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Evaluation of the Use of Solar Assisted Buoyancy Driven Natural Ventilation of Smaller Theatres in Canada

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The possibility of using stored hot water generated during the day by using solar energy to assist in the provision of adequate buoyancy driven natural ventilation flow rates through small theatres during the evening hours has been numerically investigated in a very basic manner. The hot water would be used to heat the air using a plate type heat exchanger system mounted in a roof-top chimney-like air discharge system. A simple building with a given cross-sectional design has been considered. Two-dimensional steady flow has been assumed to exist and the flow has been assumed to be symmetrical about the vertical centre-line through the building. The Boussinesq approximation has been adopted, i.e., the air properties have been assumed constant except for the density change with temperature that gives rise to the buoyancy forces, this being treated assuming a linear relation between the density changes and the temperature change. Radiant heat transfer effects have been neglected. The standard *k*-epsilon turbulence model with buoyancy effects being fully accounted for has been used. The heat generation from the audience has been treated as a uniformly distributed heat flux over the floor, the smaller the audience, the lower being this heat flux. The solution has been obtained using the commercial CFD solver FLUENT©. The results, while of a very preliminary nature, indicate that the proposed system could provide an adequate natural ventilation flow rate.

1. Introduction

A number of smaller churches and similar buildings in Canada have been converted into relatively small theatres, these theatres typically seating audiences of between 100 and 200. Performances in these theatres occur mainly at night with the theatres typically being in use in connection with these performances between about 6 pm and 11:30 pm. Many of these performances take place at times of the year when the daytime temperatures are quite high. As a result, if there is no air-conditioning system, uncomfortable temperatures can exist in the theatres during the performance period. However, at the performance times the outside air temperatures have almost always dropped to a comfortable value. In order to avoid the cost of installing an air-conditioning system and incurring the environmental effects resulting from the use of such a system, theatre groups may rely on some form of buoyancy driven natural ventilation of the theatre to deal with the problem of high inside temperature. The theatre windows, even when they exist, cannot be left open during a performance because of the disturbingly high external noise levels that can arise. Some form of system involving near floor inlet vents and a roof level or higher air discharge system is often adopted. In many cases the rate at which cooler external air is drawn into the theatre by such a system is inadequate to provide a thermally comfortable environment for the theatre audience during a performance. It has been proposed, therefore, that a solar heated hot water system should be incorporated into the natural ventilation system, the water being heated during the daylight hours when the theatre is not in use and then used to heat the

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buoyancy force driven natural ventilation air flow using a heat exchanger mounted in a chimney. A preliminary numerical analysis of the performance of such a system has been undertaken and is described in this paper.

