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A Numerical Study of the Effect of a Venetian Blind on the Convective Heat Transfer Rate from a Recessed Window with Transitional and Turbulent Flow

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Most existing numerical studies of convective heat transfer between a window-blind system and a room are based on the assumption that the flow remains laminar. However with larger windows transition to turbulent flow will occur in the flow over the window. The aim of the present study was to numerically determine the effect of a Venetian blind on laminar-to-turbulent transition in the flow over a simple recessed window and on the natural convective heat transfer from the window to the room. An approximate model of a recessed window that is covered by a Venetian blind has been considered, the window being treated as a plane isothermal vertical surface. The study is based on the use of the steady, two-dimensional governing equations, these having been solved using the commercial finite-volume based CFD code FLUENT©. The *k*-epsilon turbulence model with the full effects of the buoyancy forces being accounted for has been used. Results have been obtained for various blind slat angles and for various distances of the slat pivot point from the window. The results show that over a wide range of window height based Rayleigh numbers, the distance of the blind to the window has a stronger effect on the convective heat transfer from the window and also on the laminar-to-turbulent transition in the flow over the window than does the blind slat angle.

1. Introduction

Improved models for the convective heat transfer rate from the inner surface of a window to the surrounding room for the case where the window is fully or partially covered by a blind are needed to assist in the development of systems that reduce the overall heat transfer rate through the window. This heat transfer rate is dependent on whether the buoyancy driven flow over the window is laminar or turbulent. Most existing numerical studies of convective heat transfer between a window-blind system and a room are based on the assumption that the flow remains laminar. However, in the case of larger windows it is to be expected that transition to turbulent flow will occur in the flow over the window. The aim of the present study was to numerically determine the effect of a Venetian blind on the laminar-to-turbulent transition in the flow over a simple recessed window and on the natural convective heat transfer rate from the window to the room.

An approximate model of a recessed window that is covered by a Venetian blind has been considered, the window being treated as a plane vertical isothermal surface with a temperature that is higher than that of the air in the room. Curvature of the blind slats has not been considered. The pivot points of the blind slats have been assumed to be aligned with the wall into which the window is recessed. The flow situation considered is therefore as shown in Figure 1.

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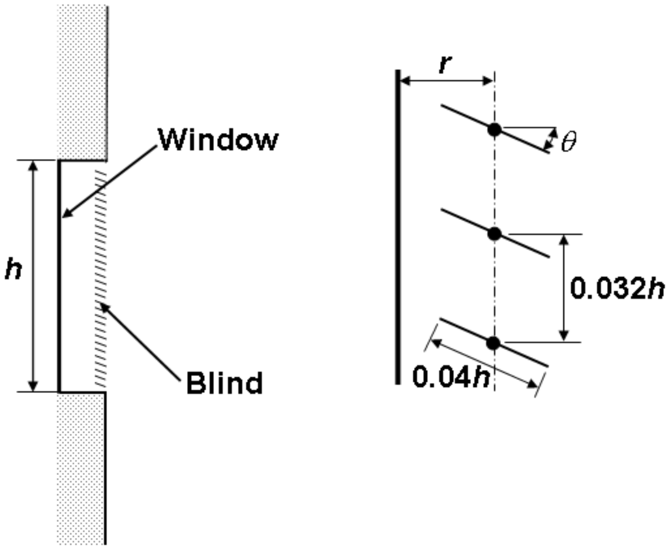

Figure 1: Flow situation considered.

There have been many studies of the effect of blinds on the heat transfer rate between the room-side of the window and the room but these have mainly been concerned with situations involving traditional plane blinds. Typical of such studies are those of Oosthuizen et al. (2008), Oosthuizen et al. (2005), and Oosthuizen (2007, 2008). Some studies of the case where the window is covered by a Venetian blind have been undertaken, typical of these being those of Collins et al (2002a, 2002b), Duarte et al. (2001), Machin et al. (1998), Shahid (2003) and Roeleveld et al. (2010). These studies are basically all for the case where the flow over the window system is laminar. The effect of flow transition to turbulence for the case of flow over a window covered by a plane blind has been considered, for example, by Oosthuizen and Naylor (2010) and Oosthuizen (2009, 2010). In the present study the effect of a Venetian blind on transition in the flow over the window has been considered. The present study, as is the case in many of the previous studies, considers only the convective heat transfer. In window heat transfer situations, the radiant heat transfer can, of course, be very important and can interact with the convective flow, e.g., see Phillips et al. (2001).

