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THE EFFECT OF DIFFERENT AIR INLET SIZES ON THE AIR FLOW THROUGH A STAIRWELL

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An experimental study of the effect of flow through an opening (or a crack) on the natural convection in a stairwell model is presented. The flow is driven by energy input from an electric panel heater located in the lower floor of the stairwell. The work concentrates on the effect of the size of inlet opening by varying it while keeping the area of the outlet constant. New data are presented for the measured temperatures and velocities at various cross-sections of the stairwell. The results also include gross parameters of the flow, such as the mass flow rates of the through-flow and recirculating flow, heat losses from the lower and upper floors and also from the stairway. The results show that the size of the opening has a significant effect on the flows of mass and energy within, and through, the stairwell.

1. INTRODUCTION

In recent years there has been an increased interest in the study of flow through large openings, such as doors and windows [1], vertical (or horizontal) openings in partitions [2] and stairways [3]. The same is true for the problem of flow through small cracks [4,5]. Such studies are important because of the significance given to savings in energy, to adequate ventilation and to safety. Previous studies have mainly dealt with the flow through two compartments. These two compartments have been, for example, two rooms or two floors of a building [6]. There are situations of practical importance where one is interested in the effect of large or small openings on the flow through another opening. The former opening might, for example, be a window and the latter one the opening between the two floors. An example of the first type is reported by Edwards et al. [7] who studied the effect of a window on the flow between the ground floor and first floor of a building. Zohrabian et al. [8] studied the effect of a small crack on the flow through a stairway. However, they considered only one size of opening for the inlet and for the outlet and compared the results with a situation when these openings were absent. The effect of various sizes of the openings was not studied. The present paper addresses this problem and describes the influence of the inlet opening size on the various parameters of interest.

2. THE EXPERIMENTAL RIG

A schematic diagram of the stairwell model showing its dimensions is shown in Figure 1. Two rectangular openings were considered, one in the lower compartment (referred to as the inlet) and the other in the upper compartment (the outlet). Three different heights of 0.01, 0.02 and 0.04 m were studied for the inlet aperture while the outlet height was kept constant at 0.01 m. The widths of the inlet and outlet openings were the same as the width of the stairwell (0.608 m). The two side walls of the model (parallel to the x-z plane) were made of Perspex of 10 mm thickness and the other walls were made of plywood of mainly 18 mm thickness. The wall behind the heater was thickened to 36 mm. The heater was a 0.579 m x 0.65 m, 1 kW electric panel heater. The heat input rate was controlled using a Variac and was measured using a wattmeter. The air velocity was measured using an omni-directional temperature-compensated probe calibrated in the range of 0.05 to 1.0 $m\,s^{-1}$. The time constant of this probe was 2 s and the accuracy of the measurements was about ± 5 per cent over 0.05 to 0.5 $m\,s^{-1}$. Air temperature was measured using ten platinum resistance thermometers. The time constant of these probes was about three minutes and the accuracy of measurement was about ± 0.25 °C.

The internal and external surface temperatures of the walls were measured using Ni-Cr/Ni-Al (type K) thermocouples. A total of 148 thermocouples were used for this purpose. The outputs from the velocity probe and resistance thermometers were digitised using an Anologue-to-Digital converter and then transferred to a microcomputer via a IEEE interface card. Forty readings of velocity and one reading of temperature were taken in three seconds. This procedure was repeated five times and the results were then averaged.

Because of symmetry conditions which existed within the stairwell, measurements were made in one-half of the stairwell only. At the throat area (TT′ in Figure 2) velocities and temperatures were measured at twenty locations along TT′ and at four locations in the direction normal to the side wall (y- direction). Ten measurements were also made along the vertical section VV′ and horizontal section HH′ shown in Figure 2. At the inlet and outlet openings measurements were made at six locations along the width of the opening.

The results presented here were recorded after an initial warm-up period of four to five hours after which the changes in temperature was insignificant (for example, less than 0.05 °C for the surface temperature of the heater). The stairwell model was placed in a room with no outside windows and therefore climatic changes had negligible effect.

The flow was visualized using smoke injected at various points in the stairwell. The velocity profiles at the mid-section of the stairwell in the throat area and also at VV′ and HH′ were visualized using the smoke-wire technique.

