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**Title :** MEASUREMENT OF HEAT AND MASS TRANSFER THROUGH TYPICAL STAIRCASES

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# MEASUREMENT OF HEAT AND MASS TRANSFER THROUGH TYPICAL STAIRCASES

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**Synopsis**

This paper is concerned with heat and mass transfer through two typical staircases. The first staircase connects the two individual floors of a two-storey building, and the other connects the three individual floors of a three-storey building. A series of experiments have been performed in order to study the buoyancy driven flow between the floors. A single tracer gas decay technique was adopted . Temperatures at various points on each floor were constantly monitored and air velocity measurements were also provided at some specific locations. The heat and mass flow rates between the two floors , through the first staircase, were calculated from the tracer gas concentrations. The analysis of experimental data gives relations for the mass and heat flow rate as a function of temperature difference between the floors, and of the geometry of the particular staircase. Simulations of the same configurations have been carried out, using validated CFD algorithms. Airflow rates estimated by these simulations showed very good agreement with experimental values. The mass flow rates through the second staircase, are estimated using the CFD method. In addition, the paper discusses the airflow patterns in the staircases.

## 1. Introduction

The study of energy and mass transfer between different zones in buildings has attracted increasing international interest and research effort. Airflow through vertical openings has been widely researched. However, little information is available regarding airflow in horizontal openings, such as staircases, especially that driven by buoyancy. Mass and energy transfer through staircases can have important implications regarding energy saving, thermal comfort, control of contaminants and spread of smoke in the interior of buildings.

A number of studies related to these phenomena, have been reported. Brown (1962) has investigated air flow through small square openings in horizontal partitions. Reynolds (1986) and Zohrabian et al (1989) have performed experiments in a scale model of a typical stairwell. Reynolds et al (1988), have also developed a model for buoyancy-driven flow in a stairwell. Riffat (1989) have studied the energy and mass transfer through a staircase in a two-floor house. Other experiments were conducted by Klobut and Siren (1994), to explore the influence of several parameters on combined forced and density-driven air flows through large openings in a horizontal partition. The above studies have been mainly of experimental or analytical nature. Studies based on the application of CFD are those of Zohrabian et al

(1989) and Riffat et al (1994), who used CFD modeling and compared predictions with experimental data. The objectives of this work are to study the buoyancy-driven air movement through two typical staircases of full-scale buildings , to compute the heat and mass transfer between floors, to compare the CFD predictions and measurements and consequently to improve the existing predictive methods of such processes.

## 2. Description of Experiments

A series of experiments were carried out in a two-storey building and in a three-storey building, in order to investigate the buoyancy-driven airflow through staircases that connect the floors of these buildings.The first staircase extends to a height of 6.3 m, while the lower and upper floor have an effective volume of 29.1 $m^3$ and 35.8 $m^3$ respectively. The second stairwell extends to a height of 13.0 m. The lower, central and upper floor have an effective volume of 41.5 $m^3$ , 24 $m^3$ and 40.0 $m^3$ respectively. Since the geometry is rather complex, figures can describe the buildings in a more effective way. Figure 1 shows schematic diagrams of these buildings with the main dimensions and the locations of the instruments.

