A study on the influence of triggering pipe flow regarding mean and higher order statistics

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Abstract. The evolution of statistical pipe flow quantities, such as the turbulence intensity, the skewness and the flatness, are investigated to clarify, which development length is needed, until the state of fully developed turbulence is achieved. This observations take place in a relatively large pipe test facility with an inner pipe diameter of $D_i = 0.19$ m and a total length of $L = 27$ m. The reached Reynolds number range is $1.5 \cdot 10^5 \leq \text{Re}_m \leq 8.5 \cdot 10^5$. To quantify the mean and fluctuating velocity as well as the depending statistical quantities, the constant temperature hot-wire anemometry is applied. Through these intensive centerline measurements we observe a development length of $L = 70 \ D$, to ensure a fully developed turbulent flow state.

1. Introduction

Turbulence is a flow phenomenon, that has attracted considerable interests among fluid mechanics researchers and practical engineers, working in different areas where high Reynolds number flows often occur. Numerous publications (Patel & Head, 1969; Perry & Abell, 1974; Doherty et al., 2007; Zanoun et al., 2009) are available, that provide information on the mean velocity distributions of different turbulent flows, but also contain data on fluctuating turbulent flow properties. The most important references are listed in Table 1.

A sub-class of the investigated flow is the internal flow, including two-dimensional fully developed turbulent plane-channel and pipe flow, which have attracted particular attention and have been investigated intensively the last few decades. But there are still a lot of questions regarding turbulent pipe flow at higher Reynolds number. For investigating fully developed turbulent pipe flow in a relatively high range of Reynolds number ($3 \times 10^4 - 10^6$) a new pipe test facility was set up at the Department of Aerodynamics and Fluid Mechanics, Brandenburg University of Technology Cottbus, Germany.

As one can see in Table 1, because of the different listed results, it exists no quite clear criterion for the establishment of fully turbulent pipe flow. Hence, the main aim of the present work is the intensive investigation of developing pipe flow towards the fully turbulent flow state, with respect to natural transition. Where natural transition depends on the smoothness of the inlet contraction, the surface roughness, triggering the flow at the entrance as well as the careful alignment of the several pipe sections. To clearly determine the development length, the length, which is needed by the pipe flow to fully develop turbulence, we study the evolution of the
**Table 1.** Results on investigating the development of pipe flow for natural and for artificial transition.

| development length L/D | type of transition | Reynolds number | reference |
|------------------------|--------------------|-----------------|-----------|
| 25 - 40                | natural            | $3.0 \cdot 10^3 - 3.3 \cdot 10^6$ | Nikuradse (1932) |
| 30                     | natural            | $5.0 \cdot 10^4 - 5.0 \cdot 10^5$ | Laufer (1954)   |
| 50 - 80                | natural            | $1.0 \cdot 10^3 - 1.0 \cdot 10^4$ | Patel & Head (1969) |
| min. 131               | natural            | $3.0 \cdot 10^4 - 3.5 \cdot 10^7$ | Zagarola & Smits (1998) |
| 70                     | natural            | $3.0 \cdot 10^4 - 1.0 \cdot 10^5$ | Zanoun et al. (2009) |
| 71.9 - 86.2            | artificial         | $8.0 \cdot 10^4 - 3.0 \cdot 10^5$ | Perry & Abell (1974) |
| 50 - 80                | artificial         | $1.0 \cdot 10^5 - 2.0 \cdot 10^5$ | Doherty et al. (2007) |

Mean flow and the higher order statistics at various streamwise locations between the entrance and the exit of the pipe test section, $L/D = 0$ and $L/D = 140$. A well-known and adequate measurement technique is therefore used, namely the constant hot-wire anemometry. Particular attention is given to:

- the bulk flow velocity $\overline{U}_b$ and the centerline-average velocity $\overline{U}_c$,
- the fluctuating velocity $u'$,
- and the centerline turbulence statistics up to the fourth moment, i.e. turbulence intensity, skewness and flatness.

### 2. Experimental setup

The relatively large pipe test facility has a 27 m long test section, which is made out of acrylic glass tubes, in order to assure a good optical accessibility. The inner diameter of the test section is 0.19 m. Air is used as the working fluid, which is driven by a radial blower with a power of 45 kW. With this assembly, we are able to reach a maximum velocity of 80 m/s, finally resulting into a Reynolds number range of $3 \cdot 10^4 \leq Re_b \leq 10^6$. Here, $Re_b$ is the bulk-based Reynolds number, which presents the ratio of the inner pipe diameter and the bulk velocity to the kinematic viscosity.

