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On flow instability in the developing region of pulsating pipe flow

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Abstract

This study is concerned with the phenomenon of flow instability in the developing region of a pulsating pipe flow. The cases reported illustrate that small disturbances may develop in the developing region, which appear intermittently in every pulsating cycle. The on-set of the flow instability was attributed to the inflection-point instability mechanism. The flow instability phenomenon was further manipulated by introducing a trip wire at the inlet of the pipe flow. The impact of trip wire to the flow instability was examined.

1. Introduction

Since Reynolds (1883), the laminar-turbulent transition phenomenon in a pipe flow has been investigated extensively. For steady pipe flows, the transition process may be characterized by a single parameter solely, known as the Reynolds number based on the bulk velocity and the diameter of the pipe flow. Nevertheless, in unsteady flows, for instance, the cases of arterial blood flows and fluid in transportation pipelines, the laminar-turbulent transition process could be dependent upon more than one parameter.

This study is concerned with the flow instability in a pulsating pipe flow, which is relevant to the situation of the on-set of the laminar-turbulent transition process. In an earlier work, Miau et al. (2016) studied the growth of instability in the developing region of pulsating pipe flow. The authors pointed out that the flow instability could be explained with the inflection point instability mechanism (Rayleigh, 1880). Ohmi et al. (1982a) conducted a series of experiments to examine the behaviors of flow disturbances in pulsatile pipe flows, and classified the laminar-turbulent transition process into three types with respect to the flow conditions. An earlier work by Hino et al. (1976) classified the flow regime into five regions, each of which featured different characteristics of flow. Moreover, Ohmi et al. (1982b) studied the relaminarization process of the intermittent disturbances after its growth temporally. A criterion was then proposed to characterize the relaminarization phenomenon. In the literature, the process of relaminarization has caught attention in a number of physical flows. One may refer to Narashima and Sreenivasan (1979) and Sreenivasan (1982) for those of which the relaminarization processes were remarkably noted.

This study is aimed to investigate the intermittent flow instability in the developing region. First of all, a case of which the flow instability taking place in the accelerating phase is reported. This case would not be possibly explained if the flow instability would have been reasoned due to the viscous mechanism (Gad-el-Hak and McMurray, 1984). Subsequently, the flow instability phenomenon was manipulated by introducing a trip wire at the inlet of the pipe flow. Discussion on the impact of the trip wire was carried out subsequently.

2. Experiment method

The experiment was made in a pulsating pipe flow facility with air as the working fluid. The flow system was equipped with a straight pipe section of 85 D long, where D = 50 mm denoting the diameter of the pipe. In order to reduce the turbulence intensity at the inlet of the pipe flow, a convergent section with a honeycomb were installed upstream of the straight pipe section. Two pressure taps were located at the inlet and exit planes of the convergent section, respectively, for obtaining a reference velocity, called U_a. Under the steady flow condition, U_a could be varied over a range of 3-50 m/s.

The present pulsating pipe flow was produced by a rotating disc situated at 82.5 D downstream of the inlet of the pipe section, which was driven by a servo motor. A photo sensor was installed under the rotating disc to provide the information of the rotation; two pulsating cycles were generated by one revolution of the rotating disc. The pulsating flow produced can be described by three independent parameters, namely, Re_u, Re_m and α. Re_u denotes the Reynolds number characterizing the time-mean flow, based on the time-mean velocity of the pulsating pipe flow, U_a, and D. Re_m is defined according to the amplitude of velocity modulation, ΔU, and D, where ΔU denotes the pulsating amplitude corresponding to the difference between the maximum and mean velocities measured at the core of the inlet of the pipe flow. α is defined as R/δ, known as the Womersley number, where R denotes the radius of the pipe, R = D/2, and $\delta = (\upsilon/\omega)^{1/2}$ characterizes the viscous diffusion thickness due to pulsation. δ is also known as the thickness of the Stokes layer in an oscillatory flow (Kerczek and Davis, 1974).

A boundary-layer type hot-wire probe was employed to obtain the real-time velocity signals in the present pulsating pipe flow. The hot-wire probe was traversed radially from r/R = 0 to 0.98, where r denotes the radial distance from the center of the pipe. At each of the positions measured, the hot-wire signals were sampled at a rate of 4 kHz over a time length of at least 50 revolutions of the rotating disc for phase averaging.

