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COMPUTATIONAL INVESTIGATION OF MIXED CONVECTION HEAT TRANSFER FROM LAMINAR OFFSET JET AND WALL JET

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ABSTRACT

Flow and heat transfer characteristics of interaction of a laminar plane offset jet with coflowing wall jet are studied at various Richardson number (Ri). The temperature of offset jet at inlet is higher than that of wall jet inlet temperature. The temperature of horizontal wall and wall jet inlet temperature are same as that of ambient temperature. The temperature of heated offset jet is varied to alter the Grashof number (Gr). The velocities of the two jets are taken equal. Study is carried out for Ri ranging from 0.0028 to 0.875 by taking Gr 1000, 10000 and 35000 for Reynolds number 200, 400 and 600. PISO algorithm based on finite volume method (FVM) is used. Power law scheme is considered for the discretization of convective terms. Boussinesq approximation is used to take into account variation in density in the buoyancy term. It is observed that mixing and heat transfer between the offset jet and wall jet increases with increase in Richardson number.

Key Words: *wall jet; offset jet; mixed convection; Richardson number; numerical simulation*

1. INTRODUCTION

A jet is a stream of fluid that is projected into ambient from a small cross-sectional area, which converts the pressure energy of fluid into kinetic energy. When more than one jet is used simultaneously in an application, it is known as multi-jets. In bounded jet, flow interacts with a wall and the interaction affects the flow of jet. The present problem consists of a lower wall jet and upper offset jet. Their interaction is studied here by taking both of them at different temperatures. Lower jet is taken at lower temperature and upper jet is taken at higher temperature. Such a situation is found in gas turbines, where a colder wall jet is used for the shielding of the turbine blades from the high temperature gases. Figure 1 shows the flow pattern for a combined offset jet and wall jet. The wall jet and the offset jet are ejected from two identical and rectangular nozzles, each one having width 12.5 mm and contained in the transverse plane (x= 0). The offset ratio is set to 3.5, this parameter is defined as OR=H/h, where H is distance between the horizontal wall (defined at y = 0) and the offset jet centre line, and h is inlet slot height [1]. A recirculation region forms just downstream of nozzle exit. Two counter rotating vortices form inside the recirculation region. Then the two jets merge together at a point known as merge point. At the merge point, both u and v velcoity components are zero [2]. The two jets combined later in the downstream direction sufficiently away from the jet inlet. Based on the literature review, it has been observed that interaction of laminar offset jet and wall jet at different temperatures in the mixed convection regime has not been studied earlier. The present study is an attempt to bridge this gap in the literature.

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2. MATHEMATICAL FORMULATION AND NUMERICAL SCHEME

The flow is assumed to be two-dimensional and laminar flow. The working fluid is air and its thermo-physical properties are assumed constant. The density is taken as constant in all terms (inertia and viscous terms) except the body force term using the Boussinesq approximation.

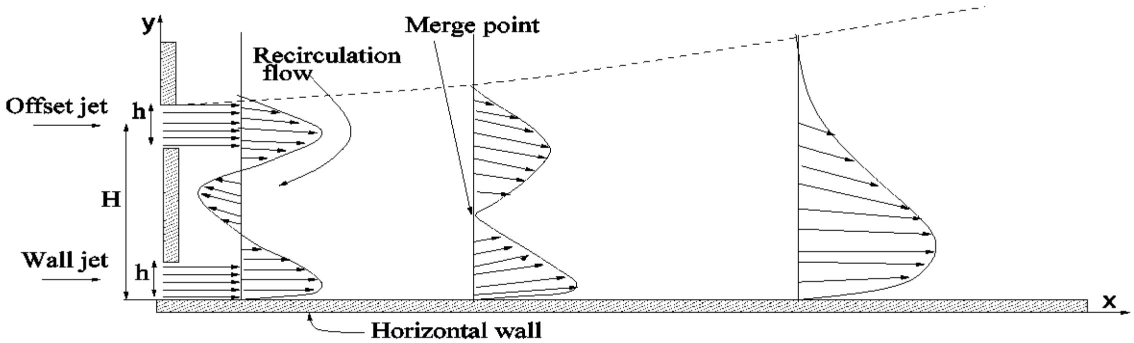


FIGURE 1. Schematic diagram of combined wall and offset jet flow

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

x Momentum equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

y Momentum equation:

