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Natural Convection Heat Loss from an Open Room

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Abstract

Natural convection heat transfer in enclosures is an area that has particular significance to a wide range of applications. However natural convection heat transfer from enclosures with openings to the surroundings, such as open windows or doors in buildings, has received far less attention. In this regard, there is still a lack of generalised relationships that can be used in determining the heat transfer in partially open enclosures. The development of such relationships is particularly pertinent to the development of more accurate modelling tools that describe the thermal characteristics and indoor air quality in low energy buildings.

As such, this work presents an investigation of the natural convection heat loss from a partly open room style enclosure, with a view to understanding the mechanism and also to developing relationships that describe it. It shows that heat transfer from the partly open enclosure is strongly influenced by both the Rayleigh number and also the opening size.

1. Introduction

Natural convection heat transfer from enclosures with openings to the surroundings is an area of work that has particular significance to the development of energy efficient buildings. Despite this, there are few studies that have examined the issue of heat loss from open or partly open enclosures.

The majority of the works undertaken on open enclosures have examined the issue of natural convection as it relates to ventilation rates in buildings, as well as more fundamental studies of the convection mechanisms under both steady and transient conditions. One such example of this is the work of (Bilgen and Muftuoglu, 2008) who computationally examined the flow in an open square cavity with multiple slots. They found that the Nusselt number and the volume flow rate both increased with Rayleigh number and also the opening ratio.

In their work (Nielsen et al, 1979) computationally examined buoyancy affected flows in a room like enclosure with ventilation. They noted the flow was affected by both the geometry and also the Archimedes number. Similarly, (Argiriou et al, 2002) examined the ventilation of buildings through large openings on a single side and with sun shades. They also found that the airflow could be related to the Archimedes number.

In a more fundamental sense, (Gladstone and Woods, 2001) examined buoyancy driven ventilation of a room with a heated floor. They undertook a series of experiments of the flow in their enclosure, and then used the results to develop a model of the flow under generalised conditions. They also note that there is a need for further work in the field with a particular emphasis on the opening size.

Despite the insights of the studies on ventilation rates, there is also a need to relate these to the heat transfer. In their study (Yu and Joshi, 1998) undertook a computational fluid dynamics (CFD) analysis of the heat transfer by laminar natural convection from electronic components housed in a vented enclosure. They found that both location and size of the openings influenced the flow and temperature in their enclosure. Also they noted that the vent size had a significant influence on the heat transfer.

Further studies have in the field have also examined the influence of opening aspect ratio as well as the inclination of enclosures on the heat transfer. Studies such as the work of (Prakash et al, 2012) and (Miyamoto et al, 1989) have explored this and have delivered a number of relationships to describe heat transfer as a function of these two parameters as well as the Rayleigh or Grashof number.

Despite the work that has been undertaken, there is still a lack of generalised relationships that can be used in determining the heat transfer in partially open enclosures. In the work of (Lomas, 1996) the effect that varying convective heat transfer coefficients in building energy simulation models is discussed; in this it is shown that varying the value of this only slightly can significantly affect the predicted heating energy required in buildings. Therefore, with partly open buildings, this prediction becomes even more difficult, and so there is a need to develop relationships to describe the impact this has on convective heat transfer coefficients. As such, this work aims to undertake a preliminary investigation of this problem with a view to developing such a relationship.

2. Numerical Modelling

As an initial step to determining the influence of natural convection heat transfer in a partially open enclosure, a steady state model was formulated in a commercial CFD solver (Cosmos, 2006) based on the finite volume method. For this study a 3-dimensional air filled cubic enclosure with single side openings of aspect ratio 5%, 10%, 25%, 50% and 75% was examined, as shown in Figure 1. For the simulations, the floor of the enclosure was heated at a constant temperature (10°C, 30°C, 50°C and 70°C above the surroundings) while all other walls were assumed to be adiabatic, this corresponded to Rayleigh numbers in the range 1×10^8 to 5×10^8, taking the enclosure height to be the characteristic length. In this regard the aim was to approximate the effect of an opening on the heat loss from a room where solar radiation had been shining on the floor, thus leading to an increase in its temperature.

