1 Preamble

1.1 Introduction

Flow through a circular cross section is one of the simplest experiments, which can be investigated under laboratory conditions. Nevertheless, pipe flow is one of the most challenging ones due to its complexity and versatile applications. This and the fact that there are still a lot of open questions on this topic motivates the recent work, which has a special focus on high Reynolds number pipe flow.
This thesis deals with two main parts, where one is the basis for the other. The first part covers the conceptual design and setup of a new pipe test facility named CoLaPipe, which is discussed in detail in Chapter 4. The given name of the wind tunnel is derived from ***Co****ttbus* ***La****rge* ***Pipe***. In this case, conceptual design means the description of the overall design study as well as the presentation of every mounted part listed in the following Table 1.1:

Table 1.1: List of all elementary parts of the CoLaPipe.

Chapter	Name of Part	Characteristic	Remarks
4.1	pipe test section	large length-to-diameter ratio	smooth-walled
4.2	settling chamber	/	circular cross section with screens
4.2.1	inlet contraction	numerical validation	polynomial curvature
4.2.2	cooling system	/	purchased part
4.3	blower unit	radial blower	combined module (blower, motor and frequency converter)

An emphasis is placed on the high accuracy assembly of the designed and manufactured parts to minimize inaccuracies, and to enable comparable experimental results supporting fluid mechanics community. The utilized measurement techniques, instrumentation and even the error quantification is presented within Chapter 5.
The second main part of this thesis is discussed in Chapter 6. It covers broad investigations on pipe flow under different boundary conditions. A useful separation between the presented results is 1.) first data sets to put the facility into service and 2.) continuative measurements to answer some of the still open questions. A selection is listed in the following:

1. Accurate positioning of the HWA measurement probe.

2. Exact estimation of the wall friction velocity.

3. Definition and prediction of turbulent flow state.

4. Influence of natural and artificial transition on development of turbulence.

5. Characteristic behavior of mean and fluctuating velocity profile.

6. Scaling behavior of mean and fluctuating velocity at high Reynolds numbers.

The whole work is accompanied by a detailed review on the existing literature (Chapter 2). Here, the focus is not only on high Reynolds number pipe flow. But also on low and moderate Reynolds numbers representing different characteristics, which account for different interests to scientists and engineers. A brief summary of the underlying theory and mathematical background is also presented through Chapter 3.
In conclusion, it can be assert, that the CoLaPipe is a well-working pipe test facility. Therewith it is possible to investigate fully developed turbulence in a circular shaped facility under different boundary conditions at high Reynolds numbers. The results, presented in Chapter 6, demonstrate the high quality and even shed light on some highly debated points. For example, the scaling behavior of the mean flow velocity within the logarithmic layer is found to be not universal. This can be an artifact due to Reynolds numbers inconsistencies. Nevertheless, there are still some open questions, which can be ordinary answered during the future operation of the test facility. One of the most important open questions is the idea behind the structural behavior of high Reynolds number pipe flow with respect to large- and very large-scale motions. Here, only initial numerical and experimental results exist but are not sufficient and satisfying enough [6, 8, 87].

