Experimental Investigation of Pressure Gradient Characteristics in a Mass Flow Rate Controlled Pulsating Pipe Flow

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Pulsating pipe flows are generated either by periodically changing pressure gradient or by imposing periodically changing mass flow rate. Most research works on this type of flow have been reported for pressure-gradient driven pulsating flows and only a few for mass flow controlled pulsating flow. In the present work, an experimental investigation of axial pressure gradient characteristics of a mass flow rate controlled pulsating flow is performed. The investigation is done for a fully developed laminar flow through 8 m long, 14 mm diameter pipe for three different types of pulsating flows (sinusoidal, triangular and square waves). A constant non-dimensional mass flow rate of 0.935 with 1.0 Hz frequency was imposed for all types of pulsation. The effect of the pulsating mass flow on the pressure gradient and the damping of the pressure variation across the whole length of the pipe are discussed. It is observed that the pressure gradient roughly follows the trend of different mass flow pulsation.

Keywords : Pulsating flow; Mass flow rate controlled; Pressure gradient

NOTATION

f : frequency of pulsation

$\dot{m}$: mass flow rate

$\dot{m}^*$: non-dimensional mass flow rate

p : axial pressure

P : axial mean pressure

t : time period of pulsation

x : coordinate along the axis of the pipe

Subscript

A : time varying part of pulsation

M : time averaged mean part of pulsation

INTRODUCTION

The unsteady flows with periodic time variations of mass-flow rate and pressure gradient are termed as pulsating flow. The study of pulsating flow through a pipe is both practically and fundamentally important. This type of flow is observed in many practical situations, such as, flow pattern in artificial heart[1], blood flow through arteries and breathing[2], exhaust from internal combustion engines[3], flow fields in centrifugal pumps[4], etc. The investigations of velocity distribution, pressure gradient and shear stress are important for designing the above-mentioned systems. On the other hand due to its intricacy and unsteadiness phenomenon the problem is interesting for fundamental research as well. Due to its importance, numerous analytical, numerical and experimental studies of the flows are available in the literature. However, most of the research works reported in the literature are for pressure-gradient driven pulsating pipe flows. In this type of pulsating flows the imposed pressure gradient has the following form

$$\frac{dP}{dx} = \left(\frac{dP}{dx}\right)_M + \left(\frac{dp}{dx}\right)_A \sin 2\pi ft \qquad (1)$$

where the first term on the right hand side of equation (1) is the time averaged mean component and second term is the time varying component. The time varying part is described by a single frequency harmonic oscillation, f and axial pressure gradient, $\left(\frac{dp}{dx}\right)_A$. When the first part is non-zero the flow is called pulsating flow and when it has zero value, the flow is called oscillating flow.

The analytical solutions of the pressure-gradient driven pulsating flows are reported by various researchers[5-10]. Moreover, several experimental investigations, especially on the oscillating flows are reported by several researchers[11-13].

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It can be seen from equation (1) that if the axial pressure gradient is given in the form of a Fourier series, the velocity field and, hence, the mass flow rate for a laminar, pulsating flow through a pipe can be obtained analytically. However, in the case of a controlled mass flow, complexity arises in the solution as the resultant pressure gradient that occurs in the governing equation is not known a priori. Earlier investigators carried out an experimental investigation of varying volume flow rate pulsating flow[14] and measured the instantaneous volume flow rate for different pulsating flows. Investigation was also performed by combining the analytical solution and measuring the instantaneous local velocity at the centre of a pipe. The analytical solutions of resulting pressure gradient and velocity distribution for a prescribed, time-varying volume flow rate through a pipe are reported by several scientists[15]. The investigations of the starting flows with trapezoidal variation in the volume flow rate with time and sinusoidally oscillating flows for the fully developed laminar flows were performed. The researchers have developed an experimental setup, where a pulsating flow is developed by a controlled mass flow rate[16-19]. The basic principles needed to develop such an experimental setup were explained[16]. By using the setup, the researchers have carried out experiments for sinusoidal and triangular mass flow controlled pulsation[17]. It was also provided with the analytical solutions for sinusoidal, triangular and power pulses and comparisons were made with the experimental results. The velocity investigations of four time-dependent periodic and non-periodic laminar and turbulent flows were experimentally done by the scientists[18]. Combined analytical and experimental investigations of the sinusoidal mass flow controlled pulsating laminar pipe flows were carried out by several investigators[19]. The general variation of the mass flow[17] rate through a pipe for a periodic flow may be defined as,

