

Experimental Probing of the Turbulent Non-Turbulent Interface in Wall Jets

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by

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Certificate

This is to certify that this dissertation entitled Experimental Probing of the Turbulent Non-Turbulent Interface in Wall Jets towards the partial fulfilment of the BS-MS dual degree programme at the Indian Institute of Science Education and Research, Pune represents study/work carried out by Pranav Sood at the Indian Institute of Tropical Meteorology under the supervision of Dr Shivsai Ajit Dixit, Scientist F, Indian Institute of Tropical Meteorology, during the academic year 2022-2023.



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This thesis is dedicated to my parents, Mrs Sunita Sood and Mr Ashwani Kumar
and my little brother Aditya

Declaration

I hereby declare that the matter embodied in the report entitled Experimental Probing of the Turbulent Non-Turbulent Interface in Wall Jets are the results of the work carried out by me at the Fluid Dynamics Laboratory , Indian Institute of Tropical Meteorology, Pune, under the supervision of Dr Shivsai Ajit Dixit and the same has not been submitted elsewhere for any other degree

A handwritten signature in black ink, appearing to read 'Pranav', with a horizontal line underneath and a period at the end.

Pranav Sood

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Abstract

Turbulent flows past a solid surface exhibit region close to the surface where the presence of the surface is felt. In external flows such as boundary layers, the turbulence is confined to a region close to the surface and separated from the outer non-turbulent freestream by a sharp interface. This interface is known as the turbulent non-turbulent interface (TNTI). Several aspects of the TNTI have been studied earlier such as its statistical location, its spread and structure. However, the TNTI in wall jets (jets blown along a solid surface) has not been studied in the literature. The study is important since the outer region of a wall jet is considered to behave similarly to a free jet. However, if there is an influence of the wall seen on the characteristics of the TNTI, this will be an evidence of the fact that the wall does not allow the outer part to behave like a free jet, i.e., there is inner-outer interaction. The project investigated the TNTI in wall jets using the wall jet setup existing in the Fluid Dynamics Laboratory (FDL) at IITM, Pune. Particle Image Velocimetry (PIV) has been used to perform high speed measurements of the flow and capture the interface.

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Chapter 1

Introduction

Fluid Dynamics is a branch of physics and engineering that concerns itself with the study of the motion of fluids such as gases and liquids [1]. A few examples of such flows include pipe flows, channel flows, jets, flows over airfoils, and on large scales, atmospheric flows such as monsoon jets and ocean currents. These flows can be characterised on the basis of many parameters, but the most fundamental and first-order characterisation is done on the basis of the flow Reynolds number. The motion of the flow can be either turbulent or laminar based on its Reynolds number. Reynolds number is a dimensionless number obtained by the ratio of the inertial and viscous forces of the flow. A basic formula for finding out the Reynolds number for a flow is given as -

$$R = \frac{\rho u L}{\mu}$$

Here, R refers to the Reynolds Number of the flow, ρ is the density of the fluid, u is the velocity of the fluid flow, L is the characteristic length scale of the flow and μ is the dynamic viscosity of the fluid [1]. A high Reynolds number indicates that the fluid motion is turbulent, which means that the flow is chaotic, whereas a low Reynolds number indicates that it is laminar, which means the flow is smooth. There still exists a subtle subjectivity to this categorisation because the words “high” and “low” do not give us an objective, numerical sense of the relationship between the two. The field of fluid dynamics is marred with such subjectivity, due to which the technique of scale analysis is most prevalent and highly used in this field of study [2]. The problem of subjectivity can be simplified by making a few assumptions about the flow. A simple solution is to make the variable flow parameters, such as density and the viscosity of the fluid, constant. As a result, the velocity field, velocity vectors inside the flow and streamlines (trajectory of a fluid particle) become the sole differentiating factor for categorising a fluid flow as turbulent or laminar [2].

The motion of the fluid is said to be turbulent when the fluid is moving in a chaotic, non-uniform manner. The velocity vectors inside the fluid do not point in the same direction, and the streamlines of the flow are rough and jagged. On the other hand, if the fluid is

moving uniformly, it is said to be laminar. The velocity vectors, in this case, point in the same direction and the streamlines of the flow are smooth. Generally, fluids at a low flow velocity are laminar. As the flow velocities become higher, the motion of the fluid becomes more chaotic, which results in the flow becoming turbulent. This phenomenon can be easily observed in the water coming out of a tap. When the tap is kept slightly open, the stream is relatively smooth and shows a laminar motion. The flow becomes more chaotic when we open the tap further, and thus, it shows a turbulent motion.

Turbulent flows generally carry a high rotational motion, but the flow outside this turbulent flow is irrotational [3]. This outer flow is known as a non-turbulent flow. The velocities in this outer part of the flow are relatively low, and it represents the layer outside the turbulent layer. These two layers, turbulent and non-turbulent, interact with each other at an interface known as the turbulent non-turbulent layer. A large number of studies done on such boundaries have shown the existence of a sharp, distinct interface that separates the turbulent part of the flow from the non-turbulent part. This interface is known as the Turbulent Non-Turbulent Interface (TNTI) [3]. This TNTI acts as a fine interface through which the two layers exchange momentum and energy. The process of diffusion, mixing of the two layers and entrainment of outer fluid into the turbulent layer also occurs through this interface. These processes lie at the centre of every fluid-fluid interaction in fluid dynamics. A better understanding of this TNTI will aid us in understanding this interaction, and thus, it becomes crucial to understand this interface. TNTI is not just a laboratory artefact. Atmospheric flows such as monsoon low-level jets (LLJs) [4], real world flows such as wakes [5] over surfaces are just a few examples of real-world flows and processes where this TNTI is observed.

1.1 Previous Works

Study of turbulence has long been a keen area of interest for the scientific community. Richardson, in the 1920s [6], suggested that there seems to be energy transfer from larger scales to smaller scales by the process of a cascade, but this energy cascade theory was represented mathematically by Kolmogorov in the 1940s [6]. It has been said that Richardson presented his idea in the form of a poem. There have been many attempts made in the past to make a theory of turbulence, but none have been as successful as Kolmogorov's. Kolmogorov's theory of turbulence suggests that the small-scale structures in turbulent flows show statistical homogeneity and are quite different from the large-scale structures in

the flow. It also gives an accurate mathematical description of the process of energy cascade from large-scale turbulent eddies to small-scale eddies, which exist at a characteristic length scale known as the Kolmogorov length scale. Through these eddies, the turbulent energy gets dissipated in the form of heat below the Kolmogorov length scales [6].

The studies done by Townsend and GK Batchelor in the 1940s [7] focused on the hotwire signal obtained from a turbulent flow. A hotwire signal is a simple time series data about the instantaneous velocity of the turbulent flow. They came up with a factor known as the Intermittency factor (γ), which gives us the fraction of time for which the signal is turbulent. Corrsin and Kistler, in the 1950s [8], built upon the work done by Townsend and GK Batchelor and studied the wakes left behind by a high-speed projectile. They observed that there exists a sharp instantaneous edge between the outer (non-turbulent) and inner (turbulent) part of the wakes. This was the first evidence of the existence of TNTI.

The work done by Beinot Mandelbrot in the 1970s and 1980s brought the idea of self-similarity and fractals to the forefront of science [9]. The concept of self-similarity can simply be understood as a scalar or functional transform that connects the two different scales. In other words, if two scales are self-similar, then the features or structures that exist at a particular scale can be transformed into the other by a simple scalar or functional transform. This sort of self-similarity is also seen in the field of fluid dynamics because there seems to exist a scale invariance in the governing equation of fluid dynamics, i.e., the Navier Stokes Equation (especially in the regime of high Reynolds number) [6]. This concept led the researchers to look for self-similar structures at various scales in the flow. The turbulent non-turbulent interface became an object of interest because it has been shown to have self-similar structures at various scales, as seen in the studies done by Prasad and Sreenivasan [10], where they look at a few geometric properties of TNTI, such as its fractal dimension. They carried out their studies on two types of interfaces. First, a scalar interface is obtained by doing a LIF experiment which physically marks such an interface. Second, a vorticity interface is obtained by using a criterion (in this case, a vorticity-based one), which discriminates between the turbulent and non-turbulent region of the flow in order to identify this TNTI [10].

The detection of TNTI by the second method, i.e., using a criterion to discriminate between turbulent and non-turbulent layers, has been an area of interest for quite some time. In this method, the detection of this interface depends upon a function, usually called a

discriminating function, that behaves differently or shows different properties for the two regions. This function should show a sharp transition when it switches between turbulent and non-turbulent regions, but this still depends on our definition of what we deem as sharp. Thus, we need something that can quantify what we mean by sharp [8, 10]. This is done by something known as a threshold value. The discriminating function, along with this threshold value, helps us to detect this interface. The threshold value is a critical value which marks the limit in the function which separates the two regions. The discriminating functions are usually some physical quantity such as temperature, pressure, turbulent kinetic energy or vorticity and are known as a detection criterion. The threshold value is calculated by studying the quiescent region of the flow (the region not affected by the turbulent flow), detailed discussion on this is in Chapter 2 and 4.

There are many criteria used in the literature to differentiate between the turbulent and non-turbulent parts of the flow to mark this TNTI [8, 11-12]. Prasad and Sreenivasan [10] used the Image Density criterion in their (Laser-Induced Fluorescence) LIF experiments where a scalar (a dye), when introduced in the flow, shows sharp edges in high Reynolds number axisymmetric jets. This sharp edge was marked by the image pixel density. In the area where the image pixel density was lower than the threshold, that region was marked as non-turbulent, whereas the other region was marked as turbulent. Another physical quantity often used in this detection process is the vorticity of the velocity field. Corrsin [8] found that vorticity shows a sharp change across this interface, with a low magnitude in the non-turbulent region, but quite high in the turbulent region. The interface detected by this method is known as a Vorticity interface. Turbulent Kinetic energy also shows a similar discriminating behaviour between the two regions. The non-turbulent region possesses less TKE because the velocities in this region are quite low. In contrast, the opposite is true for the turbulent region, where the increased velocities lead to an increased TKE for that region. Chauhan [3] used this criterion in his studies to detect the TNTI in boundary layers. Another quantity used in the literature is Homogeneity [13]. Reuther used the homogeneity criterion, which is based on the homogeneity of the velocity field [13]. This quantity is calculated by taking the standard deviation of velocity fluctuations in a small box in the whole field. It is observed that the local standard deviation is quite low for the non-turbulent region because the local change in the velocity is quite low in this region. This quantity is quite high for the turbulent region because the change in the velocity is quite abrupt here. In other words, the non-turbulent region is homogeneous, and the turbulent region is inhomogeneous. A few of

these criteria are also used to detect the TNTI for wall jets in our project. The ones that have been used are properly discussed in Chapter 2.

The non-linear nature of the Navier-Stokes equation makes it impossible to find analytical solutions to all kinds of flows [2]. The solutions that do exist come out as a result of approximations in certain regimes and under certain assumptions. In this situation, experimentation becomes a tool of choice. Studying the flows through experiments helps us collect empirical data about the nature and behaviour of fluids, which in effect, helps us to come up with better approximations and solutions. Over the years, many experimental techniques have been employed to study turbulent flows. A few examples of these techniques are hot wire anemometry, Laser-Induced Fluorescence (LIF) and Particle Image Velocimetry (PIV). These are flow analysis techniques as they collect physical data about the flows. In this work, we take the help of high-speed PIV to study the wall jet flow along with the hotwire data obtained earlier in our lab [4].

TNTIs have been studied in various kinds of flows like boundary layers, free jets, wakes, wall-bound layers and mixing layers [5, 8, 10-13], but little is known about the TNTIs present in the wall jets. A wall jet is a unique flow where the fluid coming out of a nozzle is restricted by a solid boundary on one side. Wall jets find their application in many places. Car defoggers, oil coolants in gas turbines and circulation pumps in nuclear reactor sites are a few examples where wall jets are used. They are also useful for understanding atmospheric flows. Monsoon low-level jets, generally known as LLJs, are modelled in laboratories with the help of wall jets [4].

The study of these flows has been an area of major interest for the scientific and engineering community for a very long time. A better understanding of these flows helps us to understand various processes like diffusion, mixing, and entrainment. Fluid dynamics helps us to get a better understanding of these flows, build models, and make predictions based on these models. One such clear example is the field of atmospheric science which deals with explaining the climate phenomenon and predicting the weather.

The outer and inner parts of the wall jet interact with each other at this TNTI. Studies have shown that the outer part of the wall jet behaves like a free jet, but very few studies have been done on the effect of the wall on the outer part of the flow. This effect might manifest itself as changes in the characteristics of TNTIs of wall jets when compared to those in free jets.

These changes might be a sign of the effect of the wall on the outer part of the flow. Since very little is known about the TNTIs in wall jets, we cannot make these comparisons. Thus, it becomes essential to study the TNTIs in wall jets.

1.2 Objective

The goal of the project is to detect the TNTI in the wall jets with various criteria, understand its geometric properties and compare a few of them with free jets. The first part is to understand the wall jet flow and its characteristics. The second part is to detect the interface with a robust criterion, set a properly calibrated threshold and differentiate between the turbulent and non-turbulent layers. The third part is to look at geometric and statistical properties of the detected TNTI, such as probability distributions, mean location and so on. The experiments are done at three different Reynolds numbers, so we also try to see the effect of changing the Reynolds number on the flow and the TNTI. The thesis also includes some preliminary data analysis on hotwire anemometry data obtained by earlier experiments in the lab. The aim of this preliminary analysis is to understand the wall jet flow and deduce some insights for detecting the TNTI.

1.3 Overview

The thesis is further divided into four chapters. Chapter 2 contains the necessary theoretical background needed to understand the wall jet flow, TNTI and its detection. It describes the wall jet flow in detail, explains the concept of TNTI and describes all the detection criteria used in the project. Chapter 3 gives detailed technical descriptions of the two experimental setups, the wall jet setup and the high-speed PIV setup, used in the project. It explains the PIV technique in detail and how the velocity information is extracted from the flow using this technique. Chapter 4 discusses all the results obtained from analysing the data gathered from the experiment and discussions of these results. Chapter 5 concludes the thesis with a summary of essential results, closing remarks and the future direction of this project.

Chapter 2

Theoretical Background

This chapter attempts to explain the basic theory behind the experiment and the nomenclature associated with the wall jets. It is divided into two sections. Section 1 explains the concept of a wall jet and the nomenclature associated with it. Section 2 describes the turbulent non-turbulent interface, its properties and a few real-world problems where its study might be helpful. This section also lists an ensemble of criteria used in literature for the detection of this turbulent non-turbulent interface.

2.1 Plane Turbulent Wall Jets

A turbulent jet refers to a high Reynolds number flow ejected out of a nozzle into open space. There are widely two types of jets - free jets and bound jets. When the nozzle opens into free space with no boundaries, the jet is known as a free jet. In the case of a wall jet, the nozzle opens up into free space on one side and onto a plane, solid wall on the other side. A few real-world examples of this type of jet can be found in automobile defoggers, oil cooling in industry components of gas turbines and the flows that occur in the circulation pumps of a nuclear reactor site. Low-level monsoon jets (LLJs) can also be modelled in laboratories using this concept of wall jets [4]. As a result, wall jets are pretty important in the academic community and the industry. Figure 1 illustrates the side view of the plane wall jet flow development.

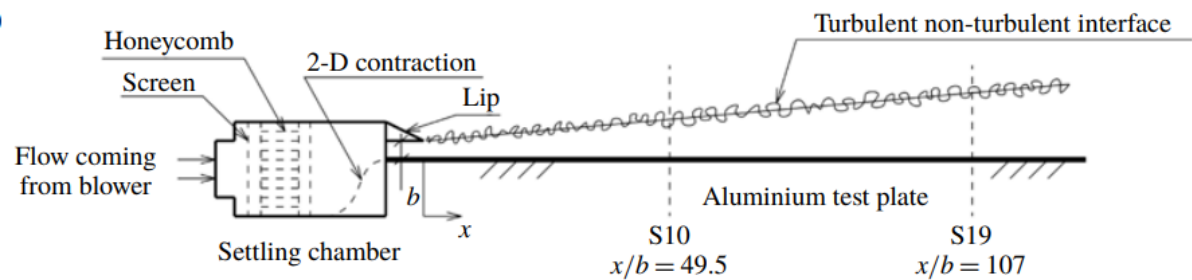


Fig. 1 - Side view of the plane wall jet flow development [4].

The flow coming out of the nozzle spreads onto the wall, but on the other side, it develops freely into the open space. As seen in the diagram above, the direction in which the flow

progresses is known as the streamwise direction (i.e., the x-direction). The direction perpendicular to the wall is known as the wall-normal direction (i.e., the z-direction). The direction perpendicular to the flow and the wall-normal direction (the x - z plane), i.e., the direction into the plane of the figure, is known as the spanwise direction (i.e., the y-direction). The instantaneous velocities in the streamwise, spanwise and wall-normal directions are denoted by u , v and w , respectively. The averages of these velocities are denoted by U , V and W , respectively. Velocity fluctuations are the differences between these averages and the instantaneous velocities and are represented by u' , v' and w' , respectively. The relation between average, instantaneous and fluctuation velocity is given as -

$$u = U + u'$$

$$v = V + v'$$

$$w = W + w'$$

A plane wall jet implies that the flow is two dimensional, i.e., it is coming out of a slit instead of an orifice. The turbulence is assumed to be homogenous in the spanwise direction for this case, which means that the mean statistics and velocity profile of the flow is invariant in one of the three directions [4]. This is true for the spanwise direction in our wall jet. The earlier experiments done in the lab have demonstrated this to be true. Thus, the wall jet, in our case, is a plane turbulent wall jet [14].

The mean velocity profile for a wall jet looks like the one in figure 2.

