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Experimental study of natural convection between two compartments of a stairwell

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Abstract—The study describes an experimental study of buoyancy-driven flow between lower and upper compartments of a stairwell model with through-flow via two small openings, one as the inlet located in the lower compartment and the other as the outlet, in the upper compartment. The driving force for the flow is the energy input from a heater located in the lower compartment. The emphasis of the paper is on the effect of the outlet size on the fluid flow and energy transfer between the two compartments and on the heat losses from the stairwell to the surrounding. The velocity and temperature profiles at various cross sections of the stairwell are presented and discussed. The results also include the gross parameters of the flow such as the mass flow rates of the upflow and downflow and the effects of the opening size on them. The results show significant influence of the opening size on the fluid flow and energy transfers within the stairwell.

1. INTRODUCTION

Fluid motion driven or affected by buoyancy forces occurs in many fields of science and technology and is therefore of major significance. Comprehensive reviews of such flows are given by Brakat [1], Ostrach [2], Ede [3] and Gebhard [4]. In buildings, buoyancy-driven flows are important because of their effects on the air movement and transfer of energy and mass between different zones. Increased interest and regard for safety, energy conservation, health, fire prevention and adequate ventilation has resulted in a significant rise in research activity in this area.

Brown and Solvason [5] were among the first investigators who carried out extensive studies of natural convection through an opening in a partition separating two enclosures. Van der Mass [6] reviewed more recent studies, methods and applications of buoyancy-affected flows in buildings. Significant air movement usually takes place between different floors of a building via stairwells. Therefore, a better understanding of such flows can result in a better control of energy transfer, smoke movement, fire control and transfer of contaminants. A review of current literature in this area can be found in Zohrabian [7] and Ergin-Özkan [8]. Here, only a brief reference to some of the most recent studies will be made.

Feustal *et al.* [9] studied the air flow within the stairwell of a high rise building using tracer gas and fan pressurization techniques. They showed that at low wind speeds the flow regime was dominated by buoyancy forces and air flowed from the lower floor to top ones. At high speeds the flow direction changed because of increased pressure and leakage at upper floors.

Marshall [10] carried out tests on a one-fifth scale model of a five storey staircase and the attached fire compartment. It was found that increasing fire size resulted in an increase in the flow rate entrained into the stairwell via door openings. Also, the height of the stairwell model was found to be important, showing a decrease in the amount of air entrained when the height was reduced.

The flow of air and micro-organisms within a nine-storey hospital was investigated by Münch *et al.* [11]. The results showed that the transport of micro-organisms depended on the temperature difference between the inside and outside of the stair shaft. It was found that the infection rate increased as the height of the stair shaft increased.

Riffat *et al.* [12] used a tracer gas technique to study the flow between two floors of a house. The results showed dependency of the air flow on the temperature difference between the two floors.

Edwards and Irwin [13] performed experiments in a two-storey house to assess the efficiency of a partial heating scheme which used two heat sources on the ground floor and no heating on the first floor. The effect of the window opening was also investigated in their work.

A number of recent studies on the flows of mass and energy between different zones of a building should also be mentioned. Mahajan [14] studied the interzonal heat and mass transfer in two adjoining rooms. Kirkpatrick and Hill [15] investigated the

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NOMENCLATURE

A	throat area
c_p	specific heat
Fr	Froude number, $Fr = \dot{V}_m/A(gh)^{0.5}$
g	gravitational acceleration
Gr	Grashof number, $Gr = g\beta\Delta TAh/\nu^2$
h	one half stairwell height
h_i	inlet height
h_o	outlet height
$\dot{m}_u$, $\dot{m}_d$	mass flow rates of the upflow and downflow, respectively
$\dot{m}_T$	mass flow rate of the through-flow
Q	heat input by the heater
Q_u, Q_d, Q_s	heat loss from the upper compartment, lower compartment and stairway, respectively.
Q_T	heat loss via through-flow
Re	Reynolds number, $Re = \dot{V}_m/\nu A^{0.5}$
St	Stanton number, $St = Q/\rho c_p T_{av} A(gh)^{0.5}$
T	temperature
T_{av}	average temperature in the stairwell
T_h	average temperature in the upflow
T_c	average temperature in the downflow
u	resultant velocity
u_i	average velocity at the inlet
$\dot{V}_m$	arithmetic average of the volume flow rates of the upflow and downflow
w	stairwell width
z_1, z_2, z_3	defined in Fig. 1
ΔT	difference between temperatures of the upflow and downflow
ΔT_T	difference between mean air temperatures at inlet and outlet.

Greek symbols

β	coefficient of thermal expansion
ν	kinematic viscosity
ρ	density.

interzonal natural and forced convection between zones of a full-scale passive solar building in order to determine the effect of temperature difference, stratification and forced convection.

The work described in this paper is part of an experimental programme aimed at obtaining a better understanding of the buoyancy-driven flows of mass and energy between two floors of a building via the connecting stairwell [16–21]. The experimental test rig described in Section 2 represents a simplified geometry compared with the situation usually found in practice. But, it provides conditions within which the fundamental mechanisms governing the flow, and quantification of factors affecting the flow, can be studied under controllable laboratory conditions. It is therefore hoped that this kind of investigation would lead to an improved knowledge and add to the existing data base necessary to improve current building design practice where saving of energy, moisture and pollutant transfer, thermal comfort and control of fire and smoke spread are of prime importance. The data can also be used to validate [20] and lead to improvement of numerical models which are now being established as new tools in the design stage.