1.2 Motivation

Flows of any kind come along with the humans in every common situation. This can be for example the strong flowing air between houses, which makes it sometimes difficult to walk further on; or it can be the simple flowing system within every peoples bath - the water-tap. Also the weather forecast would not be that sufficient if the scientists behind it have had no or pure knowledge about the flows in the oceans and clouds. Even the flow in piping system for energy supply, e.g. cold and hot water and air, are flow systems, which are common and transport the medium through circular shaped tubes. The flow geometry behind is a pipe, which is on one side simple and on the other challenging. Also in larger dimensions pipe flow is the preferred system to transport fluids of any kind. Here, the transportation process of oil and gas over more than thousand kilometers, as in the *Druschba pipeline*, which is the connection from east Russia to Germany, is no curiosity. Hence, it is not particular that pipe flow acts as a well known model for shear flow and its instabilities, due to the importance in technical applications for more than 120 years. In addition to the aforementioned applications pipe flow phenomena are also present in automotive engineering and air conditioning technology, and hence a detailed knowledge on it is important for this kind of industry.
The pioneering work of Reynolds [85] is the beginning of an outstanding interest on the knowledge of the dynamics within pipe flow. Several researchers inspired by him pick up his discoveries, like Nikuradse [74] and Laufer [57], who are only a selection, and extend the overall background on fluid mechanics in particular pipe flow. Nevertheless it persists until now the necessity to investigate this kind of wall-bounded flow because of the immense practical relevance, which is still increasing due to more and more complex systems, e.g. to solve economic and environmental requirements, especially in the case of high Reynolds number turbulence as well as the qualitative physical understanding of the transition process. To get as close as possible to the answers of all the open questions different test facilities with circular cross section exist or are planned (refer to Table 1.2).
Table 1.2 lists physical dimensions of test facilities, where Re_m is the bulk-based Reynolds number, L/D is the length-to-diameter ratio and D_i is the inner diameter of the test section. In all cases air under ambient conditions is used as working fluid except in the Princeton SuperPipe, where additionally pressurized air is applied to the system to reach the maximum laboratory Reynolds number.
The non-dimensional factor L/D is very important evaluating facilities with respect to the full development of turbulence. Patel and Head [78] as well as Zanoun et al. [116] claim a minimum developing length of about 70 D. With this consideration all presented facilities in Table 1.2 provide the basis for intensive investigations on fully developed

Table 1.2: Overview of present and planned pipe test facilities contributing to high Reynolds number turbulence in pipe flow.

	Re_m	L/D	D_i	working fluid
CICLoPE (Forlí)	$4.0 \times 10^4 - 2.0 \times 10^6$	100	0.90 m	air
CoLaPipe (Cottbus)	$4.0 \times 10^4 - 1.5 \times 10^6$	148	0.19 m	air
CoLaPipe (return line)	$2.3 \times 10^4 - 6.0 \times 10^5$	79	0.342 m	air
Zanoun et al. [116]	$3.0 \times 10^4 - 1.0 \times 10^5$	187.5	0.032 m	air
SuperPipe (Princeton)	$3.0 \times 10^4 - 3.5 \times 10^7$	200	0.129 m	air

turbulent pipe flow. Even the transition process from laminar to turbulent without triggering the flow artificially - natural transition - can be investigated using the presented facilities.

In addition to Table 1.2 Figure 1.1 is depicted, which is in a similar way shown in Talamelli et al. [96], to give an access to the facilities turbulence resolution. Even the main difference and limitations of the pipe experiments are demonstrated. Figure 1.1 represents ranges of capabilities of various pipe facilities in terms of the wall turbulence length scale, $l^* = \nu/u_\tau$, as a function of the Kármán number ($R^+ = u_\tau R/\nu$), where u_τ is the wall friction velocity, R is the pipe radius and ν is the kinematic viscosity.

The figure points out the spatial resolution limitations ($0.3 \leq l^* \leq 25$) of the Princeton SuperPipe in spite of the large achievable Reynolds number range, see also Talamelli et al. [96]. This is also marked by the green dashed line, which characterizes the minimum sufficient spatial resolution when using the common HWA measurement technique. Compared to the SuperPipe the other two presented facilities, i.e. CoLaPipe and CICLoPE, provide an adequate spatial resolution within the range of $10 \leq l^* \leq 100$. Especially the CoLaPipe allows measurements with high spatial resolution ($100 \leq l^* \leq 300$) utilizing the return line for a Kármán number range of $500 \leq R^+ \leq 2000$. The return line has an inner diameter of 340 mm that permits also enough separation between the inner and outer scales to study the desired characteristics of turbulence. Even labeled within Figure 1.1 are some important values concerning numerical procedures to support the ongoing discussion in the field of pipe flow turbulence. Here, the brown dashed line represents the actual maximum achievable Reynolds number utilizing DNS obtained by Wu and Moin [106]. But it is a great request among all related researchers either experimentalists or computational scientists to enhance the lower limit beyond $R^+ = 5000$ [44, 106]. This purpose is marked by the blue dashed line. The black dashed line shows the starting point for very high Reynolds number turbulence. And it is obvious from Figure 1.1 that this is hard to realize since the physical laboratory space is limited everywhere. With one exception, CICLoPE will provide access to very high Reynolds number turbulence, but is restricted to the resulting spatial resolution ($10 \leq l_* \leq 60$).

