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DIRECT QUANTITATIVE MEASUREMENT OF THE LIFE TIME OF LOCALIZED TURBULENCE IN PIPE FLOW

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ABSTRACT

In pipe flow at low Reynolds number, decay of localized turbulent structures is observed. As the Reynolds number is increased, the question emerges whether the life time of these structures diverges at a finite Reynolds number or remains transient. In the current investigation we determine the life *time* of localized structures quantitatively from pressure measurements, while in previous investigations the *distance* over which a structure survived has been determined. The obtained results confirm that the life time of localized turbulent structures does not diverge for this Reynolds number regime.

INTRODUCTION

One of the last unsolved problems in classical mechanics is the description of turbulence. An unexplained aspect of turbulence is the transition from laminar to turbulent flow in a pipe (Eckhardt et al. 2007). Pipe flow is the most common flow in industrial applications, where the turbulent flow state has a much higher friction than the laminar flow state.

Theoretical analysis shows that laminar pipe flow is stable for all Reynolds numbers, while in practice sustained turbulent flow exists above a finite Reynolds number (Drazin and Reid 2004). Recently, new exact solutions in the form of *travelling waves* (TW) were found as alternative solutions to the familiar Hagen-Poiseuille flow (Faisst and Eckhardt 2003, Wedin and Kerswell 2004). Later these solutions were actually observed in experimental data (Hof and van Doorne et al. 2004). It was conjectured that above a critical Reynolds number ($\mathrm{Re_c}$) these solutions form a strange attractor in state space, which would explain that a sustained turbulent flow state could exist. Early numerical simulations by Faisst and Eckhardt (2004) indicated that the life times of the turbulent flow state increases inversely proportional to $1/(\mathrm{Re} - \mathrm{Re_c})$, and thus the life time becomes infinitely large at a finite Reynolds number: $\mathrm{Re_c}$.

This would apply to localized disturbances, called 'puffs', that are created by injecting fluid and that are able to exist for times that exceed the eddy turn-over time of the flow. The divergence of the life times of these puffs at a finite Reynolds number were initially confirmed by experimental results (Peixinho and Mullin 2006) and detailed numerical simulations (Willis and Kerswell 2007). However, in both cases the total pipe length (or equivalent total simulation time) was too short to consider the very long time behaviour of puffs for life times beyond 1000 integral time scales. New experiments in a very long pipe, with a total length of about 7,500 pipe diameters, demonstrated that the life time does not decay according to $1/(\mathrm{Re} - \mathrm{Re_c})$, but rather exponentially (Hof et al. 2006). This has the important implication that in a pipe flow turbulence is not a sustained flow state, but remains a transient.

In a more recent study, using a similar approach as Hof

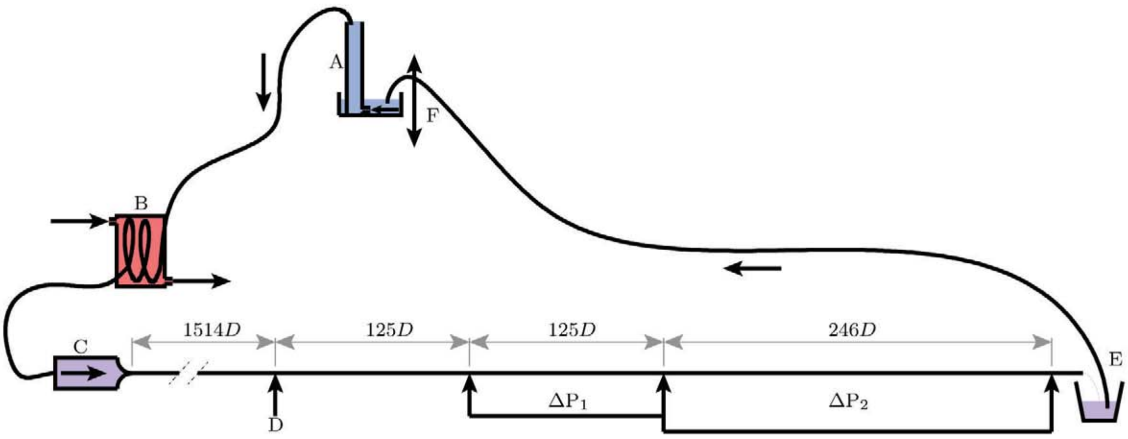

Figure 1: Schematic drawing of the used experimental facility (not to scale), A) contineously overflowing reservoir which can be traversed: indicated by F, B) counter flow heat exchanger, C) flow conditioner D) disturbance mechanism, E) pipe exit, with return line through which the fluid is pumped back regularly into reservoir A, ΔP_1) first section over which the pressure drop is measured, ΔP_2) second section over which the pressure is measured, the length of each pipe section is indicated above the corresponding section

et al. (2006), Hof et al. (2008) determined the life time distribution over 8 orders of magnitude in time. Concluding that the scaling, over this large range in time, is superexponential rather than exponential. Although a different scaling is found, it still supports the view that turbulence in pipe flow remains a transient.

