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Characteristics of oscillating flow through a channel filled with open-cell metal foam

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Abstract

An experimental study was performed to investigate the characteristics of oscillating flow through a channel filled with open-cell metal foam with a fully inter-connected pore structure. Detailed experimental data of oscillating flow pressure drops and velocities for a wide range of oscillatory frequency and the maximum flow displacement were presented. A correlation equation for the maximum friction factor of metal foams subject to oscillating flow was obtained and compared with the results for channels inserted with wire-screens obtained by other investigators. The results showed that oscillating flow characteristics in an open-cell metal foam are governed by a hydraulic ligament diameter based kinetic Reynolds number $Re_{\omega(Dh)}$ and the dimensionless flow displacement amplitude A_{Dh}. The effects of kinetic Reynolds number on the variations of pressure drop and flow velocity in metal foam are more significant than that of the dimensionless flow displacement amplitude. The maximum friction factor of oscillating flow in open-cell metal foams is much smaller than that of oscillating flow in wire-screens for large flow displacement amplitudes.

Keywords: Dimensionless flow displacement amplitude; Friction factor; Kinetic Reynolds number; Open-cell metal foam; Oscillating flow; Pressure drop

1. Introduction

The porous medium with high thermal conductivity has emerged as an effective method of heat transfer enhancement due to its large surface area to volume ratio and intense mixing of fluid flow. Heat transfer of a porous medium subject to oscillating flow has been investigated widely for a channel filled with spherical particles, granular beds or wire-screens (Sozen and Vafai, 1990; Khodadadi, 1991; Kim et al., 1994; Guo et al., 1997). Some research efforts have been made to obtain fundamental understanding of oscillating flow characteristics in a channel filled with particles or wire-screens. Tanaka et al. (1990) studied the oscillating flow characteristics of a Stirling engine regenerator made of wire-screens or sponge metals. They found that the prediction of pressure drop loss was possible by use of the hydraulic diameter as the representative length defined by the friction factor and Reynolds number. Zhao and Cheng (1996) experimentally investigated oscillatory pressure drop characteristics in a packed column composed of three different sizes of woven screen and subjected to a periodically reversing flow of air. They showed that the oscillatory pressure drop factor increases with the kinetic Reynolds number and the fluid displacement and a correlation equation for the friction factor was obtained. Ju et al. (1998) studied the oscillating pressure drops and phase shift characteristics for regenerators filled with wire-screens under high frequency oscillation. They obtained values for the

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Nomenclature

A_{Dh}	dimensionless flow displacement amplitude	$Re_{\omega(Dh)}$	kinetic Reynolds number defined in Eq. (5)
D_h	hydraulic ligament diameter of aluminium foam	$Re_{\max(Dh)}$	maximum Reynolds number defined in Eq. (8)
D_l	ligament diameter of aluminium foam	U	cross-sectional mean velocity
F	inertia coefficient of porous media	$u_{\max}$	maximum velocity of fluid in metal foam channel
f	friction factor of steady flow in metal foam	w	channel width
$f_{\max}$	maximum friction factor of oscillating flow in metal foam	$x_{\max}$	amplitude of flow displacement
H	height of the channel		
K	permeability of the porous medium	*Greeks*	
L	length of the tested foam	μ_f	dynamic viscosity of fluid
n	number of cycles	ω	angular frequency
ΔP	pressure drop across the test section	ν_f	kinematic viscosity of fluid
$\Delta P_{\max}$	maximum pressure drop across the test section	ρ	density of fluid
Re_d	Reynolds number based on wire diameter and peak velocity	δ	uncertainty
Re_H	Reynolds number based on the metal foam height	θ	phase lag
		ε	porosity of the metal foam
		α	Stokes number
		γ	shape parameter of porous medium

cycle-averaged pressure drop in the oscillating flow across the regenerator which are two to three times higher than that of a steady flow at the same Reynolds numbers based on the cross-sectional mean velocity. Wakeland and Keolian (2003) reported the pressure losses across single screens subjected to low-frequency oscillating flow for $0.002 < Re_d < 400$, where Re_d is the Reynolds number based on wire diameter and peak approach velocity. The friction factor was found to depend on Reynolds number, but not on the oscillatory amplitude, over the range of conditions measured.

When compared to a porous channel inserted with particles or wire-screens, the sintered metal foam is a new type of porous media with open-cell structure, which is manufactured from a variety of molten metal processes. The metal foam with fully inter-connected structure and high permeability opens itself to many applications such as mechanical energy absorbers, electronics cooling, Stirling engine regenerators, flow straighteners, filters, catalytic reactors and heat exchangers. Depending on the particular open-cell metal foam configuration, the specific surface area varies between 500 to more than 10,000 m^2/m^3 for different types, and the solid component can be manufactured by aluminium or copper with high thermal conductivity. The overall heat transfer rate of fluid flowing through metal foam can be increased dramatically by the presence of extremely large fluid-to-solid contact surface area and tortuous coolant flow path inside the metal foam. Therefore, oscillating flow in open-cell metal foam channels is employed for heat transfer enhancement applications in electronics cooling and in heat exchangers (Calmidi and Mahajan, 1999; Kim et al., 2000; Bhattacharya and Mahajan, 2002). Fu et al. (2001) experimentally investigated the heat transfer of a channel filled with metal foam subjected to oscillating flow. Their results showed that the length-averaged Nusselt number for oscillating flow is higher than that for steady flow, and that the temperature distribution for oscillating flow is more uniform than that for steady flow. They concluded that the metal foam heat sink in oscillating flow can be considered as an effective method for electronics cooling. Boomsma et al. (2003a,b) studied the heat transfer performance of aluminium foams used as compact heat exchangers. They reported that metal foam heat exchangers decreased the thermal resistance by nearly half when compared to currently used heat exchangers designed for the same application. Zhao et al. (2004) presented results from experimental measurements on the effective thermal conductivity of FeCrAlY foams. The contribution of natural convection to heat conduction was found to be significant, with the effective thermal conductivity at ambient pressure twice the value obtained under vacuum conditions. Their results also showed that natural convection in metal foams is strongly dependent upon porosity. Leong and Jin (2005) experimentally studied the heat transfer of oscillating flow through a channel filled with an aluminium foam subjected to a constant wall heat flux. The cycle-averaged local Nusselt number was found to increase with both the kinetic Reynolds number and the dimensionless amplitude of flow displacement. The length-averaged Nusselt number is effectively increased by increasing the kinetic Reynolds number in a suitable range.

