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Verfolgung transitionaler Strömungstrukturen bei kleinen Reynoldszahlen in einer 3200D Rohrmessstrecke

Tracking transitional flow structures at low Reynolds number in a 3200D pipe flow facility

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Rohrströmung, Transition, Strukturverfolgung, Puff und Slug, Hitzdraht
pipe flow, transition, tracking structures, puff and slug, hot wire

Abstract

During laminar-to-turbulent transition in pipe flows, puff structures can be initiated by inducing disturbances in the pipe. At low Reynolds number, these structures are dissipating all of a sudden. At higher Reynolds number, disturbances grow as they move along the pipe and evolve from puff to slug through multiple splitting (Wygnanski et al. 1973, 1975, Eckhardt et al. 2007, Nishi et al. 2008). In our previous studies (Ertunç et al. 2010, 2012, Krauss et al. 2011), single puffs, slugs and various forms of splitting structures were classified using the hot-wire signals obtained at the end of pipes with different lengths up to 566 D. These signals were later used to find the occurrence probability of those structures, their propagation speed and length as a function of Reynolds number. However, it was observed that the pipe length was not sufficient to obtain remarkable difference in probability curves within the last 200 D and, consequently, in this domain the lifetime determination was not possible. In the present study, we report on the development of a 3200 D pipe flow facility along which 36 new dedicated hot-wire sensors were installed. The characterization of the sensors, the flow facility, the disturbance unit and the signal processing will be reported in detail. Resulting statistics for the dissipation and growth of puff structures will be presented.

Introduction

The study of space-time dynamics of transitional structures in circular cylindrical pipes at low Reynolds numbers offers to reveal the transition mechanisms from a deterministic state to a stochastic state, the role of coherent structures during this transition and the control of transition and, may be, turbulence. Since its first observation by Reynolds (1883), the transition in pipe flow at low Reynolds numbers remains an intriguing phenomenon. One reason why this phenomenon is of such great interest is that a fully developed laminar pipe flow is stable when axisymmetric small amplitude disturbances are induced Salwen et al. (1980). However, the flow becomes unstable and turbulent above a critical Reynolds number when disturbed by non-axisymmetric and/or high amplitude disturbances altering the form of the velocity profile Drazin et al (2002), Meseguer et al. (2003). Reynolds (1883) showed that transition phenomena in pipe flow at low Reynolds number are intermittent. He defined the Reynolds number as $Re = \frac{U_b D}{\nu}$, where U_b, D and ν are the bulk velocity of the fluid, diameter of the pipe and the kinematic viscosity of the fluid, respectively. In Reynolds' visualization experiments he observed puff- and slug-like structures, which were also documented in the example hot-wire signals provided by Rotta (1956) and were later extensively investigated by Wygnanski et al. (1973, 1975). According to Wygnanski's investigations, a puff (figure 1 left) can be observed in a flow with a low Reynolds number below $Re \approx 2000$. This flow structure has a clear back edge and an unclear laminar-to-turbulent boundary at the front edge. In contrast, a slug (figure 1 right) can be found only at $Re > 2500$ and has a very clear laminar to turbulent boundary at both edges in the structure. Wygnanski et al. (1973, 1975) investigated puff splitting (figure 1 middle), which occurred at $Re \approx 2300$ in their flow facility. Recent reviews of the transition in pipe flow by Eckhardt et al. (2007), Willis et al. (2008) and Mullin et al. (2010) address many open questions regarding transition in pipe flows. The unknown issues include, for example, the ultimate low and high critical Reynolds numbers, the minimum disturbance amplitude required to cause transitions at different Reynolds numbers, necessary evolution distances into puffs after the flow is disturbed and puff lifetime as a function of the Reynolds number.

