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Friction factor, permeability and inertial coefficient of oscillating flow through porous media of packed balls

Mehmet Turgay Pamuk, Mustafa Özdemir *

Istanbul Technical University, Mechanical Engineering Faculty, 34437 Istanbul, Turkey

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ABSTRACT

In this paper, oscillatory and steady flows of water through two different porous media consisting of mono-sized stainless steel balls are studied experimentally. The friction factors, permeabilities and inertial coefficients are determined experimentally for steady and oscillating flows. The correlations of maximum friction factor for oscillating flow are presented and they are compared with those of steady flow. Permeability and inertial coefficient of porous media subjected to the oscillating flow are obtained by using the correlation equations of maximum friction factor. Pressure variations calculated by using these coefficients are in good agreement with experimental data. It is experimentally shown that the permeability and inertial coefficient of oscillating flows are greater than those of steady flow in the same range of Reynolds number.

1. Introduction

The porous media have been used widely in many engineering fields such as cryocoolers, solid matrix heat exchangers, cooling of electronic equipment, and regenerators in order to enhance heat transfer. Heat and mass transfer formulation of porous media with continuum modeling based on a representative elementary volume was improved, and wide information can be found in the studies of Vafai [1], Kaviany [2] and Nield and Bejan [3]. Coefficients of the constitutive equations required by the continuum modeling such as permeability and inertial coefficient of porous media were obtained by experimental studies as done by Ergun [4]. These experimental coefficients can be found widely in the literature according to the types of porous media. On the other hand, fluid flow has an oscillating characteristic in many engineering applications such as internal combustion engines, Stirling engines, cryocoolers and other periodical processes in thermal and chemical systems. Heat transfer is enhanced also under oscillating fluid flows through empty channels. Zhao and Cheng [5] presented an extensive review of oscillatory duct flows including heat transfer characteristics.

Heat enhancement is ensured by both the presence of porous medium and oscillatory flow. Hence, Nusselt number for oscillating flow in a porous channel can be up to several times larger than in empty channel [6]. Frictional losses increases several times by oscillating flow in porous media as well as heat transfer.

Zhao and Cheng [7] investigated experimentally oscillatory pressure drops through a woven-screen packed column. They presented correlations for maximum pressure drop factor and cycle-averaged pressure drop factor in the kinetic Reynolds number range of 0.001–0.13 and in dimensionless fluid displacement range of 614.73–2827.56, under the condition of sinusoidal motion of air. They found that the values of cycle-averaged pressure drop of oscillatory flow were several times higher than that of steady flow.

Jin and Leong [8], and Leong and Jin [9] have conducted an experimental study regarding steady and oscillating flows through open cell aluminum foams. Considering various porosities and permeabilities, they conclude that flow resistance increases with form coefficient and decreases with the increasing permeability for a given porosity. Form drag is the primary reason for pressure loss by increasing flow velocity. They presented correlations of friction factors as Zhao and Cheng [7]. They also showed that the pressure loss is increased both with increasing A_o and kinetic Reynolds number Re_{ω}.

Hsu et al. [10] performed experiments to cover a wide range of very low and very high Reynolds numbers so that the correlations of pressure drop for both steady and oscillating flows could be compared. For oscillating flows, the velocity responses quite linearly to the pressure gradient when the piston amplitude is small. This suggests that Darcy's law is valid for small amplitude oscillating flows. When the piston amplitude becomes large, the response and therefore the correlation of pressure-drop and velocity in the regenerator become nonlinear [10].

* Corresponding author. Address: Department of Mechanical Engineering, Istanbul Technical University, Istanbul, Turkey. Tel./fax: +90 212 251 7368.

E-mail addresses: turgaypamuk@hotmail.com (M.T. Pamuk), ozdemirmu4@itu.edu.tr (M. Özdemir).

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Nomenclature

A	cross-sectional area of the test chamber
A_p	cross-sectional area of double acting cylinder
A_o	non-dimensional displacement defined as $A_o = x_{max}/D$
d	ball diameter
D	inner diameter of test chamber
f	temporal friction factor defined in Eq. (8)
f_{max}	maximum friction factor defined in Eq. (9)
F	inertial coefficient
K	permeability
L	length of the porous medium
ΔP	pressure difference
ΔP_{max}	amplitude of pressure difference
P'	non-dimensional pressure parameter defined in Eq. (1)
R	radius of flywheel
Re_D	Reynolds number defined in Eq. (1)
Re_{max}	Reynolds number defined as $Re_{max} = A_o Re_\omega/2$
Re_ω	kinetic Reynolds number ($\rho\omega D^2/\mu$)
t	time
u_m	cross-sectional mean fluid velocity
u_{max}	amplitude of mean fluid velocity
x_m	temporal fluid displacement at the inlet of the test chamber
x_{max}	maximum fluid displacement at the inlet of the test chamber

Greek symbols

ε	porosity
ρ	fluid density
ω	angular frequency (rad/s)
ν	frequency (1/s)
μ	dynamic viscosity

Clearman [11] has conducted an experimental study on measurement and correlation of directional K and F coefficients of microporous structures used in pulse-tube cryocoolers. His investigation also directly compared with the steady flow and periodic flow viscous and inertial resistances for identical porous structures. He concluded that the behavior of periodic flow within the porous cryocooler regenerator cannot be accurately predicted based on steady flow hydrodynamic parameters.