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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 window-blind system has been assumed to be wide enough to allow the flow to be assumed to be two-dimensional. The solution has been obtained by numerically solving the governing equations subject to the boundary conditions using the commercial CFD solver, FLUENT©.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. This turbulence model has in past studies 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 used and of the convergence-criterion used.

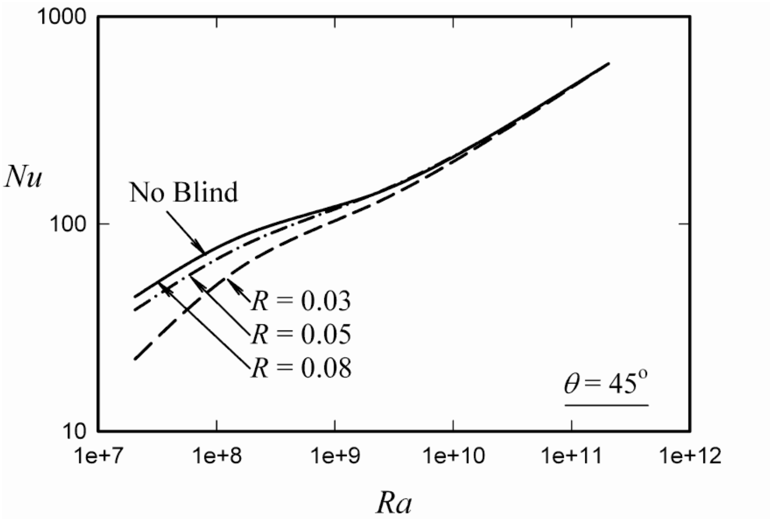

Figure 2: Variation of Nusselt number with Rayleigh number for a slat inclination angle of 45 ° for three values of the dimensionless window recess depth. Results are also shown for the case where there is no blind, these results being essentially equal to those for a dimensionless recess depth of 0.08.

The mean convective heat transfer rates from the window have been expressed in terms of the mean Nusselt number defined by $Nu = \bar{q}' h / [k(T_W - T_F)]$ where $\overline{q'}$ is the mean heat transfer rate from the window considered, k is the thermal conductivity, TW is the window surface temperature, TF is the room air temperature, and h is the height of the window. The Rayleigh number used is 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 $Ra = \beta g \rho^2 c_p (T_W - T_F) h^3 / \mu k$ 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 / h, r* being the window recess depth, and the angle that the blind slats make to the horizontal, *θ* , which is as defined in Figure 1. Results have only been obtained for *Pr* = 0.74 which is essentially the value for air at conventional room temperatures. Values of the Rayleigh number based on *h*, i.e., *Ra*, of between 10^7 and 10^{12} and values of the dimensionless recess depth, *R,* of between 0.03 and 0.08 have been considered.
Typical variations of Nusselt number with Rayleigh number for various values of *R* for slat inclination angles of +45 °, -45 °, and 0 ° are shown in Figures 2, 3, and 4 respectively. A slat angle of 0 ° corresponds to the case of a fully-open blind. It should also be noted that in this *θ* = 0 ° case the gap between the window surface and the end of the slat closest to the window surface at a given value of *R*

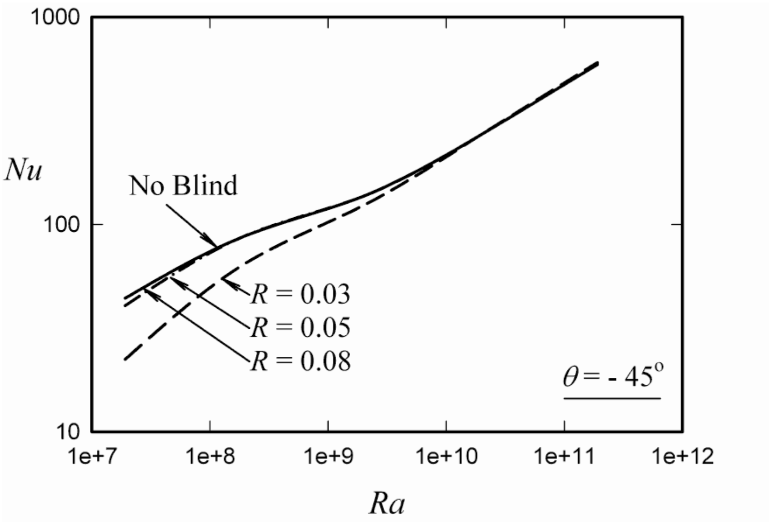

Figure 3: Variation of Nusselt number with Rayleigh number for a slat inclination angle of -45 ^{o} for three values of the dimensionless window recess depth. Results are also shown for the case where there is no blind, these results being essentially equal to those for a dimensionless recess depth of 0.08.

