HIGH-FREQUENCY OSCILLATING WATER FLOW IN HIGHLY-POROUS MEDIA: EXPERIMENTAL RESULTS FOR 10-PPI METAL FOAM

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ABSTRACT

It is well known that oscillating flow can increase heat transfer over steady-state flow. Inserting porous media in the path of a flow also enhances convection heat transfer. Combining these two effects (oscillating flow and porous media) is supposed to substantially augment heat transfer. In order to understand the heat transfer in such arrangement, one must first understand the flow behavior. Oscillating water flow in open-cell metal foam having 10 pores per inch (ppi) has not been reported in the literature. In this paper, main characteristics of oscillating water flow in 10-ppi open-cell metal foam is reported. The foam had a porosity of 87%. Three flow displacements 74.3, 97.2 and 111.5 mm were applied at the relatively high flow frequencies of 0.46, 0.58 and 0.69 Hz. The effect of flow displacement and frequency on important parameter is presented and discussed. The appropriately defined friction factor correlated well with the kinetic Reynolds number. Steady-state experiments were also conducted for Darcy and Forchheimer water flow through the same metal foam, and the permeability and form/inertial drag coefficient were obtained. Comparisons of the friction factor for oscillating and steady flows is presented. The results of this study are very likely applicable to similar foam-like highly porous media, and is critical for interpreting oscillating heat transfer in metal foam.

INTRODUCTION

Open-cell metal foams are a highly porous, permeable and thermally conductive class of porous media with high surface area densities and they have been discussed in terms of various aspects in [1]. Their internal structure of ligaments promotes repetitive disruption of boundary. Therefore metal foams are preferable for heat transfer enhancement.

Heat transfer can be further enhanced in terms of mitigating hot spots, employing oscillating flows. Oscillating flow and heat transfer are essential to many engineered systems, e.g., heat pipes, regenerators (e.g. in Stirling engines and cryocoolers). For establishing a solution involving heat transfer driven by oscillating flow, the flow characteristics, in terms of increased pressure drop regarding the pumping power, effects of frequency and stroke length needs to be known well.

Oscillating fluid flow and heat transfer in traditional porous media (spherical particles, granular beds and mesh screens) have already been studied [2-6]. Pamuk and Özdemir [7, 8] experimented on oscillating water flow in packed beds of 1- and 3-mm steel spheres with porosities of 36.9% and 39.1%, respectively. They found the permeability and inertial coefficient for oscillating flow to be greater than those for steady-state flow. The friction factor was also correlated with the Reynolds number.

The published studies on oscillating flow in metal foam are scarce. Leong and Jin [9] oscillated air in a channel filled with open-cell metal foam. They determined that the hydraulic-ligament-diameter was a suitable characteristic length for the kinetic Reynolds number and the dimensionless flow displacement. They found out the dominance of the kinetic Reynolds number on the pressure drop. They also noticed a small phase difference between the pressure drop and the velocity. The maximum friction factor increased with decreasing displacement amplitude.

In a different study, Leong and Jin [10, 11] studied heat transfer due to oscillating air flow through channels filled with 10-, 20- and 40-ppi aluminum foams experimentally. The velocity and pressure drop were also measured. The pressure drop and flow velocity increased with increasing oscillating frequency and varied almost sinusoidally. Fu et al. [12] carried out experiment on heat transfer of oscillating air flow in aluminum and carbon foams. The pressure drop and velocity were also measured.

A similar experimental study about oscillating water flow through a 20-ppi metal foam was conducted by Bağcı et al. [13]. The friction factor of oscillating flow was found to be higher than its steady-state counterpart. As the velocities inside the test section increased, the behavior of the hydrodynamics changed and a high-frequency regime was identified.

Most experimental studies in the literature concerning oscillating flow in porous media used air, as the working fluid. Oscillating flow of a liquid, e.g., water, in a 10-ppi metal foam has not been presented. The dispersion of liquid flow in porous media is more significant than that of air flow [14]. By this experimental study, the determination of the characteristics of oscillating water flow in commercial open-cell metal foam was aimed. Therefore a solid foundation of knowledge could be established for future heat transfer experiments with similar metal foams.

