CHAPTER 1

Introduction

The irregular fluctuations, chaotic and highly mixing flow is characterised as the turbulent flow. These characteristics of turbulent flow are very important. The optimisation of the turbulence characteristics can increase the durability and efficiency of these components, e.g. enhancement of the turbulence inside the heat exchanger, combustion chamber, internal cooling of a turbine blade, or decreasing the turbulence over the aeroplane wings. The turbulent flow has many practical applications, and a plethora of research is devoted to the turbulent flow, but the fundamental understanding is still lacking due to its complex nature. The great physicist and Nobel laureate Richard Feynman stated that

> '*Turbulence is the most important unsolved problem of classical physics*'

1.1 Turbulent jet

The turbulent jets are defined as the jet which flow through the nozzle and the condition at the nozzle exit is turbulent. The essential characteristics of the turbulent jets are the entrainment of the ambient fluid into the flow stream, spreading of the flow stream, and mixing of the ambient fluid and flow stream. The turbulent jet characteristics depend on the different parameters of the jet, like exit cross-sectional area, type of nozzle geometry, jet exit velocity profile conditions, and the ambient conditions. These parameters can be optimised by knowing their physics. The turbulent jet is classified into different groups based on the interaction of the flow stream with the different boundary conditions such as: Free jet, wall jet, offset jet and impinging jet.

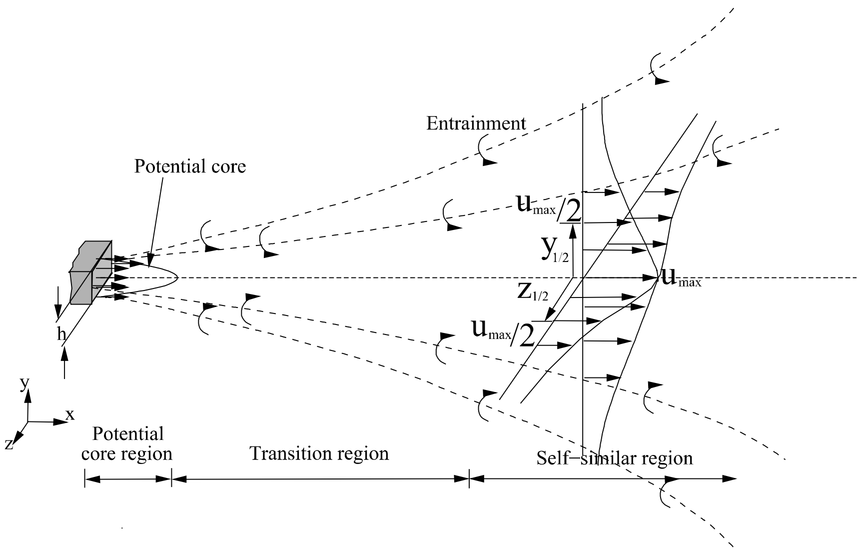

Figure 1.1: Schematic diagram of the free jet

1.1.1 Free jet:

A jet is characterised as a free jet when the jet stream is far from the solid boundary. A schematic diagram of the free jet is shown in Figure 1.1. As there is no solid boundary of the wall which interacts with the flow stream, a free shear layer is formed in which static pressure is throughout constant. At the exit of the jet, fluid forms a free shear that mixes with the interacting surrounding fluid; its mass flow increases due to this phenomenon to conserve the momentum and its centerline maximum velocity gradually decreases. The flow field of the free jet is divided into three different regions as potential core region, transition region and self-similar region.

