Abstract

An experimental and numerical investigation of the three-dimensional turbulent wall jet is carried out for the fluid flow and heat transfer characteristics for different developing initial conditions and different boundary conditions. The developing initial conditions are generated using a square nozzle of height(h) 20mm by changing the nozzle lengths(l). The boundary conditions of the three-dimensional turbulent wall jet are varied by the different sidewall enclosures (SWEs). The width of the SWEs is varied from 140mm to 200mm. A three-dimensional wall jet without sidewall is also considered for the comparison with the SWEs. The mean velocity inside the flow field is measured with a single probe hotwire anemometer. The temperature field is measured with a fine wire K-type of thermocouple. The surface temperature is measured with the thermal imaging infrared camera. The numerical studies are carried out by solving the three-dimensional Reynolds averaged Navier-Stokes (RANS) equations for different developing initial conditions and different boundary conditions. The three-dimensional RANS equations are discretized using the finite volume method. A collocated variable arrangement is utilized for the numerical simulations. The two different low Reynolds number turbulence models suggested by Yang and Shih (YS) and Launder and Sharma (LS) are considered for the numerical simulations. The turbulence models are validated with the present experimental results for fluid flow and heat transfer characteristics. Both the experimental and numerical investigations are performed at a Reynolds number of 25,000 based on the jet height ($h = 20mm$), and the jet exit bulk mean velocity ($u_b = 20.3m/s$). The different fluid flow and heat transfer characteristics of the three-dimensional wall jet are presented in the lateral and wall-normal directions for the downstream locations (x/h) 0 to 50.

The results and discussion of the present work is divided into three different sections. In the first section, the effect of developing initial conditions on three-dimensional turbulent wall jet are investigated inside a $200mm \times 1000mm \times 400mm$ SWE. The developing initial conditions are varied by varying the nozzle length as l/h=10, 50, and 90. The velocity distribution in the lateral and wall normal directions, the jet half width, spread rate, decay of maximum mean velocity, local Reynolds number and similarity behaviour are investigated through the experimental method while the contours of velocity and turbulent kinetic energy, skin friction coefficient and generation of Reynolds shear stress $< u_i u_j >$ in different planes are investigated through the numerical methods. The spread rate is found independent of the initial condition of the nozzles in the fully developed region. The decay rate of maximum mean velocity is found higher for l/h=10 in the region $5 \le x/h \le 25$, whereas in the fully developed region ($x/h \ge 25$), the decay rate of maximum velocity becomes independent of the initial conditions. The local Reynolds number (Re_x) reaches approximately 56% of the jet exit Reynolds number (Re_{jet}) at $x/h = 40$ for the nozzle length l/h=10, while it is 59% and 58% of Re_{jet} for the nozzles l/h = 50 and l/h = 90 respectively at this location. It is found that the contours of streamwise velocity and turbulent kinetic energy exhibit the effect of the initial conditions in the near field. The self-similar profile is obtained earlier for the nozzle length l/h=10 as compared to the other nozzle lengths l/h=50 and l/h=90 in the wall-normal direction, whereas lateral similarity is insignificantly influenced by the initial conditions. The Reynolds shear stress component $< u'v' >$ dominates in the vertical jet centerline plane, and it increases with decrease in the nozzle length. The Reynolds shear stress component $< u'w' >$ dominates in the lateral plane. The decay rate of maximum velocity is categorized into three different regions. The first and second regions of the maximum velocity decay are strongly dependent on the initial condition. It is seen that the decay rate of maximum mean velocity becomes independent of the initial conditions in the far-field locations.

