Computers & Fluids 95 (2014) 132–158

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Numerical study of turbulent wall jet over multiple-inclined flat surface

Shantanu Pramanik[1], Manab Kumar Das *

Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, West Bengal 721302, India

ARTICLE INFO

Article history:
Received 16 May 2013
Received in revised form 11 November 2013
Accepted 14 January 2014
Available online 7 February 2014

Keywords:
Wall jet
Inclination angle
Turbulent flow
Inlet velocity profiles
Multiple-inclined wall
Numerical simulation

ABSTRACT

In the present work flow field of a turbulent oblique wall jet with multiple flat inclined wall has been numerically investigated. The Reynolds averaged Navier–Stokes (RANS) equations for incompressible flow are solved in transformed geometry using boundary-fitted coordinate system. The aim of the work is to investigate the influence of three inlet conditions: uniform, parabolic and trapezoidal inlet velocity profiles, on the mean flow and turbulent characteristics of the jet flowing tangentially along a multiple inclined solid wall. The results show that the inlet conditions affect the flow in the vicinity of the nozzle exit area and also the far field region. Mean flow has been presented in terms of evolution of mean velocity profiles, jet spread, decay of streamwise maximum velocity, distribution of wall pressure and skin friction coefficients, and streamwise variations of integrated momentum and energy fluxes. Discontinuities in the boundary slope of the segmented wall produces oscillations in distribution of skin friction and pressure coefficients. Reduced pressure in the region of wall discontinuity appeared to be causing the deflected jet to remain attached to the wall. The growth of the inner layer of the jet is relatively high with uniform inlet velocity profiles in the near-field region, but in the far-field region the inner layer grows with higher rate for the trapezoidal and the parabolic profiles. The rate of decay of maximum streamwise velocity for oblique wall jet on segmented wall is higher than that of plane wall jet. The jet with parabolic and trapezoidal inlet profiles show higher rate of decay than that with a uniform inlet profile. Similarity of streamwise velocity and velocity component parallel to the oblique wall has been observed in the developed region of flow. The volume flow rate of the jet varies linearly along the flow direction due to entrainment of the fluid from the surrounding. Sudden change in slope of the wall causes a sharp rise in entrained volume of fluid. The distribution of near wall velocity in the inner coordinates of the boundary layer is grossly altered and the profiles do not conform to the *universal* velocity profiles in the form of the law of the wall. Relatively higher position of defect law data signifies comparatively lower turbulence in the outer mixing layer. Cross-stream distribution of Reynolds stresses shows that the effect of inlet velocity profiles is more pronounced in the near field region of flow. Self-similarity is observed in the normalized turbulent shear stress profiles whereas considerable scatter can be noticed in the profiles of turbulent normal stresses for all the inlet velocity conditions. Two distinct peaks in the normalized turbulent kinetic energy profiles characterize the two shear layers of the jet and shifting of the outer peak toward the wall suggests a strong interaction of the outer layer with the inner layer as the jet develops.

1. Introduction

In plane wall jet configuration, the jet flows tangentially to a solid wall parallel to the axis of the nozzle. The wall configuration is changed from parallel to inclined orientation with respect to the nozzle axis in an oblique wall jet flow. The jet turns after exit from the nozzle and flows along the direction of the inclined wall. However, the maximum angle of inclination of the wall for which the jet develops along the solid surface without separation is limited due to the increasing wall static pressure with progressively increasing distance along the wall. It has been found that for wall jet flow on a multiple inclined flat wall, with each increase in angle of the surface with respect to the jet stream, an increase in the negative pressure is again obtained on the wall. Because of this phenomena, wall jet flow on multiple inclined wall or curved wall provides greater angle of deflection for the jet without separation at the wall than that available with single inclined wall configuration. The wall jet resembles half of a free jet with wall boundary layer imposed on one side, and the effect of the wall is felt across the width of the jet along the direction of flow. Due to the presence

---

* Corresponding author. Tel.: +91 3222 282924; fax: +91 3222 282778.
E-mail address: manab@mech.iitkgp.ernet.in (M.K. Das).

[1] Address: Department of Mechanical Engineering, National Institute of Technology Durgapur, West Bengal, India.

http://dx.doi.org/10.1016/j.compfluid.2014.01.020

of the wall boundary and consequent damping effect of wall on the size of the large eddies, entrainment of the surrounding fluid which occurs from the free side of the jet is lower for wall jet than that of a free jet, resulting in a decreased rate of jet growth and slower decay of spanwise maximum velocity of the jet. Plane and oblique wall jets have wide industrial applications such as cooling of a combustion chamber wall in a gas turbine, generating lift force in VSTOL and VTOL aircraft, controlling air-contaminants, cooling of gas turbine blades, automobile demister and boundary layer control, to name but a few.

Forthmann [17] was the first to carry out an experimental investigation of flow field of a plane turbulent wall jet. A theoretical analysis of radial and plane wall jets was performed by Glauert [21] in laminar and turbulent flow regimes and comparison was made with existing experimental data. Experimental investigation of plane wall jet by Bakke [7] concluded that within the range of experiment, the wall jet was found to be self-preserving and that the decay of maximum velocity and jet spread can be expressed by simple power laws ($U_{max} \propto X^{-0.5}$ and $Y_{0.5} \propto X$). Results of experimental investigation on distribution of skin friction along the solid wall of a wall jet were presented by Sigalla [64]. The author presented the variation of skin friction for wall jet by a correlation which was similar to the Blasius formula based on turbulent pipe flow and expressed decay of maximum velocity and spread of the jet with simple power law expressions. The *Coanda* effect was used by von Glahn for obtaining jet deflection and lift for single flat plate [76] and multiple flat plate and curve plate [75] configurations. The ratio of lift and axial thrust to undeflected thrust of nozzle deflection-plate configurations was determined from force measurements. For large angle of deflection, multiple flat plate and curve plate deflectors are more suitable than a single flat plate.