The application of open-cell metal foam in heat transfer subject to oscillating flow requires a better understanding of pressure drop and friction factor in the porous channel. However, results of oscillating flow behaviour in a channel filled with open-cell metal foam are rather scarce. Several researchers have studied the characteristics of steady flow in terms of pressure drop and friction factor in a channel filled with metal foam. Kim et al. (2001) studied the impact of the presence of aluminium foam on the flow and convective heat transfer in an asymmetrically heated channel. Their experimental results revealed that the friction factor is much higher for lower permeability aluminium foams with a significantly higher Nusselt number. Boomsma and Poulikakos (2002) investigated the hydraulic characteristics of a liquid flowing through a rigid, open-cell metal foam. They showed that the permeability and form coefficient can be used to accurately describe the pressure drop versus flow velocity behaviour in a porous medium. Ko and Anand (2003) investigated forced convection in a rectangular channel inserted with metal foam baffles. Their results showed that the friction factor decreased slightly with an increase in the Reynolds number and increased with baffle thickness and pore density. Boomsma et al. (2003a,b) used a new approach for modeling the flow through a porous medium with a well-defined structure. The mesh-independent results from their numerical simulations on flow through the foam showed good agreement with their experiments considering the increased flow resistance generated by wall effects from the foam container.

The above review shows that flow characteristics in open-cell metal foams were investigated under steady flow conditions, while oscillating flow characteristics were studied based on channels filled with particles or wire-screens. As mentioned before, the structure of the open-cell metal foam is completely different from that of packed beds of spheres or wire-screens, which have been investigated widely. As shown in Fig. 1(a), the structure of an open-cell foam is composed of dodecahedron-like cells, which have 12–14 pentagonal or hexagonal faces. The edges of these cells are held by aluminium ligaments. It can be seen that pores inside the medium are open to one another and fully inter-connected. Three parameters are used to describe the metal foam, namely, porosity ε, pore density PPI (pores per linear inch) and ligament diameter D_l. Due to these structural differences, the behaviour of oscillating flow through the open-cell metal foam require a renewed investigation. Based on authors' previous works (Fu et al., 2001; Leong and Jin, 2005) an extensive study was performed to achieve a fundamental understanding of oscillating flow in open-cell metal foams. This paper describes an experimental investigation on the pressure drop behaviour of oscillating flow through a channel filled with open-cell aluminium foam. Three porosity densities of 10, 20 and 40 PPI aluminium as shown in Fig. 1(b) were employed, and different oscillatory frequencies and flow displacement amplitudes were chosen in the present experiments. The pressure drop characteristics in oscillating flow through an aluminium foam channel were analysed. A correlation equation of friction factor for metal foam was obtained and compared with the result for wire-screens obtained by other investigators under the oscillating flow condition.

2. Experimental setup and procedures

2.1. Experimental setup

Fig. 2 shows the schematic overview of the experimental setup. The facility consists of three major parts: oscillating flow generator, velocity measurement section and test section. The oscillating flow generator is a mechanism that generates a sinusoidal oscillating flow.

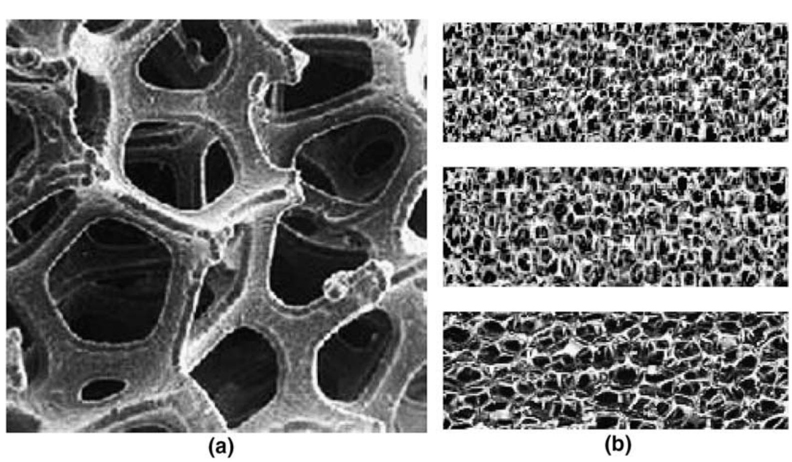

Fig. 1. (a) Typical pore structure inside an aluminium foam and (b) aluminium foams with pore densities of 10, 20 and 40 PPI.

