Evolution of transitional structures from puff to slug through multiple splitting in a pipe flow at low Reynolds number

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Abstract. During laminar-to-turbulent transition in low Reynolds pipe flows, three main types of flow structures occur: traveling waves and the turbulent flow structures, namely puffs and slugs. In the present work, detailed experiments on the probability of occurrence and propagation speed of puffs, splitting puffs and slugs were conducted with the transition pipe-flow facility of LSTM-Erlangen. During the investigations, fully developed laminar pipe flow was triggered by an iris diaphragm with a pre-defined amplitude and lapse time. Different types of single and multiple puffs are classified and the probability of their occurrence as well as their propagation speed at the end of pipes with different lengths are evaluated.

1. Introduction

Pipe flow (PF) is a nonlinear dynamical system $d\mathbf{u}/dt = f(\mathbf{u}, Re)$ defined by the Navier-Stokes equations together with the appropriate boundary conditions, and the Reynolds number ($Re$) parameterizing the system. After the famous work of Reynolds (1883), investigations on transition in PF were extensively conducted and reported by Rotta (1956); Wygnanski & Champagne (1973); Wygnanski et al. (1975); Eckhardt et al. (2007); Mullin (2011). The investigations conducted up to now revealed three distinct transitional flow structures: traveling waves (Eliahau et al., 1998; Faisst & Eckhardt, 2003; Wedin & Kerswell, 2004) and the turbulent flow structures, namely puffs and slugs (Reynolds, 1883; Rotta, 1956; Wygnanski & Champagne, 1973; Wygnanski et al., 1975). Those structures can be generated at low Reynolds numbers by inducing short-time, large amplitude localized disturbances in the pipe.

Traveling waves start to occur at lower Reynolds numbers than the lowest Reynolds number, where turbulent puffs can occur. They are highly unsteady and characterized by streamwise rolls (Eckhardt et al., 2007). TW’s are not turbulent structures, but some sets of vortex structures in pipe flows which may evolve into puffs and, therefore, TW’s are believed to form the start of transition process. Nevertheless, there exists a critical Reynolds number below which turbulent puff structures does not occur.

After its generation, puffs do not grow, while they travel down in the pipe, but they might relaminarize suddenly (Hof et al., 2006). The lifetime of each puff can take a random value, but it increases with increasing Reynolds number. There is a debate going on whether, at a certain Reynolds number, mean lifetime of puffs attains a very high value (Hof et al., 2006,
2008) or diverges (Peixinho & Mullin, 2006; Mullin & Peixinho, 2006; Willis & Kerswell, 2007). Detailed studies conducted by varying the type and amplitude of induced disturbance revealed the dependence of lifetime statistics on those factors (Mullin & Peixinho, 2006; Peixinho & Mullin, 2007).

At higher Reynolds number, disturbances evolves from puff to slug through multiple splitting, so that the structures fills the space Wygnanski & Champagne (1973); Wygnanski et al. (1975); Nishi et al. (2008). During this evolution, many types of turbulent flow structures occur. This evolution is associated with transition from laminar to turbulent flow. Slug is the more developed state of the puff toward a fully developed turbulent PF. Nishi et al. (2008) showed that the puff starts to split at a certain Reynolds number after the probability of occurrence of puffs reaches 100 % and before it becomes a turbulent slug downstream in the pipe, either at the same Re or at a higher Re. Later, Nishi et al. (Nishi et al., 2009; Nishi, 2009a,b) measured the life-time of puff structures directly by using pressure transients in the pipe and have shown that a single puff favors to breakdown into two or more (splitting) puffs at \( Re \approx 2300 \), where the life-time of single puffs diverge in their investigation.

In the present work, fully developed laminar pipe flow was disturbed by an iris diaphragm by blocking the flow near the wall with a pre-defined amplitude and duration. Different types of single puffs and slugs and multiple (splitting) puffs and slugs are classified and the probability of their occurrence as well as their propagation speed at the end of pipes with different lengths are evaluated. The Reynolds number range of the investigations was \( 1500 < Re < 2900 \).