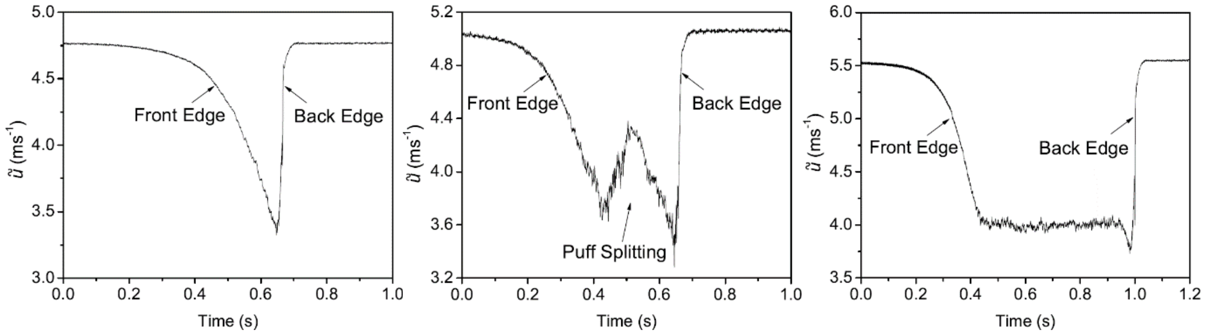

Figure 1: Centerline velocity of puff (left), puff splitting (middle) and slug (right) (Nishi 2009)

The probability of occurrence of puffs $(P(t))$ and puff splitting are quantities relevant to the relaminarization of transitional flow structures and onset of turbulence, respectively. Therefore, statistical data like their occurrence probability, lifetimes and growth rates characterize their dynamics. Kinematical properties are their lengths, propagation speeds and distribution of the anisotropy of Reynolds stresses within the structures. The disturbance induced in the pipe acts as an initial condition for the generation of transitional flow structures. Once the transitional flow structures are generated, they are supposed to forget their initial state (memoryless process) (Brosa 1989, Faisst et al. 2004, Eckhardt et al. 2008, Hof et al. 2008). In other words, properties of disturbance influence heavily the generation of transitional flow structures but not the dynamics and kinematics at later stages.

The present study focuses on transitional flow structures, which are turbulent, namely puffs which do not grow in time and space and the growing structures like puff splittings and slugs. Those structures are examined by a new experimental method, which allows the tracking of each structure along a 3200 D long pipe after they are generated by a localized disturbance unit. The considered properties of the structures are their probability of occurrence, lifetimes and lengths. Moreover, critical Reynolds number for the onset of turbulence are examined using the lifetimes of puffs and growing structures as was done by Faisst et al. (2004), Peixinho et al. (2006), Willis et al. (2007), Hof et al. (2006, 2008), Kuik et al. (2010) and Avila et al. (2010, 2011). The details of the experimental technique are presented in this paper.

Experimental set-up

The schematic of the experimental set-up is shown in figure 2. A mass flow controller generated a continuous air flow and a settling chamber is placed prior to the 15 mm diameter pipe to suppress rotational, radial and acoustic disturbances. Additionally a heat exchanger is installed to minimize the heat transfer through the pipe wall in the measurement section. The disturbance unit is placed at $x = 3m$ (200 D) downstream of the settling chamber such that the flow develops into a Hagen-Poiseuille laminar velocity profile before it is disturbed by two synthetic jets. In the measurement section a transducer reads the pressure loss ΔP over 47.7 m and the pipe Reynolds number Re is computed, which is used as the control quantity in the set-up. In order to compute the Reynolds number density ρ and kinematic viscosity ν of the air are needed. They are dependent on inlet flow temperature T_{in} and inlet pressure P_{in} and can be derived from correlations found in literature (VDI 2006, Lemmon et al. 2004). The inlet flow temperature T_{in} is measured using a Pt100 sensor in the settling chamber and the inlet pressure P_{in} is determined at $x = 0.05m$ behind the disturbance unit. The critical Reynolds number of the naturally occurring transition of this set-up is measured to be approximately $Re \approx 13000$.

