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DIRECT MEASUREMENT OF LIFETIME OF TRANSITIONAL STRUCTURES IN LOW REYNOLDS NUMBER PIPE FLOWS

Mina Nishi
Institute of Fluid Mechanics (LSTM-Erlangen)
Friedrich-Alexander-Universität Erlangen-Nürnberg,
Cauerstr.4 D-91058 Erlangen, Germany
nishi@thtlab.t.u-tokyo.ac.jp

Özgür Ertunç
Institute of Fluid Mechanics (LSTM-Erlangen)
Friedrich-Alexander-Universität Erlangen-Nürnberg,
Cauerstr.4 D-91058 Erlangen, Germany
ertunc@lstm.uni-erlangen.de

Antonio Delgado
Institute of Fluid Mechanics (LSTM-Erlangen)
Friedrich-Alexander-Universität Erlangen-Nürnberg,
Cauerstr.4 D-91058 Erlangen, Germany
antonio.delgado@lstm.uni-erlangen.de

ABSTRACT

The lifetime of transitional flow structures in low Reynolds number pipe flows, namely puffs, was directly measured by measuring pressure drop transients in the pipe, which occur due to the generation and existence of a single transitional flow structure in the pipe. Transitional structures were generated by disturbing the flow with an iris diaphragm, which blocked the fully developed laminar flow with a certain blockage ratio and duration. Simultaneous to pressure measurements, measurements of velocity were conducted at the exit of the pipe by a hot-wire anemometry. Pipes having lengths of 200, 300 and 566 pipe diameters were employed. Pressure measurements allowed the direct determination of the lifetime of a puff, only when it dissipates in the pipe. The velocity measurements allow to determine the structure of single puffs and used to evaluate the probability of puff occurrence (survival) at the end of the pipe. The investigations of lifetime exhibited three possible routes for the development and/or the dissipation of puffs with increasing Reynolds number: Up to $Re \approx 1880$, the disturbed structures develop into puffs then dissipate. After that Reynolds number, some of the puffs started to sustain remarkably longer within the pipe and some of them reaches to the end of the pipe before they dissipate. Within a very narrow Re range around 1500, the life of transitional structures was observed to remain constant. The directly measured lifetime in the range $1600 \leq Re \leq 1880$ revealed a divergence of lifetime at $Re \approx 2300$. It is demonstrated that disturbance amplitude and duration do not influence the directly measured lifetime, whereas they influenced the probability of occurrence of the puffs at the exit of the pipe.

INTRODUCTION

After the famous work of Reynolds (1883), transition in pipe flows were extensively investigated and reported by Rotta (1956), Wygnanski and Champagne (1973) and Wygnanski et al. (1975). Recently, Eckhardt et al. (2007) and Willis et al. (2008) reviewed the transition phenomena in pipe flows. Reynolds (1883) readily showed that transition phenomena in pipe flow are intermittent and the critical Reynolds number Re_{tr}, at which transition starts to occur naturally, varies depending on the inlet conditions. If the disturbances are carefully suppressed, one can maintain laminar flow in pipe at very high Reynolds number (e.g. 10^5 by Pfenninger, 1961), however not infinitely high, as linear stability analysis suggests. Nevertheless, there exists a critical Reynolds number Re_{low} below which no transition is observed. Wygnanski and Champagne (1973); Wygnanski et al. (1975) showed that transition at low-Re ($Re \geq Re_{low}$) triggered by a short-time finite amplitude disturbance starts with distinct flow structures, namely puffs and slugs. Slug is the more developed state than the puff, toward a fully developed turbulent pipe flow. They showed that the puff starts to split at around $Re \approx 2300$, before a slug is formed, either at the same Re or at a higher Re (depending on the pipe length). Nishi et al. (2008), which was a continuation work of Durst and Ünsal (2006), investigated the propagation velocity of puffs and slugs as well as the transition from puffs to slugs through puff splitting. Theoretical analysis of Jovanović and Pashtrapanska (2004) based on a Reynolds stress anisotropy model revealed that for $Re \leq 1930$ no transitional structures can sustain in the pipe flow, if the disturbance has only two components. Different to this model-based prediction, experiments of Darbyshire and Mullin (1995) showed an existence of sustaining transitional flow structures for $Re \geq 1760$ and, in addition to these structures, they observed flow structures for $Re < 1760$ which dissipated before they form a sustaining puff.