NOMENCLATURE

a	[-]	Constant, Eq. (4)
b	[-]	Constant, Eq. (4)
$\tilde{a}$	[-]	Correlation constant, Eq. (8)
$\tilde{b}$	[-]	Correlation constant, Eq. (8)
A	[m^2]	Cross-sectional area of test section
D	[mm]	Inner diameter of test section
f	[-]	Friction factor for steady flow $= [2(\Delta p/L)D]/[\rho u^2]$
$f_{\max}$	[-]	Oscillating flow friction factor $= [2(\Delta p_{\max}/L)D]/[\rho u_{\max}^2]$
F	[-]	Forchheimer coefficient
K	[m^2]	Permeability
L	[m]	Length of porous medium
p	[kPa]	Static pressure
Re	[-]	Reynolds number for steady flow $= (\rho u D)/\mu$
$\mathrm{Re}_{\max}$	[-]	Reynolds number for steady flow $= (\rho\omega D x_{\max})/2\mu$
Re_ω	[-]	Kinetic Reynolds number $= (\rho\omega D^2)/\mu$
S	[m]	Maximum displacement of piston
t	[s]	Time
u	[m/s]	Average velocity
$x_{\max}$	[mm]	Maximum flow displacement

Special characters

Δ	[-]	Change
ε	[-]	Porosity
μ	[Pa.s]	Viscosity
ω	[Hz]	Flow frequency
ρ	[kg/m^3]	Density

EXPERIMENT

A schematic of the experimental setup is shown in Figure 1. The test section 1 is made from an aluminum alloy (6061-T6) pipe having inner diameter of 50.80 mm, wall thickness of 6.35 mm and length of 325 mm. An open-cell aluminum foam having 10 pores per inch (ppi) and porosity of 88.49% is brazed to the inside surface of the pipe, Figure 2. The alloy of the foam is 6101-T6.

50.8-mm-wide and 200-mm-long polyethylene tubes 2 are connected to the test section on both sides. Pressure taps reside on these tubes. The outlets of the tubes are connected to stainless steel pipes 32 mm in diameter and 110 cm in length, 3. The ends of these tubes are connected to an oscillating flow apparatus 5-9 via hoses 4. A double-acting cylinder is connected to an electrically driven motoreductor for generating oscillation. Rotational speed of the 7.5-kW motoreductor is controlled via a variable speed AC-drive (6.99-20.97 rpm). A radial groove on the flywheel is used for changing the stroke size.

Depending on the operating configuration, pressures on both ends of the test section are measured using Keller models PR-23R and PA-21Y piezoresistive pressure transmitters. PR-23R has a gauge pressure range of 100 mbar, whereas PA-21Y comes with a range of 2.5 bars. The analogue signals between 4-20 mA are acquired by a data logger 10. Those signals are then converted to actual pressure values using linear relations between current and pressure.

In order to fill the system with water completely, the whole system is vacuumed down to 60 mmHg, absolute pressure. Then, domestic water passing through sediment and resin filters is allowed to flow inside the test conduit.

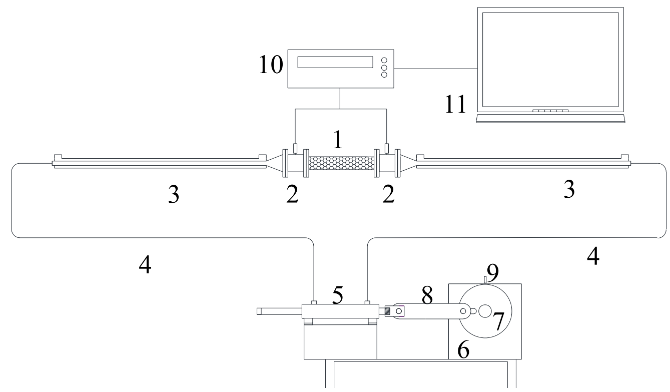


Figure 1 Schematic of the experimental setup: 1.Test Section, 2. Polyethylene tubes, 3. Steel pipes, 4. hoses, 5. Oscillation Generator, 6. Motoreductor, 7. Flywheel, 8. Crank Arm, 9. Optical sensor, 10. Data logger, 11. Computer.

Figure 2 Photograph showing metal foam brazed to inside surface of the test section

For a given oscillating-flow run, the stroke length of the piston is adjusted, and the oscillation frequency is set to a desired value. After quasi-steady-state is achieved (up to 10 minutes), a Keithley 2700 XLINX data acquisition software is employed to communicate with the data logger and record the pressure signals from the two pressure transmitters and one signal from an optical sensor activated once per cycle. This signal is used to approximate the real-time velocity along with the pressure signals.

