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A Numerical Study of the Development of Turbulent Flow over a Recessed Window-Plane Blind System

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Most existing studies of the convective heat transfer from a window-blind system to a room have assumed that the natural convective flow over the system remains laminar. However, under some conditions this flow becomes turbulent. The conditions under which turbulent flow occurs in such situations have been numerically studied here. Attention has here been restricted to an approximate simplified model of a recessed window that is, in general, covered by a plane blind. The conditions under which turbulent flow occurs in such situations and the convective heat transfer rate that exists when turbulence does occur have been numerically studied here. Radiant heat transfer effects have been neglected. The governing equations have been solved using the commercial finite-volume based cfd code FLUENT. The k-epsilon turbulence model has been used. The effect of the depth to which the window is recessed on the development of turbulence and on the mean heat transfer rate has been studied. Results have been obtained both for the case where the blind is fully open and for the case where it is fully closed.

1. Introduction

Improved models for the convective heat transfer rate from the inner surface of a window to the surrounding room are required to assist in the development of systems that reduce the overall heat transfer rate through the window. Most existing studies of the convective heat transfer from the inner surface of a window-blind system to a room have assumed that the natural convective flow over the window remains laminar. However under some conditions this flow becomes turbulent and the conditions under which turbulent flow occurs in such situations and the convective heat transfer rate that exists when turbulence does occur have been numerically studied here. Attention has here been restricted to flow over an approximate model of a recessed window that is in general covered by a plane blind. The "window" is assumed to be at a uniform surface temperature, i.e. is represented as an isothermal plate. Radiant heat transfer effects have been neglected. The Reynolds averaged governing equations have been solved using the commercial finite-volume based cfd code FLUENT. The k-epsilon turbulence model has been used. Calculations have been undertaken with increasing Rayleigh numbers to determine when turbulent flow occurs and what effect the development of turbulent

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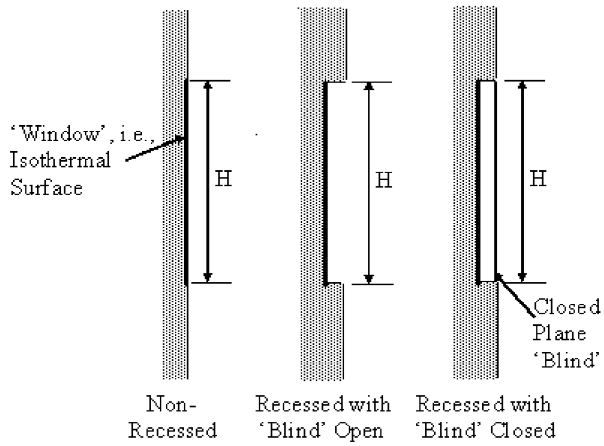

Figure 1 The three flow situations considered.

flow has on the mean heat transfer rate from the inner surface of the "window" to the room. The effect of the depth to which the window is recessed on the development of turbulence has been studied. Results have been obtained both for the case where the blind is fully open and for the case where it is fully closed.

The numerical approach used here to determine when turbulence develops, i.e., solving the Reynolds averaged governing equations together with a turbulence model and then monitoring the solutions obtained with increasing Rayleigh numbers to determine when significant turbulence effects develop has been used quite extensively for forced convective flows, e.g. see Savill (1993), Dick and Steelant (1997), Schmidt and Patankar (1991) and Zheng et al. (1998). There have also been some studies of transitional natural convective flow, e.g. see Albets-Chico et al. (2008), Xaman et al. (2005) and Manz (2003). The results obtained in these studies indicate that while k-epsilon turbulence models do not give good predictions in all cases they do appear to give acceptable results for the type of situation here being considered.

This study attempts to predict for the first time where and under what conditions transition to turbulence occurs in a window-blind system.

2. Solution Procedure

Attention has been given to the three flow situations shown in Fig. 1. The first situation considered involves a plane isothermal vertical surface in the same plane as the surface of the surrounding adiabatic surface, i.e., to the classic case of flow over a wide vertical isothermal plate. Results for this situation were obtained to ensure that methodology adopted did give good predictions of when transition occurs, experimental results for transition in the flow over a vertical isothermal flat plate being available. The second case considered involves a recessed isothermal window with an open blind, i.e., to the case where there is no blind. Results were obtained for this case to determine if recessing the window has a significant effect on when transition occurs. Lastly the case where the recessed isothermal window is fully covered by a plane blind, i.e. where the