In this study, the flow instability was manipulated by a trip wire installed at x/D = 0.5, where x/D=0 denotes the streamwise location at the inlet of the pipe flow section. See Fig. 1 for an illustration of the installation of the trip wire. In this study, two kinds of trip wires were employed, whose diameters were 0.5 and 1 mm, respectively, which correspond to 1% and 2% of the diameter of the pipe.

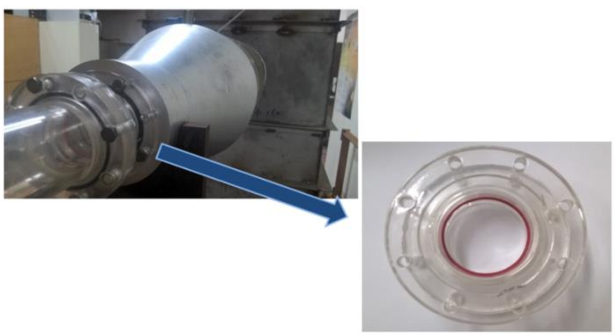


Fig. 1: An illustration of the trip wire at the inlet of the pipe flow.

3. Results and discussion

The flow disturbances concerned in this study are required to be small in amplitude, in order that the flow instability can be treated as linear. To comply with this consideration, during the experiment we were particularly keen at the situations where the disturbances were small in amplitude, i.e. in the order of 1% of U_a.

The results reported in this paper are divided into two parts corresponding to the cases without and with the installation of the trip wire, respectively. The experimental parameters of these cases are listed in Tables 1 and 2.

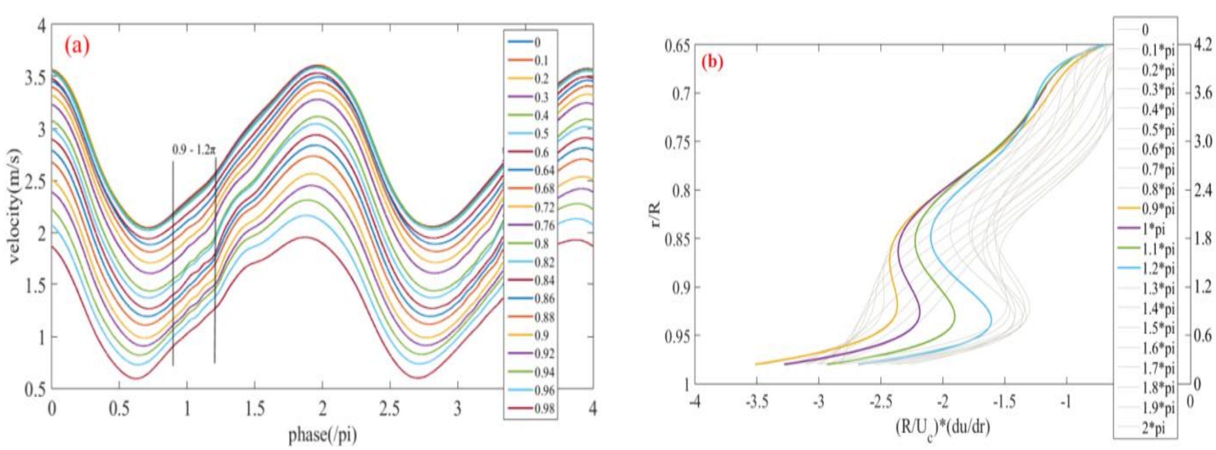
Table 1. The cases studied without trip wire

Case	Br (%)	x/D	α	Re_u	Re_m	f_d	Ω	l/δ
A	85	36	12	8.6×10^3	2.8×10^3	----	----	----
B		41		9.1×10^3	2.6×10^3	9.41	0.12	1.8

Table 2. The cases using trip wire

Case	Br (%)	D_t/D (%)	x/D	α	Re_u	Re_m	f_d	Ω	l/δ
C	85	1	36	12	8.6×10^3	2.9×10^3	20.61	0.23	2.64
D		2	11		8.2×10^3	3×10^3	26.63	0.23	1.44
E			21		8.2×10^3	3×10^3	24.22	0.18	0.72
F			31		8.2×10^3	2.8×10^3	19.1	0.15	1.2
G			41		8×10^3	2.6×10^3	32	0.41	1.68