The uncertainties in the directly-measured length and diameter of the metal foam tube were 0.33% and 0.04%, respectively. As for pressure measurements, the transmitters had an error band of ±1% of full scale. These values were provided by the manufacturer and included effects of linearity, hysteresis and repeatability. The uncertainties in the calculated angular frequency and maximum fluid displacement are estimated as 0.43% and 0.51%, respectively [15].

Data Reduction

For oscillating flow, the maximum fluid displacement is related to the displacements of the piston according to conservation of mass, and the fact that water is an incompressible fluid. In this case, the maximum flow displacements ($x_{\max}$) at the entrance of the metal foam is calculated from the ratio of the cross-sectional areas of piston and entrance of porous channel as

$$x_{\max} = \frac{2SA_p}{A} \quad (1)$$

where S, A_p and A are the maximum displacement of the piston, cross-sectional areas of double acting cylinder and metal-foam pipe, respectively. The short, medium and long maximum flow displacements for this study were 74.35, 97.23 and 111.53 mm, respectively.

The flow frequency changed in the range of 0.348-0.696 Hz, depending on the 6.97-21.0 rpm speed of motoreductor. The motoreductor operated at 69.7 rpm at 50 Hz line frequency.

At the entrance of the foam, the time-dependent fluid displacement x_m varied with angular frequency ω and time t according to

$$x_m(t) = \frac{x_{\max}}{2}(1 - \cos\omega t) \quad (2)$$

The cross-sectional mean fluid velocity is

$$u(t) = u_{\max}\sin\omega t \quad (3)$$

where $u_{\max} = \omega x_{\max}/2$.

RESULTS AND DISCUSSION

Figure 3 is a plot of maximum pressure amplitude on one side of the foam as a function of flow frequency for the three flow displacements. For the low frequencies, the effect of displacement on pressure amplitude is not significant. Also the effect of frequency on the pressure amplitude is mild for short displacement. The line pressures inside the conduit, also acting as the mean value for pressure change, had an effect on the inlet pressures depicted in Figure 3.

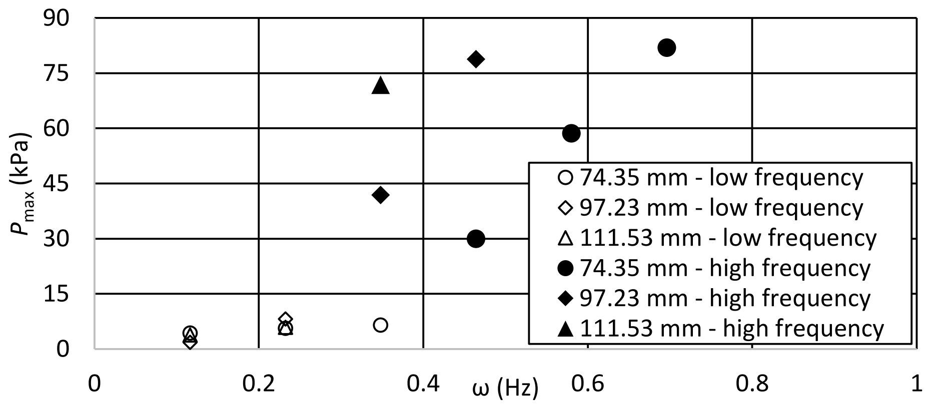


Figure 3 Inlet pressure amplitude as a function of flow frequency for different fluid displacements.

In Figure 4, the average velocity through the foam is plotted together with the pressures at the inlet and outlet for the case of $x_{\max}$ = 73.25 mm and ω = 0.580 Hz. It is clear that there is a phase shift of approximately 40° between these pressures and flow velocity. However, in contrast with the low frequency region reported in [13], there is no phase shift between the two end pressure changes. Pamuk and Özdemir [7] reported no phase shift between the pressures and flow velocity for oscillating water flow in packed spheres. Khodadadi [3] reported a phase shift of 90° between the velocity and pressure gradient based on his analytical solution. Zhao and Cheng [5] also reported a phase shift between pressure drop and velocity for air flow in screens. The channeling effect (flow velocity exhibiting maxima next to the solid wall) reported by Khodadadi [3] could be responsible in part for this phase shift.

