Chapter 1: Introduction

1.1 Motivation

Turbulent flows exist in nature, and many engineering applications encountered in our daily life, such as water streams in rivers, the motion of the air in the earth atmosphere, blood in our veins, and fluids in pipes ... etc. Turbulence is the most complicated and challenging form of fluid motions. For that, Tennekes and Lumley 1972 defined turbulence as a comprehensive description instead of giving a precise definition with the main characterisation represented in; Large Reynolds number, diffusivity, desperation at small scales, three-dimensional vorticity fluctuations, and irregularity. In the study of turbulence, devising methods to separate the complex turbulent motions into simplified events called (coherent structures) has been a challenging task. However, by increasing the Reynolds number, the separation in scales increases and analysing spatially and temporally. In wall-bounded turbulent flows, a grasped the attention for intensive research based on experimental and numerical analysis had been proceeded to understand the mechanism of coherent structures. Investigation of coherent structures in turbulent boundary layers has caught great experimental and numerical interest in the last decades, as they are known to play a significant role in the production of turbulent kinetic energy (Ganapathisubramani et al. 2005 and Vallikivi et al. 2015). In spite of the occurrence and length of these structures that have been documented, the relationship between these coherent structures and the energy spectrum has not yet been fully resolved (Srinath 2017) .

Although, researchers start to implement direct numerical simulation (DNS) due to its known advantages, such as resolving all relevant turbulent length and time scales. Nevertheless, its computational power is incapable of investigating at high Reynolds numbers and complex geometries. A recent effort was done to implement a new numerical technique, so-called characteristic dynamic mode decomposition (CDMD). It was performed to approximate the coherent structures head vortex as dynamic modes in space and time (Sesterhenn and Shahirpour 2019).

In the foreseeable future, direct numerical simulation is still far beyond the needs of the investigations and limited to very low Reynolds numbers and simple shapes. For that, direct numerical simulation is not a realistic possibility in most cases compared to the experimental investigation, and in any event, simulation by itself does not substitute the need for experimental investigations.

In addition, due to the lack of sufficiently high Reynolds number data and large test facilities, understanding of wall turbulence through experimental investigations are sparse. However, the length of large-scale structures up to 14 δ in external flow (Kim and Adrian 1999; Hutchins and Marusic 2007a; Lee and Sung 2013) and needs a large field of view and high spatial resolution. SuperPipe in Princeton University and Center for International Cooperation in Long Pipe test facility (CICLoPE) in Bolognia University are the most popular large test facilities used to investigate turbulent pipe flow structures. In the Aerodynamics and Fluid mechanics department, Cottbus Large Pipe test facility (CoLaPipe) was built to improve the understanding of turbulent flow by performing the characterisation of the flow (Drag, flow structures, boundary layers, ...etc.).

1.1.1 How is the High Reynolds Number Differ from the Low Reynolds Number?

Most of the previous experimental investigations in the wall turbulence field have been performed at low and moderate Reynolds numbers. This range of Reynolds number was preferred as it provides a physically thick viscous layer at the near-wall region. In addition, researchers were driven by the fact that the peak kinetic energy occurs at the viscous buffer region where $y+ \approx 12$. This fact occurs at a low Reynolds number where the major contribution to bulk production occurs at the near-wall region. However, the major contribution to the turbulence at high Reynolds numbers produced at the logarithmic region appears in fig.(1.1) as the logarithmic region dominates at sufficiently high Reynolds numbers. It was reported that the contribution of the bulk production to the logarithmic region was equal to the near-wall region at $y^+ \leq 30$ at $Re_\tau = 4200$ (Smits et al. 2011).

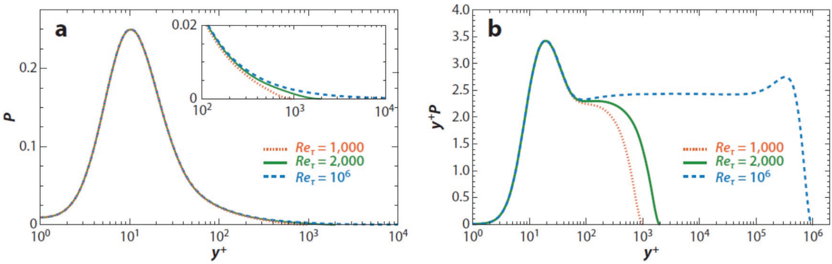


Figure 1.1: Turbulence kinetic energy production for a range of Reynolds numbers: (a) Semi-logarithmic representation and (b) Pre-multiplied representation (where equal areas represent equal contributions to the total production). Adopted from Marusic et al. 2010.

