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Thermal development in open-cell metal foam: An experiment with constant wall heat flux

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ABSTRACT

Experimental heat transfer results for a commercial open-cell aluminum foam cylinder heated at the wall by a constant heat flux and cooled by water flow, are presented. The results cover thermal-entry and fully-developed regions. Measurements include wall temperature along flow direction as well as average inlet and outlet temperatures of the water. Flow rates are in the Darcy and non-Darcy (transitional and Forchheimer) regimes. The wall temperature along the foam clearly shows two distinct behaviors related to thermally-developing and fully-developed conditions, which is confirmed by the behavior of local Nusselt number. The thermal entry length is determined and discussed in detail; it is also compared to its analytical counterpart for Darcy flow. The thermal entry region in metal foam is found to be significant and much longer than its analytically-predicted value. A method for estimating the bulk fluid temperature is envisioned for calculating the local Nusselt number. Previously undiscussed phenomenon is captured in the behavior of Nusselt number for non-Darcy regimes, which suggests periodic thermal development along the foam. The fully-developed data for the Darcy flow cases is compared to its analytical counterpart, and a correlation for the Nusselt number as a function of Reynolds number is proposed for non-Darcy flows.

1. Introduction

Open-cell metal foams are excellent heat exchange cores [1]. They have high conductivities and very large surface area density. The internal structure of the foam causes vigorous mixing and dispersion, which augment convection.

Solutions and simulations, e.g., [2–4], of heat transfer inside metal foam, along with various assumptions, require experimental validation. Experimental data also has intrinsic value and can provide empirical correlations for practical design. In 2012 a review by Zhao [5] indicated that there has been a lack of reliable experimental heat transfer data for open-cell metal foam in general. In 2006, no experimental data was available for metal-foam-filled pipes, Lu et al. [4].

Some recent experimental studies were geared toward practical applications, e.g., testing metal-foam designs for cooling future generation fuel cells. Odabaee et al. [6] experimentally showed that air-cooled fuel-cell systems employing metal foam required half the pumping power of current water-cooled systems, while removing the same amount of heat at identical operating conditions. In a related study Fiedler et al. [7] experimentally established the relationship between the thermal and electrical contact resistances and the compressive stress applied between metal foam and graphite plates. This study was a step toward reducing cost for future generation air-cooled fuel cells.

Metal foam has also been used to extend external surfaces in order to enhance heat transfer from such surfaces. Recently, Khashehchi et al. [8] investigated the wake region behind a foam-covered cylinder subjected to cross air flow. Chumpia and Hooman [9] evaluated the performance of single tubular aluminum-foam heat exchangers in which foam layers were attached to the outer surface of tubes subjected to cross flow of air. The foam-covered tubes performed substantially better than finned tubes under the same test conditions.

A summary of some experimental studies for heat transfer in metal foam due to strictly internal flow of air and water is given in Table 1. It should be noted that the last number is the length of the foam test sample in flow direction for each study.

From Table 1, three facts emerge: (a) experimental studies concerning heat transfer in metal foam in general employed small foam sample sizes (or at least small dimension in one direction)

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Nomenclature

A	cross-sectional area (m^2)
D	diameter of foam cylinder (m)
k	thermal conductivity (W.m^{-1}.K^{-1})
Nu	Nusselt number
Pe'	Péclet number
Pr	Prandtl number
q''	heat flux (W.m^{-2})
T	temperature (°C)
u	flow velocity (m.s^{-1})
U	mean flow velocity (m.s^{-1})
r_o	radius of foam cylinder (m)
Re	Reynolds number
z	axial coordinate along flow direction (m)
Greekμ	viscosity (Pa.s)
ρ	density (kg.m^{-3})
Subscriptsf	
	fluid
b	bulk (mean) value
e	effective
D	developing
FD	fully-developed
LTE	local thermal equilibrium
$LTNE$	local thermal non-equilibrium
w	wall

or a short length in the flow direction relative to flow area hydraulic diameter, which makes their results specific to the samples tested, as the data may contain unassessed size and/or entry and exit effects (b) studies with water as the cooling fluid are few indeed; water flow provides much higher heat transfer rates due to it higher thermal conductivity (compared to air) and also due to dispersion which is negligible for air flow in metal foam, and (c) only one experimental study involved the cylindrical geometry, such geometry is most suited for many practical heat exchange designs and reactors.

