Abstract

Depending upon the distance of the confining boundaries from the discharge, a jet can be analyzed as a free jet or a bounded one. If the boundaries (parallel to inlet axis) are sufficiently away from the origin of the jet, the flow is termed as a free jet. However, a bounded jet will occur when it interacts with a parallel wall. Bounded jet flows occur in many engineering applications such as environmental discharges, heat exchangers, fluid injection systems, cooling of combustion chamber wall in a gas turbine, automobile demister and others. Bounded jets can be classified into three types: (a) impinging jet aimed toward the boundary; (b) wall jet where fluid is discharged at the boundary; and (c) offset jet from a vertical wall of a stagnant pool issuing parallel to a horizontal solid wall. The present work is aimed to understand the flow and conjugate heat transfer characteristics of wall bounded laminar jet flows. The study is carried out for plane wall jet flow and offset jet flow. Another study covered is plane wall jet flow over backward facing step.

Glauert (1956) defined plane wall jet as a stream of fluid blown tangential along a plane wall. The wall jet consists of an inner region and an outer region. It is a combination of boundary layer flow over flat plate at inner region and plane free jet at outer region. The velocity profile has a point of inflexion. The surrounding medium of wall jet may be quiescent or co-flow or counter-flow depending upon the applications. Similarity solution for plane wall jet as well as radial wall jet for both laminar and turbulent cases were presented with the introduction of Glauert constant F.

Offset jet flow occurs when fluid is discharged from a slot in a vertical wall into the ambient near a horizontal solid boundary parallel to the inlet jet direction. Due to the entrainment of fluid between the jet and the bottom plate, there is a reduction of pressure in this region forcing the jet to deflect towards the boundary and eventually attach with it. This is called Coanda effect (Tritton, 1977). The offset jet flow features are different in various regions. In the near-field within a very short distance from the point of discharge, the jet flow is dominated by momentum and has the properties of a free jet. Attachment occurs when the jet is deflected towards an adjacent solid wall and tends to flow along the boundary. In the region around the attachment point, that is, the impingement region and part of the recirculation region, the jet can be partly characterized as an impingement jet. The offset jet becomes a wall jet in the far field. Other factors like free-stream velocity, ambient stratification, buoyancy (density difference), discharge orientation etc. further complicate the jet-boundary interaction and the behavior of an offset jet.

In another type of problem geometry, fluid is discharged from a slot along vertical wall into the ambient near a horizontal solid boundary parallel to the inlet jet direction. The flow passes through a step in the downstream direction and forms the wall jet over step flow situation. The flow kind is common in industrial applications like electronics cooling, high speed engine cooling etc.

The understanding of the flow behavior of wall bounded jet is important in engineering practices. If attachment is not desired for more mixing, a knowledge of calculation and design is required to prevent it. For a case where attachment is desirable, study of the involved variables is required so that a precise location of the attachment point and the containment of the flow can be established. A conjugate heat transfer problem occurs when the fluid regime is coupled with the conducting solid wall having finite thickness. The temperature and the heat fluxes at the solid-fluid interface are considered to be equal. This is referred to as the fourth-kind boundary condition. Conjugate heat transfer is involved in many applications like high speed jet engines, electronics cooling, film cooling of turbine blades, extrusion of materials etc.

In the present work, the flow features, non-conjugate heat transfer and conjugate heat transfer characteristics of wall jet, offset jet and wall jet over backward-facing step are investigated. Analytical solutions of the wall jet are available, based on the self similarity of velocity field (Schlichting and Gersten, 2000). However, these solutions are valid only far away from the jet inlet, and in most applications, the near-field development holds the key to important features of the jet flow. Therefore, the near-field development of a wall jet has been the subject of a lot of research in recent years.