1.1.2 Wall jet:

A jet is characterised as a wall jet when the jet stream flows tangentially to the wall surface. A schematic diagram of the wall jet is shown in Figure 1.2. Like free jet regions, the wall jet flow stream is divided into three regions called as the potential core region, transition region, and self-similar region. The wall jet stream forms two distinct shear layers after exit from the nozzle called as the 'inner shear layer' and 'outer shear layer'. The region from the bottom wall to the maximum streamwise velocity (y_{max}) is called the inner shear layer, whereas the region above it is called the outer shear layer. The maximum streamwise velocity (y_{max}) location continuously changes with the downstream location and so as the width of inner and outer shear layers. The inner shear layer interacts with the bottom wall, whereas the outer shear layer interacts with the surroundings. The interaction and mixing

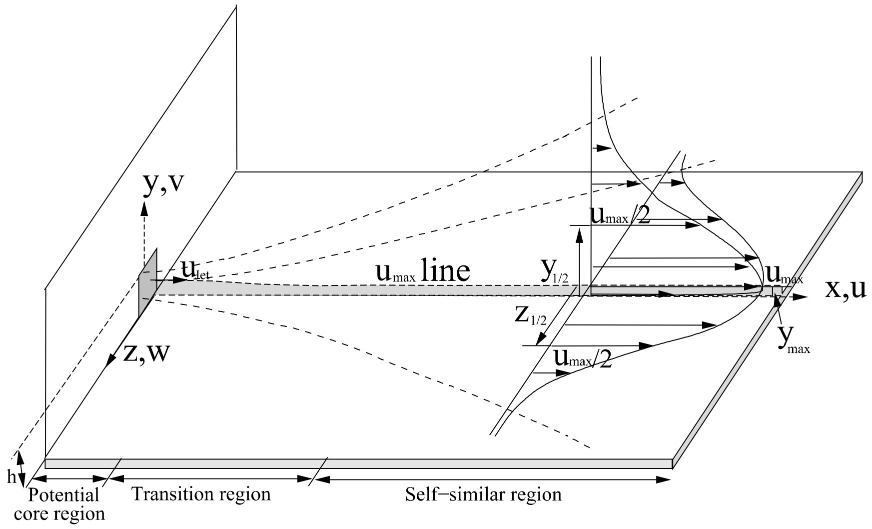

Figure 1.2: Schematic diagram of the three-dimensional wall jet

characteristics of the flow stream with surroundings exhibit the dependency on the jet initial and boundary conditions. The development of the flow field of a three-dimensional wall jet strongly depends on the initial and boundary conditions of the jet.

1.1.3 Offset jet:

A jet is characterised as the offset jet when the jet stream is discharged into a medium from a certain height parallel to the wall surface. An offset jet can be thought of as the combination of a free jet and a wall jet. The schematic diagram of the offset jet is shown in Figure 1.3. The offset jet region is divided into re-circulation region, followed by developing and self-similar regions.

1.1.4 Impinging jet:

A jet is defined as the impinging jet when the interacting wall is placed normal to the jet stream. An impinging jet generates different regions from the jet exit, which are: free jet region, stagnation region, and the wall jet region. These regions are strongly dependent on the initial conditions and boundary conditions. The schematic diagram of the impinging jet is shown in Figure 1.4.

The nomenclatures u_{max}, u_{jet}, y_{max}, $y_{1/2}$ and $z_{1/2}$ used in the schematic diagram are defined as the maximum streamwise mean velocity, jet exit velocity, transverse location of the maximum streamwise velocity, jet half-width in wall-normal direction and jet half-width in the lateral direction, respectively. The jet half widths $y_{1/2}$ and $z_{1/2}$ are defined as

