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Three-Dimensional Flow Effects on Convective Heat Transfer from a Cold or a Hot Window Covered by a Simple Plane Blind to a Room

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Almost all existing studies of convective heat transfer through a window-blind arrangement assume that the flow is two-dimensional. These often also assume that the convective heat transfer rate is the same for the case where the window is colder than the air in the room and where the window is hotter than the air in the room. However, in situations involving tall narrow windows, three-dimensional flow effects can become very important. In many cases, the temperature of the window relative to that of the air in the room (colder or hotter) has a significant influence on the convective heat transfer rate. The present study was undertaken to numerically determine when these effects must be taken into account for a system involving a plane blind. In the situation considered, the window is represented by a rectangular vertical isothermal wall section imbedded in a large vertical adiabatic wall surface and exposed to a large surrounding room in which the mean temperature is assumed to be known. The plane blind is represented by a thin straight wall which offers no resistance to heat transfer across it and in which conduction heat transfer is negligible. The blind has the same size as the window and is aligned with the window with a relatively small gap between the window and the blind. The gap at the top of the window between the window and the blind is closed by a horizontal blind section. The flow has been assumed to be laminar. Fluid properties have been assumed constant except for the density change with temperature that gives rise to the buoyancy forces. The governing equations have been written in dimensionless form and the resultant dimensionless equations have been numerically solved. The solution has the following parameters: the Rayleigh number based on the window height, the Prandtl number, the dimensionless horizontal distance between the window and the blind, the dimensionless temperature of the window relative to that of the air in the room (colder or hotter) and the dimensionless width of the window. Results have been obtained for a Prandtl number of 0.7. The effect of the other variables on the window Nusselt number has been numerically determined.

1. Introduction

Blinds can be used to reduce building energy use and improved models for the effects of blinds on window heat transfer need to be developed. Almost all available studies of window-blind systems assume that the flow is two-dimensional. It is also frequently assumed that the convective heat transfer rate is the same for the case where the window is colder than the air in the room and where the window is hotter than the air in the room. The purpose of the present numerical study is to further investigate whether these assumptions are justified for a plane blind system. The actual situation considered here is only an approximate model of the real situation. However, the results obtained here will give an indication of the effect of the governing parameters on the convective heat transfer rate from an actual covered window.

In the present study the window is represented by a rectangular vertical isothermal wall section imbedded in a large vertical adiabatic wall surface. The window is exposed to a large surrounding room in which the mean temperature is assumed to be known and can be either lower than or higher than the window temperature. The plane blind is represented by a thin straight wall which offers no resistance to heat transfer across it and in which conductive heat transfer is negligible. This blind is of the same size as the window and is mounted parallel to the window with a relatively small gap between the window and the blind. The gap at the top of the window between the window and the blind is closed by a horizontal blind section. The assumed situation is as shown in Fig. 1. Attention has only been given to the convective heat transfer from the window, i.e., radiative heat transfer and the effects of solar radiation have not been considered. Although the model used here is only an approximation of the real situation, the results obtained with this model will give an indication of the effect of the governing parameters on the convective heat transfer rate from an actual window.

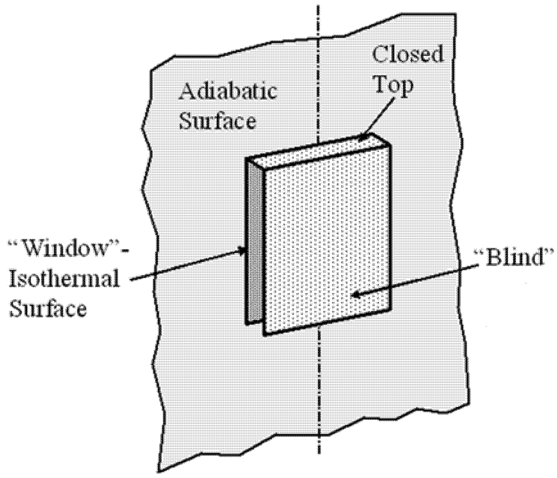

Figure 1. Flow situation considered.

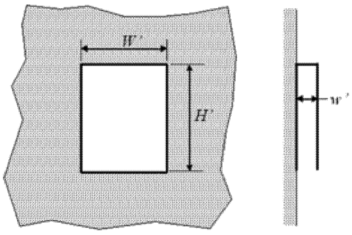

Figure 2. Window-Blind system dimensions.

The present work was undertaken as part of a wider study of the effect of window coverings on the heat transfer rate from windows. The work initially concentrated on the case where the window is hotter than the room air; see for example Collins et al. (2002a, 2002b). These studies and those described by Phillips et al. (1999) have concentrated on Venetian blinds. Some studies involving vertical blinds have also been undertaken, e.g., see Oosthuizen et al. (2002a, 2002b). Studies of situations involving plane blinds have also been undertaken, e.g., see Oosthuizen (2002a, 2002b). A review of much of this work is given by Oosthuizen et al. (2005). All of these studies have assumed that the flow over the window-blind was two-dimensional. Later studies, e.g., Oosthuizen (2006) have shown that three-dimensional flow effects can be very important. The present study, as is the case in most of the previous studies mentioned above, considers only the convective heat transfer. In window heat transfer situations, however, the radiant heat transfer can be very important and can interact with the convective flow, e.g. see Collins et al. (2002a) and Phillips et al. (1999).

