2m, (volume = 69m^3). Room 2 is located upstairs and has dimensions 3.6m × 11.7m × 3.2m, (volume = 135m^3). The two rooms are connected via a horizontal opening.

The dimensions of the opening were varied between 0.288 and 0.48 m^2 while the thickness was kept at 0.3m.

Room 1 was heated to various temperatures using thermostatically-controlled heaters. Room 2 was unheated. The temperature was measured at three different heights in each room using grids situated at the centre of the opening.

Airflow measurements were carried out using a single tracer-gas technique . Several tracer gases are available, but sulphur hexafluoride was chosen for this work since it has desirable characteristics in terms of detectability, safety, and cost and it has been used successfully in previous air movement studies. To estimate the airflow between the two rooms, two multi-point sampling systems were used. The first system was used to collect tracer-gas samples from room 1, while the second was used to collect samples from room 2. At the beginning of each test the communication door between the two rooms was closed and gaps between the door and its frame were sealed. This prevented heat and tracer-gas leakage prior to starting the test. The tracer-gas was released in room 1, where it was mixed with air using an oscillating fan. To ensure that a uniform concentration had been achieved in room 1, samples were taken at ten sampling points in each room. After a mixing period of about 15 minutes, the communication door was opened. Samples were taken every 60 seconds for a total duration of 60 minutes. The concentration of SF_6 was measured using a BINOS 1000 analyser made by Rosemount Ltd, U.K. The temperature at various locations in each room was measured using thermocouples. The wind speed and direction were recorded during the test.