The previous results using the present experimental facility concentrated on various aspects of the buoyancy-driven flow between two compartments located at two different levels and connected via a section which comprised a number of steps. The driving force for the flow was the energy input from a heater located in the lower compartment. Two small openings, one located in the lower floor and the other in the upper one, simulated the presence of cracks which may be found, for example around doors or windows. The former opening acts as an inlet through which air enters and the latter opening acts as an outlet. The parameters of interest in these studies were the magnitude and direction of velocity at various locations, temperature distribution, heat losses through the walls and the mass and energy transfer between the two compartments.

Earlier studies were concerned with the case of a so-called closed stairwell, that is, a situation where both openings were closed and as a result the flow was isolated from the outside, except for the heat losses through the walls. Later, the work was extended to consider the effect of the through-flow which took place via the openings (so-called open stairwell case). The effect of the inlet opening size on the flow is reported by Ergin-Özkan [19]. The present work presents the results of measurements aimed at studying the effect of varying the outlet size on the buoyancy-driven flow within the stairwell model. The effect of the inlet size is mentioned where necessary to help the discussion of the results.

2. EXPERIMENTAL RIG AND INSTRUMENTATION

2.1. *Experimental rig and measurement positions*

Figure 1 shows the design of the experimental rig. It is a simplified representation of a stairwell connecting two floors of a building via 13 steps. The model was built to one-half scale. This reduction from full scale was considered unlikely to affect significantly the essential flow processes, while allowing for the construction of a two-storey model within the height constraints of a laboratory. It was also possible to generate velocity and temperature fields of correct order of magnitude that can be measured using available measuring equipment. Reynolds [21] has shown that using analytical relations it is possible to relate

Wall dimension [mm]	AB	BH	BT	TD	DE	EV'
	2520	1136	1285	940	1155	940
	H'G	IJ	MN	MP	RS	
	1200	608	650	25	579	

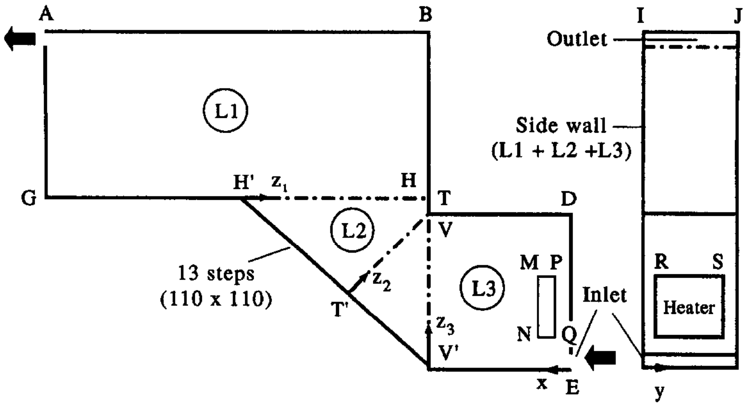

Fig. 1. Experimental rig.

the results of a scaled model to that of full scale. For one-half scale model adopted in the present work, these relations indicated that by appropriate choice of the operating conditions the essential dynamical features of the fluid motion within the full scale can be preserved.

The model was composed mainly of Perspex and plywood, mounted within a Dexion frame. The side walls of the model were made of Perspex of 10 mm thickness. All other walls were made of plywood of 18 mm thickness, except the steps which were made of plywood of 4 mm thickness strengthened from below by plywood of 18 mm thickness. The wall behind the heater was also thickened using an additional board of the same thickness.

The air inlet was located in the lower compartment and the outlet in the upper one. For the results presented here, the outlet height took values equal to 0.01, 0.02 and 0.04 m and the inlet height was fixed at 0.02 m. Other inlet sizes were adopted in the experimental study of Ergin-Özkan [19] and the effects were fully described. In the present work such effects are only briefly referred to as part of the discussion.

A 1 kW oil-filled electric heater with an overall surface area of 0.751 m^2 was located in the lower compartment, mounted 0.01 m above the floor and 0.045 m away from the front wall. The heat input rate was controlled using a Variac and was measured using a digital Wattmeter. The results reported here are for three different heat inputs, namely, 100, 300 and 600 W.

The following measurements were carried out. Velocities and temperatures were measured at a number of locations in three planes defined in Fig. 1 (HH′, TT′, VV′) and at the inlet and outlet. The plane TT′ is perpendicular to the stairway and is referred to as the throat area. There were twenty measurement points at TT′, ten at VV′ and HH′, and six at the inlet and outlet. These measurements were obtained at various distances from the side wall, namely, at 1/6, 1/3 and 1/2 of the stairwell width.

The wall temperatures were measured at 148 positions, half of which were on the internal surfaces and the rest were on the external surfaces. The temperatures measured at these points were used to calculate the heat losses through the walls. The temperatures on the heater surface were measured at 18 points, half of which were on one side and the rest on the other side.

Because of the symmetry about the mid-plane, all the above measurements were carried out on one-half of the stairwell only.

2.2. *Instrumentation*

The main instruments were one air velocity transducer, ten platinum resistance thermometers to measure the air temperature and thermocouples to measure wall surface temperatures.