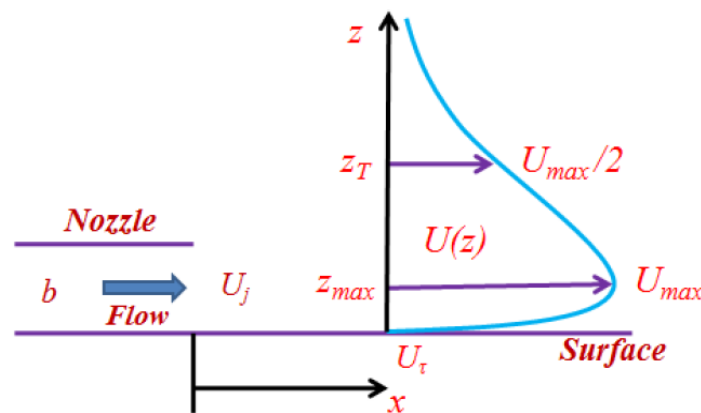


Fig. 2 - Mean Velocity Profile with its nomenclature of Wall Jet [14]

The velocity of the flow out of the nozzle is the nozzle exit velocity U_j . The velocity at the surface (the wall) is zero because of the no-slip condition. The no-slip condition implies that near any physical boundary (in this case, a wall), the relative velocity between the surface

and the fluid immediately adjacent to it is zero. Thus, the fluid does not slip at the boundary. As we move in the positive wall-normal direction, i.e., away from the wall, the velocity starts to increase. The velocity increases up to a maximum value known as U_{MAX} . The height at which the flow achieves this U_{MAX} is known as Z_{MAX} . As we move further away from the wall, the velocity starts to decrease and approaches zero in the outer region. The point in the profile above Z_{MAX} where velocity becomes $U_{MAX} / 2$ is known as the characteristic length scale of a wall jet and is denoted as Z_T in the current work, as shown in the profile diagram. The studies carried out by many people [4,14-15] suggest that the lower part of the profile, i.e., below U_{MAX} , behaves like a boundary layer, and the profile between Z_{MAX} and Z_T behaves like a free jet profile. Beyond Z_T , the velocities gradually go to near zero due to the presence of the outer “non-turbulent” region. This region is also known as the outer region or the quiescent region. These values (U_{MAX} , Z_{MAX} and Z_T) also represent a scale in wall jets known as the outer scaling. The velocities and length scales of the outer region can be normalised using these values. The other scale present in the system is known as the inner scaling, which is applicable below U_{MAX} . This inner scale includes quantities like friction velocity, denoted by u_τ , and kinematic viscosity, denoted by ν . Kinematic viscosity is the ratio of the dynamic viscosity (the measure of the resistance shown by fluid to external forcing) and the density of the fluid [14].

2.2 Turbulent Non-turbulent Interface (TNTI)

The studies by Corrsin and Kistler [8] pointed out the existence of a sharp boundary between the turbulent and non-turbulent layers of the flow. In Corrsin and Kistler’s case [8], they found an instantaneous sharp edge separating the external flow and the wakes left behind by a high-speed projectile in their shadowgraphs. This “sharp edge” is known as the turbulent non-turbulent interface (TNTI). The TNTI acts more like a boundary at which the turbulent and non-turbulent layers interact with each other. Many processes, such as mixing, diffusion and entrainment, to name a few, happen across this TNTI as a result of this interaction. It is essential to understand this TNTI because it will help us to better understand energy and momentum exchange between the two layers. As a result, we will be able to better understand the processes like mixing, diffusion and entrainment. This makes it very important to study this interface and understand its properties. An illustration of the TNTI we found in our wall jet flow is given in figure 3.

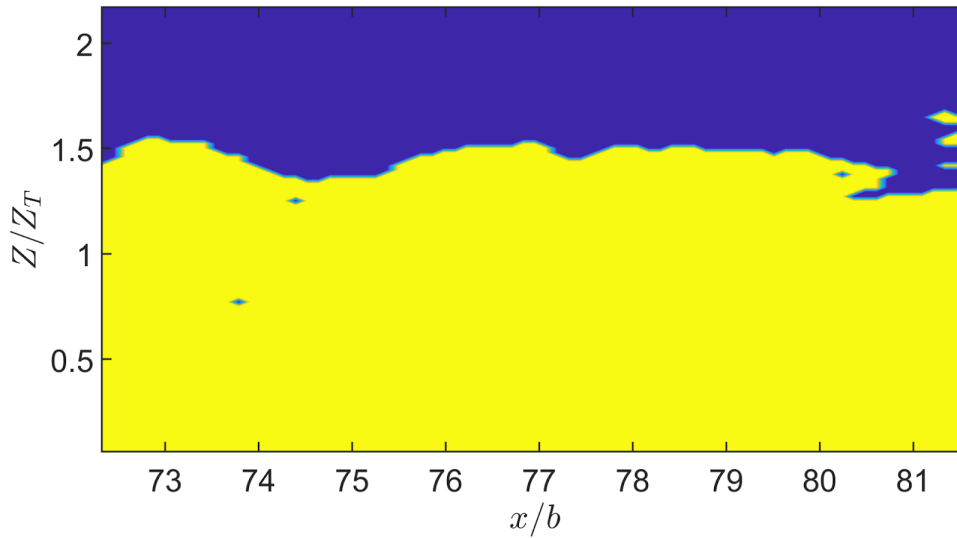


*Fig. 3 - Turbulent Non-Turbulent Interface obtained from high speed PIV Data
the yellow region marks the turbulent layer and the blue region marks the
non-turbulent layer*

Accurate detection of this TNTI is a very challenging problem. A detection criterion is such that it discriminates between the turbulent and non-turbulent parts of the flow. In other words, a quantity that behaves differently or has a different value in the two layers can act as a detection criterion. Various types of criteria have been used to detect TNTI. A few quantities used to detect this interface are - Pressure, Temperature, Turbulent Kinetic Energy, Vorticity, Enstrophy and Homogeneity of velocity fields. Among these few quantities and many others used in the literature [3,5,10-11], two are predominantly used, turbulent kinetic energy and vorticity, for the detection of TNTI. In this project, we have used three criteria. These are Chauhan's turbulent kinetic energy criterion, the vorticity criterion and the homogeneity criterion.

2.2.1 Chauhan's Turbulent Kinetic Energy Criterion

This criterion is based on the turbulent kinetic energy (TKE) of the velocity field [3,16], i.e., it identifies a point as turbulent or non-turbulent on the basis of the TKE at that point. It has been observed that the quiescent flow has very low velocities, and the turbulent flow has higher velocities. As a result, the TKE in those regions will be quite different, thus separating the two layers. Chauhan applied his criterion in boundary layers, which are inherently different from the wall jet. As a result, a few modifications have been made to the original criterion such that it can work for the wall jet flow as well. These modifications are mentioned below.

The original criterion is given as -

$$\tilde{k} = 100 * \frac{1}{9 * U_{\infty}^2} \sum_{m,n=-1}^1 [(u_{m,n} - U_{\infty})^2 + (w_{m,n})^2]$$

Here, u and w represent the instantaneous velocities. U_{∞} represent the average velocity in the quiescent region of the flow, which is the same as the average fluctuations in that region. This is because the instantaneous velocities in the quiescent region are so low that they are of the same order as the velocity fluctuations in that region. Here, the $\tilde{k}$ value is normalised using the TKE in the quiescent region. Thus, it becomes a fraction of local TKE with respect to the quiescent TKE. The scalar multiple of 100 just converts this fraction into a percentage. The criterion calculates the TKE by taking an average over 9 local points (a centre point and 8 adjacent points). This sort of averaging is commonly known as box filtering. Box filtering is a technique generally used in image processing where a high-resolution image needs to be made smaller in size. Chauhan [3] uses a box filter because a single point might give us spurious velocities due to any reason, error in focusing, poor resolution and so on, but a local patch will give us a reliable average. This sort of use of box filters is also seen in many other criteria in the literature.

The modified criterion is given as -

$$\tilde{k} = 100 * \frac{1}{9 * (U_{\infty}^2 + W_{\infty}^2)} \sum_{m,n=-1}^1 [(u_{m,n} - U_{\infty})^2 + (w_{m,n} - W_{\infty})^2]$$

The only modification we made to the original criterion is to add the missing w component while calculating the quiescent TKE and in the local TKE. W_{∞} represents the average w in the quiescent field. For boundary layers, this is zero [3,14] hence, we do not see Chauhan using it in his criterion. But for the wall jet flow, this number is not zero and hence, cannot be neglected.

The points in the velocity field where the $\tilde{k}$ value is below a threshold value, those points are assigned as non-turbulent. Those that lie above this threshold are assigned as turbulent points. This threshold has a subtle subjectivity to it and is highly sensitive to the setup and conditions in which the experiment is done. In our case, we calculate the threshold by taking a common patch in all the quiescent fields for one Reynolds number and taking an average of the $\tilde{k}$

values there. As a result, we get a threshold value for that particular Reynolds number. We do this for all three Reynolds numbers, and thus we obtain three threshold values. An average of these three gives us a common threshold value for all three Reynolds numbers. The quiescent region is defined as the outer region which is not affected by the flow, and thus, taking a common threshold for all three Reynolds numbers is justified.

Since this criterion uses TKE, it is influenced by the large-scales the interface and turbulence. This is because TKE carries the large-scale interactions in the flow. Thus, this criterion works in systems where we do not have high resolution.

2.2.2 Vorticity Criterion

The rotational motion in the flow increases as the flow becomes more and more turbulent [17]. The non-turbulent region is relatively quieter than the turbulent region, and it has more irrotational motion [16]. As a result, the vorticity of the velocity field becomes a good indicator of turbulence. The criterion uses the absolute value of vorticity, i.e., $|\omega|$. This is done in order to avoid differentiating between clockwise and anti-clockwise vortices. In 2-D PIV, only one component of vorticity can be calculated because only two velocity components are captured by this method. Since, in our case, we have streamwise and wall-normal velocities (x and z direction components), we can calculate the spanwise component of vorticity, i.e., $|\omega_y|$. Vorticity is calculated as -

$$|\omega_y| = \frac{Z_T}{U_{MAX}} \left| \frac{dw'}{dx} - \frac{du'}{dz} \right|$$

Here, u' and w' are the velocity fluctuations in the x and z direction, respectively. Vorticity is normalised using the outer scales, i.e., U_{MAX} and Z_T .

This criterion also requires us to set a threshold value. The threshold is set in a similar manner as seen for the TKE criterion [3]. The average vorticity for a common patch in all the velocity fields is calculated in the quiescent region, which gives us a vorticity threshold value for one Reynolds number. Three such averages are calculated for the three Reynolds numbers used in the experiment. An average of these three gives us a common threshold for all three

sets. Any point having vorticity less than this threshold is marked as non-turbulent, otherwise, it is marked as turbulent.

Enstrophy is calculated as the square of the vorticity, i.e., $|\omega|^2$. Enstrophy enhances the details seen by the vorticity field as it is the square of vorticity. As a result, we are able to get much better distinctions in turbulent and non-turbulent areas. This criterion is applied in exactly the same manner as we apply the vorticity criterion.

Vorticity and Enstrophy both look at fine-scale turbulent structures as they involve the gradient of the velocity fields [12]. As a result, high spatial resolution is required to apply this criterion properly. The results obtained from this criterion are discussed in Chapter 4 of this thesis.

2.2.3 Homogeneity criterion

The velocities in the turbulent region change rapidly from one point to another, which makes the fluctuation of these velocities very high [13]. The opposite is true for the non-turbulent region, i.e., the velocity fluctuations are low. Homogeneity gives us a measure of how much the local velocity varies in a given region, and based on this variation, it assigns the region as turbulent or non-turbulent. These variations are high in the turbulent region and low in the non-turbulent region. The homogeneity criterion is defined as -

$$\tilde{s} = \sqrt{\frac{1}{N-1} \sum_{m,n=-1}^1 (u_{m,n} - \langle U \rangle)^2}$$

Here, u is the instantaneous velocity, and $\langle U \rangle$ is the local instantaneous velocity average. N is the number of elements in the box size chosen with m,n being the indices of the elements in that box. The criterion fundamentally is a simple standard deviation formula. It calculates the standard deviation of local velocity in a box size (3 x 3 for our case). This is the same box filtering method used in the TKE criterion. The $\tilde{s}$ value is close to zero for the non-turbulent region because the variations in the velocity fluctuations from one point to another are very low. These variations increase rapidly in the turbulent region, which rapidly increases the

value of $\tilde{s}$. The TNTI is identified using this disparity in the behaviour of $\tilde{s}$ in the turbulent and non-turbulent regions.

The above criterion has been used for boundary layers but not wall jets. Thus, this criterion requires some modifications in order to meet the needs of our flow. The modified Homogeneity criterion is given as -

$$\tilde{s} = \sqrt{\frac{1}{N-1} \sum_{m,n=-1}^1 [(u_{m,n} - \langle U \rangle)^2 + (w_{m,n} - \langle W \rangle)^2]}$$

Here, we have included the w component of velocity in the formula by appropriately adding the standard deviation of the w ' velocity fluctuations to get a combined standard deviation. We normalise this quantity somewhat differently than the method of normalisation seen for earlier criteria. Instead of normalising by any scale or physical quantity, we normalise homogeneity by itself. We use the average homogeneity value calculated in the quiescent field to normalise the criterion. Thus, we calculate $\tilde{s}'$, which becomes a fraction of $\tilde{s}$ and $\tilde{s}_q$, where $\tilde{s}_q$ is the homogeneity calculated in the quiescent region. This is given as -

$$\tilde{s}' = \frac{\tilde{s}}{\tilde{s}_q}$$

Here, we do not need to calculate a threshold value because the nature of this fraction gives us that value. When the region is non-turbulent, $\tilde{s}'$ is closer to or less than one, otherwise, it is higher than one in the turbulent region. This becomes our thresholding value for this criterion.

All the results obtained using these criteria are provided in Chapter 4 of this thesis. The application of these criteria and discussions on the results obtained are also given in that chapter.

Chapter 3

Experimental Setup and Methodology

This chapter explains the experimental facility and the test setups used for this thesis. This chapter gives a detailed description of the wall jet setup used to establish the flow and the high-speed Particle Image Velocimetry setup used to analyse the flow. It also describes the Pitot tube method used to keep the wall jet flow statistics consistent with the flow statistics of the earlier experiments. A brief outline for the chapter is as follows. Section 1 describes the wall jet setup. Section 2 introduces the various techniques used in the flow analysis and describes the Pitot tube method used here to calibrate the flow. Section 3 gives a detailed description of the Particle Image Velocimetry (PIV) setup. Section 4 explains the workings of this PIV setup. Section 5 lays out a general procedure we used to carry out the PIV experiments. Section 6 describes the hotwire anemometry technique in brief.

3.1 Wall Jet Setup

The wall jet setup used in this project was developed in the Fluid Dynamics Laboratory (FDL) at the Indian Institute of Tropical Meteorology (IITM), Pune, Maharashtra [14]. The main task of the setup is to help us establish a plane turbulent wall jet. It does so with the help of three main components. These are - a blower, a settling chamber and an aluminium plate. These three are the core components of our wall jet setup.

The blower used here is an Ametek Nautilair with 8.9 inches impeller diameter. The speed of the blower (in rotations per minute) ranges from 1000 rpm to 9000 rpm. A Pulse Width Modulator (PWM) controller is used to control the speed of the blower. This PWM supplies the blower with a constant current which rotates the fan at a constant speed, thus maintaining a constant flow rate. All these components can be seen in figure 4

A 100 mm diameter copper lining is used to connect the outlet of the blower to the settling chamber. The chamber has an inlet for the blower on one side and a 10 mm thick ($b = 10$ mm) and 300 mm wide nozzle on the other. The settling chamber is a wooden box with dimensions 300 mm x 300 mm x 120 mm (length, width and height). The air coming out of the blower is not a plane wall jet and needs to be converted somehow, for this the settling chamber is designed.

