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Definition of sub-classes in sinusoidal pulsatile air flow at onset of transition to turbulence in view of velocity and frictional field analyses

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ABSTRACT

The definition of the sub-classes in sinusoidal pulsatile pipe flow at the onset of transition to turbulence is given through the analyses of the velocity and the frictional field measurements conducted. For this reason, a systematic experimental study was carried out and the validation of the results was compared with those available in the literature. The time averaged and the oscillating components of the local velocities, $\overline{U}_{ta}(r)$ and $|\overline{U}_{os,1}|(r)$ are measured throughout the pipe cross-section and compared with the theoretical background. A variety of friction factors are also evaluated and the correlations in terms of the functional relationship between dimensionless parameters of $\lambda_{sL}/\lambda_{u,ta} = f\left(\sqrt{\omega'}/\sqrt{\mathrm{Re}_{ta}^{3/4}}\right)$ are proposed. Therefore the limit between quasi steady and intermediate region, and the limit between intermediate and inertia dominant region in the pulsatile pipe flow are found to be at the magnitudes of $\sqrt{\omega'}/\sqrt{\mathrm{Re}_{ta}^{3/4}} = 0.145$ and $\sqrt{\omega'}/\sqrt{\mathrm{Re}_{ta}^{3/4}} = 1.5$, respectively. Laminar pulsatile flows even at onset of transition can be classified as quasi-steady and inertia dominant sub-classes for $\sqrt{\omega'} < 5.44$ and $\sqrt{\omega'} > 27.22$, respectively. According to the presented experimental study, the intermediate region can also be divided into two sub-classes for $\sqrt{\omega'} \le 8.61$ and $\sqrt{\omega'} > 8.61$ as a result of the velocity and the frictional fields. Furthermore, the relationships among time averaged pressure drop, time averaged mean velocity and time averaged friction factor are investigated and the critical limit of $\sqrt{\omega'} = 8.61$ is found. A new parameter, normalized pressure drop, ΔP^* is proposed and a common relationship between ΔP^* and $\mathrm{Re}_{ta,crit}\sqrt{\omega'}$ is derived as $\Delta P^* = f(\mathrm{Re}_{ta,crit}\sqrt{\omega'})$ with a mean deviation of ±25%.

1. Introduction

Transition process from laminar to turbulence in both steady and time dependent flows drastically affects transport efficiency of mass, momentum and heat which result in energy consumption. For this reason, velocity and frictional field analyses play important roles in transitional flows. In many practical applications as well as in the field of medicine, time dependent flows are available. Therefore it is needed to become aware of recent developments on this type of flows, especially in transitional regime.

One of manageable patterns in time dependent flows is pulsatile one which is a type of time dependent flow composed of a steady component and a superimposed periodical time varying component called oscillation. One of the

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most important phenomena in pulsatile flow is determination of regions. In the study of Ohmi et al. [1], the flow pattern for pulsatile laminar pipe flow was classified into three types as quasi-steady ($\sqrt{\omega'} < 1.32$), intermediate ($(1.32 < \sqrt{\omega'} < 28$) and inertia dominant ($\sqrt{\omega'} < 28$) with respect to the dimensionless frequency parameter, Womersley number, $\sqrt{\omega'} = R\sqrt{\omega/\nu}$ where R is the pipe radius, ω is the angular frequency ($\omega = 2\pi f$), f is the oscillation frequency and ν is the fluid kinematic viscosity.

Some studies in literature are also concerning about stability theory which suggests that flow remains laminar for all flow rates, but in practice flow through pipeline becomes turbulent even at moderate speeds. According to other studies, stability has both frequency and Reynolds number dependency [2]. Contrary to this statement, flow may be found to be stable for all frequencies and all Reynolds numbers as in the study of [3]. As is seen, there are some conflicting results among the studies from the point of the stability of time dependent flows.

Investigations for time dependent flows in the relevant literature are mainly based on observations of velocity waveforms and detection of disturbance growth. The related literature can be found in the studies of [4,5]. There are very few studies in which cross sectional velocity profiles are investigated. Mizushina et al. [6] studied the effect of $\sqrt{\omega'}$ on the shapes of velocity profiles. Later, Ohmi et al. [1] investigated time averaged and oscillating velocity distributions for pulsatile air flow at onset of transition and compared their results with theory and found a good agreement between them up to $\mathrm{Re}_{ta} = 1200(\mathrm{Re}_{ta} = \overline{U}_{m,ta}D/\nu$ where $\overline{U}_{m,ta}$ is the time averaged component of cross-sectional mean velocity and D is the pipe diameter). On the other hand, Trip et al. [7] found that pulsatile effects did not play a role in transitional regime and only effective parameter was found as mean Reynolds number at different values of $\sqrt{\omega'}$. This argument seems to be a questionable one.