The velocity transducer was a constant temperature thermal anemometry type and temperature compensated (7–60°C) with an operating range of 0.05 to 1.0 ms^{-1} and a time constant of 2 s. It had a spherical sensor of 3 mm diameter and thus was sensitive to the magnitude of the velocity only, not to its direction. This sensor was heated and kept at a constant elevated temperature (relative to ambient temperature) by means of control electronics. The velocity transducer was calibrated to provide a linear output between 0 and 5 V for 0–1.0 ms^{-1}. The accuracy of the probe was about $\pm 3\%$ of the reading for 0–270°C solid angle. For larger angles the accuracy was less, about 10%. Because of the small size of the spherical sensor compared with the stairwell, the effect on the velocity reading was negligible.

The platinum resistance thermometers were manufactured according to DIN 43760. The detector element of the probe was protected by a stainless steel metal sheath 0.457 m long and 4 mm in diameter.

The probe comprised a power supply and a four-wire bridge which allowed for correction of the lead resistance. The output from the probe was linear, varied from 0 to 100 mV for temperatures in the range of 0–100°C. The time constant of the probe was 3 min. The accuracy of the probe was about ±0.05°C.

The thermocouples, Ni–Cr/Ni–Al type, were employed to measure the internal and external surfaces of the stairwell walls and of the heater surface. They had an operating range up to 250°C. Their conductors of 2 mm diameter were insulated using Teflon.

The data acquisition system comprised a personal computer, an IEEE interface card and two Analogue-to-Digital converters. Forty readings of velocity were taken in about 4 s and one reading of temperature for each probe in 40 s. This procedure was repeated five times and the results were then averaged.

Two types of flow visualization were used. The general flow pattern was studied using a smoke generator and also ventilation smoke tubes. The smoke wire technique was used to visualize the velocity profiles at mid-section of the stairwell, along TT′, VV′ and HH′ (see Fig. 1). It will be seen in Section 4 that the air flow direction changes at a location on these lines and therefore the visualization of the velocity profile was necessary for establishing the position of the turning point. In this type of visualization, very small droplets of oil formed on a stainless steel wire of 0.05 mm diameter which were then vaporized by passing an electric current through the wire.

The leakage rate through the joints of the stairwell were measured for both the inlet and outlet closed, using the concentration decay method and carbon dioxide as the tracer gas. The leakage rate was less than 0.3% of the heat input rate and was therefore assumed negligible. The calculation of heat flow rate from the leakage rate was based on the difference between the average air temperature in the stairwell and the ambient temperature.

The experiments were carried out at a steady state condition which was achieved after about 4–5 h during which the air velocity and temperature were monitored. The surface temperature of the heater was also monitored during this time. The stairwell rig was placed in a room with no windows and this helped to achieve the required steady state condition. The ambient temperature remained constant during each set of experiments. However, for the whole range of results presented here the range of ambient temperature was between 21°C and 24°C.

3. PROCESSING OF THE DATA

Conduction heat losses through the walls of the stairwell were calculated using the thermal conductivity of the wall materials, thickness of the wall and the measured temperature difference between the internal and external surfaces of the wall. The thermal conductivities of plywood and Perspex were taken as 0.14 and 0.18 W m^{-1} K^{-1}, respectively. It was mentioned earlier that the wall temperatures were measured at 148 positions on both internal and external surfaces. Therefore, the heat loss calculations were carried out using a grid of 74 cells. There were small variations of temperature within each cell, but these were neglected.

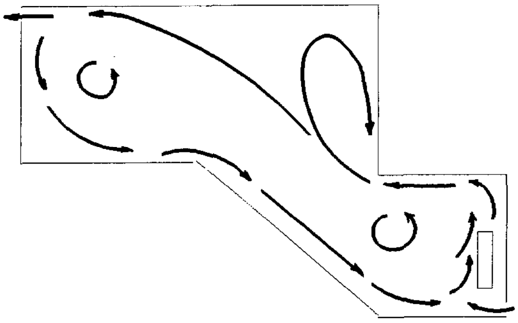

Fig. 2. General flow pattern in the stairwell.

The volume and mass flow rates at the throat area were calculated by integrating the velocity along TT′ and then across the half-width of the stairwell. In the above calculations, the component of the velocity normal to the throat area was used. The visualization tests showed that, on the average, the flow direction was mostly perpendicular to the throat area, except in the upper region where it was parallel to the ceiling of the lower compartment. Establishing the position of the interface between the upflow and downflow was also necessary in these calculations. This was determined using the visualized velocity profile at the mid-section of the stairwell and was assumed to be the same along the width of the stairwell.

The heat loss by convection through the outlet opening was calculated using the measured mass flow rate through the opening and measured air temperatures at the outlet and inlet.

4. RESULTS

Figure 2 shows the general flow pattern within the stairwell model. The measurements of velocity and temperature at three planes located at different distances from the side wall, inlet height of 0.02 m and outlet height of 0.04 m and heat input equal to 300 W are shown in Figs. 3 and 4, respectively. The effects of outlet height on the velocity and temperature at the mid-plane are shown in Figs. 5 and 6. The gross parameters of the flow for various outlet heights are shown in Fig. 7. The rate of heat losses through the walls of the stairwell are shown in Fig. 8 and Table 1. Finally, the characteristic dimensionless numbers are shown in Fig. 9.