In the present work an analytical solution is investigated for forced convection heat transfer from a laminar plane wall jet as conjugate case. Vynyycky et al. (1998) have presented a procedure to solve conjugate heat transfer from a flat plate problem. Similar approach has been used to solve the present situation. For $Re \gg 1$, boundary layer theory is used for the investigation. The problem has been solved for two classic cases such as $Pr \geq 1$ and $Pr \ll 1$. The conjugate model consists of considering the full Navier-Stokes equation in the fluid medium and coupling of energy equations in the fluid and the slab through the interface boundary conditions. Closed-form relations are found for Nusselt number (Nu), average Nusselt number ($\overline{Nu}$) and conjugate interface boundary temperature (θ_b). The effects of the Reynolds number (Re), the Prandtl number (Pr), the thermal conductivity ratio (k) between the slab and the fluid medium and the slab aspect ratio (λ) are investigated on the heat transfer characteristics. The analytical results are compared with the full numerical results.

The steady state results are obtained as the asymptotic solution of an unsteady state equation. The unsteady state stream function-vorticity equation governing the incompressible laminar flow in non-dimensional form are solved by Alternate Direction Implicit (ADI) method. Clustered grids are used for the computations. From Taylor series expansion the temperature gradients are evaluated and substituted for heat flux equation at interface and the conjugate interface temperature at new time step is obtained. To validate the developed code, two-dimensional lid-driven square-cavity flow problem (Ghia et al., 1982) and the backward-facing flow problem (Armaly et al., 1983, Gartling, 1990 and Dyne and Heinrich, 1992) have been solved. Sudden expansion flow problem is solved and compared with Durst et al. (1993). For split domain problem, L-shape lid driven cavity Oosterlee et al. (1993) and backward-facing step with upstream channel Barton (1997) are solved and results compared with them. Excellent agreement has been obtained with the benchmark solutions reported in the above references. The laminar plane wall jet problem then has been solved and the computed velocity profiles are compared with the similarity solutions of Glauert (1956) and the experimental results of Quintana et al. (1997) in a similar way as represented by Seidel (2001). It is observed that at different downstream locations x/h, a good agreement amongst them has been obtained. The non-conjugate heat transfer case has been solved for Prandtl number (Pr) equal to 1.4 and compared in a similar way for five downstream locations.

Flow and heat transfer characteristics are studied for an offset jet flow. Reynolds number and offset ratio are taken into account for finding the reattachment length and centerline velocity decay. Effect of Prandtl number is considered for the heat transfer study. It is noticed that the peak Nusselt number is falling downstream of the reattachment location. The conjugate heat transfer study of an offset jet flow is carried out to find the effect of slab thickness, conductivity ratio, Re and Pr. Here the bottom wall is kept constant temperature and side walls are insulated. Results are presented for interface temperature, local Nusselt number distribution and average Nusselt number.

The flow and heat transfer study of plane wall jet over backward-facing step are presented in detail. It is noticed that when the step length is increased the recirculation eddy size is reduced. The wall jet region results are compared with similarity solution and Quintana et al. (1997) and are in good agreement with them. It is found that peak Nusselt number is coming near the inlet due to heavy entrainment and the second peak Nusselt number is occurring after the reattachment location. The conjugate heat transfer has been studied to

find the effect of properties of fluid and solid and effect of geometry. Reynolds number, Prandtl number, conductivity ratio, length of the step (l), height of the step (s) and thickness of the bottom solid wall (w) are the parameters considered for study. When $Re = 600$, the isotherms are deflected towards the bottom wall and have become denser near the recirculation region. It is observed that thermal gradients in the normal direction are following linear trend whereas in streamwise direction non-linear trend is occurred. In streamwise direction isotherm is reduced to a minimum value and further downstream direction is increased. In fluid region it is noticed that at higher k, isotherm has become less sensitive in the fluid whereas in the solid wall, the are sensitive to the k values considered for study. Local Nusselt number distribution for different k values are reported. Results have been compared with non-conjugate case. Effect of geometry is studied in detail.