Besides velocity field analyses, some studies based on frictional field analyses can be found in both laminar and transitional pulsatile pipe flows with some conflicting results. This may be partly due to the fact that response characteristics of measuring devices used in time dependent flows are not good enough in early times. Also, the substitution method of the experimentally obtained instantaneous pressure drop per unit length, $\Delta\overline{P}(t)/L$ and instantaneous mean velocity, $\overline{U}_m(t)$ into the below mentioned time dependent momentum integral equation (Eq. (1)) causes a noticeable error when oscillation frequency is increased [8,9].

$$\rho\frac{d\overline{U}_m(t)}{dt} + \frac{4\overline{\tau}_w(t)}{D} = \frac{\Delta\overline{P}(t)}{L} \tag{1}$$

where ρ is the fluid density and $\overline{\tau}_w(t)$ is the instantaneous wall shear stress.

In early times, the study of Hershey and Im [10] is seen for the comparison of the experimental friction factor, $\lambda_{p_{\exp}} = \Delta P_{ave}R/\rho\overline{U}_{ta}^2L$ and theoretical friction factor, $\lambda_{p_theo} = 16/\mathrm{Re}_{ta}$ where ΔP_{ave} is the averaged pressure drop and $\overline{U}_{ta}$ is the time averaged component of local velocity. Comparison of $\lambda_{p_{\exp}}$ and $\lambda_{p_{theo}}$ has shown an excellent agreement between them in laminar regime. The departure from theory was accepted as onset of transition from laminar to turbulence just after time averaged Reynolds number, Re_{ta} = 2100. Ohmi and Iguchi [8,9] found that instantaneous friction factor, $\lambda_u(t)$ and time averaged friction factor, $\lambda_{u,ta}$ might be generally expressed as a function of $\sqrt{\omega'}/\sqrt{\mathrm{Re}_{ta}^{3/4}}$ as a result of their verification with the experimental results. As a further step, they expressed limit between quasi-steady and intermediate regions of pulsatile flow by $\sqrt{\omega'}/\sqrt{\mathrm{Re}_{ta}^{3/4}} = 0.145$, and limit between intermediate and inertia dominant regions by $\sqrt{\omega'}/\sqrt{\mathrm{Re}_{ta}^{3/4}} = 1.5$ where instantaneous friction factor, $\lambda_u(t)$ and time averaged friction factor, $\lambda_{u,ta}$ are described as follows:

$$\lambda_u(t) = 8\overline{\tau}_w(t)/\rho\overline{U}_m^2(t) \tag{2}$$

$$\lambda_{u,ta} = \frac{8}{\rho\overline{U}_{m,ta}^3T}\int_0^T \overline{\tau}_w(t)\overline{U}_m(t)dt \tag{3}$$

where T is the oscillation period.

Ohmi and Iguchi [8,9] also expressed that instantaneous friction factor, $\lambda_u(t)$ in oscillating flow was almost equal to quasi-steady friction factor, $\lambda_{qL}(t)$ (Eq. (4)) in quasi-steady region ($\sqrt{\omega'} \leqslant 1.32$). Besides they found that in intermediate region ($1.32 < \sqrt{\omega'} < 28$) and inertia dominant region ($\sqrt{\omega'} \geqslant 28$), $\lambda_u(t)$ was always larger than $\lambda_{qL}(t)$ in accelerating phase and at first part of the decelerating phase while this was reversed in rest of decelerating phase.

$$\lambda_{qL}(t) = \frac{64}{(\overline{U}_m(t)D/\nu)} \tag{4}$$

In the study of Çarpınlıoğlu [11], an approach which consists of attempts to correlate governing flow parameters was presented to reveal transition process on frictional field proposing a new parameter as a reference friction factor ratio, λ_R. The onset and the end of transition in pulsatile flow were predicted through the functional relationships of λ_R with time averaged and oscillating Re numbers of Re_{ta} and Re_{os} ($\mathrm{Re}_{os} = |\overline{U}_{m,os,1}|D/\nu$) where $|\overline{U}_{m,os,1}|$ is the oscillating component of cross sectional mean velocity for the fundamental first wave in the finite Fourier expansion).

$$\lambda_R = (\lambda_{u,ta}/\lambda_{sL})_{\max} \tag{5}$$

and

$$\lambda_{sL} = \frac{64}{\left(\frac{\overline{U}_{m,ta}D}{\nu}\right)} \tag{6}$$

Çarpınlıoğlu [11] estimated $\mathrm{Re}_{ta,crit}$ = 17,929 and $\mathrm{Re}_{os,crit}$ = 23,763 for their pulsatile pipe flow in the given experimental ranges as a critical limit for onset and end of transition, respectively.

According to the studies based on flow visualizations, investigations of cross sectional velocity distributions, frictional field analyses, stability theories and proposed models, it can be deduced that there are still some gaps due to the conflicting results in this manner. Therefore there is a need for a study in order to investigate velocity and frictional field analyses in pulsatile air flow.