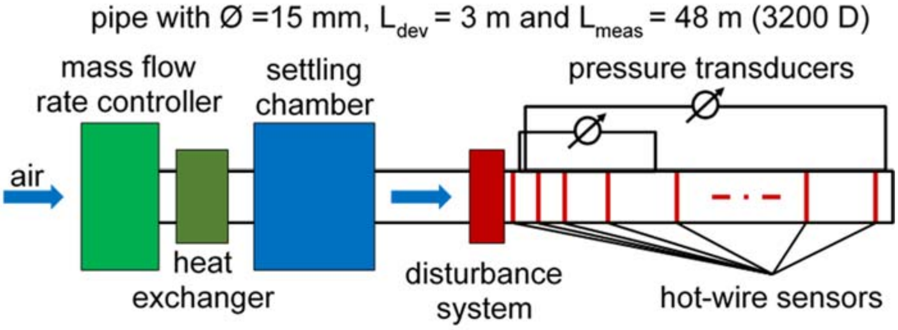

Figure 2: Schematic sketch of the experimental test rig

Two horn speaker drivers (figure 3) are used to trigger the transition. When operated, the drivers generate two synthetic jets at 1000 Hz, which can be operated in phase or 180° phase delayed (figure 4). In the experiments the jets are operated in the phase opposition mode in order to not introduce any additional mass flux. The horn speaker drivers are triggered via analog signals generated by the data acquisition system, to enable the disturbance time to be adjusted. Initial tests showed that the generated disturbances are highly reproducible and the system is able to induce a disturbances as short as one period $(1\ ms)$, corresponding to a time scale of less than $2D/U_b$.

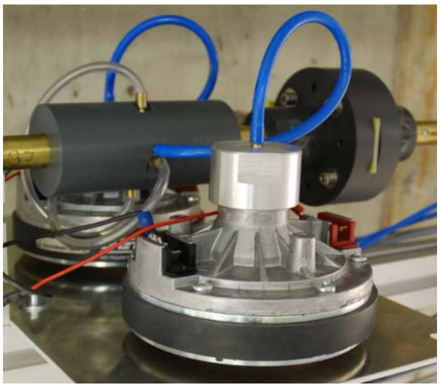

Figure 3: Two horn speaker drivers are generating the transitional structure through synthetic jets

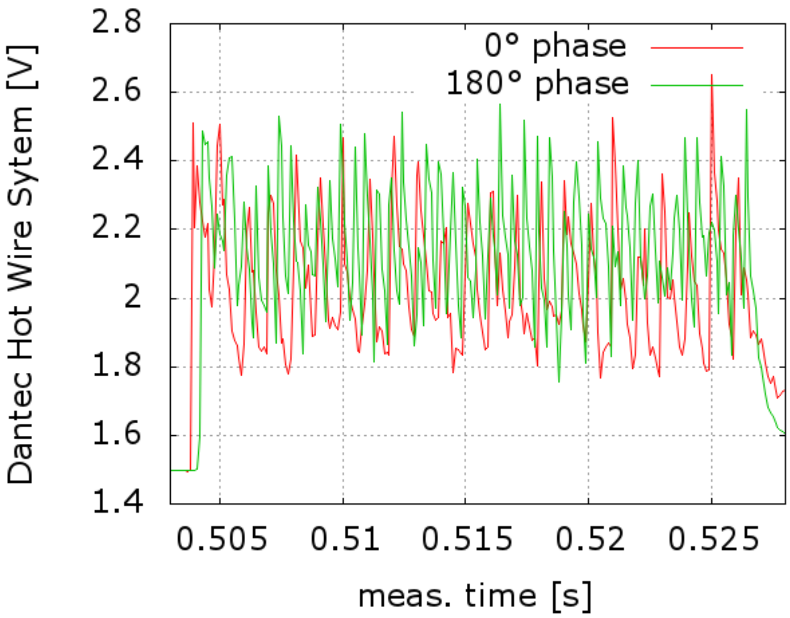

Figure 4: The horn speaker drivers run at 1000 Hz and can work in phase or 180° phase delayed

The tracking system is based on house made hot-wire anemometers (HWA) with overall 36 house made hot-wire sensors (figure 5). The anemometers use the constant temperature technique and the hot wires are positioned along the pipe diameter. These sensors are made of platinum wire with 10 µm diameter and were partially galvanized with copper so that they have a maximal diameter of 30 µm at the ends. The sensitive portion of the wire is in the center of the pipe to measure the centerline velocity (figure 6). For this purpose, 13 hot wire sensors are installed at distances of 0.5 m along the first 6 m behind the disturbance system, followed by 3 at 1 m and 20 at 2 m distance. The developed tracking method allows the observation of dissipation, survival, splitting and growth of individual transitional structures and the determination of lifetime, length and speed. As examples figure 7 (left) shows a generated single puff, which decays within the first 8 sensors, figure 7 (right) shows a splitting puff, which grows through subsequent splitting from a double to a five-fold puff within the first 10 sensors.