2. Experimental Setup

The experiments on the evolution of puffs and splitting puffs was conducted with the transition pipe-flow facility of LSTM-Erlangen, which was modified after the investigations of Nishi et al. (Nishi et al., 2008, 2009; Nishi, 2009a,b). An additional differential pressure transducer and an absolute pressure transducer were added for setting the \( Re \) number. The disturbance unit was equipped with two photoelectric barriers for accurate determination of real disturbance time. Moreover, the disturbance unit was covered by an airtight box. Important components of the set-up is shown in figure 1. The mass flow rate controller generates a steady air flow. After the settlement chamber, the flow attains a block profile at the entrance of the pipe having a diameter \( (D) \) of 0.015 m. The development of the Hagen-Poiseuille-Profile is enabled along a 3 m long pipe before the disturbance system.

An iris diaphragm induces the disturbance in the form of aerial blockage for a certain duration. The iris diaphragm is triggered by two electromagnets, one for closing and the other one for opening. The electromechanical system allows the setting of both the blockage (amplitude of disturbance) and the disturbance time. The duration at which diaphragm is fully closed is accepted to be the disturbance duration. The real closing time is measured by the signals obtained from two photoelectric barriers. In the present investigation, 36% blockage is applied with a duration of \( 100 \pm 10 \text{ ms} \), which corresponds to \( 8.5D/V_b \) to \( 21.5D/V_b \) over the Reynolds range \( 1500 \) to \( 2900 \) for the full closing time of iris diaphragm.

Downstream of the disturbance system a pipe is connected with the same diameter \( D \) of 0.015 m and a maximal length \( (L) \) of 8.5 m. Hence, development of structures can be tracked up to the \( 566D \) with this facility. The pipe is equipped with two differential pressure transducers, which can measure \( \pm 50 \text{ Pa} \) and \( \pm 100 \text{ Pa} \). The pressure transducer \( \pm 100 \text{ Pa} \) is used for tracking the development of the induced disturbances and two inputs of the transducer are installed just after the disturbance unit and before the exit of the pipe. The second pressure transducer is used for setting the Reynolds number, \( Re = V_b D/\nu \). In laminar pipe flow, the pressure drop along a pipe is exactly:

\[
\Delta P = 32 \frac{L}{D^2} \rho (P_a, T_a) \nu (T_a) V_b
\]
Hence, knowing the density $\rho$ and the kinematic viscosity $\nu$, one can easily calculate the bulk velocity $V_b$ and, finally, Reynolds number in the pipe. As $\rho$ and $\nu$ are functions of ambient temperature $T_a$ and ambient pressure $P_a$, the latter quantities are also measured besides $\Delta P$ in order to get the desired Reynolds number by setting the mass flow rate controller and to determine the Reynolds number for each realization of disturbance. For ambient pressure, $P_a = 1$ bar, and temperature, $T_a = 298$ K, $\Delta P$ takes the values $35.3$ Pa to $68.3$ Pa over the Reynolds number range $1500$ to $2900$. During the measurements, if $T_a$ and $P_a$ show deviation more than $\pm 0.5$ K and $\pm 2$ hPa, which correspond to $\Delta Re = \pm 10$ and $\Delta Re = \pm 5$, respectively, compared to the set values, the mass flow rate input is corrected to attain the required Reynolds number.

The disturbances, which turn into transitional flow structures and survive down to the exit of the pipe, are detected there with the help of a hot-wire sensor. The pipe lengths employed in this work are $166$ D, $300$ D, $433$ D and $566$ D. The measurements are conducted over the Reynolds number range $1500$ to $2900$ with a step of $20$. For every Reynolds number, the flow is $1000$ times disturbed and the resulting signals are recorded and analyzed. The various types of structures are automatically identified via the length and amplitude of the hot-wire signals of the structures (single puffs and/or slugs), so that the occurrence probability of those structures can be evaluated from the vast number of realizations conducted. The algorithm shown in figure 2 is used for the recognition of various transitional flow structures from hot-wire signals. Some parameters used during recognition is optimized and verified. Besides the structure identification, the propagation speed of the structures, which is the time elapsed between the induction of disturbance and the moment of arrival of the front edge of the flow structure to the hot-wire sensor, are evaluated.