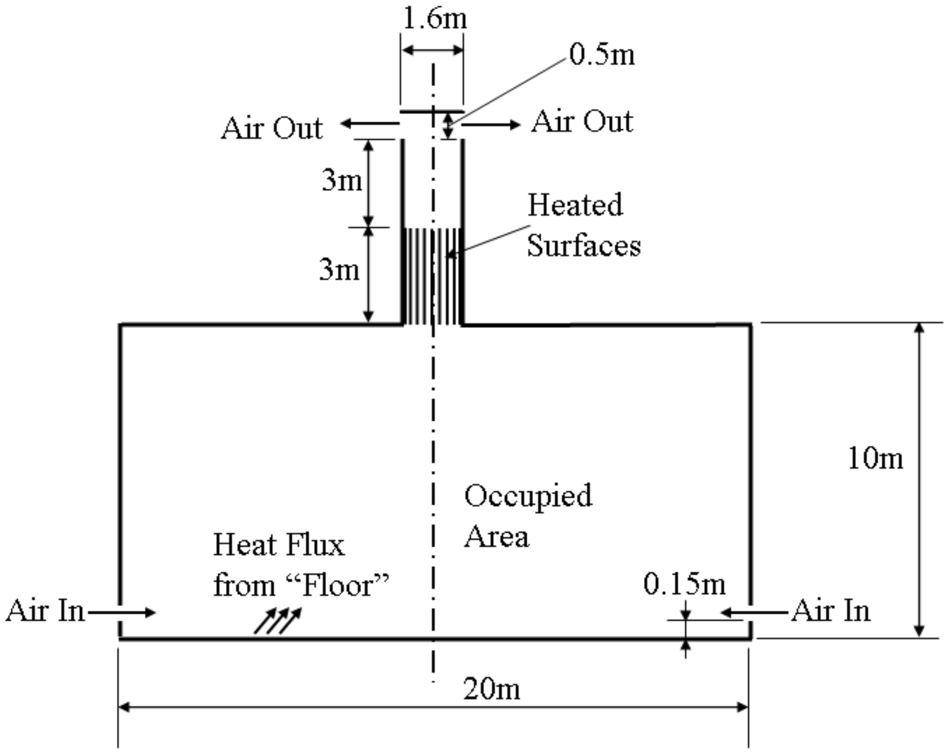

Figure 1: Flow situation considered.

A simple two-dimensional model of a typical theatre building of the type here being considered has been introduced. The presence of the heat generated by the audience in this building has been represented by a uniform heat flux distributed over the floor of the theatre. Inlet vents have been assumed to be located low on the side-walls of the theatre and the air-flow from the theatre has been assumed to be through vents at the top of the roof-mounted chimney. It has been assumed that the water heated by the solar system is circulated through a plate type heat exchanger system in the roof-top chimney-like air discharge system. The situation considered is therefore as shown in Figure 1.

There have been many studies of various aspects of natural ventilation. Typical of the general studies of natural ventilation are, those described by Allocca et al. (2003), Chen (2009), Chen and Li (2002), Etheridge and Sandberg (1996), Holford and Hunt (2003), Hunt and Linden (1999), Jiang and Chen (2003), Linden and Cooper (1996), and Owens (1987). Studies of natural ventilation flows based on the use of CFD methods, for example, are described by Ji et al., (2007), Ji and Cook (2007), Liu et al. (2009), Park and Holland (2001), Tan and Glicksman (2005), Wang and Wong (2009), and Wong and Heryanto (2004). A study of the cooling of a building by night time natural ventilation is described by Pfafferott et al. (2004). There do not appear to be any studies directly related to the situation being considered in the present study.

2. Solution Procedure

As mentioned, two-dimensional steady flow has been assumed to exist. The flow has been assumed to be symmetrical about the vertical centre-line through the building. The air properties have been assumed constant except for the density change with temperature that gives rise to the buoyancy forces, this having been treated using the Boussinesq approach. Radiant heat transfer effects have been neglected. The standard *k*-epsilon turbulence model with buoyancy effects being fully accounted for has been used. The heat generation from the audience, as already mentioned, has been treated as a uniformly distributed heat flux over the floor, the smaller the audience, the lower being this heat flux. The solution has been obtained using the commercial CFD solver FLUENT©. The effects of the chimney heat exchanger plate temperature, the external air temperature, the audience size, and the size of the inlet vents on the induced air flow rate through the theatre have been examined to determine the feasibility of using such a chimney heated system to improve the natural ventilation flow rate.