2. Solution Procedure

The flow has been assumed to be laminar and two-dimensional. Fluid properties have been assumed constant except for the density change with temperature that gives rise to the buoyancy forces, this being treated by means of the Boussinesq type approximation. The covering over the heated wall section (the "blind") has been assumed to offer no resistance to heat transfer and to have negligible thickness so that conduction along it is negligible. The effects of radiative heat transfer have been neglected. The governing equations have been written in terms of dimensionless variables using the height, H', of the heated wall section (the "window") as the length scale and the overall temperature difference $(T_w - T_a)$ as the temperature scale, T_a being the air temperature in the "room" to which the window is exposed. The "window" temperature, T_w , can be higher or lower than the temperature of the air in the "room". The resultant set of dimensionless equations have been solved using a commercial finite-element based code, FIDAP. Only the mean heat transfer rate from the isothermal surface (the "blind") will be considered here. This has been expressed in terms of a mean Nusselt number, *Nu*, based on the window height, H', and on the absolute value of the overall temperature difference $|(T_w - T_a)|$.

3. Results

The dimensionless governing equations have the following parameters: 1) the Rayleigh number based on the window height, H', and on $|(T_w - T_a)|$, *Ra;* 2) the Prandtl number, *Pr;* 3) the dimensionless horizontal distance between the window and the blind, w = w' / H' (see Fig. 1); 4) the dimensionless width of thw window, $W = w' / H'$ (see Fig. 1); and 5) whether the window temperature is higher (hot window case) or lower (cold window case) than the air in the room.

Consideration will first be given to some typical results for the case of a 'cold' window to examine whether they differ in any fundamental way from those previously obtained for the 'hot' window case.

The variation of the mean Nusselt number with dimensionless window width, W, for a fixed dimensionless window-blind separation distance, w, of 0.08 are shown in Figs. 3 and 4 for Rayleigh numbers of 10^5 and 10^6 respectively. It will be seen that in both cases the Nusselt number decreases from high values at low values of W towards the constant value that applies at vary large values of W. However it will be noted that over the range

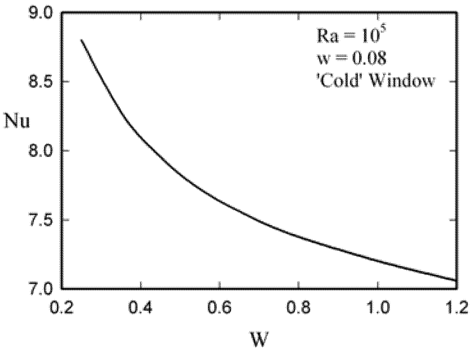

Figure 3. Variation of Nu with dimensionless plate width W for a 'cold' window for Ra= 10^5 and a dimensionless window-blind gap of 0.08.

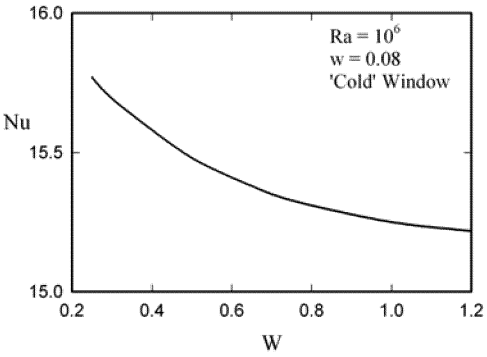

Figure 4. Variation of Nu with dimensionless plate width W for a 'cold' window for Ra= 10^6 and a dimensionless window-blind gap of 0.08.

of *W* values considered here, three-dimensional effects, i.e., the Nusselt number is still decreasing with increasing *W* at even the largest value of *W* considered. When the results given in Figs. 3 and 4 are compared, it will be seen that the Nusselt number approaches its final effectively two-dimensional value at lower values of *W* as the Rayleigh number increases.