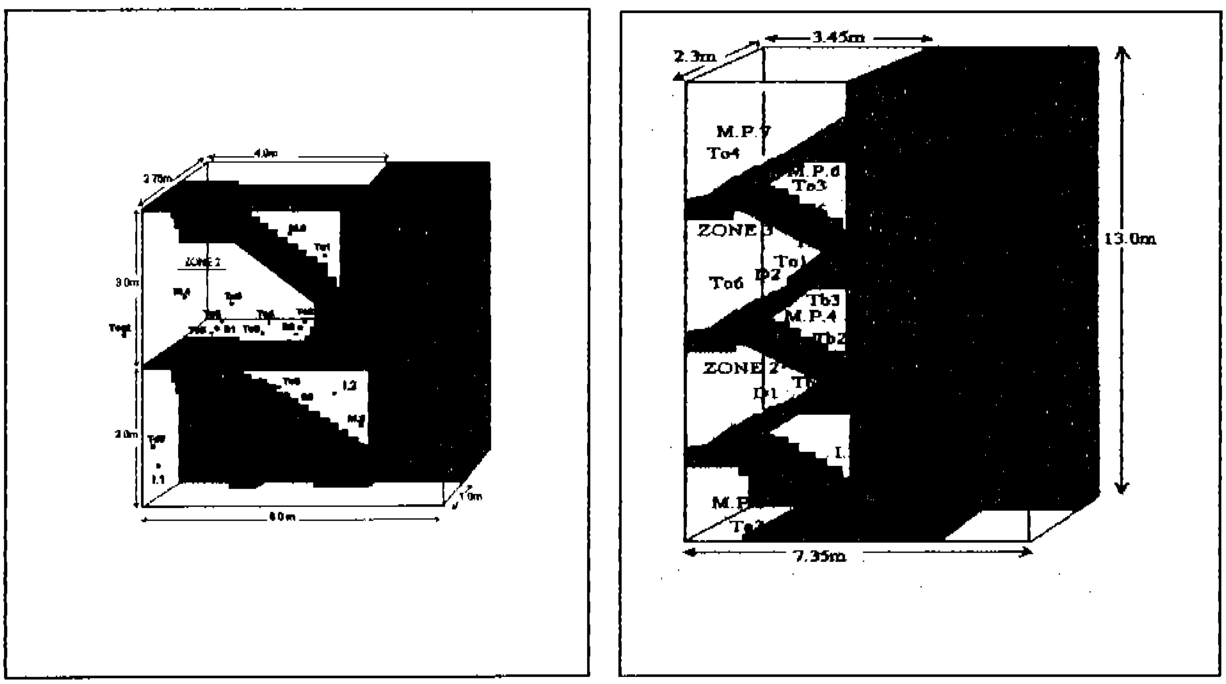


Figure 1: Schematic diagrams of the two staircases and instrumentation.
(T : temperature sensor,D : air velocity sensor,
M:measuring point and I : injection point).

All the openings, such as the main door, the doors connecting the staircases with the appartments and the windows were kept closed and sealed during all the experiments. Some small openings and cracks were also sealed in order to reduce the infiltration as much as possible. The mass and heat flow rates between the floors are mainly determined by the size and geometry of the openings connecting the floors. These horizontal openings are defined by the staircases geometries. The opening of the first staircase has dimensions of 1.5 m by 2.7 m while the two openings connecting the three floors of the second staircase have dimensions of 2.15 m by 2.30 m (Fig.1).Furthermore, an additional obstacle was placed suitably across the opening of the first staircase, decreasing its size. This modified opening had dimensions of 1.5m by 2.15 m.Under this configuration, additional experiments were carried out in order to study the effect of size of the opening on the values of the rates mentioned above. The experiments characterized by the original configuration, will be referred as runs with opening A, while the others will be referred as runs with opening B. The mass and heat flow rates between the floors are also affected by the temperature differences of these floors. The temperature differences between the floors were defined as the differences of the average storey temperatures. In order to investigate this dependence, the lower zone was heated while the other floors were unheated. This was done by using thermostatically controlled heaters. The airflow rates between the floors were measured using a single tracer gas decay technique. Several tracer gases are available , but $N_2O$ 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. The concentration of gas was measured using an infrared gas analyzer (accuracy:± 1%). At the beginning of each experiment the opening between the two floors at the first building and similarly the opening between the lower and the central floor at the second experimental building, were closed by PVC sheets and every gap between these sheets and the adjacent surfaces was sealed. Tracer gas was released in the lower floor (zone 1), where it was mixed with air. This was accelerated by using small fans near the injection points of gas. After uniformity had been achieved in zone 1, the PVC sheets were removed and the evolution of tracer gas concentration in all zones, was monitored.

