TRANSIENTS IN THERMAL PLUMES OVER HEAT ISLANDS IN OPEN ENVIRONMENT

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EXTENDED ABSTRACT

The treatment of open boundaries in numerical simulation and modelling of fluid flow and convective heat transfer still poses a challenge. The problem is especially acute when considering thermal convection over (nearly) horizontal surfaces, such as encountered over flat or rugged terrains with heat islands. The first problem is the definition of the minimum solution domain and the treatment of inflow and outflow that can coexist along the same boundary depending on the local flow characteristics inside the computational domain. Of course, for isolated heat source(s) on flat surfaces the problem can be obviated by moving the boundaries far away from the heat source, but expanding the solution domain leads inevitably to an increase in computation costs, especially when dealing with unsteady flows. Besides, in environmental flows over complex terrain configuration, moving the solution boundary away from the area in focus may bring in additional uncertainties. The studies reported in literature are mainly for the laminar flows, and simple configurations Wei *et al.* (2002), Sani and Gresho (1994). For high Ra numbers the turbulence makes this sensitive problem even more difficult. The main reason is that turbulent free convection over horizontal or inclined surfaces is often inherently unstable and transient despite steady bulk conditions - making it difficult to model sensitive coupling between the velocity, pressure and temperature fields.

We report on the numerical simulations of transient behavior of turbulent thermal plumes in open environment over horizontal and slightly inclined heated surfaces with either full or only a part of the bottom wall heated. Several types of boundary conditions have been investigated both for laminar and turbulent cases, the latter in conjunction with the transient RANS (T-RANS) approach in which the unresolved motion is modelled by a three-equation $k{-}\varepsilon{-}\overline{\theta^2}$ algebraic flux model. For the velocity and pressure fields we used the pressure boundary conditions. The combination of zero pressure corrections ($p'{=}0$) for the side boundaries and the zero-pressure gradient ($dp'/dn{=}0$) for the vertical boundary provided best results. For the remaining scalar variables (temperature, turbulence energy and its dissipation rate, temperature variance) the extrapolation of the upstream gradients seemed the most realistic choice. When the fluid flows out of the domain (outflow conditions), the boundary values of the variables are obtained by the extrapolation of the inner field. In the opposite case the boundary variables are specified as values of the outer field ($T{=}T_{in}$, $k{=}k_{in}$, $\varepsilon{=}\varepsilon_{in}$, $\overline{\theta^2}{=}\overline{\theta^2}_{in}$). Since the flow is unsteady, the flow direction changes in a pseudo-periodic manner over the portions of the boundaries and the boundary conditions need to be adjusted after each time step.

For the bottom wall we also considered several different treatments, which include the standard and buoyancy-modified wall functions. Unfortunately, both treatments, yielded serious over-predictions of the integral wall heat transfer. Much better agreement with experiments was achieved by applying exact boundary conditions for the mean fields, $U{=}V{=}W{=}0$ and $T{=}T_w$, but with "wall-function" values for turbulence variables in the first near-wall grid cell.In the latter case a significantly finer mesh must be applied, especially in the vertical direction. The results show realistic unsteady behavior of turbulent thermal plumes in good agreement with experiments.

Some Results

We present some results for two typical situations where the treatment of open boundaries is critical: a thermal plume rising over a completely heated surface, and over a surface heated only over its portion - ”heat island”, placed centrally. The first configuration is more challenging and serves for critical assessment of the stability and physical validity of imposed conditions at three open boundaries. The length of the simulation domain coincide with the length of the underlying thermally active surface for both flat and inclined plate. The necessary height of the solution domain is also uncertain: at the onset of heating, a number of small plumes emerge from the hot surface and further flow development depends on the domain aspect ratio and boundary conditions on the top boundary. In order to make it possible for the flow to develop eventually as a single plume, the height of the solution domain needs to be larger than its length, otherwise, multiple plumes and convective rolls can develop, depending on the conditions on the upper boundary. We considered the two heights, one equal to the length and one twice as high. Fig.1 shows the comparison between experimentally and numerically obtained flow patterns at selected (corresponding) time instants for aspect ratio of one. Many flow features observed in the experiments are numerically reproduced, including the characteristic down-flown regions for the case of a horizontal plate ($\alpha{=}0^o$), and the characteristic shift of the plume release location for a slightly inclined plate ($\alpha{=}5^o$).

