Experimentelle Untersuchung der turbulenten Rohrstrukturen bei hohen Reynolds Zahlen

Experimental investigation of turbulent pipe structures at high Reynolds numbers

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Summary

At the Department of Aerodynamics and Fluid Mechanics, Brandenburg University of Technology Cottbus-Senftenberg, the unique pipe facility "CoLa-Pipe" (Cottbus Large Pipe) is designed and built to investigate fully developed pipe flow at high Reynolds numbers ($Re_m \leq 1.5 \times 10^6$). The type of this facility is closed-return with two available test sections providing a length-to-diameter ratio of L/D = 148 and L/D = 79 (Figure 1). This paper will give an overview about the CoLa-Pipe by introducing the various components in detail. The application of different measurement techniques such as hot-wire-anemometry (HWA) and static pressure measurements to quantitatively evaluate the mean flow characteristics and turbulence statistics will also be mentioned. Additionally, capabilities and limitations of available and new pipe flow facilities are presented and reconsidered based on their length-to-diameter ratio and the achieved high Reynolds numbers in the previous studies. The main purpose is description of this facility as well as the presentation of some basic characteristics and their influence to some specific questions still arising about turbulent pipe flow.

Introduction

As one of the most significant flows in technical applications, like in automotive engineering, transportation processes of oil, gas and water and air conditioning technology, pipe flow is a common example for shear flows. In the course of time, many scientist and engineers have studied many different parameters about pipe flow. Nevertheless until now the investigation of wall-bounded flow in the case of high Reynolds number turbulence has not been well understood yet. One of the current purposes in this field of study is to identify the physical properties in fully developed turbulent flow.

Considering the dimension L/D, Patel & Head (1969) and Zanoun et. al. (2009) declared a minimum development length of about 70D. In Table 1 a basis about similar facilities is mentioned which can be used to investigate transition and fully developed turbulence.

Facility	***L/D***	***Re_m***	***D_i***
CoLa-Pipe / BTU	148	$4.0\times10^4 - 1.5\times10^6$	0,19 m
Superpipe / Princeton	200	$3.0\times10^4 - 3.5\times10^7$	0,129 m
CICLoPe / Bologna	100	$4.0\times10^4 - 2.0\times10^6$	0,90 m

Table 1: Overview of well-known high Re-number pipe flow facilities

Experimental Facility

The main objective of the CoLa-Pipe as a high Reynolds number test facility is to conduct fundamental research, e.g. a contribution to understanding the physical processes and dynamics of turbulence, as well as for supporting industrial projects. In this chapter all the relevant components described, i.e. test section, settling chamber, inlet contraction, tripping devices, power assembly and cooling unit.

