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A Numerical Study of the Effect of a Pair of Horizontal Frame Members on the Laminar and Turbulent Natural Convective Heat Transfer from a Recessed Window to a Surrounding Room

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The vertical and horizontal frame members that often protrude from the inner surface of the window can have a significant effect on the convective heat transfer rate from the inner (room-side) surface of the window. The purpose of the present numerical study was to determine, in a basic way, how the relative size of a pair of horizontal frame members mounted symmetrically about the centre of the window affect this convective heat transfer rate. A recessed window has been considered. The flow has been assumed to be steady and both laminar and turbulent flows have been considered. Fluid properties have been assumed constant except for the density change with temperature that gives rise to the buoyancy forces, this being dealt with using the Boussinesq approach. The governing equations have been solved using the FLUENT commercial CFD code, the *k*-epsilon turbulence model with standard wall functions having been used in the calculations. The solution has the following parameters: the Rayleigh number, the Prandtl number, the dimensionless horizontal distance between the inner window surface and the inner surface of the wall in which the window is mounted (the dimensionless recess depth), and the dimensionless width and depth of the frame members. Results have only been obtained for a Prandtl number of 0.74, which is effectively the value for air, and for single values of the dimensionless window recess depth and of the dimensionless frame height. The effects of the other dimensionless variables on the window Nusselt number have been numerically studied.

1. Introduction

Improved models for the convective heat transfer rate from the inner surface of a window to the surrounding room are needed to assist in the development of systems that reduce the overall heat transfer rate through the window. The horizontal portions of the window frame that often protrude from the inner surface of a window can significantly affect the convective heat transfer rate from the window to the room. The purpose of the present numerical study was to determine, in a basic way, how the relative size of these horizontal frame members affects the convective heat transfer rate from the inner,

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i.e., room-side, surface of the window to the room. A recessed window with a pair of horizontal frame members has been considered, the geometry considered being shown in Figure 1.

There have been many studies of the effect of frames on the overall heat transfer rate through a window but these have mainly been concerned with the heat conduction through the frame and with the effect of the frame on the heat transfer through the

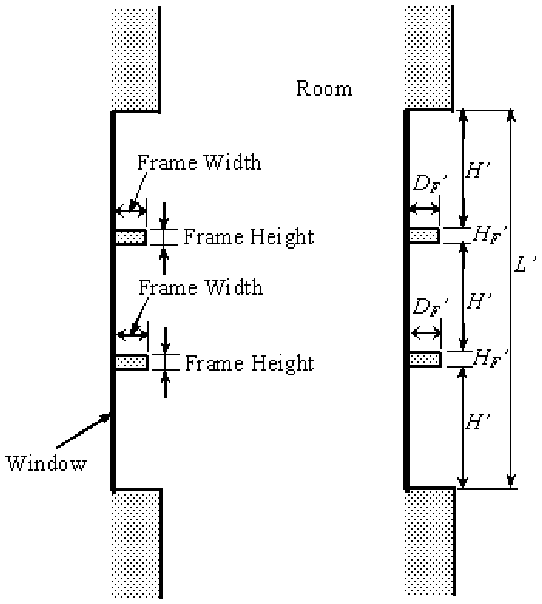

Figure 1: Situation considered.

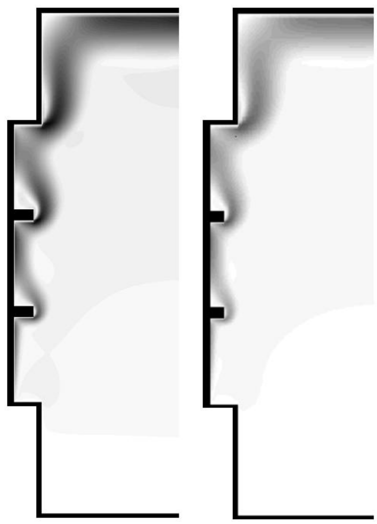

Figure 2: Typical Velocity Distributions. Results are for Ra = 10^9 and D_F = 0.07 (left) and 0.05 (right).

