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Experimental heat transfer due to oscillating water flow in open-cell metal foam

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ABSTRACT

While studies concerning heat transfer due to oscillating air (and few other gases) flow in metal foam are available, heat transfer due to oscillating water flow in metal foam has not been offered in the literature. This paper presents characteristics of heat transfer of oscillating water flow in commercial open-cell metal-foam pipe that were obtained experimentally, most likely for the first time. One main difference between gas and liquid flows in porous media is that dispersion is far more significant in the latter. Another difference is the length of the entrance region, which depends strongly on the Prandtl number. The trends in the cycle-averaged wall temperature, length-averaged wall temperature and cycle-averaged Nusselt number were similar to those for oscillating water flow in packed spheres and for oscillating air flow in aluminum, copper and graphite foams in a rectangular channel. For the higher flow frequency of the current study, the cycle-averaged Nusselt number was higher for higher flow displacement amplitude.

1. Introduction

Open-cell metal foams are relatively new class of porous media that have been recently discussed in Ref. [1]. These foams have high porosity, permeability, thermal conductivity and surface area density. The web-like internal structure of metal foams promotes mixing of through flowing fluids. As such, metal foams are attractive for heat transfer enhancement systems. Some preliminary steady-state convection heat transfer results for water flow in metal foam were recently published [2].

It is well-established that heat transfer can be augmented substantially by employing time-dependent flow as compared to heat transfer due to steady-state flow. Oscillating (or reciprocating) flow is time-dependent periodic flow. Lambert et al. [3] proposed enhancing heat-transfer performance of solar devices by employing oscillating flow. He showed that for oscillating flow, the effective thermal diffusivity was several orders of magnitude higher than the fluid molecular diffusivity. Pamuk and Özdemir [4] indicated that heat transfer due to oscillating flow is comparable to that of heat pipes.

Oscillating flow and heat transfer in porous media occur in many applications, e.g., heat pipes, regenerators (e.g. in Stirling engines and cryocoolers), cooling designs of nuclear power plants and reciprocating internal combustion engines. Oscillating heat transfer in porous media can produce two advantageous effects: 1) a high heat transfer rate and 2) a more uniform temperature distribution on a hot substrate or surface due to the presence of two thermal entry regions. Therefore, oscillating heat-transfer designs can be used to cool modern high-speed devices (e.g., microprocessors and transistors). The reliability and operation speed of these devices depend not only on their average temperature, but also on their temperature uniformity.

Transport phenomena due to oscillating flow are naturally complex; and they are not very well understood [5]. Heat transfer due to oscillating flow in traditional porous media (packed spheres, granular beds and mesh screens) has received considerable attention. Sozen and Vafai [6] numerically investigated forced convection due to oscillating compressible ideal gas (Refrigerant-12m) flow in a packed bed. The porosity of the bed was 39%. Byun et al. [7] analyzed heat transfer due to oscillating flow through infinitely large porous slab using the two-equation model (thermal non-equilibrium). Habibi et al. [8] solved the heat transfer equations for a two-dimensional channel partially filled with a porous medium subjected to reciprocating air flow. The channel was discretely heated on one side to simulate compact circuit boards.

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Nomenclature

A	cross-sectional area of test section (m^2)
A_o	non-dimensional displacement
I_{uni}	index (for temperature uniformity)
L	length of porous medium (m)
Nu	local cycle-averaged Nusselt number
ppi	number of pores per inch of foam
q''	heat flux ($W\ m^{-2}$)
Re_D	Reynolds number based on pipe diameter
Re_ω	kinetic Reynolds number
t	time (s)
U	average velocity (m/s)
x_{max}	maximum flow displacements (mm)
z	coordinate along flow direction, distance from entrance
Greek	
μ	viscosity (Pa s)
ω	angular frequency (rad/s)
ρ	density (kg/m^3)
Subscripts	
f	fluid
i	inlet
max	maximum
min	minimum
w	wall
z	flow direction, local

Pamuk and Özdemir [4] presented experimental heat transfer results for oscillating water flow in two sets of mono-sized packed steel balls (1 and 3 mm). The porosity of the first set was 36.9%, while it was 39.1% for the other. The effect of various parameters on heat transfer was studied, e.g., frequency, flow displacement and heat input. Results were presented in terms of cycle-averaged local Nusselt number and space-cycle-averaged Nusselt number. The latter correlated well with the kinetic Reynolds number and non-dimensional flow displacement.