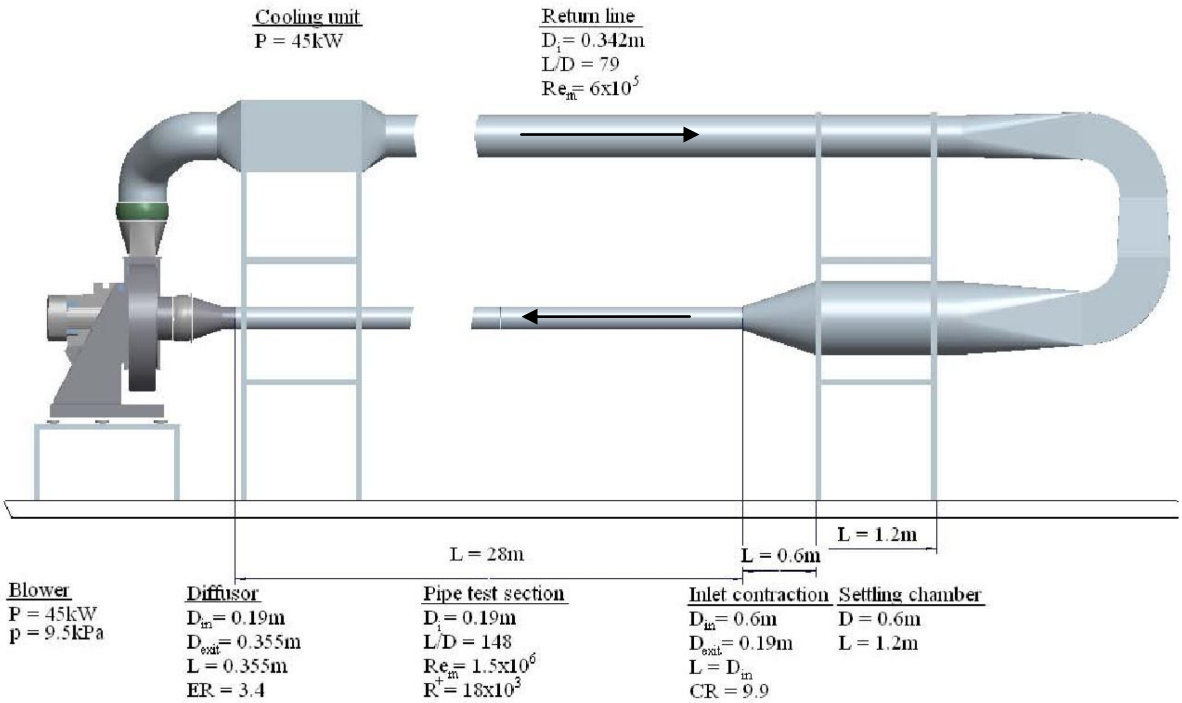
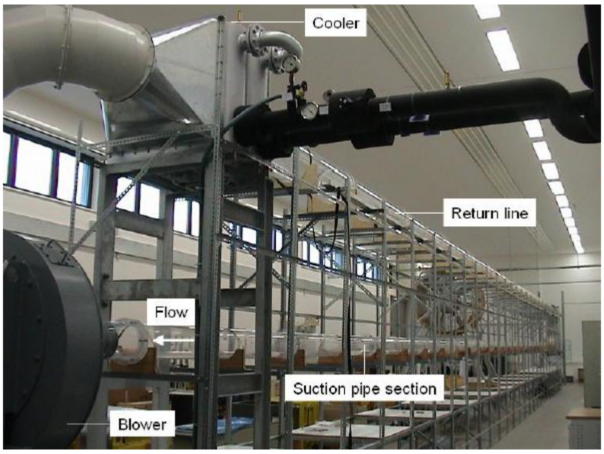


Figure 1: CoLa-Pipe facility at Brandenburg University of Technology (BTU)

Two pipe test sections are available. The lower one is connected to the blower suction side and the other one is mounted at the delivery side of the blower called return line. Both pipe test sections are critical components in the present facility in terms of circularity, degree of surface roughness, straightness, alignment and optical accessibility for special measuring devices such as laser-Doppler anemometry (LDA) and particle image velocimetry (PIV). The inner pipe diameter of the lower side test section is D_i = 190± 0.23mm which has a deviation of less than 0.12%. The total length of the suction side, L = 28m, provides a test section length-to-diameter ratio of $L/D_i \approx 148$. The return line has an inner diameter of $D_i = 342 \pm 0.32$mm and a total length of L = 27m as well, providing a length-to-diameter ratio of $L/Di \approx 79$. Both test sections interior surfaces have a measured surface roughness of approximately 3µm being in terms of wall units 0.6 for the maximum Reynolds number of 1.5×10^6. The height of the centerline of the lower pipe test section is 1.55m from the ground, in order to support an easy access to the test section while the operator is standing on the floor of the laboratory and the height of the upper line is 4.55m from the ground, which definitely requires a working platform (Figure 2, Figure 3)