$$\dot{m} = \dot{m}_M + \dot{m}_A f_m(t) \qquad (2)$$

where $\dot{m}_M$ is the cycle-averaged mass flow rate and $\dot{m}_A$ is the corresponding amplitude of pulsation flow. The function $f_m(t)$ is a periodic function in time and has a period t_p, such that $f_m(t + t_p) = f_m(t)$.

The literature shows that the pulsations, having wave forms other than sinusoidal, for example, triangular pulsations with time, have not yet been investigated, probably because of the experimental difficulties associated with accurate and reproducible generation of the desired pressure gradient. It may also be noted that there is no experimental study reported in the literature for the pressure drop measurements along with the full length of the pipe for different pulsating pipe flows. The present work addressed both these issues and the pressure drop characteristics are measured by all the eight pressure sensors across the length of the pipe for three different types of mass pulsations, namely, sinusoidal, triangular and square. The objective of the present paper is to study the effect of pulsating mass flow on the pressure gradient and the damping of the pressure variation across the whole length of the pipe. To meet these objectives an experimental test bed with a mass flow controller has been installed. Three different types of mass pulsations are generated, *ie*, sinusoidal, triangular and square waves. The pressure characteristics are measured at different locations of the pipe for all such cases.

EXPERIMENTAL SETUP

The present experimental investigations of mass controlled pulsating flow are done with newly installed pulsating flow setup in the Fluid Mechanics Laboratory of Mechanical Engineering Department, Indian Institute of Technology Guwahati. The setup is procured from LSTM-Erlangen, Germany and its design concepts and descriptions of various parts have already been described by earlier researchers[16]. A schematic diagram of the setup is shown in Figure 1.

The setup consists of mass flow control unit, flow conditioner, 8.0 m long and 14.0 mm diameter copper pipe, pressure transducers and velocity measuring probe. Along the length of the pipe there are eight pressure transducers, which measure the static pressure of the pulsating flow. The velocity is measured at the end of the pipe with a Testo make vane probe anemometer. The controlling and generating pulsation of the mass flow rate is done with an electronic circuit which is operated by LabView programme. A computer with data

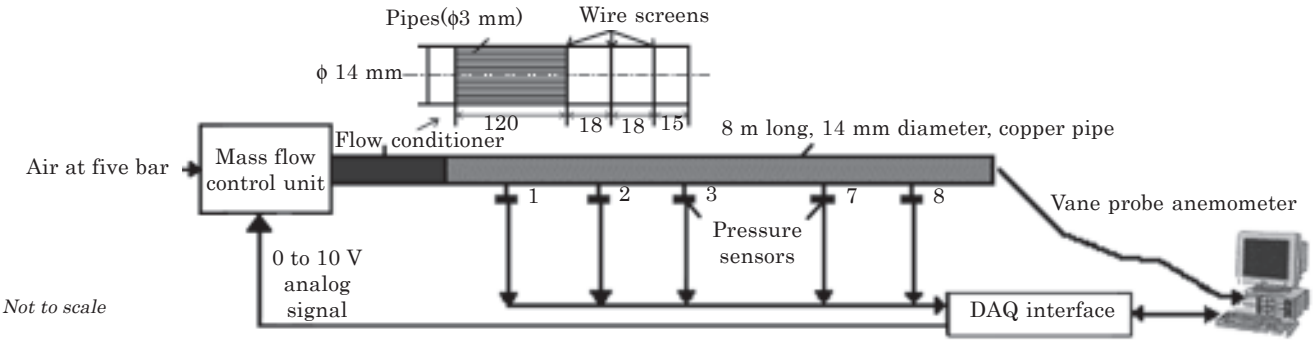


Figure 1 Schematic diagram of the experimental setup[16]