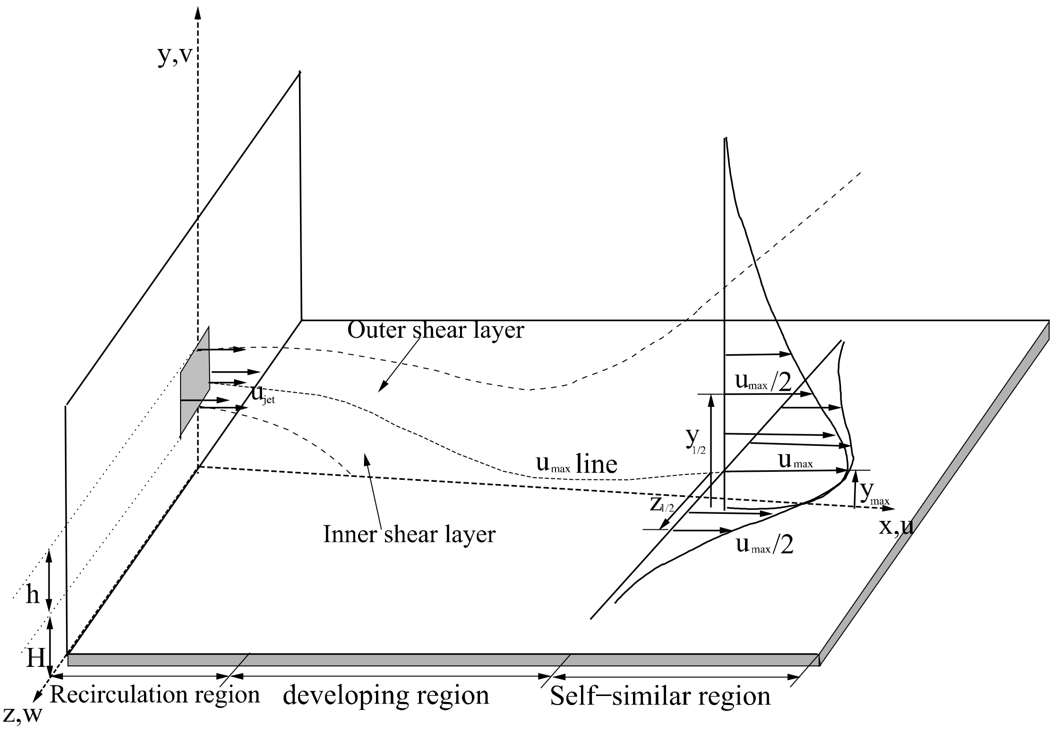

Figure 1.3: Schematic diagram of the three-dimensional offset jet

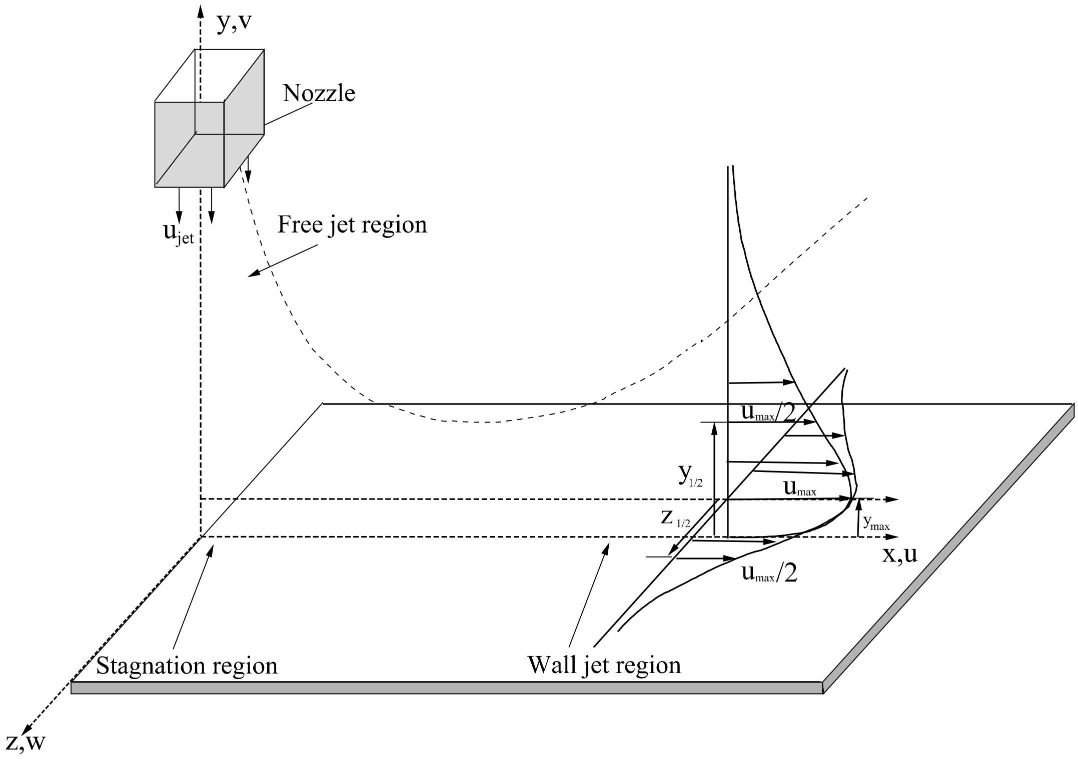

Figure 1.4: Schematic diagram of the three-dimensional impinging jet

the location of the velocity in the wall-normal and lateral directions, where the streamwise velocity becomes half of the maximum streamwise velocity (u_{max}). The slopes of the spread width $\left(\frac{dy_{1/2}}{dx}\right)$ and $\left(\frac{dz_{1/2}}{dx}\right)$ are defined as the spread rate in wall-normal and lateral directions.

The turbulent jet attached from the wall at the different positions has very diverse industrial applications. These applications include automobile demister, cooling for the peripheral of the electric motor, thrust injector during the aircraft vertical take-off, entrainment and mixing inside the combustion chamber, cooling of the electronic component, mold cooling, internal cooling of the turbine blade, air discharge for the enclosed environmental, and solar air heater. Some of the other applications of the three-dimensional jet attached to the wall surface are the disposal of the power plant and various industrial wastes, prevent flow separation control at the verge of separation, and discharge of the pollutants. Various applications of the jet attached to the wall attracted many researchers to explore the physics for optimisation and to enhance the efficiency of various equipment. The jet attached to the wall surface form a very complex flow behaviour. A three-dimensional wall jet can be a suitable test case to investigate the complex flow behaviour for exploring the turbulent flow physics. The physics of these complex flow behaviours near the wall surface and free shear layers can be examined by a simple three-dimensional wall jet geometry. The anisotropic growth of the flow stream and lateral spread make the turbulent wall jet very challenging to predict. Thus, the simple three-dimensional wall jet configuration provides the performance test of the different turbulence models for these complex flow behaviours.