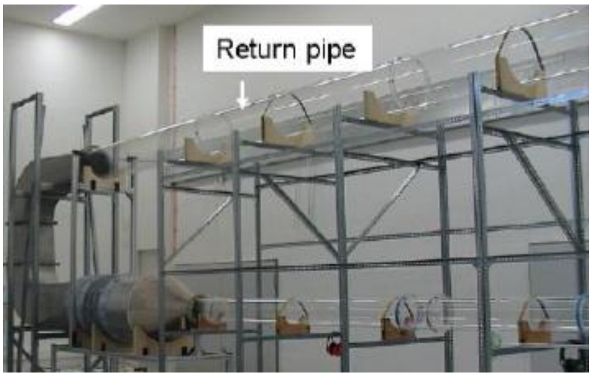
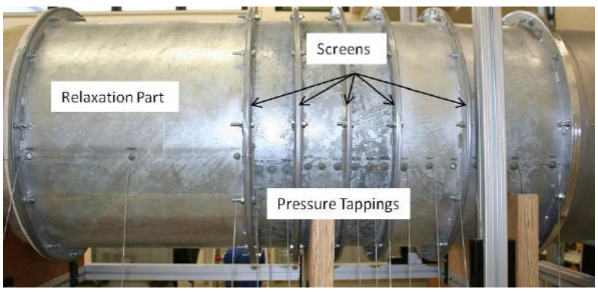


Figure 2: (left) Overview of CoLa-Pipe showing important components
Figure 3: (right) Corners, settling chamber, nozzle and both test sections of CoLa-Pipe

The settling chamber is responsible to eliminate flow disturbances before entering the test section and ensuring the uniformity of the inlet flow with low turbulence intensity (Figure 4). It is carefully designed according basic suggestions by Loehrke & Nagib (1976) and Groth & Johansson (1988) especially regarding the separation distances between the elements.



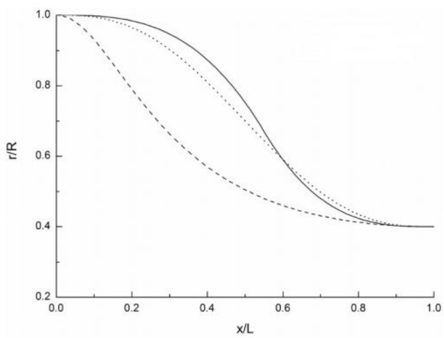


Figure 4: (left) Settling chamber, nozzle and both test sections
Figure 5: (right) Different contraction contours of nozzle (–– two-cubic arcs contour, ··· 5th order polynomial contour, - - - Witoszynski (1924))

The contraction at the inlet of the pipe test section accelerates the flow coming from the settling chamber. Furthermore it reduces variations of the mean axial velocity in the plane of symmetry. The objectives for well-designed contractions are to uniform velocity at the contraction exit with low turbulence intensity level and to provide small exit boundary layer thickness. According to the numerical simulations as well as the literature survey a 5th-order polynomial for the contraction is chosen, having a high area ratio of 9 (Figure 5). The used material for contraction part is glass fiber, which enables high accuracies and a near-net-shape assembly during the production process. Furthermore the inner surface is polished after the production process to guarantee high-quality flow conditions at the exit.

The power unit of CoLa-Pipe facility (Figure 2) is working with a nominal power of 45 kW contains a powerful radial blower connected to the pipe on its suction side, a three-phase motor, and a frequency converter which provides a flow rate of $0.05m^3/s - 2.5m^3/s$ and can be controlled by changing the frequency of the radial blower blades utilizing the frequency converter unit. With these properties and in conjunction with the inner diameter of 0.19m of the lower test section the power assembly provides a maximum velocity of 80 m/s at the contraction exit. The turbulence intensity level at this position is less than 0.5%. Also a heat exchanger (Figure 2) is set up to stabilize the working temperature inside both test sections. The temperature range can be varied between 15°C and 21°C with a maximum deviation of $\Delta T = \pm 0.5K$ at the actual measuring location.

To acquire the data a computer-controlled three-dimensional traverse system (Figure 6) with a spatial resolution of 6.35µm is used. However, this resolution is not fixed due the repeat accuracy of 20µm, which is too high for the smallest step. Figure 7 shows a typical placement of hot-wire-probe which is mainly used to measure mean and fluctuating velocity in the mentioned location.