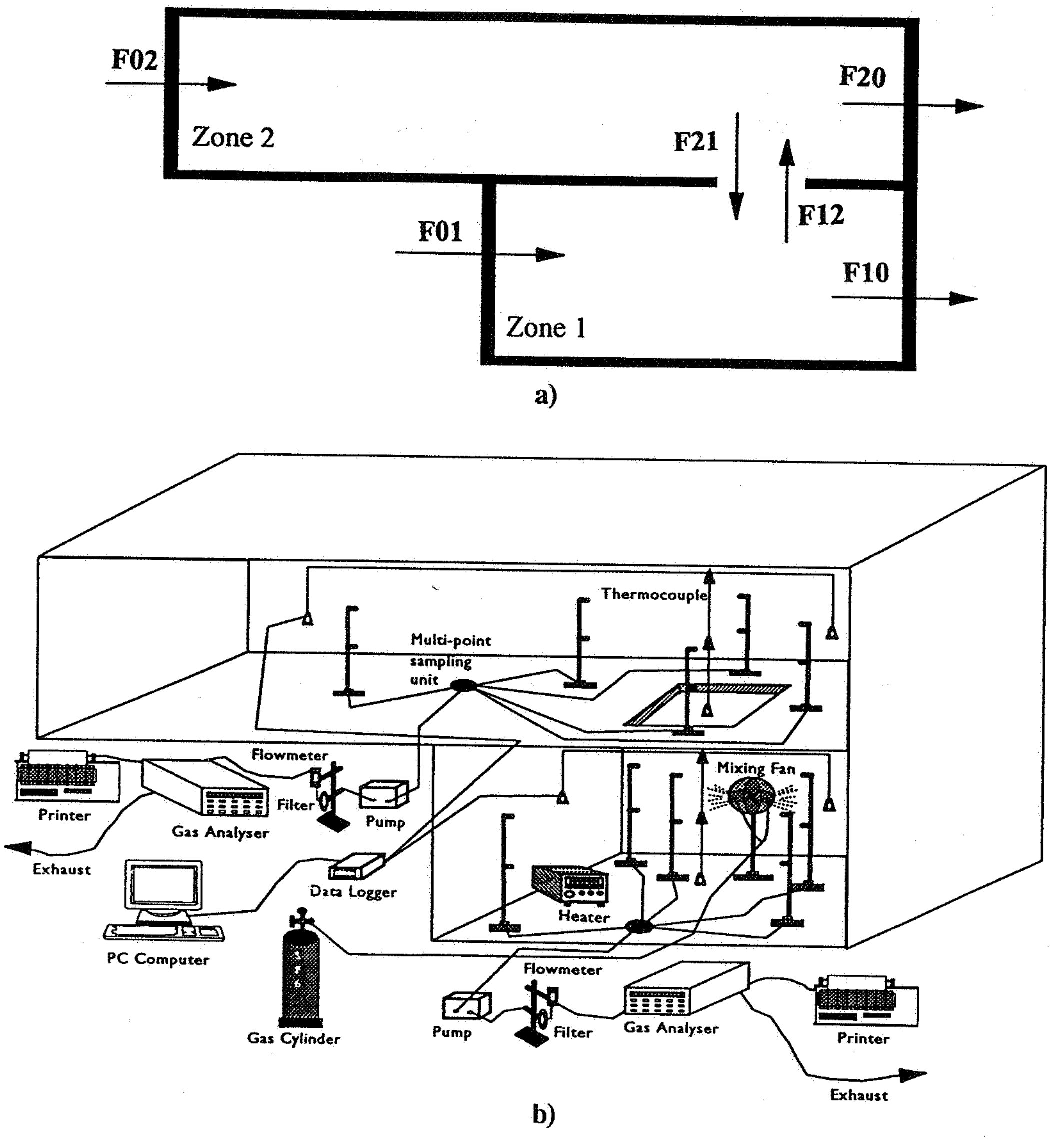

Fig. 1. Schematic of the rooms and instrumentation.

4. Results and discussion

The airflows between the two rooms were estimated from the tracer-gas concentration data using the method described in section 2.1. Several experiments were carried out for various temperature differences and opening sizes and square and circular cross-sections; only room 1 was heated to temperatures in the range 18°C to 33°C. Following this, the communication door was opened and temperature and tracer-gas concentration were monitored. The temperature in room 1 fell rapidly during the first 10 minutes and then decreased at a much slower rate. The temperature in room 2 increased during the first 10 minutes and then gradually stabilized at an almost constant value.

Fig. 2 shows an example of tracer-gas concentration against time for a temperature of 7.3 °C. To evaluate the coefficient of discharge, K for the horizontal opening, the airflow measured using the tracer-gas technique was divided by the theoretical airflow given by equation 5 (see section 2.2).

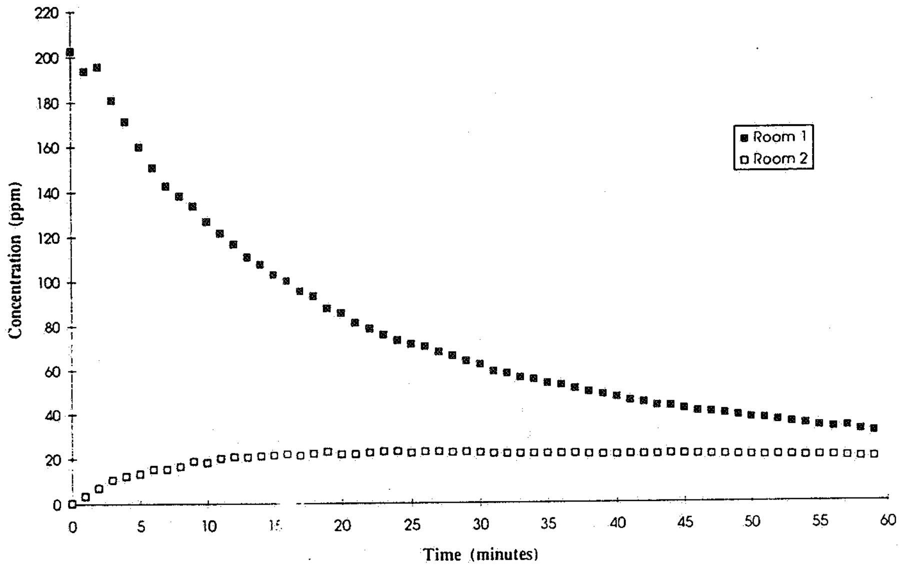

Fig. 2. Time dependency of tracer-gas concentration in rooms 1 and 2, $\Delta T = 7.3$ °C, K = 0.46 square opening.