Applying the tracer material balances in the two zones of the first experimental building , the rate of change of tracer concentration in zone 1 and in zone 2 at time t are given respectively by :

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

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

where $V_1$ and $V_2$ are the effective volumes of each zone, $Q_{10}$ and $Q_{20}$ are the volumetric flow rates of air that exfiltrate from each zone to the outside,$Q_{01}$ and $Q_{02}$ are the volumetric flow rates of air that infiltrate from outside into each zone and $Q_{12}$ and $Q_{21}$ are the volumetric flow rates of air that exchanges between the two zones through the stairwell in both directions. $C_1$ is the concentration of the tracer at time t in zone 1 and similarly $C_2$ is the concentration of the tracer at time t in zone 2. The other two flow volumetric rates can be determined using the continuity equations:

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

$$Q_{02} = Q_{20} + Q_{21} - Q_{12} \qquad (4)$$

These equations are valid, provided that a steady state exists and that the concentration of tracer gas in the outside air is negligible. These volumetric-balance equations can be solved using the theoretical technique based on the Sinden (1978) method. A similar method was adopted by Afonso and Maldonado (1986). According to this method, a multizone system may be represented by a series of cells of known and constant volume that are all connected to a cell of infinitely large volume (outside). Since the unknown flow rates involved in these equations are six, it was suggested by Sinden that equations (1) and (2) could be integrated from two different intervals from the concentration decay curves for each zone. This technique would yield the necessary number of equations to solve for all the unknowns. Equations were integrated using Simpson's rule and the final system of simultaneous equations was solved numerically by Gauss elimination. This method was employed only for the first staircase, since it's implementation results to significant errors when it is applied in buildings with more than two zones. In these situations multiple tracer-gas procedures are recommended (Roulet and Vandaele (1991) ). For this reason , the airflow rates through the second staircase, are estimated using the CFD method.

The air temperature was constantly monitored by thirteen thermocouples (accuracy: ± 0.2 ° C) which had already been calibrated (Fig. 1). Surface temperatures on almost all the internal surfaces, were measured by an infrared thermometer (accuracy: ± 0.1%). Limited air velocity measurements were also provided by three air velocity sensors (accuracy:± 0.01 m/sec ± 5%) (Fig. 1).

## 3. Measurements and Results

Eleven experiments were performed in the two-storey building and five in the three-storey building described above, under various temperature differences between the floors. The lower floor was heated for a long time before the beginning of monitoring so as to reach thermal equilibrium. The measurements verified the initial assumption that every floor can be considered as a different zone at least for flows driven by buoyancy as those investigated here. Figure 2 shows the tracer gas concentration level in zones 1 and 2 against time during the second run as it was monitored in the first building and similarly, Figure 3 shows the tracer gas concentration level in zones 1, 2 and 3 against time during the first experiment in the three-storey building.

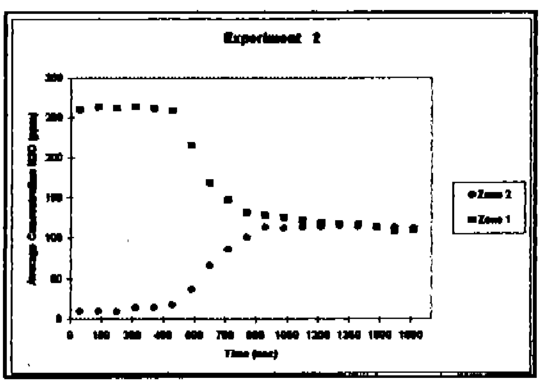

Figure 2: Variation of concentration of $N_2O$ with time (First Building)