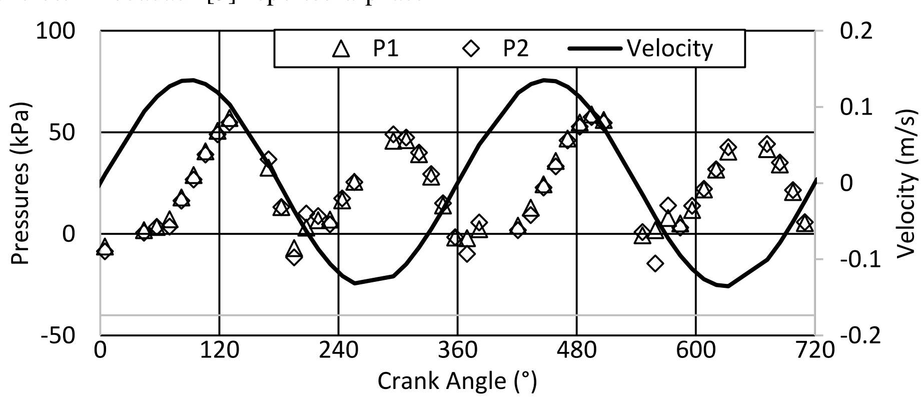
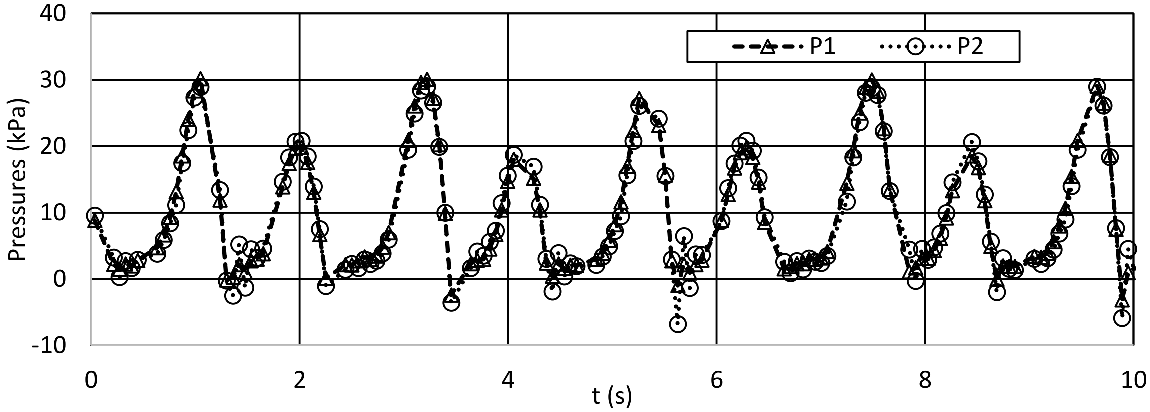


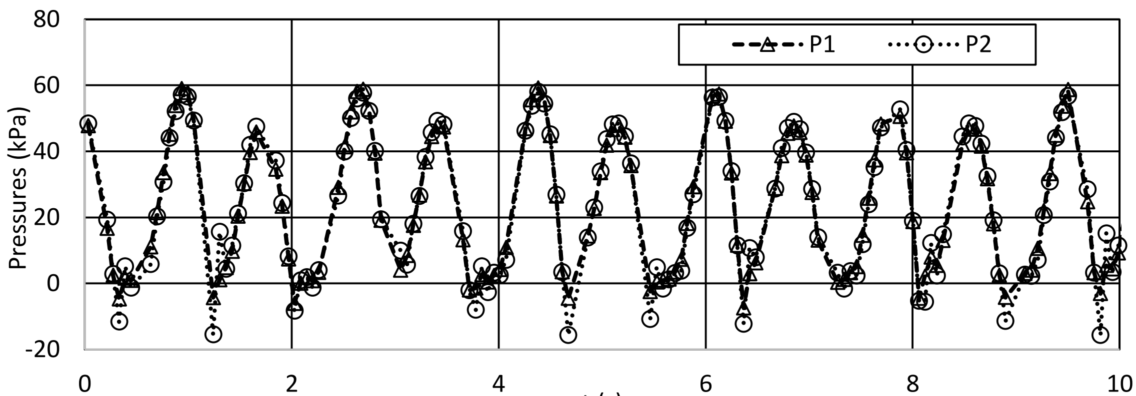
Figure 4 Temporal pressures at inlet and outlet and average flow velocity for $x_{\max}$ = 73.25 mm: ω = 0.580 Hz.