Numerical and experimental studies (Faisst and Eckhardt, 2003; Wedin and Kerswell, 2004; Eliahau et al., 1998) revealed another kind of flow structure, namely traveling wave in pipe flow, which starts to occur at a lower Re range than the one necessary for the occurrence of puffs, i.e. at

$Re \leq Re_{low}$. Traveling waves are characterized by streamwise rolls and they are highly unsteady. However, they are not turbulent structures but they were shown to exist within puffs (Hof et al., 2004, 2005). Some sets of vortex structures in pipe flows which may evolve into puffs and, therefore, TW's are believed to form the transition process. Briefly, there are three distinct transitional flow structures at low-Re range, which occur consecutively with increasing Reynolds number: Traveling waves, puffs and slugs.

Hence, the induced disturbances in a pipe at low Re range follow different stages of evolution during their travel in a pipe: Some of them immediately dissipate, some of them evolve into puffs and then dissipate and some of the dissipating puffs sustain for extremely long times with increasing Re (Peixinho and Mullin, 2006; Hof et al., 2006; Willis and Kerswell, 2007), and some of them start to split prior to its development into slugs (Wygnanski et al., 1975; Nishi et al., 2008). As dissipation of a transitional flow structure has a stochastic nature, its rate is characterized by *lifetime* of the transitional flow structures, which is an adopted notion from the definition of half-life in radioactive decay phenomenon. Thus, the time required for the occurrence (survival) probability of puffs drops to 0.5, is called *lifetime* (e.g. see, Peixinho and Mullin, 2006; Hof et al., 2006). For the determination of lifetime, after disturbing the flow in a pipe, the occurrence probability of puffs were measured at different locations downstream of the locus of induced disturbance. Mullin and Peixinho (2006) clearly showed that lifetime based on probability curves resulted in different lifetime-Re dependence when the properties of disturbance was changed and, consequently, lifetime started to diverge (increase drastically) at $Re \approx 1695$ and $Re \approx 1820$. After all, the lifetime determined by this indirect method was still used to understand the routes of transition. Direct numerical simulations Willis and Kerswell (2007) showed that $Re = 1870$ is a crisis Reynolds number, at which the lifetime of transitional structure start to diverge. On the other hand, Hof et al. (2006) showed by their experimental and numerical investigations that the lifetime of transitional structures will not diverge but have extremely long finite value.

In this study, the authors present a simple pressure drop measurement method for the direct measurement of the *full-lifetime* of transitional structures in low-Re pipe flow, which is defined as the time required for the puffs to dissipate fully just after the flow is disturbed. Besides the direct full-lifetime measurements, the hot-wire measurements were conducted at the exit of pipe to monitor the velocity form of transitional structures and complement the direct full-lifetime measurements with probability of occurrence analysis. A detail account of our findings relevant to the full-lifetime measurement, and its relevance to different routes of transition and probability of occurrence statistics are provided.

TEST RIG AND MEASUREMENT METHOD

For the investigation of lifetime of transitional structures, the experimental set up of Nishi et al. (2008) was modified to achieve a higher resolution in controlling Reynolds number. The experimental set up is sketched in Fig. 1. A mass flow rate controller (Bronkhorst, F-202AC-FB-44V) was employed which has a deviation less than 0.4 % from the required mass flow rate value and allows adjustment of the Reynolds number with steps of 5 in the present set up. A critical nozzle was connected to exit of the mass flow rate controller in order to have always chocked flow and as such it was able to maintain a constant mass flow rate independent from the pressure drop caused by the transition downstream of the pipe. A flow conditioner was used prior to the 15 mm diameter pipe to suppress the irregularities in the flow and the acoustic disturbances. In this flow facility, the laminar-to-turbulent transition starts naturally at $Re_{tr} \approx 13000$, which allows us to study the low-Re transition phenomena by artificially induced disturbances onto the laminar flow.