5. DISCUSSION

The flow pattern shown in Fig. 2 is the overall pattern observed, governed by the energy input from the heater, and the size of the opening had only small,

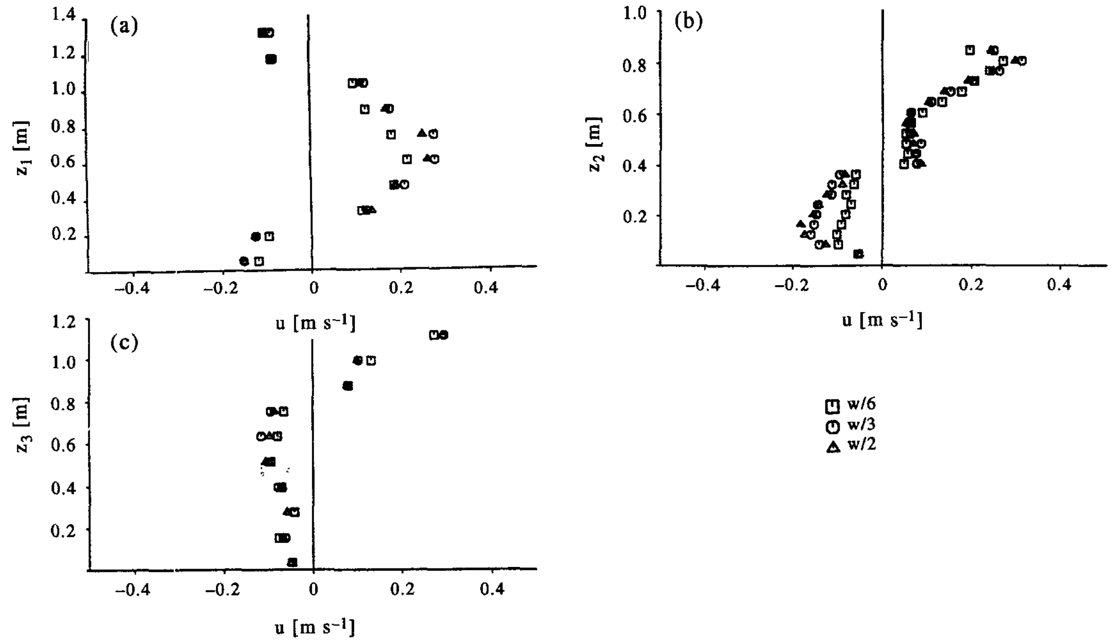

Fig. 3. Velocity profiles at various distances from the side wall. $h_i = 0.02$ m, $h_o = 0.04$ m, $Q = 300$ W. (a) at HH′, (b) at TT′ and (c) at VV′.

but noticeable, effect on the flow in the lower compartment. The main features of the flow are the formation of the two-directional flow in the stairway and three recirculation zones, two in the upper compartment and one in the lower compartment. A small area of recirculating air was also observed next to each step. The air entering the stairwell travelled for a short distance along the floor of the lower compartment before rising and joining the air flowing down along the steps. The distance along which the air penetrated decreased when the outlet height decreased. The opposite effect was observed for changes in the inlet height [19], that is, the distance decreased with an increase of the inlet size. There existed a clear turning point separating the upflow from the downflow. The position of this point, however, was not fixed and varied by about 2 cm for given heat input and size of the opening. Increasing the inlet or the outlet height resulted in a shift towards the steps. Rapid mixing of smoke was observed in most parts of the stairway and the lower compartment, but noticeably less in the upper compartment. Figure 2 shows a flow pattern which is the same along the width of the stairwell. Smoke movement in the direction perpendicular to the side wall was also observed, but this was less significant than the movement in the planes parallel to the side wall. This behaviour is a direct effect of the position of the heater and the overall symmetry about the mid-plane. A more realistic position of the heater, say next to the side wall, would induce a flow of three-dimensional nature.

The velocity profiles at the throat area (TT′) and also along the vertical (VV′) and horizontal (HH′) sections are shown in Figs. 3 (a)–(c). The hot air rising along the heater has resulted in the formation of a layer of fast moving air close to the ceiling of the upper compartment within which a maximum velocity occurs. The velocity varies rapidly in this area, while it is nearly uniform in the lower parts of the lower compartment. In entering the throat area, the air keeps its horizontal direction and high velocities before turning upwards towards the upper compartment. Along TT′ two distinct regions of flow, one moving upward from the lower to upper compartment and the other returning in the opposite direction, can be seen. As was mentioned earlier, the position of the turning point and therefore the distinction between the positive and negative velocities was determined by flow visualization. There is, however, some degree of uncertainty in the exact definition of this point caused

Table 1. Rate of heat loss (W) through the stairwell walls and via the openings, $Q = 300$ W

Wall	$h_o = 0.0$ $h_i = 0.0$	$h_o = 0.01$ $h_i = 0.02$	$h_o = 0.02$ $h_i = 0.02$	$h_o = 0.04$ $h_i = 0.02$
AB	14.2	12.3	9.6	6.0
BT	3.9	3.2	2.3	3.1
TD	20.8	18.5	18.4	14.4
GH′	9.8	9.8	9.5	10.2
GA	6.0	4.3	4.7	6.0
DF	16.1	15.9	15.0	14.2
FV′	14.8	15.8	15.7	14.1
V′H′	41.1	38.5	38.1	33.5
2 × (L1 + L2 + L3)	171.9	149.6	127.3	145.8
Through-flow	0.5	33.6	60.6	56.9
Total heat measured	299.1	301.5	301.2	304.2

