

### 1.1 Turbulent jet

The jet is said to be formed when the fluid flow originating inside an orifice enters the quiescent surrounding of the same fluid. A jet is said to be fully turbulent when the condition at the orifice exit is turbulent and the entrainment of ambient fluid starts immediately after the jet exit from the nozzle. Irregularities, diffusivity, Reynolds number, vorticity fluctuations and energy dissipation are the important characteristics to define turbulence [99].

**Irregularities:** The randomness of fluid in the flow is very high in the turbulent flow, which makes it impossible to follow the deterministic approach and one has to depend on the statistical methods for solving the turbulent flow problems.

**Diffusivity:** From the application point of view, this is the most important feature of turbulence. Diffusivity leads to the rapid mixing of fluid, which increases the rate of heat and mass transfer as well as momentum in the flow. It also helps in delaying the separation of the boundary layer from the surface. Turbulent flow is applicable in many engineering applications where a high rate of heat and mass transfer is required and it is also required to avoid separation as well.

**Reynolds number:** The Reynolds number for the turbulent flow is always high. If the Reynolds number is too high, the turbulence originates from instability in the laminar flow. The instabilities are related to the interaction of viscous terms and nonlinear inertia terms in the equations of motion. The equation becomes so complex: to date, there is no

mathematical solution available to solve the nonlinear partial differential equation to give the general solution. That is why “Turbulence is the most important unsolved problem of classical physics,” as said by Richard Feynman, the great physicist and Nobel laureate.

**Vorticity fluctuation:** The level of vorticity fluctuation is very high in the turbulent flow.

**Energy dissipation:** The turbulent flow is dissipative in nature. The turbulent kinetic energy is converted into internal energy due to the viscous shear stress. To cope with these viscous losses, a continuous energy supply is required to maintain the turbulence. In the absence of an energy supply, the turbulence decays very fast.

Due to its diffusive nature, the turbulent jet has been widely used in different industrial applications, wherever the enhancement in heat and mass transfer is required, like for drying cloths in textile industries, cooling of turbine blades, cooling of electronic devices, deicing of aircraft and defrosting of the windshield and much more.

The turbulent wall jet is broadly classified into two types: the first one is a free jet and the second is wall bounded jet. The wall bounded jet is further classified into turbulent wall jet, offset jet and impinging jet based on the orientation of the jet with respect to the axis. The brief introduction of different types of jets is as follows:

### 1.1.1 Free jet

A free jet is formed when a jet is discharged into a free quiescent surroundings and there is no wall present in the flow region. The schematic diagram of the free jet is shown in fig. 1.1 with the important terminology. In the absence of a solid boundary, the jet directly interacts with the surrounding fluid through the top and bottom sides and free shear layer is formed due to discontinuity in the velocity of the jet and the surrounding fluid. The static pressure remains constant throughout the free shear layer. As free jet moves forward the mass flow increases and to conserve the momentum the centerline maximum velocity decreases. The free jet flow field is divided into three regions: first one is the potential core region followed by the transition region and finally the fully developed region. In the developed region, the velocity profile follows self-similar behaviour, that is why this region is also called self-similar region.

### 1.1.2 Wall jet

In the case of a wall jet, the jet is placed tangential to the wall from one end and another end is open in the surrounding with the quiescent condition of the same fluid. Due to the compact orientation, the turbulent wall jet has vast industrial applications for film