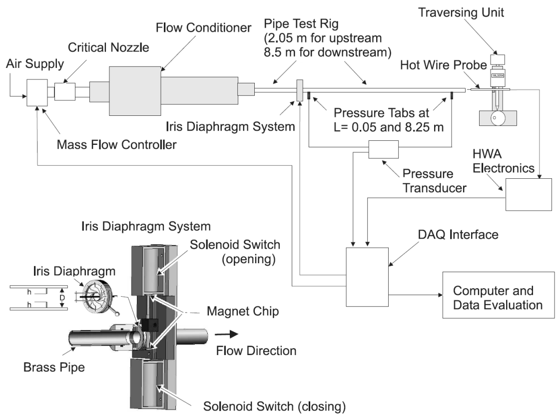
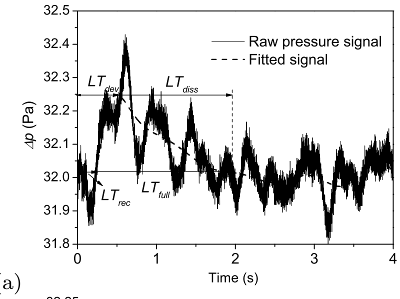


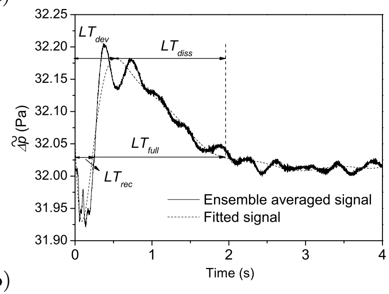
Figure 1: Schematic diagram of the experimental test rig with the details of the iris diaphragm system.

To trigger transition, an iris diaphragm system was employed (Fig. 1). The system is able to control closing area (blockage ratio) as well as closing duration (lapse time) of the iris diaphragm. It was set constant values for closing area 30% and the closing time 40 ms for most of the experiments. The iris diaphragm was placed at L=2.05 m (137D) downstream of the flow conditioner, so that the flow could develop into Hagen-Poiseuille flow up to $Re \approx 2440$, before it was disturbed by the iris diaphragm. Pipes with various lengths were connected after the iris diaphragm system to obtain the probability of occurrence curves. The maximum length of the pipe was 8.5 m (566D) in the present experiments. A hot wire anemometer (HWA) was employed to measure the center line velocity at the pipe outlet and a piezo-resistive pressure sensor (RCI, PD 2915 SM1) was used to measure the pressure difference Δp between L=0.05 (3D) and 8.25 m (550D) after the iris diaphragm. Figure 2 (a) shows an example of pressure signal, in which x-axis is the time after the iris diaphragm operated and y-axis is the pressure difference. Figure 2 (b) depicts the ensemble averaged pressure signal $\widetilde{\Delta p}$ over 200 realizations. The increase and decrease of pressure difference indicate the development and the dissipation of transitional structures at the set Reynolds number, respectively. Thus, the elapsed time between the operation of iris diaphragm ($t = 0$) and the pressure difference's returning back to its original value is defined as full-lifetime LT_{full}. Moreover, recovery-time LT_{rec}, development-time LT_{dev} and dissipation-time LT_{diss} are defined in Fig. 2. LT_{rec} is the time for the pressure to recover from its initial drop owing to the opening of the iris diaphragm. The time for the transitional structures taking to reach the maximum value is called LT_{dev}. LT_{diss} is defined as the time between the start and the end of the decay of pressure signal. Thus, the following relation holds between the definitions of characteristic times:

$$LT_{full} \approx LT_{dev} + LT_{diss}. \quad (1)$$



(a)



(b)

Figure 2: The definition of various characteristic times in the experiments based on (a) the curve fits of each pressure drop signal and (b) ensemble averaged pressure drop signal at ($Re = 1850$).