To display the effect of frequency on inlet and outlet pressures, these pressures as functions of time, for the short stroke, are shown in Figure 5. It is clear that the frequency has an effect on these pressures. There is a significant resemblance between the inlet and outlet pressure behaviors. As P_1 completes one cycle, P_2 is seen to complete the same cycle over the period. The explanation to those stroke-frequency couples constituting trends in a different regime unlike those in low frequencies, is that this behavior exists for increasing frequencies per stroke. The inertia of the flow are so dominant that the foam behaves like a hollow pipe. Nevertheless, there always exists a pressure gradient signifying the flow direction and pressure loss. This regime was never observed in the study of Pamuk and Özdemir [7] who studied pressure loss in packed spheres with much lower porosities.

An FFT analysis showed the magnitudes of the harmonics for an end pressure. It was observed that the line frequency was never that of the dominant harmonic. This was not the case of oscillations in low-frequency region. This finding was identified by Hsu et al. [6] as an evidence to a non-linear relation between pressure loss and velocity.



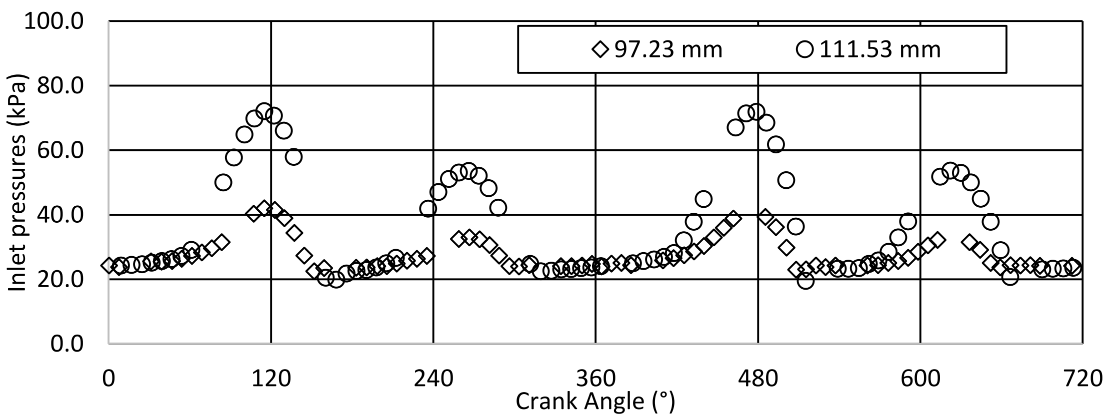
(a)



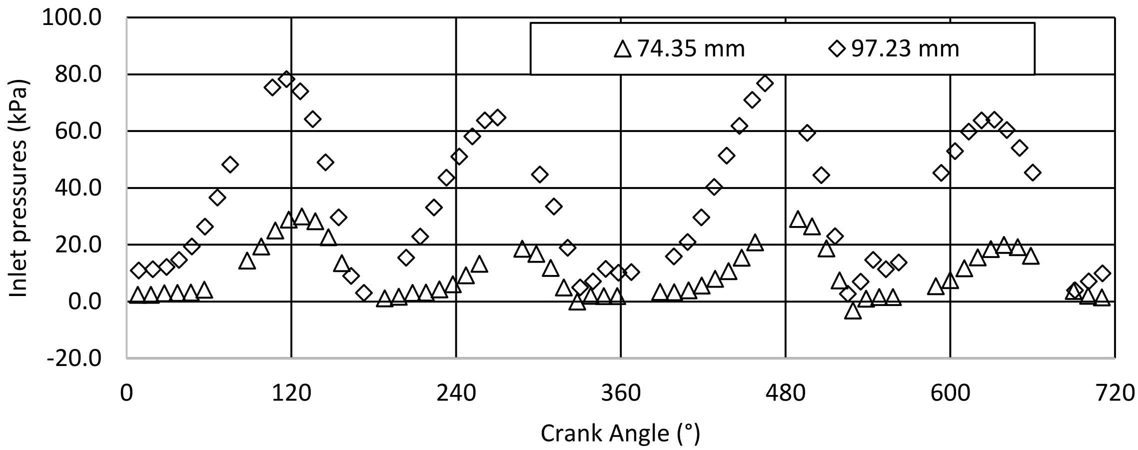
(b)

Figure 5 Temporal pressures at inlet and outlet for xmax= 73.25 mm: (a) ω = 0.464 Hz, (b) ω = 0.580 Hz

The effect of maximum fluid displacement on the pressure at the inlet of the foam is shown in Figure 6 for two frequencies. As expected, there is a positive correlation between the displacement and the inlet pressure.