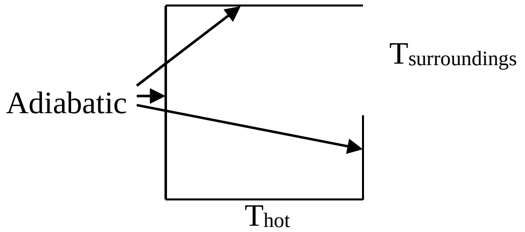

Figure 1. Schematic representation of enclosure

The solver utilises the Reynolds averaged Navier-Stokes equations in the prediction of turbulent flows. Further it uses a Cartesian coordinate system to spatially distribute a rectangular computational mesh; in this case, after a mesh dependence study, a mesh of approximately 500,000 cells was used. In its treatment of turbulence, it employs transport equations for the turbulent kinetic energy and turbulence dissipation rate using the standard k-ε model. Additionally it uses a Modified Wall Function approach, where a Van Driest's profile is utilised to describe the near wall flow. It is suggested by that this treatment provides accurate velocity and temperature boundary conditions in the conservation equations.

The solver utilises a cell-centred approach to obtaining a conservative approximation of the governing equations. The second-order upwind approximations for the fluxes are treated using the QUICK scheme and a Total Variation Diminishing (TVD) method. Finally, a SIMPLE-like approach and an operator-splitting technique are used in the treatment of time-implicit approximations made in the continuity and convection/diffusion equations. Despite its limitations has shown that the solver is able to provide accurate prediction of natural convection in a square enclosure when compared with the benchmark numerical solution of (de Vahl Davis, 1983).

3. Numerical Results

In considering the results of the simulations, it was apparent that increasing the temperature of the heated floor led to an increase in heat transfer from this surface. It was noticeable that as the opening size increases, so does the heat transfer from the heated wall as shown in Figure 2 and also by (Prakash et al, 2012) and (Miyamoto et al, 1989). In this regard the Nusselt number for the heated wall could be represented as a function of the opening aspect ratio (d/D) and the Rayleigh number. For this study this can relationship be expressed by $Nu=0.12\ Ra^{0.34}\ (d/D)^{0.4}$.

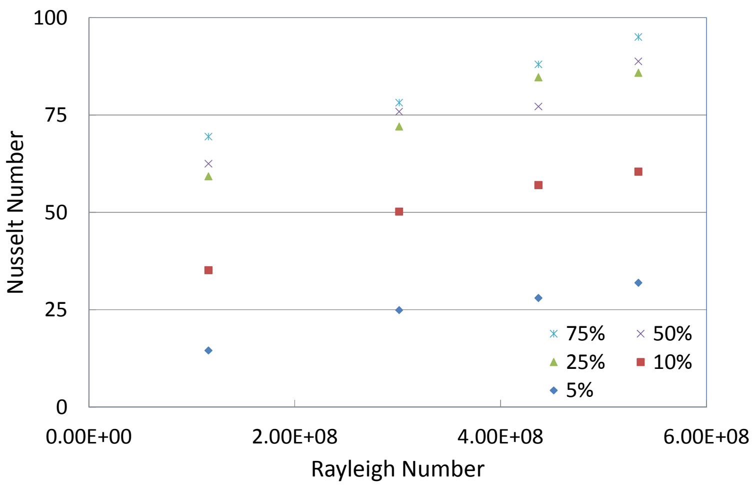

Figure 2 Nusselt v Rayleigh Number for an open enclosure with various opening sizes

When considering this, it is interesting to examine the flow in the enclosure. In Figure 3 it can be seen that for a small opening, a significant part of the flow is recirculating in the enclosure whereas for a larger enclosure there is a greater exchange of flow between the enclosure and the surroundings. In addition, a plume of cold air extends almost the entire height of the enclosure for large openings; these factors would explain why the heat transfer is higher with larger openings.

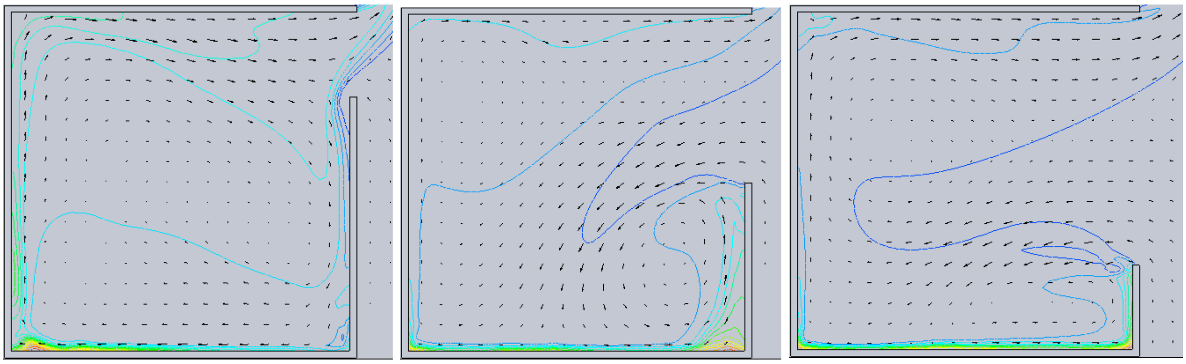

Figure 3 Flow in an open enclosure with various opening sizes

3. Experimental Setup

The computational modelling of the partly open enclosure suggested that the Rayleigh number and also the size of the opening played an important role in the determination of the flow and heat transfer for such systems. In order to verify this observation, it was decided to develop an experiment to explore this further.

