CHAPTER 7

Conclusions and future work

The three-dimensional turbulent wall jet is used in many engineering and research applications. In this thesis, the three-dimensional square wall jets are studied for different initial and boundary conditions through experimental and numerical methods. The initial condition of the jet is varied by varying the nozzle length of $200mm$, $1000mm$ and $1800mm$. The boundary conditions of the jet are varied by employing the sidewalls parallel to the vertical jet centerline plane at the lateral locations of $\pm 70mm$, $\pm 80mm$, $\pm 90mm$ and $\pm 100mm$. Another case of without sidewall is also included for comparison with the sidewall configuration. All the experiments and numerical simulations are performed at the jet exit Reynolds number of 25,000. The jet exit Reynolds number is calculated based on the bulk mean velocity ($u_b = 20.3m/s$) and height ($h = 20mm$) of the square nozzle.

The velocity is measured with the single probe hot-wire anemometer, while temperature is measured with a fine wire K-type thermocouple. The anemometer and thermocouple probes are mounted on a 3D transversal mechanism to measure the velocity and temperature fields in lateral and wall-normal directions from $x/h = 0.2$ to $x/h = 45$. The numerical simulations are performed by using two different low Reynolds number $k - \epsilon$ turbulence models suggested by Yang and Shih [47] and Launder and Sharma [48]. The measured mean velocity and temperature profiles at different lateral and wall-normal locations are used to validate the numerical models. The additional results such as entrainment, shear stress, Reynolds stress, turbulent kinetic energy, dissipation, turbulent heat flux are also evaluated by the numerical simulation, which are not possible through the experimental method.

This chapter provides the conclusions of the experimental and numerical results of the thesis. Some of the important recommendations are also presented for future work.

7.1 Conclusions

The first part of this thesis considered the effect of the developing initial velocity profiles at the jet exit. The experimental method measured the mean quantities and the numerical results show some additional results with the turbulence characteristics. After the potential core region, the decay rate of the mean velocity increases with the increase in the nozzle length up-to the downstream locations $x/h \leq 25$, whereas after $x/h = 25$, the decay rate of the mean velocity is almost independent of the initial conditions. The nozzle length also influences the spread in wall-normal direction, whereas lateral spread is independent of the initial conditions. The present spread rates (0.056 and 0.26 in wall-normal and lateral directions respectively) are found within the range of reported literature values. The wall-normal similarity region is little delayed from the lateral similarity region indicating the presence of turbulence structure in upper shear layers. The wall-normal similarity is affected by the nozzle length whereas lateral similarity is unaffected by the initial condition of the jet. The wall-normal similarity for the 200mm nozzle is achieved at $x/h = 20$, while for other nozzles it gets a little delayed ($x/h = 25$). The Reynolds shear stress ($< u'v' >$) in wall-normal direction at the symmetry plane is quite high as compared to other Reynolds stresses. But in lateral direction, $< u'w' >$ dominates over the other Reynolds stresses. The Reynolds shear stresses decrease with increase in the nozzle length. It indicates higher mixing behavior of shorter nozzle with ambient fluid as compared to the longer nozzles. It is noticed that the sidewall plays an important role in assessing the properties of fluid flow. As a result, after the jet's reattachment to the sidewalls, the flow velocity near the sidewall is equal to the core velocity indicating a positive effect on the overall performance of turbulent wall jet. The skin friction coefficient shows the dependency on the initial conditions in near-field of the wall jet, whereas in far-field, skin friction coefficient attains nearly a constant value.

The second part of this thesis dealt with the characterization of the heat transfer and fluid flow characteristics of the three-dimensional wall jet for with and without sidewalls through experimental and numerical methods. The results indicate that the decay rate of the jet centerline temperature decreases for with sidewall configurations. The case with sidewall configuration shows the early thermal stability than the without sidewall configuration due to less interaction and mixing of the ambient fluid. The temperature fluctuation is minimum at the jet centerline. The temperature fluctuation gradually increases in the lateral direction due to entrainment of the ambient fluid into the flow stream. The case without sidewall configuration shows a higher range of temperature fluctuation than the sidewall configuration due to the uniformity of the temperature inside the flow domain. The probability density function (p.d.f.) shows normal distribution for both the configurations. However, the normal distribution is little deviated for the case with sidewall configuration at $x/h = 20$ due to the interaction of the flow stream with the sidewall. Further downstream, again both the configurations show the similar pattern adhering to the normal distribution curve. The decay rate of centerline temperature is ~25% higher in the case of without sidewall configuration than in the configuration with sidewall, whereas the decay rate of maximum streamwise velocity in without sidewall configuration is decreased by about 9% than in the with sidewall configuration. Initially, the turbulent kinetic energy in without sidewall configuration is higher as compared to with sidewall configuration, but in the downstream locations, due to sidewall interaction with the flow stream, the generation of maximum turbulent kinetic energy in with sidewall configuration is increased by nearly 10% than the without sidewall configuration. The Reynolds shear stress $< u'v' >$ dominates in the vertical jet centerline plane whereas $< u'w' >$ dominates in lateral direction at the y_{max} plane in both the configurations. The Reynolds shear stress $< u'v' >$ is increased by nearly 10% in with sidewall configuration as compared to without sidewall configuration. The Reynolds stress component $< u'v' >$ crosses zero in wall-normal direction at the location of y_{max} in each configuration. The turbulent heat flux $< T'V' >$ dominates in the lateral and wall-normal shear layers in both the configurations. The turbulent heat flux $< T'V' >$ increases by approximately 15% due to the sidewall interaction in with sidewall configuration.