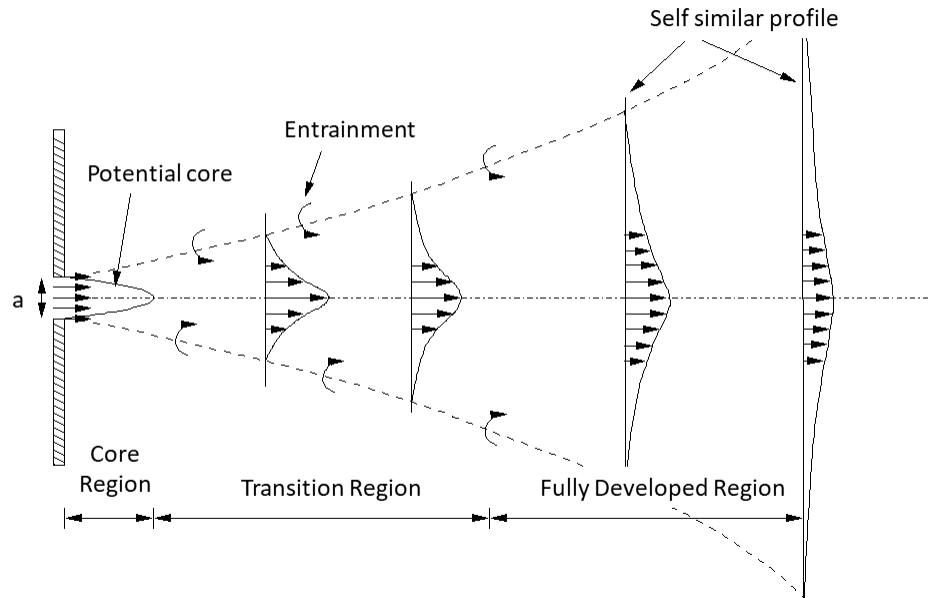


Figure 1.1: Schematic diagram of a free jet.

cooling. The schematic diagram of wall jet is shown in fig. 1.2. The jet evolution is divided into three zones: core region, transition region and fully developed region. In the core region, the viscosity effect is neglected and the flow is treated as the inviscid flow. However, due to the wall friction, the inner shear layer is formed and due to the discontinuity in the jet and surrounding fluid velocities, the outer shear layer is created. The characteristics of the inner shear layer are similar to the wall boundary layer and the characteristics of the outer shear layer are similar to the free jet. Once the potential core is consumed, the inner shear layer and the outer shear layer interact with each other, which is called the transition zone. In this zone, the upper shear layer and lower shear layer mix together, giving rise to high turbulence. In this zone, the jet decays at a high rate. The fluid enters the developed zone when the outer shear layer and inner shear layer merge and combine into a single layer. The decay of the jet follows the power law and the spreading of the jet becomes linear in the developed zone [25, 84]. The terminologies  $U_{max}$  and  $Y_{0.5}$  are used in fig. 1.2, where  $U_{max}$  stands for the maximum streamwise mean velocity and  $Y_{max}$  is the position normal to the wall where  $U_{max}$  is achieved and  $Y_{0.5}$  is the location normal to the bottom wall where the streamwise velocity becomes half of the  $U_{max}$ . Because of its vast applicability and interesting characteristics, the turbulent wall jet is popular among researchers to explore. The wall jet has been investigated as two-dimensional wall jet and three-dimensional wall jet. A wall jet is said to be two-dimensional when the jet spreads