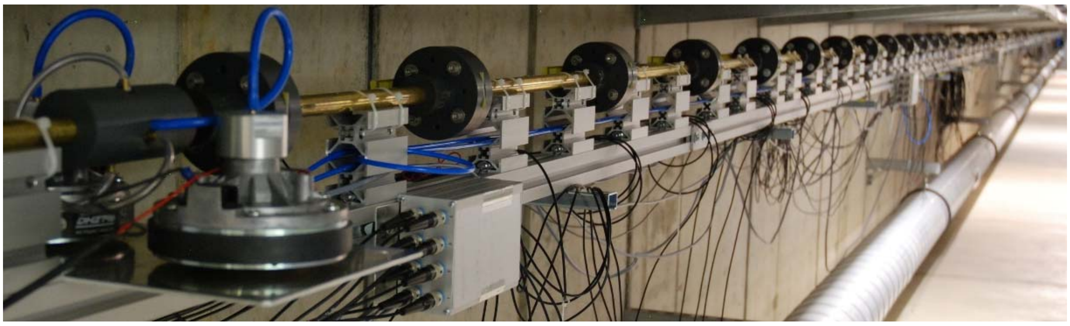

Figure 5: A 48-m-long pipe section (3200 D) with 36 hot wires is connected downstream of the disturbance system

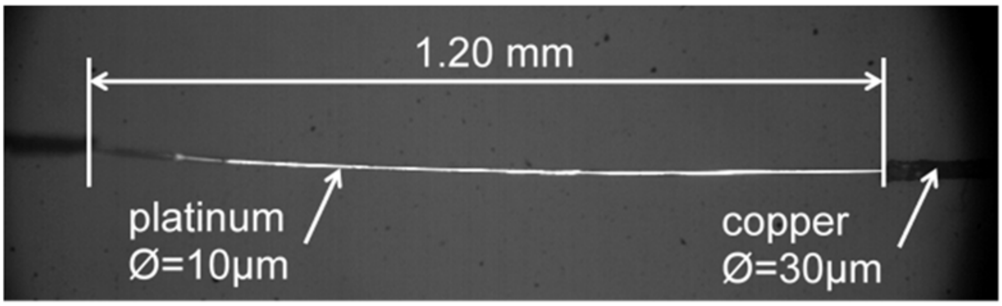

Figure 6: Hot wire sensor made from platinum wire with galvanized copper plated ends