1.2 Description of wall jet:

The wall jets are studied as two-dimensional and three-dimensional jets with different initial conditions and boundary conditions. The two-dimensional wall jet is defined as a jet whose flowing stream has the longitudinal and normal variation along the downstream locations. The lateral variation of two-dimensional wall jet flow is statistically independent. The jet issuing from a rectangular nozzle, having a very large width than the height, is considered as a two-dimensional jet. Many researchers investigate the physics of the two-dimensional wall jet. The recent study on the two-dimensional wall jet included Lai and Lu (1994), George et al. [25], Kumar [26], McIntyre et al. [6], Singh et al. [27]. They have considered different initial and boundary conditions. The three-dimensional wall jet flow is defined as the flow having an additional variation in the lateral direction, making the flow more complex. A plethora of research is carried out on the three-dimensional turbulent wall jet in the last six decades (Agelin-Chaab and Tachie [11], Kwakye et al. [13], Godi et al. [28]), but basic physics is still not explored due to its complex nature of the flow. The development of the three-dimensional turbulent wall jet depends on the initial conditions (Sun and Ewing [4], Hall and Ewing [9], Agelin-Chaab and Tachie [11], Kwakye et al. 2015 [13]). The shape of the initial velocity profile at the nozzle exit plane (top hat profile and fully developed profile) enables the large scale turbulence structure to affect the mixing and developing characteristics of the turbulent wall jet. The nozzle shape (different geometry at the jet exit plane) affects the flow field (Padmanabham and Gowda [2], Mohammadaliha et al. [29]) developed by the three-dimensional wall jet. The presence of backwall at the nozzle exit plane (Sun and Ewing [4]) influences the flow characteristics in the near field of the jet, whereas the corner wall jet also shows the dependency on the boundary condition of the jet (Poole and Hall [30]). The above applied different conditions on the three-dimensional turbulent wall jet influence the development of the jet stream and its physics. The recent studies on the three-dimensional turbulent wall jet are listed in table 1.1. The turbulent wall jet characteristics like spread rate, decay rate, self-similarity region, entrainment and mixing depend on the different parameters of the jet, like jet inlet profile, the shape of the bottom wall, boundary condition, back and corner walls etc. The spread rate in the wall-normal direction $\left(\frac{dy_{1/2}}{dx}\right)$ is approximately 5-6 times higher than the lateral spread rate $\left(\frac{dz_{1/2}}{dx}\right)$. The spread rate for the corner wall jet in the wall-normal direction $\left(\frac{dy_{1/2}}{dx}\right)$ is approximately 3.3 times higher than the lateral spread rate $\left(\frac{dz_{1/2}}{dx}\right)$. Due to the wall interaction, the vertical growth of the wall jet is suppressed. A backwall at the nozzle exit plane reduces the spread rate by approximately 20% compared to without a backwall.

The flow development of a three-dimensional turbulent jet is defined by the self-similar solution. The self-similar solution of a three-dimensional turbulent wall jet is achieved when the congruence of the velocity profiles is obtained by scaling a factor. Wygnanski et al. [32] suggested the similarity scaling for the different jet flows. After achieving the similarity solution, no dynamic readjustment inside the flow field takes place, and this situation of the flow field is called the developed flow. The similarity solution exhibits its dependency on the initial and boundary conditions of the turbulent wall jet. The location of similar solutions gets delayed for the fully developed profiles as compared to the top hat profiles. The similarity solution is influenced when any physical boundary conditions (corner wall and backwall) are introduced. This also indicates the generation of the large turbulence structure inside the flow domain. The Reynolds shear stresses $\left(< u'_i u'_j >\right)$ signify the mixing characteristics of the turbulent wall jets. The mixing characteristics depend on the amount of fluid entrainment and spread of the flow streams. The Reynolds

Author	Initial conditions	x/d	Bottom wall geometry	Re	$\frac{dy_{1/2}}{dx}$	$\frac{dz_{1/2}}{dx}$	n
Hall and Ewing [9]	Rectangular	$3-60$	$1800mm$	89,600	0.051	0.28	1.144
	$h = 2.54cm$		$1200mm$				
	$w = 0-25cm$		$2400mm$				
Sun and Ewing [4]	Contoured Nozzle	$0-90$	Flat plate	65,000	0.053	0.27	1.14
	$d = 3.8cm$		$2.5m \times 1.8m \times 1.1m$	108,000	0.060	0.28	1.19
Koso and Ohashi [7]	Semi-circular	$30-50$	Flat plate	66,200	-	-	1.27
	$d = 50mm$		$2mm$ thickness				
Law and Herlina [31]	Circular	$0-50$	Smooth Plane	5,500-13,700	0.042	0.21	1.07
	$d = 5.5mm$		$1m \times 0.5m \times 3m$				
Abrahammsson et al. [12]	Circular	$50-90$	flat Plate	53,00-105,000	0.065	0.32	1.29
	$d = 20mm$		$2.1m \times 3.2m$				
Poole and Hall [30]	Circular	$0-40$	$0.58m \times 1.41m$	159,000	0.0497	0.165	-
	$d = 25.4mm$						
Agelin-Chaab and Tachie [11]	Circular type	$0-120$	$1000mm$	5000	0.054	0.255	1.15
	$d = 7 \pm 0.2mm$		$500mm$	10000			
	Long pipe		$300mm$	20000			
Padmanabham and Gowda[2]	Circular	$0-100$	Flat plate	95,400	0.045	0.216	1.15
			$1.45m$		0.043	0.215	
			$2.05m$		0.049	0.245	
			$18mm$		0.04	0.250	