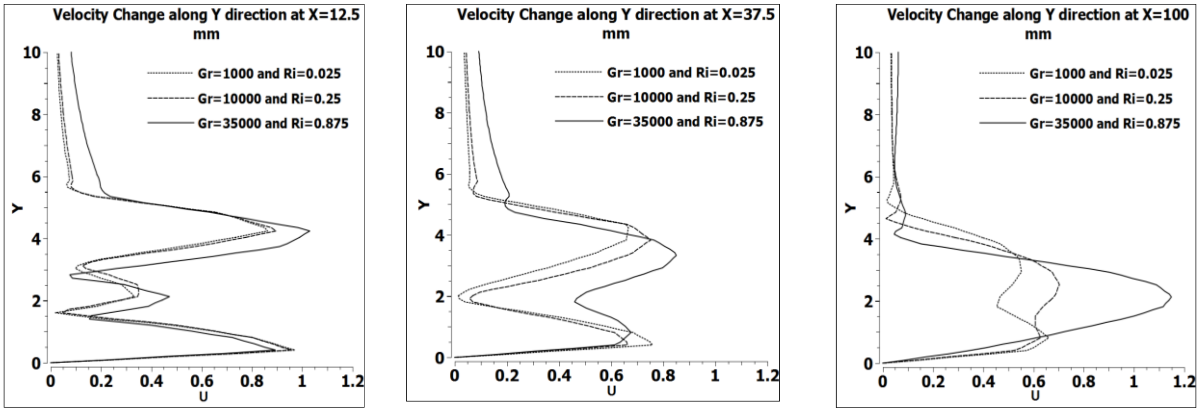
$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\rho g\,\beta\,(T-T_{ref}) \quad (3)$$

Energy equation:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{1}{\alpha}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (4)$$

The unfirom velocity profile is considered at the inlet of offset jet and wall jet. The no-slip and no-penetration boundary conditions are used at the solid walls. The temperature of the wall jet is taken as 300 K. Temperature of offset jet is varied to alter Grashof number (Gr). The vertical walls are considered as adiabatic. The bottom horizontal plate is kept at a constant temperature of 300 K. The pressure outlet and pressure inlet boundary conditions are considred at the exit and top open boundary, respectively. The governing differential equations are solved based on PISO (Pressure-Implicit with Splitting of Operators) algorithm [3] in Ansys 17.2. Second order central differencing scheme is considered for the discretization of diffusive terms and power law scheme for the discretization of convective terms. Systematic grid refinement study is carried out by taking various grids viz. 50×40, 60×60, 70×60, 80×80, 100×80 and 120×80. Mesh size of 120×80 is selected for all computations after grid independence study. The domain is taken to be a rectangle having length 55×h and width 35×h.

3. RESULT



(a). x=12.5 mm (b). x=37.5 mm (c). x=100 mm

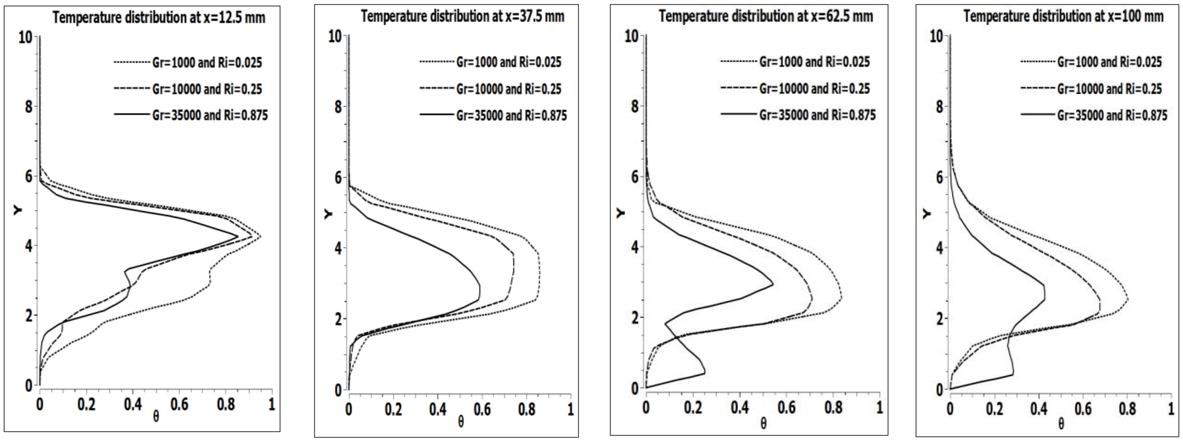
FIGURE 2. Velocity profiles for various Richardson numbers at different axial locations (Re=200)