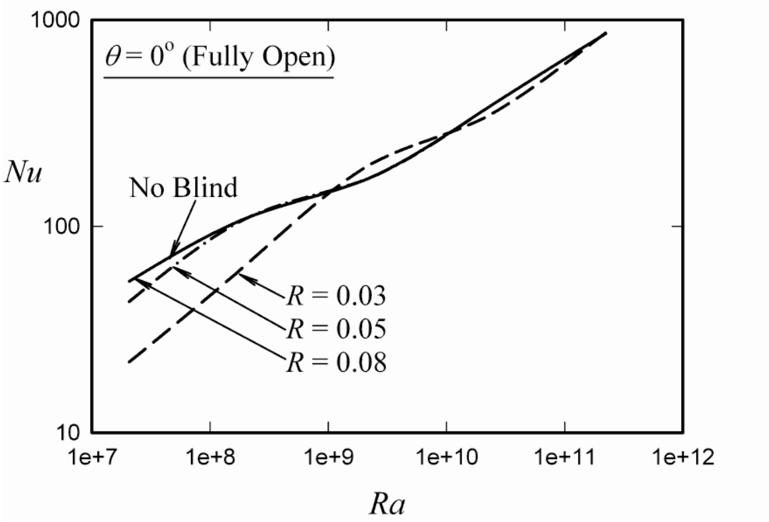

Figure 4: Variation of Nusselt number with Rayleigh number for a slat inclination angle of 0 ^{o} for three values of the dimensionless window recess depth. Results are also shown for the case where there is no blind, these results being essentially equal to those for a dimensionless recess depth of 0.8.

has the smallest value. It should also be noted that the smaller the value of *R* the smaller will be the gap between the window surface and the end of the slat closest to the window surface at a given value of *θ*.

It will be seen from the results given in Figures 2 to 4 that for all slat angles considered the Nusselt number variation for the largest value of *R* considered, i.e., 0.08, is essentially the same as the variation that exists when there is no blind, i.e., for this value of *R* the slats have no effect on the flow over the window. It will be seen from Figures. 2 and 3 that in the laminar and transitional flow regions for both $\theta = 45^{o}$ and $\theta = -45^{o}$ the presence of the slats near the window produces a decrease in the

Nusselt number, this decrease growing larger as *R* decreases. In the turbulent flow region however because the boundary layer thickness in the flow over the window is so low because of the high Rayleigh numbers the blind has essentially no effect on the Nusselt number for all values of *R* considered. It will also be noted from Figures 2 and 3 that for $\theta = 45^{o}$ and $\theta = -45^{o}$ the presence of the blind has essentially no effect on the conditions under which transition starts and the conditions under which the flow becomes fully turbulent. From Figure 4 it will be seen that, because with $\theta = 0^{o}$ the slats are very close to the window, with the smallest value of R considered the conditions under which transition starts and the conditions under which the flow becomes fully turbulent are different from those that exist with no blind. An overall consideration of the results given in Figures 2 to 4 indicates that for the range of conditions considered, the changes in the value of R have a greater effect on the Nusselt than do the changes in the value of θ.

4. Conclusions

The results of the present study indicate that:

1. For the conditions considered in the present study the presence of the blind does have a significant effect on the convective heat transfer rate when laminar and transitional flow exist and when *R* is small. However the blind has essentially no effect on convective heat transfer rate when turbulent flow exists.
2. Except when the blind is very nearly fully open, i.e., when θ is close to 0^{o} , the presence of the blind has essentially no effect on the conditions under which transition starts and on the conditions under which the flow becomes fully turbulent.
3. Under most of the circumstances considered, the presence of the blind tends to produce a reduction in the heat transfer rate in the laminar and transitional flow regions when *R* is small.

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