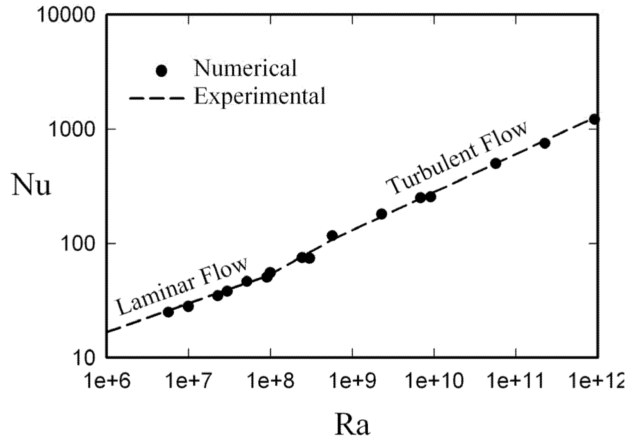

Figure 2 Variation of the mean Nusselt number with Rayleigh number for non-recessed plate case.

blind is fully closed, has been considered. In all cases the effect of flow transition on the mean Nusselt number variation with Rayleigh number has been studied.

The solution was obtained using the Reynolds averaged Navier-Stokes equations in conjunction with the k-epsilon turbulence model including full buoyancy force effects. Steady mean flow has been assumed and 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 temperature of the fluid far from the plate has been assumed to be constant and specified. Radiant heat transfer effects have been neglected. The governing equations have solved using the commercial finite-volume based cfd code FLUENT. A wide heated surface (window) has been assumed, i.e., basically a two-dimensional flow has been assumed. However the solution for a finite width of plate has been obtained so the three-dimensional form of the governing equations have actually been used. This was done in order to check whether a three-dimensional secondary flow developed during transition. However in none of the cases considered did such a flow develop. Calculations have been undertaken with increasing Rayleigh numbers to determine when turbulent flow occurs and what effect the development of turbulent flow has on the mean heat transfer rate from the inner surface of the "window" to the room.

3. Results

For the situations considered, the mean heat transfer rate has been expressed in terms of the mean Nusselt number for the window, i.e.:

$$Nu = \frac{\bar{q}H}{(T_W - T_F)k} \tag{1}$$

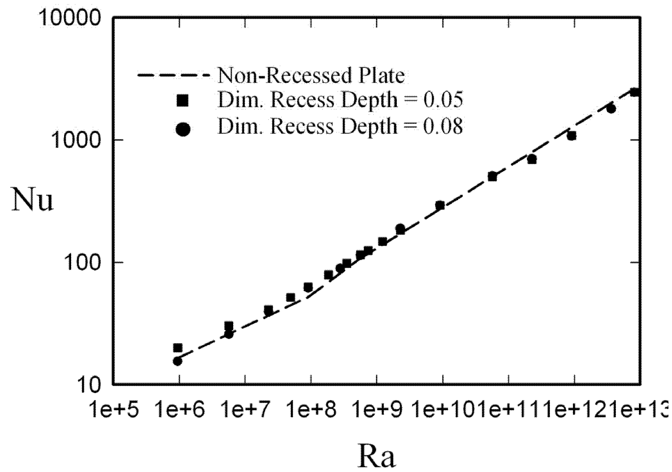

Figure 3 Variation of mean Nusselt number with Rayleigh number for the recessed window with no blind case.

where $\overline{q}$ is the mean heat transfer rate per unit area, H is the height of the window, T_W is the plate temperature, T_F is the temperature of the undisturbed fluid far from the window and k is the thermal conductivity. The Nusselt number will depend on the Rayleigh number based on H and $(T_W - T_F)$ and on the Prandtl number Pr. Because of the application being considered results have only been obtained for $Pr = 0.7$, i.e., the approximate value for air. The Nusselt number will also depend on the dimensionless window recess depth, i.e., d/H where d is the recess depth, and on whether the blind is open or closed.

Results for the non-recessed plate case will first be considered, i.e., for the first situation shown in Fig. 1. The variation of the mean Nusselt number with Rayleigh number for this case is shown in Fig. 2. Also shown in Fig. 2 is the mean line through available measurements of the heat transfer rate from wide vertical isothermal plates. It will be seen that good agreement between the numerical and the experimental results is obtained indicating that the numerical approach being adopted is adequate for indicating the conditions under which transition to turbulence occurs for the type of flow situation being considered.