Fig. 3 shows the variation of M with $(\Delta T)^{0.5}$ for square and circular cross-section openings, respectively. The mass flow rate between the two rooms can be given in the form of a straight line (linear function of $(\Delta T)^{0.5}$) for each set of openings . The heat flow rate between the two rooms can be given in the form of a quadratic function of (ΔT) for each set of openings. (see table 1). The mass flow rate through the circular openings was generally higher than that through square openings.

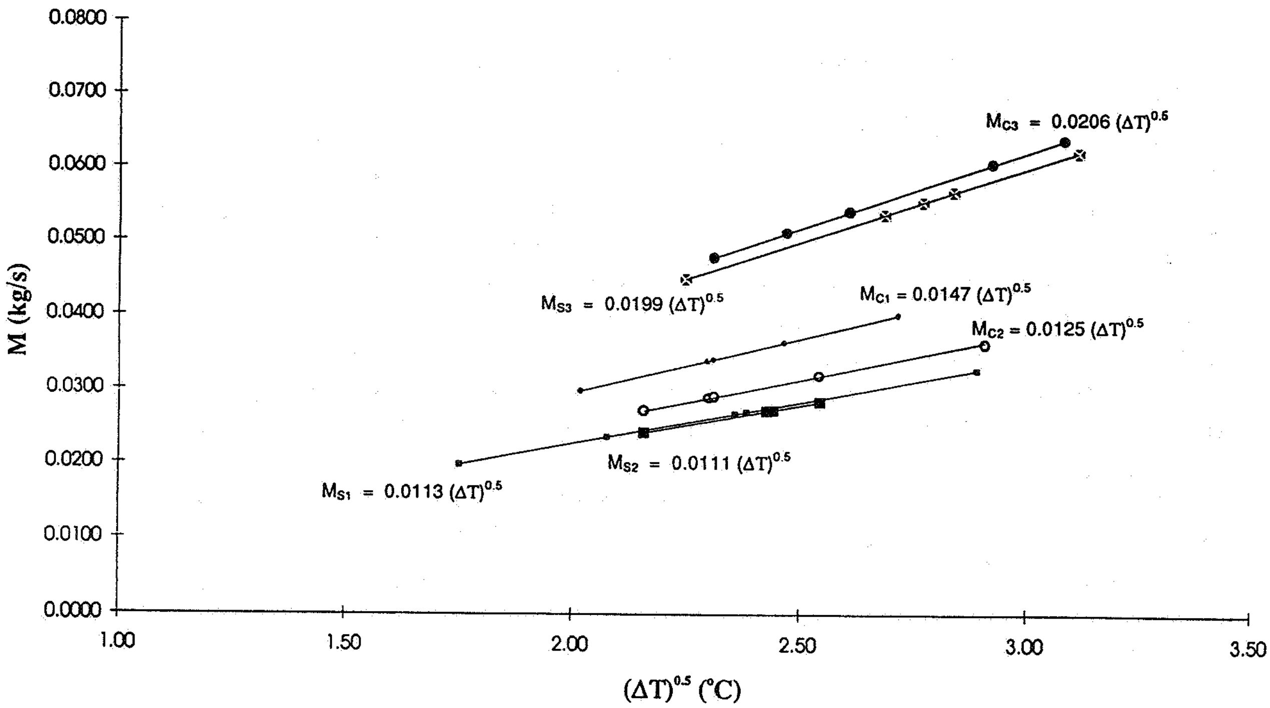

Fig. 3. Variation of mass flow rate with $(\Delta T)^{0.5}$ for two set of openings.