Experimental study of wall jet on plane and cylindrical surface with and without external stream by Bradshaw and Gee [12] reported that the centrifugal instability on the small-scale turbulence in the jet layer was the cause of quicker jet growth on a curved surface than that on a flat surface. The experimental and analytical investigations of Myers et al. [42] on a two-dimensional wall jet showed that variation of maximum streamwise velocity was same as that of a plane free jet which signifies the role of the outer free region in the development of a wall jet. Experimental data of Kruka and Eskinazi [33] for plane, steady, turbulent wall jet in a constant moving stream has shown the preservation of momentum in the outer layer in contrast to the constant loss of momentum in the inner layer due to the wall friction. Similarity was found to exist in both the inner and the outer layer for mean as well as turbulent quantities; however, with separate scale for both layers. Theoretical analysis and experimental investigation of the flow field of radial wall jet by Poreh et al. [49] indicated that mean radial velocity can be correlated with the maximum velocity and jet thickness at each section and that the shear stress at any section was found to be non-zero at the location of zero velocity gradient which is a significant retreat from the assumptions of Boussinesq hypothesis.

Sforza and Herbst [57] characterized the flow field of a three-dimensional wall jet by three distinct regions in the axial velocity decay. In the near field, the decay rate and spanwise growth were found to be dependent on the nozzle geometry, whereas at far downstream of exit the jet decay was unaffected by the shape of the nozzle. Simple integral approach was used by Patel [47] for prediction of the turbulent flow field of free shears flow and wall jets. The predicted length scale and velocity scale were in good agreement with experimental result for the range of free-stream to jet velocity ratio investigated. Rajaratnam [52] applied a simple theoretical method combined with experimental data to predict the variation of velocity and length scale and wall shear stress for the flow field of a turbulent wall jet in a freestream with constant velocity. Experimental results of Gutmark and Wygnanski [25] on two-dimensional plane incompressible jet showed a self-preserving property beyond a streamwise distance of 40 jet width. The results also showed the effect of initial conditions on the jet spread, decay of maximum velocity and lateral distribution of the turbulent intensities. In the experimental study of Wilson and Goldstein [77], curved wall jet on a circular cylindrical surface was described as a non-equilibrium flow which showed large departures from self-preservation in the turbulent quantities. The entire curved wall jet boundary layer was defined as a region of counter-gradient shear stress due to inward shift of the position of zero shear stress from its plane flow position in the wall jet boundary layer. Ljuboja and Rodi [39] applied a modified version of two equation $k-\epsilon$ model to wall jet flow in stagnant surroundings as well as in a moving stream, and the numerical predictions showed good agreement with experimental data. Turbulent flow field of a wall jet was distinctly classified in five regions by Curd [13] according to the development of flow. Comparing plane and reattached wall jets with plane free jet, it was suggested that the wall jet offers considerable advantage over the free jet with the same energy input which was attributed to its greater self-preserving nature due to its much lower rate of air entrainment than the free jet. An analytical expression for the complete velocity profile of a plane wall jet in stagnant surroundings was presented by Hammond [26] for proper resolution of the *log-law* region. To review the effect of wall curvature on turbulence, Kobayashi and Fujisawa [31] found that the production of turbulence energy in the jet region was remarkably increased with the wall curvature and the increase in turbulent kinetic energy stimulated the advection between jet region and wall region. Experiments by Fujisawa and Kobayashi [18] also revealed that strong centrifugal effects on the production of the turbulent fluctuation normal to the surface coupled with the production of the shear stress and the advection of streamwise turbulent fluctuation, increase the interactions of mean flow and turbulence.

Self-similarity of plane wall jet in an uniform stream was shown by Zhou and Wygnanski [81] with separate length scale and velocity scale for the inner and outer layer of the jet. The study indicated the dependency of the scales on the momentum flux at the nozzle, the viscosity, and the initial velocity ratio between the jet and the freestream. Strong interaction between the inner wall layer and outer free region of a wall jet was indicated by the experimental data of Abrahamsson et al. [1] which also corroborated the existence of a short inertial sub-layer as compared with a wall boundary layer in a self-preserving plane wall jet. Experimental data from *LDA* measurements of a two-dimensional turbulent wall jet were compared with previously existing hot wire data by Schneider and Goldstein [55]. The measured turbulent normal stresses were found to be somewhat higher than previously reported data throughout the flow field. Near-wall turbulent shear stress data were in good agreement with previous hot-wire data, but in the outer region Reynolds stresses data showed relatively higher values. For wall jet flow on an inclined surface, Lai and Lu [34] experimentally established that with increase in angle of inclination of the wall, the decay of jet centreline velocity, the jet spread and the rate of entrainment increased, whereas the length of the potential core decreased. Lai and Lu [36] indicated that for wall inclination of 30°, the issuing jet separated from the wall at the nozzle exit and reattached at downstream. The reattachment length was independent of nozzle aspect ratio (for $X > 30$) and exit Reynolds number within the given range of Reynolds number and limit of inclination angle.

Gerodimos and So [20] made a comparative study of four near-wall two-equation models and compared the predicted result with available experimental data for critical assessment of their ability to replicate plane wall jets. The study revealed that the