Table 1.1: Summary of three-dimensional turbulent wall jet for different initial conditions and boundary conditions

shear stresses are predicted by measuring the fluctuating velocity component in different directions as, $< u_i' u_j' >= -\frac{\vartheta_n}{Re}\left(\frac{\partial \overline{u_i}}{\partial (x/h)_j} + \frac{\partial \overline{u_j}}{\partial (x/h)_i}\right) + \frac{2}{3}k_n$. The location of zero Reynolds shear stress $< u'v' >$ of the wall jet is lower than the location of maximum velocity from the bottom wall. This deviation of the location of the zero Reynolds shear stress from the location of maximum velocity is known as the asymmetric property of the wall jets. The turbulent kinetic energy is maximum at the edge of the viscous sub-layer. The Reynolds shear stress and turbulent kinetic energy show its dependency on the jet initial and geometrical boundary conditions (Namgyal and Hall [23], Agelin-Chaab and Tachie [11], Padmanabham and Gowda [2]). The maximum production of the turbulent kinetic energy is in the upper shear layer (at the interface of the flow stream and the stagnant fluid), whereas the maximum dissipation occurs in the inner shear layer (near the bottom wall). The turbulent heat flux for a heated wall jet is not much seen in the literature due to the lack of study of the three-dimensional heated wall jet. The turbulent heat fluxes in different directions can be calculated as $< t' u_i' >= -(\nu_t/Pr_t)(dT/dx_i)$.

1.3 Research methodology

The physics and different features of the three-dimensional turbulent wall jet are primarily explored through experimental and computational methods. With the development in the experimental and computational facilities deeper insights of turbulent wall jet are explored. The experimental methods are carried out using intrusive and non-intrusive techniques. The intrusive methods (hotwire anemometer, pressure tap and Pitot static tube, thermocouple) are relatively cheaper than the non-intrusive methods (particle image velocimetry (PIV), laser Doppler anemometer (LDA), infrared thermal imaging camera), that is why they are more popular methods.

In the recent days, the hotwire anemometer, particle image velocimetry (PIV), laser Doppler anemometer (LDA) are commonly used to characterize the turbulent wall jet characteristics. The particle image velocimetry (PIV) and laser Doppler anemometer (LDA) are non-intrusive methods with high accuracy but are very expensive. The hotwire anemometer is very popular because it is less expensive. Although the hotwire anemometer is an intrusive method, it provides satisfactory results for the turbulent wall jet flow. The hotwire anemometer is a single point measurement technique, so it measures the different shear layers and velocity profiles at different locations of the jet with the transversal mechanism. The thermocouple is commonly used to measure the heated jet characteristics of the wall jet. The thermocouple is also an intrusive method, so it requires a transversal mechanism. The accuracy of the thermocouple depends on the response time, bead size, and wire diameter of the thermocouple. The surface temperature of the heated wall jet can be measured with either thermocouple or the infrared thermal imaging camera. During the measurement of the surface temperature, the thermocouple removes heat from the measuring surface, resulting in the display of a lower temperature than the actual surface temperature. The infrared thermal imaging camera utilizes a non-intrusive measurement technique by which the temperature of the surface is accurately measured. The experimental methods are time consuming and expensive than the computational methods, but they play a very important role to understand the physics behind the flow.