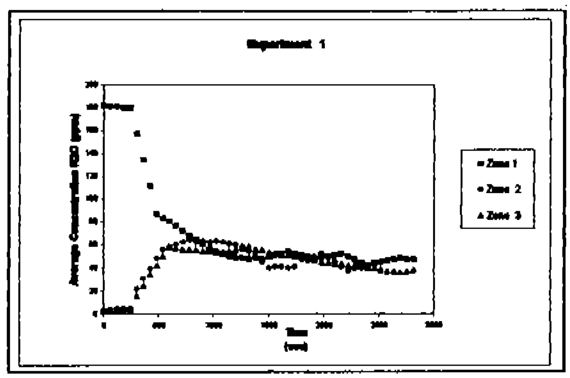

Figure 3: Variation of concentration of $N_2O$ with time (Second Building)

The average temperature difference between the zones for the duration of each run, the ambient temperature and the wind speed for all the experiments carried out in the first building and in the second one are given in Table I and II respectively.

The airflow volumetric rates between the two zones of the first building, were estimated from these tracer gas concentration data using the method described above. Since infiltration and exfiltration of air, due to the temperature difference between the inside and outside of the building and the wind speed can affect the interzonal airflow, the induced flow was subtracted from the total airflow between the two floors. The results verified that the airflow rate between the two zones is a function of the temperature difference between the zones and of the size of the opening.

Table I
Experimental Conditions (First Building)

| *Run* | *Average Temperature Difference between zones 1 and 2 (° C)* | *Ambient Temperature (° C)* | *Wind Speed (m/sec)* |
|---|---|---|---|
| 1 | 6.2 | 14.8 | 1.8 |
| 2 | 0.5 | 15.6 | 1.6 |
| 3 | 0.2 | 16.7 | 1.5 |
| 4 | 3.3 | 17.5 | 1.4 |
| 5 | 1.1 | 17.5 | 1.3 |
| 6 | 4.9 | 19.5 | 1.4 |
| 7 | 3.4 | 19.6 | 1.7 |
| 8 | 0.7 | 18.1 | 1.3 |
| 9 | 2.4 | 19.6 | 1.7 |
| 10 | 0.1 | 20.4 | 1.2 |
| 11 | 2.7 | 20.0 | 1.3 |

Table II
Experimental Conditions (Second Building)

| *Run* | *Average Temperature Difference between zones 1 and 2 (° C)* | *Average Temperature Difference between zones 2 and 3 (° C)* | *Ambient Temperature (° C)* | *Wind Speed (m/sec)* |
|---|---|---|---|---|
| 1 | 3.1 | 0.2 | 18.1 | 2.5 |
| 2 | 4.0 | 0.6 | 17.7 | 2.8 |
| 3 | 4.8 | 0.5 | 17.2 | 1.9 |
| 4 | 0.9 | 0.2 | 19.0 | 2.1 |
| 5 | 2.3 | 0.1 | 19.1 | 2.4 |

Applying Bernoulli's equation [1], the volumetric flow rate and the mass flow rate through a horizontal opening separating two zones can be given approximately by :

$$Q = A\ C\ \sqrt{\Delta T\, g\, H/T} \qquad (5)$$

and

$$M = \rho\, A\ C\ \sqrt{\Delta T\, g\, H/T} \qquad (6)$$

where A is the cross-sectional area of the opening, C is the coefficient of discharge, $\Delta T$ is the average temperature difference between the zones, T is the mean absolute temperature of the two zones, $\rho$ is the average air density and and H is the thickness of the partition separating the zones. This equation was employed despite the complex geometry of the specific building. To evaluate the coefficient of discharge for this opening, the measured volumetric airflow rate was divided by the theoretical one, given by equation (5). Since two different opening sizes (opening A and B) were investigated as mentioned before, it was found that the coefficient of discharge was rather independent of the opening size.