Table 1 shows the values of coefficient of discharge together with correlations for mass and heat flow rates. The coefficient of the discharge was found to be in the range 0.29 to 0.43 for circle openings and 0.26 to 0.35 for square openings depending on the temperature difference between the two zones.

OPENINGS		AREA (m^2)	K (Av.)	M (kg/s)	q (kW)
CIRCLE	C 1	0.28	0.43	$0.0147\ (\Delta T)^{0.5}$	$0.0147\ C_p\ (\Delta T)^{1.5}$
	C 2	0.36	0.29	$0.0125\ (\Delta T)^{0.5}$	$0.0125\ C_p\ (\Delta T)^{1.5}$
	C 3	0.48	0.36	$0.0206\ (\Delta T)^{0.5}$	$0.0206\ C_p\ (\Delta T)^{1.5}$
SQUARE	S 1	0.28	0.33	$0.0113\ (\Delta T)^{0.5}$	$0.0113\ C_p\ (\Delta T)^{1.5}$
	S 2	0.36	0.26	$0.0111\ (\Delta T)^{0.5}$	$0.0111\ C_p\ (\Delta T)^{1.5}$
	S 3	0.48	0.35	$0.0199\ (\Delta T)^{0.5}$	$0.0199\ C_p\ (\Delta T)^{1.5}$

Table 1. Correlations for mass and heat transfer rate for circular and square cross-section openings.

5. CFD Simulation

The CFD code FLUENT was used to simulate the buoyancy driven flow through horizontal openings by solving the Navier-Stokes equations. To predict the transient mass and energy transfer between building zones, the time dependent versions of the above equations were used. Because the information regarding the boundary condition of the test building was (e.g., wall temperature distribution/history, background leakage, wind environment) incomplete, it was not possible to simulate the test building. Instead two zones of simpler geometry were chosen for numerical simplicity (Fig.4). The two zones, both two-dimensional with a width of 3m and height of 2m, are connected via a horizontal opening in the partition (10cm in thickness). All the solid boundaries, i.e., walls, ceilings and floors were assumed to have a constant temperature of 10°C except the floor of the lower zone which was assigned the temperature of 27°C. A small opening was built into one of the side walls of the upper zone and the building was otherwise air tight. The Reynolds number was in the low region of 10^3-10^4 and to avoid over-prediction of heat and mass transfer, the turbulence models were not utilised. The computations were time dependent to deal with the temperature decay and the constantly varying flow field. Small time steps of around 1/10th of the characteristic time scale were used and at the end of each time step, the normalised residuals for the equations were around 10^{-6}. At the beginning of the tests, which last 800 seconds, the upper zone was a uniform air temperature of 10°C and the lower zone 27°C and the air in both zones was stationery. As the test proceedes, the mass and energy transfer between the two zones caused variations in air temperature and velocities which were recorded and subsequently analysed to obtain the temperature histories and air exchange rates between the two rooms.

Previous research has show that the buoyancy driven flow through horizontal openings is highly transient and occurs in intermittent pulses. Good agreement between CFD predicted flow rate and that based on experimental measurement has been obtained with a relative difference of 10.5% (6). In this study, the effect of the size of the horizontal opening on interzonal flow rate is examined, by computing there cases of buoyancy driven flow between two zones. The zones and boundary/initial conditions for the three cases are identical except the size of the horizontal opening which is assumed to be 1.0, 0.8 and 0.6 m wide.