In all previous life time investigations the life time was determined by visual inspection. Peixinho and Mullin (2006) observed the decay of puffs by visualizing the flow using Mearlmaid Pearlessence. From 20 to 50 observations per Reynolds number the life time was determined. Hof et al. (2006) determined the probability a disturbance survived after a fixed distance by determining the flow state on the outflow angle. About 50 observations per distance and Reynolds number were used for the statistics. In the present paper we determine the life time of a puff quantitatively based on pressure drop measurements for at least 1000 measurements per Reynolds number.

EXPERIMENTAL FACILITY

Pipe section

For the present investigation we built a 2030 diameter (D) long precision bored glass pipe with a diameter of 10 ± 0.01 mm. The pipe consists of 16 sections with a length between $120D$ and $130D$ each supported individually by two metal holders. Each section was aligned using a laser beam and two apertures, resulting in a estimated maximum error of 0.5 mm over the entire length of the pipe. The sections were connected using PMMA push fittings with the same inner diameter, resulting in no measurable gap between a section and the connector or difference in the diameter. Each connector was equiped with one up to six, 0.5 mm diameter ports, either used for applying the disturbance or for measuring the pressure.

Before the flow enters the pipe, the fluid passes a settling chamber containing several meshes with reducing grid size to get rid of remaining fluctuations of the entering fluid, followed by a contraction (contraction ratio ten to one). With laser Doppler anemometry (LDA) the base flow was checked by measuring a velocity profile $2000D$ downstream of the entrance at $\mathrm{Re} = 1750$, the result is presented in figure 3. In the same figure the calculated Poiseuille profile based on the flow rate is given by the dashed line, showing excellent agreement between the expected and measured velocity profile.

The base flow is also checked by meausuring the pressure drop using an inverted u-tube manometer and the flow rate. The results are presented in the figure 2, showing that laminar flow can be maintained beyond $\mathrm{Re} = 8 \cdot 10^3$. However, measuring the pressure drop by an inverted u-tube introduces a disturbance into the flow when the pressure drop changes. When the inverted u-tube was removed and the flow state was judged on the outflow angle, laminar flow was observed beyond $\mathrm{Re} = 9 \cdot 10^3$, i.e. disturbances due to fluid in and out the manometer cause transition.

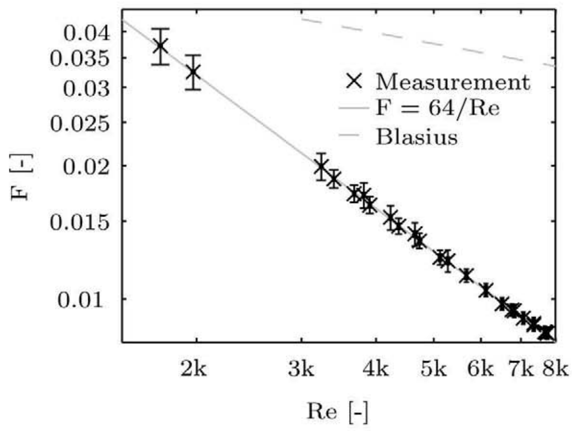

Figure 2: Friction factor vs Reynolds number, errorbars indicate an estimate of the total experimental error.

Flow rate control and driving

The flow through the pipe is driven by a constant pressure head of approximately 3 m water column. An overflowing reservoir ensures a constant water level and therefore a constant pressure drop. The fluctuations on the free surface were minimized by supplying the fluid from the bottom of the reservoir and using flow straightners. The flow rate through the pipe setup could be adjusted by changing the height of the overflowing reservoir with respect to the pipe exit using a traverse.