![Figure 1: Schematics of the transition pipe flow facility of LSTM Erlangen](image)

3. Results and Discussions

The examples of disturbance ($Z(t)$), raw pressure ($P(t)$) and velocity signals ($V(t)$) for $566$ D pipe are shown in figures 3, 4, 5. The signals are normalized so that all signals can be observed within the same graph. The equations used for normalization of signals are

$$V^*(t^*) = \frac{V(t) - V_{center}}{1.16}, \quad P^*(t^*) = \frac{P(t) - P_{min}}{P_{max} - P_{min}} - 1, \quad Z^*(t^*) = \frac{Z(t) - Z_{min}}{Z_{max} - Z_{min}} - 1,$$
Figure 2: Flow chart of recognition algorithm employed to classify the transitional turbulent flow structures.

where the superscript * denotes the normalized values of the signals and time is made nondimensional as follows:

\[ t^* = \frac{t}{D/V_b} \]

These signal plots depict clearly the influence of Reynolds number on the evolution of the disturbances into different types of transitional flow structures. The pressure signals for \( Re < 1900 \) show no puff structure at the end, but the comparison between \( Re = 1820 \) and \( Re = 1900 \) suggests that the disturbances start to sustain longer for the higher \( Re \). At a slightly higher \( Re \), about 1940, the puff structures start to appear by the end of 566 \( D \) pipe. The hot-wire signals in figure 6 show the splitting puff signals and how the number of splitting apparently increases by the increasing \( Re \). With the further increase in \( Re \), the splitting effect increases and the occurrence of multiple puffs, single slugs and multi slugs set on (figure 5). These observations are in accordance with those of Wygnanski et al. (1975); Nishi et al. (2008); Nishi (2009a). However, a close look into the available signals reveals that at the same \( Re \) and with the same disturbance, different types of structures might occur after a certain distance downstream of the disturbance unit (figure 6) (Ertuğ et al., 2010).

The occurrence probability of the structures are evaluated by dividing the number of detected structures at the exit of the pipes with the number of disturbances at a certain Reynolds number. Figure 7 shows the measured evolution of probability along the pipe. The probability curves
Figure 3: Normalized signals from disturbance(green), velocity at the exit of the pipe (blue) and pressure drop (red) along the pipe are showing (a) no puff at $Re = 1820$, (b) no puff at $Re = 1900$ and (c) single puff at $Re = 1940$.

Figure 4: Normalized signals from disturbance(green dashed line), velocity at the exit of the pipe (blue cont. line) and pressure drop (red dots) along the pipe are showing (a) double puff at $Re = 2300$, (b) triple puff at $Re = 2400$ and (c) quadruple puff at $Re = 2540$.

Figure 5: Normalized signals from disturbance(green dashed line), velocity at the exit of the pipe (blue cont. line) and pressure drop (red dots) along the pipe are showing (a) double slug at $Re = 2780$ and (b) single slug at $Re = 2900$.

Almost overlaps after 300 $D$ and do not show the expected drop of probability downstream of that location. It is suspected that the type, amplitude and duration of the disturbance causes such behavior in the probability statistics. This issue is still being investigated by the authors.

In figure 8, probabilities at the exit of 566 $D$ pipe is shown. This picture shows the hierarchical formation of transitional structures. The disturbances evolve first into puffs. The probability of puffs increases starting from 1900 reaches to unity by around 2100. The probability below
unity suggests that some of the puffs die out (dissipate) before they reach to the pipe exit. The structures start to split and grow in size only after $Re \approx 2200$. As they grow, multiple splits occur and at $Re \approx 2400$, single slugs start to appear and their probability increases together with the multiple slugs and mixed type of structures (puffs and slugs). Figure 8 suggests also for $Re > 2200$, at the same Reynolds number, flow can evolve to different types of structures.