It was also found to decrease from about 0.76 to 0.34 as the temperature difference between the two floors increased from 0.2 to 6.2 ° C (Figure 4). This decrease in the coefficient of discharge may be due to an increase in interfacial mixing as a result of the direct transfer of some air from the upper zone into the inflowing warmer air from the lower zone. It also appeared to remain constant near 0.34 for high temperature differences. Brown (1962) and Riffat (1989) investigated similar phenomena and suggested comparable values for this coefficient. The coefficient of discharge C and the dimensionless ratio $\Delta T/T$ were correlated very well (with r-squared value equal to 0.96) :

$$C = 0.1469 \ (\Delta T/T)^{-0.2} \tag{7}$$

From equations (6) and (5), the mass flow rate between the two zones can be given by :

$$M = 0.1469 \ \rho \ A \ \sqrt{gH} \ (\Delta T/T)^{0.3} \tag{8}$$

and similarly the heat flow rate between the two zones can be given in the form :

$$Q = 0.1469 \ \rho \ c_p \ A \ \sqrt{gH} \ (\Delta T)^{1.3} / T^{0.3} \tag{9}$$

where $c_p$ is the specific heat of air. These equations indicates that the mass flow rate through the first staircase increase linearly with $(\Delta T/T)^{0.3}$ for each opening configuration. A plot of the mass flow rate against $(\Delta T/T)^{0.3}$ for both opening sizes of the first building is shown in Figure 5. The airflow rates through the second staircase, are going to be estimated by using the CFD method for the reasons mentioned before.

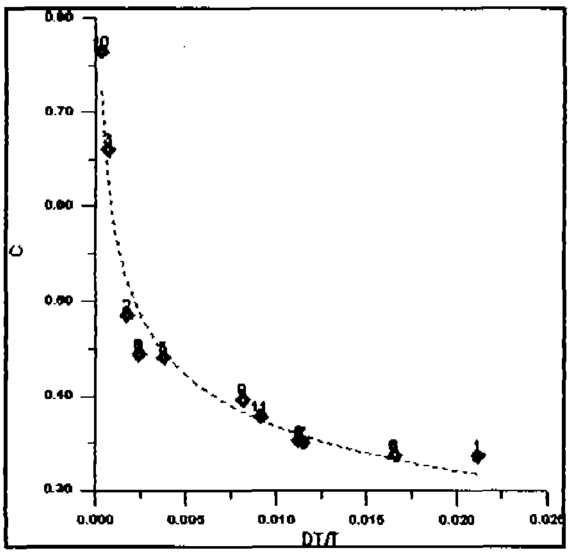


Figure 4: Variation of coefficient of discharge with ΔT/T (First Building)

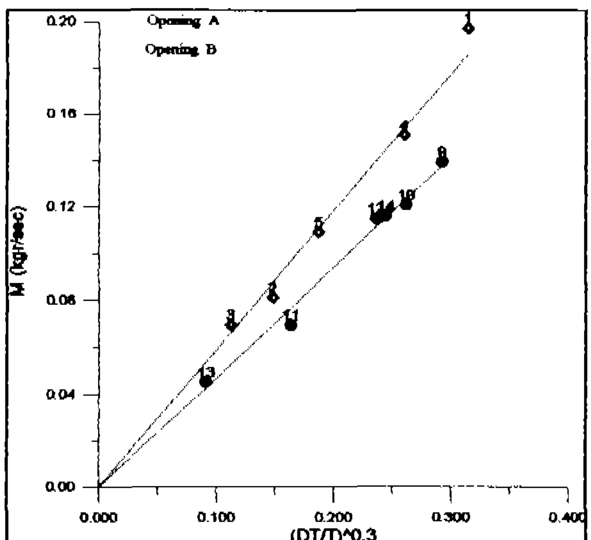


Figure 5: Mass flow rate against $(\Delta T/T)^{0.3}$ (First Building)