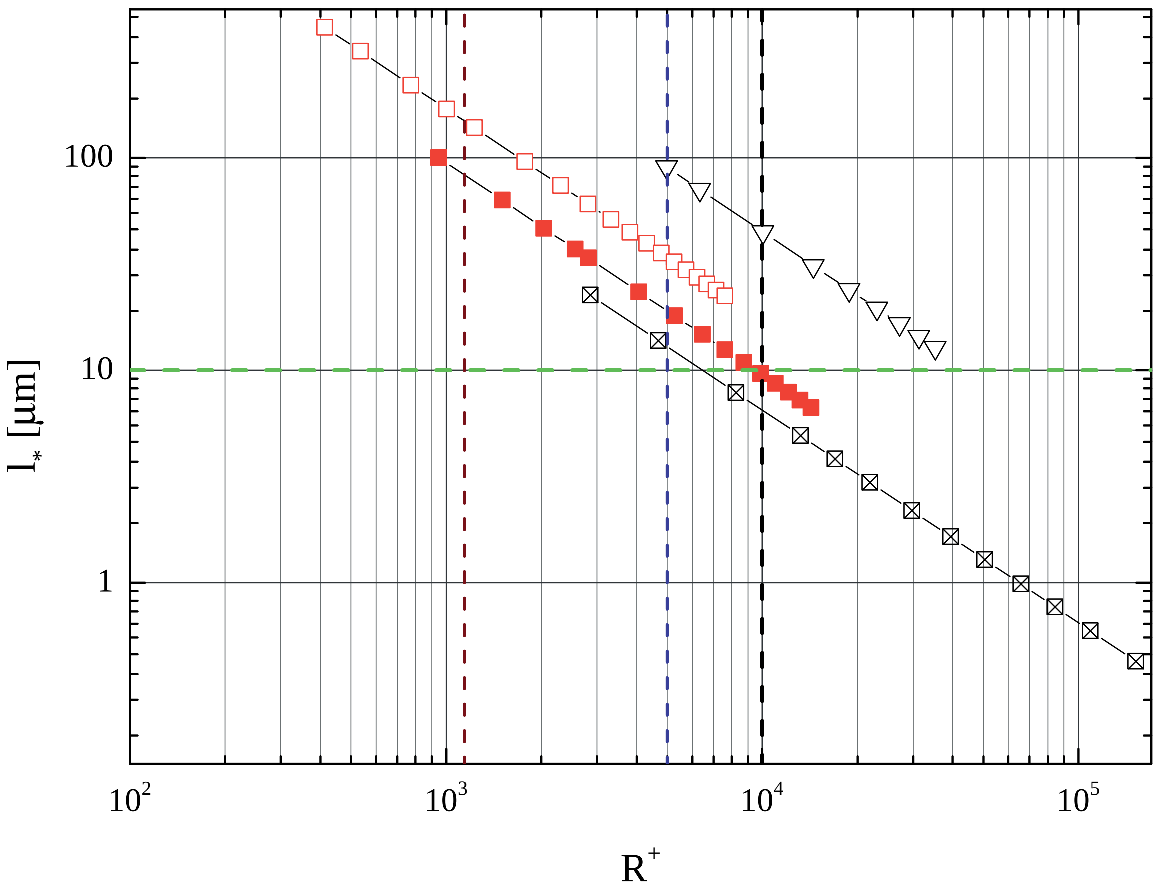

Figure 1.1: Overview of recent pipe test facilities relating the viscous length l^* to the Kármán number R^+. ⊠ Princeton SuperPipe; ■ CoLaPipe; □ CoLaPipe return line; ▽ CICLoPE; – – – minimum for sufficient spatial resolution; – – – highest Reynolds number for DNS, $R^+ = 1142$ [106]; – – – future Reynolds number for DNS; – – – start of very high Reynolds number turbulence

1.3 Preliminary Work

Investigations on pipe flow have a long tradition, and hence detailed results on this topic exist. Nevertheless, in preparation for the setup of the CoLaPipe test facility preliminary results are established using another test facility, which is described in detail elsewhere [116]. These results contain information on the transition behavior and the development length utilizing the evolution of statistical quantities along the pipe axis. The main difference between these preliminary results and the those presented within this thesis is the diverging Reynolds number range. The preliminary work is conducted for moderate Reynolds numbers ($Re \leq 106 \times 10^3$), whereas the CoLaPipe is mainly designed for investigations on high Reynolds numbers turbulence.