![Figure 6: Normalized signals from disturbance (green dashed line), velocity at the exit of the pipe (blue cont. line) and pressure drop (red dots) along the pipe are showing (a) single puff, (b) double puff and (c) triple puff.](image)

The occurrence probability of structures at the exit of different pipe lengths are shown in figure 9. Accordingly, the probability of puff splitting increases with the increase in pipe length, i.e. travel time of the structure in the pipe. Only the data taken at $L/D = 166$ shows higher probability values than those measured with longer pipes. This deviation from the general trend implies that double puffs might decay first to a single puff and later split again.

Figure 10 depicts that the probability of single slug decreases with the increase in pipe length, because the probability of multiple slugs and mixed type of structures exist at the same Reynolds number and have a higher maximum with increasing pipe length. Slugs and mixed type of structures occurs more often at downstream locations. The probability of the formation of single slugs decreases with increasing pipe length, while mixed types can develop more in the longer pipe. However, the probability of multiple slugs and mixed types decrease with the increasing Reynolds number, as they start to merge or the disturbances evolve immediately to a single slug and do not split at all.

![Figure 7: Probability of occurrence of single puffs at the exit of pipes having different lengths.](image)
Figure 8: Probability of occurrence of all types of structures at the exit of 566 $D$ pipe.

Figure 9: Probability of occurrence of (a) double and (b) triple puffs at the exit of 166 $D$, 300 $D$, 433 $D$ and 566 $D$ pipes.

The propagation speeds of the structures relative to the bulk velocity are shown in figure 11 by plotting the ratio between the velocity of the structure $V_{struct}$ and the bulk velocity of the pipe flow $V_b$. It can be seen in this figure that the structures do not travel along the pipe with a constant speed. Nevertheless, as the speeds measured at 433 $D$ and 566 $D$ do not differ, it is reasonable to assume that after traveling some time structures attain a constant speed in the pipe. However, this speed is dependent on $Re$. The convergence of the speed of structures after 300 $D$ can be in connection with the overlapping of probability curves after 300 $D$. It is possible that in the present facility transitional structures needs a certain travel time to stabilize their speed and only after this length probability of occurrence should be considered.

The measured speeds are in agreement with those of Nishi et al. (2008). In contrast to this observation, propagation speed of slugs increases with increasing Reynolds number. The average speed of all structures reflects the superposed propagation speed trends of puffs and slugs: It
decreases first at low Reynolds numbers, where single puffs predominantly exists and increases at higher Reynolds numbers, where all other sorts of growing structures start to appear.

4. Conclusions

When observed at a certain distance from the locus of disturbance, hierarchical formation of various structures can be observed with the increasing Reynolds number. Splitting of transitional structures (transition from puff to slug) is a process, where turbulence grows within the pipe. The puffs split after a certain Reynolds number and pipe length. These structures later evolve into various types of structures. The occurrence probability curves clearly shows that the probability is strong function of pipe length (travel time of structures) and $Re$. The longer is the pipe and the higher is the $Re$, the higher is the probability of splitting.

The probability curves shows also that at a certain Reynolds number and pipe length, various types of transitional structures might appear at one pipe location. In other words, the development of a disturbance into a transitional structure is a random process, but with certain statistics as shown by the probability curves. The dependence of these curves on the
type, duration and amplitude of disturbance is still a subject of discussion. Furthermore, the probability of occurrence curves of multiple structures give evidence of merging and splitting of structures consecutively. However, this kind of dynamics of structures can be better understood when the transitional structures are tracked for a long time. We have ongoing activities to track single structures.

In contrast to the expected trends, the probability of occurrence curves of puffs overlap with each after 300 $D$ and the speed of the structures attain a higher value than the bulk velocity immediately after they are generated and slow down to a constant value after 400 $D$ in our experimental facility. However, this value is also a function of $Re$. With increasing Reynolds number, the puffs slow down to a value 1.05 and the slugs becomes gradually faster.

The stabilization of probability curves and speed of structures downstream of the disturbance system and their dependence on the disturbance type, amplitude and duration are being investigated by the authors with the help of the single structure tracking experiments.

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