3. PROCESSING OF THE EXPERIMENTAL DATA

The mass flow rates in the throat area were obtained using the measured local velocities and temperatures, the local densities calculated using the perfect gas law, and Simpson's rule, which was applied along the length and then across the width of the throat area.

The heat losses by conduction through the stairwell walls were calculated using the measured surface temperatures (internal and external). The heat conductivities of plywood and Perspex were taken as 0.14 and 0.18 $W\ m^{-1}\ K^{-1}$, respectively. The heat transfers by convection through the openings were calculated using averages of measured local velocities and temperatures.

4. RESULTS AND DISCUSSION

The general flow pattern within the stairwell is shown in Figure 2 which agrees with the observations of Zohrabian et al. [8]. The size of the inlet had noticeable effect on the flow pattern in the lower compartment (near the opening) and also in the throat area, but the overall flow pattern did not change significantly. The inlet air flow induced by the temperature difference between inside and outside travels a short distance along the floor before rising along the heater walls. This distance decreased with an increase in the inlet size, because of the reduction in the average velocity in the opening. The visualization of the velocity profile at the throat area indicated a clear turning point separating the upflow from the downflow. For an opening of zero height (closed stairwell) this point was approximately in the middle of the throat area. With increasing the inlet height this point was shifted towards the stairs by about 4 to 8 cm. It should be noted that a variation of about 2 cm was observed in the position of this turning point. This was due to the unsteady behaviour of the flow in the throat area which resulted from the flow separation at the sharp discontinuity (T′ in Figure 2), the interaction of the warm upflow and cold downflow, and the complicated flow along the stairs, where local flow separation occurs at the surface discontinuties.

Figures 3 (a to i) and 4 (a to i) show the temperature and velocity profiles, at the mid-plane of the stairwell, along TT′, VV′ and HH′ (see Figure 2) for various inlet heights and heat inputs. Figure 3 shows a clear reduction of temperature in the stairwell as the inlet height increases. This reduction is approximately proportional to the inlet height and heat input. The temperature profile at the throat area shows a maximum slightly below the ceiling of the lower compartment.

This maximum is absent in the profile at VV´ (located between the last measurement point and the wall) while at HH´ it is shifted towards the middle of the section. This is due to the hot air moving along the ceiling of the lower compartment and then entering the stairway while maintaining its horizontal direction for a distance before moving into the upper compartment. Considering the profile at the throat area, the temperature is more uniform in the cold downflow than in the warmer upflow.

Figure 4 also shows that the velocities in all three sections decrease with the inlet height, although the change is not as distiguishable as it is in the case of temperature. The effect of the inlet height is, however, more pronounced in the downflow than in the upflow. The velocity changes with heat input approximately linearly.

Figure 5 (a to d) shows the gross parameters of interest. The temperature difference ΔT decreases as the inlet height increases (Figure 5 (a)). The same is true for the mean temperatures in the lower and upper compartments. This results in a reduction in the mass flow rate of the recirculating flow, as shown in Figure 5 (b). The same behaviour can be seen in the variation of mass flow rate of the upflow (Figure 5(c) and also of the average temperature in the throat area, T_{av} (Figure 5 (d)). The mass flow rate of the through-flow, on the other hand, increases with the inlet height (Figure 5 (e)). This increase is significant when the inlet height changes from 0.01 m to 0.02 m, whereas the rate of increase is much smaller beyond the inlet height of 0.02 m. The reason for this behaviour can be realized with reference to the following mass balance equation

$$\dot{m}_T=\dot{m}_u-\dot{m}_d \qquad (1)$$

The effect of the inlet height is greater on the downflow than on the upflow as can be seen in Figures 5 (b) and (c). As the inlet height increases the downflow decreases initially at a faster rate compared with the upflow.

Figure 6 (a to d) shows a small decrease in the rate of heat loss through the walls of the upper and lower compartments and of the stairway as the inlet height increases, whereas the rate of heat loss via through-flow tends to increase. The change, however, is more significant for smaller inlet heights. It should be noted that the rate of increase in the heat loss via the through-flow is smaller than the rate of increase in the mass flow rate, because of the reduction in the mean temperature difference between inside and outside of the stairwell.

The variations of Froude, Grashof, Reynolds and Stanton numbers are shown in Figure 7 (a to d). Except for the Stanton number, which increases slightly, these parameters display a gradual decrease as the inlet height increases. The change in the average temperature has only a small effect on the Stanton number, whereas the effects on the other parameters are more significant because of the reduction in the influence of buoyancy force.