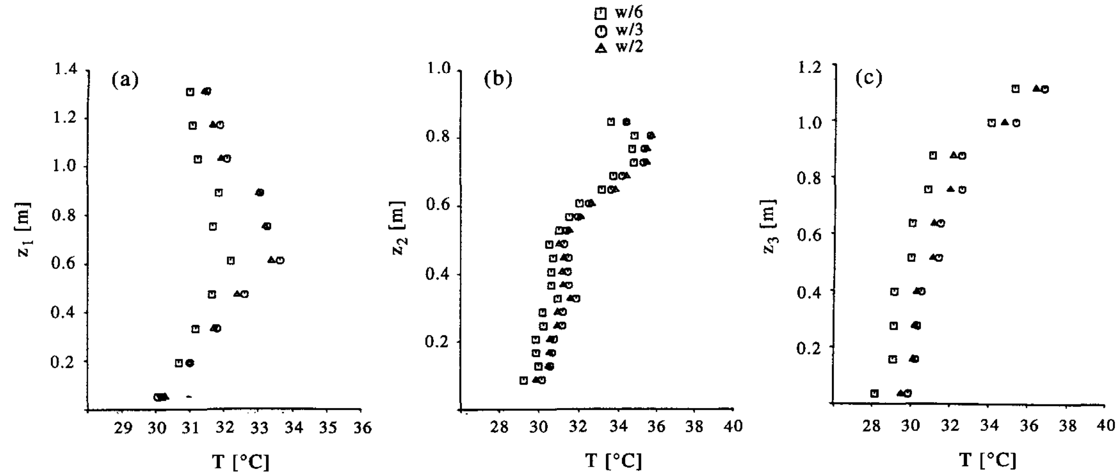

Fig. 4. Temperature profiles at various distances from the side wall. $h_i = 0.02$ m, $h_o = 0.04$ m, $Q = 300$ W. (a) at HH′, (b) at TT′ and (c) at VV′.

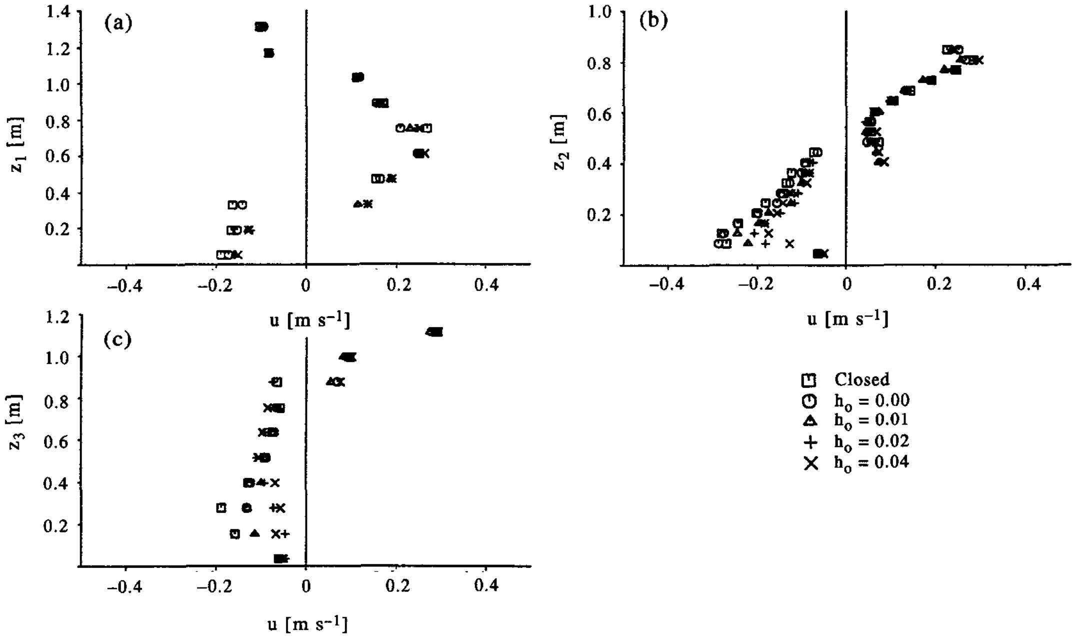

Fig. 5. Velocity profiles for different outlet heights at half width of the stairwell. $h_i = 0.02$ m, $Q = 300$ W. (a) at HH′, (b) at TT′ and (c) at VV′.

by instability of the flow and relatively low velocities occurring there.

As the air enters the upper compartment, it spreads and as a result the position of the maximum velocity shifts towards the centre of HH′. It should be noted that the velocities shown in Fig. 3 are the velocities measured, thus they contain a significant horizontal component. Similar behaviour resulting from the formation of the hot and fast moving fluid, turning and spreading into the upper compartment, can be seen in the temperature profiles shown in Figs. 4 (a)–(c). The formation of two regions of hot and cold air in the throat area can also be seen. The temperature distribution is more uniform in the cold downflow region because of more mixing caused by the presence of the steps and the interaction between the upflow and downflow. Figure 3(b) shows that the position of the turning point is not at the middle of the throat area and is shifted towards the steps. Relating the position of the turning point to Fig. 4(b) shows that the interaction between the upflow and downflow has resulted in a uniform temperature distribution in the interface region.