The LT_{rec} and LT_{dev} are characteristic times which are supposedly dependent on the flow facility and the properties of the disturbance.

One can observe low frequency oscillation in the pressure signal (Fig. 2 a). Such oscillations was seen in hot wire anemometry signal as well. Therefore, it was concluded that they are the oscillations of the flow rate. This occurs due to the response characteristics of the mass flow controller. However, as the measured range of pressure difference is already less than 0.5 Pa, the resulting deviation in Re is within ±0.5%. Therefore, it is plausibly argued that the influence of these fluctuations on the general behavior of transitional structures is negligible.

The procedure for direct measurement of LT_{full} of transitional structures was as follows:

1. Set the flow rate by the mass flow controller according to a chosen Reynolds number
2. Operate the iris diaphragm to trigger the flow.
3. Measure the center line velocity at the outlet of the pipe as well as the pressure difference along the fully developed portion of the pipe. Repeat this step and previous step to collect data for many realizations of disturbed flow.
4. Pick up the pressure signals of the realizations, for which HWA did not show a typical puff signal (transient drop of velocity at the center of the pipe).
5. Take a ensemble average of pressure signals, picked up in step 4, and evaluate the full-lifetime from the mean signal.
6. Alternative to step 5, for each pressure signal picked up in step 4, curve-fits were made and values of all characteristic times were extracted from them.

By the above-described method, one can only measure the full-lifetime of transitional structures which completely dissipate in the pipe. If they do not dissipate, they would appear as puffs at the end of the pipe with a lifetime beyond the measurable range. At least 60 realizations were taken for

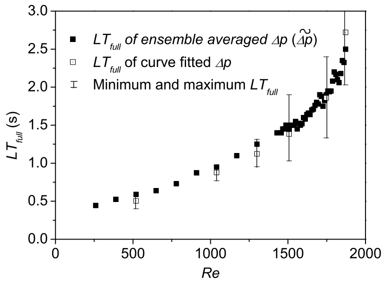


Figure 3: Comparison of LT_{full} evaluated with two different methods of analyzing transient pressure signals (measurements were made in the pipe with $L = 566D$).

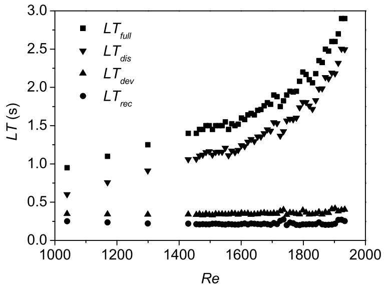


Figure 4: Variation of different types of LT with Re for $L = 566D$.

each Reynolds number for $Re < 1830$, but over 200 realizations were sampled for $Re \geq 1830$ to obtain a good ensemble average. The time between each disturbance was chosen as 10 s, which was sufficiently long for the flow to recover the original laminar flow state after the iris diaphragm was operated. LT_{full} determined from the ensemble averaged signal (step 5) and from the curve-fits (step 6) are matching well as shown in Fig. 3. The analysis made by curve-fits (Fig. 2 a) allows to observe the scatter of LT_{full}, which increases remarkably for $Re > 1550$ as shown in Fig. 3. The lifetimes extracted from curve fits in Fig. 3 revealed a distribution such that 80% of all realizations remained within a deviation of ±10% about the average value of the lifetime. In the ongoing analysis, LT_{full} evaluated from the ensemble averaged signal is used.

In Fig. 4, the changes of previously defined types of lifetimes (see Fig.2) are shown for pipe with $566D$ length. As can be seen in this figure, LT_{rec} and LT_{dev} remains constant in the whole Reynolds number range with the values ≈ 0.22 s and ≈ 0.4 s, respectively, whereas LT_{full} and LT_{diss} increase with increasing Reynolds number.