5. CONCLUSIONS

The effect of inflow of air caused by a temperature differential across a small opening on the transfer of energy and mass between two floors of a building was studied using a simplified half-scale model. The study indicated the significant effects which such flows, as may occur through cracks around doors or windows, can have on the transfer processes within a building. Particular attention was given to the effect of the opening size. The results show that, as the opening size was increased, the average temperature within the experimental model and also the temperature difference between the lower and upper floors decreased. Consequently, the mass flow rate of air circulating between the two floors was also reduced. The mass flow rate of the through-flow, on the other hand, increased with inlet height, although not with a constant rate. The results also indicated an increase in the area occupied by the warm upflow in the stairway, resulting in a shift (towards the stairs) of the interface between the upflow and downflow. The average air velocity in the stairway also decreased as the inlet area increased.

6. ACKNOWLEDGEMENTS

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7. NOMENCLOSURE

A	Throat area (m^2)
C_p	Specific heat at constant pressure ($J\ kg^{-1}\ K^{-1}$)
g	Gravitational acceleration ($m\ s^{-2}$)
h	One-half height of the stairwell model (m)
h_i	Inlet height (m)
h_o	Outlet height (m)
$\dot{m}_T$	Through-flow rate ($kg\ s^{-1}$)
$\dot{m}_u$, $\dot{m}_d$	Upflow and downflow mass flow rates ($kg\ s^{-1}$)
$\dot{Q}$	Rate of supply of heat to the stairwell (W)
$\dot{Q}_d$, $\dot{Q}_u$, $\dot{Q}_s$	Rate of heat losses from the walls of the lower compartment, upper compartment and stairway, respectively (W)
$\dot{Q}_T$	Rate of heat loss by through-flow (W)
T	Temperature (°C)
T_{av}	Arithmetic average of all the temperatures measured in the throat area (°C)
u	Velocity ($m\ s^{-1}$)
zH, zT, zV	Coordinates shown in Figure 2
$\dot{V}_m$	Average volume flow rate ($m^3\ s^{-1}$)
β	Coefficient of thermal expansion (K^{-1})
ν	Kinematic viscosity ($m^2\ s^{-1}$)
ρ	Fluid density ($kg\ m^{-3}$)
ΔT	Temperature difference between the mean temparatures of warm upwards-flowing air and cold downwards-flowing air (°C)
Gr	Grashof Number $= \frac{g\,\beta\,\Delta T\,A\,h}{\nu^2}$
Fr	Froude number $= \frac{\dot{V}_m}{A\,(g\,h)^{1/2}}$
Re	Reynolds number $= \frac{V_m}{\nu\,A^{1/2}}$
St	Stanton number $= \frac{\dot{Q}}{\rho\,C_p\,T_{av}\,A(g\,h)^{1/2}}$