Furthermore, experimental investigations show that in pipe flow, the logarithmic region starts for $y^+ \leq 600$ (Zagarola and Smits 1998). However, they mentioned that the logarithmic variation was observed at $Re_\tau > 50000$. Normally, the classical estimation was known for the logarithmic region for wall-normal range 30 $\nu/u_\tau <$ y $< 0.15\delta$ need only Re_τ= 2000. Similar behaviour was reported in the boundary layer but at higher friction Reynolds number $Re_\tau = 13300$ (Nagib et al. 2007; Sreenivasan and Sahay 1997). Another advantage of the high Reynolds numbers experimental investigation was reported by Hutchins and Marusic 2007a,b. They investigate the stream-wise velocity spectrogram in the boundary layer flow at low and relative high Reynolds number. As depicted in fig.(1.2), they clearly observe the two distinct peaks in the stream-wise velocity pre-multiplied spectra at higher Reynolds number as the very large scale peak was hard to distinguish at the low Reynolds numbers. Hutchins and Marusic 2007b proposed that the spectral peaks need $Re_\tau > 4000$ is required to ensure the occurrence of the scale separation of high Reynolds number turbulence.

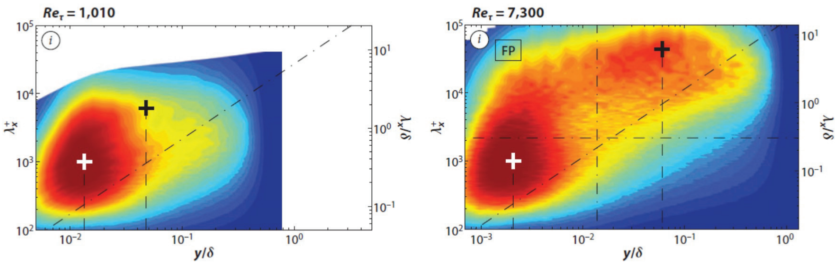


Figure 1.2: Contour maps showing the variation of one-dimensional pre-multiplied spectra with wall-normal position for two Reynolds numbers. An inner and an outer peak are noted at the higher Reynolds number. Adopted from Hutchins and Marusic 2007a.

Turbulent coherent structures, large scale motions (LSMs) and very large scale motions (VLSMs), are studied inside the first phase of the Schwerpunktprogramme (SPP) at the aerodynamics and fluid mechanics department of Brandenburg University of Technology (BTU) experimentally in turbulent pipe flow at high Reynolds numbers using hot-wire anemometry measurement technique. This program SPP-1881 was funded by Deutsche Forschungsgemeinschaft (DFG). The results of the SPP first phase are reported, such as one-dimensional spectral analysis conducted in CICoLPE (Öngüner et al. 2017a) and CoLaPipe (Zanoun et al. 2017) test facilities at low and high Reynolds numbers. Preliminary PIV measurement (100 snapshots) at CoLaPipe was used in applying auto-correlation analysis (Öngüner et al. 2017b). In addition, Zanoun et al. 2019 examined the direct and indirect measurement techniques for measuring the Reynolds stress tensor in low and high Reynolds numbers.

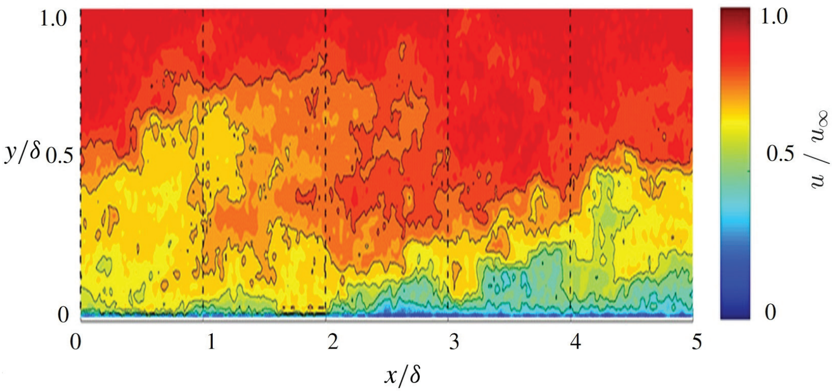
The objective of the second phase is to characterize further, experimentally and numerically, the large-scale turbulent structures (LSMs and VLSMs) in turbulent pipe flow at low and high Reynolds numbers. In support of the SPP second phase, the present dissertation is focused on studying the coherent structures in logarithmic and outer region experimentally at relatively high Reynolds numbers. The experiments are carried out by using high-speed PIV and HWA at high spatial and temporal resolution. The main aim of this thesis is to represent the answers to the following questions:

- Does the length scale value of large scale motions and very large scale motions provide a significant change by increasing Reynolds number?