acquisition (DAQ) interface is connected to the controller and the pressure transducers. The NI (National Instruments) made DAQ interface is used both for generating pulsation and controlling the mass flow rate. Moreover, it is used to obtain the signal from pressure transducers through the LabView programme. The accuracy of the mass flow controlled pulsating flow depends mainly on the control unit. The mass flow control unit used in the present work is capable of generating any kind of preset time-dependent mass flow rate variations. The control unit possesses also a very high cycle to cycle repeatability and accuracy in the range of 0 g/min to 217.8 g/min.

EXPERIMENTAL INVESTIGATION

For the present work, the mass flow rate control system is supplied with the pressurized air at a pressure of five bar from a compressor. An externally produced signal from the computer is used to supply the time-dependent mass flow rate signal to the mass flow control unit. The signal can be, in principle, any function of time and can be processed by the LabView software. After the mass flow control unit, the flow is conditioned with wire screens and a flow straightener, which reduces the turbulence and dust particles flowing through the pipe. Copper pipe of 8 m length and 14 mm diameter is connected at the exit of the flow conditioner. Under steady state condition, the flow through the present experimental setup remains laminar up to the Reynolds number of 6000. However, the present investigation is performed at a very low Reynolds number of 1059 for all the pulsation flows. Static pressure measurements are performed with eight pressure transducers distributed along the length of the pipe. The operating range of the pressure sensors is 20 mbar with an accuracy of ± 0.25% and repeatability of ± 0.1%. The pressure transducers are also temperature compensated. The natural frequency of these transducers is approximately 1.0 kHz, which allows tracking of fast pressure changes resulting due to pulsating flows. All the measurements are digitized simultaneously by the computer through a 16 bit 333 kHz DAQ card and measurements are synchronized with input signals of the mass flow rate controller, which are produced by a 12 bit 200 kHz DAQ card.

RESULTS AND DISCUSSIONS

Since, the setup is newly installed, the mass control unit has to be calibrated before any experimental investigation. The calibration of the mass controller is done by specifying a known amount of mass flow to the controller through the LabView program and measuring the corresponding average velocity by the vane probe anemometer at the exit from the pipe. The mass flow rate is calculated based on the measured velocity.

A calibration graph of the input mass flow rate (given to controller) against output flow rate (measured) is made as shown in Figure 2. The calibration graph shows the best fit curve based on 'least square method' with an error of 0.008%. Moreover, the slope of the best fit line is 45° indicating the exact match of input mass flow rate with measured flow rate.