In the second section, the sidewall effect on a three-dimensional turbulent wall jet is studied for fluid flow and heat transfer characteristics. For this, the two configurations are considered: one with the sidewall and the other without sidewall. The heat transfer characteristics are presented through temperature decay, thermal half widths, temperature fluctuation, statistical quantities like probability density function and skewness and flatness factors. It is observed that the decay rate of centerline bottom wall temperature of without sidewall is almost half than the corresponding case with the sidewall. The sidewall influences the temperature variation drastically. As a result, the asymptotic nature of the temperature is lost. Also, the thermal half width in the wall normal direction varies non-linearly as compared to the linear variation for the case without sidewall. Further, the mean fluid flow characteristics for these configurations are also investigated. The measured mean velocity profile and temperature profile are used for the validation of the numerical models. After the validation of the numerical methods, the turbulent characteristics are presented through numerical simulations. It is observed that the sidewall affects the temperature distribution just after the potential core region , whereas the velocity distribution is affected in the fully developed region, after the $x/h = 22.5$. The sidewalls drastically influenced the thermal and velocity decays in the wall-normal and lateral directions. It is found from the numerical simulation that the decay of maximum streamwise velocity is increased by 9%, whereas centerline temperature decay is decreased by 25% in configuration 2 as compared to configuration 1. The Reynolds shear stress $< u'v' >$ dominates in the vertical jet centerline plane (at $z = 0$), whereas $< u'w' >$ dominates in the lateral direction at the y_{max} plane in both the configurations. On the vertical jet centerline plane (at z =0), Reynolds shear stress $< u'v' >$ is nearly increased by 10% in the presence of sidewall as compared to the without sidewall configuration. The entrainment of the ambient fluid initially decreases, but after the $x/h = 22.4$, it increases for the case of the sidewall as compared to the corresponding case without the sidewall. This happens owing to an increase in the maximum turbulent kinetic energy generation inside the flow domain by 10%. The turbulent heat flux $< T'V' >$ dominates in the lateral and wall-normal shear layers in both the configurations, after the consumption of the potential core region.

In the third section, the effect of the SWE width is studied for the fluid flow and heat transfer characteristics. The width of the SWE is varied from 140mm to 200mm. The velocity and temperature measurements are also performed in the $z-y$ lateral plane at (x/h =) 30, 35, 40 and 45. The results indicate that the mean velocity profile in the lateral and wall normal directions behave differently depending on the width of the SWEs. The decay rate of mean velocity increases with decrease in the width of the SWEs after the $x/h = 20$. The decay rate of the maximum mean velocity increases about 5% in $140mm$ SWE as compared to 200mm SWE. It is noted that spread of the jet in the wall normal and lateral directions increases with decrease in the width of the SWEs after the attachment of the flow stream to the sidewalls. The self similar profile gets delayed in the wall normal direction than the lateral direction for all the cases. The wall normal self-similar profile is obtained early with increase in the width of the SWEs and it is obtained at $x/h = 30$, 27, 24 and 20 for $140mm$,$160mm$,$180mm$ and $200mm$ SWEs respectively. The flow stream seems to climb the sidewall and this tendency increases with increase in the width of the SWEs. The temperature decay rate is increased with increase in the SWE width in the downstream locations after $x/h = 35$. The decay rate of the jet centerline temperature in $200mm$ SWE is 4.6% higher than the $140mm$ SWE. The lateral spread increases with a decrease in SWE width due to the accumulation of thermal energy in the lateral shear layers. In the near field, thermal spread in the wall-normal direction increases with increase in the SWE width, but in the far-field locations ($x/h = 30$), the thermal spread increases with decrease in the SWE width. The thermal similarity is reached early with an increase in the width of the enclosure, and it is found at x/h =25, 22, 19 and 15 for the $140mm$, $160mm$, $180mm$, and $200mm$ SWEs, respectively. The temperature field shows the climbing effect over the sidewalls similar to the velocity field in the transverse plane ($z-y$). The one point temperature fluctuation shows the normal distribution of the probability density function along the jet centerline for all the cases of SWE. The probability density function is independent of the SWE width before the attachment ($x/h \leq 10$) of the flow stream to the sidewall; but, after the attachment ($x/h \geq 10$) of the flow stream to the sidewalls, the probability density function gets deviated from the normal distribution curve. The skewness and flatness factors are also calculated based on the instantaneous temperature fluctuation inside the SWE. The variation of local Reynolds number, entrainment, wall shear stress, spread ratios are also computed, and a detailed discussion has been provided for different SWE widths through numerical simulations. In the vertical jet centerline plane ($x - y$ plane), the Reynolds shear stress $< u'v' >$ dominates while $< u'w' >$ dominates in the lateral direction at the y_{max} plane. The Reynolds shear stress $< u'v' >$ is approximately 10% higher in 140mm SWE than the 200mm SWE at the $x/h = 30$ while Reynolds shear stress $< u'w' >$ in the lateral plane is approximately 8% lower in 140mm SWE than the 200mm SWE.

Keywords: Three-dimensional wall jet; Sidewall effect; Fluid flow characteristics; Heated jet characteristics; Low Reynolds number model; Experimental analysis