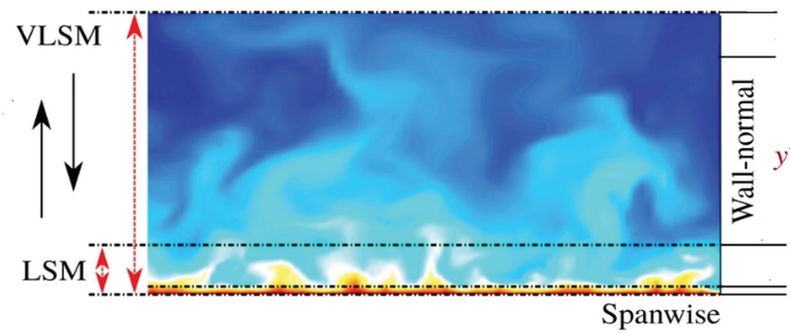
- To which extend does the wavelength of large and very large scale motions persists in the pipe flow?
- How LSMs and VLSMs contribute to stream-wise turbulent kinetic energy and Reynolds shear stress at high Reynolds numbers in pipe flow?
- What is the contribution of large scale structures in the first proper orthogonal decomposition (POD) mode?

1.1.2 Turbulent Structures

Turbulent flows are known by the characteristic recurrent forms of structural packets. These structured packets are collectively known as coherent structures (Holmes et al. 2012). Coherent structures in canonical wall-bounded turbulent flows are commonly used to interpret and understand turbulent physics (Theodorsen 1952; Robinson 1991; Jiménez and Moin 1991; Adrian et al. 2000). Many of the structures that have been identified have been common among the three canonical wall-bounded flows (boundary layers, channels, and pipes) as shown in fig.(1.3). It is observed from studies that these structures are energetically dominant in many flows (Perry and Marusic 1995; Marusic et al. 2010; Monty et al. 2009; Mckeon 2017). Turbulent structures and their contribution to turbulent statistics came to prominence decades ago (Adrian 2007). The bulk motions of large-scale structures with stream-wise extent $\sim$ o(R), where R is the pipe radius, can be divided into large and very-large-scale motions (LSMs and VLSMs) (Adrian et al. 2000; Kim and Adrian 1999). The large-scale motions (LSMs) are recognised to be created by the vortex packets formed when multiple hairpin structures travel at the same convective velocity as shown in fig.(1.4) (Kim and Adrian 1999; Zhou et al. 1999; Guala et al. 2006; Balakumar and Adrian 2007). LSMs have characteristic features representing in the hairpin vortices within the packet align in the stream-wise direction and induce regions of low stream-wise momentum between their legs (Brown and Thomas 1977; Adrain et al. 2000; Ganapathisubramani et al. 2003; Tomkins and Adrian 2003; Hutchins et al. 2005). Its length scale is demonstrated to be common of approximately 2-3R for pipe and boundary layer in stream-wise direction. On the other side, a structural element of wall-bounded turbulent flow that has recently received attention is the ”regime of very long meandering positive and negative stream-wise velocity fluctuations” (Hutchins and Marusic 2007a). These structures are defined as superstructures but are also commonly known as very large-scale motions (VLSMs) in internal flows (e.g. pipes and channels) and superstructures in external flow (e.g. boundary layers).



(a) Instantaneous stream-wise flow field for boundary layer. (Saxton and Mckeon 2017)



(b) Stream-wise velocity contour in the cross-stream plane of R^+=550 open channel flow. (Wang and Richter 2019)

Figure 1.3: Flow Structures in turbulent boundary layers.

The characteristic features of VLSMs are relatively similar to LSMs, only being larger in size and length scale. They are known to carry over 20 δ in stream-wise direction through turbulent boundary layer flow. As well as, these features are also found in pipe and channel flow with wavelength of 10-20 R (Kim and Adrian 1999; Monty et al. 2007). Throughout a simulation study done by Lee and Sung 2013 on a pipe and boundary layer to directly compare the characterisation of VLSMs in both flows, it is indicated that VLSMs in pipe flow were generally much longer (up to 30 δ than in boundary layer).