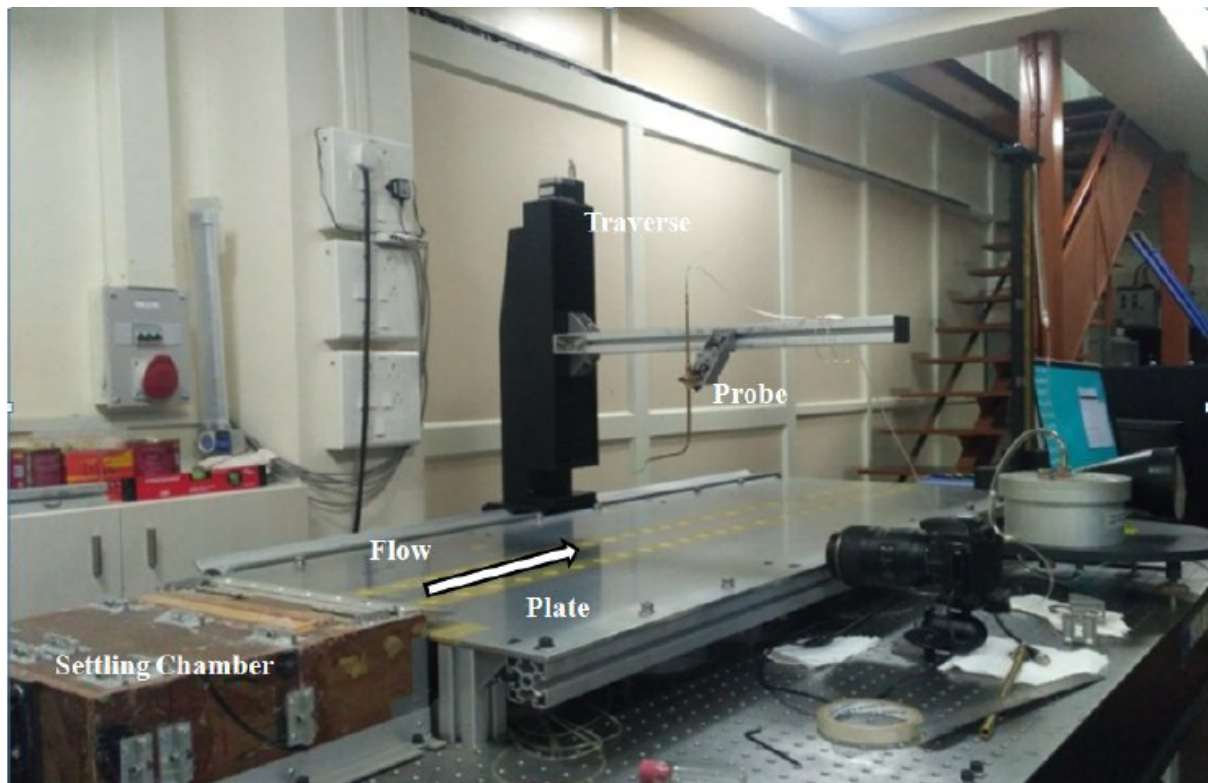


Fig. 4 - Wall-jet setup at Fluid Dynamics Laboratory (FDL), IITM, Pune

There are honeycomb filters fitted inside the chamber after a fixed distance from the inlet to help straighten the flow, followed by screens to reduce the turbulence in the flow as seen in figure 1. These filters give the air coming out of the blower time to homogenise. This filtering helps in homogenising the turbulence in the spanwise direction. Next, this air encounters a 2-D contraction (similar to the ones used in a wind tunnel). This contraction acts like a narrow tapering nozzle attached in front of a large garden hose, which increases the speed of the fluid coming out of the hose. This contraction leads up to the mouth of the nozzle, gradually decreasing the height of the jet from 120 mm to 10 mm at the exit of the nozzle using a fifth-order polynomial curvature, which in turn increases its speed. The nozzle exit is fitted with an extended aluminium lip which helps in maintaining good initial conditions. Further details about these initial conditions can be found in [14].

The nozzle opens up on an aluminium plate of dimensions 1500 mm x 600 mm x 6 mm (length, width and thickness), which acts as the wall in the setup. The surface of this plate is well polished in order to avoid the development of secondary flows in the system due to roughness. The centre area of this aluminium plate is blackened with the help of blackboard

paint [14]. This is done to minimise the reflections caused by the laser hitting the wall. This point will be further explored in the PIV section of this chapter.

This flow does not show any variance in the mean statistics for the spanwise direction at a particular range of streamwise locations ($x/b = 49.5$ to 107 , where x is the distance from the nozzle exit and b is the jet exit thickness). As a result, this setup establishes a 2-D plane turbulent wall jet. This setup is used to study the flow at three different nozzle Reynolds numbers ($Re_1 = 10244$, $Re_2 = 15742$ and $Re_3 = 21228$).

3.2 Pitot Tube Setup and Flow Calibration

There are many techniques to study turbulent flows, such as hotwire anemometry, PIV, LIF etc. These techniques help us to analyse the flow quantitatively and qualitatively. Pitot tube is one such technique. It helps us to obtain the mean statistics of the flow. The Pitot tube measures the change in pressure when the pitot is kept in the flow with respect to when there was no flow. This pressure difference helps us to obtain the velocity of the flow. This technique is widely used to calibrate the speed of the flow. We have used this technique to set the flow speeds for the three Reynolds numbers used in the experiment. The reason for employing this technique is to match the new velocity profiles at the primary experimental location ($x/b = 77$, where x is the distance from the nozzle exit and b is the jet exit height) with the old data set. This helps to keep the data consistent and allows us to use parameter values like friction velocity ($u\tau$), which were calculated earlier using extensive experimentation in the lab.

The Pitot tube has an outer diameter of 1.2 mm, and it has been made in-house by the IITM workshop. The pitot tube is connected to a digital manometer which displays the change in pressure with respect to the static pressure in terms of the height of the methanol column (**mm of Al**). The acquisition rate of the manometer is 100 Hz which means that it collects 100 values per second. The manometer, by default, gives an average change in pressure by taking the averages of these values. We can set the time for which it gives us an average. In our case, we obtain the average change for 10 seconds. These measurements are taken for 100 seconds in order for the mean value to saturate at a particular height. These pressure difference values are used to calculate the mean velocity profile of the flow at the given location and given

height. The fundamental relation used to calculate the velocity from column height difference is given below

$$\frac{\rho_a U^2}{2} = \rho_m gh$$

where ρ_a is the air density, ρ_m is the methanol density, g is the acceleration due to gravity ($g = 9.8 \text{ m/s}^2$ has been used), U is the mean velocity. ρ_a is calculated using the pressure and temperature values of the room and the relation given below

$$P_a = \rho_a RT_a$$

where P_a is the barometric pressure of the room, T_a is the temperature of the room, and R is the ideal gas constant ($R = 287 \text{ J/kg} \cdot \text{K}$ has been used). The pressure and temperature values are collected using two Arduino sensors. The pressure and temperature values are collected for the course of the experiment, and the averages of these values are used in order to account for any fluctuations during the course of the experiment.

3.3 Particle Image Velocimetry (PIV)

Particle Image Velocimetry (PIV) is a technique used to measure the velocity of the flow by tracing the motion of the fluid particles [18]. It is a non-intrusive technique as it does not disturb the flow. The particles in the fluid are first visualised by using a technique known as seeding. Seeding is a technique by which tracer particles are introduced into the fluid in order for us to understand the behaviour of the fluid by studying the motion of these tracer particles. Various materials are used for seeding depending upon the medium of the fluid. For example, in water, dyes and glass beads are used for seeding, and in air, smoke particles are used. Since the medium is air in our project, we have used fog particles (smoke) generated from a fog machine as our choice for seeding particles [14]. The size of these seeding particles should be such that they are large enough to scatter the light but small enough that the flow can carry them without altering the flow parameters drastically. These seeding particles are illuminated using a laser sheet. As a result, these particles scatter the light coming from the laser. This scattered light is then captured using cameras, and images are taken in successive motion.

These images are captured in a unique way which helps us to calculate the velocity of the flow. Instead of capturing single images, a pair of images is captured at a time. This is done by using special lasers known as dual pulse lasers. A dual pulse laser emits two pulses of

laser separated by time dt at a fixed frequency f , where $dt \ll 1/f$. In our setup, this dt is of the order of microseconds, and $1/f$ is of the order of milliseconds. The camera imaging the flow also takes images in this manner, i.e., it takes a pair of images (i.e., it shoots two frames) separated by the same dt as that of the laser and captures these pairs (double frames) at the same frequency f . This process of capturing the images is synchronised with the pulse rate of the laser so that the images can be captured at the same time instant the laser pulse illuminates the seeding particles. These pairs of images capture the motion of particles from the first frame to the second frame. The images are calibrated for the actual physical length scale with the help of a calibration plate. A calibration plate is a dotted plate (as shown in the figure) which helps to set the images captured by the cameras to the real-world scale. The distance between the dots is fixed (here, 1.5 mm horizontally and vertically and 1 mm diagonally). Images of these calibration plates are captured after the experiment is done. Multiple images are captured in order to have a robust final image as the average of these images. The LaVision software automatically searches for these dots in the final calibration plate image and makes a scale grid once we toggle the calibration operation button. This grid is then overlaid over all the images to calibrate them to the new scales.

As a result of this unique way of imaging, we obtain double-frame images of the flow. These double frames capture the displacement of the particles from one frame to the next. This displacement is calculated using interrogation windows. An interrogation window is a small window of pixels in the image captured. The shape of the interrogation windows is generally a square (a box), but it can have various shapes like circles, triangles and ellipses. Square is simple to work with and is generally used in the literature. So, we have also used square interrogation windows. The images captured are divided into two interrogation window sizes. A first pass of 96×96 (W_1) and a second pass inside this W_1 of size 32×32 (W_2). A common W_2 is taken between the double frames, and a spatial correlation between the particles in these two windows is calculated. This correlation shows a peak in some direction with respect to the centre of that window which helps us to determine the direction of motion. The distance of this peak with respect to the centre of the window is taken as the displacement. Hence, we get the displacement vector which then can be divided by dt in order to get the velocity vector for that window. The time gap dt is kept such that the motion of particles is captured in the double frames, and we do not have particles totally moving out in the second frame. When the program wants to move to the next location, it does so by maintaining a 50 % overlap with the last window it processed. This overlap is taken so as to account for the

particles that may have moved out of the second frame. So, this overlap helps us to account for the particles present on the edge of the window.

This procedure is carried out for the whole image to get a single velocity field. After the processing of all the double-frame images is done, we obtain a data set of velocity fields. Since we get a single velocity field from a pair of images, the number of velocity fields is half of the total number of images captured. In our case, we capture 17400 double frame images, which gives us 8700 velocity fields.

3.4 Experimental setup of PIV

The experiment uses two High Speed Star UX 100 cameras by the company LaVision, based in Germany. The resolution of these cameras is 1.3 megapixels (1.3 MP, i.e., 1280 x 1024 pixels). The cameras are fitted with a CMOS image sensor. 50 mm Nikon AF Nikkor f/1.4 lenses are used for the current work. These cameras can capture images at a rate of up to 4 kHz in single frame mode and up to a rate of 2 kHz in double frame mode. Single frame mode refers to simple frame-by-frame capturing. Double frame mode refers to the acquisition of a pair of frames at a time. In the double frame mode, the cameras capture two frames separated by time dt at a rate of f , where $dt \ll 1/f$. As explained earlier, this mode is needed to calculate the velocity fields in the flow. In our case, $dt = 50\mu s$ and $f = 1000$ Hz. These cameras are calibrated using the 106-10 calibration plate provided by LaVision. The field of view captured by the camera has a physical dimension of 101.04 mm x 125.38 mm (length and height) and is centered around streamwise location of $x/b = 77$. The experimental setup can be seen in figure 5.

The high-speed PIV setup consists of a dual pulsed Photonics Industries high-speed Nd:YAG laser with a wavelength of 527 nm, i.e., a green laser. The maximum output of the laser is about 70 mJ per pulse. This laser gives out dual pulses of laser at a maximum rate of 5kHz. The time gap (dt) between the pulses can be calibrated manually between a range of 10 μs to 900 μs . The laser is connected to a laser guiding arm. This arm helps us to guide the laser from the laser port to the top of the table. The region where the laser hits the wall is painted black with the help of blackboard paint. This is done in order to lessen the laser reflections from the aluminium wall. These reflections increase the noise level in the images, thus reducing the accuracy with which we can resolve the particles. Higher reflections also

increase the intensity of light falling on the camera sensors which in turn increases the chances of the camera sensor burning out. Here, the guiding arm opens up into a cylindrical lens of focal length $F \sim -20\text{mm}$. These cylindrical optics spread the laser beam into a 2-D sheet, with a sheet width of the order of 0.5 mm . This laser comes with a Lytron chiller that helps to keep the internal parts of the laser cool.

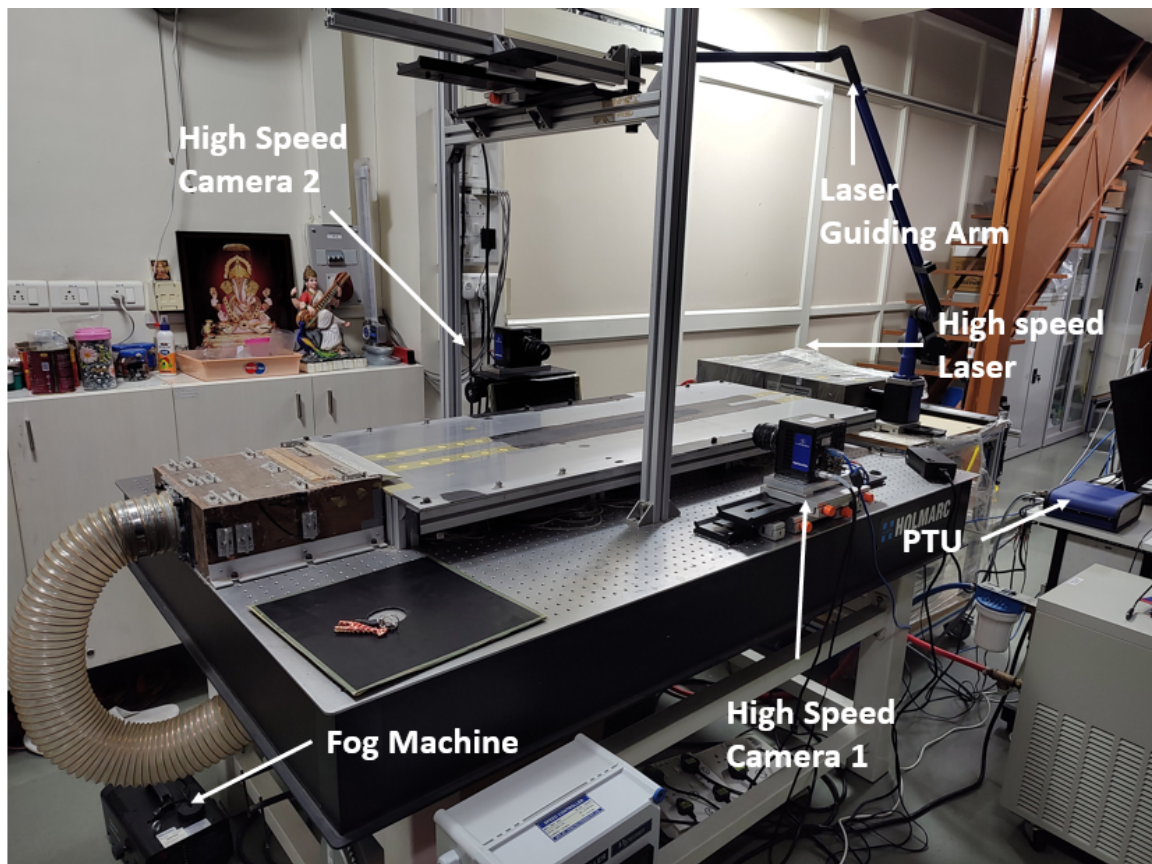


Fig. 5 - High speed PIV setup

The crucial part of the high-speed PIV setup is to run the above two components in a synchronised manner. This task is overtaken by a Programmable Timing Unit (PTU) by the name of PTU X provided by LaVision. This unit works as an “interface” between the cameras and the laser. The PTU is used to sync the capture rates for the cameras and the laser pulse rates for the PIV setup to capture data correctly. As a result, the double frames captured by the cameras occur at the same time the dual pulse of the laser strikes. In other words, the first laser pulse and the first frame are shot at the same time, and the same happens for the second frame and the second laser pulse. All three components - laser, cameras and PTU, are connected to a host computer which runs the DaVis software provided by LaVision. This

DaVis software allows us to remotely control all three components and calibrate them properly.

The high-speed PIV setup also consists of a fog machine operated remotely via a switch. This fog machine gives out fog particles of size 1-3 microns for seeding the flow. The fog machine uses a glycerol-based fluid to create the fog. This fog particle size has been shown to work for our setup. The experiment is performed in a closed room. The room is big enough that the wall jet flow is unaffected by any secondary flows.

3.5 Procedure for PIV experiments

The PIV experiments are performed in a closed room in the FDL lab. The laser chiller and the laser controller are turned on first. We then wait for the laser to reach the operable temperatures (the temperature at which lasing starts to happen). The DaVis software is opened in the host computer, which helps us to control the cameras, laser and PTU. Now, the room is seeded using the fog machine, and the blower is turned on and set to the desired speed. We wait for a few minutes until the seeding in the flow and the surrounding air is homogeneous. This is checked by taking live images in the DaVis software. Once we are satisfied with the seeding, the focus of both camera lenses is adjusted so that they properly focus on the seeding particles. This is also monitored with the help of a live feed provided by the DaVis software. Once the cameras are focused, the recording is turned on, and the images are captured. After the recording is over, the room is opened in order to clear out the fog particles. In the meantime, the data acquired is transferred to the host computer with the help of an ethernet wire. The calibration plate (106-10) the one seen in figure 6, is placed on the wall such that its face coincides with the plane of the laser and the centre triangle of the plate coincides with the experimental location ($x/b = 77$). This is done with the help of the laser. 10-20 images of the calibration plate are captured without changing the focus of the cameras. This finishes the physical work of the experiment.

Next, the data acquired is processed using the DaVis software. The images, firstly, are calibrated and then put up for PIV processing in the software. After the processing is done, the velocity fields thus obtained are converted to .dat files which are then further analysed in the MATLAB software.

