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Transition phenomena and velocity distribution in constant-deceleration pipe flow

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ABSTRACT

The critical Reynolds number for transition to turbulence in a constant-acceleration pipe flow is well known to be significantly higher than the value for steady pipe flow. This is a consequence of the significant suppression of amplification of disturbances entering the pipe by the acceleration in spite of the increase of inertial force due to increase in instantaneous Reynolds number. In contrast, relatively little is known of the transition phenomena in a constant-deceleration pipe flow. Such a flow system is investigated by an experimental method in which the cross-sectional mean velocity is initially kept constant and subsequently decreased linearly to zero. The characteristics of the transition phenomena will be determined by two factors – deceleration and viscosity. Deceleration will amplify the disturbances, while a decrease in the instantaneous Reynolds number is expected to suppress the amplification of the disturbances due to viscosity. The study uses hot-wire experiments to clarify which of the two effects predominates in constant-deceleration pipe flow.

1. Introduction

Transition to turbulence in a constant acceleration pipe flow has been widely investigated [1–11]. In contrast, relatively limited information exists on transition to turbulence and reverse transition in a constant-deceleration pipe flow [2,3]. This paper considers experimental investigation of the latter type of flow, with emphasis on the relative contribution of deceleration and viscosity to the flow characteristics. Such a study will have significant practical relevance. For example, if transition to turbulence can be controlled by imposing unsteadiness such as periodic acceleration and deceleration on steady pipe flow, the energy required to deliver fluids may be reduced due to a decrease in the pipe frictional loss. The study could also enhance our understanding of fluid flow phenomena such as water hammer which results from rapid valve closure in pipeline systems.

In the aforementioned studies on constant acceleration [1–11], the fluid in a pipe initially at rest is typically accelerated at a constant rate. The cross-sectional mean velocity, u_m, therefore is linearly increased from zero. The critical Reynolds number for the transition to turbulence, Re_{cr}, is equal to that in a steady pipe flow [12], $Re_{st,cr}$, when the acceleration is lower than a certain critical value, while Re_{cr} becomes much higher than $Re_{st,cr}$ when the acceleration exceeds that critical value. The value for $Re_{st,cr}$ and consequently, the critical acceleration, is dependent on the extent of disturbances entering the pipe [11]. The critical Reynolds number, Re_{cr} often exceeds $1x10^6$ [1–7], a condition attributed to the significant suppression of the disturbances under constant acceleration, although increased inertial force will likely amplify the disturbances.

Previous studies have also found that there exist two types of transition patterns with respect to constant acceleration [1–4]. For example, flow transition has been found to occur simultaneously over the whole pipe due to flow instability when the constant acceleration is relatively large [3]. The other transition pattern appears under relatively small constant-acceleration condition. Flow transition occurs near the pipe inlet and forms a discontinuous surface propagating in the downstream direction with a velocity greater than the cross-sectional mean velocity. The limit between the two patterns is expressed by $D/(2aT^2) = 1 \times 10^{-3}$, where D is the pipe diameter, a is the constant acceleration, and T is the time required for complete opening of the valve. This critical value seems to be dependent on the disturbance level of the flow entering the pipe [11]. Further investigations are therefore still necessary to fully establish this critical value.

In the present study of constant-deceleration phenomena, the cross-sectional mean velocity, u_m, is initially kept constant and

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Nomenclature

a	constant acceleration, m/s^2	r	radial distance measured from the pipe centerline, m
a'	dimensionless constant acceleration = R^3a/ν^2, –	p	pressure, Pa
D	pipe diameter, m	t	time, s
J_0	Bessel functions of the first kind, –	u	axial velocity component, m/s
R	pipe radius, m	u_m	cross-sectional mean velocity, m/s
Re_{cr}	critical Reynolds number in unsteady pipe flow, –	u_{sta}	short-time averaged value of u, m/s
Re_{st}	Reynolds number in steady pipe flow, –	x	axial distance measured from the pipe inlet, m
$Re_{st,cr}$	critical Reynolds number in steady pipe flow, -	ν	kinematic viscosity, m^2/s

then linearly decreased to zero, as illustrated in Fig. 1. Constant deceleration will amplify the disturbances entering the pipe, while viscous force will damp them. The objective of the study is to investigate which of the two effects predominates in a constant-deceleration pipe flow. The radial velocity distribution in a constant-deceleration turbulent flow has been found to deviate from the quasi-steady velocity distribution as the deceleration increases, and the frictional loss is greater than the quasi-steady value [2]. The critical Reynolds number for reverse transition to laminar flow (re-laminarization) is beyond the scope of the present study and not considered here.