Case A in Table 1 is regarded as a reference that for (Re_u, Re_m, α) = (8.6×10^3, 2.8×10^3, 12) no flow instability was found at x/D = 36. In comparison with Case A, Case B in Table 1 signifies that for (Re_u, Re_m, α) = (9.1×10^3, 2.6×10^3, 12), the initial instability was found at x/D = 41. This can be further discussed with Fig. 2. Fig. 2a presents the phase-averaged velocity traces over two pulsating cycles, equivalent to one revolution of the rotating disc regulating the flow rate. Since the flow instability appears repeatedly in each of the pulsating cycles, in the following our discussion will be focused on the first cycle of the phase-averaged results. As seen, the flow instability takes place as the pulsating flow in the acceleration phase, at φ = 0.9-1.2π, where φ = 0 denotes the reference phase at which the phase-averaged velocity trace obtained at r/R = 0 reaches the maximum value. Referring to Miau et al. (2016), the intermittent flow disturbance in a pulsating cycle can be further extracted by a method called Empirical Mode Decomposition (EMD) (Huang et al., 1998). On the other hand, the velocity profiles corresponding to different pulsating phases can be reconstructed from the velocity traces in Fig. 2a. Subsequently, shown in Fig. 2b are the curves corresponding to the velocity gradient profiles for different phases over a pulsating cycle, in which the inflection points can be easily identified. Figure 2c makes a comparison of the intensity of the flow disturbances extracted from the EMD procedure mentioned and the locus of the inflection points of the velocity profiles against the pulsating phase φ,. It is seen that the appearance of the flow instability is coincided with that the inflection point reaching the farthest distance from the wall, about 1.8 times the thickness of the Stokes layer **δ**. Those phases are also highlighted in Fig. 2b for inspection. Referring to (Miau et al., 2016), the flow instability development can be reasoned due to Rayleigh's inflection point theorem (Rayleigh, 1880). This is supported by the non-dimensionalized characteristic frequency of the flow instability called **Ω,** which is 0.12 shown in Table 1. The value is deemed close to the range of 0.2-0.25, characterizing the non-dimensionalized frequency of the linear instability in a mixing layer (Monkewitz and Huerre, 1982).



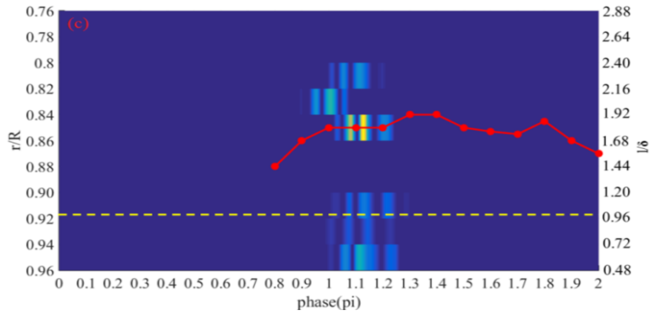


Fig. 2: The obtained results measured for (Re_u, Re_m, α) = (9.1 x 10^3, 2.6 x 10^3, 12), at x/D = 41. (a) Phase-averaged velocity pattern. (b) The radial gradient curves of the phase-averaged velocity profiles reconstructed from, Fig. 2a, where *l* denotes the distance from the wall. (c) A comparison of the intensity of disturbance with respect to the phase angle and the locus of the inflection points in the phase-averaged velocity profiles.

In comparison with Case A, Case C in Table 2 signifies a situation that the initial flow instability developed at x/D=36 for the parameters of Re_u, Re_m and α almost the same as those of Case A, but a trip wire of 0.5 mm in diameter installed upstream. While for Case A, Fig. 3 shows no appearance of instability in the phase-averaged velocity traces, for Case C Fig. 4 indicates that disturbances appear in the accelerating phase region at φ = 1.2-1.5π. Moreover, it is noted that the boundary layer thickness of Case C is larger than that of Case A, which can be realized from a comparison of Figs. 5 and 6. In these two figures, the boundary layer thickness can be identified as the distance from the wall where the phase delay of velocity pulsation reaches the maximum. Note that the phase delay is referenced to the phase of velocity pulsation at r/R=0.98.