LIFETIME AND PROBABILITY MEASUREMENTS

Figure 5 shows probability curves of the occurrence of puffs detected by the HWA at the end of the pipes having lengths of $L = 200D, 300D$ and $566D$. The probability is the ratio between the number of realizations, for which puffs were detected by the HWA, and the the total number of realizations. For $L = 566D$, the probability curve starts to increase from $Re = 1890$ and reaches 1 at around $Re = 2080$, which means that no realization was detected as a puff for $Re < 1890$ and all realizations were detected as puffs for $Re \geq 2080$ by the HWA at the end of the pipe. Thus, according to Fig. 5, all the triggered structures completely dissipated in the pipe having $L = 566D$ at $Re < 1890$. Although there were some structures which were dissipated in the pipe at $Re \geq 1890$, some of them were sustained longer

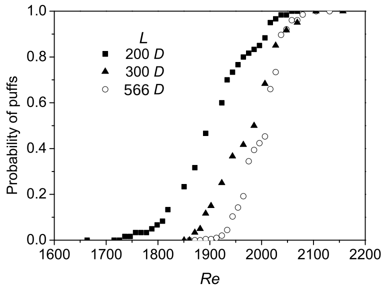


Figure 5: Probability curve for the occurrence of puffs detected by the HWA at the end of pipes with three different lengths.

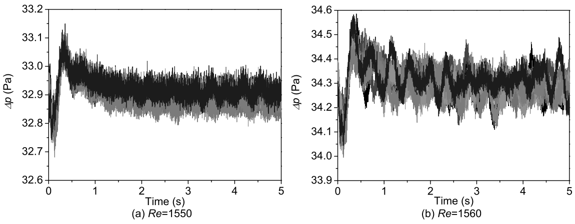


Figure 6: Δp of seven realizations in the pipe having $L = 566D$ at $Re =$ (a) 1550 and (b) 1560.

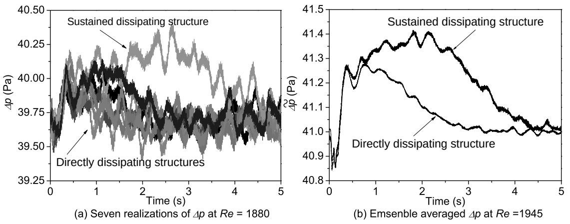


Figure 7: (a) Δp-time profile of seven realizations at $Re = 1880$ and (b) ensemble-averaged $\widetilde{\Delta p}$-time profile at $Re = 1945$

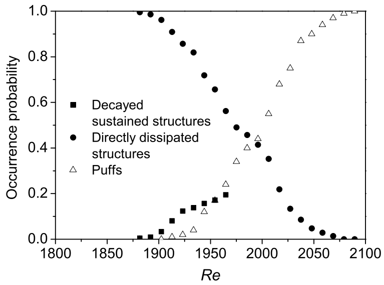


Figure 8: Occurrence probability of the three types of transitional flow structures for $Re > Re_{crit}$

than the pipe length, hence they were detected by the HWA as puffs. Therefore, LT_{full} is plotted in Fig. 3 and in the following figures only for $Re < 1890$.

LT_{full} data depicted both in Fig. 3 and 4 (a) shows a gradual increase with increasing Reynolds number, then there is a plateau of LT_{full} in the range $1450 \leq Re \leq 1550$ and, subsequently, it starts to increase rapidly. Moreover, as shown in Fig. 6, Δp suddenly started to show fluctuations with higher amplitudes and considerable differences from one realization to the other can be observed at $Re = 1560$, when compared to the Δp signals for $Re \leq 1550$. The results in Fig. 4 (a) shows an apparent discontinuity in the rate of increase of LT_{full} with increasing Reynolds number at around $Re \approx 1550$. Hence one can plausibly argue that the boundary between two distinct transitional flow structures, namely *just triggered* structures and *developed* structures, lies at this Reynolds number.