The final part of the thesis is to investigate the effect of sidewall enclosure (SWE). The velocity decay rate increases with the decrease in the width of sidewall enclosure. The decay rate of maximum mean velocity starts increasing with decrease in the width of SWEs. The decay rate is approximately 5% higher for 140mm SWE than 200mm SWE. This difference is observed due to the higher resistance offered by the smaller width of SWEs. The resistance inside the SWEs is responsible for the momentum loss of the mean flow. This leads to a decrease in the maximum mean velocity at the centerline plane as compared to the larger width of SWEs. The spreading rate of the three dimensional turbulent wall jet is observed to be different in different SWEs, in far field locations. The centerline temperature decay decreases with decrease in the width of SWE. The decay rate of the centerline temperature is approximately 4.6% lower for $140mm$ SWE than the $200mm$ SWE. The jet spreads faster in the smaller width SWEs than the larger width SWEs in lateral and normal directions. It has been observed that 140mm SWE has 14.3% and 26.2% higher spread rates as compared to 200mm SWE in wall-normal and lateral directions, respectively. The temperature spread in the lateral direction is found to increase with decrease in the SWE width, whereas thermal spread in wall-normal direction increases with increase in the width of SWE in the near field due to higher spread of the flow stream. But in far-field location, the higher spread is observed for the smaller width of SWEs. The spread rate is approximately 13.6% and 17.8% higher in lateral and wall-normal directions, respectively, for 140mm SWE than the 200mm SWE. The mean velocity in wall-normal direction shows self-similar behaviour after $x/h = 20$ for 200mm SWE. In contrast, the flow in smaller width of SWEs is still developing at this downstream location indicating the effect of sidewall. The self-similarity behaviour of the wall jet is delayed with decrease in the width of SWE. This indicates an increase in the turbulence and dynamic readjustment of the temperature profiles with decrease in the width of SWE. The spreading of the flow stream is found to be maximum near the sidewall for all the cases, referred to as the climbing tendency of the flow near the sidewalls. The mean flow characteristics in the lateral direction exhibit similar characteristics with the mean flow of the centerline plane except near the sidewall ($\lambda = 0.9$). This behaviour of the jet shows that the dynamic readjustment takes place inside the lateral shear layers. The normal distribution curve is independent of the SWE before the attachment of the flow stream to the sidewall, i.e. $(x/h \leq 10)$. After the interaction of the flow stream with the sidewalls $(x/h \geq 20)$, the probability distribution curve is deviated from the Gaussian curve. The Reynolds shear stress $< u'v' >$ dominates in the vertical jet centerline plane whereas $< u'w' >$ dominates in lateral direction at y_{max} plane. In the vertical jet centerline plane, the Reynolds shear stress component $< u'v' >$ increased approximately by 8.1% in 140mm SWE as compared to 200mm SWE at the downstream location x/h=30. In the lateral plane, $< u'w' >$ decreases with the decrease in the width of SWE. Approximately 7.1% Reynolds shear stress $< u'w' >$is suppressed in 140mm SWE as compared to 200mm SWE at y_{max} plane in the lateral direction.

7.2 Recommendation of future works

Based on the present work, the future work on the three-dimensional turbulent wall jet is recommended as below:

- The mean velocity measurement was performed with a single probe hot-wire anemometer for the different initial and boundary conditions. Although the present study of the three-dimensional wall jet is the most comprehensive study with experimental and numerical analysis but the measurement methods which have been used in the study are intrusive in nature. Therefore, it is suggested to use non-intrusive measurement methods which can provide a better thermal and flow field. The non-intrusive techniques like Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) could provide a better understanding of the mechanism for different initial and boundary conditions.

- Because of the intrusive measurement technique, we could not go below 140 mm width of the sidewall enclosure. The non-intrusive measurement technique will allow one to go for the smaller width of the sidewall enclosure at different Reynolds numbers.

- The present study is performed for the smooth surface. It would be interesting to study the effect of surface roughness and wavy surface on the fluid flow and heat transfer characteristics.

- The use of Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) can provide the interaction of the large and small scales eddies with each other and also with the sidewall which was not possible with the RANS simulations.