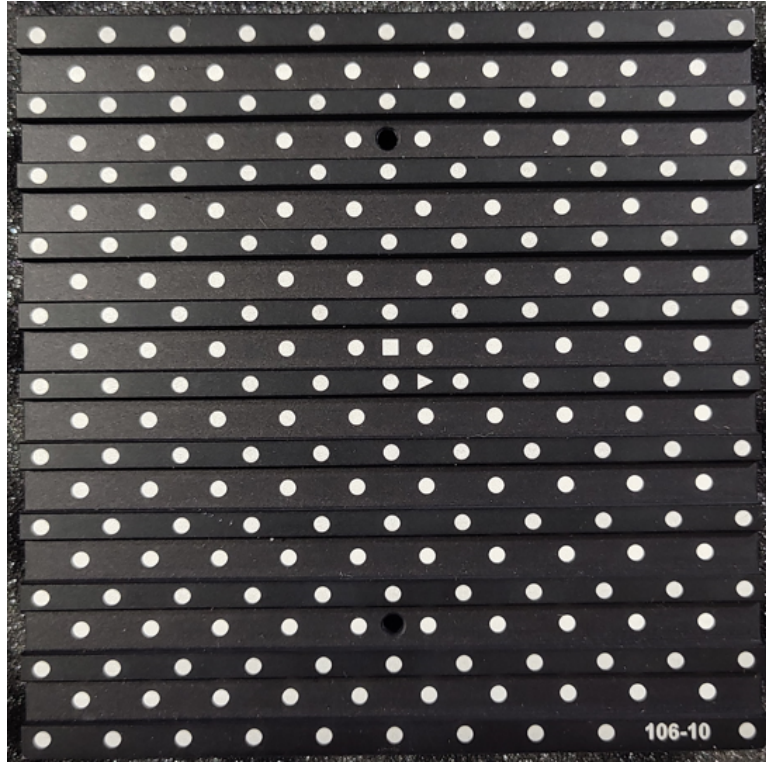


Fig. 6 - Calibration plate of size 100 mm x 100 mm

3.6 Hotwire Anemometry (a brief look)

Hotwire anemometry is a technique used to measure the velocities of a fluid flow. This technique provides a single point time series data for the flow velocity. The data acquisition rate of this technique is relatively high, and thus, it is used extensively for studying turbulent flows. The fundamental principle behind the functioning of a hotwire anemometer is a Wheatstone bridge circuit. Since the project does not employ the hotwire anemometry technique but uses the data acquired earlier by the lab to do some preliminary analysis, a detailed explanation of the technique and the setup is not provided here. Readers are encouraged to refer to [14] for a detailed explanation of the technique and setup used for the experiment. The data used in this project was acquired at a frequency of 25 kHz using a constant temperature hotwire probe at different heights for various locations (including the location where $x/b = 77$) for the same three Reynolds numbers at which the PIV experiment in this project is done.

Chapter 4

Results and Discussion

This chapter lays out all the insights and results we obtained from analysing the hotwire anemometry data and the new high-speed PIV data. Section 1 contains the calibration curves for the velocity profile of the flow. In this section, we describe the method to calibrate the flow before any PIV measurements can be done. Section 2 includes the preliminary analysis of the data obtained through hotwire anemometry. Section 3 contains the main results of the present work. The few things discussed in this section are the interfaces we obtained, their statistical properties and discussions regarding these results. This section contains the main insights we obtained through the analysis of this data.

4.1 Initial Calibration using Pitot Tube

Pitot tube experiment helps us to measure the mean velocity at a given location so it can be used to measure the velocity profile for a flow. We take measurements at different wall-normal locations, which helps us to build a velocity profile. This velocity profile is matched with the earlier velocity profiles obtained from hotwire and pitot. Hence, it helps us to calibrate the flow speed and keep the flow Reynolds number more or less consistent with the previous data. The calibration plots for the three Reynolds numbers are presented in figures 7,8 and 9.

In figures 7,8 and 9, the velocity profile of the flow is depicted at location $x/b = 77$. The velocity profiles at all three Reynolds numbers match with the older velocity profiles of hotwire and pitot. This allows us to use the parameters which were obtained earlier. The percentage deviations between the velocity maxima of the pitot with respect to hotwire and old pitot measurements are summarised in table 1.

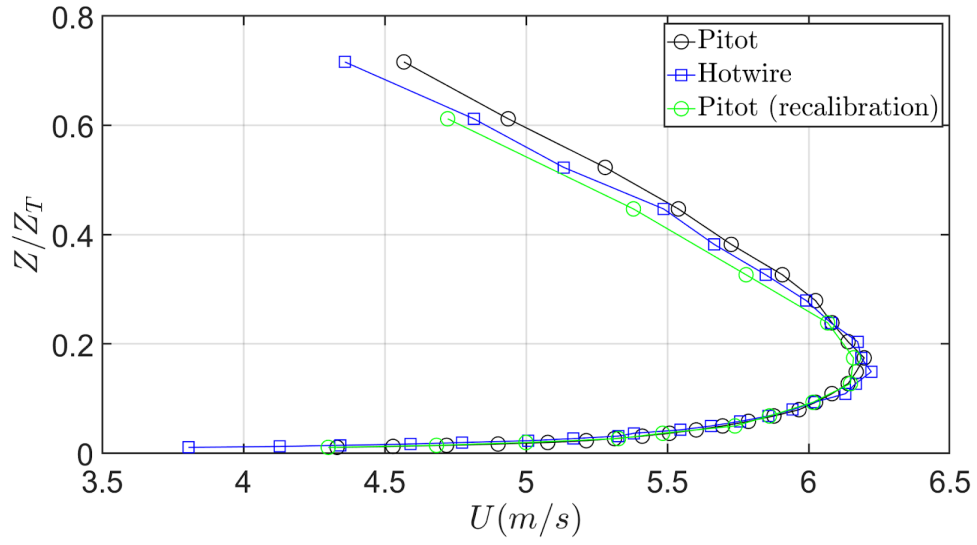


Fig. 7 - Velocity profiles obtained from recalibration experiment for Re_1 .

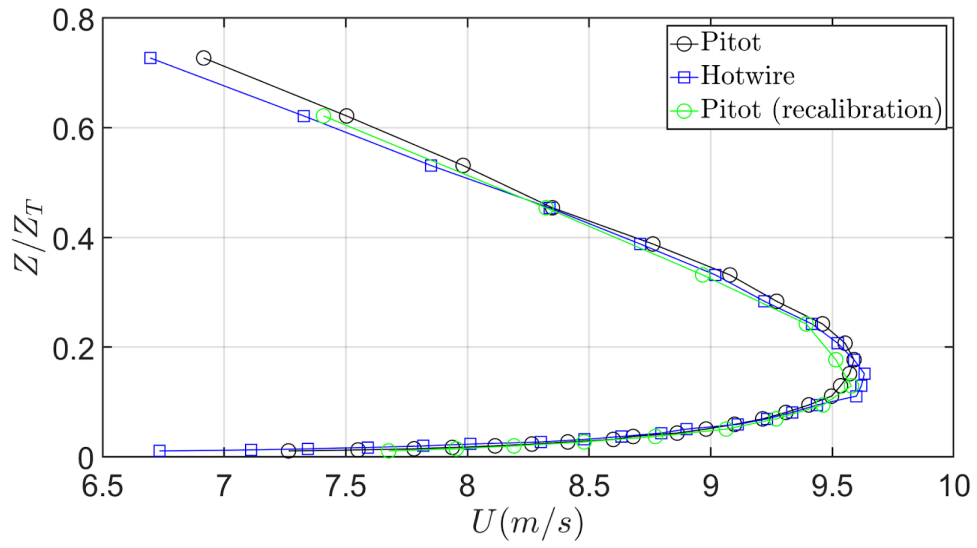


Fig. 8 - Velocity profiles obtained from recalibration experiment for Re_2 .

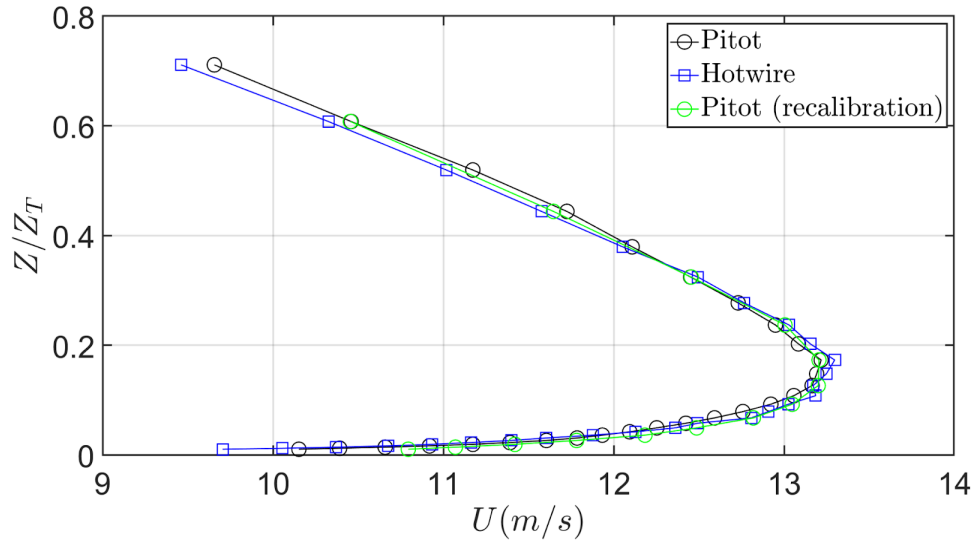


Fig. 9 - Velocity profiles obtained from recalibration experiment for Re_3

The new velocity profiles also lie on the older velocity profiles. The percentage deviations of the velocity maxima are also within a reasonable limit of 1 % from the older data. This assures us that the flow is correctly calibrated.

Reynolds Number	Deviation between U_{MAX} of new pitot and hotwire	Deviation between U_{MAX} of new pitot and old pitot
Re_1	1.007 %	0.608 %
Re_2	0.553 %	0.112 %
Re_3	0.693 %	0.098 %

Table 1 - Percentage deviations of the U_{MAX} obtained from recalibration experiment with respect to older hotwire and pitot data at all Re

4.2 Hot-Wire Anemometry Data Analysis

The hotwire data obtained is used to calculate the velocity fluctuations in the streamwise direction of the flow [19]. As a result, we obtain the time series data for u' values at different

wall normal locations (heights). In other words, we have a distribution of velocity fluctuations at different heights. We calculate a factor known as the Kurtosis or flatness factor, which is the fourth-order moment of a distribution and describes the spread of a distribution.

$$K = \frac{\overline{u'^4}}{\sqrt{\overline{u'^2}}^2}$$

In turbulent flows, this factor describes the spread of turbulent events. Literature [20-22] shows that the flatness factor of turbulent flows is nearly 3 which is close to the flatness of a Gaussian distribution. In our case, the expected behaviour of this factor is that it should remain near 3 for the turbulent part of the flow and move away from 3 when it enters the non-turbulent layer. The figures below plot the behaviour of this factor with respect to height.

In the figure n, we observe that the flatness for all the Reynolds numbers hovers around 3 till $Z/Z_T \sim 1.2$, and beyond this value, it starts to increase. One thing to note in this plot is that the flatness remains the same for all Reynolds numbers up to $Z/Z_T \sim 1.8$. Beyond this, the curves diverge and that too without any particular order because the Re_1 curve lies in the middle of Re_2 and Re_3 . For now, we are not able to explain this behaviour, but more importantly, we do not know if this behaviour is common because our data set covers only three Reynolds numbers, and there are no reports of such behaviour in the literature.

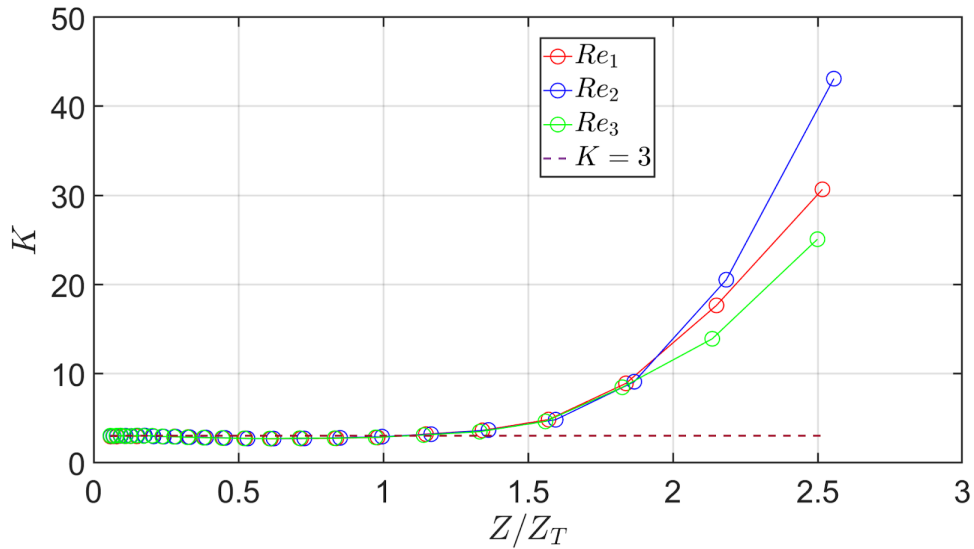


Fig. 10 - Flatness vs Height curve for hotwire data different Re

Since we are looking for the exact point where the slope of the curve changes, it is better to look at the gradient of the flatness. The figure below plots the curve of the gradient of the flatness with respect to height.

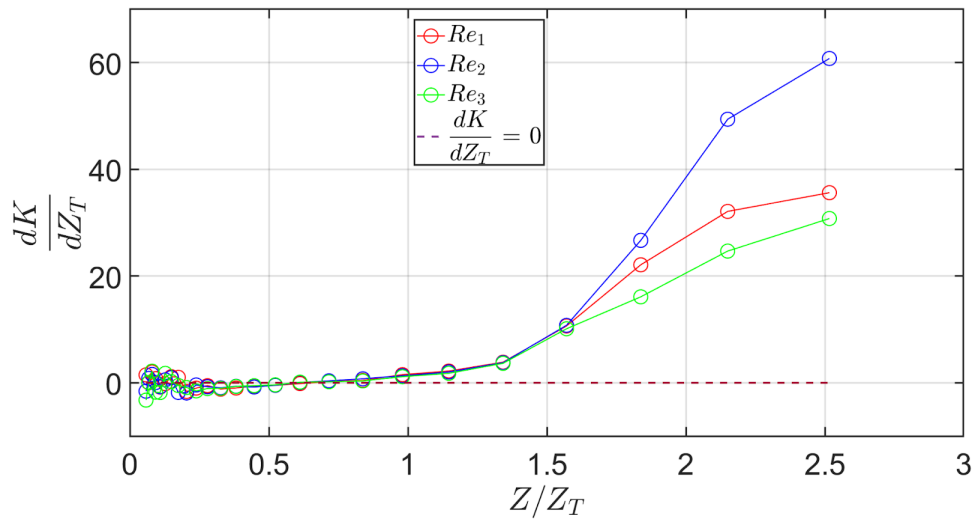


Fig. 11 - Gradient of flatness vs height curve for hotwire data at different Re

The above plot makes it more clear to see the point where the slope of the flatness curve changes. We can observe that beyond $Z/Z_T \sim 1$, the slope of the flatness curve becomes greater than zero. Though we can see that this starts to happen around $Z/Z_T \sim 0.8$, the gradient is still very small, but beyond $Z/Z_T \sim 1$, the slope becomes large enough to say that the value has shifted. This gives us an insight as to where the effect of the turbulent non-turbulent interface (TNTI) starts to come in. From the above plots, we observe that the TNTI definitely lies above $Z/Z_T \sim 1$, which gives us a physical height of around 58.1 mm from the wall. This allowed us to set the field of view of the cameras and the physical heights they both should be capturing. This height of $Z/Z_T \sim 1$ gives us a minimum on the possible height of the TNTI.

The PIV experiments were carried out keeping in mind the insights that we obtained from the analysis of the hotwire anemometry data.

4.3 High-Speed PIV Data Analysis

4.3.1 Flow Statistics

The velocity field data obtained from the workstation is in the form of .dat files, which are converted to velocity fields using a MATLAB program. We removed the top and bottom rows

and the left and right columns of the velocity field in order to avoid any processing error that might have occurred at the boundaries of the image. The figures 12 - 15 depict the velocity fields obtained from a single PIV field at Re_1 .