As such, an acrylic tank 1.2m x 1.2m x 0.6m was designed to contain a small open cavity acrylic enclosure that was subsequently submerged under water (rather than in air). The acrylic open cavity was a cube with internal dimensions of 100mm and a wall thickness of 4.5mm. The cube cavity had one vertical side open to the surrounding fluid in the larger tank, and a set of walls of different heights were designed to fit into the vertical open wall to create four sets opening sizes, 100%, 75%, 50% and 25% open. In this work two locations were tested for the opening; top open and bottom open.

As with the computational model, the floor of the small enclosure was heated using a variable power supply feeding a stick-on resistance heating element attached to a 5 mm thick aluminium plate in order to provide a uniform surface temperature. The heater plate had four T-type thermocouples symmetrically placed across its surface to record the temperature. Mineral wool was packed under the heating element to eliminate heat loses through the bottom. In this manner the heat transfer was predominantly from the surface of the aluminium plate in contact with the water in the tank. In addition four thermocouples where then used to measure fluid temperature in the tank (thus giving the temperature difference between the heater and the surroundings) and also the local air temperature. Figure 4 shows a schematic representation of the experimental setup.

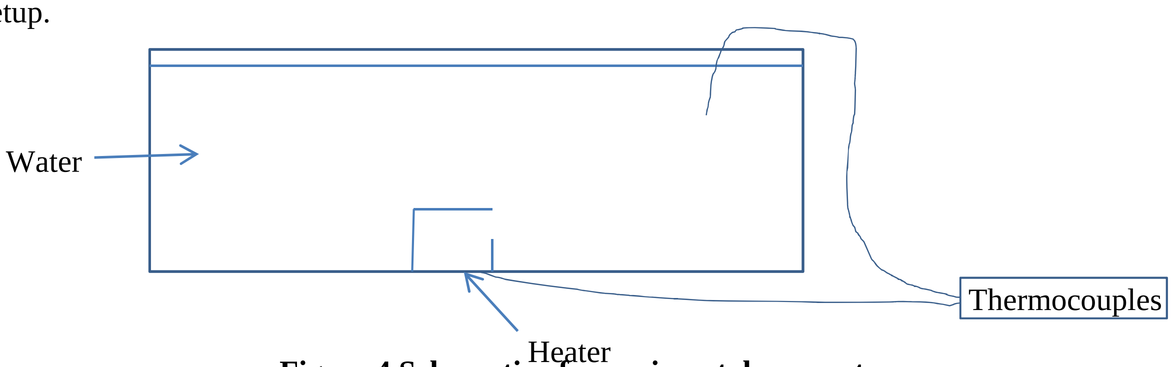

Figure 4 Schematic of experimental apparatus

To vary the Rayleigh number in the enclosure, the temperature difference across the enclosure was controlled using a variable DC power supply connected to the resistance heating element. The power being drawn by the heater was controlled by varying the voltage with a fixed current. These voltages and the corresponding drawn current produced 1, 2, 5, 7.5 and 10W power outputs. To determine the temperature gradient in the enclosure (between the heater and surrounding water) the thermocouples were connected to a Picolog TC-08 eight channel thermocouple data acquisition system and recorded by a computer via the USB interface.

Finally, to accurately determine the heat transfer coefficient within the enclosure it was necessary to allow the system to reach steady state conditions. To do this, the heater power was set and the water and heater temperatures were monitored. When the variation of the temperature difference between the heater and the cover was not more than 0.6K over a 30 minute period, it was assumed that the system had reached a steady state. Subsequently, the readings taken during this period were used to determine the natural convection heat transfer coefficient where the natural convection heat transfer coefficient for the heated surface (h_c) in the enclosure can be determined from Newton's law of cooling as shown in Equation 1.

$$h_c = \frac{Q}{A_p(T_p - T_w)} \quad (1)$$

Where Q is the rate heat is supplied to the heater (electrical power) and the temperature difference is that between the average heater temperature (T_p) and the average water temperature (T_w) for a heater area (A_p).

