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Hydrodynamics of piston-driven laminar pulsating flow: Part 2. Fully developed flow

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HIGHLIGHTS

- The piston-driven laminar pulsating flow in a pipe is studied.
- Fully developed flow is examined analytically, numerically and experimentally.
- An increase in *F* results an increase in the amplitude of the GAfigure velocity.
- The characters of the radial velocity profiles critically depend on both the frequency and the phase angle.
- The near/off-wall flow reversals are observed for *F* = 105, 226 and 402.

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ABSTRACT

Piston-driven pulsating flow is a specific type of pressure-driven pulsating flows. In this study, piston-driven laminar pulsating flow in a pipe is studied. This study mainly exists of two parts: developing flow and fully developed flow. In this part, hydrodynamically fully developed flow is examined analytically, numerically and experimentally. A constant value of the time-averaged Reynolds number is considered, *Re* = 1000. In the theoretical studies, both analytical and numerical, an inlet velocity profile representing the experimental case, i.e., the piston driven flow, is assumed. In the experiments, in the hydrodynamically fully developed region, radial velocity distribution and pressure drop are obtained using hot-wire anemometer and pressure transmitter, respectively. The effect pulsation frequency on the friction coefficient as well as velocity profiles are obtained. A good agreement is observed among analytical, numerical and experimental results.

1. Introduction

The practical importance of pulsating flows in engineering applications and biological systems has been mentioned in the first part of this study (Aygun and Aydin, 2014). Two categories of pulsating flow, mainly pressure-driven and boundary-driven have been also given in detail there.

In this part of the study, we concentrate our interest on the pulsating flow studies for hydrodynamically fully developed, while the first part has been on the hydrodynamically developing flow. In his pioneering work, Uchida (1956) analytically studied pulsating flow in a pipe for an arbitrary, time-varying, axial pressure gradient. He obtained a general solution for pressure-driven pulsating, laminar fully developed flow in a pipe. Zhao and Cheng (1996) studied fully developed laminar reciprocating pipe flow analytically and experimentally. They showed that the oscillation amplitude affected the friction coefficient considerably. Haslam and Zamir (1998) analytically treated fully developed laminar pulsatile flow in tubes of elliptic cross sections. Yakhot et al. (1999) numerically investigated fully developed, laminar pulsating flow in a rectangular duct. They analyzed influence of the aspect ratio of the rectangular duct and the pulsating pressure gradient frequency on the phase lag, the amplitude of the induced oscillating velocity, and the wall shear.

As it has been noted in the first part, recently, a group from LSTM-Erlangen (Institute of Fluid Mechanics, Friedrich-Alexander University, Erlangen, Nurnberg, Germany) contributed a lot into the existing knowledge on pulsating flows in pipes. Their articles also present a good summary of the efforts made in the open literature. Ray and Durst (2004) carried out a semi-analytical analysis of laminar, fully developed pressure-driven flow through any arbitrary-shaped duct. Comparisons were made for some conventional duct geometries like circular, square and rectangular. Ray et al. (2005) extensively investigated sinusoidal mass-flow-driven

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Nomenclature

c_f	friction coefficient
D	pipe diameter
f	frequency of the pulsating inlet velocity
F	dimensionless frequency of the pulsating inlet velocity
J_0, J_1	zeroth and first order Bessel functions of first kind
L	length of the pipe
L_p	length of the piston joint
P	pressure
r	radial coordinate
R	radius of the cylinder or radius of the pipe
Re	Reynolds number
x	axial coordinate
t	time
u	axial velocity component
v	radial velocity component

Greek letters

ρ	density
μ	dynamic viscosity
$\boldsymbol{\nu}$	kinematic viscosity
ω	angular frequency

Subscripts

A	amplitude
av	average
c	centerline
m	mean
ta	time-averaged

pulsating, laminar and fully developed pipe flow analytically and experimentally. Haddad et al. (2010) carried out analytical investigations on pulsating laminar incompressible hydrodynamically fully developed pipe and channel flows for a large range of the pulsating frequency. Chang et al. (2012) studied pressure-driven laminar pulsating flow both in circular pipes and parallel-plate channels and analyzed the existence of the phase-lag between pressure gradient and flow rate.

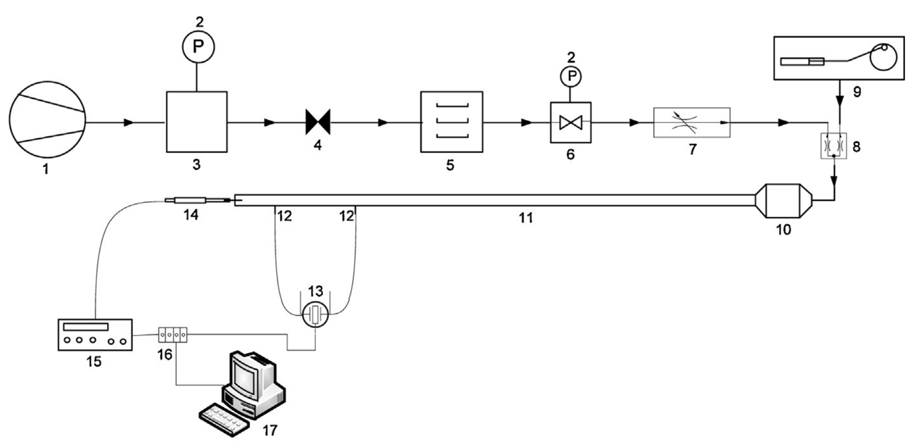
As stated in the first part, most studies on pressure-driven pulsating flows in pipes assume a periodical pressure, usually in a sinusoidal form, at the inlet. However, a piston-driven pulsating flow does not represent the classical pressure-driven flow. In this regard, the piston velocity should be incorporated into the pressure distribution at the inlet. The purpose of this part of the present study is to both experimentally and theoretically investigate hydrodynamically fully developed piston-driven pulsating flows in pipes. The focus is concentrated on the effect of the pulsating flow frequency of some hydrodynamical parameters.

2. Theoretical analysis

The theoretical analysis includes both the analytical and numerical investigations.

2.1. Governing equations

The axially symmetric, unsteady, 2-D, incompressible and hydrodynamically fully developed laminar flow with constant thermo-physical properties is considered. With the regarding simplifications, the corresponding governing equations in the cylindrical coordinate system are reduced as:



1. Compressor
2. Pressure gauge
3. Air tank
4. Valve
5. De-humidifier
6. Pressure regulator
7. Volumetric flow controller
8. Flow divider
9. Oscillating unite
10. Settling chamber
11. Test section
12 Pressure taps
13 Pressure sensor (LPX9481B)
14 Hotwire probe
15 Flow analyzer
16 DAS20 Hardware board
17. Computer

Fig. 1. The schematic of the experimental set-up.