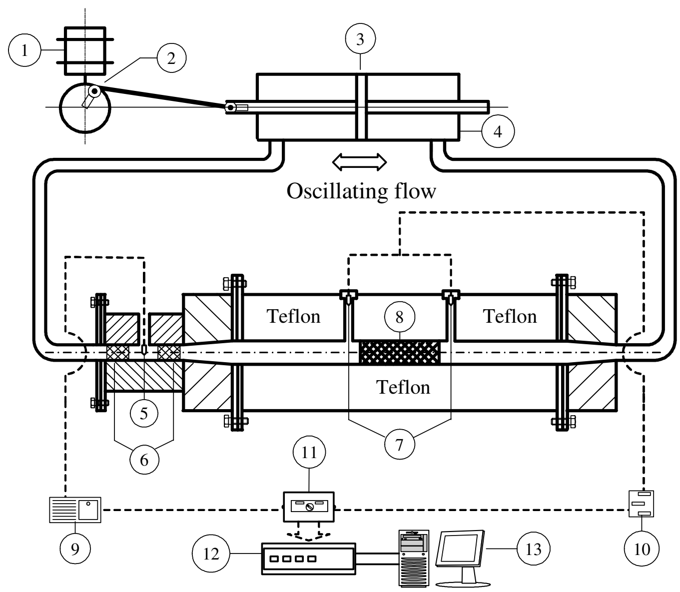

Fig. 2. Schematic diagram of experimental setup.

The mechanism consists of a compression cylinder, a piston and a crankshaft with adjustable stroke lengths. These were firmly fixed at the base onto a solid board by screw bolts to withstand strong vibrations caused by the oscillating motion of the generator. The supporting shafts are two ball bearings elevated to the height of the piston axis to ensure smooth oscillatory movement. The crankshaft was driven by a DC electric motor (LEESON 0.75 kW) with variable speed capabilities to drive the piston forward and backward sinusoidally. By adjusting the motor speed through a transducer, oscillating flows of different frequencies can be generated. In the present experiments, oscillating frequencies from 1 to 10 Hz were employed. Different oscillating amplitudes were obtained by varying the distance of the crank from the plate center. The locations of 25, 30 and 35 mm from the center of the plate were selected and oscillating flows with maximum displacements of 50, 60 and 70 mm were provided. The velocity measurement section was made of an aluminium column with a diameter of 16 mm. A hot-wire sensor (TSI 1210-20w) was mounted at the center of the two ends packed with 40 mesh woven screen discs. The packed screen provides a uniform velocity profile. The velocity measured by this arrangement is approximately the same as the cross-section averaged velocity through the column due to the extremely thin velocity boundary layer of flow through the porous media. A constant temperature hot wire anemometer (TSI IFA-100) was used to measure the velocity at the velocity measurement section which was then converted to that through the test section. It is noted that the measured velocities will always be positive even though the velocity direction is reversed on every other half cycle. This is because of the fact that the single hot-wire sensor cannot distinguish the flow direction. To reflect a correct velocity direction, the measured values of velocity were processed by reversing its sign on every other half cycle.

The test section is a well-shaped block of Teflon material with a channel (dimensions of 50×10 mm) in the center. The tested materials include three different pore sizes of aluminium 10, 20 and 40 PPI foam. All materials are shaped with the dimensions of $50 \times 50 \times 10$ mm. The two taps of the pressure transducer (VALIDYNE DP15) are located before and after the test section for pressure drop measurements. The transducer was connected to a carrier demodulator (VALIDYNE CD15), which converts the input value into standard digital signals with outputs of 4–20 mA. The signals of flow velocity and pressure drop across the test section were collected by a data acquisition system consisting of a 12-bit A/D card (KEITHLEY DAS-1402), control software (CEC TestPoint) and a personal computer.

2.2. Procedures and uncertainties

By looping the test section to the oscillating flow regenerator, experiments for oscillating flow in porous channel can be conducted. The frequencies of oscillating flow were adjusted by controlling the motor speed. For prescribed amplitude, the experiments were proceeded by increasing the oscillating frequency while keeping the stroke length unchanged. To obtain a cyclic steady state, the pressure drop and flow velocity through the porous media were monitored by the data acquisition system. Fifty cycles of data were obtained under different sampling rates by adjusting the acquired A/D rate for different oscillating frequency. After a set of readings had been recorded, the stroke length was changed to perform another set of experiments. In the present experiments, the flow velocity through the channel and the pressure drop across the test section were measured three times for each type of aluminium foam.

The critical physical properties of the tested metal foams were obtained before the commencement of the experiments. The permeability K and the inertia coefficient F were determined by applying the quadratic curve fitting method to pressure drop versus fluid velocity data obtained under steady flow conditions. The following relation between measured pressure drop and flow velocity was derived:

$$\frac{\Delta P}{L} = AU + BU^2 \tag{1}$$

where ΔP is the pressure drop across the media, L is the length of the media, U and ρ are mean velocity and density of the fluid, respectively.

The two coefficients are defined as

$$A = \frac{\mu_f}{K}, \quad B = \rho\frac{F}{\sqrt{K}} \tag{2}$$

Eq. (1) can be used to fit the data. By fitting a second-order polynomial through these points, coefficients A and B can be determined.

Fig. 3 presents the pressure drops measured at different flow velocities through the aluminium 10, 20 and 40 PPI foams, respectively. By substituting the values of A and B from these figures into Eq. (2), the corresponding values for permeability K and inertia coefficient F can be obtained. The ligament diameters D_l of aluminium foams were measured using a scanning electron microscope. The porosity ε was calculated by dividing its weight by the volume which was measured by the external dimensions, and then comparing this value to the density of the solid metal. The measured values of ε and D_l, and calculated parameters of F and K for the tested metal foams are shown in Table 1.