4. Experimental Results

In order to generalise the results of the experimental testing, the heat transfer data was non-dimensionalised in terms of the Rayleigh and Nusselt numbers. In doing this, the characteristic length chosen was the enclosures height, while the fluid temperature for the calculation of the Rayleigh number is taken as the film temperature, the average of the averaged fluid and plate temperatures.

As described previously, the small enclosure was designed such that the size and location of the opening in the enclosure could be easily varied. As such for the first series of experiments, the opening was positioned at the top half of the enclosure (as illustrated in Figure 4) and the heater power varied. In Figure 5 it can be seen that with the side completely open (100%), that there is the greatest amount of heat transfer as one would expect. Further, by reducing the opening size it can be seen that this is reduced as was seen in the computational results.

In the second experiment, the location of the opening was changed to be at the bottom of the enclosure (close to the heated surface). Now in Figure 6 it can again be seen that reducing the opening size reduces the heat loss from the enclosure.

As such the observations from the computational study would appear to be correct, and it can be seen that the heat transfer coefficient in a partly open enclosure is dependent on both the Rayleigh number and also the opening size. However, the suggestion from previous studies that the location of the opening affects the heat loss cannot be confirmed from the experimental data.

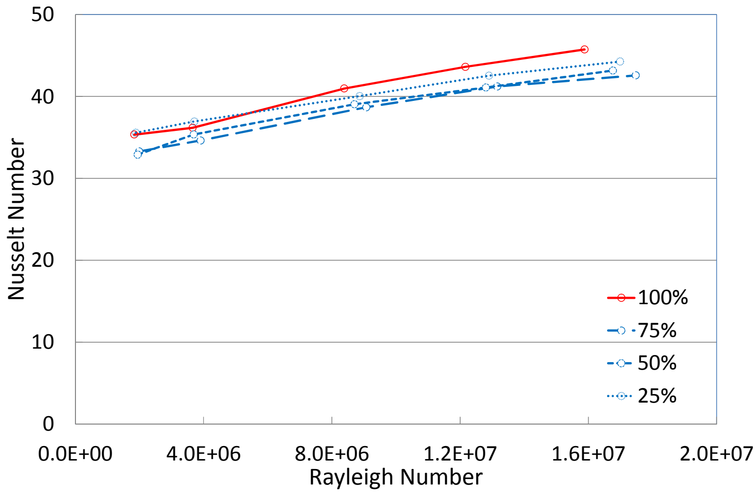

Figure 5 Heat transfer for enclosure with opening at top

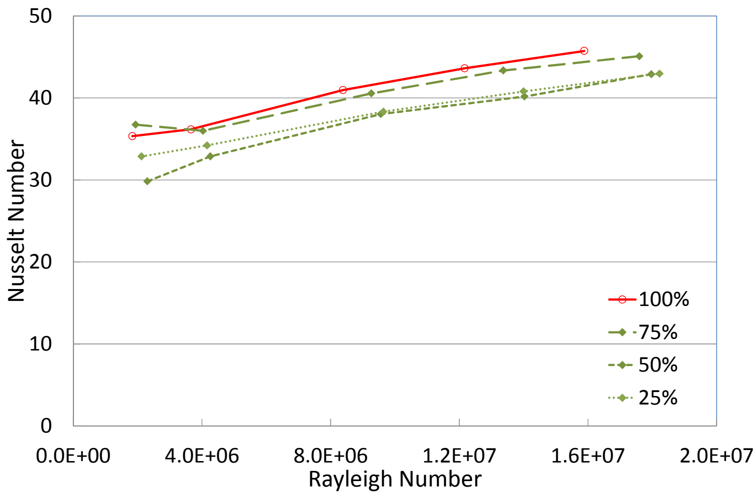

Figure 6 Heat transfer for enclosure with opening at bottom

5. Discussion and Conclusion

Natural convection heat transfer from enclosures with openings to the surroundings, such as open windows or doors in buildings, has received little attention and so there is a lack of relationships that can be used in determining the heat transfer in such systems. In order to develop more accurate modelling tools that describe the thermal characteristics and indoor air quality in low energy buildings, the development of such relationships is paramount.

This work has shown both computationally and experimentally, that heat transfer from partly open enclosures is strongly influenced by both the Rayleigh number and also the opening size. Such a finding, though significant requires further work to develop a generalised relationship for a wider range of Rayleigh numbers. Further, though not observed in this study, it is possible that the location of such openings may influence the heat transfer coefficients which would also influence the nature of a relationship to describe this. As such, there is still a significant amount of work to be undertaken in the development of such expressions.

6. References

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