Figure 7 (a) shows Δp signals of seven realizations at $Re = 1880$. As can be seen, most of the realizations reach the maximum value of Δp, and decrease immediately. Only one signal in Fig. 7 (a) shows a different tendency, i.e. first it increases similar to those in the other realizations but then it continues to increase further and subsequently decreases. As a consequence, these kind of transitional flow structures have different lifetimes. This kind of large deviation from one realization to the other appeared suddenly at $Re = 1880$. This Reynolds number is defined in the present investigation to be the *critical Reynolds number* Re_{cr}, which can be interpreted as Re_{low}. In the following discussion, the transitional flow structure, which is dissipating immediately after they reach a peak Δp as most of the signals shown in Fig. 7 (a), is called *directly dissipating* structure; the single long lasting Δp signal shown in the same figure is called *sustained dissipating* structure. The term *dissipating* in the name was necessary because *non-dissipating sustained* structures were also observed at higher Re's, which propagated further downstream and were finally detected as puffs by the HWA. Hence there are two *sustained* structures, and the lifetimes of only the dissipated ones could be measured. As the Δp signals of *directly dissipating* and *sustained dissipating* structures are considerably different from each other, one can make two clearly distinguished ensemble-averaged $\widetilde{\Delta p}$ signals for them (see Fig. 7 b). Compared to *directly dissipating* structures, *sustained dissipating* structures have typical characteristics: They need longer time to develop and they reach higher maximum value in Δp.

For $Re \geq 1890$, the HWA starts to detect puffs in addition to *directly dissipating* and *sustained dissipating* structures. With increasing Reynolds number, the number of *sustained* structures increased. Figure 8 shows the occurrence probability curves for each structure. The occurrence probability of *directly dissipating* structures decreases with increasing Reynolds number and for $Re \geq 2080$ none of them exists. These results reveal that, for example, at $1880 \leq Re \leq 1970$, more than 50% of transitional structures dissipate directly. Accordingly, the occurrence probability of *sustained dissipating* structures increases with increasing Reynolds number together with that of puffs. The existence of *directly dissipating* structures up to $Re = 2080$ gives the reason why the probability curves of puff occurrence for the three pipes with different lengths in Fig. 5 start to increase at different Reynolds numbers but reach 1 at more or less the same Reynolds number. The probability curve for the occurrence of puffs for $L = 200D$ pipe covers a wider range of Reynolds number, ca. 350, than that for an $L = 566D$ pipe, ca. 200.

The lifetimes extracted from the ensemble-averaged signals (Fig. 7 b), which were evaluated separately for the *directly dissipating* and *sustained dissipating* structures show two possible LT_{full} at a Reynolds number for $Re > Re_{cr}$ (Fig. 9). The lifetimes of *directly dissipating* structures do not increase with increasing Reynolds number but remain constant at around 2.6 s. The lifetimes of *sustained dissipating* structures increase with increasing Reynolds number with a tendency that is similar to that for $Re < Re_{cr}$. Note that it was possible to measure the lifetime of *sustained dissipating* structures only up to $Re \leq 1964$, since all *sustained* structures reach to the end of the pipe and appear as puffs (see Fig. 8).

