PHASE TRANSITION TO SUSTAINED TURBULENCE IN PIPE FLOW

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Abstract In a pipe, the onset of turbulence is intermittent in both space and time, and undergoes a phase transition to sustained turbulence at a critical Reynolds number. This transition has not been quantified so far due to the extremely long observation times needed near the critical point. In this paper, we exploit the memoryless nature of the turbulence proliferation and decay processes at Reynolds numbers around the onset of turbulence, to construct a pipe with quasi-periodic boundary conditions. This allows us, for the first time, to directly measure the asymptotic evolution of turbulent flow and to study the phase transition to sustained turbulence.

CONTEXT

In spite of the considerable attention it has received, several aspects of the transition to turbulence in a pipe flow continue to be poorly understood [4, 6]. Turbulence in a pipe first arises at Reynolds numbers (Re) a little below 2000, in the form of localized structures called puffs. Though these puffs can decay, turbulence can also spread by a process called puff splitting, which generates a new puff downstream of the existing one [9, 7]. The flow undergoes a phase transition to sustained turbulence at a critical Reynolds number above which turbulence proliferates faster than it decays. The critical Reynolds number has been recently estimated to be Re = 2040±10 [1].

In order to quantify the phase transition in pipe flow, we plan to determine the equilibrium turbulent fraction as a function of Reynolds number close to the critical point. In order to do this, the spatial interaction between puffs is the crucial process that needs to be quantified. However, near the critical point, decay and spreading of puffs occur very rarely (at Re = 2040, the mean lifetime of a puff before it splits or decays is of the order of 10^7 D/U). Observing puffs for such long times would then require pipes longer than 10^7 D, making direct measurements close to criticality impossible. The principal idea here is to exploit the memoryless nature of the puff decay and splitting processes [5, 1]. While the internal dynamics of puffs are highly chaotic, quickly erasing any memory of initial conditions, they travel downstream at a fixed average speed (U) and size, without aging. In this paper, we present an experimental set-up in which the laminar turbulent pattern exiting the pipe can be reintroduced at the pipe entrance. Thus the overall pattern can now evolve, and if puffs are indeed memoryless, will settle to an equilibrium fraction after time scales much longer than the passage time through the pipe. One can then examine the nature of the phase transition in pipe flow and uncover any universal properties it shares with transitions in other systems and models that exhibit spatio-temporal intermittency [8, 2, 3].

EXPERIMENT

The experiments are carried out in a glass pipe with an inner diameter of D = 4.00 ± 0.01 mm and a length of 2700 D. A continually overflowing reservoir supplies water to the pipe, ensuring a well defined pressure difference that drives the flow. The water at the pipe outlet is automatically collected for fixed amount of time (typically 100 seconds) and weighed, thus obtaining the flow rate at regular intervals with an accuracy of better than 0.1%. A feedback loop monitors the flow-rate and water temperature, and adjusts the height of the reservoir if needed, indefinitely maintaining the Reynolds number constant with an extremely high accuracy (within 0.075% of the desired value).

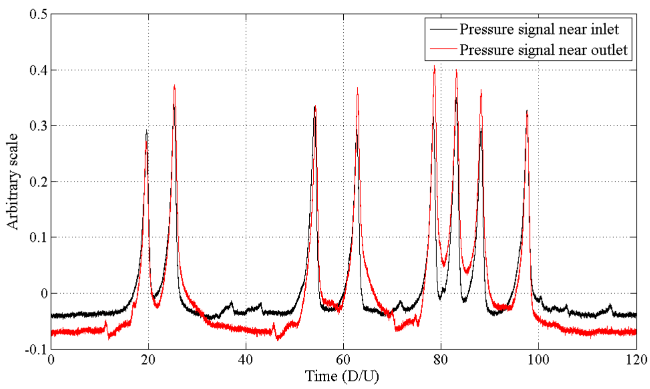

Figure 1. Signals from the pressure sensors showing that the puff sequence is well reproduced

Puffs are generated 150 D from the pipe entrance by perturbing the flow for a period of around 1 D/U by a transverse jet of water. Pressure sensors are used to monitor the flow 50 D (near the inlet) and 2500 D (near the outlet) downstream of the injection point, a puff appearing as a localized peak in the pressure signal. To observe the asymptotic evolution of the flow at a given Reynolds number, an arbitrary sequence of puffs (corresponding to a given turbulent fraction) is injected in the flow and serves as the initial condition As they pass the downstream sensor, the pressure signal from the sensor is used to determine the spacing between successive puffs. By controlling the time between successive perturbations, puffs with the same spacings are generated at the injection point. The signal from the upstream sensor is used to verify that the generated puffs have the required inter-puff spacing. Due to the memoryless nature of the decay or splitting of puffs, this procedure does not, on the average, change the evolution of the flow. Figure 1 shows a comparison of the pressure traces from the downstream and upstream sensors showing that the sequence of puffs is well reproduced. The analysis of the downstream signal, the generation of puffs with the required spacings and the verification are all carried out in real time with a LABVIEW program. This quasi-periodic pipe then allows us to follow the evolution of the flow indefinitely, permitting direct observations of the asymptotic state.

RESULTS

At Re lower than 2040 we find that the turbulent fraction regardless of the initial conditions (i.e. number of and spacing of puffs in the pipe) eventually always goes to zero, albeit close to 2040 this process can take more than 10^7 D/U (several days measurement time in our experiment). At Re higher than 2040 on the other hand, we indeed find that the flow always evolves to a fixed equilibrium turbulent fraction which only depends on Re and is independent of initial conditions. Figure 2 shows the time evolution of the flow at Reynolds number of 2100, where the flow reaches the same average turbulent fraction starting from initial puff sequences with differing initial turbulent fraction. Hence the experimental procedure proposed above works and this suggests that this experimental technique will for the first time allow us to characterize the phase transition from laminar to turbulent flow in pipe flow. We will present the first data on the critical exponents characterizing this transition.

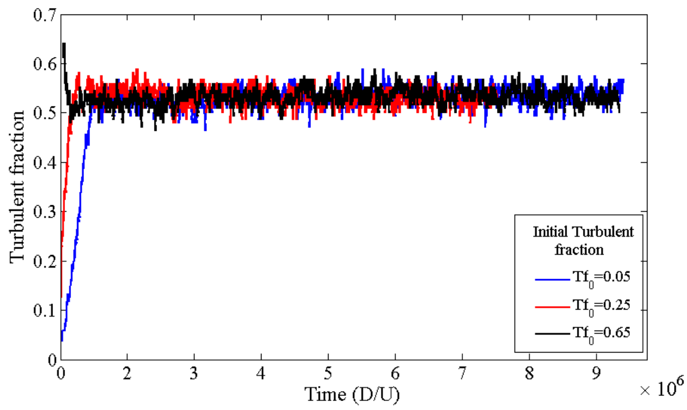

Figure 2. Time evolution of the turbulent fraction at Re = 2100, showing that the flow reaches a well defined asymptotic state, irrespective of the initial turbulent fraction.

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