The following chapter is about a brief description of the constructive setup of the preliminary used facility and the applied measurement techniques. In conclusion, the main results with the focus on the development length are presented.

1.3.1 Experimental Setup

The laboratory of the Department of Aerodynamics and Fluid Mechanics, BTU Cottbus-Senftenberg, maintains a high quality aero-acoustic test facility. It is an open wind tunnel with a free jet at the exit of the nozzle, i.e. no direct feedback. Air with a maximum velocity of 60 m/s is provided by a radial blower. This configuration, depicted in Figure 1.2, yields a centerline turbulence intensity of less than 0.35 %. To realize the main aim a test section with circular cross section of $D_i = 0.032$ m and a total length of $L = 6$ m is connected to the nozzle exit, referred as to *Pipe test section* in Figure 1.2. This provides a length-to-diameter ratio of $L/D = 187.5$.

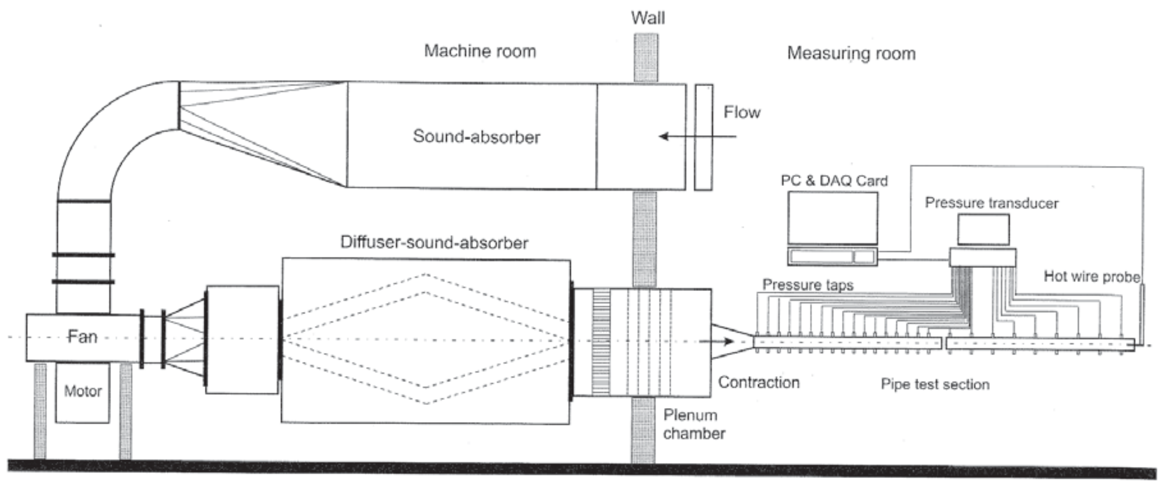

Figure 1.2: Schematic of the aero-acoustic test facility at the laboratory of the Dept. of Aerodynamics and Fluid Mechanics with adapted circular cross section and measurement techniques. From [116].

1.3.2 Measurement Techniques

To indicate the flow field within the pipe test facility different measuring techniques are applied. For information on the velocity, here mean and fluctuating velocity as well as bulk velocity, two independently working systems are installed. One is a LDA system for the wind tunnel calibration and the measurement of U_{bulk}; and the other is a HWA system collecting the mean and fluctuating velocity along the pipe axis. The local mean static pressure is captured through static pressure holes. They are distributed equally spaced along the axis and therewith provide sufficient information on the streamwise pressure gradient. The results of these intensive measurements are presented within the next chapter.