The effect of the dimensionless window-blind gap, *w* , is illustrated by the results given in Fig. 5 which gives results for two values of *W* for a fixed Rayleigh number. It will be seen that as *w* increases, the mean Nusselt number first decreases but it then passes through a minimum and then increases with increasing *w*. This form of behavior arises because when *w* is small there is very little convective motion between the blind and the window and the heat transfer is mainly by conduction so the heat transfer rate decreases as the thickness of the air layer increases. However as *w* increases, convective motion begins between the blind and the window. This tends to increase the heat transfer rate thus leading to the minimum in the *Nu*-*w* variation. It will also be seen from the results that the value of *w* at which the minimum heat transfer rate occurs is essentially the same at the two values of *W* considered, it being mainly dependent on the Rayleigh number value. The results given in Figs. 3 to 5 indicate that the general form of the Nusselt number variation for the 'cold' window case is similar to that for the 'hot' window case. The actual Nusselt numbers for these two cases will now be directly compared. Figure 6 shows a comparison of the variations of Nusselt number with *w* for the two cases for the same values of *Ra* and *W*. While the form of the variation is the same in the two cases, it will be seen that the Nusselt number values for the 'hot' window case are always higher than those for the 'cold' window case. However, the difference between the two results never differs by more than 5 per cent. Figures 7 and 8 show the variations of *Nu* with *W* for a fixed value of *w* for *Ra* =10^5 (Fig. 7) and 10^6 (Fig. 8). It will again be seen that the Nusselt number values for the 'hot' window case are higher than those for the 'cold' window case.

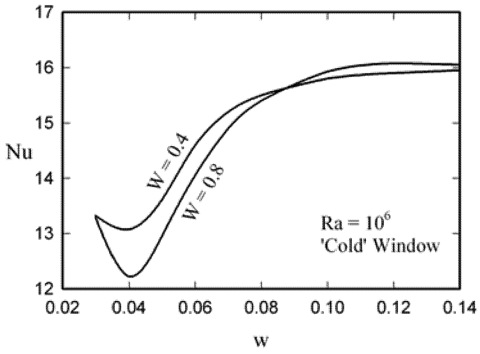

Figure 5. Variation of Nu with dimensionless window-blind gap w for two values of the dimensionless plate width W for a 'cold' window for Ra = 10^6.

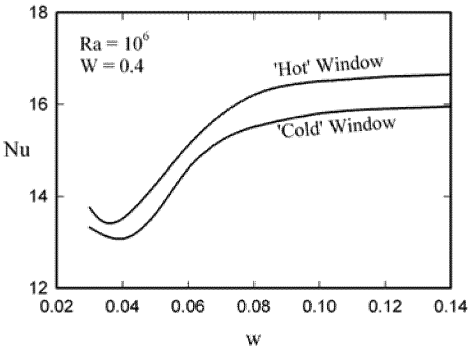

Figure 6. Variation of Nu with dimensionless window-blind gap w for a 'hot' and a 'cold' window for a dimensionless plate width W of 0.4 and for Ra = 10^6.

It will also be seen that for the higher Rayleigh number, the Nusselt number values for the 'hot' the 'cold' window cases are essentially equal at the higher values of *W* considered, i.e., as the effectively two-dimensional flow situation is approached. At the lower Rayleigh number, the Nusselt number values for the 'hot' window case are always higher than those for the 'cold' window case although the percentage difference between the *Nu* values for the two cases decreases as *W* increases.

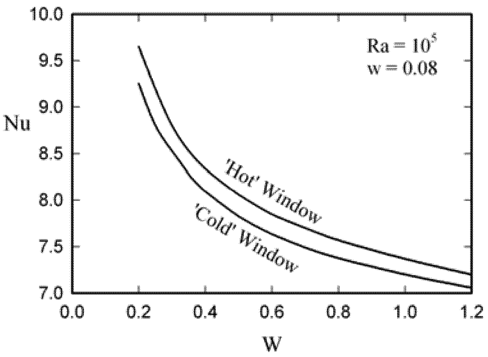

Figure 7. Variation of Nu with dimensionless plate width W for a 'hot' and a 'cold' window for Ra = 10^5 and a dimensionless window-blind gap of 0.08.

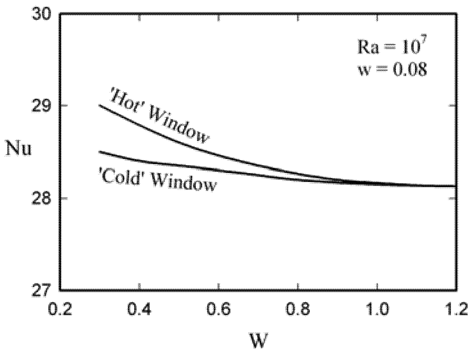

Figure 8. Variation of Nu with dimensionless plate width W for a 'hot' and a 'cold' window for Ra = 10^7 and a dimensionless window-blind gap of 0.08.

4. Conclusions

The results of this study indicate that the basic form of the variation of the mean Nusselt number with the dimensionless parameters *w*, *W*, and *Ra* is the same for the 'hot' and 'cold' window cases. However, under all conditions considered, the Nusselt number values for the 'hot' window case are higher than those for the 'cold' window case, the difference between the values for the two cases being less than about 5 per cent. The results also show that, in both cases, three-dimensional flow effects are important under all conditions considered, these three-dimensional flow effects being particularly significant at lower W and Ra values.

5. Acknowledgements

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