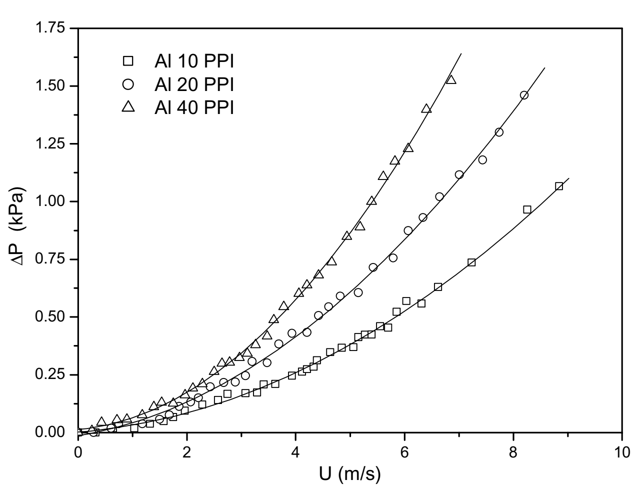

Fig. 3. Velocity versus pressure drop for aluminium foam 10, 20 and 40 PPI with length $L = 50$ mm.

Table 1
Physical parameters of aluminium foam

Tested materials	Ligament diameter D_l (μm)	Porosity ε	Inertia coefficient F (m^{-1})	Permeability K (10^{-8} m^2)
Al 10 PPI	427.2	0.91	0.0076	4.21
Al 20 PPI	221.3	0.90	0.0105	3.12
Al 40 PPI	112.6	0.90	0.0155	2.86

In general, the uncertainties of the measured data can be classified into two groups: random uncertainties, which can be treated statistically; and systematic uncertainties, which cannot be treated in the same way. With careful calibration and experimentation, systematic uncertainty was minimised. The accuracies of the pressure transducer readings and the accuracy of the velocity measured by the hot-wire anemometer are ±0.25% of full-scale and ±0.01 m/s, respectively. After the cycle-averaging process, uncertainties of pressure drop and velocity are 3.0% and 2.0%, respectively. The uncertainties of D_h, x_{max}, D_l, and A_{Dh} were estimated to be 2.5, 1.0, 1.0, and 3.5, respectively. The uncertainties δ of $Re_{\omega(Dh)}$, $Re_{max(Dh)}$ and f_{max} were determined by the method described by Taylor (1995). Suppose that $v, \ldots, y, \ldots, z$ are the measured quantities with uncertainties $\delta v, \ldots, \delta y, \ldots, \delta z$, and the measured values are used to compute the function $q(v, \ldots, y, \ldots, z)$, then the uncertainty in q is given by

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial v}\delta v\right)^2 + \cdots + \left(\frac{\partial q}{\partial y}\delta y\right)^2 + \cdots + \left(\frac{\partial q}{\partial z}\delta z\right)^2} \tag{3}$$

In the present experiments, the uncertainties of the measured data were assumed to be independent and random with normal distribution. Using Eq. (3), the uncertainties of $Re_{\omega(Dh)}$, $Re_{max(Dh)}$ and f_{max} were calculated to be 3.9%, 6.5% and 9.7%, respectively.

3. Results and discussion

3.1. Definitions of dimensionless parameters

Previous works (Tanaka et al., 1990; Zhao and Cheng, 1996) presented results of friction coefficient for oscillatory flow in a channel inserted with wire-screens. Tanaka et al. (1990) investigated the oscillating flow through wire-screens for a fixed flow amplitude and pointed out that the friction factor is governed by the kinetic Reynolds number. Zhao and Cheng (1996) studied oscillating flow in wire-screens with various flow displacements. A correlation equation for friction factor in terms of the hydraulic wire diameter based kinetic

Reynolds number and the dimensionless fluid displacement amplitude was presented. The wires and the ligaments are the solid struts inside the woven screen and metal foam, respectively. The flow restrictions and pressure drops in metal foam will be influenced significantly by the ligament's shape and structure. To study the characteristics of oscillating flow in metal foams, and to compare our results for woven screens, it is necessary to employ the hydraulic ligament diameter based kinetic Reynolds and dimensionless amplitude in the present investigation. The effect of the aluminium foam on the oscillating flow characteristics is accounted for by defining the hydraulic ligament diameter of metal foam as

$$D_h = \frac{\varepsilon D_l}{1-\varepsilon} \tag{4}$$

where D_l and ε are the ligament diameter and porosity of the aluminium foam respectively. The similarity parameters of the hydraulic ligament diameter based kinetic Reynolds number and the dimensionless fluid displacement amplitude are defined as

$$Re_{\omega(Dh)} = \frac{\omega D_h^2}{v_f} \tag{5}$$

$$A_{Dh} = \frac{x_{max}}{D_h} \tag{6}$$

where x_{max}, ω and v are the maximum flow displacement, oscillatory frequency and kinematic viscosity of fluid, respectively.

To explore the difference between the oscillating flow characteristics in metal foams and wire-screens, the maximum friction factor and Reynolds number defined by Tanaka et al. (1990) are employed as follows:

$$f_{max} = \frac{\Delta P_{max} D_h}{\frac{1}{2}\rho L (u_{max})^2} \tag{7}$$

$$Re_{max(Dh)} = \frac{u_{max} D_h}{v_f} \tag{8}$$

where ΔP_{max} and u_{max} are the maximum pressure drop and flow velocity of oscillating flow through porous channel, respectively. ρ and L are the flow density and the length of aluminium foam, respectively. It is noted that the hydraulic diameter employed by Tanaka et al. (1990) for wire-screens is equivalent to the hydraulic ligament diameter of aluminium foams in the present study.