The second case is free convection over localized thermally active area ($l/L{=}0.25$) on a horizontal or inclined surface. Here, though depending on the plate size, the side effects are less influential as compared to the previous situation. The time evolution of the instantaneous velocity field is shown in Fig.2. In the initial stage of heating, the flow symmetry is preserved until approximately $\tau{=}36$ when the oscillatory behavior starts to develop. It is observed that due to this oscillatory behavior, the thermal plume moves from left to right in an irregular fashion and crosses not only the upper boundary but also the side boundaries. The new pressure-boundary condition allows for the coexistence of fluid inflow and outflow along the same boundary providing communication between simulated and surrounding areas, which is a key prerequisite for this type of simulations.

In order to gain a better insight into this oscillatory plume behavior, the time evolutions of horizontal and vertical velocity components at three characteristic locations (at the edges -MON1,MON2 and in the center -MON3) just above the thermally active area are plotted in Fig. 3. The horizontal velocity components at the MON1 and MON2 locations show almost identical evolution (but with the opposite signs). Similarly, the maximum of the vertical velocity oscillations occurs at the same location corresponding to the thermal plume ejections in the vertical direction, Fig. 3b. The additional imprints of these thermal plumes bursts can be seen in the time evolution of the temperature, Fig. 3c. The time evolution of the integral Nusselt number is shown in Fig. 3d. As seen, both the classical wall function and the buoyancy extended wall functions approach failed in giving correct values of Nu. The alternative approach resulted in quite good agreement with experimental value ($Nu_{exp}{=}62.3$, $Nu_{sim}{=}64.5$). The time-dependence of the thermal plume is captured very well with all three wall treatments. More results, including the characteristic distributions of the contours of temperature, horizontal and vertical components of the turbulent heat flux, will be shown in the full paper.

REFERENCES

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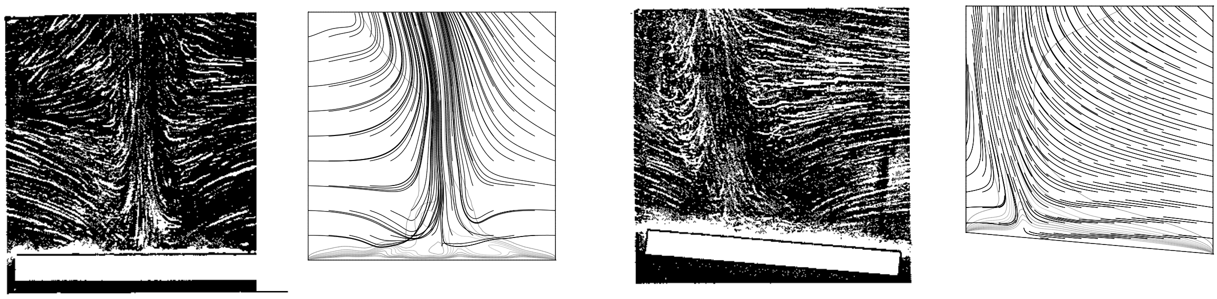

Figure 1: Free convection over flat (left) and slightly inclined (α=5^o - right) heated surface; Comparison between experimental visualization of Fujii and Imura (1972) and numerical simulations, Ra=6×10^7, Pr=7.

