RELAMINARIZATION OF WALL TURBULENCE BY HIGH-PRESSURE RAMPS AT LOW REYNOLDS NUMBERS

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Summary
Reverse transition from the turbulent towards the laminar flow regime was investigated experimentally by progressively increasing the pressure up to 400 MPa in a fully developed pipe flow operated with silicone oil as the working fluid. Using hot-wire anemometry, it is shown indirectly that at low Reynolds numbers a rapid increase in pressure modifies the turbulence dynamics owing to the processes which induce the effects caused by fluid compressibility in the region very close to the wall. The experimental results confirm that under such circumstances, the traditional mechanism responsible for self-maintenance of turbulence in wall-bounded flows is altered in such a way as to lead towards a state in which turbulence cannot persist any longer.

INTRODUCTION

From the analysis of numerical databases obtained from DNS it appears that compressibility of fluid acts to increase the anisotropy of turbulence by decreasing the pressure-strain correlations in the region very close to the wall where turbulence show pronounced tendency to tend towards the one-component state with invariance to rotation about the axis aligned with the mean flow [1]. The present paper is therefore centered around the following fundamental hypothesis: Is it possible to influence the dynamics of wall turbulence by a sudden increase in pressure through rapid variation of the physical properties of the flow medium and in this way force initially fully developed turbulence to return back to the stable laminar state?
The objective of the paper is to confirm the above mentioned hypothesis and in this context verify further the results and the idea of the theoretical investigations of Jovanović and Hillerbrand [2], who examined constraints which lead to complete suppression of the velocity fluctuations near the wall. They showed analytically, using only kinematic constraints, that the effective way to damp fluctuations in the near-wall region is to force them to be predominantly one-component. For this very special state of wall turbulence, it can be proved analytically and confirmed numerically, using the databases from direct numerical simulations, that the turbulent dissipation rate must vanishes at the wall $\epsilon_{\rm wall} \to 0$. Using a Taylor series expansion of the instantaneous velocity fluctuations about the wall ($x_2 = 0$) which satisfies the continuity equation Jovanović and Hillerbrand showed that the effective amplification of turbulent kinetic energy across the viscous sublayer is entirely determined only by the value of $\epsilon_{\rm wall}$:

$$k = \frac{1}{2}\,\frac{\epsilon_{\rm wall}}{\nu}\,x_2^2\;+\;...\,,\qquad \text{as}\quad x_2 \to 0. \tag{1}$$

The above limiting behavior of k suggest that if turbulence reaches the one-component state at the wall it cannot be amplified at all (since $\epsilon_{\rm wall} \to 0$ in this limit) and therefore laminarization of flow must occur as a logical consequence.

RESULTS

Since there is no experimental evidence available on the appearance of turbulence at high pressures in the range P = 10-400 MPa, the goal of the experimental investigations was to provide first evidence how turbulence is modified at high pressures. Such experiments have been attempted employing hot-wire probes and constant-temperature anemometry in a specially designed autoclave, shown in Fig. 1, which was pressurized by pumping liquid through long circular tube in which fully developed flow was maintained.
For initial experiments, silicon oil was chosen as the working fluid since it is a very low electrically conductive medium and therefore permits the application of both hot-wire and hot-film probes. By varying the pressure ramps and by measuring the volume flow rate, pressure and temperature during pressurization well-defined conditions were ensured to permit parameterization of turbulence development.
Figure 2 shows typical trace recorded from hot-wire probe located at the pipe centerline and very close to its exit. During the pressurization process fully developed turbulent flow is established initially with the bulk Reynolds number of $Re \simeq 1\times 10^4$. During progressive increase of pressure turbulence level increases showing evidence of intermittency in the hot-wire signal caused by swapping of the velocity profile between fully turbulent and laminar flow states. Results displayed in Fig. 2 suggest that complete suppression of turbulence and flow relaminarization occur at pressure of about 150 MPa and the Reynolds number of about $Re \simeq 4\times 10^3$. The results displayed in Fig. 2 clearly demonstrate that high pressure ramp is capable of producing complete relaminarization of a fully developed turbulent pipe flow.