The computational methods are cheaper than the experimental methods, and it provides more flexibility to understand the physics and optimise any component design. However, the computational methods have also some limitations like computational cost and accuracy of the model. The available computational methods are Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), and Reynolds Averaged Navier Stokes (RANS) equations modelling. The DNS and LES methods are computationally very expensive. The smallest grid size of the DNS methods is in the order of the Kolmogorov scale. Till now, there is no study available on the DNS method for the three-dimensional turbulent wall jet flow. Naqavi et al. [33] applied the DNS for the plane turbulent wall jet at a Reynolds number of 7500 for an isothermal wall. The LES method was proposed by Smagorinsky [34] to reduce the computational cost by neglecting the smaller-scale eddies. The LES method accurately predicts at the expense of computational cost. The LES simulations are recommended in highly mixing flow like combustion and offset jet, where separation or backflow occurs very often. For the three-dimensional wall jet, the RANS turbulence modelling gives good results with the limited computational resources. The majority of the current industrial and laboratory studies use the RANS turbulence modelling. In this method, the flow variables are decomposed into time averaged variables and fluctuating variables by using the Reynolds decomposition method. By decomposing the RANS equation, additional non-linear terms appear in the governing equations. These additional non-linear terms are modelled by using different turbulence models. These models predict the turbulent flow quantity, but the accuracy of the models is problem-dependent. It has been seen that the RANS turbulence model predicts satisfactory results of the simple three-dimensional wall jet. Hoff et al. [35] investigated the three-dimensional buoyant turbulent flows for the rectangular jet by using the fully turbulent $k-\varepsilon$ model and low Reynolds number $k-\varepsilon$ model. The fully turbulent $k-\varepsilon$ model was developed by Harlow and Nakayama [36]. In this model, it is assumed that all the points are in full turbulence region. Further, this method was modified by Launder and Spalding [37]. The Low Reynolds number $k-\varepsilon$ model was developed by Launder and Spalding [38]. It has a more refined grid compared to the full turbulent $k-\varepsilon$ model. The Re-normalization group (RNG) turbulence model was developed by Yakhot and Orszag [39]. This model uses dynamic scaling and invariance together with iterative perturbation methods, by which it can evaluate the transport coefficients and transport equation for the large scale modes. Further, this method was modified by Yakhot et al. [40] for the shear flow. Nasr and Lai [41] studied the turbulent plane offset jet with different offset ratios for different turbulence models like standard $k-\varepsilon$, RNG $k-\varepsilon$ and RS $k-\varepsilon$ models in a homogeneous meshing with a power law, QUICK scheme, and second-order upwind schemes. They found that $k-\varepsilon$ model is appropriate for the offset jet type of flow. This method was counter verified by the different researchers for the different situations for turbulent wall jet flow. Kechiche et al. [42] adopted the low Reynolds number $k-\varepsilon$ models to study the turbulent wall jet. Kumar [26] studied the mean flow and thermal characteristics of the dual jet for the high Reynolds number two-equation $k-\varepsilon$ model. Markatos [43] did the mathematical modelling for the turbulent flow. He studied the different types of the model involved in the turbulent flow, like $k-\varepsilon$, $k-\omega$, and LES. They found that the $k-\varepsilon$ and $k-\omega$ modela are fairly good. A multi-grid procedure was presented by Demuren [44] for the turbulent jet in cross-flow. He applied $k-\varepsilon$ turbulence model and second-moment closure model. A very rapid convergence was obtained with $k-\varepsilon$ model as compared to any other models with the fine grid. Faghani and Rogak [45] studied numerically and analytically the turbulent plane jet by using the bending model and compared with $k-\varepsilon$ model. Kumar and Das [14] verified the $k-\varepsilon$ turbulence model for the dual jet (combination of a wall jet and an offset jet). Singh et al. [27] verified the $k-\varepsilon$ model for the heat transfer characteristics of a wavy wall jet. Rathore and Das [46] used the low Reynolds number $k-\varepsilon$ model for the wall-bounded jet. They have tested the accuracy of Yang and Shih [47] and Launder and Sharma [48] models.