1.3.3 Results

The results obtained by Zanoun et al. [116] highlight several different aspects. Therefor the focus is only on those, which have a direct feedback on the design concept of the CoLaPipe.

The limited laboratory space and the fact, that most of the literature results are inconsistent, like [57, 74, 78, 80] and [108], have motivated the intensive measurement series prior to the completion of the CoLaPipe concept. One main point is the identification of fully developed turbulence under natural transition conditions. For this aim different approaches are available and well known, but no clear criterion could be defined through the years. Hence, the flow field within the pipe is investigated for different initial conditions, e.g. varying Reynolds numbers. At this phase of the measurements the focus is on the evolution of the statistical quantities at the centerline of the test section to detect the transitional regime within the setup. Additionally, the turbulent flow state is identified and gives answers on the necessary length to achieve this flow state. These information obtained from the centerline turbulence statistics are plotted as a function of the dimensionless pipe length x/D[1]. The resulting data are presented in Figure 1.3.

The tendency, which can be extracted from this figure, is that after a development length of nearly $x/D \approx 70$ the turbulent flow state is achieved. This is indicated through the invariant behavior of the statistical quantities, which means that they approach a constant value and persists with increasing x/D. For the design considerations of the CoLaPipe it denotes that at least $x/D = 100$ is required to investigate turbulence under natural conditions. The realization depends on the chosen pipe diameter, which can be a limiting property with respect to the spatial resolution. This relation will be discussed in detail in Chapter 4.

The work of Zanoun et al. [116] supports also the debate on the correct scaling of the mean velocity profiles with the presentation of certain profiles for a sufficient range of R^+. The most important results are presented in Figure 1.4, where the normalized mean

[1]Note, that within numerical results the dimensionless pipe length is defined as x/R.

[2]Remark: The used nomenclature u'_c represents the root-mean-square value of the fluctuating velocity at the centerline of the pipe. Hence, u'_c equals $\sqrt{\overline{u'^2}}$. This is also valid for the used nomenclature $S_c(u')$ as well as $F_c(u')$.