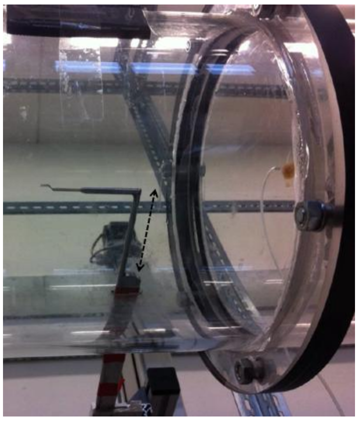


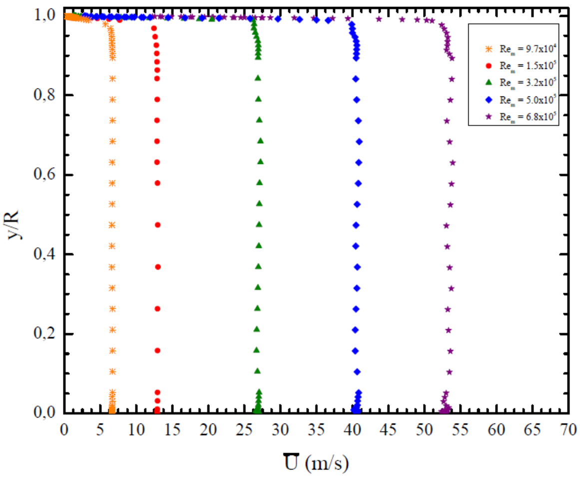
Figure 6: (left) Traverse mechanism able to move in x-, y- and z- directions
Figure 7: (right) Placement of probe and probe support in the test section

Pressure and Velocity Measurements

For pipe flow investigations it is essential to perform static pressure measurements to characterize the flow field and in order to determine the wall friction velocity (defined as: $u_\tau = \sqrt{(\tau_w/\rho)}$, τ_w = wall shear stress, ρ = fluid density). To calculate the pressure gradient pressure tappings are located along the pipe test section. All pressure measurement points are connected to two pressure scanner (PSI 9116 Ethernet Pressure Scanner) provided with sixteen channels for simultaneous pressure readings.

Before running velocity measurements it is required to calibrate the hot-wire-probes against a reference velocity to determine the relationship between the anemometer output voltage and the corresponding physical property. For an accurate calibration an ex-situ calibration procedure is followed which is providing a well-known uniform velocity profile. Using the control unit of the CTA (constant temperature anemometer) it is able to adjust the reference velocities in the desired range within an accuracy of 0.15%, and to determine the calibration curve and the related calibration coefficients. The ambient conditions are monitored during each test run using an electronic barometer and thermometer. All the measuring equipment is connected to an A/D converter board with a 16-bit resolution. In addition, a computer-based programming system is used for acquiring and processing all measurement data.

Flow Characteristics



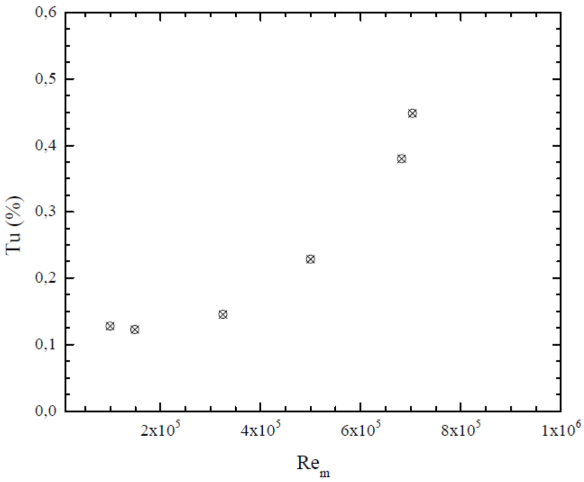


Figure 8: (left) Velocity profiles for various bulk Reynolds numbers
Figure 9: (right) Turbulent intensity level vs. bulk Reynolds number