8. REFERENCES

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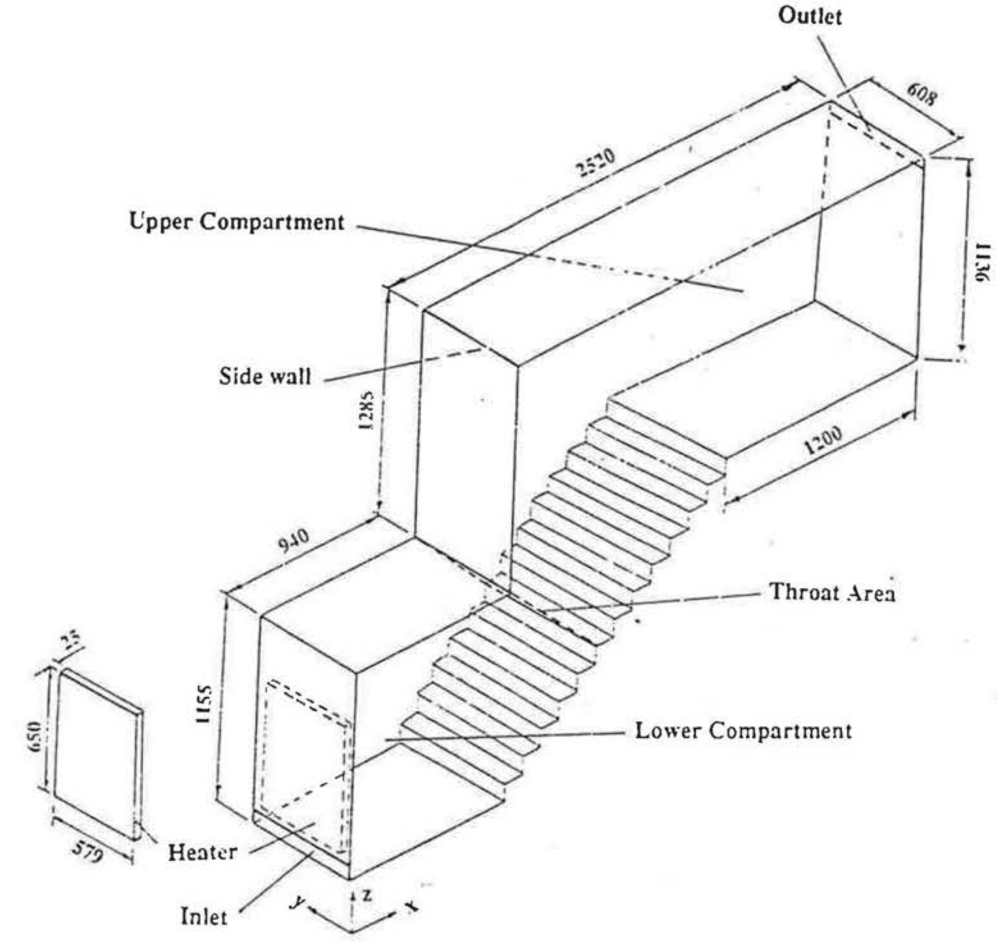

Figure 1. Schematic diagram of the stairwell model (dimensions are in mm).

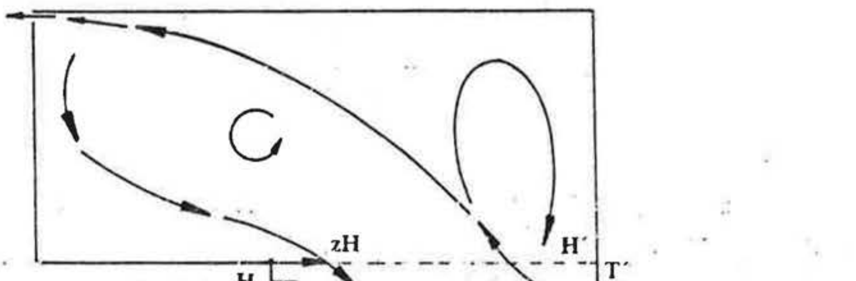

Figure 2. Measurement sections and two-dimensional view of the flow pattern.