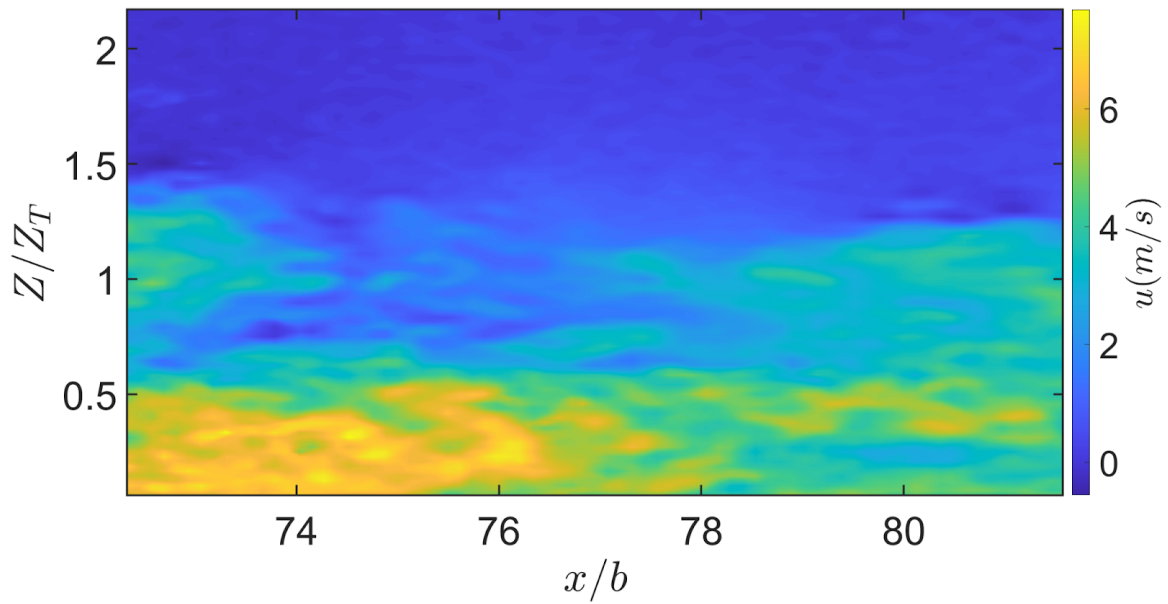


Fig. 12 - Streamwise Instantaneous Velocity field for Re_1

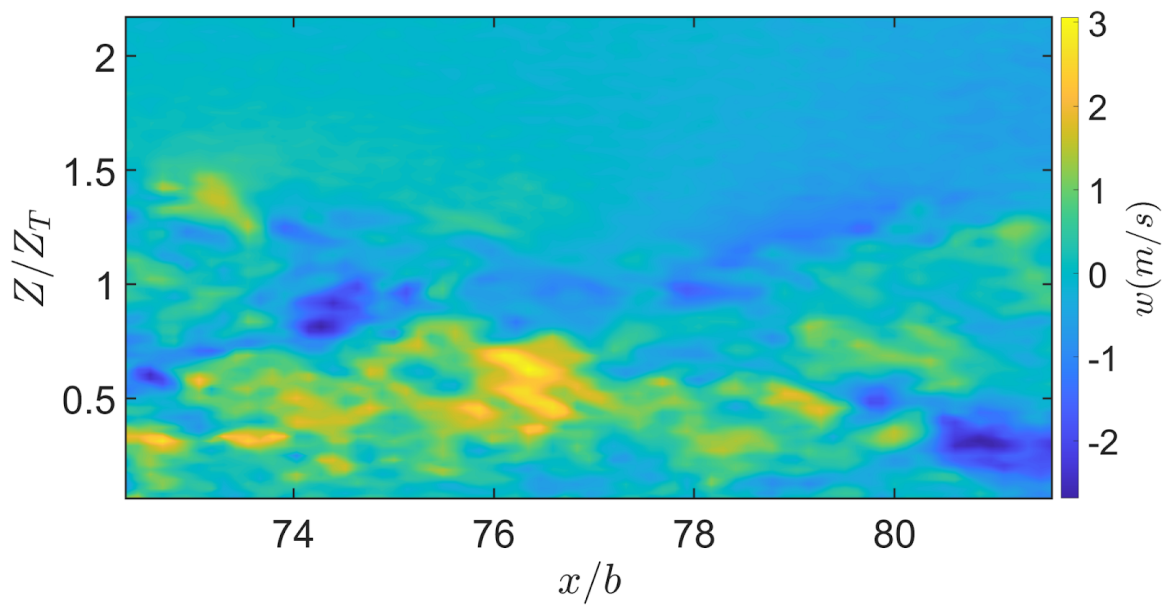


Fig. 13 - Wall-Normal Instantaneous Velocity field for Re_1

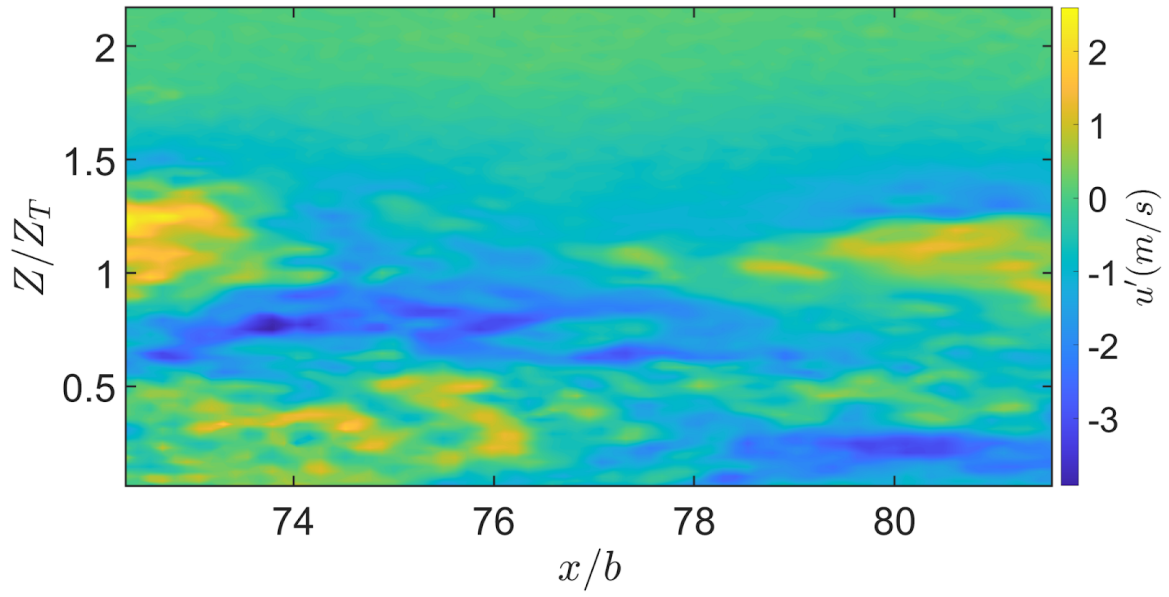


Fig. 14 - Streamwise Fluctuation Velocity field at Re_1

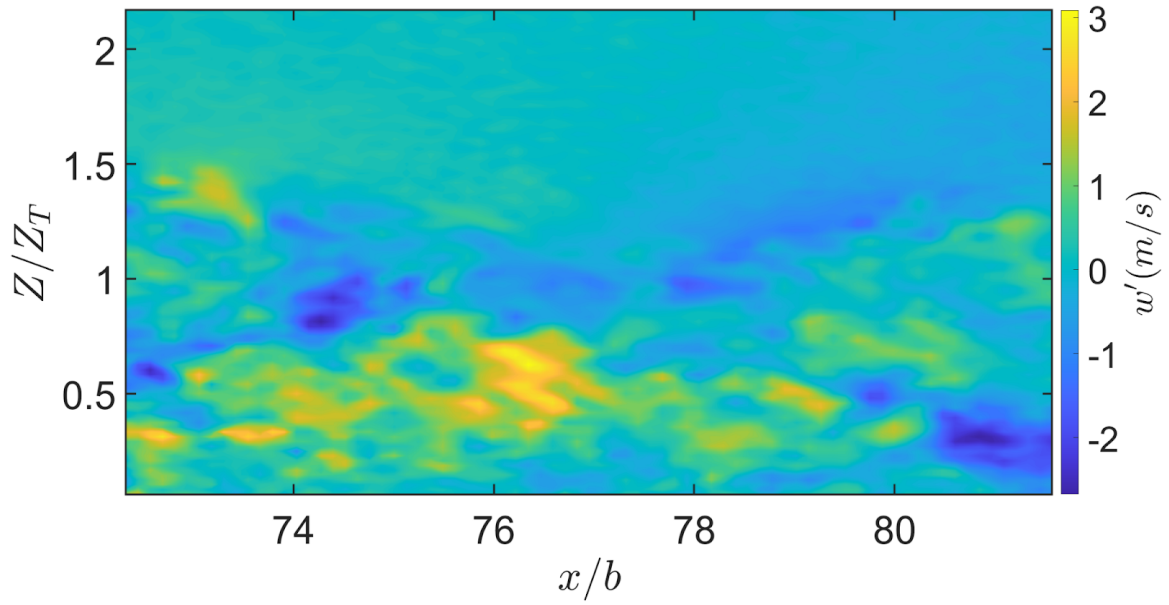


Fig. 15 - Wall-normal Fluctuation Velocity field at Re_1

The mean velocity fields (average of instantaneous velocities) for all three Reynolds numbers are given in figures 16 - 18.

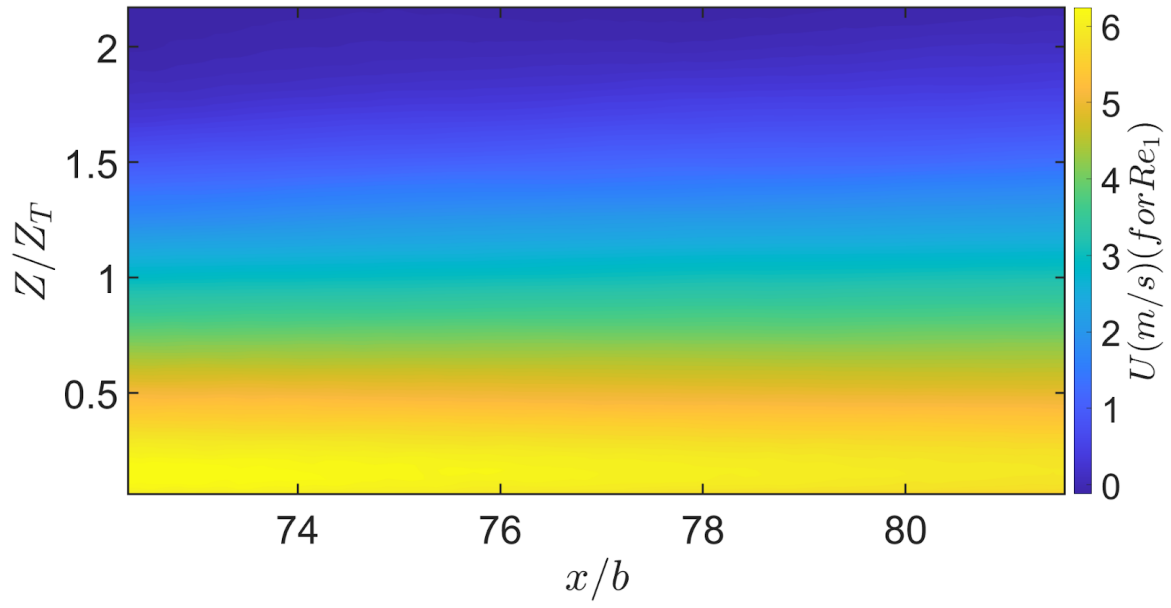


Fig. 16 - Streamwise Average Velocity field (U) at Re_1

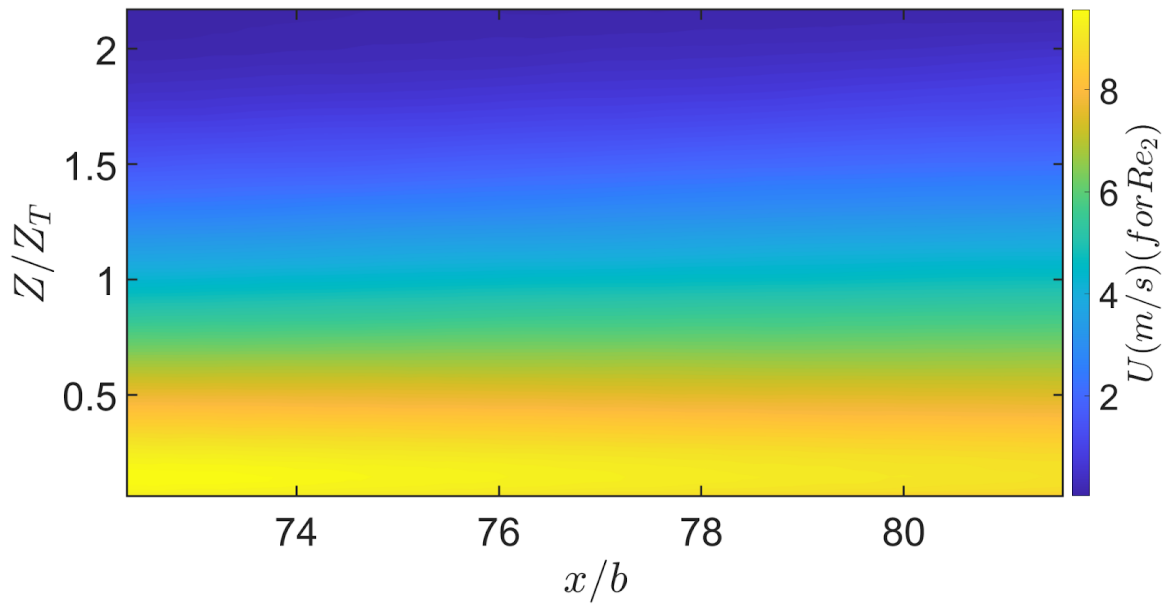


Fig. 17 - Streamwise Average Velocity field (U) at Re_2

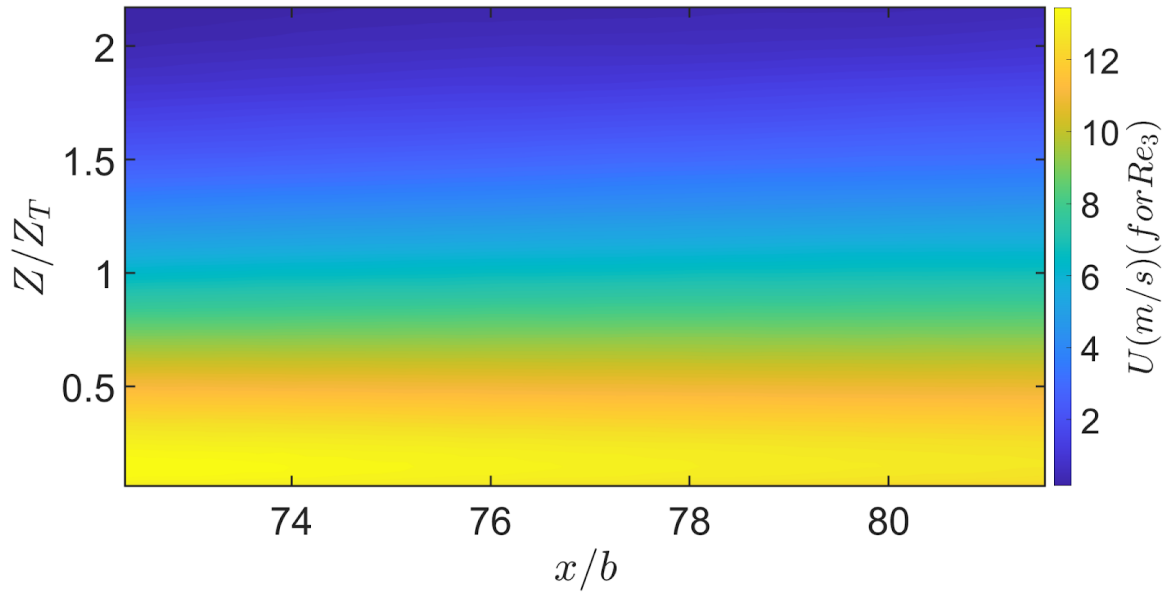


Fig. 18 - Streamwise Average Velocity field (U) at Re_3

The mean velocity fields look similar to each other despite the change in their Reynolds number. This is also evident in their velocity profiles at the same location. The velocity profiles at $x/b = 77$ for all three Reynolds numbers are depicted in the figure 19.

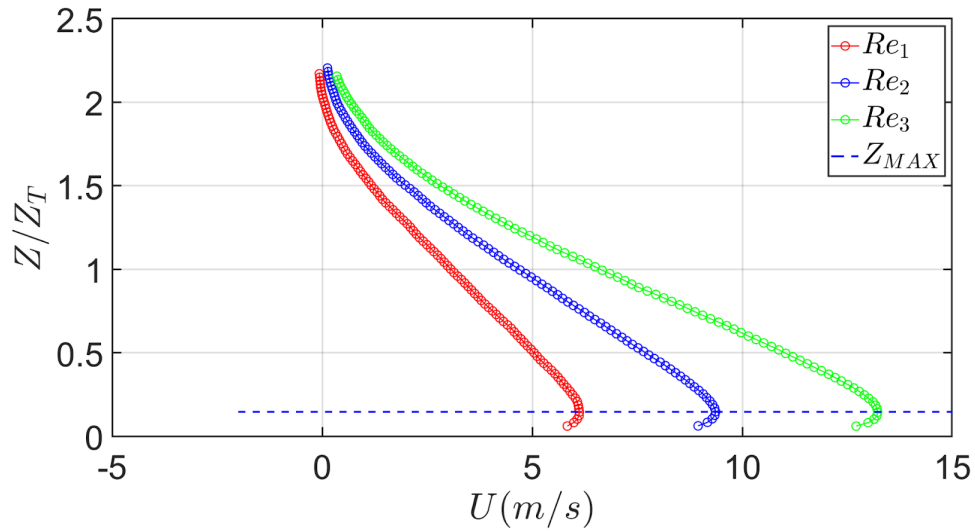


Fig. 19 - Velocity Profiles at $x/b = 77$ at different Re

The flow statistics from these velocity profiles are summarised in the table 2.

Reynolds Number	Re_1	Re_2	Re_3
U_{MAX} (in m/s)	6.12	9.36	13.22

Z_{MAX} (in mm)	8.5	8.5	8.5
Z_T (in mm)	58.3	57.4	58.7

Table 2 - Flow Statistics for different Re

Here, we observe that the Z_{MAX} is exactly the same for all three Reynolds numbers. Moreover, the locations of Z_T are also similar, with a standard deviation of 1.15 %, for all three Reynolds numbers. The deviation in the location of Z_T is very low. This implies that the angle at which the wall jet spreads is independent of the Reynolds number. This is only an observation and cannot be stated as fact because our set of Reynolds numbers is pretty low. This sort of behaviour is known in the literature [23 - 25] for free jets, i.e., the thickness of the jet (determined by the distance between the location of U_{MAX} and $U_{MAX}/2$) is independent of the Reynolds numbers. The occurrence of such behaviour for our flow can be explained by stating that the upper part of a wall jet (above Z_{MAX} and up to Z_T) behaves like a free jet. This sort of statement has been made in a few studies which have worked on wall jets.

The upper part of all three velocity profiles seems to approach zero. This suggests that the influence of the jet starts to die down beyond $Z_T = 2$. This is where the quiescent region starts since the quiescent region is not affected by the flow.

Further information about the behaviour of the flow can be obtained from turbulence intensity plots. Turbulence intensity is defined as the mean of the squared velocity fluctuations. This quantity helps us to quantify the level of turbulence at any given point. The figure below depicts the turbulence intensity of the flow at $x/b = 77$.