Fig. 4 shows a typical flow pattern obtained from the CFD simulation. The arrows indicate the flow directions and flow velocities by using stems with lengths proportional to the local air speed. The flow pattern is dominated by vortices. A major vortex can be identified in the lower zone accompanied by three smaller, weaker ones. These eddies promote heat transfer and uniformity of temperature within the zone. The situation in the upper zone is similar, with two large eddies containing weaker, smaller eddies which prevent the thermal isolation of the central regions of the former. The air exchange between the two zones taking place at the horizontal opening is clearly shown by the velocity arrows in that region. Warmer air from the lower zone flows through the right half of the opening into the upper zone causing the temperature there to rise while cooler air moving downwards causes the temperature in the lower zone to fall. The vigorous vortical movement induced by this air exchange keeps the temperature distribution virtually uniform in individual zones throughout the test duration of 800 s. The value of the air exchange rate is obtained using

$$M = \rho \sum_{i=1}^{n} |U_i| \, A_i \, /2 \qquad (7)$$

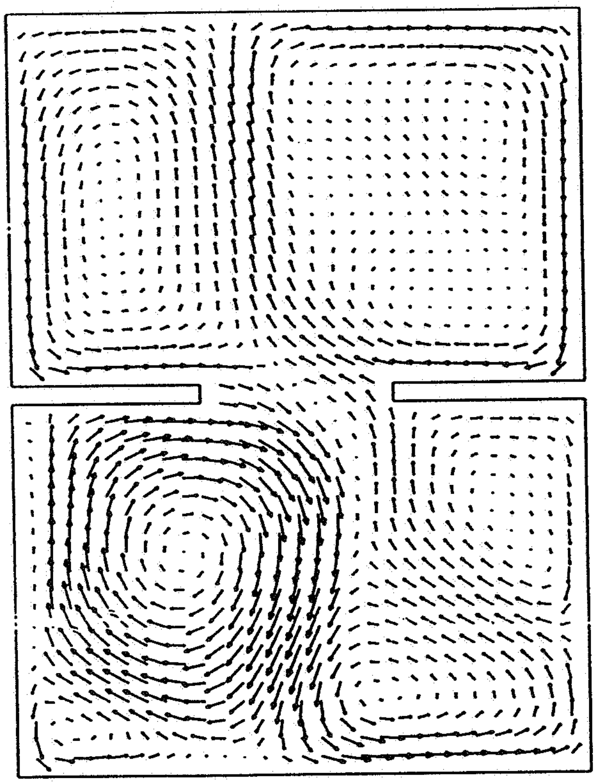

Fig. 4. CFD Simulation of flow pattern within two zones linked by a horizontal opening.

Fig. 5 shows the histories of air exchange rate of the three cases. Fig. 5(a) corresponds to the case with a horizontal opening of 0.6m wide and Fig. 5(b) and 5(c) correspond to openings of 0.8 and 1.0 m respectively. As can be seen, for all three cases the air exchange occurred in pulses, reaffirming the conclusions of previous research (6). On the other hand, the patterns and distribution of pulses for the three cases are quite different, which points to the random nature of buoyancy driven flow through horizontal openings. The average exchange rate over the 800-s duration are 0.010808 m^3/s, 0.011337m^3/s and 0.014897m^3/s for opening widths of 0.6m, 0.8m and 1.0m, respectively. This result agrees well with the analytical prediction of the effect of opening size on exchange rate, as shown by equation (5). The CFD prediction is not exactly linear as indicated by equation (5). This is probably due to the short averaging period and the random nature of the pulse flow through the openings.