The velocities are nearly uniform in the mid-region of the stairwell, although there is an obvious reduction of velocities as the side wall is approached (see results at w/6 in Fig. 3). The changes in temperature are, however, more significant because of large heat losses which occur at the side walls. Thus, the special design of the stairwell causing a predominantly two-dimen-

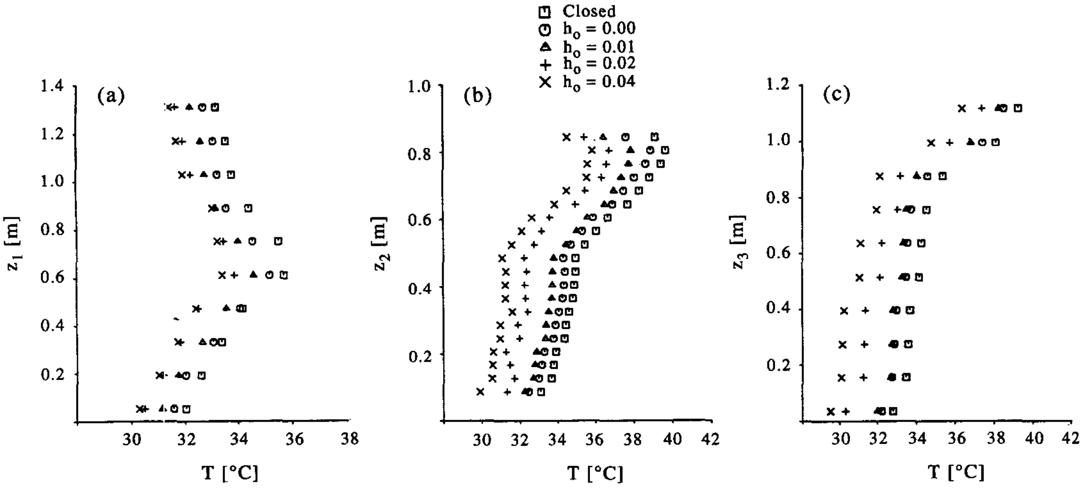

Fig. 6. Temperature profiles for different outlet heights at half width of the stairwell. $h_i = 0.02$ m, $Q = 300$ W. (a) at HH′, (b) at TT′ and (c) at VV′.

sional behaviour, as mentioned above, has more effect on the temperature distribution than on the velocity distribution.

The effect of varying the outlet size is shown in Figs. 5 (a)–(c) and 6 (a)–(c). The results for the closed stairwell are also included in these figures. It should be noted that the condition for which h_0 is zero refers to the situation where the outlet was closed but the inlet remained open. This case was therefore different from the closed stairwell case for which both inlet and outlet were closed. The results show that there is a reduction of temperature as the outlet height increases. The same trend is true for the velocities in the downflow (negative velocities) but not for the velocities in the upflow where the opposite effect has been resulted. While the reduction in temperature is significant in both cold downflow and warm upflow regions, the effect on the velocity is less pronounced in the upflow. Similar reductions in temperature were also obtained when the inlet size increased [19].

The variations of the gross parameters are shown in Figs. 7 (a)–(i). The results show that the average temperatures in the warm upflow (T_h) and cold downflow (T_c), the average temperature in the stairwell (T_{av}) and the mean temperature difference between the upflow and downflow (ΔT) all decrease with increase in the outlet height. Similar variations were obtained for changes in the inlet height in the range of 0.01 to 0.04 m.

The mass flow rate of the through-flow is given by

$$\dot{m}_T = \dot{m}_u - \dot{m}_d. \tag{1}$$

In the above equation the mass flow rate due to leakage via the stairwell joints has been neglected due to its small value. As the outlet height increases the mass flow rate of the upflow ($\dot{m}_u$) increases, while the mass flow rate of the downflow ($\dot{m}_d$) decreases, resulting in an increase in $\dot{m}_T$. The effect on the upflow is, however, small beyond the outlet height of 0.02 m. Changing the inlet height showed similar effect on $\dot{m}_d$, but resulted in a decrease in $\dot{m}_u$. The through-flow $\dot{m}_T$, however, still increased but at a smaller rate.

The rates of heat losses through the stairwell walls are shown in Figs. 8 (a)–(d) and Table 1. The heat losses through the walls of the upper and lower compartments (Q_u and Q_d) and through the stairway (Q_s) decrease with increase in both outlet and inlet heights up to the size of 0.02 m. Beyond this opening size the rate of decrease slows down and, in the case of changes in the outlet size, tends to increase slightly. The heat loss via the through-flow, however, increases with the outlet height at first. When the outlet height increases from 0.02 to 0.04 m, Q_T decreases because of the decrease in the difference between the air temperatures inside and outside the stairwell, which overcomes the increase in the mass flow of the through-flow.

The rate of heat loss via the leakage through the stairwell joints was measured for the closed stairwell, i.e. when both the inlet and outlet openings were closed. The results showed that the rate of leakage increased nearly exponentially with increase in the heat input rate. These losses were in the range of 0.1–0.3% of the heat input rate.

The relationship for the overall mass balance is given by equation (1). A difference of about 1–5% was found to exist between the mass flow rates obtained from the two sides of this equation. In the case of the closed stairwell, the discrepancy between the measured upflow and downflow was about 2%. The reason for this discrepancy can be attributed to the experimental errors and the assumptions made in the calculation procedures. The uncertainty in defining the position of the interface between the upflow and downflow is also responsible, by about 2%.