Shen and Ju [12] investigated oscillating flow characteristics of cryocooler regenerator at low temperatures. They proposed a new universal correlation of friction factor for engineering design of cryocooler regenerators for different frequencies and temperature regions.

Cha et al. [13] have studied experimentally and numerically on oscillating flow in eight different microporous media. They solved the problem numerically by using the CFD code called Fluent in order to predict the permeability and inertial coefficient of the porous media under steady-periodic flow conditions. Their findings show that pressure drop in oscillatory flow is not necessarily lower than that of steady flow.

Gas, especially air has been used as a working fluid in all the experimental studies in literature. These studies are concentrated mostly on obtaining friction factors for practical reasons. In this paper, oscillatory and steady flows of water through two different porous media which are made of mono-sized stainless steel spheres are studied experimentally. Exact values of permeability and inertial coefficient belonging to steady flow through packed beds of spherical balls are known as the results of experimental studies of Ergun and successors. For this reason, comparison of the friction factors, permeabilities and inertial coefficients for steady and oscillating flows through these media are made in this study. A correlation of maximum friction factor for oscillating flow is presented and it is compared with that of steady flow. K and F coefficients are calculated by using the quadratic relation between the pressure drop and flow velocity. Pressure variations calculated using these coefficients are compared with experimental data.

2. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1. The test section is in the middle of the setup as shown in figure. This test chamber is connected to the oscillation generator by means of pipes of 32 mm in diameter and hydraulic (high pressure) hoses of ½ in. diameter. The main component of oscillation generator is a double-acting cylinder which is connected to an electrically driven motoreductor by means of a flywheel and an adjustable crank-arm. Inner diameter of hydraulic cylinder is 50 mm and the diameter of the piston rod installed inside it is 32 mm. The maximum stroke of the movement obtainable by this mechanism is 200 mm. Rotational speed in rpm of the 7.5 kW motoreductor is controlled via a variable speed AC-drive. Additionally, an adjustment system mounted on the flywheel allows changes in stroke.

Pressure taps are drilled on the Polyethylene (PE) pipes of 51.4 mm in diameter and 200 mm in length installed at the both sides of the test chamber. Keller brand (series PR-21Y, 0–10 bar) piezo resistive pressure transmitters are installed into these taps. Data collected from these sensors by means of Keithley 2700 data acquisition system are sent to a PC to be processed. An inductive type proximity sensor is installed to sense a metallic target mounted on the periphery of the flywheel such that the location of the target corresponds to the maximum piston movement (full stroke). Since pressure and location signals are both collected by the data acquisition system, it is possible to synchronize them.

Experimental set-up can also allow to conduct experiments regarding steady flow (non-oscillating) by means of valves

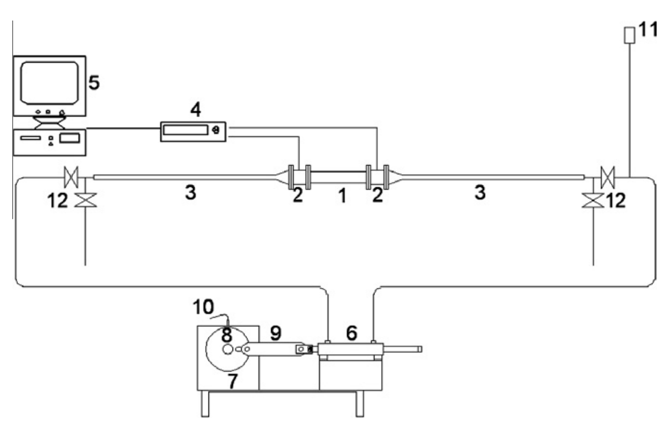

Fig. 1. Experimental setup: 1. Test Section (porous medium), 2. PE Pipe, 3. Pipe of 32-mm in diameter, 4. Keithley 2700, 5. PC, 6. Oscillation Generator, 7. Motoreductor, 8. Flywheel, 9. Crank Arm, 10. Inductive Proximity Sensor, 11. Air Purger, 12. Separating valves for steady and oscillating flows.