The relation between the LT_{diss}^{-1} and the Reynolds num-

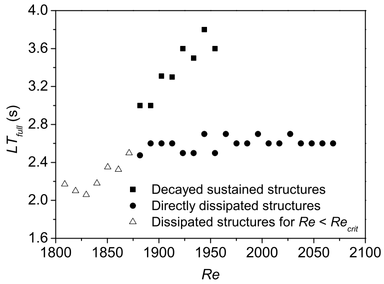


Figure 9: Change of LT_{full} with increasing Reynolds number for $Re > Re_{crit}$

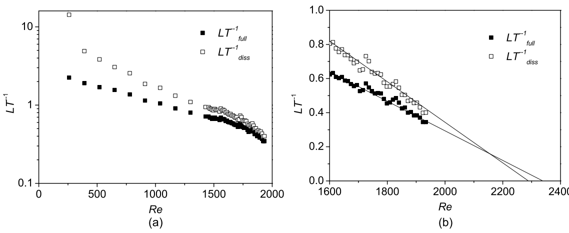


Figure 10: (a) Change of LT^{-1}_{full} and LT^{-1}_{diss} with increasing Reynolds number, (b) trend of LT^{-1}_{full} and LT^{-1}_{diss} extrapolated from the measured data in the Reynolds number range $1550 < Re < Re_{crit}$

ber reveals the divergence trend of the lifetimes of transitional structures (e.g. see, Faisst and Eckhardt, 2004; Peixinho and Mullin, 2006). Figure 10 (a) shows that LT^{-1} decreases exponentially for $Re \leq 1450$, then it stays constant up to $Re \approx 1550$ and subsequently it decreases linearly with increasing Reynolds number for $1550 \leq Re \leq 1880$. The extrapolation of the linear trend lines of LT^{-1}_{full} and LT^{-1}_{diss} plotted in Fig. 10 (b) diverge at $Re \approx 2300$, i.e. they would have infinite lifetime at this Reynolds number. In the experiments of Peixinho and Mullin (2006) divergence of lifetime occurred at $Re = 1760$ in another study Mullin and Peixinho (2006) found divergence to occur at $Re = 1695$, depending on the disturbance amplitude. Willis and Kerswell (2007) have applied direct numerical simulation and found $Re = 1870$ as the divergence Reynolds number. On the other hand, Hof et al. (2006) showed by their experimental and numerical investigations that the lifetime of transitional structures will not diverge, instead they would have extremely long but a finite value. As the lifetime diverges rapidly after for $Re > Re_{cr}$, owing to the necessary pipe lengths, it is technically close to impossible to determine directly the lifetime beyond Re_{cr} via measurements and simulations and, consequently, confirm the existence of diverging trend.

Apart from the present study, the lifetimes in the abovementioned studies were evaluated from the probability of occurrence curves. The effect of disturbance type and amplitude on the probability of occurrence of puffs and, consequently, on the derived lifetimes, can be readily seen in Mullin and Peixinho (2006). Therefore, it is not surprising that many Reynolds numbers for the divergence of lifetime were found in the literature. In order to figure out the effect of disturbance amplitude on the directly measured LT_{full}, one set of experiment with a different disturbance amplitude and duration was carried out in the pipe with $L = 566D$. The new disturbance was set for the iris diaphragm system as 40% area blockage and a lapse time of 50 ms, which are larger and longer than the previous settings (30% blockage ratio and 40 ms lapse time, respectively). Comparison of

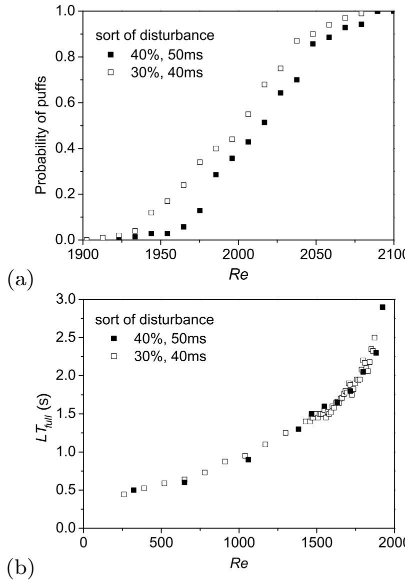


Figure 11: (a) Probability of occurrence of puffs detected by the HWA with two disturbances of different amplitudes and duration and (b) corresponding LT_{full} of transitional flow structures.