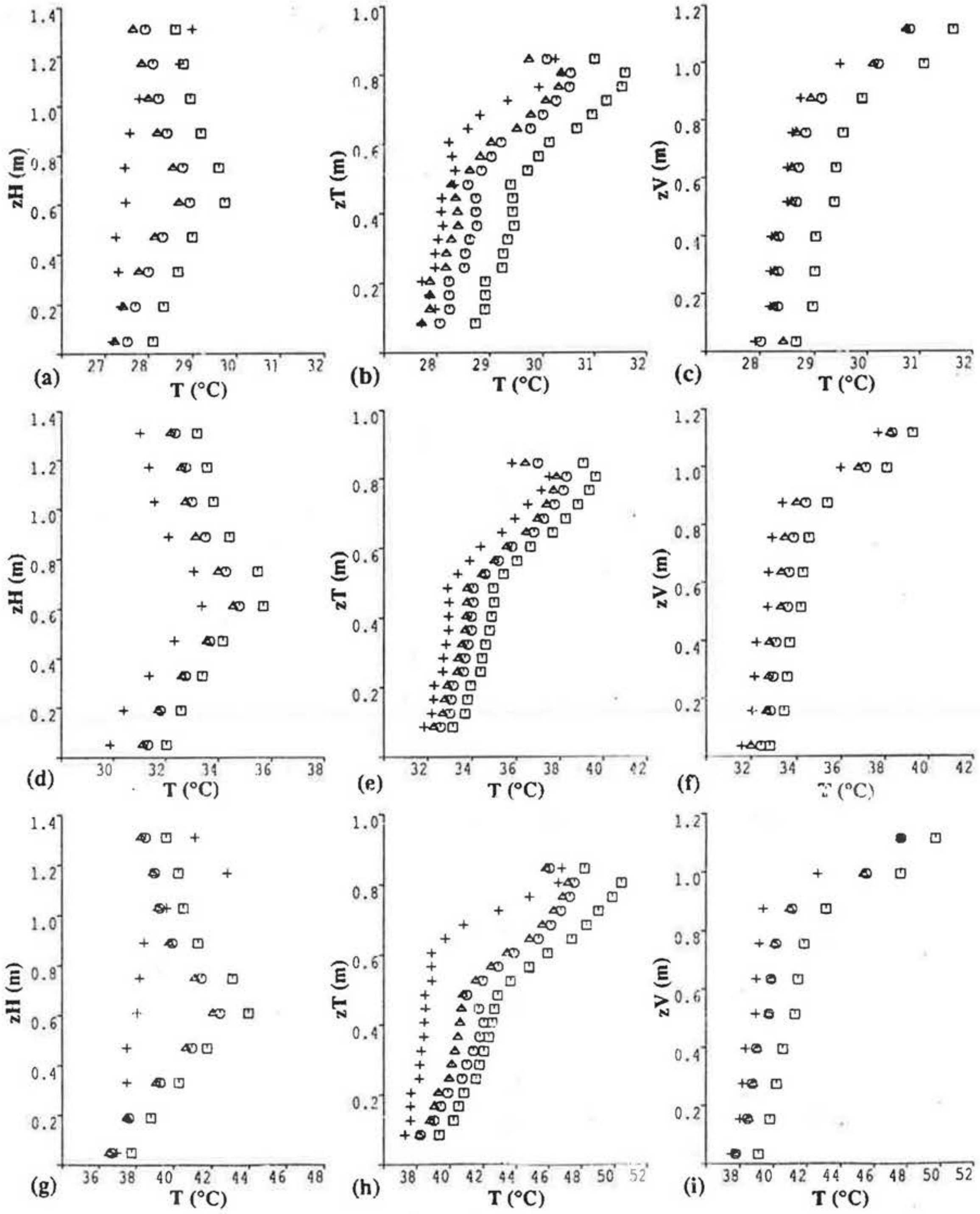

Figure 3. Temperature profiles for different inlet heights at one half width of the stairwell. (a), (d), (g) HH'; (b), (e), (h) TT'; (c), (f), (i) VV'. (a)-(c) 100 W; (d)-(f) 300 W; (g)-(i) 600 W. □ closed; ○ h_i=0.01 m; △ h_i=0.02 m; + h_i= 0.04 m.