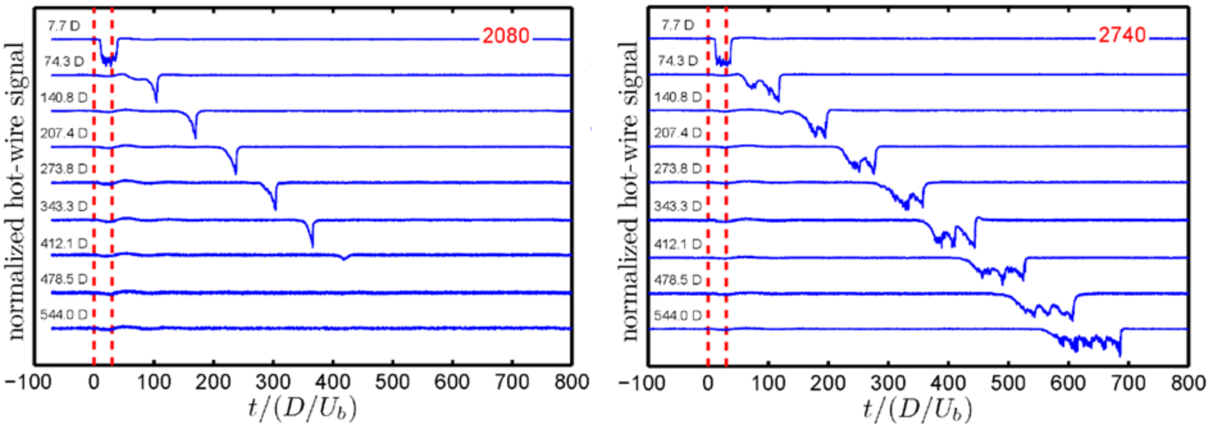

Figure 7: Examples for decay of puff (left) and splitting puff (right), the graph show the first 10 hot wire sensors and the normalized hot-wire signals are sorted by the location along the pipe

Results and discussions

The measurements reported in the following are performed with a disturbance time of $6D/U_b$ (approximately 30 ms to 50 ms) and within a Reynolds number range between 1700 and 3000. This range is covered by 65 discrete intervals with a band width of $\pm 5\,Re$ each. For data processing, the fifth hot wire sensor (133 D) is chosen as the reference sensor, that means, only measurements, which have a single puff at 133 D are considered in the statistics of probability of occurrence, length and lifetime. For every Reynolds number at least 200 valid realizations are processed, which makes up for 34496 measurements in total (figure 8).

Figure 9 shows the probability of occurrence of single puffs, depending on Reynolds number and hot wire sensor position which corresponds to travelling time. Three different regimes can be distinguished. In the middle regime at around Reynolds number 2100 only single puffs are observed. That is, all generated disturbances, which are single puffs, were stable and do not grow within traveling time.

In the first Reynolds number regime between 1700 and 2000, disturbances develop into a single puff, but do not survive and die along the pipe. With increasing Reynolds number, the decay rate decreases until it becomes zero at around $Re \approx 2100$ and all structures survive. The dispersion of the graphs indicate that the decay rate stabilizes with increasing distance from the disturbance unit with only very small change within the last 1200 D, therefore the graphs for 2000 D to 3200 D almost collapse.

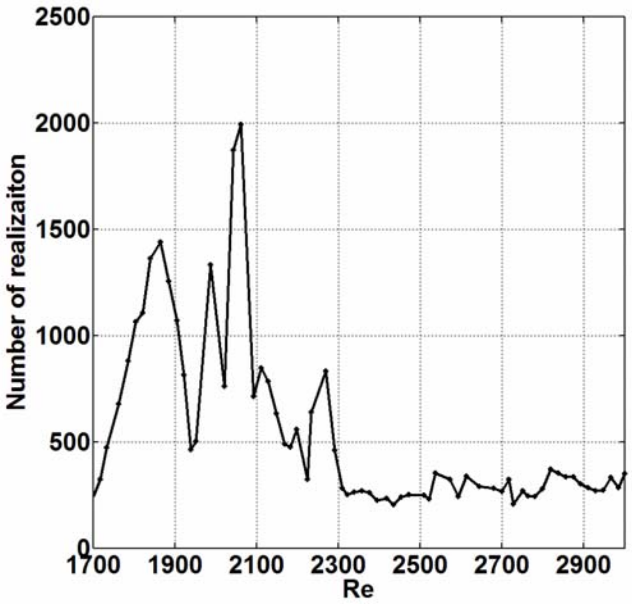

Figure 8: The experimental data is based on 34496 measurements distributed over 65 Reynolds numbers with a minimum of 200 per Reynolds number