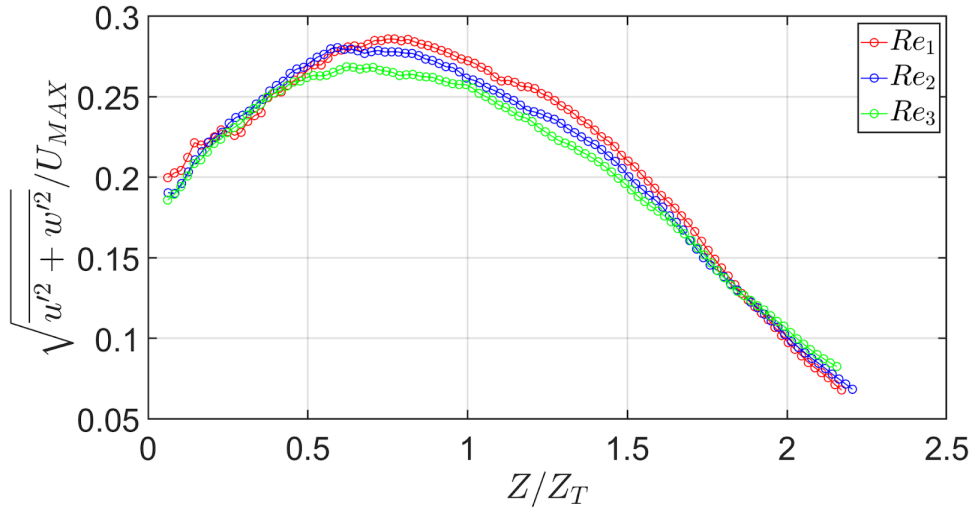


Fig. 20 - Turbulent Intensity at $\mathbf{x}/\mathbf{b} = 77$ for different Re

Here, we observe that the turbulence intensity for all the Reynolds numbers follow same trend and there values are close to each other. This is occurring because we have normalised the turbulence intensity with the outer scale velocity, i.e., U_{MAX} . This is especially seen at $\mathbf{Z}/\mathbf{Z}_T \sim 1.8$, where the three curves converge. Other than that, we can observe that the peak of turbulence intensity is higher for Re_1 , followed by Re_2 and then Re_3 . The turbulence intensity goes down beyond $\mathbf{Z}/\mathbf{Z}_T = 2$. This means that the region beyond this height is definitely quiescent.

These flow statistics, especially the velocity profile and turbulence intensity plots, help us to understand the behaviour of the flow. The above plots, especially the velocity profiles plots, seem to indicate that the quiescent region where the velocities, as well as the turbulent intensities, are very low lies beyond $\mathbf{Z}/\mathbf{Z}_T \sim 2$. The PIV data that we collected till this point has a maximum height of $\mathbf{Z}/\mathbf{Z}_T \sim 2.18$. This encouraged us to take another data set at heights higher than $\mathbf{Z}/\mathbf{Z}_T = 2.18$.

The average velocity fields of the quiescent regions for the three Reynolds numbers are given in figures 21 - 23.

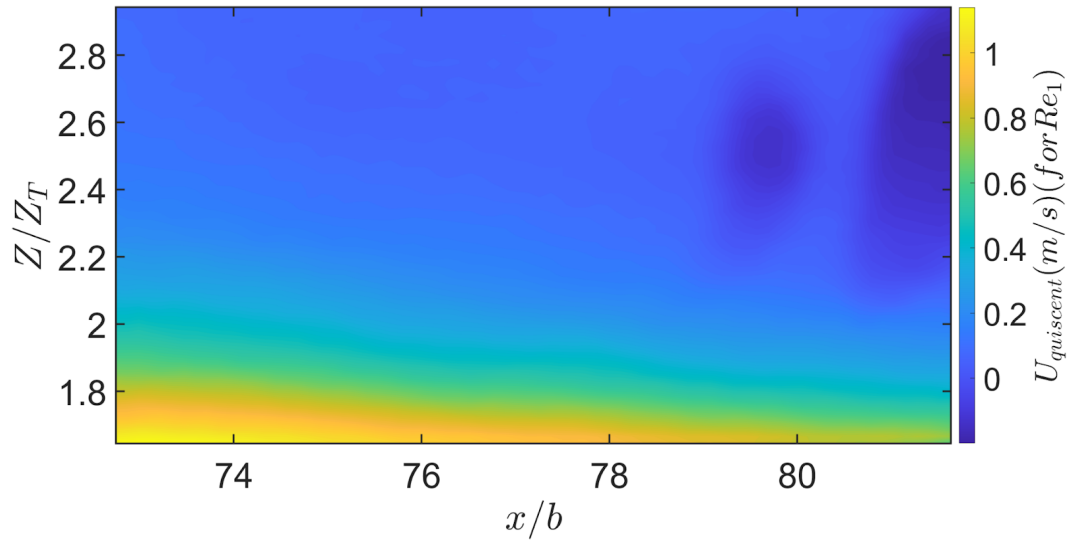


Fig. 21 - Average Streamwise Quiescent field at Re_1

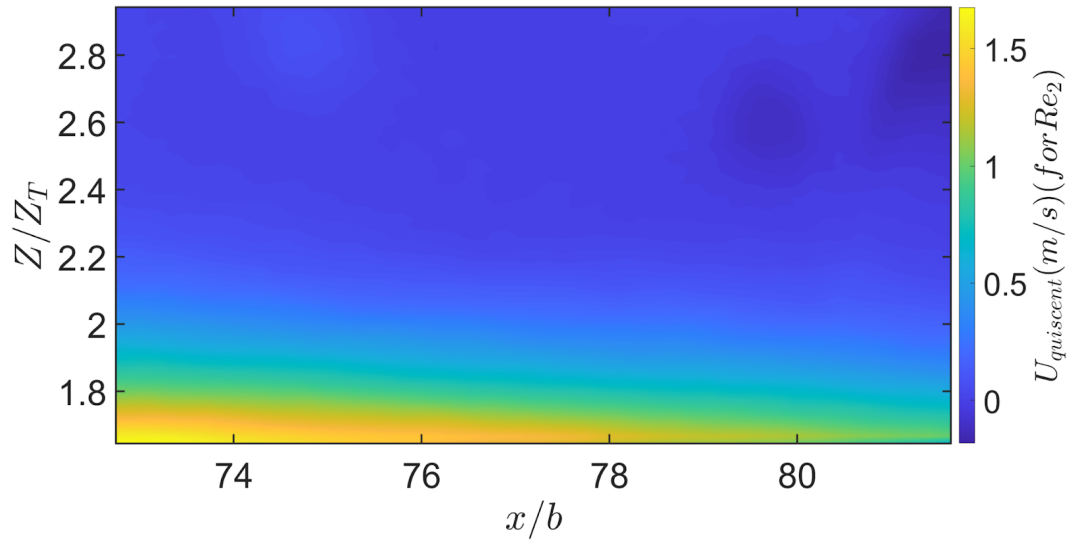


Fig. 22 - Average Streamwise Quiescent field at Re_2

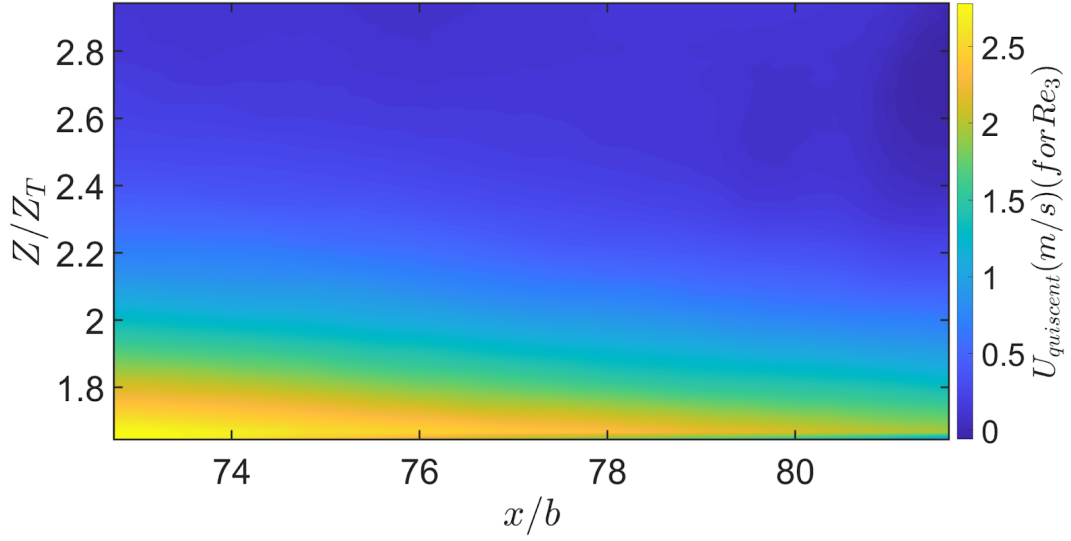


Fig. 23 - Average Streamwise Quiescent field at Re_3

The average velocity fields of the quiescent region comply with our notion of the quiescent being the region unaffected by the flow. The velocities in this range of heights, especially beyond $Z/Z_T = 2.2$, are pretty low for all the Reynolds numbers.

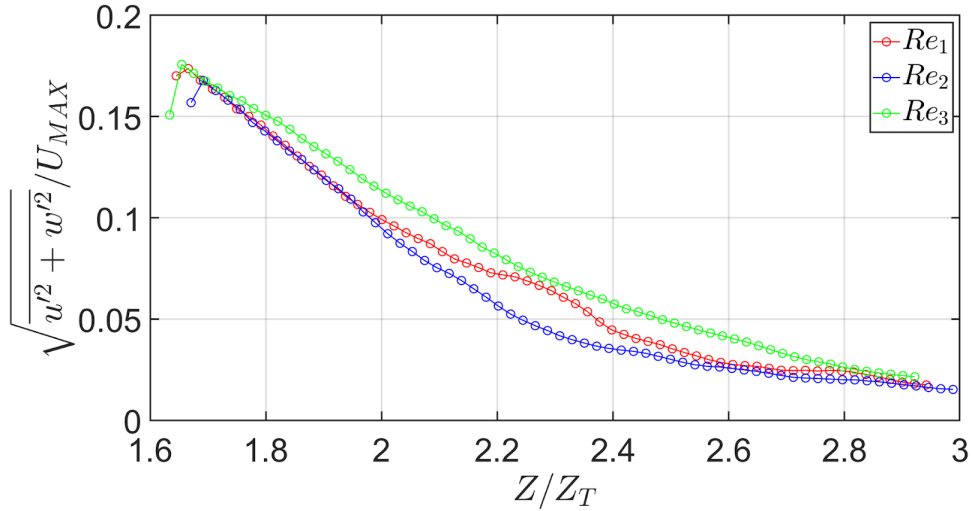


Fig. 24 - Turbulence Intensity in the Quiescent field at different Re

The turbulence intensity plots also confirm that these set of heights capture the quiescent region pretty well. We can observe that the turbulence intensity for all three Reynolds numbers is very low and starts to approach zero at the upper limit. We do notice that the plots more or less follow the same trend and are pretty close to each other. This is because we have used the outer scales to normalise the turbulent intensity, due to which the curves converge towards each other in this region.

Now, we have two data sets. The first one is the primary data set on which the interface detection algorithms are run. The second data set, i.e., the quiescent data set, captures the quiescent and is mainly used for calibrating the thresholds for the different criteria used. The next section gives us the results we obtained by applying various criteria on the main data set. Now we will process to the results we obtained from applying the various detection criteria discussed in chapter 3

4.3.2 Detection of TNTI

4.3.2.1 Chauhan's Kinetic Energy Criterion -

This criterion works by calculating the value as mentioned in Chapter 2. The U_∞ and W_∞ values are calculated by considering a common patch ($Z/Z_T = 2.75$ to $Z/Z_T = 2.94$) in all the quiescent fields for a single Reynolds number. An average value of the u and w in this common patch gives us the average quiescent velocities for that Reynolds number. The same procedure is carried out to calculate the U_∞ and W_∞ for the other Reynolds numbers.

$\tilde{k}$ is calculated for this common patch and is averaged over all the fields and the whole patch to obtain a single $\tilde{k}$ value for a particular Reynolds number. This value represents the quiescent region and thus can be used as a threshold. We obtain two more values by doing this for the other two Reynolds numbers. The values of these three thresholds are nearly - 29.32, 22.57 and 27.70 for Re_1 , Re_2 and Re_3 respectively. These three representative values are then combined by taking an average of the three which gives us the value of 26.53. This mean value is finally used to detect the interface in the primary data set. The reason for taking an average of the three values is to obtain a number that serves a universal threshold for all three data sets.

For the points where $\tilde{k}$ is less than 26.53, those points are marked as zero (representing the non-turbulent region), and the remaining points are marked as one (representing the turbulent region). Thus, we get a binary representation for the turbulent and non-turbulent layers, which helps us to visualise the boundary clearly. The figure 25 represent the Chauhan's Kinetic energy field. Figure 26 shows the log plot of the kinetic energy to enhance the gradient. Figure 27 shows the contour plot of the respective binary field.

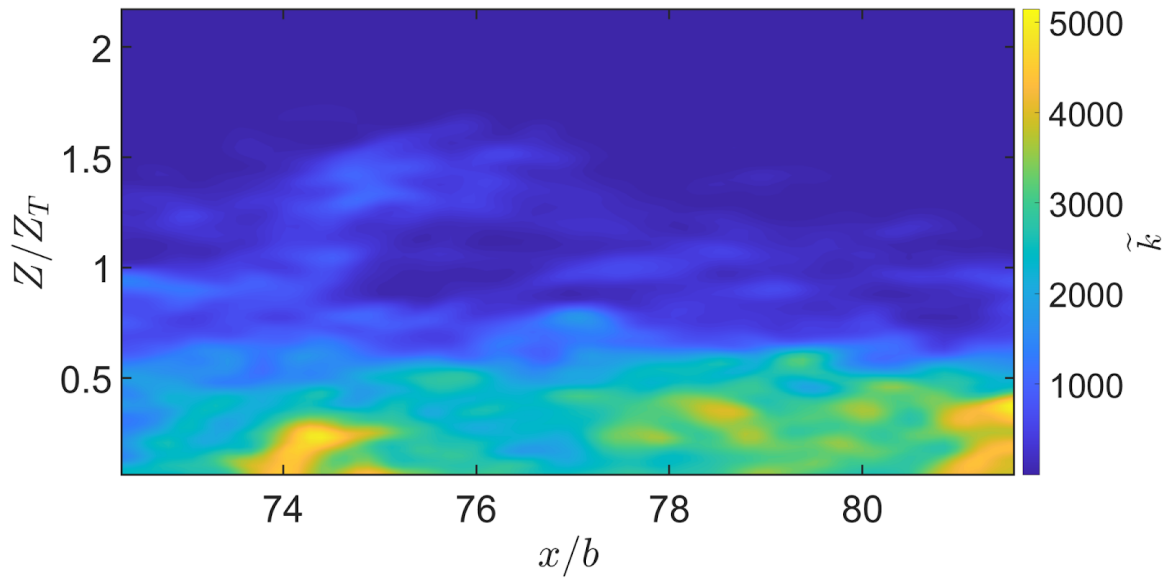


Fig. 25 - TKE using Chauhan's criterion at Re_l

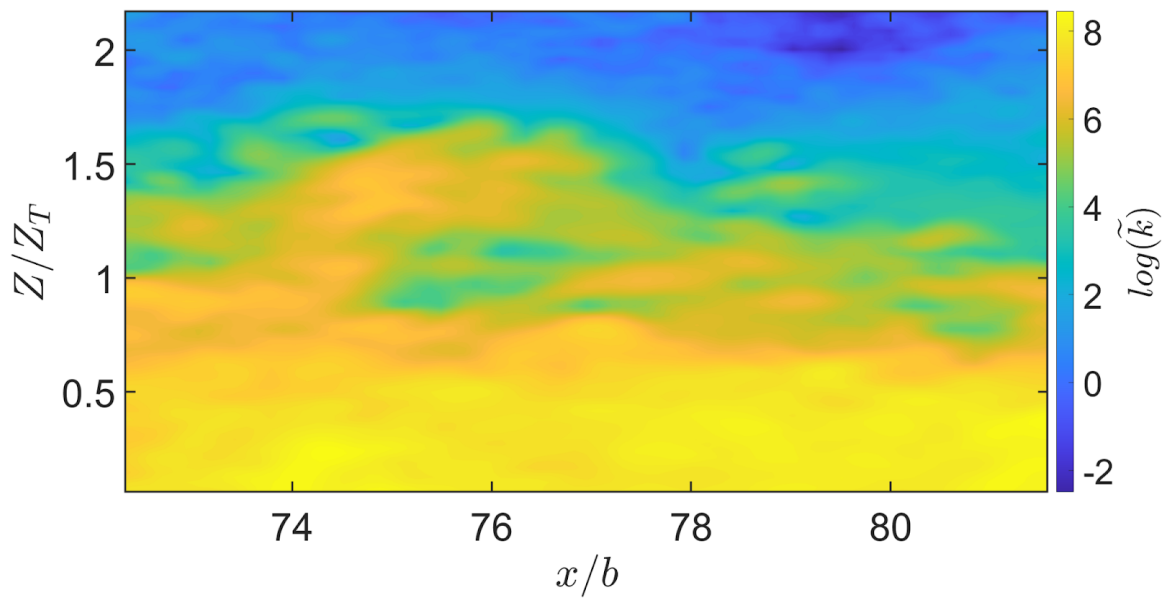


Fig. 26 - $\log(TKE)$ using Chauhan's criterion at Re_l

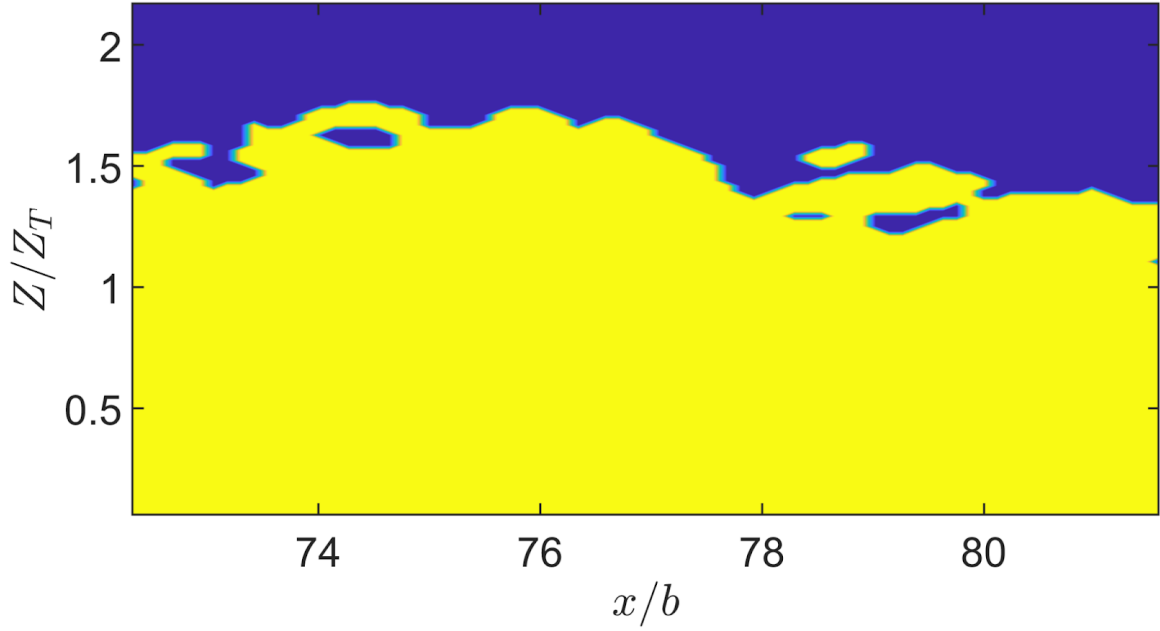


Fig. 27 - TNTI based on Chauhan's criterion

Figure 27 is a good representation of the TNTI images we obtained for the whole data set. Here, we can make a few observations. In figure 27, a few patches of the non-turbulent layer are inside the turbulent layer. These isolated patches get entrained from the outer region and get trapped inside the turbulent layer until they get mixed with the turbulent flow. The height at which the interface is present keeps on changing from one field to another. TNTI observed here does not show finer details but is not totally smooth. This is to be expected because kinetic energy is only able to capture the large-scale details, whereas vorticity captures the small-scale details.