They explained this to the entrainment occurring in the external flow, causing a more frequent break down stream-wise coherence, thence limiting the length of the VLSMs (Dennis 2015).

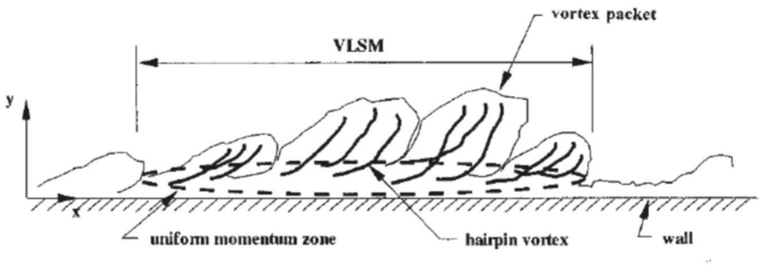


Figure 1.4: Conceptual model which describes the alignment of hairpins coherently into a package to form VLSM. (Kim and Adrian 1999)

Balakumar and Adrian 2007 provide the first evidence of VLSMs by using energy spectral analysis of pipe, channel, and boundary layers. Hutchins and Marusic 2007a demonstrated from the one-dimensional pre-multiplied energy spectra of the stream-wise velocity fluctuations that the contribution of the VLSMs to these fluctuations is Reynolds number dependence. Regions of high- momentum fluid have been observed in the logarithmic and wake regions of wall flows, and these regions are assigned to the VLSMs (Kim and Adrian 1999; Guala et al. 2006). Although the very large scale motions are found to be persisted well into the outer layer in the internal geometries (Bailey and Smits 2010), Further research on very large scale motions has discovered their influence on the near-wall small structures (Hutchins and Marusic 2007b; Abe et al. 2004).

As well, Mathis et al . 2009 and simulation results of Schlatter et al. 2009, mentioned evidence that the fluctuations of large scales in the log region are responsible for enhancing the amplitudes of small scales near the wall. This amplitude modulation was observed to increase with increasing Reynolds number over the Reynolds number range $Re_\tau \approx 10^3 - 10^6$. This relation considered LSMs and VLSMs as the most active and energetic structures that significantly contributed to turbulent kinetic energy and Reynolds stress production (Guala et al . 2006; Balakumar and Adrian 2007). However, they found that large structures greater than 3R contribute with 40-65 % of total kinetic energy and 30-50% of Reynolds shear stress. It is worth knowing that the Reynolds number plays an important role in detecting the region of energy production in-wall turbulent layers. This clarification was explained by Smits et al. 2011, who indicated from spectral analysis, low Reynolds numbers justified by the fact that the high kinetic energy occurs within the viscous buffer layer at a wall-normal distance of approximately y^+ $(yu_\tau/\nu) = 12$, while at high Reynolds numbers, the major contribution to the bulk turbulence production comes from the logarithmic region.

Furthermore, Bailey and Smits 2010 suggested that in the outer layer (beyond the logarithmic region), the hairpin packets comprise detached eddies, which have little correlation with flow near the wall, and this occurs across a wide range of azimuthal scales. On the other side, within the logarithmic region, it appears that hairpins are likely to be attached to the wall. Based on that, Bailey and Smits classified the LSMs into two classes; near-wall attached LSMs and outer-layer detached LSMs (beyond log region). Such classification recognised VLSMs to be only created due to detached LSMs aligning in the outer layer. This aligning is considered if the stream-wise alignment of LSMs causes the VLSMs. Whereas the attached LSMs appear to carry smaller transverse length-scale and smaller convective velocity in comparison with features of very large scale motions. Hence attached LSMs are unlikely to be involved in the formation of VLSMs.

Understanding the behaviour of coherent structures, including large and very large scale motions, particularly at relatively high Reynolds numbers, still attracts considerable attention due to its importance in practical applications.

1.1.3 Pipe Flow Boundary Layers

The fully developed turbulent flow in a pipe is proposed by Tennekes 1968; Afzal and Yajnik 1973; Afzal 1976 to be consisting of three main layers: outer, intermediate, and inner layers. In the terminology of classical theory, the inner layer includes the viscous sub-layer and the buffer layer. The intermediate layer encompasses the buffer region, logarithmic region, and the transition domain between the two regions. Furthermore, the outer layer contains the log region and wake region. It has been long recognised that the viscous sub-layer is at a distance from a wall $y^+=$ y $u_\tau/\nu < 30$, where u_τ is the friction velocity, y is the wall-normal location, and ν is the kinematic viscosity.