Figure 2 shows the velocity profiles at differnt axial locations for Re 200. The Richardson number Ri is changed from 0.025 to 0.875 with increase in Gr from 1000 to 35000. The decay in velocity of wall jet is more as compared to offset jet due to the presence of wall. It is found that with an increase in Ri, the two jets merge earlier with decarse in the size of recirculation region. Due to this, the merge point and lower vortex center (LVC) shifts towards the jet inlet. The LVC has x and y coordinates as (0.0137, 0.02), (0.01094, 0.02075) and (0.003789, 0.018698) for Ri=0.025, 0.25 and 0.875, respectively. The upper vortex center (UVC) has x and y coordinates as (0.01625, 0.03750), (0.01767, 0.038) and (0.0134,0.0341) for Ri=0.025, 0.25 and 0.875, respectively. The x and y coordinates of merge point are (0.03796, 0.02475), (0.03540, 0.02560) and (0.02516, 0.02018) for Ri=0.025, 0.25 and 0.875, respectively.

Figure 3 shows the variation in non-dimensional temperature $\theta [=(T - T_{\infty})/(T_j - T_{\infty})]$ with Y (=y/h) at different x-locations for Re 200 and Gr 1000, 10000 and 35000, where T_{∞} is ambient temperature and T_j is jet inlet temperature. It can be seen from the plot that initially temperature is higher and then it goes on decreasing as the flow proceeds in downstream direction because heat is transferred from offset jet to wall jet. The maximum temperature of offset jet at a given axial location is lower for higher value of Ri. This is due to fact that at higher Ri, buoyancey force promotes better mixing thus lower temperature. After a distance of 37.5 mm, heat transfer is so high that heat starts to penetrate deeper in the lower wall jet. It decreases the shielding effect of lower wall jet and due to it some heat even transfers to the plate. Figure 4 shows the temperature contour in the domain for Richardson number Ri=0.025 and Ri=0.875. It has been observed that in case of Ri=0.025 the heat transfers from offset jet to wall jet is low which is depicted by lower temperature values in the near wall region. However, with increase in Ri number, temperature difference between the two jets reduces and heat penetrates up to near wall region of wall jet as shown in Fig. 4(b).

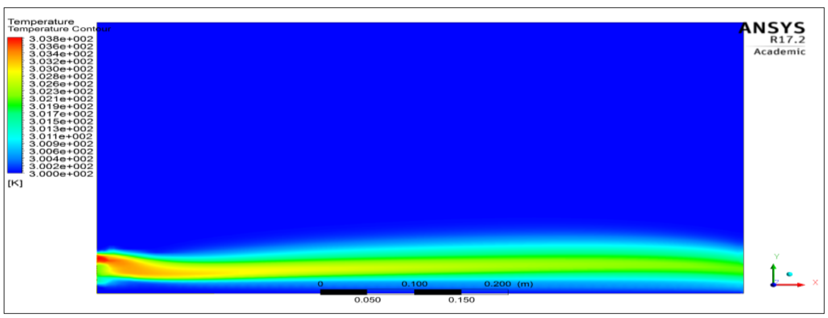
4. CONCLUSIONS

It has been observed that as Ri increases, the converging zone becomes smaller with reduction in the size of vortex. The position of the merge point moves toward the jet inlet and thus the merging zone starts earlier with increase in Richardson number. Also, with an increase in Ri, buoyancy becomes dominant which results in better mixing and heat transfer between the two jets.

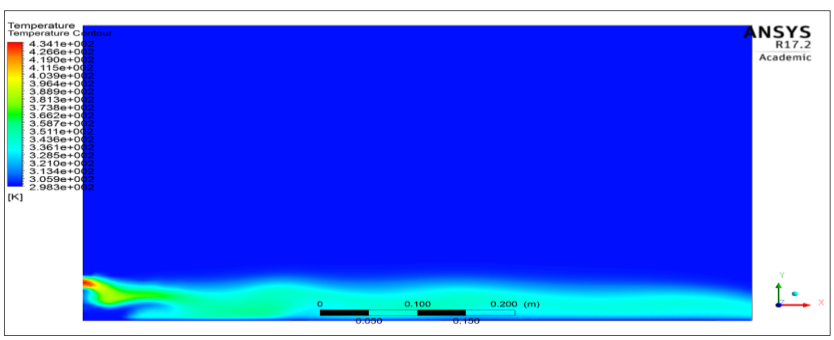


(a). x=12.5 mm (b). x=37.5 mm (c). x=62.5 mm (d). x=100 mm

FIGURE 3. Temperature profiles for various Ri at different x locations for Re=200



(a). Ri=0.025



(b). Ri=0.875

FIGURE 4. Temperature contours for Ri=0.025 and 0.875

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