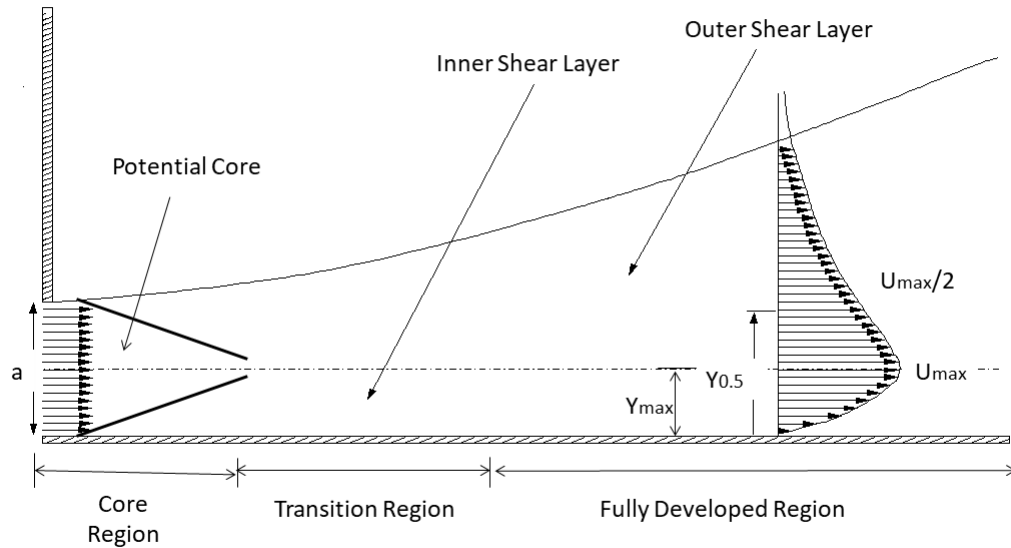


Figure 1.2: Schematic diagram of a wall jet

only in a cross-stream direction during the flow, which means the mean flow parameter varies in the streamwise and cross stream directions only and it remains unchanged in the lateral direction. The jet behaves as a two-dimensional jet when the aspect ratio of the nozzle is high. The aspect ratio is the ratio of the width of the nozzle to the height of the nozzle. Holland and Liburdy [41], Song et al [93] and AbdulNour et al. [1] have used nozzle of aspect ratio 15, 12 and 17.8 respectively in order to have a two-dimensional flow structure. The jet is enclosed from the side wall to maintain the 2-D nature throughout the flow. In the three-dimensional wall jet the aspect ratio of the nozzle is less, due to which the jet spreads in both the cross-stream and lateral directions which leads to the variation of parameters in the lateral direction. The inlet state [33, 39, 55, 62, 87], the co-flow condition [10, 31, 49, 66, 88], the curvature [22, 56, 89, 91] and the surface roughness [13, 82, 98] of the wall are the important aspects of a turbulent wall jet. The flow and thermal characteristics of the turbulent wall jet, like the thermal and velocity spread of jet, thermal and velocity decay of jet, entrainment of ambient fluid, Reynolds stress and heat transfer rate, change by changing any aspect of the turbulent wall jet.