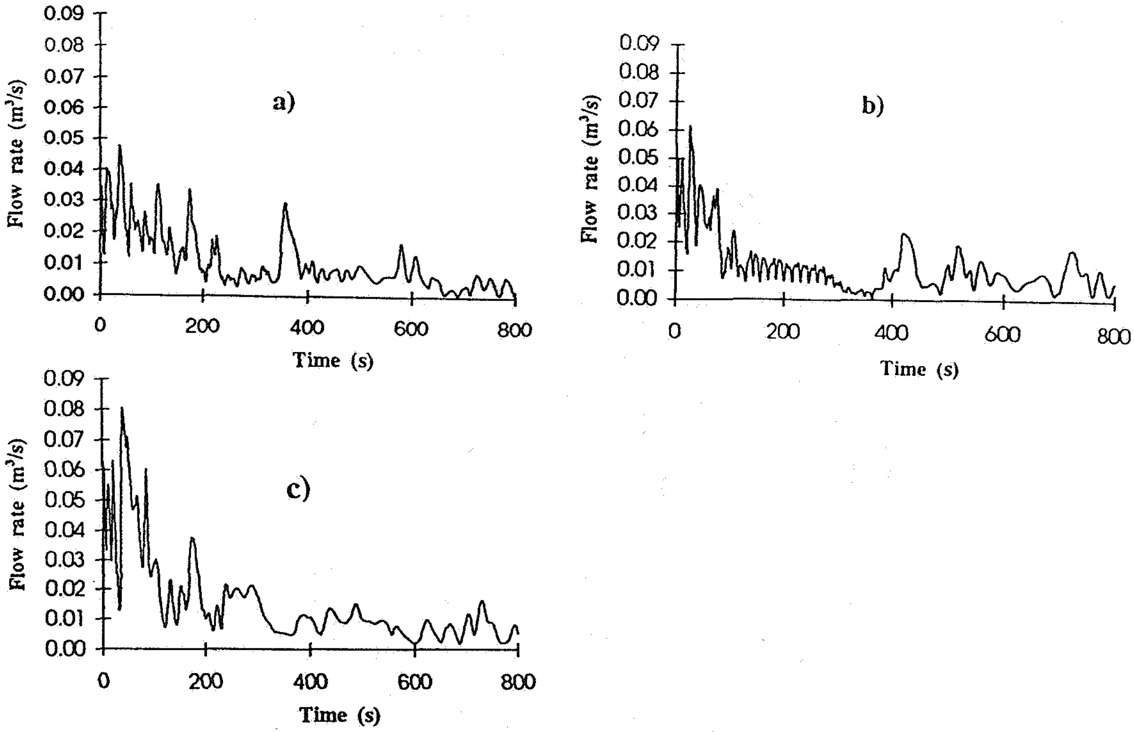

Fig. 5. Histories of air exchange through horizontal openings.

6. Conclusions

i) The experimental study shows that the average values of K is in the range 0.29 - 0.43 for circular openings and 0.26 - 0.35 for square openings depending on the interzonal temperature difference and size and shape of the opening.

ii) The heat and mass transfer through the opening was found to increase significantly with increasing temperature difference.

iii) Further work is required to examine the effect of the thickness of the opening on coefficient of discharge.

(iv) CFD simulation of buoyancy driven flow through horizontal openings has been carried out using the commercial software FLUENT. The transient velocity field was predicted using a time-dependent method. The CFD predictions agree with analytical findings that the exchange rate through the horizontal opening increases with the size of the latter. Furthermore, the results obtained reaffirm the finding of previous research that the buoyancy-driven flow occurs in random pulses through the horizontal opening.

References

1. RIFFAT, S. B. "Algorithms for Airflows Through Large Internal and External Openings"
   Applied Energy, 40, 1991, pp171-188

2. BROWN, W.G.and SOLVASON, K.R. "Natural Convection Through Rectangular Openings in Partitions, Part 2: Horizontal Partitions"
Int. J. Heat and Mass Transfer, 5, 1962, pp869-78

3. RIFFAT, S. B. "Measurement of Heat and Mass Transfer Between the Lower and Upper Floors of a House"
International Journal of Energy Research, 13, 1989, pp231-241

4. REYNOLDS, A.R., MOKHTARZADEH, M.R. and ZOHRABIAN, A.,S. " The Modelling of Stairwell Flows"
Building and Environment, 23(2), 1988, pp63-66

5. SINDEN, F.W. " Multi-Chamber Theory of Air Infiltration"
Building and Environment, 23(2), 1978, pp21-8

6. RIFFAT, S. B., KOHAL, J. S. and SHAO, L. "Measurement and CFD Modelling of Buoyancy Driven Flows in Horizontal Openings"
ASHREA IAQ'94, St. Louis, Missouri, USA, 1994.