Figure 1 – 3 show the experimental setup, where we see, besides the radial blower and the pipe test section itself, other important parts of the test facility. One is the settling chamber, which contains several screens, in order to straighten the flow and to assure a uniform velocity profile at the exit of the inlet contraction. Another is the entry section, through which the air from the laboratory is sucked. Here, as well as for the inlet contraction, special care was taken to design these parts and to find high accuracy manufacturer. This is very important to provide and maintain a good overall flow quality.

The pipe test facility consists of several sections, which are mounted together trough flanges. To realize intensive centerline measurements, we use a portable 0.25 m long test section, which allows hot-wire measurements in spacings of 1 m in streamwise direction. This provides a substantial measurement basis regarding the onset of turbulence, i.e. developing length and occurring structures.
3. Statistical flow quantities

To define the state of fully developed pipe flow, it is necessary to refer to statistical flow quantities, which is shortly discussed in the introduction. Our focus, in this case, is on the mean velocity, the turbulence intensity, the skewness and the flatness, which are given in Table 2. The correlation between those flow quantities and the minimum developing length is characterized by the following equation:

$$\frac{\delta M^n}{\delta x} \rightarrow 0, \quad \forall x_1 \geq x_{1,v}, \ n = 1, 2, 3, 4.$$  (1)
Equation (1) reveals, that pipe flow is fully developed turbulent, when all moments about the mean, i.e.

- 1st – moment $\rightarrow$ mean velocity
- 2nd – moment $\rightarrow$ turbulence intensity
- 3rd – moment $\rightarrow$ skewness
- 4th – moment $\rightarrow$ flatness

become invariant with streamwise direction after a certain length $x_{1,v}$, where $x_{1,v}$ defines the minimal necessary developing length, which we are interested in.

Table 2. Statistical flow quantities.

| statistics         | depending quantities |
|--------------------|----------------------|
| mean velocity $\bar{u} = (u + u')$ | standard deviation $\tau = \sqrt{\overline{u'^2}}$ |
| turbulence intensity $Tu = \sqrt{\overline{u'^2}^2}$ | n-moment about the mean $\mu_n$ |
| skewness $S_c(\overline{u'}) = \frac{\mu_3}{\tau^3}$ | bulk-based Reynolds number $Re_m = \frac{U_b D}{\nu}$ |
| flatness $F_c(\overline{u'}) = \frac{\mu_4}{\tau^4}$ |

4. Measurement Technique

Single hot-wire anemometry is used to measure the mean and the fluctuating velocities at the centerline of the pipe in different streamwise positions. Therefore we applied a TSI IFA 300 constant temperature hot-wire measurement system, to which a single sensor, with a diameter of $D = 3.8 \mu m$ and a length of $L = 1270 \mu m$, is connected. The signal is sampled with a sampling frequency $f = 10 \ kHz$ over a time period of $t = 26.2143 \ s$. Through a three-dimensional traversing mechanism the sensor is traversed, which is decoupled from the pipe test facility itself to avoid vibration influences. Further we investigate the resulting velocity information with an adequate analysis software, also from TSI.

5. Results

The development of the statistical quantities, i.e. turbulence intensity, skewness and flatness, is presented in Figure 4. Here the x-axis represents the dimensionless streamwise direction, $x/d$, and the y-axis represents on the left side the turbulence intensity and the flatness, and on the right side the skewness. Every measuring point at a specific distance $x$ from the entrance reflects a bulk-based Reynolds number in a range of $1.5 \cdot 10^5 \leq Re_m \leq 8.5 \cdot 10^5$.

In Figure 4 we can observe, that the trend for all three dimensions is nearly the same. When the flow covers a streamwise distance of $x = 70 \ D$, the values for turbulence intensity, skewness and flatness converge and are thus invariant in streamwise direction. If one remember Equation (1), $x_{1,v} = 70 \ D$ is then the minimum developing length and, therewith, the state of fully developed turbulent pipe flow is reached.
Figure 4. Development of the statistical quantities higher order in streamwise direction for 
\[1.5 \cdot 10^5 \leq Re_m \leq 8.5 \cdot 10^5\]

6. Conclusion and outlook

For further investigations regarding turbulence, turbulent structures and transport processes in pipe flow, we can assure, that for natural transition conditions, the state of fully developed turbulent pipe flow is reached within the relatively large pipe test facility. Consequently, it is necessary to measure after a minimum development length of \(x_{1,v} = 70 \, D\). This result is in a very good agreement with outcomes from the presented work, e.g. Patel & Head (1969), Perry & Abell (1974), Doherty et al. (2007) and Zanoun et al. (2009).

Besides turbulent and structural investigations, we will analyze the influence of artificial transition with respect to the development of the statistical quantities as well as the variation in the minimum development length for assuring the fully developed flow state. A possible Reynolds number dependence is also a part of the objectives. This will be realized by different tripping devices, such as

- organized tape letters using DYMO Label Printer (V or X notched stripes),
- inlet fences,
- sand paper stripes.
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