Recently, Dai and Yang [9] numerically studied oscillating gas flow and heat transfer in regenerative cryocoolers using the Lattice Boltzmann Method. They noted that the velocity and temperature profiles were mainly influenced by the Womersley number. Little vortices were observed near the surface of the solid phase.

Pathak et al. [5] numerically studied oscillating flow and heat transfer in a 75%-porous medium composed of square cylinders. The working fluid was helium. The Nusselt number strongly depended on flow oscillation frequency and amplitude. Significant phase lag occurred among velocity, pressure, temperature and heat transfer processes.

For heat transfer due to oscillating flow in metal foam, there are only few published studies. Leong and Jin [10] experimentally studied heat transfer due to oscillating air flow through a channel filled with aluminum foam and subjected to constant wall heat flux. The 90%-porous foam was produced by sintering and had 40 pore per inch (ppi). The cycle-averaged Nusselt number increased with both the kinetic Reynolds number and dimensionless amplitude of flow displacement. A correlation for the length-averaged Nusselt number as a function of these two non-dimensional parameters were provided.

In a different investigation, Leong and Jin [11] conducted experiments to study the effect of frequency on heat transfer performance of metal foam heat sinks subjected to oscillating flow of air. The aluminum foam used in the heat sinks had 10, 20 and 40 ppi. The cycle-averaged temperature decreased with increasing kinetic Reynolds number while the Nusselt number exhibited the opposite trend. Better heat transfer was noted for foam with low pore density.

In a third experiment, Leong and Jin [12] studied heat transfer of oscillating air flow in two porous channels having commercial aluminum (20-ppi) and copper (60-ppi) foams with porosities around 90%. The oscillating flow amplitude was larger than the length of the test section (in order to ensure proper cooling). The local wall temperature was maximum at the center of the test section, and the cycle-averaged wall temperature decreased with increasing Reynolds number. The cycle-averaged Nusselt number had a concave shape with a minimum at the center of the channel. Heat transfer was higher for the case of copper foam due to its higher conductivity, as expected. In a fourth paper, Leong and Jin [13] experimentally studied oscillating flow through a channel filled with metal foam. For fluid flow characteristics, these authors stated that the non-dimensional fluid displacement and the kinetic Reynolds number were the appropriate similarity parameters for oscillating flow in open-cell metal foam. No heat transfer information was given in Ref. [13].

Fu et al. [14] carried out experiments on heat transfer of oscillating air flow in channels filled with commercial aluminum (40-ppi) and carbon (45-ppi) foams-each having a porosity around 90%. The uniformity of the surface temperature in oscillating heat transfer was displayed.

Ghafarian et al. [15] conducted computational analysis of heat transfer for oscillating air flow through a metal-foam channel heated from one side. They invoked the local thermal equilibrium assumption between the solid and fluid phases of the foam. The effect of the porosity, thermal conductivity and solid-fluid thermal conductivity ratio of the foam on heat transfer was investigated. The main conclusion was that heat transfer increased by employing high amplitude and high frequency.

As indicated by Pamuk and Özdemir [16], and by the literature review given above, all experimental studies in the literature concerning oscillating flow and heat transfer in porous media (including metal foam) used gases, mostly air, as the working fluid. Oscillating flow of liquid, e.g., water, in metal foam has only been presented recently [17,18]; no heat transfer findings were given. One main difference between gas and liquid flows in porous media is that dispersion is significant in the latter, while so weak in the former that it has been ignored [19]. Another difference is the length of the entrance region, which depends strongly on the Prandtl number of the working fluid. Both of these matters affect oscillating heat transfer significantly.

The purpose of the current experimental study is to furnish heat transfer characteristics due to oscillating water flow in commercial open-cell metal foam in terms of pertinent parameters. The results of the current study will be contrasted to those in previous studies employing air flow in similar metal foam; and also to the oscillating flow heat transfer results obtained for different porous media (e.g., packed beds of spheres and screens). A comparison of oscillating water flow heat transfer and steady state heat transfer in the same metal foam of the current study will also be provided. The aim is to enhance fundamental understanding of heat transfer in oscillating liquid flow in metal foam in order to guide engineering design tools (analytical and numerical) for potential applications, e.g., cooling