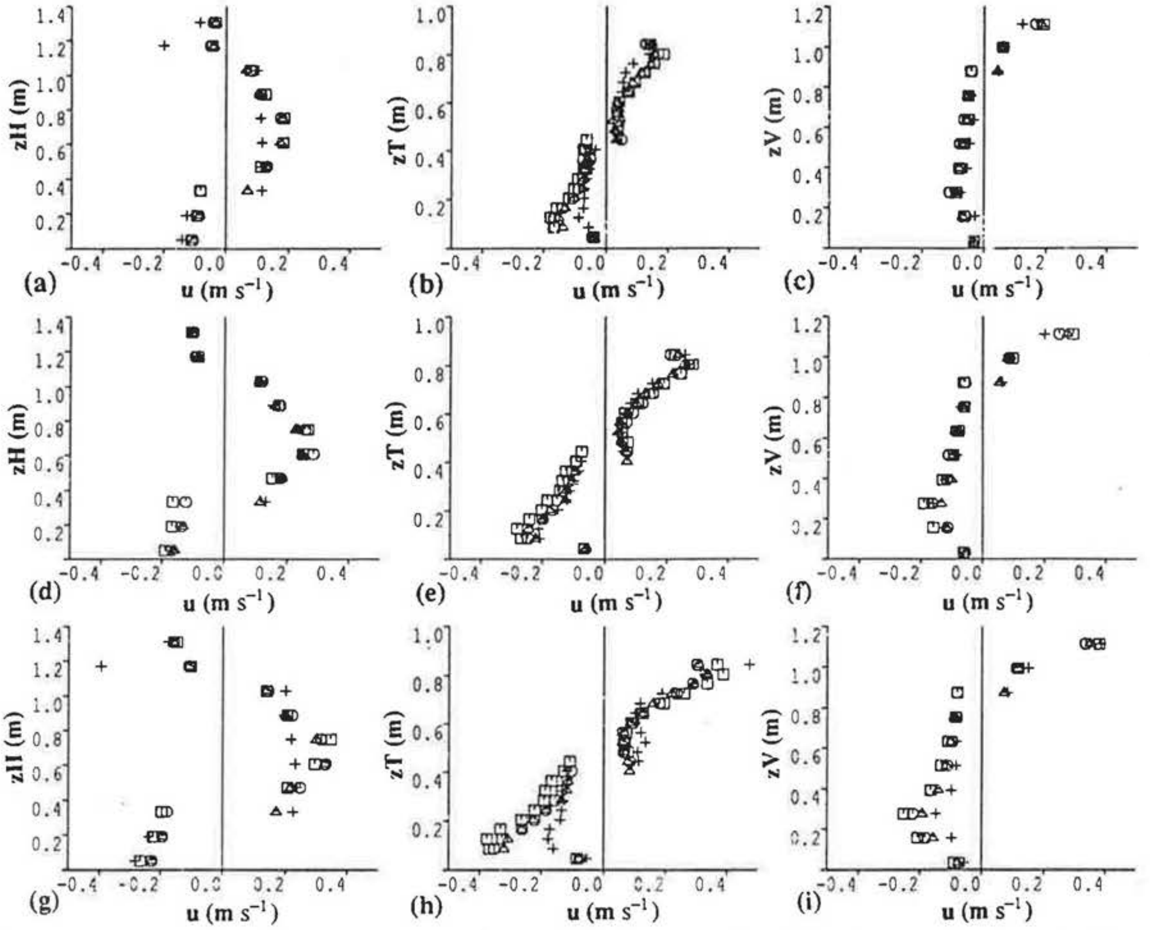

Figure 4. Velocity profiles for different inlet heights at one half width of the stairwell. (a), (d), (g) HH'; (b), (e), (h) TT'; (c), (f), (i) VV'. (a)-(c) 100 W; (d)-(f) 300 W; (g)-(i) 600 W. □ closed; ○ h_i=0.01 m; △ h_i=0.02 m; + h_i= 0.04 m.

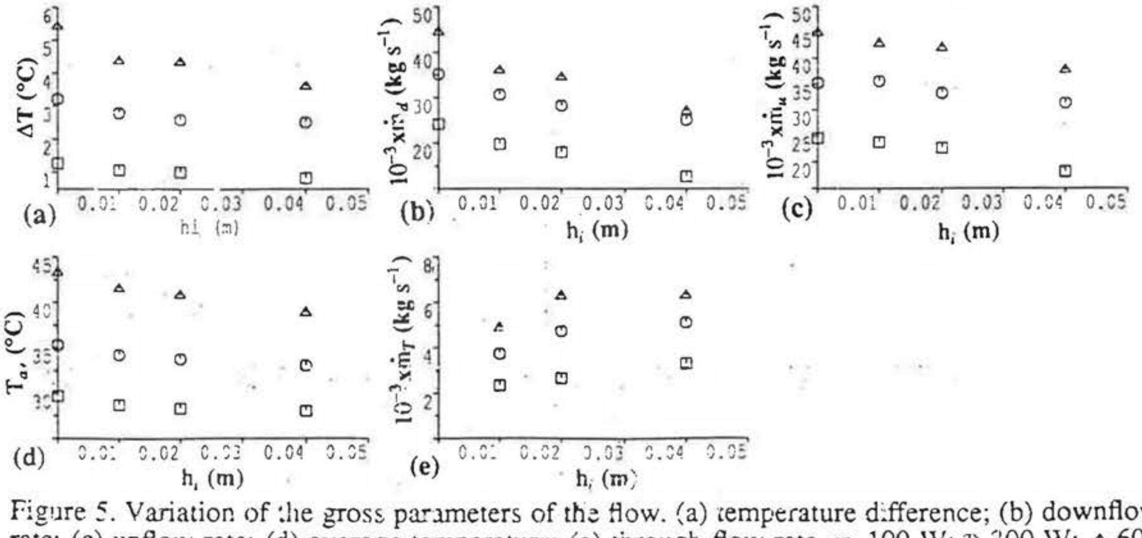

Figure 5. Variation of the gross parameters of the flow. (a) temperature difference; (b) downflow rate; (c) upflow rate; (d) average temperature; (e) through-flow rate. □ 100 W; ○ 300 W; △ 600 W.