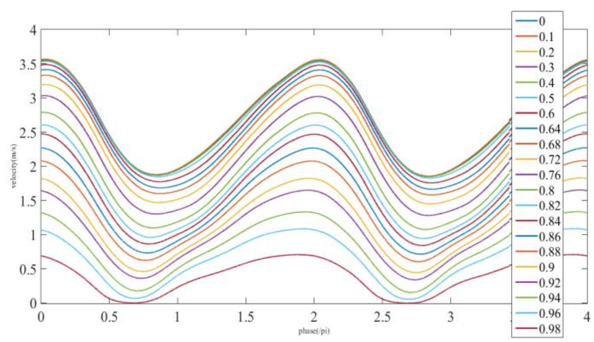


Fig. 3: The phase-average pulsating velocity patterns measured, for (Re_u, Re_m, α) = (8.6 x 10^3, 2.8 x 10^3, 12), for case A.

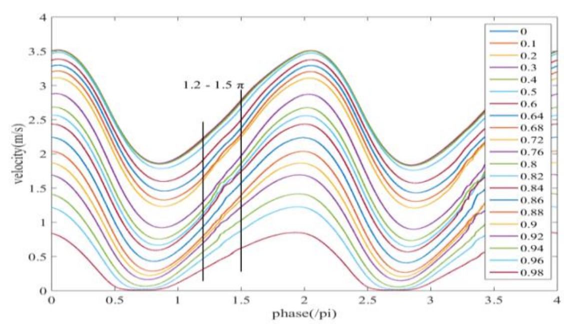


Fig. 4: The phase-average pulsating velocity patterns, for (Re_u, Re_m, α) = (8.6 x 10^3, 2.9 x 10^3, 12), for case C.

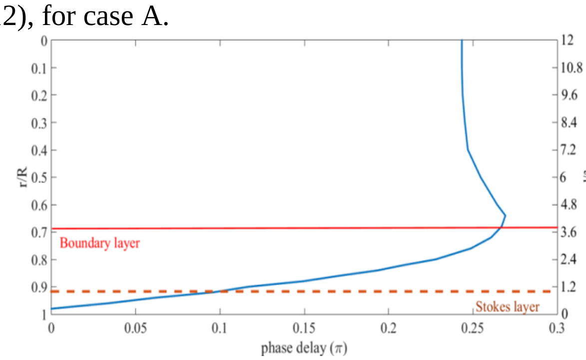


Fig. 5: The phase delay distribution (Re_u, Re_m, α) = (8.6 x 10^3, 2.8 x 10^3, 12), for case A.

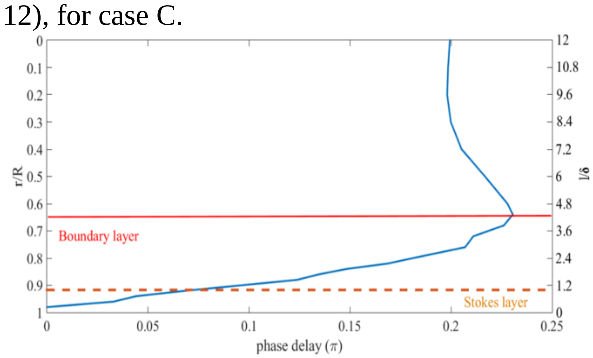


Fig. 6: The phase delay distribution (Re_u, Re_m, α) = (8.6 x 10^3, 2.9 x 10^3, 12), for case C

Case D indicates a situation that for the experimental parameters almost the same as those of Case A, but with a trip wire of 1 mm in diameter upstream, the initial instability was found at x/D = 11, which appeared in the decelerating phase. Cases E, F and G in Table 2 correspond to the pulsating flows under almost the same flow condition as Case D at x/D= 21, 31 and 41, respectively,.