The viscous sub-layers contain a buffer layer 3< y^+<30 and a linear sub-layer near the wall y^+<3. In the buffer layer, the Reynolds and viscous stress act directly on the mean flow, while in the linear sub-layer, the viscous stresses are dominant. Lately, the definition of turbulent flow layers has indicated an additional so-called overlap region. This region consists of an inertial sub-layer (y^+ >300) where the flow is nearly inviscid and a mesolayer (30<y^+<300) in which viscous stresses are neglectable.

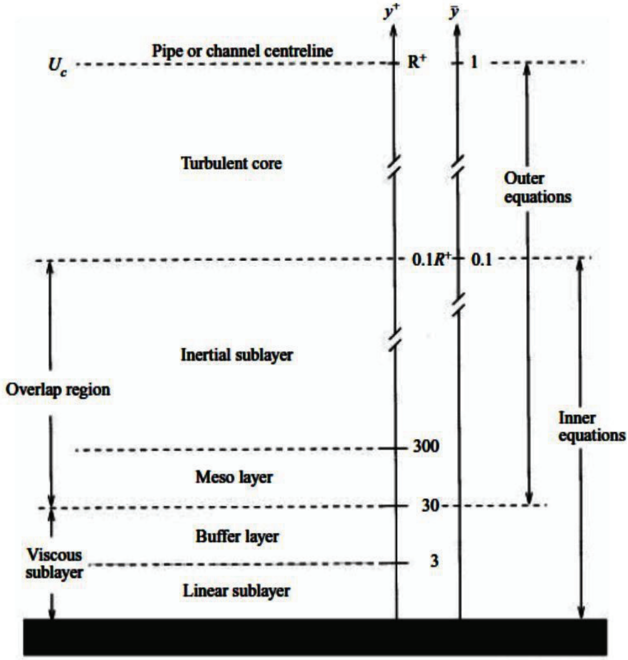


Figure 1.5: Schematic sketch of various regions and layers of pipe and channel flows, adopted from Wosnik et al. 2000.

Fig.(1.5) shows a schematic of various regions and layers of pipe flow. At very low turbulence Reynolds numbers, the near-wall region is considerably more interesting. However, the energy-containing eddies are constrained by the proximity of the wall. In this region, the dissipative and energy-containing ranges nearly overlap. The latter produces the Reynolds shear stress and feels the influence of viscosity directly. Here, the energy and dissipative scales are about the same. So, the dissipation ϵ is more reasonably estimated by $\epsilon \approx \nu q^2/\mathbf{j}^2$. Where, $\mathbf{j} \approx$ R/2 and q $\approx 3u_\tau$. Furthermore, for high Reynolds numbers $Re_\tau > 5000$, the energy dissipation is mostly determined by the large energetic scales of motions. These scales are effectively inviscid but control the energy transfer through the non-linear interactions (the energy cascades) to much smaller viscous scales where the actual dissipation occurs (Tennekes and Lumley 1972).

At the bottom of the overlap region, there will always be a mesolayer below about $y^+ \approx 300$, the dissipation and as well the Reynolds stress can never become independent of viscosity. The overlap layer is known as the averaged equations for the mean flow and Reynolds stresses from $y^+ > 30$ to the flow centreline, the averaged momentum equation is given approximately by :

$$0 = \frac{-1}{\rho}\frac{dp}{dx} + \frac{\partial(-uv)}{\partial y} \tag{1.1}$$

The Reynolds shear stress declines linearly to the center of the flow (Perry and Abell 1975), to become nearly constant outside y^+ =30. The pressure gradient vanishes in the constant Reynolds shear stress region at infinite Reynolds numbers. So the mean momentum equation reduces to :

$$0 = \frac{\partial(-uv)}{\partial y} \tag{1.2}$$

From both inner and outer momentum equations, the Reynolds shear stress gradient appears to be the common term in the overlap region that corresponds to this constant Reynolds shear stress layer (Wosnik et al. 2000). The Reynolds stress is effectively constant at finite large Reynolds numbers. At low Reynolds numbers, experiments do not have a region with constant Reynolds stress because the pressure gradient term is not truly neglectable. Although, it is observed that the viscous diffusion term is neglectable in the mean momentum equation, whereas viscosity does not appear directly in any of the single point equation governing the overlap region nor on those governing the outer layer.

1.2 Theoretical Background

To understand the experimental results of conical flows, i.e. turbulent channel and pipe flows, fundamental equations are needed to describe this phenomenon in a mathematical way.