3.2. Pressure drop and velocity

Fig. 4 presents a typical variation of flow velocity and pressure drop through aluminium 10 PPI along the cycles of oscillating flow for kinetic Reynolds number $Re_{\omega(Dh)} = 24.0$, 31.1 and 40.9 with the maximum flow displacement $A_{Dh} = 16.6$. It can be seen that the profiles of pressure drop and flow velocity increase with the increase of kinetic Reynolds number and vary almost sinusoidally due to the reversing flow direction. High pressure drop corresponds to high flow velocity which shows that the phase difference between the velocity and pressure drop is very small. Khodadadi (1991) showed that the phase lag θ_n between the velocity component and the pressure gradient can be predicted by

$$\theta_n = \tan^{-1}\left(\frac{n\alpha^2}{\gamma^2}\right) \tag{9}$$

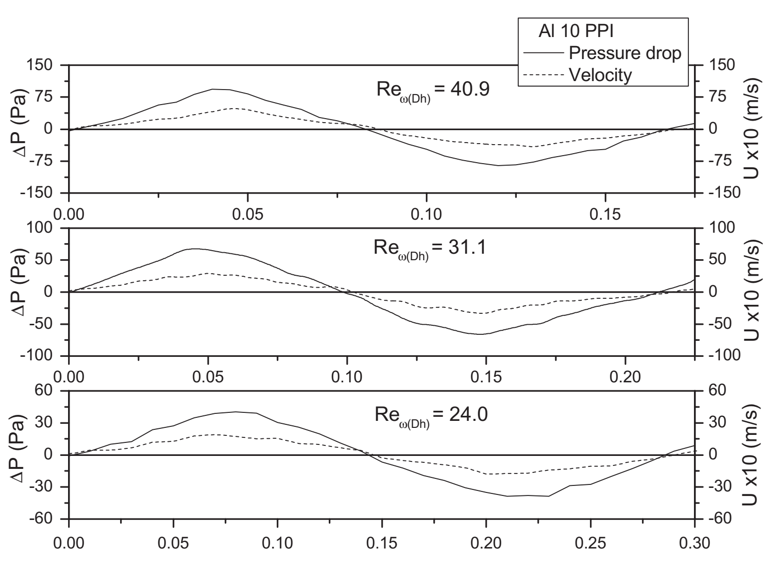

Fig. 4. Typical variations of velocity and pressure drop of oscillating flow through aluminium 10 PPI for $A_{Dh} = 16.6$ and $Re_{\omega(Dh)} = 24.0$, 31.1 and 40.9.

where $\alpha = (w^2\omega/\nu_f)^{1/2}$ is the Stokes number and $\gamma = (w^2\varepsilon/K)^{1/2}$ is the shape parameter of the porous medium. For the present experiments, the kinematic viscosity ν_f of the air is taken to be 15.7×10^{-6} m^2/s, porosity ε and permeability K of aluminium 10 PPI are 0.9 and 4.2×10^{-8} m^2, respectively. The phase lag θ_n is calculated to be 3.5° for the case presented in Fig. 4 for angular frequency $\omega = 21.4$ (i.e., $Re_{\omega(Dh)} = 24.0$) and cycle number $n = 1$. This indicates that the phase difference between velocity and pressure drop is very small for open-cell aluminium foam and agrees with the trends observed in the present experiments.

Fig. 5 shows the typical temporal variations of the pressure drop across the channel filled with aluminium 20 PPI for dimensionless flow amplitude $A_{Dh} = 26.1$, 30.2 and 34.2 at the kinetic Reynolds number $Re_{\omega(Dh)} = 6.8$. It can be seen that the pressure drop increases with the increase of the dimensionless flow displacement amplitude at a fixed value of the kinetic Reynolds number, i.e., dimensionless frequency. It appears that the temporal variations of pressure drop are almost in the same cycle for different maximum displacements of flow in metal foam channel. This indicates that the displacement of flow has a negligible effect on the moving cycle of oscillating flow in open-cell foam. Fig. 6 shows the variations of pressure drop in aluminium foams of 10, 20 and 40 PPI at a given maximum flow displacement $x_{max} = 70$ mm, i.e., the dimensionless flow oscillation amplitude $A_{Dh} = 14.6$, 30.2 and 59.5 for aluminium 10, 20 and 40 PPI, respectively. The oscillatory frequency was set to 3.9 Hz, i.e., the kinetic Reynolds number $Re_{\omega(Dh)} = 27.6$, 6.1 and 1.5 for aluminium 10, 20 and 40 PPI, respectively. It is observed that the amplitudes of pressure drop gradually increases with the increase of the foam's pore density. The effects of the different kinetic Reynolds number on the variations of pressure drop across the aluminium 40 PPI foam are illustrated in Fig. 7 for a complete cycle at $A_{Dh} = 67.5$ for $Re_{\omega(Dh)} = 1.0$, 1.7 and 2.4. It can be seen that the pressure drop for high kinetic Reynolds number is much higher than that for low kinetic Reynolds number. From the results presented in Figs. 5–7, it can be concluded that the pressure drop of oscillating flow in metal foam depends on its density, maximum flow displacement and oscillatory frequency. By comparing Figs. 5 and 7, it is noted that the effect of the kinetic Reynolds number $Re_{\omega(Dh)}$ on pressure drop is more significant than that of the dimensionless flow amplitude A_{Dh}. In fact, the pressure drop of oscillating flow in aluminium foam channel is relatively independent of the dimensionless flow amplitude A_{Dh}.