From the overflowing reservoir, the fluid flows through a feeding line of 25 m and diameter of 6 mm before entering the settling chamber. The smaller diameter causes the

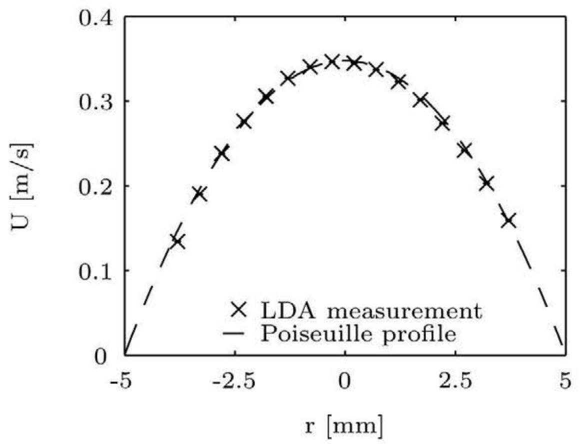

Figure 3: Measured velocity profile at Re = 1750, dashed line is the calculated Poiseuille velocity profile based on the mass flow. The maximum standard error on the mean velocity is $3 \cdot 10^{-4}$ m/s

Reynolds number to be 1.3 times higher in the feeding line than in the main pipe setup. Since the feeding line does not have a smooth entry, the flow in the feeding line was turbulent over the full Reynolds number range. The total pressure drop is dominated by the pressure drop over this feeding line, because the flow in the feeding line was turbulent, ensuring that the flow rate in the setup is independent of the flow state in the glass pipe section. This can be easily verified by the following analytical considerations:

Assume we have a pipe with length $L_1 = 2000D_1$, $D_1 = 10$ mm, water of $20°C$ is flowing through the pipe with a bulk velocity of 0.2 m/s resulting in Re = 2000 and the flow is laminar. Upstream of this pipe with laminar flow is a feeding line of $L_2 = 4000D_2$ with $D_2 = 6$ mm. Given that mass flux is conserved, Re = 3333 in the feeding line: the flow is considered turbulent, since strong fluctuations are present in the inlet of the feeding line. The total pressure drop is, ignoring minor losses, equal to

$$\Delta P = \underbrace{f_{lam}\frac{L_1}{D_1}\frac{8Q^2}{\rho\pi^2 D_1^4}}_{\Delta P_1} + \underbrace{f_{2_{turb}}\frac{L_2}{D_2}\frac{8Q^2}{\rho\pi^2 D_2^4}}_{\Delta P_2} \qquad (1)$$

where $f_{lam} = 64/\mathrm{Re}$ is the friction factor of the laminar flow, $f_{2_{turb}} = 0.3164/\mathrm{Re}^{1/4}$ the friction factor of the turbulent flow, Q the mass flow rate and ρ the density of the fluid (Schlichting 1968). Equating the pressure contribution of each part yields that $\Delta P_1 < 20\Delta P_2$: the pressure drop is dominated by the feeding line.

When the flow is perturbed a puff is generated. The additional pressure drop caused by the puff can be modelled by assuming fully developed turbulent flow over a length of $L_{puff} = 20D$. Substituting these assumptions in (1) yields for the pressure drop with a puff present in the pipe:

$$\Delta P = f_{lam}\frac{L_1 - L_{puff}}{D_1}\frac{8Q_{wp}^2}{\rho\pi^2 D_1^4} + f_{1_{turb}}\frac{L_{puff}}{D_1}\frac{8Q_{wp}^2}{\rho\pi^2 D_1^4} + \Delta P_2 \qquad (2)$$

We want to know what the change in flow rate is when the total pressure drop remains constant. By equating (1) and (2), the ratio of flow rates can be expressed as

$$\frac{Q}{Q_{wp}} = \sqrt{\frac{f_{lam}\frac{L_1 - L_{puff}}{D_1^5} + f_{1_{turb}}\frac{L_{puff}}{D_1^5} + f_{2_{turb}}\frac{L_2}{D_2^5}}{f_{lam}\frac{L_1}{D_1^5} + f_{2_{turb}}\frac{L_2}{D_2^5}}} \qquad (3)$$

Substituting the values given above for all parameters, yields that the flowrate decrease due to the presence of a puff is less than 0.01%, so effectively the mass flow is constant. In constant mass flux experiments, the flow rate could be adjusted within 1% accuracy (Mullin and Peixinho 2004). Therefore the current setup can be considered as a constant mass flux setup.