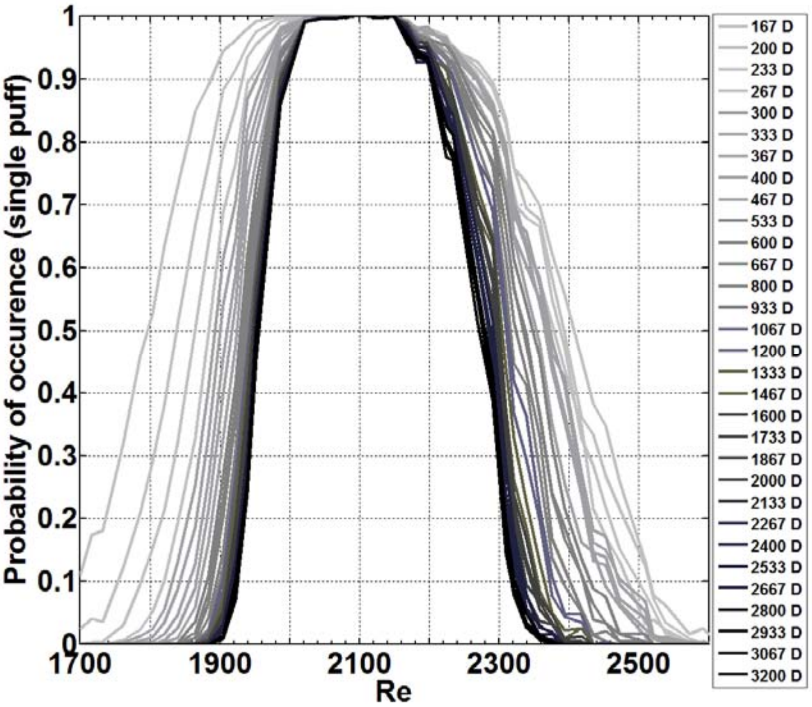

Figure 9: Probability of occurrence of single puffs in the Reynolds range from 1700 to 2600 for different distances behind the disturbance unit using the structure tracking technique

The third regime for $Re > 2200$ the probability of occurrence of single puffs decreases and in this regime, the generated disturbances grow with sensor distance (see also figure 10 and 11). The number of single puffs decrease with increasing Reynolds number and with increasing distance from the disturbance unit for a constant Reynolds number in a similar but inversed way as it developed in the first regime. Again, the biggest change in the survival rate is observed directly behind the disturbance unit (within the first 233 D) and in contrast only minimal changes are observed in the last 1200 D.

Accordingly, in figure 10 the development rate of the growing structures in the first portion of the pipe is very strong while in last 1200 D only minor changes are observed. Figure 10 also proves, that for Reynolds numbers above 2600 only growing structures exist independent of their distance to the disturbance unit. The growing structures include both splitting puffs and slugs. Starting with single puffs at 133 D already at 167 D only splitting puffs or slugs arrive. For the range 2100-2600, the probability of occurrence of such growing structures increase with the Reynolds number and with the sensor position (figure 10).