1.4 Objective of the Research

The three-dimensional wall jet characteristics like spreading, entertainment of the ambient fluid, decay of maximum streamwise velocity, turbulent kinetic energy generation, dissipation of turbulent kinetic energy, Reynolds shear stresses and turbulent heat flux generation exhibit the dependency on the initial and boundary conditions. The different jet geometries of the three-dimensional wall jet are seen in the literature to explore the different physics. It is stated that turbulent flow is the most complex problem; when it comes to contact with any solid surface, its behaviour and physics of the flow get changed. The physics of the turbulent flow also relies on the initial condition of the jet. Many en-

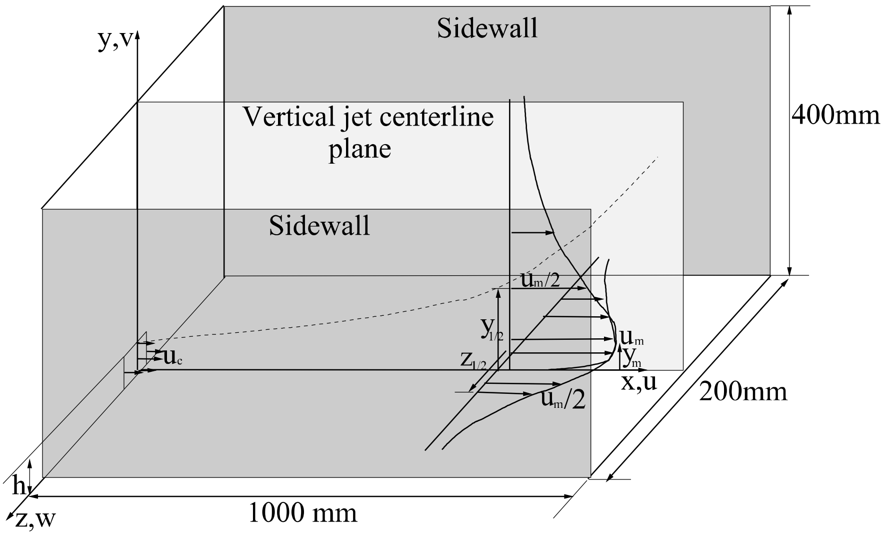

Figure 1.5: Three dimensional turbulent wall jet with sidewall

gineering components have a three-dimensional wall jet with the sidewall enclosure. The sidewall significantly influences the flow field. The initial conditions in these components have neither fully developed nor a top hat type profiles. There is no study which explores the effect of sidewall on the three-dimensional turbulent wall jet characteristics. The sidewall is defined as the two parallel plates along the downstream direction parallel to the vertical jet centerline plane, as shown in the Figure 1.5. Although, some previous studies have been carried out inside the sidewall enclosure, but, they have taken the sidewall sufficientally far away from the flow stream that has no effect on the flow field. Also, there is no literature which deals with the developing velocity profile for the three-dimensional turbulent wall jet. There are some studies on heated jets, but the detailed study of the three-dimensional heated wall jet is still missing. On the basis of this, the following objectives are set as:

1. Investigate the effect of developing initial condition of a three-dimensional turbulent wall jet inside a sidewall wall enclosure.

2. Study of fluid flow and heat transfer characteristics for with and without sidewall enclosure.

3. Study the effect of sidewall enclosure width on the fluid flow and heat transfer characteristics.

1.5 Thesis structure

The present thesis is divided into seven chapters. The first chapter contains the introduction of the turbulent jets and its applications, detailed description of the wall jet, research methodology and objective of the research. In Chapter 2, the previous studies on the different configurations of the turbulent jets with different initial and boundary conditions are reviewed. The Chapter 3 provides the experimental and numerical methods used for the present work. The Chapters 4-6 collectively present the results and discussion on the topic listed in objective of the research section (see section 1.4). In Chapter 7, the conclusion of the present work and the recommendation of the future work are presented.