(a)



(b)

Figure 6. Temporal pressure at inlet- Effect of displacement for (a) ω = 0.348 Hz, (b) ω = 0.464 Hz

The effect of frequency on the pressure drop across the foam is shown in Figure 7. For the two frequencies, the pressure drop is expected to be periodic. However this fact is not observed here clearly, due to the scatter. The reason is the massive amount of vibration, and the significant proximity of the end pressure values with respect to each other. The maximum pressure drop increases with frequency. This is similar to what has been reported by Leong and Jin [9-11] for air flow in metal foam, and by Zhao and Cheng [5] for air flow in a packed bed of woven screens.

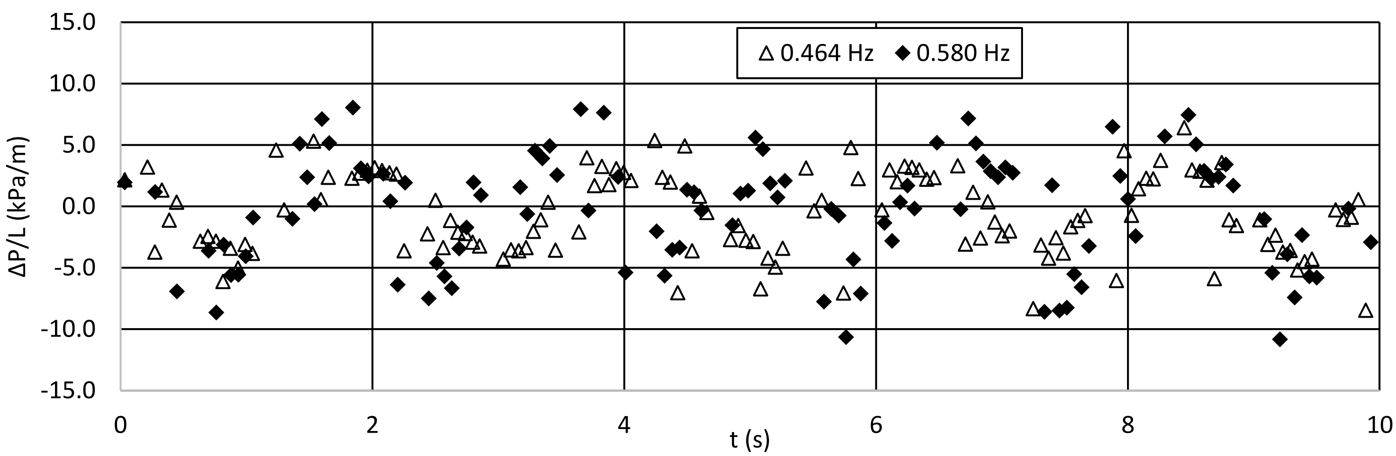


Figure 7 Pressure gradient versus time - Effect of frequency at a displacement of 97.23 mm

For steady-state unidirectional flow in porous media, the friction factor behaves according to [16, 17]

$$f = a\left(\frac{1}{\mathrm{Re}}\right) + b \qquad (4)$$

where $f = [2(\Delta p/L)D]/[\rho u^2]$, $\mathrm{Re} = (\rho u D)/\mu$ and a and b are adjustable parameters. Here D is the tube diameter. In oscillating-flow literature the friction factor is based on the amplitude of the mean velocity, or the maximum velocity, $u_{\max}$ and the maximum pressure gradient, $\Delta p_{\max}$ according to

$$f_{\max} = \frac{2(\Delta p_{\max}/L)D}{\rho u_{\max}^2} \qquad (5)$$

The kinetic Reynolds number is defined as

$$\mathrm{Re}_\omega = \frac{\rho \omega D^2}{\mu} \qquad (6)$$

where ω is the angular frequency. The Reynolds number based on maximum displacement is defined as

$$\mathrm{Re}_{\max} = \frac{\rho \omega D x_{max}}{2\mu} \qquad (7)$$

Figure 8 compares the friction factor for steady and oscillating flows. The behavior of the steady-state friction factor is consistent with the typical behavior for porous media. Equation (5) is seen to correlate the steady-state friction data very well with the values of a and b given in Table 1.