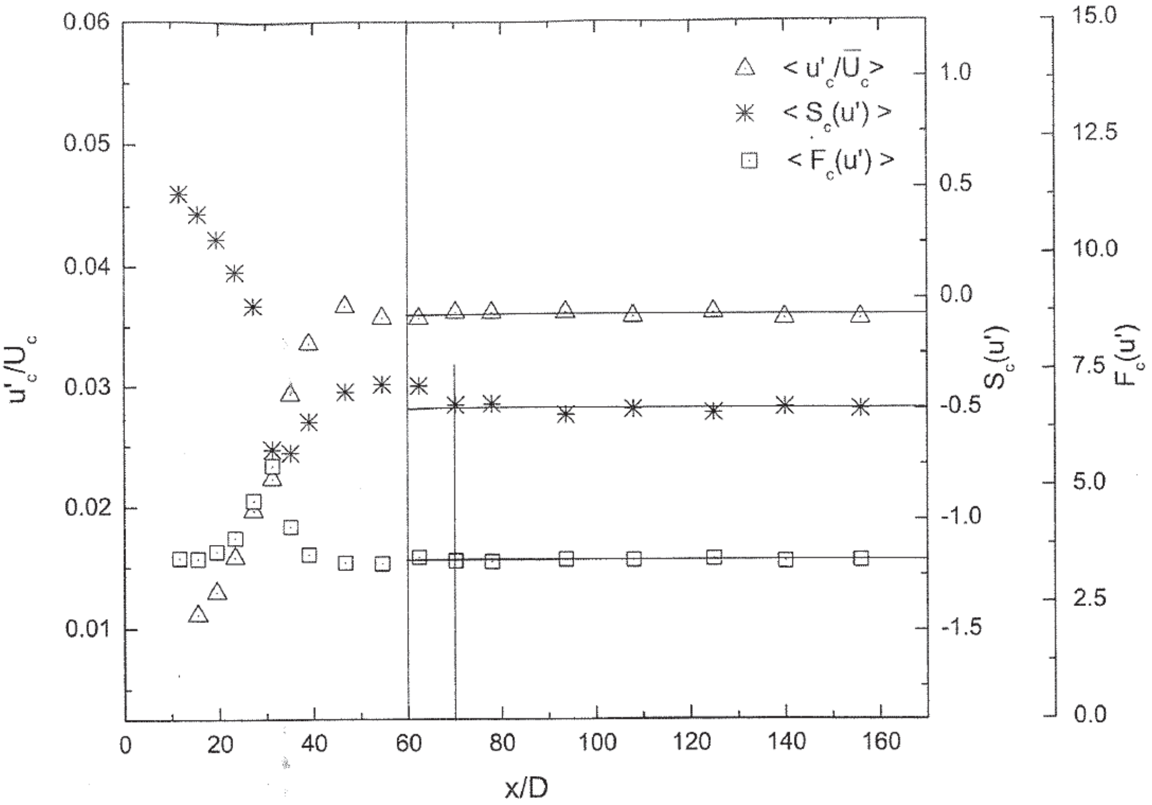

Figure 1.3: Pipe centerline statistics as a function of the normalized pipe length for no tripping[2]. From [116].

velocity is shown as a function of the normalized wall distance scaled on inner variables. The diagram shows, that the curves collapse onto one single curve and yield a good agreement with some literature results in the logarithmic region of the boundary layer. Nevertheless, this figure shows a clear deviation of the mean velocity for $y^+ \geq 150$ - a so called velocity overshoot. It is supposed by the authors that this is a possible effect due to the low Reynolds number range or it can be interpreted as the existence of a local power law. Similar results are obtained by McKeon et al. [66].
For further information one can review the results obtained by [116]. Additionally, Chapter 6 deal with a more precise interpretation of this topic.