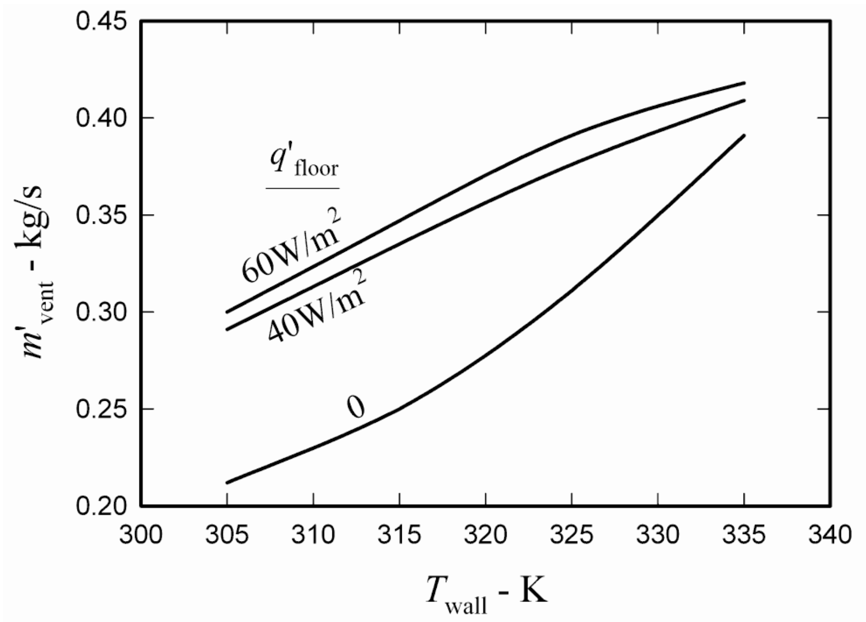

Figure 2: Variation of induced mass flow rate with the wall temperature of the heated plate surfaces in the chimney for various values of the floor heat flux for the case where the inlet vent height is 0.15 m and the outside air temperature is 290 K.

Extensive grid- and convergence criterion independence testing was undertaken. This indicated that the results presented here are, to within about 1 %, independent of the number of grid points and of the convergence-criterion used.

3. Results

Results have been obtained for the flow situation shown in Figure 1. For this situation the natural ventilation flow rate will depend on the temperature of the heated surfaces in the chimney, on the outside air temperature, on the floor heat flux rate, and on the vertical height of the inlet vents. Because the flow is assumed to be symmetrical about the vertical centre-line, the flow rate values, m'_{vent}, here presented are for flow in half of the building. These flow rate values are given in kg/s. An alternative would have been to present the flow rate in terms of air changes per hour (ACH), the two flow rate measures being related, if the chimney volume is not accounted for, and, since two-dimensional flow is being assumed, if a building depth of 1 m is considered, by:

$$ACH = \frac{3600}{\rho \, \text{Volume}} m'_{vent} = 29.4 m'_{vent} \tag{1}$$

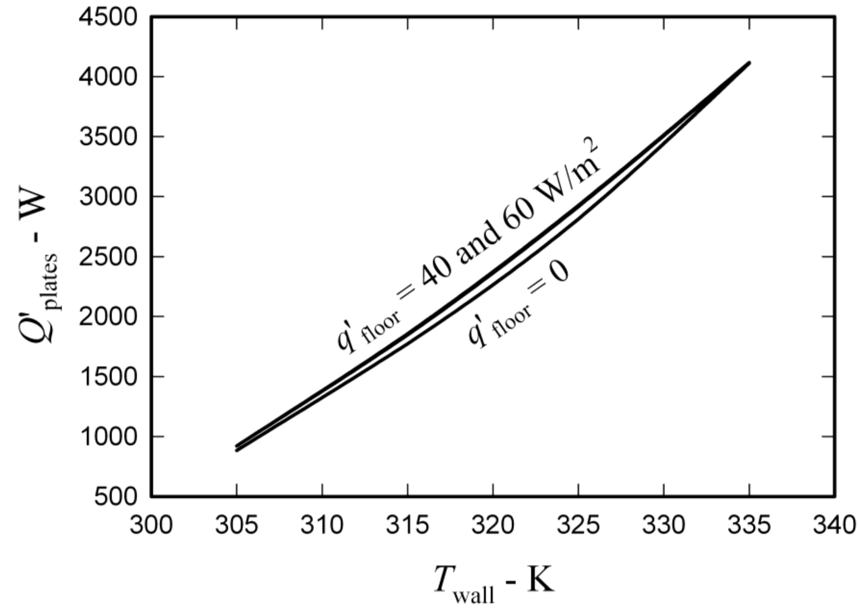

Figure 3: Variation of the total rate of heat transfer from the heated plate surfaces in the chimney for various values of the floor heat flux for the case where the inlet vent height is 0.15 m and the outside air temperature is 290 K.