Three flow conditions are worth considering in such a study. First, when the initial steady flow is laminar, there are three possible scenarios- the constant-deceleration flow remains laminar, becomes transitional, or becomes turbulent. Second, when the initial steady flow is transitional, the following three conditions are possible- the constant deceleration flow reverts to laminar flow, remains transitional, or becomes turbulent. Finally, when the initial steady flow is turbulent, the possible conditions are similar to the latter i.e. the constant deceleration flow reverts to laminar flow, reverts to transitional flow, or remains turbulent. The last two initial flow conditions (transitional and turbulent) are considered in this study in order to understand the relative effects of constant deceleration and viscous force on the transition phenomena in a constant-deceleration pipe flow.

2. Experiment

2.1. Experimental apparatus and procedure

The details of the experimental apparatus and procedure have been presented in a previous publication [11] and will only be described briefly here. Fig. 2 shows a schematic of the experimental apparatus using air as the working fluid. The test pipe was made of brass and had inner diameter, D, of 0.078 m and length, L, of 5.0 m. The origin of the cylindrical coordinates (x, r, θ) in Fig. 2 is on the centerline at the inlet cross-section of the test pipe. A bell-mouth was connected upstream to direct air smoothly into the pipe. A device capable of generating unsteady flow of arbitrary waveform was also connected downstream of the test pipe [11]. The device consisted of a circular pipe of 0.05 m inner diameter and 0.8 m length equipped with a butterfly valve that was driven by a stepper motor. The valve could not rotate but could swing around its supporting rod at programmed speeds.

The diameter of the tungsten hot-wire was 5 μm and its length was 2 mm. The frequency response of the hot-wire anemometer was 140 Kz for air flows. The anemometer was carefully calibrated near the inlet of the pipe using a precise Pitot tube system. As is widely known, the measurement of velocity data of less than about 0.5 m/s typically involves considerable uncertainty. However, such uncertainties have minimal effect on the present study due to our focus on the onset of turbulence. The measured velocity data were not filtered before digitization. The cross-sectional mean velocity, u_m, was obtained by averaging the time-averaged axial velocity component over the cross-section of the pipe.

2.2. Experiments performed

The axial velocity component, u, is measured at axial cross-sections ranging from x = 1.0 m (x/D = 12.8) to 4.0 m (x/D = 51.3) at equal intervals of 1.0 m, as shown in Fig. 2(a). There is provision for an I-probe that traverses in the vertical direction. The

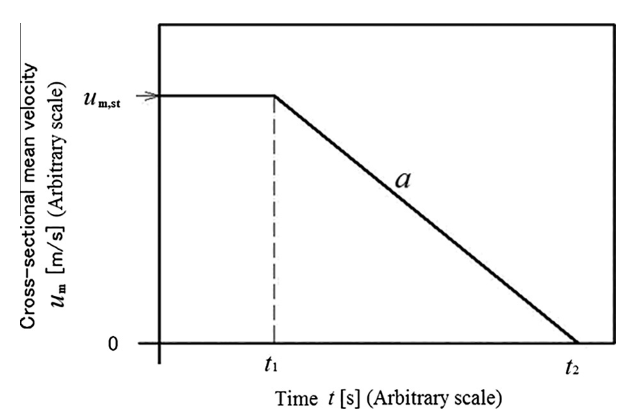

Fig. 1. Schematic of cross-sectional mean velocity history in a constant deceleration flow.

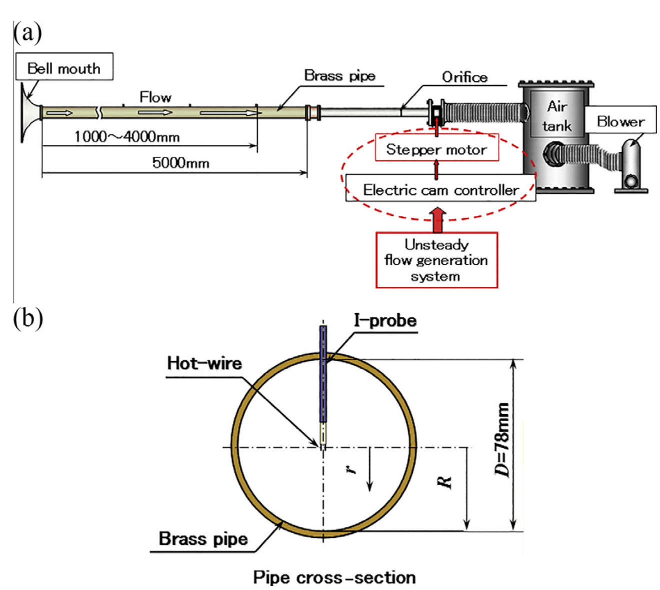

Fig. 2. Schematic of experimental apparatus.