The average height of TNTI cannot be calculated simply by taking the average of each location where the TNTI is present. We calculate the average location of the TNTI by plotting the probability distribution for the heights at which the TNTI is present at each streamwise location. This gives us a good estimate of the most probable location and the extent of the TNTI.

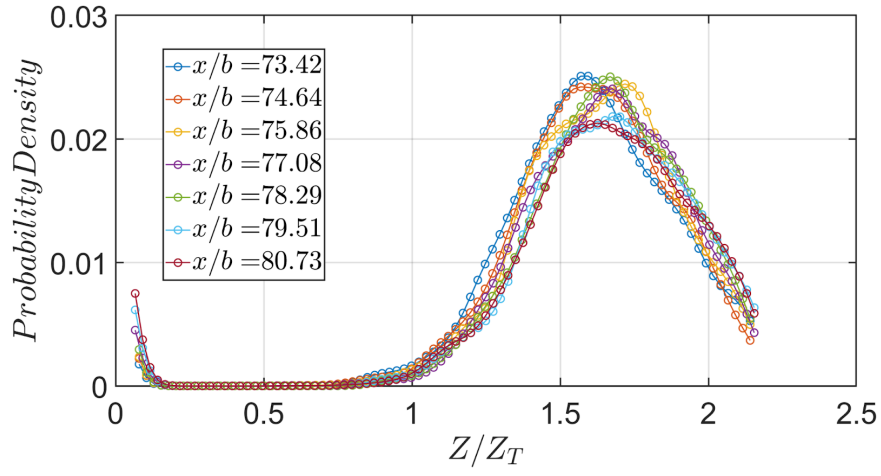


Fig. 28 - PDF of height of TNTI at different streamwise locations for Re_1

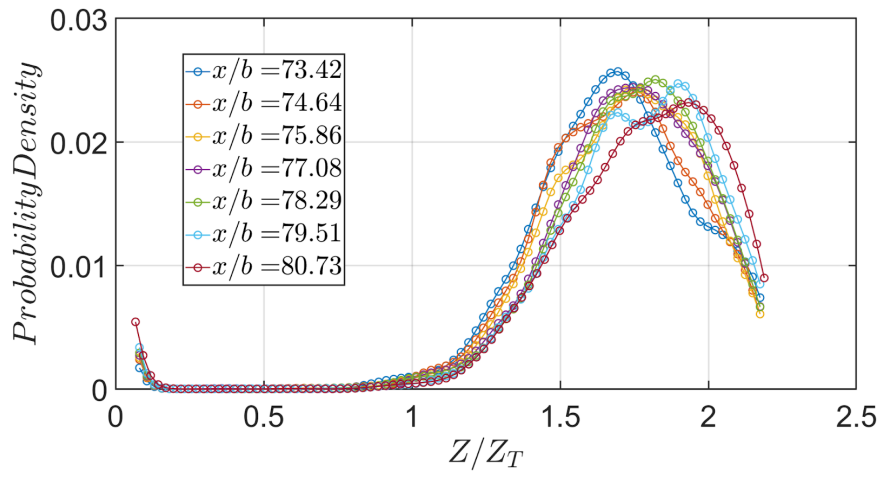


Fig. 29 - PDF of height of TNTI at different streamwise location at Re_2

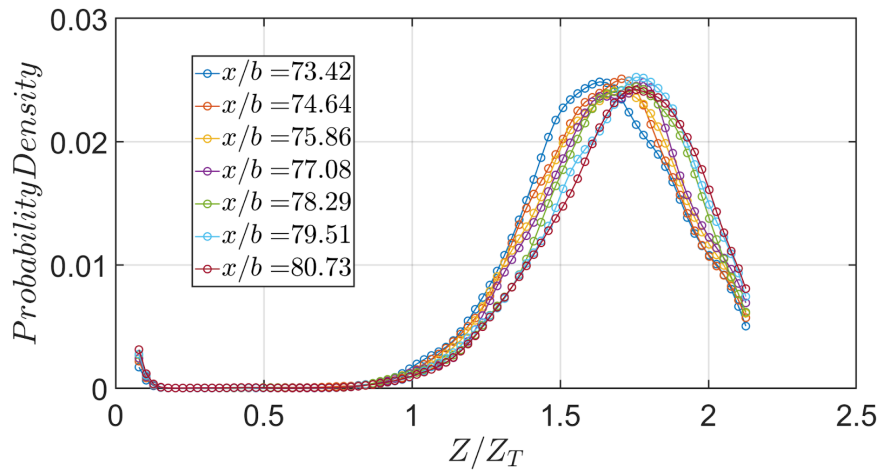


Fig. 30 - PDF of height of TNTI at different streamwise location at Re_3

In figures 28 - 30, we can observe that the TNTI is situated at heights from $Z/Z_T = 1.5$ to $Z/Z_T = 1.9$. This range is common for all Rynolds numbers. This can be seen much more clearly in the plots in figures 31 - 33.

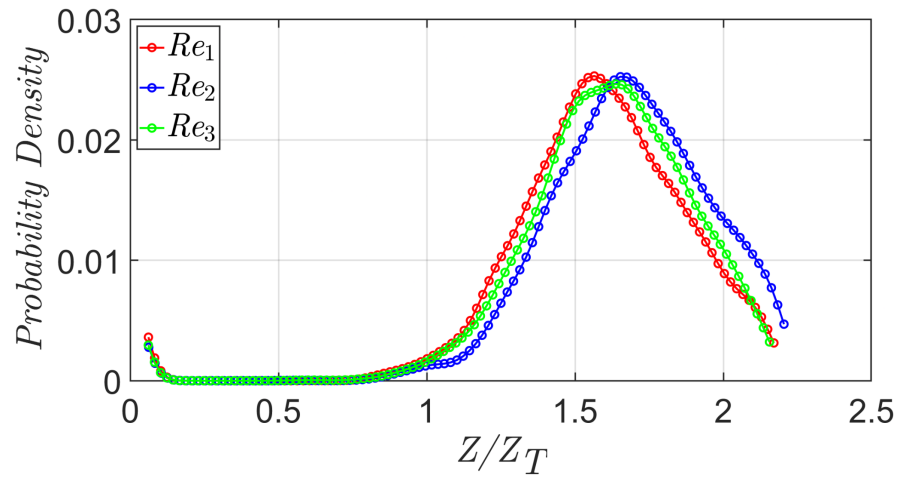


Fig. 31 - PDF of TNTI height at $x/b = 73$ for different Re

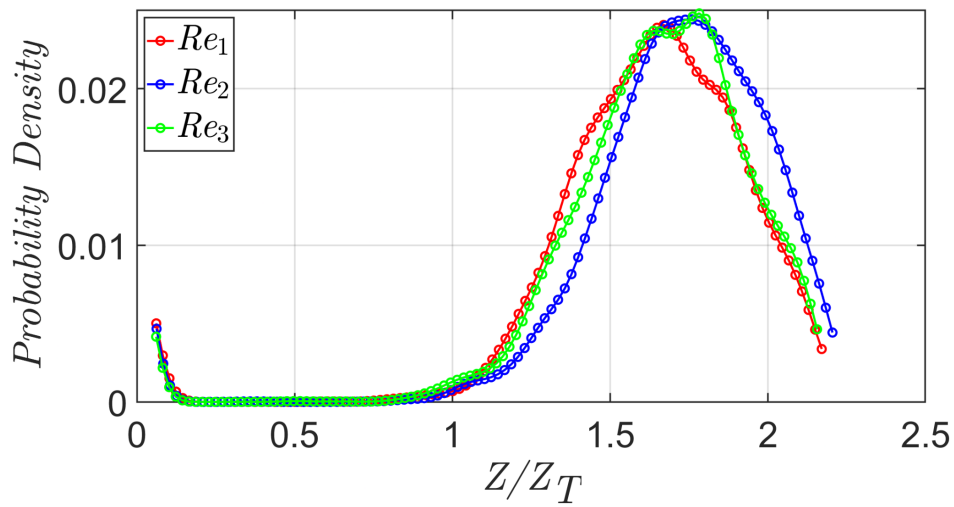


Fig. 32 - PDF of TNTI height at $x/b = 77$ for different Re

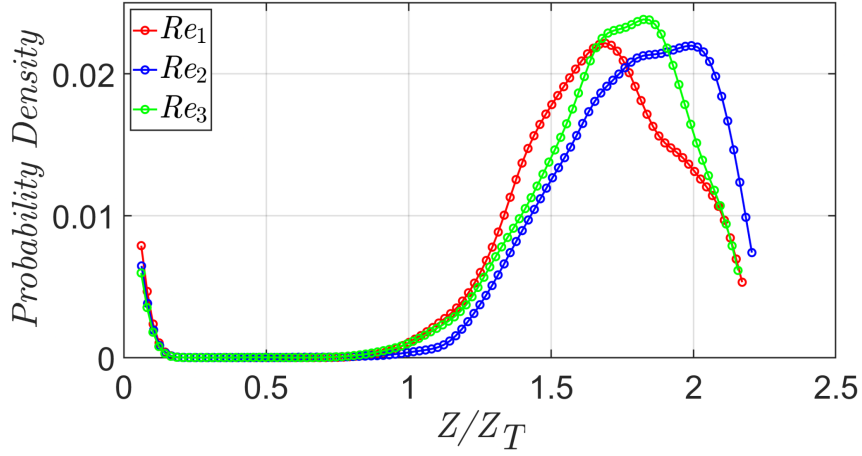


Fig. 33 - PDF of TNTI height at $x/b = 81$ for different Re

In figures 31 - 33, we can observe that height of the TNTI is more or less the same at $x/b = 73$ and 77, but it varies at $x/b = 81$ between the three Reynolds numbers. In the probability distribution plots, we also notice that the shape of the curves resembles a bell curve but has some oddities. This might be happening because the data set is not large enough. This means that we need to take more images or at least have multiple data sets for the same Reynolds numbers. In this way, we can increase the sample size, which should give us better estimates.

4.3.2.2 Vorticity Interface -

This vorticity criterion differentiates between the turbulent and non-turbulent layer on the basis of vorticity [10,11-13,17]. Only the spanwise component of the vorticity field (i.e., ω_y) can be calculated because we have data for two components of velocity (u and w) at a point. The vorticity calculated from the field is normalised using the outer scales, which are U_{MAX} and Z_T .

$$|\omega_y| = \frac{Z_T}{U_{MAX}} \left| \frac{dw'}{dx} - \frac{du'}{dz} \right|$$

The threshold for the vorticity field is set in a similar manner that we used for setting the threshold for Chauhan's criterion. In this case, instead of taking a small patch, we consider the whole quiescent field to calculate the threshold. Vorticity for the quiescent field is calculated for the quiescent region. An average is taken to get a representative number for the quiescent vorticity. We obtain three such numbers for the three Reynolds numbers. These three are again averaged to get a common threshold for the complete data set. This value is used in the denominator of the above formula to obtain a fraction of vorticity in the main

field with respect to that in the quiescent field. This simplifies our process of setting the threshold because now the threshold has a value of one. The region where this fraction has a value equal to or less than one, that region is marked as non-turbulent. Otherwise, it is marked as turbulent. The figures below show the vorticity field and the respective TNTI obtained in that field.

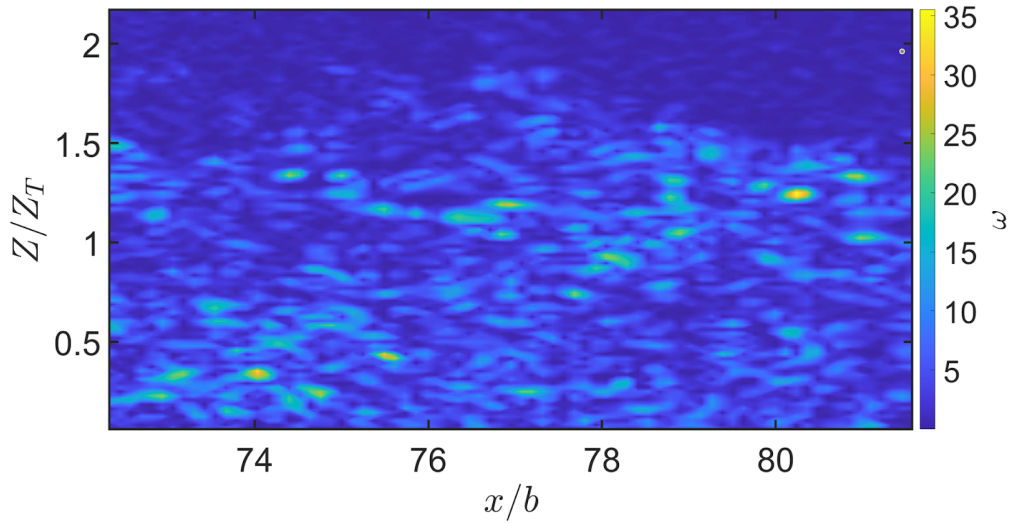


Fig. 34 - Vorticity field (ω) for Re_1

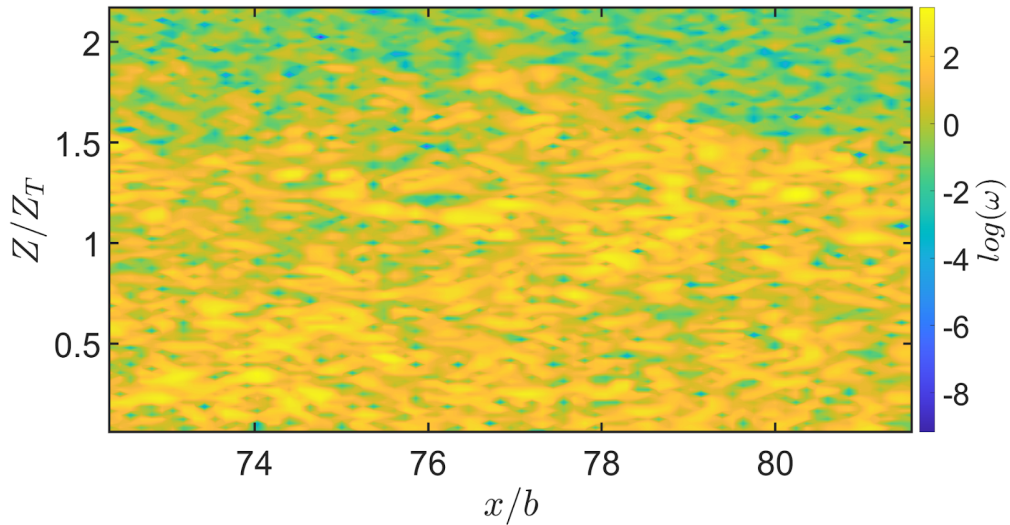


Fig. 35 - Log of Vorticity field (ω) for Re_1

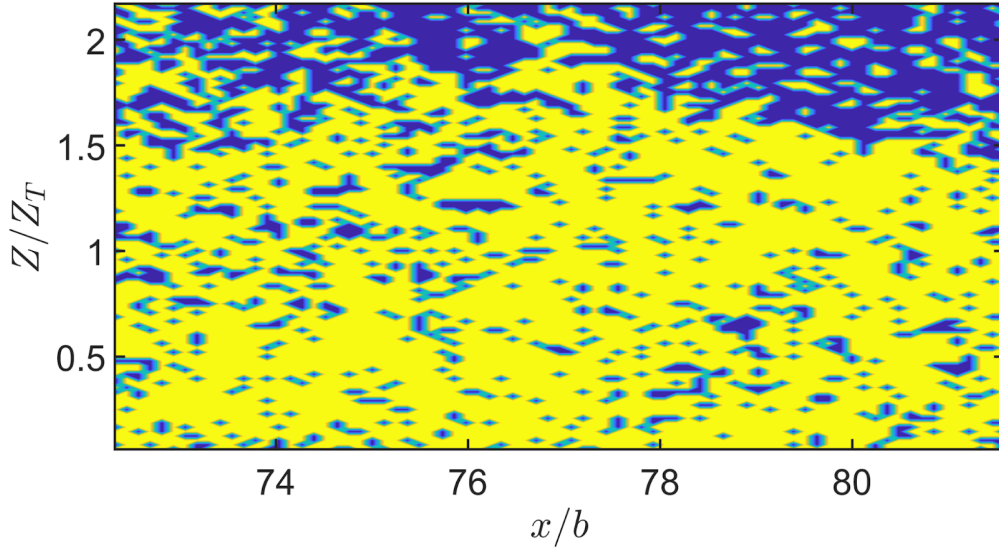


Fig. 36 - TNTI obtained using the vorticity criterion

The TNTI field and the actual vorticity field itself are quite patchy. We can observe that there are small patches of very low vorticity spread across the whole field. This can be explained by the low resolution of our camera. Since vorticity is a spatial quantity, i.e., it is calculated by the spatial gradients of the velocity fields [26,27]. So, a low spatial resolution results in a gradient that is not smooth. This is also a reason why the TNTI obtained from the vorticity criterion does not distinctly separates the turbulent and non-turbulent layer. This problem can be resolved by doing this analysis on higher-resolution images.