Table 1 Correlation coefficients for steady-state and oscillating flow.

	$a, \tilde{a}$	$b, \tilde{b}$
Steady State Flow	32168.52	24.97
Oscillating Flow	-307778.77	101.00

The friction factors for the oscillating flow both in the high frequency region and in the low frequency region, where there are much lower pressure values involved, are higher than their steady-state counterparts as also reported for air flow in packed woven screens by Zhao and Cheng [5], for water flow in packed spheres by Pamuk and Özdemir [7] and for air flow in metal foam by Leong and Jin [9].

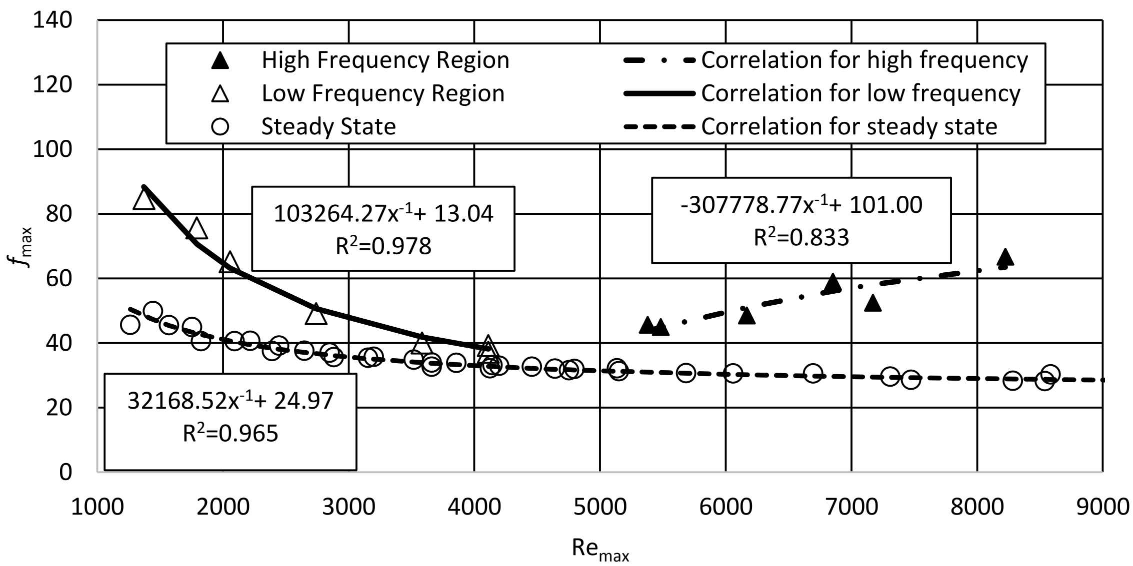


Figure 8 Friction factor versus Reynolds number for steady and oscillating flow for all flow displacements

The friction factor for oscillating flow correlates with Re_{max} according to

$$f_{\max} = \tilde{a}\left(\frac{1}{\mathrm{Re}_{\max}}\right) + \tilde{b} \qquad (8)$$

with the correlation coefficients $\tilde{a}$ and $\tilde{b}$ given in Table 1. A similar correlation to Eq. (9) was obtained by Zhao and Cheng [5] for air flow in packed woven screens, by Pamuk and Özdemir [7] for water flow in packed spheres and by Leong and Jin [9, 10] for air flow in metal foam.

CONCLUSION

Characteristics of oscillating water flow in commercial open-cell metal foam having 10 pores per inch were experimentally obtained for three flow displacements and three frequencies which are accepted to be high because inertial effects are pronounced. Based on the findings, the following remarks can be made:

- The pressure drop increases with both flow displacement and frequency, with the increase being more pronounced for high frequencies.
- There was a phase shift between the end pressures and flow velocity. However, no shift was observed between the inlet and outlet pressures.
- The functional relationship between the friction factor and Reynolds number for oscillating flow in porous media was applicable to the result of the current study for water flow in metal foam.
- The friction factors for oscillating flow was higher than that of the steady-state flow.

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