Temperature control and measurement

In the experiments performed by Hof et al. (2006) the flow rate was controlled in a similar way as in the current setup. However, the temperature was not controlled in these experiments and therefore changed with ambient temperature. This results in an uncontrolled variation in Reynolds. Since his setup was situated in an environment with minor ambient temperature variations, the variations in ambient temperature were limited. In the currenct setup the variations in ambient temperature are larger. To reduce the uncertainty in Reynolds number, a heat exchanger is incorporated in the current setup.

Ten metres of the 25 m feeding line is made of copper tubing. Around this copper tubing temperature controlled water is forced, thereby creating a counter flow heat exchanger. Although these measures considerably reduced the variations in temperature, the temperature of the working fluid varied by $\pm 0.3°$ C. Therefore the Reynolds number was determined a posteriori for each measurement.

The absolute fluid temperature was monitored by means of a mercury thermometer. A PT100 probe or thermocouple were not suitable to measure the absolute temperature because both devices showed a drift with changing ambient temperature. After every measurement, an image of the thermometer was recorded by a Kodak es 1.0 digital camera. By image processing the temperature could be measured in this way accurately within $0.1°$ C.

Disturbance

De Lozar and Hof (2009) showed that the scaling of the characteristic life time of disturbances does not depend on the type of disturbance used. They used three types of disturbances: a single point injection, an obstruction in the pipe and a "push-pull" disturbance, which injects and extracts fluid at the same time from opposite holes. Although the life times did not change, the time needed for the system to become turbulent: the initial formation time, did. The push-pull disturbance is used in the current experiments, because it minimized the disturbance to the flow up and downstream of the disturbance point.

A puff was generated by pumping fluid, with a small centrifugal pump, from one port to the opposite port of a pipe assembly connector, thereby creating a zero mass flux disturbance. The disturbance was applied approximately 1514D from the entrance, to ensure the flow was fully developed and that no spontaneously generated disturbances were present in the pipe. The amplitude of the disturbance, defined as the mass flux of the disturbance over the mass flux of the pipe, was equal to 0.1. This amplitude is above the critical amplitude to create a puff (Darbyshire and Mullin 1995). The flow was disturbed for 1.1 to 1.2 D/U, which is considerably shorter than the disturbances applied previously (Hof et al. (2006), Hof et. al. (2008) and de Lozar and Hof

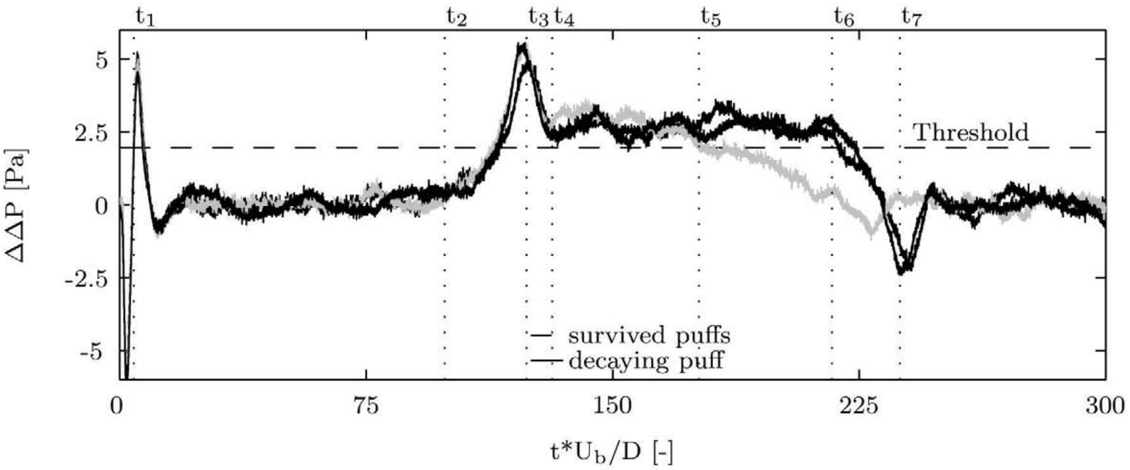

Figure 4: Instantaneous pressure drop measurements at Re = 1822, over a pipe section of $125D$, $125D$ downstream of the disturbance. The dashed line indicates the threshold used to determine the life time of an applied disturbance.

(2009)). Therefore it is expected that the initial formation time will be longer for the current investigation compared to the formation time reported by these authors.