window. Typical of such studies is that of Gustavsen et al. (2005). The effect of the external portions of the frame on the heat transfer between the room-side of the window and the room, however, has received little attention. Oosthuizen (2007), Oosthuizen and Pett (2008) and Oosthuizen et al. (2008) undertook studies of the effect of frame members on the room-side convective heat transfer but assumed that the flow remained laminar. The effect of the development of turbulent flow on the heat transfer rate was considered by Oosthuizen (2009). There have been many studies concerned with the heat transfer from the room-side of a window to the room but these have mainly ignored the possible presence of frame members on the room-side of the window. Typical of these studies are those of Oosthuizen et al. (2005), Collins et al. (2002a, 2002b), Duarte et al. (2001), Machin et al. (1998), Shahid et al. (2003), Phillips et al. (2001), Oosthuizen et al. (2008), Oosthuizen and Naylor (2009), and Oosthuizen (2008). The present study considers only the convective heat transfer as did many of these previous studies. In window heat transfer situations, the radiant heat transfer can be very important and can interact with the convective flow, e.g. see Phillips et al. (2001).

2. Solution Procedure

The mean flow has been assumed to be steady and the Boussinesq approach has been used. It has been assumed that the "window" is at a uniform temperature, T'_H , and that this window temperature is higher than the temperature of the air in the "room" to which the window is exposed, T'_F. The solution has been obtained by numerically solving the governing equations subject to the boundary conditions using the commercial cfd solver, FLUENT. Although the flow considered is fundamentally two-dimensional the possibility existed that three-dimensional flow would develop in the transition region. For this reason the full three-dimensional governing equations were solved for a finite window width. However, such three-dimensional flow was not found to exist in any of the flows considered here. In the situation considered here both laminar and turbulent flow can occur. The k-ε turbulence model with the full effects of buoyancy forces accounted for and with standard wall functions has been used in obtaining the solutions. In past studies this turbulence model has been found to give moderately good predictions of when transition to turbulence occurs and of the flow and heat transfer in the laminar, transitional, and turbulent regions. Extensive grid- and convergence criterion independence testing was undertaken. This indicated that the heat transfer results presented here are to within 1% independent of the number of grid points and of the convergence-criterion used.

When the frame width is large there are essentially separate flows on the portion of the window below the lower frame, on the portion of the window between the two frames, and on the portion of the window above the upper frame. Therefore, the mean heat transfer rates from these three sections of the window have been separately considered, the results being expressed in terms of the mean Nusselt number for these lower, middle, and upper sections of the window, this Nusselt number being defined by $Nu = \bar{q}'H'/\left[k(T'_w - T'_F)\right]$ where $\overline{q'}$ is the mean heat transfer rate for the section of the window considered, k is the thermal conductivity, T'_w is the window surface temperature, T'_F is the room air temperature, and H' is the height of the window sections, the total window height then being $3H' + 2H'_F$. The Rayleigh number used in presenting the results is also based on H' and on the overall temperature difference between the window temperature and the room air temperature, i.e. is defined by $Ra = \beta g \rho^2 c_p \left(T'_w - T'_F\right) H'^3 / \mu k$ where β, ρ and μ are the bulk expansion coefficient, the density, and the viscosity respectively.

3. Results

The solution parameters are the Rayleigh number, Ra, the Prandtl number, Pr, the dimensionless "depth" to which the window is recessed, $R = R' / L'$, and the dimensionless sizes of the frame members where L' is the overall height of the window. Results have only been obtained for $Pr = 0.74$ which is essentially the value for air. Values of the Rayleigh number based on H', i.e. Ra of between 10^5 and 10^{12}, have been considered. The characteristic dimensions D'_F and H'_F that define the frame member size are shown in Fig. 1. The dimensionless frame sizes used are then $D_F = D'_F /L'$ and $H_F = H'_F /L'$. The dimensionless window recess depth is defined by $R = R' /L'$ where