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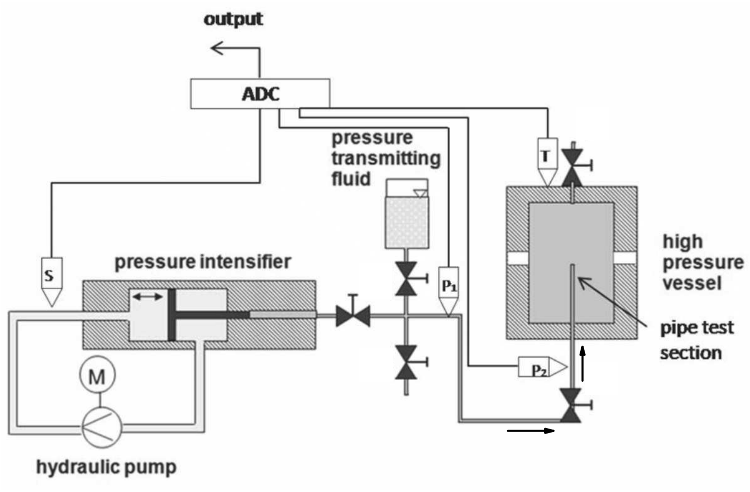

Figure 1. Experimental set-up for the investigation of reverse transition in pipe flow during rapid pressurization.

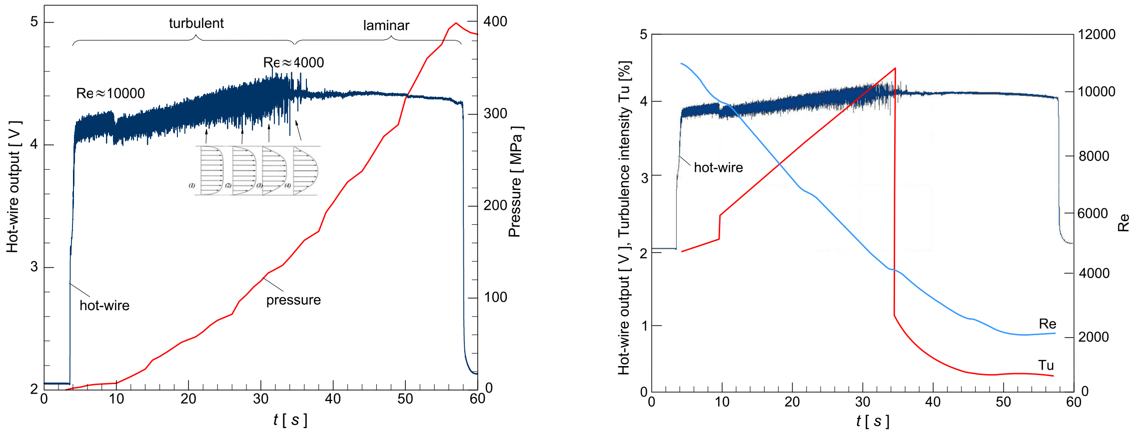

Figure 2. Hot-wire trace recorded close to the pipe exit during rapid high-pressure variation up to $P \approx 400$ MPa. In the recorded signal, it is possible to distinguish periods of turbulent and laminar flow states during the pressure build-up phase (left).Variations of estimates of the turbulence intensity and bulk Reynolds number during rapid compression leading to flow relaminarization (right).

CONCLUSIONS AND OUTLOOK

The reverse transition from fully developed turbulence towards a stable laminar regime under the influence of high-pressure ramps was studied experimentally in a pipe flow.A specially designed high-pressure facility was built which permitted flow investigations under rapid compression of liquids up to 400 MPa employing hot-wire anemometry. Mass flow fluctuations measured at the pipe centreline and very close to its exit reveal that by applying pressure ramps and using silicone oil as the working fluid, reversion of the turbulent to the laminar regime occurred at Reynolds numbers for which commonly only the turbulent regime prevails. The reversion process was observed to be accompanied by an increase in turbulence intensity and it is argued that this observation is due to the alternation of the instantaneous velocity profiles between turbulent and laminar flow regimes.

The conclusion to be drawn form the presented experimental results is that the observed effect of flow relaminarization is in agreement with the expectation that rapid changes in the fluid density during the compression process reduce the turbulent dissipation and therefore the spectral separation between large- and small-scale motions which finally lead to complete relaminarization.

References

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[2] Jovanović J., Hillerbrand R.: *J. Thermal Sci.* **9**:3–12, 2005.