Fig. 8 illustrates the maximum pressure drop of oscillating flow through aluminium foams of 10, 20 and 40 PPI for the range of hydraulic ligament diameter based

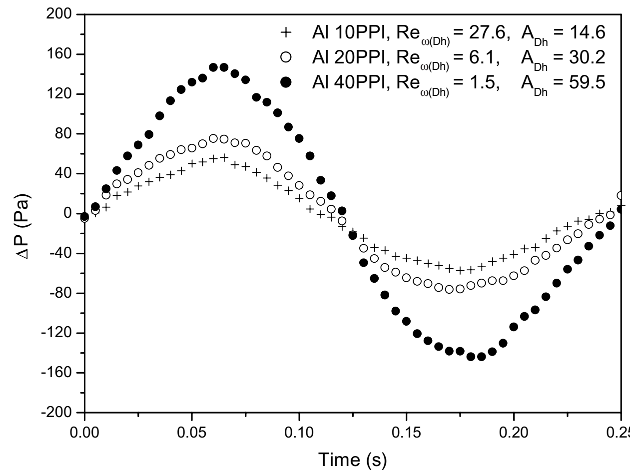

Fig. 6. Effect of different pore densities of aluminium foam on pressure drop of oscillating flow.

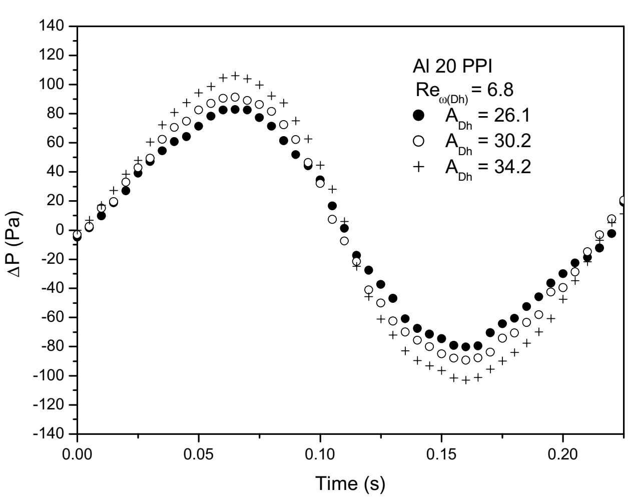

Fig. 5. Effect of the maximum flow displacement on pressure drop in aluminium foam 20 PPI.

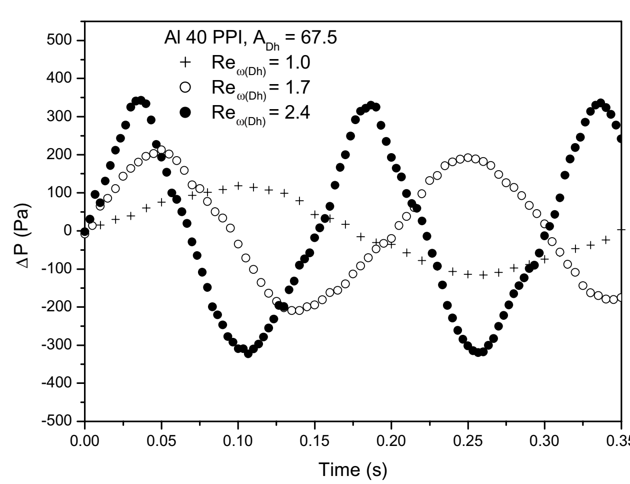

Fig. 7. Effect of kinetic Reynolds number on pressure drop of oscillating flow through aluminium 40 PPI at $A_{Dh} = 67.5$.

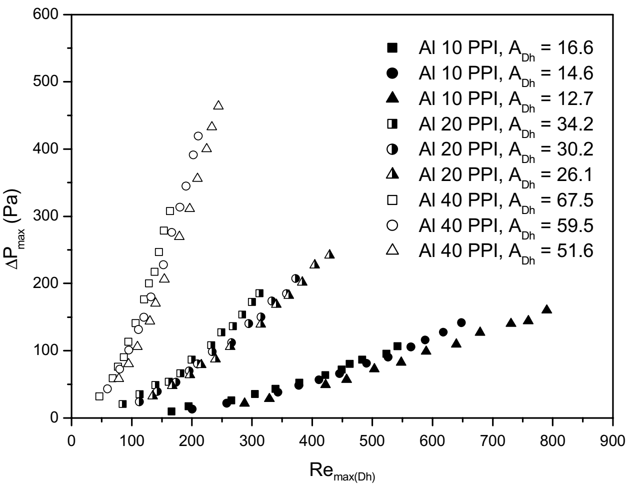

Fig. 8. Maximum pressure drop of oscillating flow versus Reynolds number based hydraulic ligament diameter of aluminium foam 10, 20 and 40 PPI.

Reynolds number $Re_{\max(Dh)} = 46$–790 and dimensionless flow displacement amplitude $A_{Dh} = 12.7$–67.5. It can be seen that for aluminium foams of different pore densities, the maximum pressure drops of oscillating flow increase with the increase of the hydraulic ligament diameter based Reynolds number and dimensionless flow amplitude. The maximum pressure drop increases substantially with an increase in the pore density for aluminium 40 PPI with the highest value of pressure drop being achieved at $A_{Dh} = 51.6$ and $Re_{\max(Dh)} = 244.3$. When compared with the pressure drop of oscillating flow through woven screens obtained by Zhao and Cheng (1996) and Ju et al. (1998), it is noted that maximum pressure drop in a channel filled with aluminium foams is much lower than that in a channel packed with wire-screens. This implies that the required power for driving oscillating flow through an open-cell metal foam is lower than that through wire-screens.