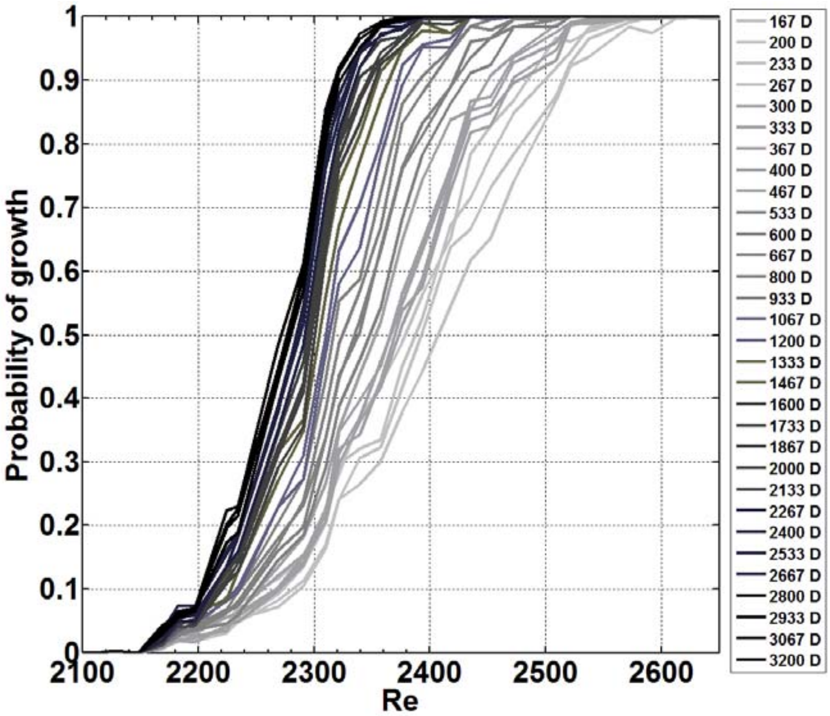

Figure 10: Probability of occurrence of growing structures (splitting puffs and slugs) in the Reynolds range from 2100 to 2700 for different distances behind the disturbance unit

Figure 11 shows the average length of the transitional structures. The length of a structure is defined by the time interval between the front edge and rear edge, and the average length is plotted for each Reynolds number. In figure 11 two characteristic regimes can be observed. For Reynolds number lower than 2200 a minimal increase of length is perceptible with increasing Reynolds number and this is independent of the sensor position. In this regime predominantly decay and survival of single puffs occur. For Reynolds numbers larger than 2200 the lengths of the structures display a strong increase with Reynolds number and traveling time. Here splitting puffs and, especially for higher Reynolds numbers, slugs prevail. Most of the transitional structures for $2200 \leq Re \leq 2600$ undergo a permanent change of structure type (evolve into a higher degree of splitting puff or slug) and grow with the distance from the disturbance unit.

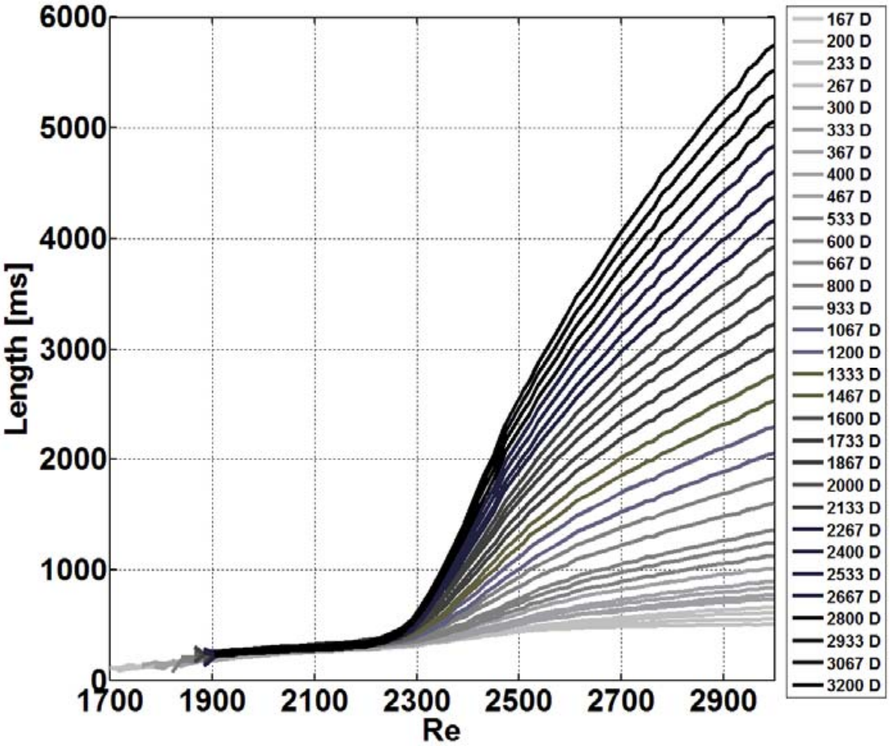

Figure 11: Development of average length of transitional structures for $1700 \leq Re \leq 3000$

In many former investigations conducted at low Reynolds numbers, the $P(t, Re)$ along the pipe is measured at various locations downstream of the disturbance over a narrow Reynolds number range, which is used to calculate the lifetimes for different Reynolds numbers $\tau(Re)$. All of the available data (figure 12) show that the puff lifetime $\tau(Re)$ in the pipe increases as Reynolds number increases. Hof et al. (2006, 2008) and Avila et al. (2010, 2011) showed that a super-exponential trend exists and that τ is not diverging but rather approaching a very high value as the Reynolds number increases. A consensus has been established regarding the super-exponential form of $\tau(Re)$, which is specific to chaotic saddles existing in such a non-linear dynamical system (Hof et al. 2008, Eckhardt et al. 2008). As shown in figure 12, also our results confirm that characteristic lifetimes are super-exponential functions of the Reynolds number. At the branch for the growing structures the data perfectly collapses while at the decay branch of the plot a minor discrepancy in absolute values is present.