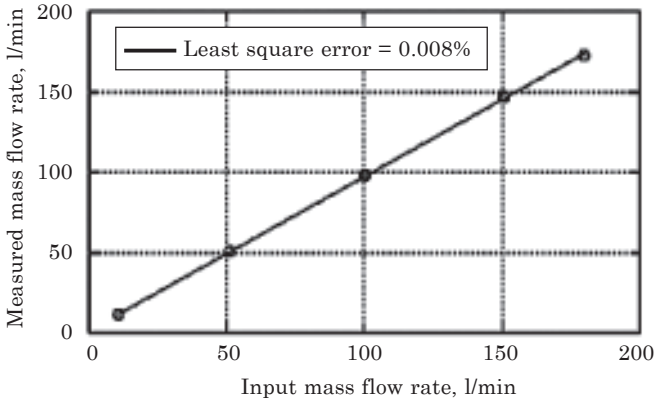


Figure 2 Calibration curve

In order to study the behaviour of mass flow rate controlled pulsating flows through the pipes, three types of pulsation, namely, sinusoidal, triangular and square mass flow rate pulsations are applied with constant flow frequencies[16] of f = 1 Hz. The resulting axial pressure gradients are measured at eight different locations. The first pressure sensor is placed at a sufficient distance away from the pipe entrance such that the flow may be considered fully developed at that position. For all the pulsations, a constant dimensionless mass flow rate amplitude of $\dot{m}_A^* = 0.935$, is used. The dimensionless mass flow rate amplitude, $\dot{m}_A^*$ is the ratio of amplitude of the time-varying part of the mass flow rate, $\dot{m}_A$ to the cycle-averaged mass flow rate, $\dot{m}_A$. The high mass flow rate amplitude is taken because, at low amplitude mass flow rate, a phase difference of mass flow and pressure gradient occurs which may lead to an inaccurate measurement of the pressure profiles.

The axial pressure gradients for the sinusoidal mass flow pulsation acquired by all eight pressure sensors are shown in Figure 3. It is observed that the pressure gradient follows the sinusoidal trend with a higher duration of time for first half than the second half. For a fixed time the value of the acquired pressure gradient reduces from the first sensor to eighth sensor. Thus for a particular time the maximum value of pressure gradient is shown by the first sensor and the minimum value by the eighth sensor. Thus the amplitude of the pressure gradient decreases as the flow progresses from inlet to the outlet due to frictional losses.

Figure 4 shows the axial pressure gradient for the applied triangular mass flow pulsations with the same

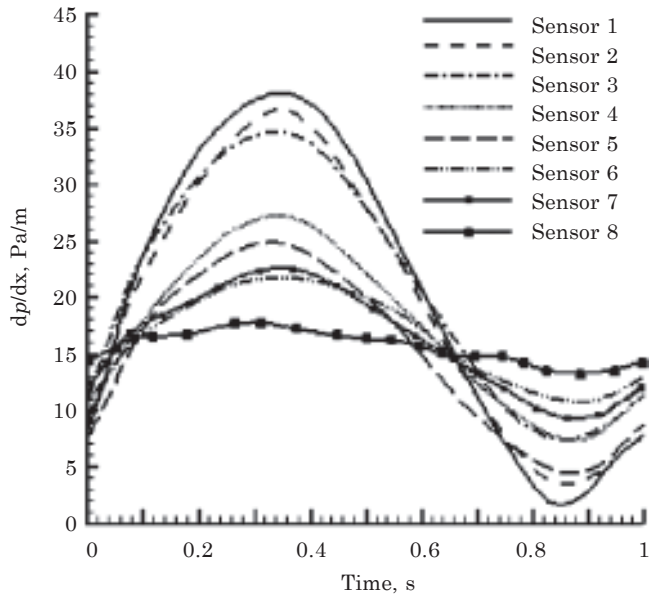


Figure 3 Pressure gradients for sinusoidal mass flow pulsation

amplitude and frequency as in case of sinusoidal pulsation. It is clear from the pressure gradient wave forms that, the resultant axial pressure-gradient also appears to be triangular. However, the shape of the pressure gradient is characterized by un-equal changes, where the accelerating or decelerating flow changes suddenly. This behaviour may be due to the fact that the mass flow variation can no longer be represented as a perfect triangular wave. In this case, the amplitude of the pressure gradient decreases from inlet (first sensor) to outlet (eighth sensor).

The axial pressure gradient for the square mass flow pulsation acquired by all eight pressure sensors are shown in Figure 5. It is observed that the resultant axial pressure gradient hardly follows the square wave trend.