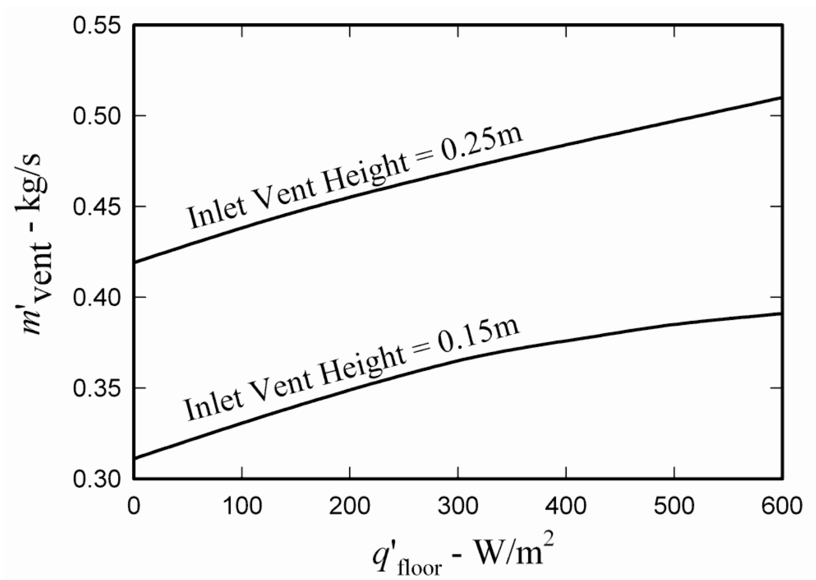

Figure 4: Variation of induced mass flow rate with floor heat flux for a wall temperature of the heated plate surfaces in the chimney of 325 K, an outside air temperature is 290 K, and inlet vent heights of 0.15 m and 0.25 m.

The variation of the ventilation flow rate in kg/s with the temperature of the heated chimney plates, T_w, for various values of the floor heat flux, q'_{floor}, is shown in Figure 2. These results are for an inlet vent height of 0.15 m. It will be seen from the results given in Figure 2 that when T_w is low and comparatively close to the external air temperature m'_{vent} is strongly dependent on the value of q'_{floor}, i.e., under these conditions the floor heating is a major factor in determining the ventilation flow rate. However, when T_w is relatively high m'_{vent} is only weakly dependent on the value of q'_{floor}, i.e., under these conditions the chimney heating is the dominant factor in determining the ventilation flow rate. Thus, the chimney heating is of particular importance in the cooling of the theatre prior to the arrival of the audience. Variations of the total heat transfer rate from the heated chimney plates with the plate temperature, T_w, for various values of the floor heat flux, q'_{floor}, are shown in Figure 3. These results are also for an inlet vent height of 0.15 m. It will be seen that the value of the floor heat flux, $q'_{floor,}$ has only a minor effect on the plate heat transfer rate. Lastly, Figure 4 illustrates the effect of the height of the inlet vent on the ventilation flow rate for various values of the floor heat flux, q'_{floor} . It will be seen that the increase in the height of the inlet vent from 0.15 m to 0.25 m increases the ventilation mass flow rate by more than 25 % at all values of the floor heat flux considered.

4. Conclusions

The results of the present study indicate that:

1. Adding the plate heat exchanger to the chimney can increase the natural ventilation flow rate by a substantial amount and this indicates that the use of this such a device should be explored in greater detail.
2. At the higher chimney plate temperatures considered the presence of the chimney plate heat exchanger has a much greater effect on the ventilation flow rate than the floor heat flux.
3. The size of the inlet flow vents has very significant effect on the ventilation flow rate and the effects of the sizing and positioning of the inlet vents will have to be explored in more detail in the future analysis of the system here considered.

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