Experimental Method

Before a series of experiments was started, the flow rate was set to obtain the desired Reynolds number. Then the following steps were continuously repeated. First the pressure drop acquisition was started, followed after half a second by the introduction of the disturbance. After a fixed time the LDA acquisition was started. Each measurement was finished by acquiring an image of the thermometer to measure the temperature. Before a new measurement was started we made sure no disturbance was present in the pipe anymore. At regular time intervals the flow rate was checked at the pipe exit by measuring the mass of the fluid leaving the pipe over approximately 200 seconds.

RESULTS

Pressure drop measurements

The pressure drop was measured by two Validyne DP45 differential pressure transducers. These pressure transducers have a full range of 150 Pa and are accurate within 0.5%.

The pressure drop was measured by one pressure transducer between $125D$ and $250D$ downstream of the point where the disturbance was introduced. The second pressure transducer was used to measure the pressure drop between $250D$ and $496D$. In figure 4 a typical pressure measurement for the first transducer is given. For clearity only the additional pressure drop is shown, hence the pressure drop caused by the laminar flow equals zero.

Although a zero mass flux disturbance is used, the effect of applying the disturbance is clearly visible as a large peak in the additional pressure drop at t_1. A negative additional pressure followed by a possitive additional pressure is observed, indicating a deceleration followed by an acceleration of the fluid downstream of the disturbance point.

If a puff passes a pressure transducer, we expect, based on the analysis by Rotta (1956), that the pressure drop first increases and then shows a maximum. A maximum is reached due to the presence of an adverse pressure gradient at the rear of a puff, caused by the transition from laminar to turbulent flow at the transition interface. When the puff leaves the domain covered by the pressure transducers, a sub-laminar pressure drop is expected when only laminar flow and the adverse pressure gradient part is inside the domain covered by the pressure transducer.

The pressure measurement in figure 4 clearly confirms this trend. The front of the puff enters the domain at t_2. At t_3 the maximum pressure drop is reached and at t_6 the front of the puff leaves the domain agian and we see a sub-laminar pressure drop at t_7. As long as the entire puff is inside the measurement domain, between t_4 and t_6, the additional pressure drop is constant.

However, one of the three measurements shows a different behaviour starting at t_5. Until this time the behaviour for all three cases is identical, but at t_5 the additional pressure drop decreases to the zero for the pressure measurement plotted in gray. In the next section it is shown that the total pressure drop can be related to the length of the puff. Therefore if the total additional pressure drop decreases either the length of the puff decreases or the turbulece intensity decreases: indicating the decay of the disturbance. The time at which the disturbance decays is found by defining a threshold value. If the additional pressure drop, drops below this threshold value the disturbance is considered to be decayed.

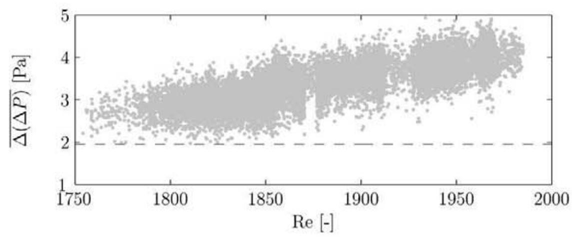

Figure 5: Mean pressure increase due to the presence of a puff vs Reynolds number. The dashed line indicates the threshold used to determine when the puff decayed.

Threshold determination

To determine the threshold used for finding the decay time of a puff, the mean pressure increase due to the presence of the entire puff is calculated. Only the additional pressure between t_4 and t_6, indicated in figure 4, contributes to this mean. Therefore only puffs that survived beyond t_7 are taken into account. In figure 5 the mean additional pressure drop is presented. Each point in this figure represents a single measurement.

In order to correctly determine the life time of a puff, the threshold should not be higher than the mean additional pressure. The threshold used here is indicated by the dashed

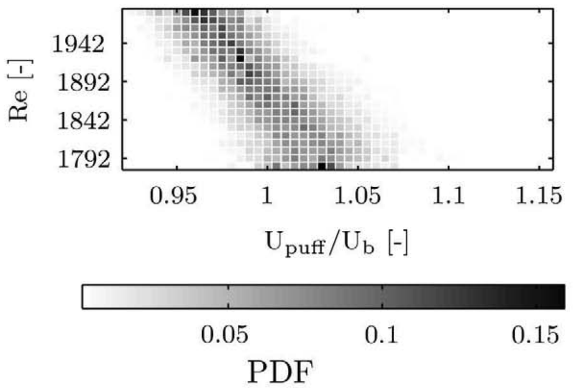

Figure 6: Mean convection velocity of a disturbance over the *first* $125D$ after applying the disturbance