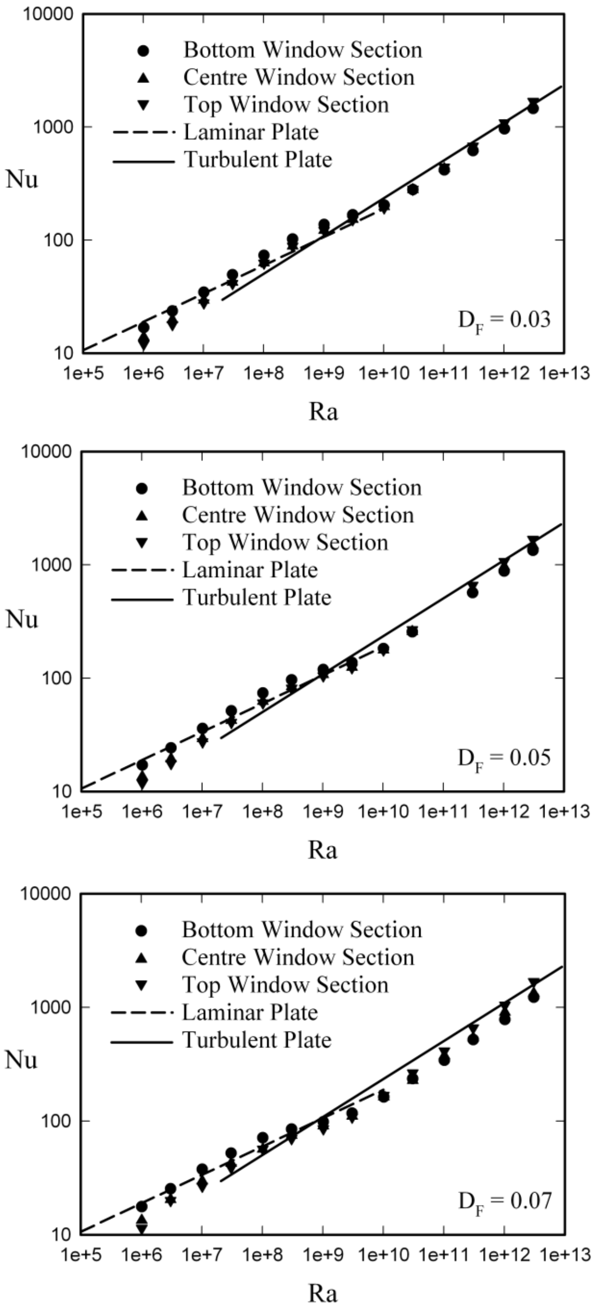

Figure 3: Variation of Nusselt number with Rayleigh number for D_F = 0.03 (top), 0.05 (centre) and 0.07 (bottom). The lines show the correlations for the cases of laminar and turbulent flow over a vertical flat plate.

R' is the depth to which the window is recessed. Results will only be presented here for H_F = 0.04 and R = 0.1.Typical flow pattern over window are shown in Figure 2. The flow separation downstream of the frame members, i.e. in the middle and upper sections of the window, will be noted and the development of a boundary layer in the flow over the middle and top section will be noted.

Typical variations of the mean Nusselt numbers for the bottom, middle, and top sections of the window with Rayleigh numbers for three different values of D_F are shown in Fig. 3. Also shown here is the variation of Nusselt number with Rayleigh number for laminar and turbulent flow over an isothermal vertical flat plate of height H'. It will be seen that, except at the lower Rayleigh numbers, the mean Nusselt numbers for the upper, middle, and lower sections are nearly the same and very close to the flat plate values. This indicates that except at the lower Rayleigh numbers the Nusselt numbers for the lower, middle, and upper window sections are very nearly independent of each other and can be adequately predicted using the flat plate equation. For Rayleigh numbers less than approximately 10^8, i.e. in the laminar flow region, the Nusselt numbers for the upper and middle window sections are lower than those for the lower window section. This results from the fact that the boundary layer thicknesses in the laminar flow region are larger than those existing at higher Rayleigh numbers, the boundary layer thicknesses in the laminar flow region being comparable to D'_F and as a result the flow over the middle and upper window sections is dependent on that over the lower window section.

Conclusions

The results of the present study indicate that:

1. For Rayleigh numbers above approximately 10^8 the mean Nusselt numbers for the three window sections are almost the same and can be calculated with adequate accuracy by separately applying the vertical isothermal plate correlation equation to each of the three window sections.
2. For Rayleigh numbers less than approximately 10^8 the mean Nusselt numbers for the middle and upper window sections are less than those for the lower window sections, the difference increasing with decreasing Rayleigh number for a fixed value of D'_F.
3. For Rayleigh numbers less than approximately 10^8 the flow is essentially laminar and for Rayleigh numbers greater than approximately 10^{10} the flow is dominantly turbulent.

Acknowledgement

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