3.3. Maximum friction factor

The maximum friction factors of oscillating flow through porous channel were calculated by Eq. (7) based on the hydraulic ligament diameter of the aluminium foams. Fig. 9 presents the friction factor of steady flow through the porous fin with various aluminium foams (Kim et al., 2000), the experimental data of the maximum friction factor of oscillating flow in aluminium foam 10, 20 and 40 PPI for dimensionless flow amplitudes $A_{Dh} = 12.7$–67.5 and the hydraulic ligament diameter based maximum Reynolds number $Re_{\max(Dh)}$ from 46.1 to 790.2. It can be seen that for both steady and oscillating flows through metal foam porous channel, the friction factor for high pore density foam is smaller than that for low pore density foam. For oscillating flow, the maximum friction factor in 10 PPI aluminium foam decreases with an increase in the dimensionless flow displacement amplitude. The same trends are observed for the other two foams tested in the experiments over different ranges of maximum

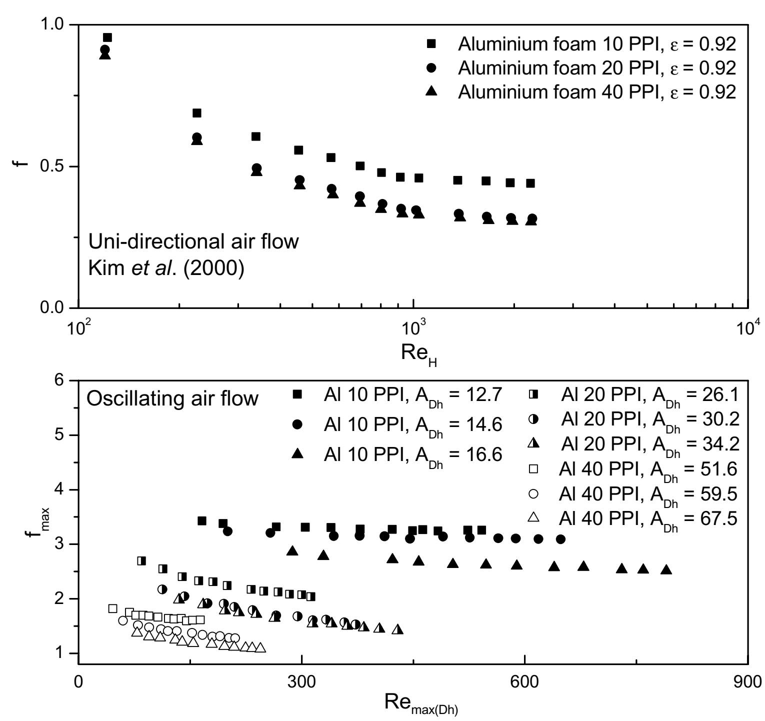

Fig. 9. Maximum friction factors of steady and oscillating flows in aluminium foam 10, 20 and 40 PPI.

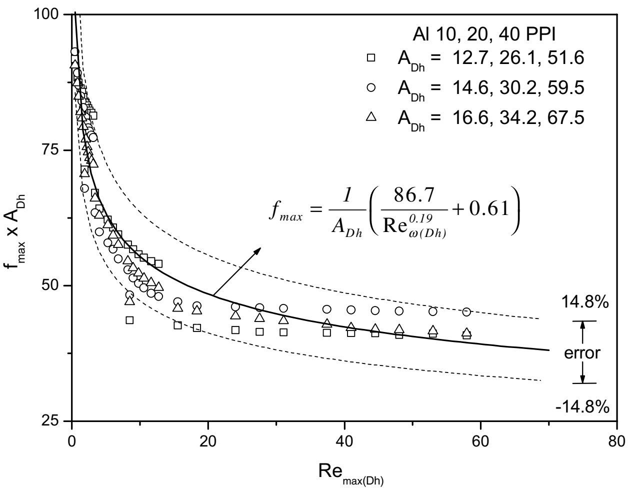

Fig. 10. Maximum friction factors for oscillating flow in open-cell aluminium foam in terms of the kinetic Reynolds number and the dimensionless flow displacement amplitude.

Reynolds number $Re_{max(Dh)}$. The value of the friction factor for oscillating flow calculated by Eq. (7) depends on the three parameters of maximum pressure drop, velocity and hydraulic ligament diameter of metal foam. Comparing the data of f and f_{max} plotted in Fig. 10, it is obvious that the maximum friction factor of oscillating flow is higher than the friction factor of steady flow obtained by Kim et al. (2000) in metal foams with different pore densities. This may due to the looped channel tested on the oscillating flow. The previous work of Zhao and Cheng (1996) obtained a similar result which showed that the average friction factor of oscillating flow is higher than that of steady flow in porous channels.

In order to obtain an empirical equation for the maximum friction factor of oscillating flow through the open-cell metal foam, the kinetic Reynolds numbers $Re_{\omega(Dh)}$ versus the computed data of maximum friction factor f_{max} times the dimensionless flow displacement amplitude A_{Dh} are plotted in Fig. 10. The data ranges of hydraulic ligament diameter based kinetic Reynolds number and dimensionless flow amplitude are $0.46 < Re_{\omega(Dh)} < 57.9$ and $12.7 < A_{Dh} < 67.5$, respectively. The following correlation for the maximum friction factor for oscillating flow in open-cell aluminium foam is derived based on our experimental data:

$$f_{max} = \frac{1}{A_{Dh}}\left(\frac{86.7}{Re^{0.19}_{\omega(Dh)}} + 0.61\right) \quad (10)$$

Eq. (10) was obtained by using a least-squares method with an error of ±14.8%. The error range of the empirical equation plotted in Fig. 10 shows that the friction factor of oscillating flow in metal foam is fitted well by Eq. (10). The correlation equation indicates that oscillating flow behaviour in an open-cell metal foam is governed by the dimensionless flow displacement amplitude and the kinetic Reynolds number based on the hydraulic ligament diameter of open-cell foam.