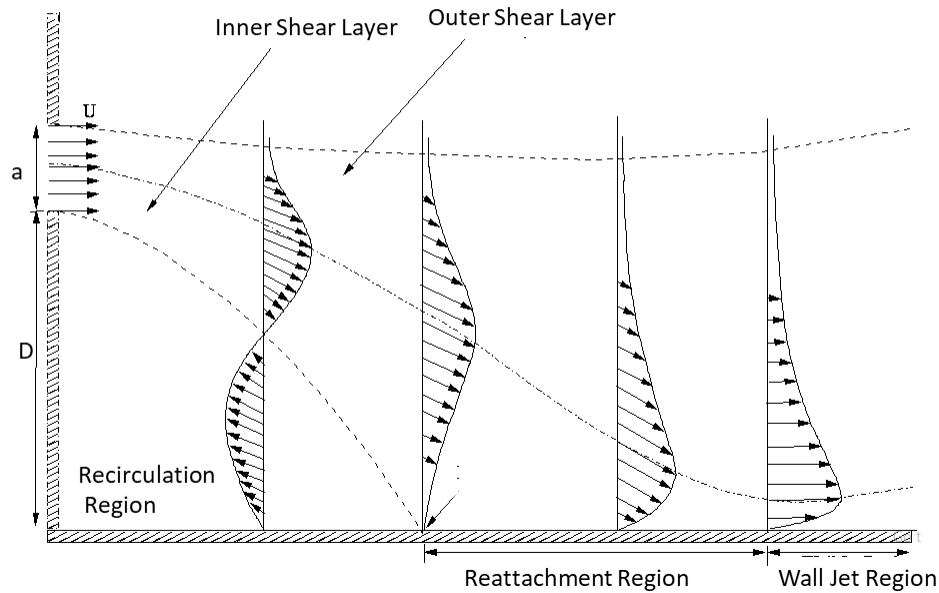


Figure 1.3: Schematic diagram of an offset jet

### 1.1.3 Offset jet

A jet is said to be an offset jet when a jet is discharged into the surrounding from a given height from the wall and the wall is placed parallel to the axis of the nozzle. The schematic diagram of the offset jet with an offset height  $D$  and the nozzle height  $a$  is shown in fig. 1.3. Initially, when a jet is discharged from the nozzle it acts as a free jet, but due to the presence of a wall at some distance, a pressure imbalance in the outer and the inner regions of the jet is generated leading to the formation of low-pressure zone in between the jet and the bottom wall. This region is known as the recirculation region; beyond this, the jet gets attached to the wall and the region is called the reattachment region. After the reattachment region, the jet behaves as a wall jet.

### 1.1.4 Impinging jet

The jet is said to be an impinging jet when a jet is discharged into the surrounding from a given height from the wall and the wall is placed vertically to the axis of the nozzle. The impinging jet has been divided into different regions as it comes out of nozzle, which are the free jet region, stagnation region and the wall jet region, as shown in fig. 1.4. The regions of the impinging jet is strongly influenced by the height of nozzle from the wall. It is mostly preferred for localized cooling. Despite having good performance, the major

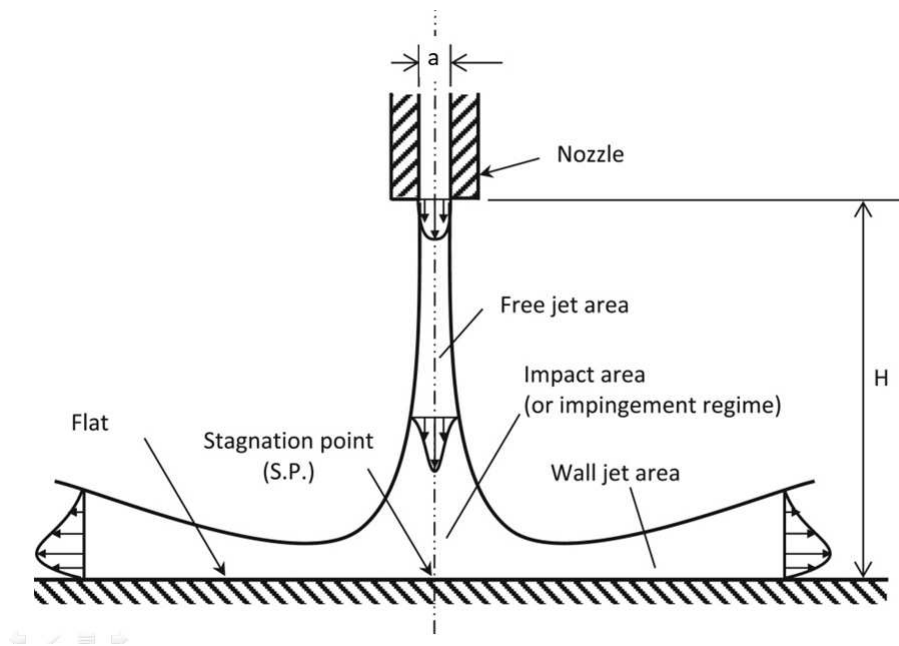


Figure 1.4: Schematic diagram of an impinging jet

drawbacks associated with this jet are that it should be maintained at some distance from the target plate and the effective heat transfer is achieved for a shorter distance.

## 1.2 Application of turbulent wall jet

The wall jet is most widely used in film-cooling technology, where turbine blades in a gas turbine and boiler combustion chamber are protected from hot gases. Application like gas turbine power plant requires the combustion chamber and the turbine blade should operate at a very high temperature; the higher the temperature, the higher will be the efficiency. The upper limit of temperature is decided by the material of the device. In order to achieve an optimum balance between efficiency and temperature, it is always required that the device should operate very close to the maximum temperature. The gases that come in contact with the turbine blade can be as hot as 1600 °C, but the base material can withstand temperatures in the range of 1200 to 1500 °C only [90]. Therefore, the optimum balance can be achieved through film cooling. Jets have been used for cooling the liner of the combustion chamber and blades of a turbine for long time. They are also used in other applications like, deicing of aircraft, cooling of electronic devices, defrosting car windshields and so forth.