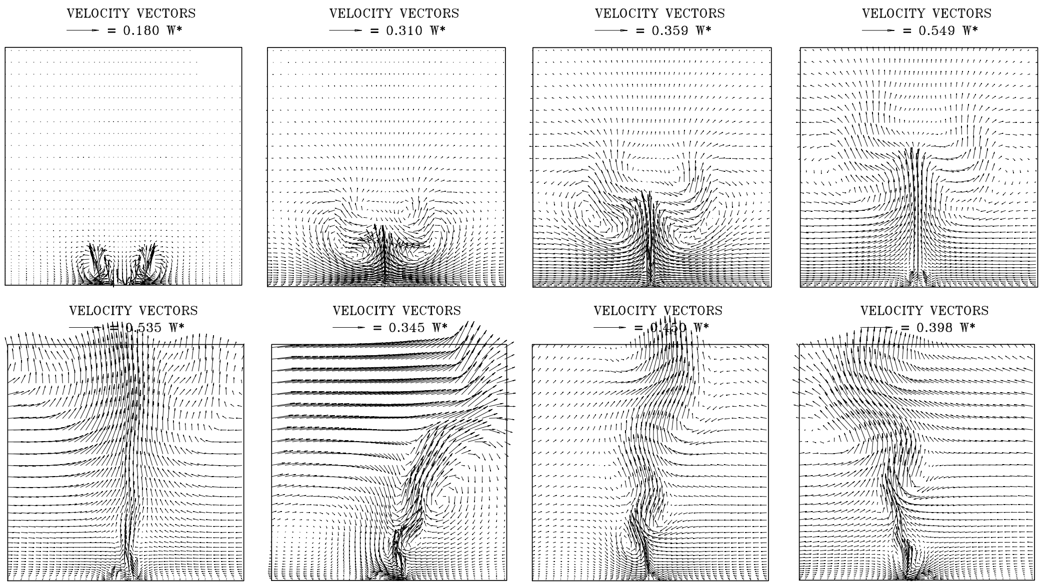

Figure 2: Time evolution of the velocity field, τ=$20, 28, 32, 36, 44, 56, 92, 108$ sec, Ra=7×10^7, Pr=7: partially heated horizontal surface ('heat island') with l/L=0.25, α=0^o where the L is total length of the horizontal plate.

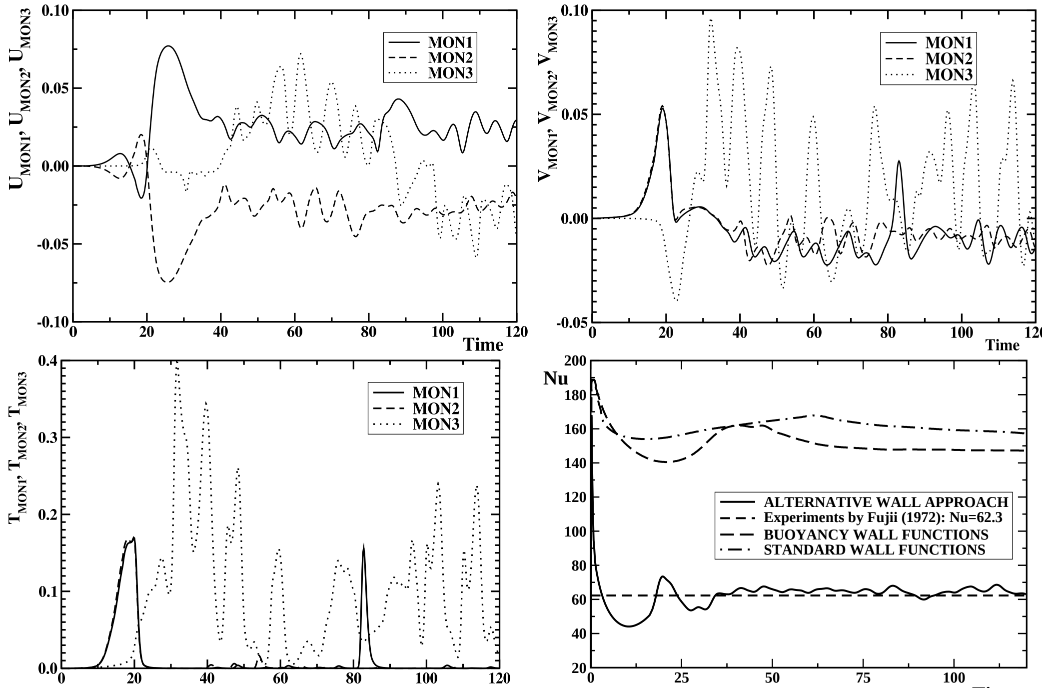

Figure 3: Time evolution of horizontal (U) and vertical velocity (V) components, temperature (T) and integral Nusselt number (Nu) in characteristic monitoring points (MON1, MON2, MON3) for the locally heated horizontal surface (heat-island), Ra=7×10^7, Pr=7.