To compare the oscillating flow characteristics in open-cell metal foam and wire-screens, the maximum friction factor versus maximum Reynolds number for both open-cell metal foams and wire-screens are presented in Fig. 11. For oscillating flow through a porous channel, the maximum cross-sectional velocity u_{max} is related to the maximum flow displacement x_{max} by

$$u_{max} = \frac{x_{max}\omega}{2} \quad (11)$$

By comparing Eqs. (5) and (8), the Reynolds number in Eq. (8) can be expressed in terms of A_{Dh} and $Re_{\omega(Dh)}$ as

$$Re_{max(Dh)} = \frac{A_{Dh}Re_{\omega(Dh)}}{2} \quad (12)$$

In Fig. 11, the solid line is plotted based on Eq. (13) obtained by Tanaka et al. (1990)

$$f_{max} = \frac{198}{Re_{max(Dh)}} + 1.737 \quad (13)$$

where $Re_{max(Dh)}$ is defined as the maximum Reynolds number based on the hydraulic diameter of the screens defined in Tanaka et al.'s paper. The other three curves are plotted using Eq. (10) for dimensionless flow displacement amplitudes $A_{Dh} = 15$, 30 and 70, which cover the range of flow amplitudes performed in the present experiments. It is obvious that the maximum friction factor for oscillating flow in open-cell metal foam is smaller than that for oscillating flow in wire-screens, especially for low Reynolds numbers and large dimensionless flow displacement amplitudes. The difference in the maximum friction factor between low and high Reynolds numbers in a metal foam channel is not as distinct as that in a channel filled with a wire-screen. It is noted that the maximum friction factor increases with

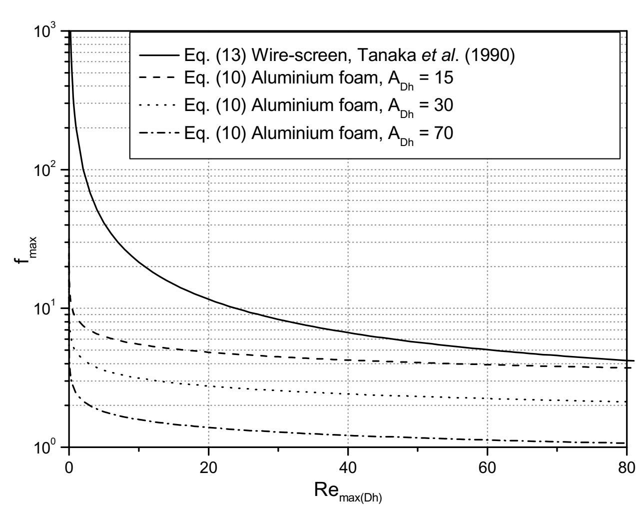

Fig. 11. Comparison of maximum friction factors for open-cell aluminium foams and wire-screens.

the decrease of the dimensionless flow amplitude A_{Dh} for oscillating flow in metal foam channel, and is closer to the result for wire-screens when the Reynolds number is high. The large difference of the maximum friction factor between oscillating flow in metal foam and wire-screen is due to the difference in structure. The cells of aluminium foam are generally 12–14 sided polyhedral whose pentagonal or hexagonal faces are open to one another. The fully inter-connected pore structure allows fluid to flow through the metal foam more readily when compared to a channel filled with wire-screens.

4. Conclusions

In the present study, the characteristics of oscillating flow through a channel filled with open-cell metal foam are investigated. The following conclusions can be drawn:

(1) The pressure drop and velocity profiles of oscillating flow in open-cell metal foam increase with the increase of kinetic Reynolds number and dimensionless flow amplitude, and vary almost sinusoidally due to the reversing flow direction. High pressure drop corresponds to high flow velocity which shows that the phase difference between the velocity and pressure drop is very small for oscillating flow in a metal foam with open-cell structure.

(2) The effect of kinetic Reynolds number $Re_{\omega(Dh)}$ on the pressure drop is more significant than that for different dimensionless flow amplitude A_{Dh}. This indicates that the pressure drop of oscillating flow in an aluminium foam channel is relatively independent of dimensionless flow amplitude A_{Dh}. The maximum pressure drop in a channel filled with open-cell metal foam is much lower than that in a channel packed with wire-screen.

(3) Based on the hydraulic ligament diameter D_{h} of aluminium foam, the kinetic Reynolds number $Re_{\omega(Dh)}$ and the dimensionless flow displacement amplitude A_{Dh} appear as appropriate similarity parameters for the investigation of oscillating flow characteristics in open-cell metal foam.

(4) A correlation equation for the maximum friction factor in terms of dimensionless flow displacement amplitude A_{Dh} and the kinetic Reynolds number $Re_{\omega(Dh)}$ is obtained. For large dimensionless flow displacement A_{Dh}, the pressure drop for oscillating flow in open-cell metal foams is much smaller than that for oscillating flow in wire-screens. The difference between the friction factors of oscillating flow for metal foam and wire-screen decreases with a reduction of oscillatory flow displacement amplitude.

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