Puff splitting and their evolution represents the onset of turbulence as the puffs start to grow into slugs. Earlier measurements Ertunç et al. (2010), Krauss et al. (2011, 2012) showed for the first time the $P(t, Re)$ of various types of transitional structures (single, double, triple puff, slugs and mixed type structures). Avila et al. (2011) argued that the Reynolds number where the two trend lines for puffs and puff splitting intersect can be considered the critical Reynolds number ($Re \approx 2040$) where turbulence starts to grow via splitting (onset of turbulence), however, with an extremely low probability. As can be seen in the figure 12, our data depicts a critical Reynolds number, which is $Re \approx 2070$.

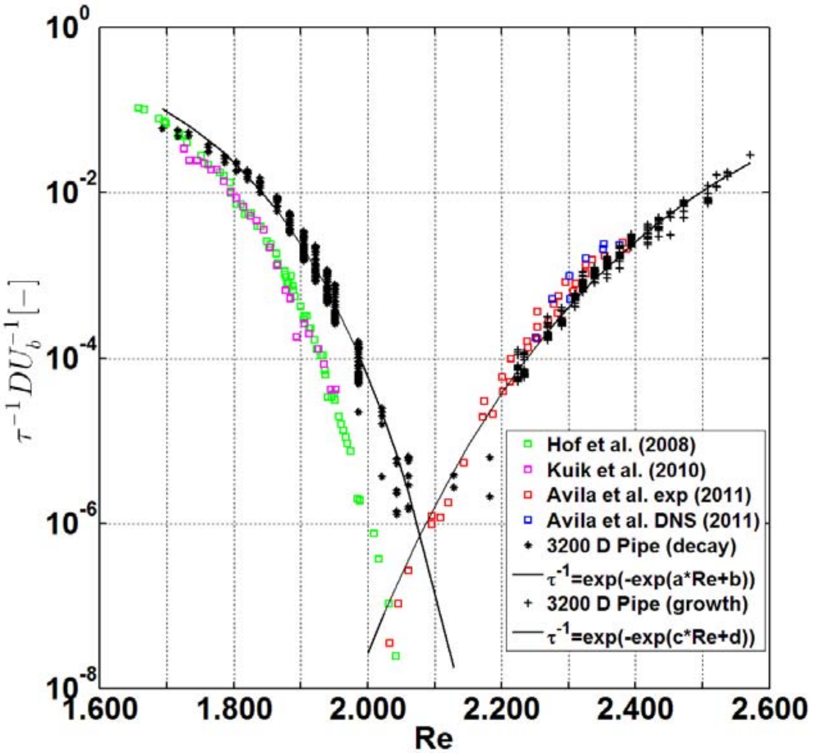

Figure 12: Inverse of dimensionless characteristic lifetime for puffs and growing structures (splitting and slugs) compared with the other available data in literature

Conclusions

The developed tracking method for transitional structures in pipe flow is able to capture the time-space dynamics and kinematics of all different types of puffs and slugs. Therefore, statistical data like occurrence probability, lifetimes and growth rates, which characterize their dynamics, as well as kinematical properties like lengths, propagation speeds and distribution of the anisotropy of Reynolds stresses within the structures can be acquired. In the present study the probability of occurrence of single puffs and growing structures, the lifetime as well as the length of structures are discussed. The critical Reynolds number obtained in this way turned out to be 2070 which is quite close to but slightly higher than the 2040 found by Hof et al. (2006, 2008), Kuik et al. (2010), Avila (2010, 2011).

Acknowledgements

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