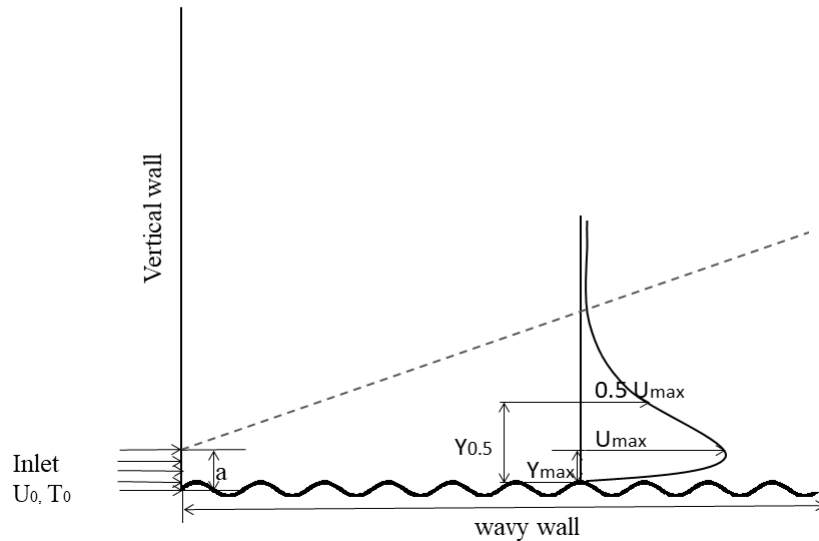


Figure 1.5: The schematic diagram of a wavy wall jet

### 1.3 Objective of the research

The main aim of the present work is to enhance the heat transfer rate of the turbulent wall jets by using a wavy surface. The enhancement of heat transfer has become important in order to develop highly efficient, reliable and compact heating or cooling systems. Because of the advancement in technology and population growth in the last few decades, the consumption of energy is increased drastically throughout the globe. Therefore, it is necessary to conserve energy for the sustainable development of the society. By keeping these points in view, in order to enhance the heat transfer, the plane wall of a turbulent wall jet is replaced by the sinusoidal wavy wall as shown in fig. 1.5. However, the influence of wavy wall on the heat transfer and fluid flow has been explored by very few researchers [89, 91, 92]. There is no study available in the literature where low Reynolds number model has been used for the investigation of turbulent jet on the wavy wall. So, the flow behaviour like separation and re-circulation near the wall which has a great influence on the heat transfer rate can be studied. Moreover, there is no experimental study available on the turbulent jet flowing over a wavy wall. These are the research gaps on which the following objectives have been defined for this research work:

- To numerically study the influence of amplitude and frequency of sinusoidal wavy wall on the flow and heat transfer characteristics for the turbulent wall jet with an

isothermal bottom wall.

- Numerical study on the enhancement of heat transfer by using partial wavy wall and linearly decaying wavy wall for the turbulent wall jet.
- The experimental and numerical study of flow and thermal characteristics of a turbulent jet on an adiabatic wavy wall with different amplitudes.

## **1.4 Thesis Structure**

The present work is presented in seven chapters. The first chapter includes an introduction to turbulent jet and their types, the application of turbulent wall jet and the objectives of the research. The previous studies on the influence of different parametric conditions on the flow and heat transfer of turbulent wall jet are reviewed in chapter 2. Chapter 3 describes the numerical and experimental methods which are used in performing the present work. Chapters 4 to 6 include the results and discussion on the three objectives mentioned in the “Objective of the research” section. In Chapters 4 to 6, the results and discussion of 6 journal papers are presented in such a manner that each chapter contains the results and discussions of 2 papers. The details of the papers are given at the end of the dissertation, under the section “List of Publications”. Finally, the conclusions from the present work is summarised along with the future scope in the last chapter.