Comparing the phase-averaged velocity traces of Cases D, E, F and G in Fig. 7, 8, 9 and 10, one realizes that the flow disturbance was actually travelling downstream through pulsation. A rough estimation of the travelling speed of the disturbances is about 1.38 m/s, which is comparable to the convection speed of flow at the radial location where the disturbance was pronouncedly seen. More interestingly, Figs. 8 and 9 show that the intensity of disturbance in Case F is reduced substantially in comparison with Case E, inferring that a relaminarization process is taking place in the streamwise region of x/D=21 to 31. In the literature, a number of studies on relaminarization of turbulent boundary layers due to streamwise acceleration have been reported (Narasimha and Sreenivasan, 1979; Sreenivasan, 1982). Regarding the on-set of relaminarization, Badri Narayanan and Ramjee (1969) suggested a criterion that if the Reynolds number based on the momentum thickness, Re_θ, fall in range of 300-400, reverting the flow transition would take place. Fiedler and Head (1966) proposed differently if the shape factor of the accelerating boundary layer, H, would reach the minimum value in a range of 1.2-1.3, the relaminarization process would be initiated. In Case F, the minimal values for Re_θ and H found in the accelerating phase were 314 and 1.78, respectively.

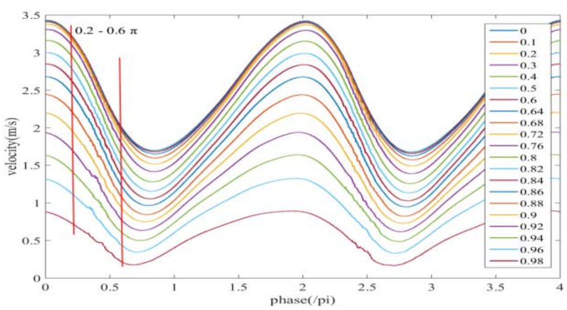


Fig. 7: The phase-average velocity, for (Re_u, Re_m, α) = (8.2 x 10^3, 3 x10^3, 12), case D.

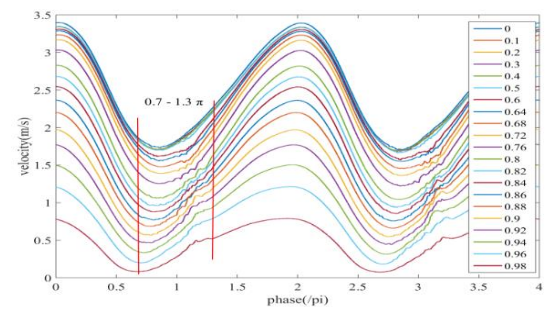


Fig. 8: The phase-average velocity for (Re_u, Re_m, α) = (8.2 x 10^3, 3 x 10^3, 12), case E.

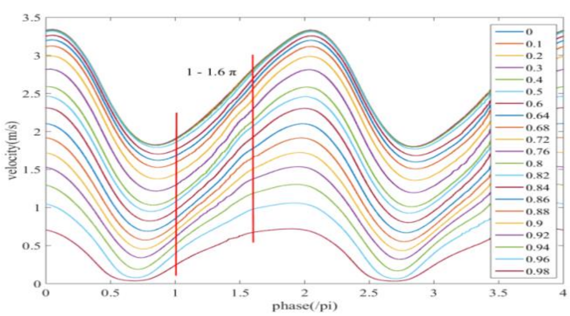


Fig. 9: The phase-average velocity, for (Re_u, Re_m, α) = (8.2 x 10^3, 2.8 x 10^3, 12), case F.

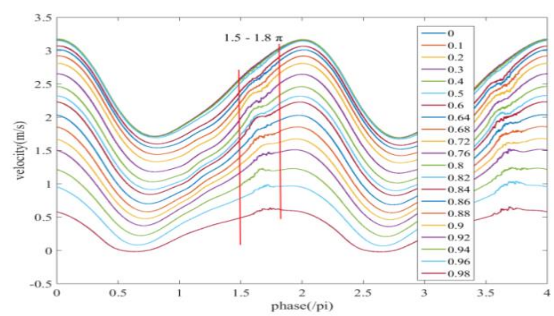


Fig. 10: The phase-average velocity, for (Re_u, Re_m, α) = (8 x 10^3, 2.6 x 10^3, 12), case G.

4. Conclusion

Case B in Table 1 unveiling a situation that the flow instability develops in the accelerating phase evidences the mechanism of Rayleigh's inflection-point theorem. For the cases with a trip wire shown in Table 1 evidence that while the flow instability could be triggered further upstream, the flow instability might decay downstream, inferring that a relaminarization process would be taking place. A brief comparison on the relaminarization process observed in the present flow and those reported in the literature regarding the accelerating boundary layers was made. More efforts in this regard will be carried out in the future.

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