## 4. CFD Simulations

Simulations were performed, applying CFD algorithms which had already been developed and extensively validated. These algorithms generate approximate solutions to the Navier-Stokes equations, i.e. the conservation equations of mass, momentum, thermal energy and concentration species. In particular, these algorithms used the finite volume method, based on a Cartesian grid and the power–law interpolation scheme. To derive the pressure the SIMPLE algorithm was employed. After descretization these equations were solved numerically using the Tri-Diagonal Matrix algorithm. These algorithms incorporated the more recent RNG k-ε model based on Renormilized Group theory established by Yakhot and Orszag (1992). The advantage of this model is that it is valid for a very wide range of flow types including both high and low Reynolds number flows. To simulate the highly transient mass and energy transfer between zones, time dependent versions of the above equations were used. Small time steps of around 1/10 of the characteristic time scale were used in order to improve the accuracy of results. The computations were performed over the whole period of each run. Computations were also three-dimensional since the flow had been expected to be highly assymetrical due to complex geometry of the staircases. For simplicity, an orthogonal, equally spaced grid system was used to cover the domain.

First, the CFD algorithms were employed to simulate the cases corresponding to the eleven runs of the first building described in Table I. Five different grid sizes were investigated to determine the necessary resolution for grid-independent solutions. These grid sizes ranged from 2160 cells (15x9x16) to 35280 cells (42x20x42). Comparison of simulated volumetric flow rate between the zones showed that a grid-independent solution was achieved by using a 30x14x30 mesh (12600 cells). Since our main goal was only to model the general flow patterns and to predict the volumetric flow rate between the zones, further refinement of the grid would not produce any appreciable gains in accuracy. The criterion for convergence was to achieve a small value ($\sim 10^{-4}$ kgr $sec^{-1}$) for the sum of the mass residuals at the end of each time step. However, the convergence becomes quite problematic in low-Reynolds number flows. Tight control with variable relaxation factors were applied during simulations in order to achieve convergence. Care was taken to set the boundary conditions and the initial conditions of each zone, for the concentration level ,air and surface temperature which are necessary for the simulations. These values were provided by the experiments.

As the simulation proceeded, mass and energy transfer between the two zones caused variations in air temperature and velocity. These were recorded and analysed to reveal flow patterns , airflow rates and their variation with time.The volumetric flow rate between the two zones is obtained using :

$$Q = \sum_{i=1}^{n} |Wi| \, Ai/2 \qquad (10)$$

where n is the number of cells within the span of the horizontal opening connecting the two floors,$W_i$ is the vertical component of air velocity at individual grid points within the opening and $A_i$ is the area perpedicular to $W_i$ of individual cells within the opening. These rates were calculated at the end of each time step and averaged over the whole duration of each experiment. The final values were compared with experimental measurements. The relative difference between the simulated predictions and experimental estimations ranged from about 2.0 % to 11.6 % , with an average value equal to 5.5 % for all the experiments. This is a very good agreement, considering the many factors - such as the turbulence model, experimental errors and boundary conditions- which affected the accuracy of results.