puff occurrence probability curves for two different amplitudes in Fig. 11 depicts the influence of disturbance in the probability statistics. The probability curve for the disturbance with 40% blockage starts to increase at $Re \approx 1920$ and reaches 1 at $Re \approx 2080$ and consequently shifts toward a slightly higher Reynolds number region than that of the disturbance with 30% blockage. In other words, the flow is more stable against the higher disturbance amplitude, which indicates the complexity of the relation between the disturbance amplitude, the development and the dissipation of transitional flow structures. The LT_{full} of transitional flow structures triggered by the higher amplitude collapse on those measured with lower disturbance amplitude as shown in Fig. 11 (b). In contrary to the lifetime evaluated from probability curves, matching of LT_{full} for different disturbance amplitudes suggests that the lifetimes of transitional flow structures do not depend on the amplitude of disturbances for $Re \leq Re_{crit}$. Furthermore, these results shows the necessity of the interrogation of the lifetime considerations based on probability of occurrence statistics.

CONCLUSIONS AND OUTLOOK

The lifetime of transitional flow structures in low Reynolds number pipe flow was analyzed by direct measurements of full-lifetime LT_{full} and probability of occurrence of puffs by the measurements of pressure drop transients in the pipe and velocity transients at the exit of the pipe, respectively. The direct measurement of lifetime gave information not only about the lifetime but also about the possible evolution routes of transitional flow structures in the present low-Reynolds number pipe flows investigations:

1. *Just triggered* structure occurs for $Re \leq 1450$. LT_{full} increases linearly in this Re range.
2. At $1450 \leq Re \leq 1550$, the evolution of *just triggered* structures into *developed* structures starts. LT_{full} remains constant in this range.
3. At $1560 \leq Re \leq 1880$ disturbances evolve into *developed* structures and *directly dissipating* structures. LT_{full} increases exponentially in this Re range.

4. *Sustained* structures starts to appear at $Re \approx 1880$ and their probability of occurrence increased with increasing Re in the range $1880 \leq Re \leq 2080$. It is shown that LT_{full} of sustained *dissipating structures* increase with increasing Re, whereas those of *directly dissipating* structures remains constant for $Re \geq 1880$.
5. Puff splitting and slug formation in the range $2300 \leq Re \leq 2600$ (Wygnanski et al., 1975; Nishi et al., 2008).

The last evolution route is not the topic of this study, but added for the sake of completeness.

Due to the sudden occurrence of *sustained* structures at $Re = 1880$, this Reynolds number is defined as critical Reynolds number Re_{cr} for the present investigations. For $1550 < Re < 1880$, trend lines of LT^{-1} decreases linearly with increasing Reynolds number, which shows the possibility for transitional flow structures to have an infinite lifetime at a finite Reynolds number $Re \approx 2300$.

It is shown clearly that the directly measured lifetime LT_{full} is not affected from the disturbance amplitude in contrast to those evaluated from probability of occurrence curves. It is possible to obtain lifetime τ by using the probability curves of three different length pipes shown in Fig. 5. Nevertheless, we deliberately avoid the evaluation of this quantity in this study and comparison of it with the other available data in the literature, because of the following reasons:

1. Owing to the dependence of τ on the probability curve and the dependence of probability curve on the disturbance type and amplitude, it is not expected that τ from different facilities should match.
2. Depending on the Reynolds number and the employed pipe length, different kinds of transitional structures would be involved in the probability of occurrence statistics (Fig.5 and 8). For example for $L = 200D$ at $Re \approx 1880$, one would register *directly dissipating* structures as if they are sustaining puffs. This mixture would bias our conclusion regarding the lifetime of puffs.
3. Regardless of the two issues mentioned above, for proper evaluation of τ, pipes with $L < 200D$ have to be tested so that the region where $P(\tau) \approx 1$ is better resolved.

In particular, the connection between the directly measured lifetime and those evaluated from the probability statistics are being investigated more in detail by the authors.

ACKNOWLEDGMENTS

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