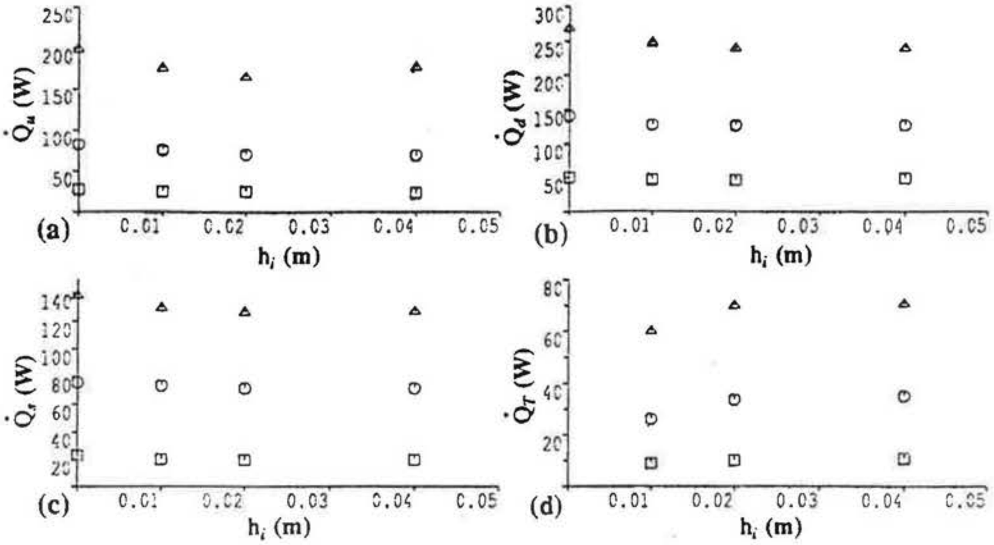

Figure 6. Heat losses from stairwell. (a) upper compartment; (b) lower compartment; (c) stairway; (d) through-flow. □ 100 W; ○ 300 W; △ 600 W.

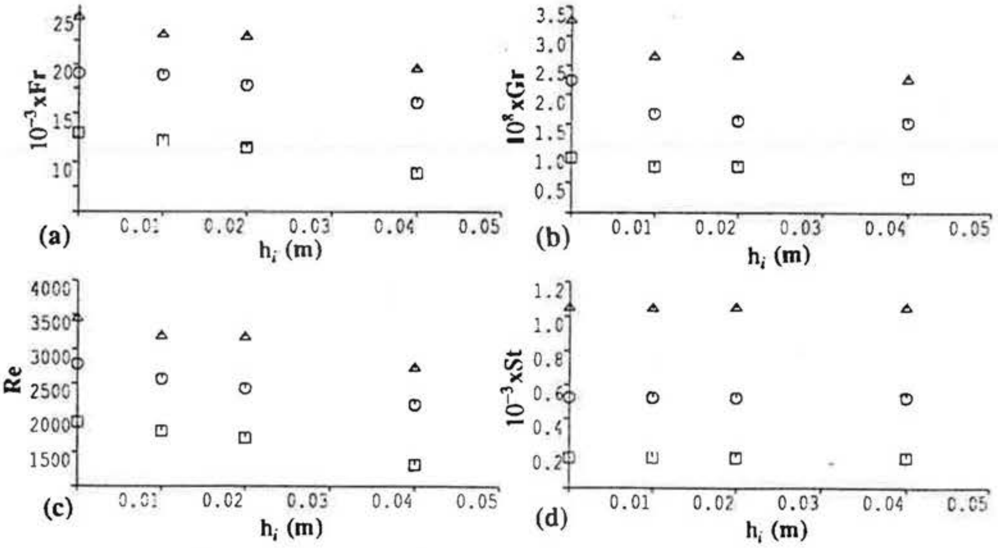

Figure 7. Characteristic dimensionless numbers. (a) Froude number; (b) Grashof number; (c) Reynolds number; (d) Stanton number. □ 100 W; ○ 300 W; △ 600 W.