The overall heat balance requires that the heat input to the stairwell must be equal to the sum of the heat losses through the stairwell walls, the openings, and via the leakage. The results showed a difference of about 3% between the measured heat input rate and the total heat loss. The assumption of uniformity of

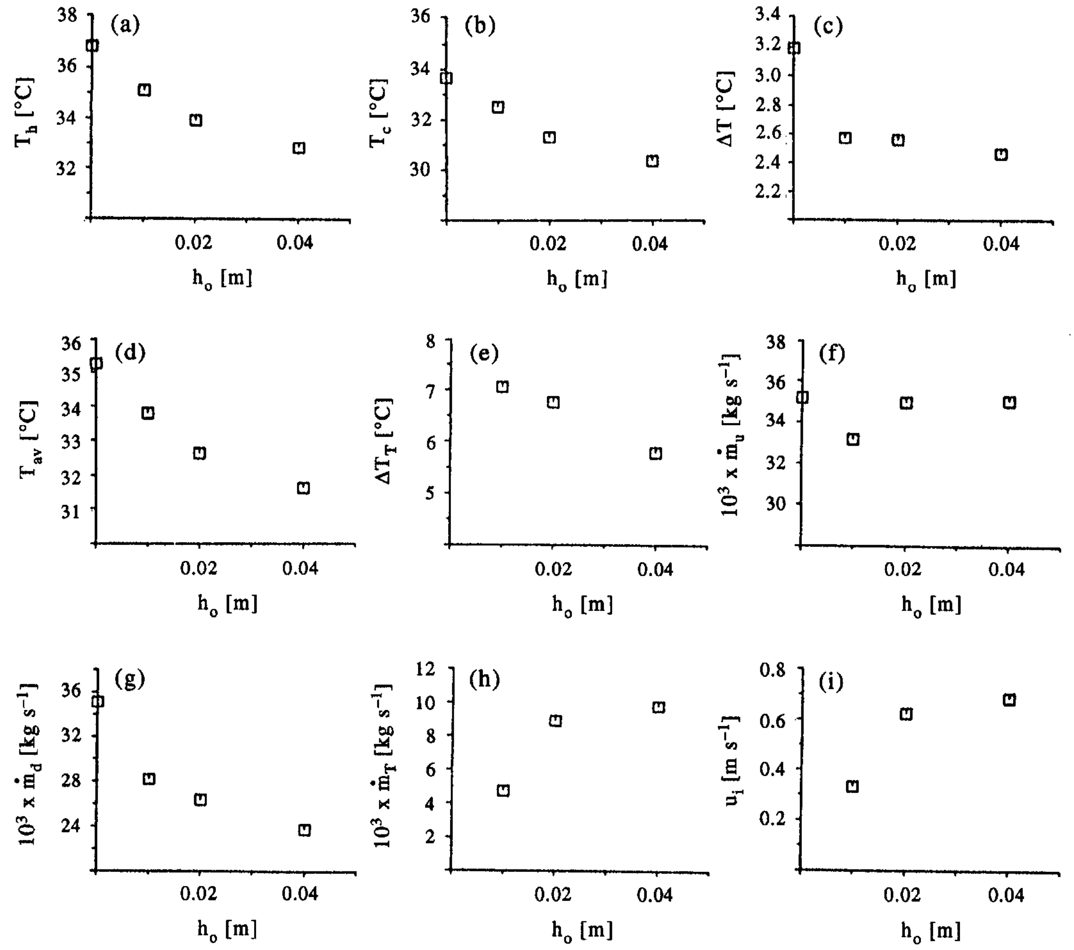

Fig. 7. The gross parameters of the flow for various outlet heights. $Q = 300$ W, $h_i = 0.02$ m, $h_o = 0$ denotes closed stairwell case.

temperature over a measurement cell may be considered to be the main cause of the discrepancy. Other factors are errors in the measurement of the heat input rate, air temperatures and velocities in the inlet and outlet openings and the values of heat conductivities used in the calculations.

The range of values and variations of characteristic dimensionless numbers for various outlet heights are shown in Figs. 9 (a)–(d). There is an increase, followed by a smaller decrease, in the values of Froude and Reynolds numbers as the outlet height changes from 0.01 to 0.02 m, and then to 0.04 m. On the whole, the variations of all four dimensionless numbers could be considered to be small for the range of outlet heights studied here.

Although direct comparisons with the previous works on real buildings is not possible, the values of volume flow rates between two floors of a real building are mentioned here to give an idea of the typical values found in practice. Riffat and Eid [22] found that the airflow rate between two floors of a domestic building was in the range of 0.027–0.05 m^3 s^{-1} for temperature differences between 0.2 and 4°C. Edwards and Irwin [13] obtained values in the range of 0.017–0.069 m^3 s^{-1} for a temperature difference between 1 and 6°C. Their results showed that the recirculating flow rate was reduced by 50% when two windows, one in the lower floor and one in the upper floor, were opened. In another study, based on the multi-cell theory, Liddament [23] found that the recirculating flow rate was in the range of 0.024–0.033 m^3 s^{-1}. In the present work the recirculating flow rate was in the range of 0.011–0.04 m^3 s^{-1} for a temperature difference, between the lower and upper compartments, in the range of 1.0–5.5°C.

In terms of characteristic dimensionless numbers, the full-scale measurements in a two-storey house of Riffat *et al.* [22] can be referred to here. They obtained Reynolds and Grashof numbers, respectively, in the range of 4410–21110 and 10^8 to 10^{10} for temperature differences between 0.5 and 13°C between the two floors.