Considering the design requirements of the CoLa-Pipe we should focus on high-quality results in all fields of interest, especially in turbulence. This implies fully developed turbulent pipe flow and for this reason a developed velocity profile. To approach these aims well defined inlet flow conditions, i.e. a uniform velocity profile with low turbulence intensity level at the exit of the contraction, have to be provided. Figure 8 shows the measured mean velocity profiles presented for a selected Reynolds number range ($Re_m = 0.97-6.8\times10^5$). Represented is the normalized wall normal distance y(R)/R versus the time-averaged mean velocity. Figure 9 depicts the slightly increasing turbulence intensity always less than 0.5%, with respect to the bulk-based Reynolds number Re_m. These plots indicate perfect inlet flow conditions of the introduced high Reynolds numbers pipe facility.

On Figure 10 one mean velocity profile is shown at the lower bound of the feasible Reynolds number range. The viscous sublayer region is able to be resolved in a quite good manner with a sufficient number of data points. However, this distance is strong affected by increasing the Reynolds number due to the decrease in the viscous sublayer thickness. Another important fact is that there exists enough separation between the boundary layers, e.g. the linear and the logarithmic as well as the outer part.

Further details can be obtained by Zimmer et. al. 2013, König et. al. 2013 and König et. al. 2014.

Considering these achievements the current work at Department of Aerodynamics and Fluid Mechanics is to focus on capturing any possible turbulent structures (LSM – Large Scale Motions and VLSM – Very Large Scale Motions) in the range of available high Reynolds numbers.

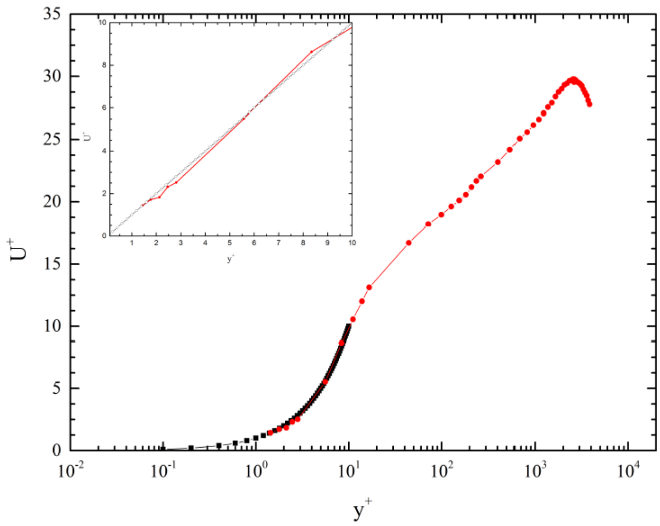


Figure 10: Mean velocity profile U^+ as a function of the normalized wall distance y^+ for $Re = 1.6 \times 10^5$

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References

V. Patel and M. Head, 1969, Journal of Fluid Mechanics 38, 181
E. Zanoun, M. Kito, and C. Egbers, 2009, Journal of Fluids Engineering 131, 10
R. Loehrke and H. Nagib, 1976, Journal of Fluids Engineering 98, 342
J. Groth and A. Johansson, 1988, Journal of Fluid Mechanics 197, 139
F. Zimmer et al., 2011, A Study on the Influence of Triggering Pipe Flow Regarding Mean and Higher Order Statistics, 13. European Turbulence Conference ETC, 12.-15. September, Warsaw, Poland
F. König et al., 2013, The CoLaPipe - A high Reynolds number pipe test facility, 4th International Conference on Jets, Wakes and Separated Flows, Sept.17-21, Japan
F. König et. al. 2014, The CoLa-Pipe – The new Cottbus Large Pipe Test Facility at BTU Cottbus, Review of Scientific Instruments, accepted, will be published on Vol. 85, Issue 7, July 2014