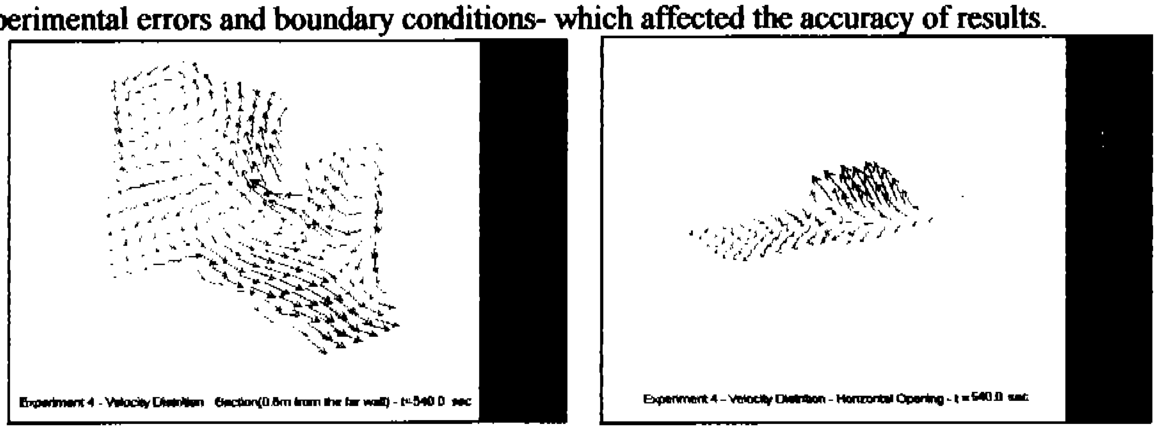


Figure 6: Air flow pattern through the first staircase and in the opening at t =540 sec during experiment 4.

These simulations revealed also the airflow patterns in the zones as well as in the opening connecting the two zones. It was found that these patterns are affected mainly by the temperature difference between the floors and by the geometry. The flow patterns in the zones were dominated by many vortices which promoted heat transfer and uniformity. The higher the temperature difference was, the more intense the eddies are. These flow patterns varied with time. Figure 6 shows examples of the predicted airflow through the first staircase and in the opening, at a moment 540 sec into the fourth experiment.

In order to estimate the airflow rates between the three zones of the second building, simulations of the cases corresponding to the five runs are carried out. From the first simulations, the convergence appears more problematic than before. So care must be taken for the appropriate relaxation factors. This work is still in progress.

## 5. Conclusions

The mass and heat flow rate through the opening connecting the two zones was a function of the interzonal average temperature difference and of the size of the opening. The mass and heat flow rate increased significantly with increasing temperature difference. In particular the mass flow rate increased linearly with $(\Delta T/T)^{0.3}$. Further experimental work is required to investigate the possible effect of staircase geometry and size of the opening on the value of these rates.

CFD simulations of buoyancy-driven flow through two typical staircases, were carried out. These simulations revealed the general airflow patterns. Comparison of the simulated volumetric airflow rates between the two zones of the first building and those based on experimental measurements, showed very good agreement, despite the difficulties of CFD method to model these phenomena. Investigation is required so as to improve the effectiveness of these algorithms to model these airflow phenomena.

## 6. References

Afonso,C.F.A., and E.A.B. Maldonado (1986). Single tracer gas method to characterize multi-room air exchange. Building and Environment 9(4), pp273-80.

Brown W. G. (1962). Natural convection through rectangular openings in partitions-2 : Horizontal Partitions. Int.J.Heat and Mass Transfer,Vol5, pp 869-81.

Klobut K. and Siren K. (1994). Air Flows Measured in Large Openings in a Horizontal Partition. Building and Environment,Vol.29 (3), pp 325-335.

Reynolds A. J. (1986). The scaling of flows of energy and mass through stairwells. Build. and Envir. ,Vol 21, No 314, pp 149-153.

Reynolds A J , M.R. Mokhtarzadeh-Dehghan (1988). The modeling of stairwell flows. Build. and Envir. ,Vol 23, No 1, pp 63-66.

Riffat S. B. (1989). Measurement of heat and mass transfer between the lower and upper floors of a house. Int.J. of Energy Research , Vol.13, pp 231-241.

Riffat S. B. ,Kohal J. S. ,Shao L. (1994). Measurement and CFD modelling of buoyancy-driven flows in horizontal openings. Proc. ASHRAE IAQ 94, Conf.Engineering Indoor Environment, St Louis.

Sinden, F.W. (1978). Multi-chamber theory of air ifiltration. Building and Environment 13, pp 21-28.

Yakhot,V., Orszag,S.A.,Thangham,S.Gatski,T.B. and Speziale,C.G.(1992). Development of Turbulence Models for Shear Flows by a Double Expansion Technique. Phys.Fluids A 4, No.7, pp 1510-1520.

Zohrabian A S , Mokhtarzadeh M R ,Reynolds A J, and B.S.T. Marriott (1989). An experimental study of buoyancy-driven flow in a half scale stairwell model. Build. And Envir., Vol 24, pp 141-148.