6. CONCLUSIONS

Changes in the size of a relatively small opening located in the upper floor of a stairwell model, were

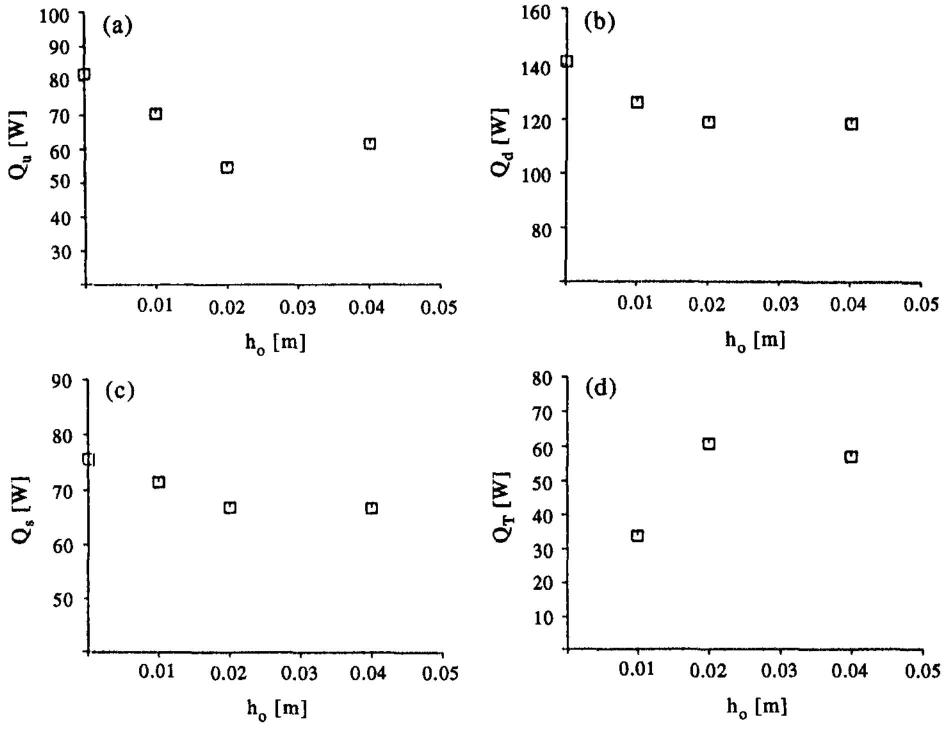

Fig. 8. The rate of heat loss for various outlet heights. $Q = 300$ W, $h_i = 0.02$ m, $h_o = 0$ denotes closed stairwell case.

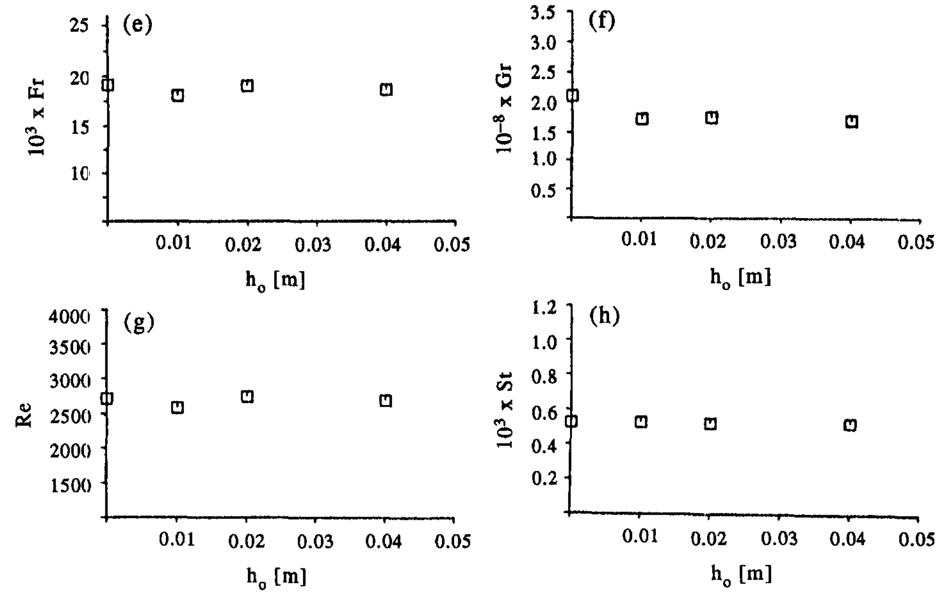

Fig. 9. Characteristic dimensionless numbers for various outlet heights. $Q = 300$ W, $h_i = 0.02$ m, $h_o = 0$ denotes closed stairwell case.

shown to have significant effect on the characteristics of the buoyancy-driven flow within the stairwell. The overall flow pattern, however, remained the same, except for a small, but noticeable, effect on the air movement close to the inlet, in the lower compartment.

Increasing the outlet size resulted in a reduction in the average temperature of the stairwell, and also of the temperatures of the upflow and downflow. The effect on the through-flow was to increase the mass flow rates. The mass flow rate of the recirculating flow between the floors, however, decreased as the outlet height increased. The rate of heat loss through the upper and lower compartments and the stairway also decreased, but only up to about an outlet size of 0.02 m. For large outlets there was a tendency to increase the heat loss. The opposite was true for the heat loss via the flow leaving the stairwell. On the whole, variations in the gross parameters of the flow were more sensitive to the outlet size in the lower range of the opening, from 0 to ~ 0.02 m in the present case. Once the size was increased beyond this range, the parameters became less sensitive to changes.

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