Attention will next be given to the recessed window case, i.e., to the second situation shown in Fig. 1. The variations of the mean Nusselt number with Rayleigh number for two dimensionless recess depths for this case are shown in Fig. 3. For comparison the mean line through the results for the non-recessed plate case is also shown in Fig. 3. It will be seen from the results given in this figure that recessing the window has a relatively small effect on the mean Nusselt number variation, i.e., that the results for all the dimensionless recess depths considered are in quite close agreement with each other and with the results for the non-recessed plate case. The recess depth was found to have some effect on the local Nusselt number variation along the hot surface but this has a minor effect on the mean value of the Nusselt number.

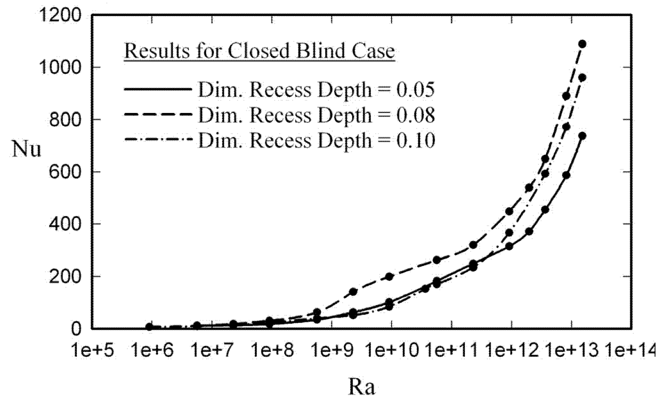

Figure 4 Variation of mean Nusselt number with Rayleigh number for the recessed window with blind case.

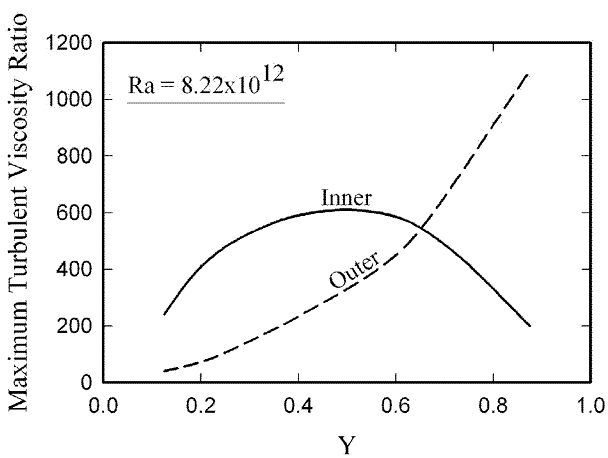

Figure 5 Typical variations of the maximum value of the turbulent viscosity ratio with dimensionless distance up the window in the inner flow region between the window and the blind and in the outer flow region on the outer surface of the blind.

Attention will lastly be given to the recessed window covered by the closed plane blind case, i.e., to the third situation shown in Fig. 1. The variations of the mean Nusselt number with Rayleigh number for various dimensionless recess depths for this case are shown in Fig. 4. In this closed blind case there are two separate but interconnected flows, that between the window and the blind and that over the outside of the blind. The effect of changes in these two flows leads to the form of variations shown in Fig. 4. It will be seen from Fig. 4 that in all cases the Nusselt numbers for the blind-covered-window case are lower than those for the equivalent open blind case. It will also be seen by comparing the results given in Fig. 4 with those given in Fig. 3 that the differences between the results for the blind-covered case and the blind-open case are particularly significant at low Rayleigh numbers when there is little convective motion between the window and the blind and the heat transfer across the gap between the window and the blind then essentially being by conduction. The development of turbulence in the two flow regions can be illustrated by considering the variations in the maximum value of the turbulent viscosity ratio, v_T / v, at a particular distance up the window in the inner flow region between the window and the blind and in the outer flow region on the outer surface of the blind with dimensionless distance $Y=y/H$ up the window. A typical such variation is shown in Fig. 5. In the inner flow region the maximum turbulence viscosity reaches its highest value near the mid-height of the flow region while in the outer region the maximum turbulence viscosity continues to increase along the entire window height.

4. Conclusions

The results of the present study indicate that:

- The solution procedure adopted, which is based on the use of the k-epsilon turbulence model, appears to adequately predict the conditions under which transition occurs for natural convection flow situations of the type here considered.
- The recess depth of the window when the blind is open does not have a significant effect on mean Nusselt number variation.
- When the blind is closed there is a very significant reduction in the mean Nusselt number.

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