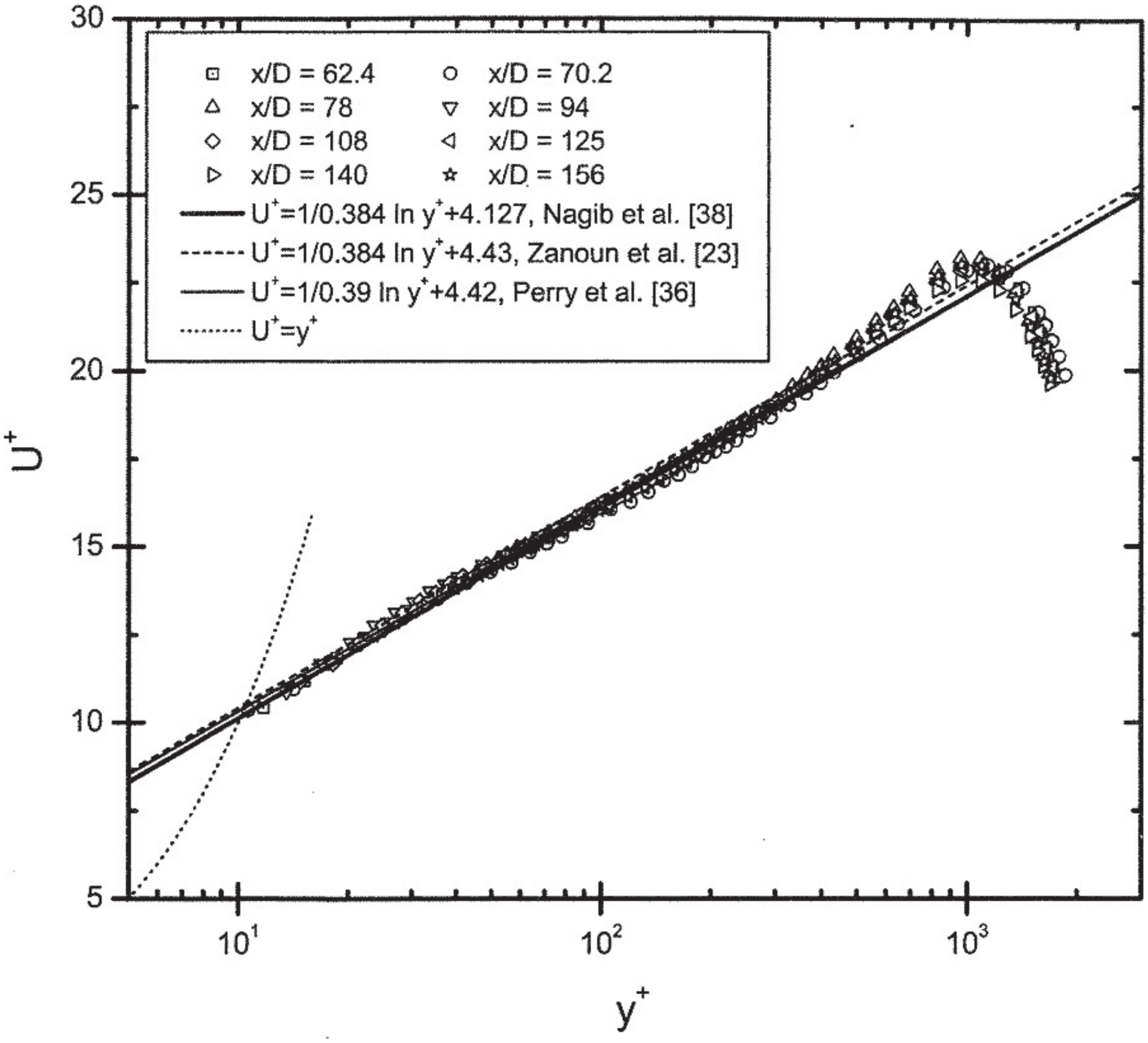

Figure 1.4: Presentation of the inner scaled mean velocity profiles for $1040 \leq R^+ \leq 1140$ and for different literature results. From [116].

2 Literature Review

As mentioned before, pipe flow is one of the most intensively investigated types of wall-bounded flows due to its immense practical relevance, e.g. in automotive and shipping industry. It also seems that pipe flow is of infinite complexity, and is therefor still a highly discussed field in fluid mechanics. The interest on this field of fluid mechanics has a long history starting with the pioneering experiments of Reynolds [85]. His investiga-

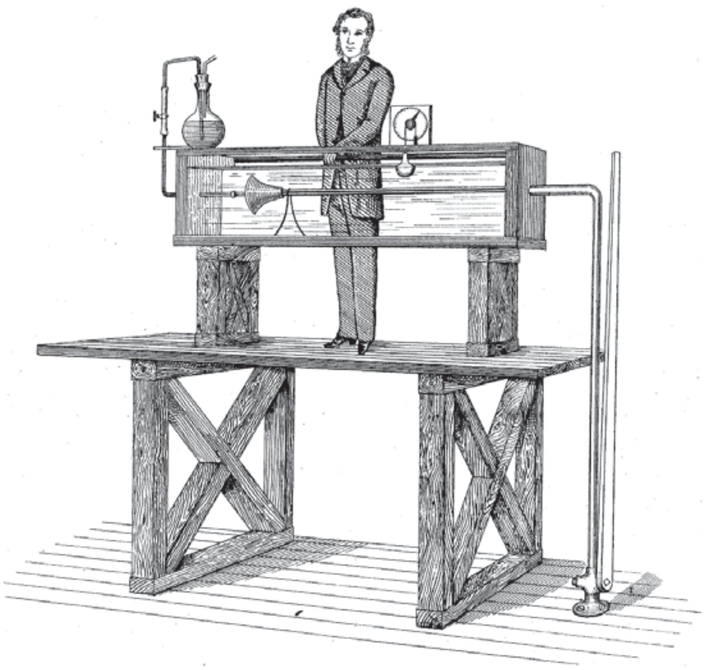

Figure 2.1: Osborne Reynolds' revolutionary experiment. From [85].

tions on fluid motion in glass tubes with water as the working fluid (see Figure 2.1) made it possible to observe "two broadly distinguishable forms - either the element of the fluid follow one another along lines of motion which lead in the most direct manner to their destination, or they eddy about in sinuous paths the most indirect possible " [85]. These fundamental results are obtained investigating the effects of different velocities along tubes visualized using colored water. For sufficiently low velocities Reynolds observed a constant colored streak trough the pipe, which is illustrated in Figure 2.2a. During the increase of the inlet velocity the colored water began to mix up with the surrounding