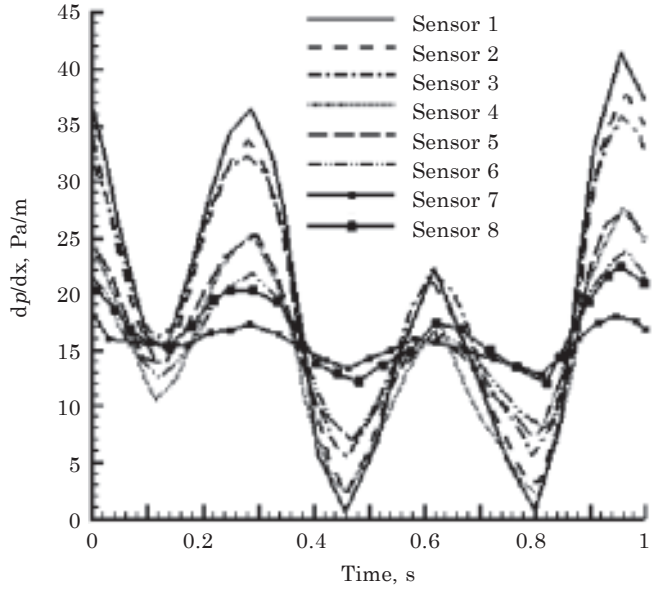


Figure 4 Pressure-gradients for triangular mass flow pulsation

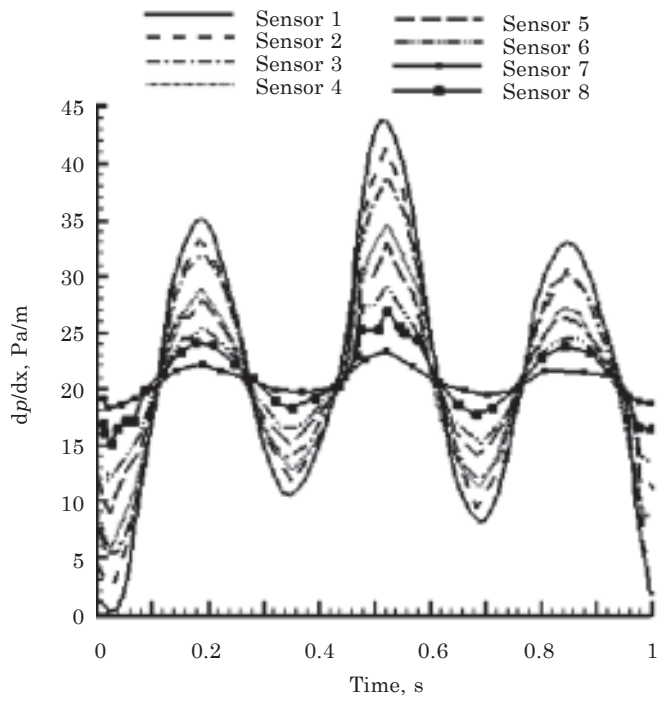


Figure 5 Pressure-gradients for square mass flow pulsation

This behaviour may be due to the difficulty in generating variation of the mass flow rate represented by the square wave. In this case also the decrease of amplitude of pressure gradient also is observed from inlet to outlet of the pipe. However the amount of decrease of amplitude is lower from first sensor to eighth sensor compared to that in previous two cases, *ie*, sinusoidal and triangular cases. From Figures 3, 4 and 5 it is observed that the pressure gradient profiles do not follow the exact profile of the input mass flow pulsations. This may be due to a limited response time of the long pipe. The mass flow changes rapidly at the controller whereas the test pipe section cannot respond due to its low inertia and frictional losses.

CONCLUSIONS

Axial pressure-gradient characteristics of a mass flow rate controlled pulsating flow are investigated experimentally. Three different types of pulsation (sinusoidal, triangular and square waves) with 1.0 Hz frequency are applied to a fully developed laminar flow through 8 m long and 14 mm diameter pipe. The mass flow controller is calibrated before measurements with least square error of 0.008%. It is observed that,

- In all types of pulsating flow, the pressure gradient profiles roughly follow their respective input mass flow pulsations.
- The amplitudes of the output pressure gradient decrease from the inlet to the exit of the pipe and are minimum in the case of square type of flow pulsation.

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