4.3.2.3 Homogeneity Criterion -

The homogeneity criterion distinguishes between the turbulent and non-turbulent layers based on the Homogeneity of the instantaneous velocity fields [13]. The velocity fields are homogeneous in the non-turbulent region, which means that local variations are low. On the other hand, the turbulent layer is quite inhomogeneous as the local velocity variations are high. This difference in the statistical behaviour of the velocity fields in both layers becomes the basis of applying a Homogeneity based criterion. The criterion, in its mathematical form, is a simple standard deviation formula for a local velocity field.

$$\tilde{s} = \sqrt{\frac{1}{N-1} \sum_{m,n=-1}^1 (u_{m,n} - \langle U \rangle)^2}$$

The above criterion was modified in order to include the effects of w velocity fields. The modified criterion is given below.

$$\tilde{s} = \sqrt{\frac{1}{N-1} \sum_{m,n=-1}^1 [(u_{m,n} - \langle U \rangle)^2 + (w_{m,n} - \langle W \rangle)^2]}$$

This $\tilde{s}$ value is calculated everywhere, in the quiescent field and the jet field. This value is again normalised with respect to an average $\tilde{s}_q$ value. This $\tilde{s}_q$ value is calculated by taking an average of $\tilde{s}$ values in the quiescent field over all images. The three values obtained from doing this procedure for all three Reynolds numbers are then averaged to get a common average value. The $\tilde{s}$ is then normalised using this value, and a new value, $\tilde{s}'$, is calculated. This $\tilde{s}'$ is fundamentally a fraction of homogeneity in the flow field and the homogeneity in the quiescent field. The fraction goes below one for the non-turbulent layer and stays above one for the turbulent region.

The figures 37-39 show the homogeneity field followed by a log field of Homogeneity for enhancing the gradient and lastly the corresponding TNTI obtained from that image.

Figure 39 is a good representation of the whole TNTI images that we obtained by this criterion. We can make a few observations here. The TNTI is rough and convoluted. There are a lot of non-turbulent patches inside the turbulent layer. We even see a non-turbulent patch coming down to the wall in figure 39. Homogeneity is based on the standard deviations in the velocity field. Due to this, it becomes sensitive to the resolution of the velocity field, which in turn is dependent on the resolution of the cameras.

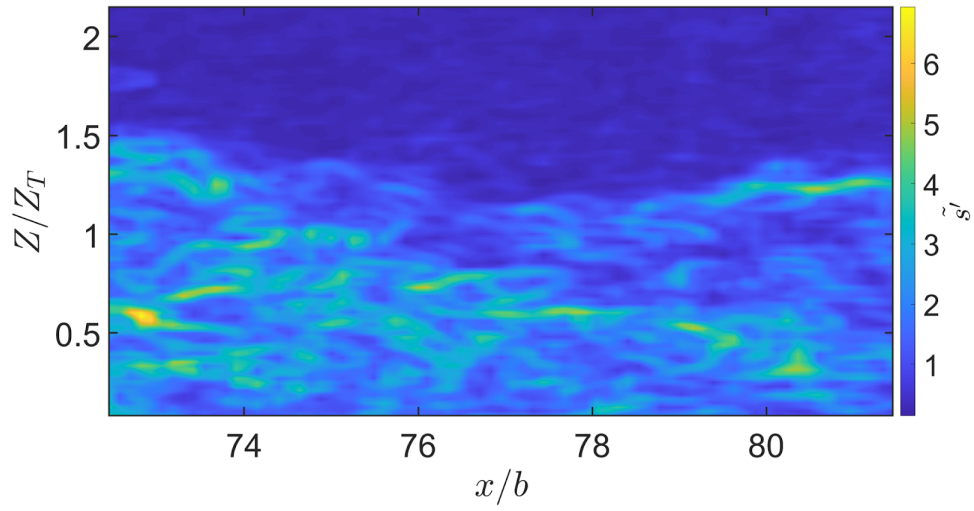


Fig. 37 - Homogeneity field for Re_1

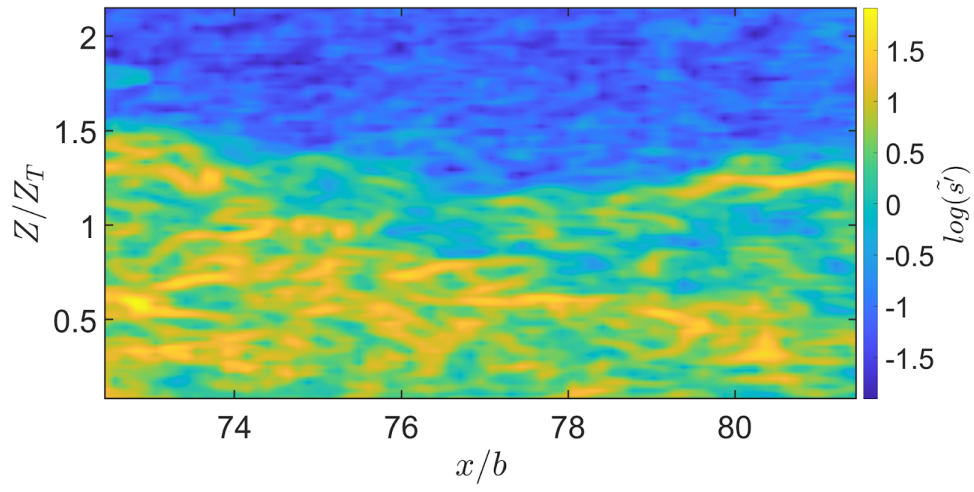


Fig. 38 - Log of Homogeneity field for Re_1

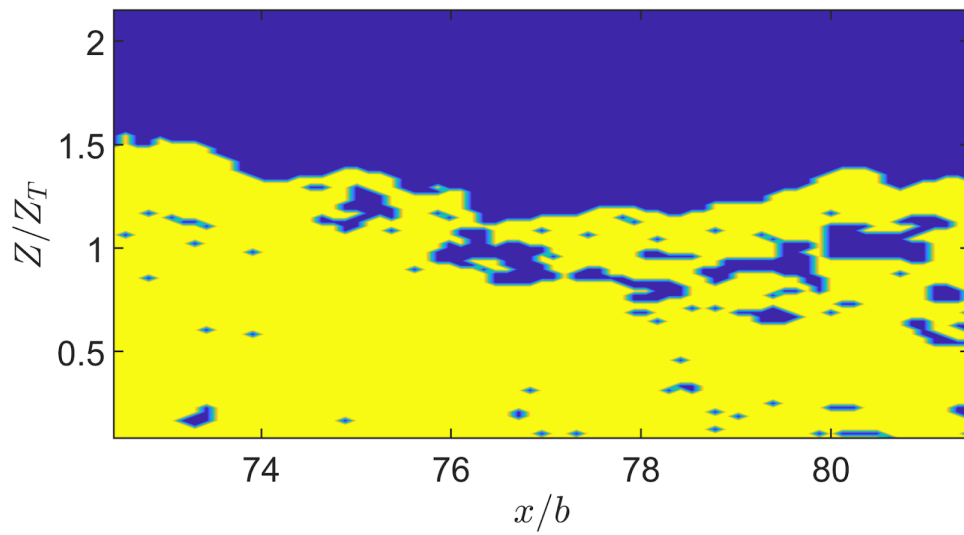


Fig. 39 - TNTI obtained using the Homogeneity criterion

The height where the TNTI is present is calculated by the probability distribution plots.

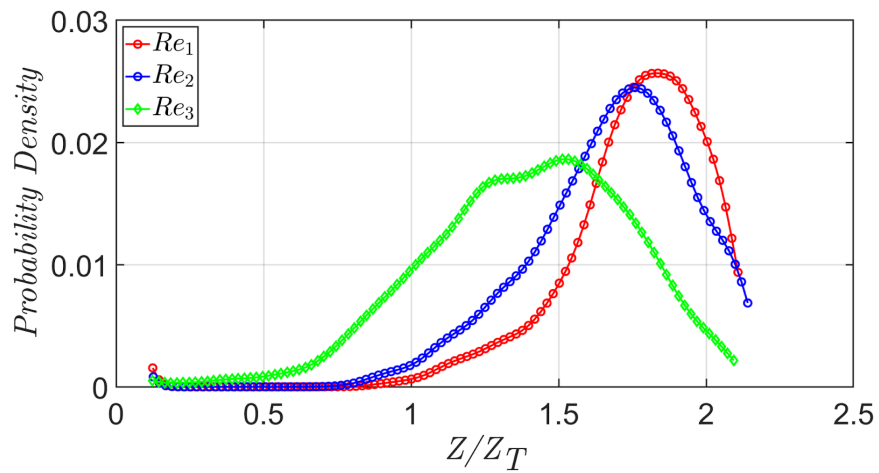


Fig. 40 - PDF of TNTI height at $x/b = 73$ for different Re

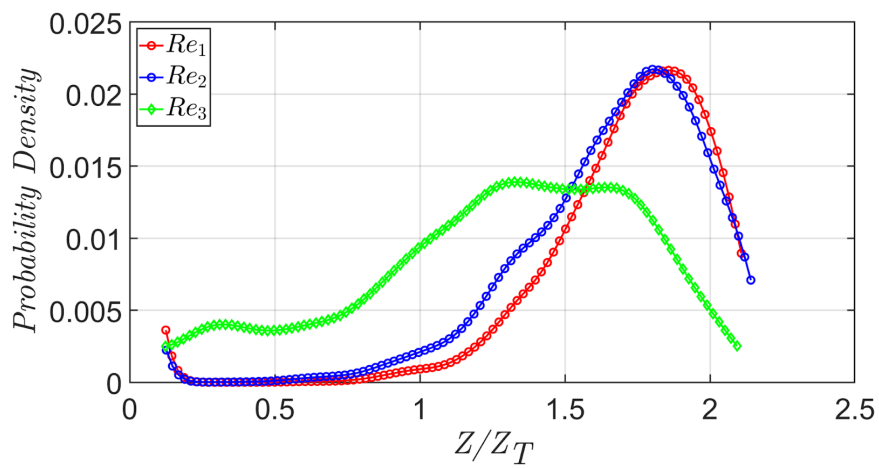


Fig. 41 - PDF of TNTI heights at $x/b = 77$ for different Re

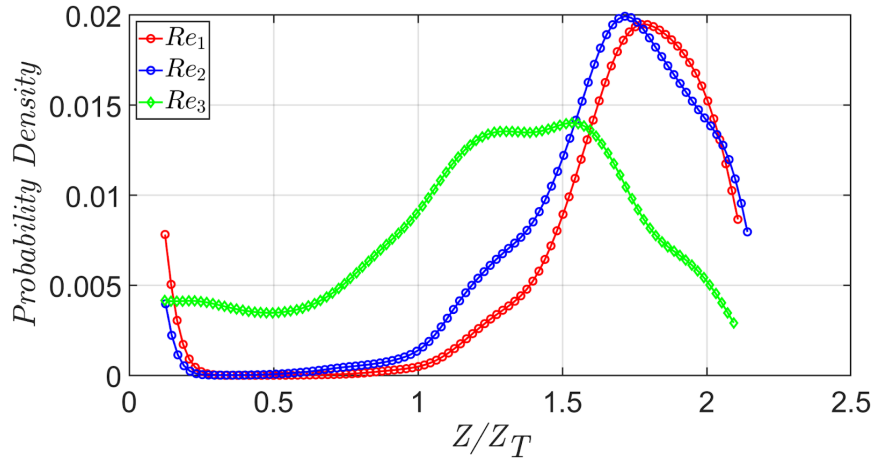


Fig. 42 - PDF of TNTI height at $x/b = 81$ for different Re

The figures 40 - 42 make it clear that the most probable distance lies in the middle of the field, for all streamwise locations, seems to peak around or beyond $Z/Z_T = 1.2 - 1.7$. The probability density increases right after $Z/Z_T \sim 1$ (for lower Re numbers). This was also observed in the flatness analysis done on the hotwire data, according to which the influence of the outer non-turbulent layer starts to come in after the height $Z/Z_T \sim 1$. For Re_1 and Re_2 , the probability density peaks are very close to each other. For Re_3 , the interface location seems to be centered around $Z/Z_T \sim 1.5$.

In the above plots, we can observe that the peaks of the distribution are close to each other at $x/b \sim 77$ but are slightly away from each other at $x/b \sim 73$ and 81 . The trends of the PDFs suggests that the TNTI location remains more or less the same irrespective of the streamwise location.

The TNTI is quite patchy for few fields as the one depicted here.. The homogeneity field depends on the variations in the velocity field. The poor resolution of the cameras used in this experiment may lead to wrong estimates of homogeneity. This is evident in the TNTI we obtained from this criterion. The TNTI is still patchy and discontinuous like the one in the vorticity field.

This covers all the criteria that we have used to obtain TNTI. The method used to apply the threshold for a particular criterion is subjective, and it is highly sensitive to the conditions under which the experiment is performed, the flow setup, effects from any secondary flows

and so on. We have tried to minimize this subjectivity by taking proper averages and normalizations in order to scale the quantities properly. This exercise still does not make the threshold independent of the criterion that is being used. This problem can be resolved if we can get an estimate for the real location of the TNTI before performing the experiments. This requires more than the insights we get from doing the flatness analysis or looking at the turbulent intensity plots.

Chapter 5

Conclusion

This chapter gives a brief summary of the result obtained from the experiments, proposes a few modifications in the setup and the hardware used and gives a brief outlook on the future of the project.

5.1 Summary of Essential Results

Chauhan's TKE criterion has given us the most promising results. The average interface height comes ranges from $Z/Z_T \sim 1.5$ to 1.85 , which translates to a physical height of nearly 85 mm to 107 mm from the wall. This result seems to be an overestimation. The reason is that the turbulent intensity peaks for all three Reynolds numbers were around $0.6 Z_T$. This means the maximum turbulent activity is happening at that location. The height of the interface that we have obtained is much higher than $0.6 Z_T$, as pointed out in the previous chapter. The subjectivity in calibrating the threshold value for this criterion might have some role in this overestimation. The method used for setting the threshold depends on the interpretation of the quiescent region. If we start the region lower than where we have currently taken it to be, we might see different results.

Another interesting fact we observed from the probability distributions of TNTI heights obtained from this criterion is that the probability distribution curves do not have a smooth shape. It seems that a much larger amount of data set is needed in order for the mean of the distribution to saturate. The work presented here only works with 8700 images due to limitations on the onboard storage of the camera.

The vorticity criterion provides insight into the necessity of higher spatial resolution while doing PIV experiments. High-resolution cameras are especially needed when working with a criterion that depends on spatial gradients or is dependent on the small scales of the flow.

The homogeneity criterion also faces the same issue of overestimation, just like the kinetic energy criterion as well as the problem of poor resolution. This is evident in the TNTI fields observed for this criterion and the probability distribution curves.

5.2 Future Work

The solution proposed for the variability in setting the threshold value is a modified imaging experiment on the fields. The experiment will be done on a non-seeded jet with a seeded room. As a result, the wall jet will have no seeding particles and hence will not be “seen” by the cameras. The outer part, on the other hand, will be captured by the cameras due to the presence of the seeding particles. These images will clearly show an interface which will be marked by the layer which separates the seeded region from the black non-seeded region. This layer should be the TNTI. The images captured will be used to make a probability distribution for the interface height. This probability distribution will then be used to set the proper threshold parameters for the different criteria. The PDF of the interface height produced by a range of threshold values will be compared to this “true” PDF of the interface height. The threshold value at which the two PDFs are a close match will be used. The method has not been used in any literature. It seems a good way of setting the threshold values since it makes the process of setting the threshold value of a criterion independent of the criterion itself.

As discussed in Chapter 4, the TKE is influenced by the larger scales of the turbulent flows, whereas the vorticity is influenced by the finer scales present in the flows. The future goal of the project is to find a way to combine the two methods of detecting the interface. This will allow us to capture the larger and the finer details of the interface at the same time.

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