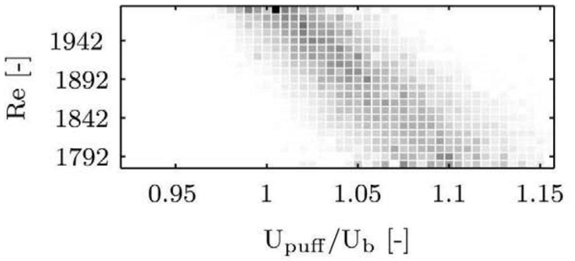

Figure 7: Mean convective velocity of a disturbance over the *second* $125D$ after applying the disturbance, gray scale ranges are the same as in figure 6

line in figure 5 and is lower than the mean additional pressure over the entire Reynolds number range. The life time is determined by the time at which the additional pressure falls below this threshold.

Puff velocity

In previous life time experiments, e.g. Hof et al. (2006), Peixinho and Mullin (2006) and Hof et al. (2008), the survival *distance* was used instead of the survival *time*. By using the advection velocity of the puff the survival distance can be found.

The average advection velocity of a disturbance was determined from the pressure traces as given in figure 4. By measuring the time needed by the puff to reach the first pressure port, we can determine the average velocity over the first $125D$. In figure 6 a pdf of the *average* velocity, with respect to the bulk velocity, over the first $125D$ is given as function of Reynolds number. The same is given for the second $125D$, between $125D$ and $250D$ after the disturbance, in figure 7. In both figures the same trends can be observed: The velocity of the disturbance, with respect to the bulk velocity, decreases linearly for increasing Reynolds number. Next to that, the distribution of observed velocities broadens with decreasing Reynolds number. The most important observation is that there is a considerable variation in the mean velocity of a puff at a given Reynolds number.

Although the same trends can be observed for the velocities in the two sections of the pipe, there are differences. The mean velocity at a given Reynolds number is higher in the second section. This indicates that after the generation of the disturbance the puff accelerates. The velocities observed in the second $125D$ correspond very well to the values found by Hof et al. (2005). Nishi et al. (2008) also observes accelerating puffs and they found that after a short time the advection velocity becomes constant. However, neither the

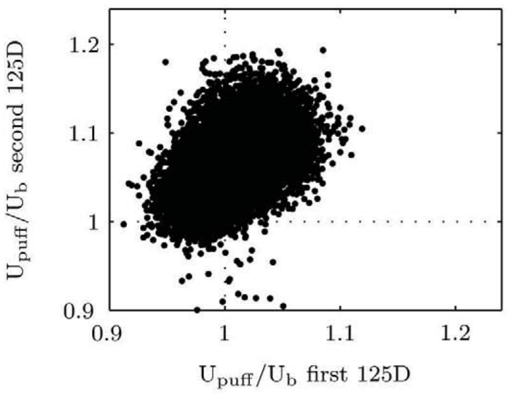

Figure 8: Correlation between the velocity of a disturbance in the first $125D$ and the velocity in the second $125D$, for the distribution of the velocity see figures 6 and 7

results of Hof et al. nor the results of Nishi et al. were based on single observations and therefore they did not observe the variations that can be seen here.

In figure 8 the correlation between the velocity in the first $125D$ and the second $125D$ is given. If the advection velocity of a puff would be constant as it travels downstream, we would expect a high correlation. It is clear from figure 8 that the velocity of a puff is not constant as it travels downstream.

Life time of disturbances

For each measurement the life time of the disturbance was determined by the time at which the additional pressure dropped below the prescribed threshold. Then the measurements were sorted based on their Reynolds number, resulting in at least 1000 measurements per Reynolds number.

Using the mean advection velocity of a disturbance, the position at which the disturbance decayed was obtained. Now the probability a disturbance survived up to a certain distance could be derived. This probability is presented in figures 9 and 10.

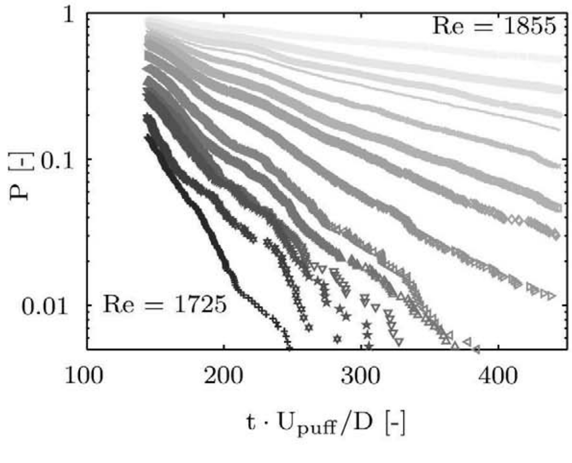

Figure 9: Probability a introduced disturbance survives over a distance $t \cdot U_{puff}/D$, for Reynolds number ranging from 1725 ± 5 up to 1855 ± 5 in steps of 10. At each Reynolds number at least 1000 measurements were performed.

The distributions given in figures 9 and 10 show clearly that the tails of the decay are of exponential nature and thereby confirming that the appropriate description of the decay can be given by:

$$P(t - t_0, Re) = \exp\left((t - t_0)\,\tau^{-1}(Re)\right) \tag{4}$$

Even at Reynolds numbers above 1900 the exponential decay of puffs is observed. By fitting a straight line through the curves given in figures 9 and 10 both the initial formation time t_0 and the inverse of the characteristic life time τ^{-1} can be determined.

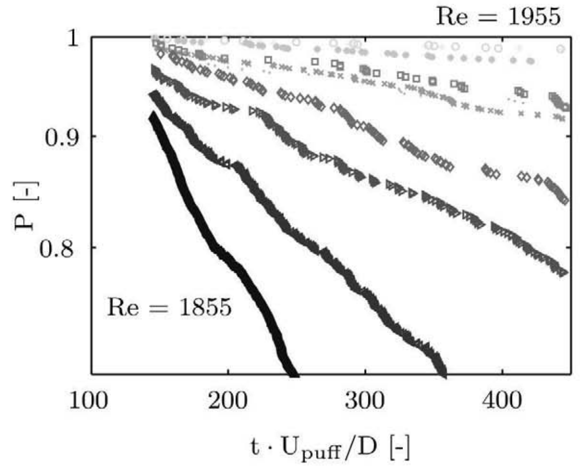

Figure 10: The same as figure 9 but here Reynolds numbers range from 1855 ± 5 to 1955 ± 5, in steps of 10

The inverse of the characteristic life time is presented in figure 11 together with the recent results obtained by Hof et al. (2008). An excellent agreement is observed, and therefore these results support that the correct dynamical model of linear stable shear flows is that of a strange repeller.

To show the robustness of the present detection method, the results obtained for different tresholds is given in figure 11. Only for low Reynolds numbers and high thershold values a larger variation is observed, which could be expected because the threshold is now higher than the average additional pressure for a number of measurements at these Reynolds numbers. For almost all Reynolds numbers the characteristic life time found is independent of the threshold used.

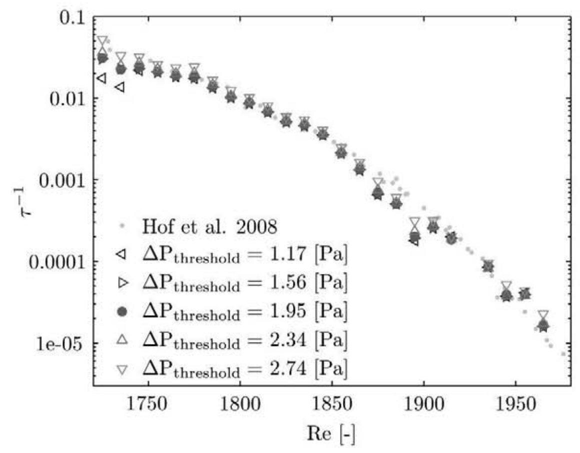

Figure 11: Inverse of the characteristic life time for different thresholds, showing that the obtained results do not depend on detection threshold

CONCLUSIONS

In the present paper we showed the direct measurements of the life *time* of turbulent structures by pressure measurements. To our knowledge this is the first time the life *time* of puffs is measured *quantitatively*, because in previous investigation the *distance* over which a turbulent structure survives has been determined by visual inspection. The results show excellent agreement with the results of Hof et al. (2008) and therefore support that the life time of puffs does not diverge for a finite Reynolds number, but rather increases exponentially. The exponential scaling of the life times supports the notion that turbulence in a pipe is a transient flow state for this Reynolds number range.

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