While literature on porous media flow and heat transfer is abundant, the issue of thermal development in porous media is addressed, or displayed, in only several articles [21–36]. These articles employed various geometries, boundary conditions and simplifying assumptions. Haji-Sheikh et al. [31] investigated the thermal entrance length for flow through rectangular porous passages with difference aspect ratios, and subjected to constant wall temperature and constant wall heat flux. Hydrodynamic development was ignored and local thermal equilibrium was imposed on their analysis. For narrow passages with constant wall heat flux, they indicated that thermal fully developed conditions may not be attainable in practical applications. Hooman et al. [32] analytically investigated thermal development in the same geometry but subjected to isothermal walls and including viscous dissipation. Similar to [31], hydrodynamic development was ignored and local thermal equilibrium was imposed.

Table 1
Experimental studies on heat transfer due to internal flow in metal foam from the literature.

Working Fluid	Study	Geometry	Dimensions (mm)
Air	Calmidi and Mahajan [2]	Block	45 × 63 × 196
	Hwang et al. [10]	Block	60 × 25.4 × 60
	Bhattacharya et al. [11]	Block	43.75 × 62.5 × 192.5
	Bhattacharya and Mahajan [12]	Fin	3.12 × 56.25 × 62.50 & 6.25 × 56.25 × 62.50
	Zhao et al. [13]	Block	12 × 127 × 127
	Kurbas and Celik [14]	Block	8 × 52 × 62 & 13 × 52 × 62
	Mancin et al. [15]	Block	20 × 20 × 100
	Dukhan et al. [16]	Cylinder	255.6 × 152.4
	Odabaee et al. [6]	Block	100 × 5 × 100
	Mancin et al. [17]	Block	100 × 20 × 100 & 100 × 40 × 100
	Mancin et al. [18]	Block	100 × 20 × 100 & 100 × 40 × 100
Water	Boomsma et al. [1]	Block	40 × 40 × 2
	Hetsroni et al. [19]	Block	2 × 10 × 54
	Kim et al. [20]	Fin	9 × 90 × 30
	Noh et al. [21]	Annulus	38.24OD × 15.88ID × 400

Hooman and Ejlali [33] and Hooman and Haji-Sheikh [34] investigated thermal development and entropy generation due to forced convection in a porous tube with uniform wall temperature and a rectangular porous duct with isoflux walls, respectively. In both cases, the effect of viscous dissipation was included, while the assumption of local thermal equilibrium and hydro-dynamically fully-developed flow were imposed. Nusselt number depended on Darcy-Brinkman number and clearly showed thermal development behavior. In the latter study, it was observed that viscous dissipation reduced Nusselt number in both thermally developing and fully-developed regions.

Hooman and Gurgenci [35] investigated the effect of viscous dissipation on forced convection in parallel-plate channel filled with a porous medium. The plates were subjected to constant temperature and constant wall heat flux- one boundary condition at a time. The local thermal equilibrium model was solved numerically. Nusselt number behavior showed dependence on Brinkman number in the thermally-developing region for isothermal walls and isoflux walls cases. Hydrodynamic development was presented in terms of velocity profiles.

In a different study [36] Hooman and Gurgenci numerically studied the effect of temperature-dependent viscosity on forced convection due to liquid flow through a porous medium sandwiched between two isoflux parallel plates. Here too the assumption of local thermal equilibrium was imposed. Velocity and temperature profile shapes as well as hydrodynamic and thermal development was seen to be affected by changes in viscosity.

Noh et al. [21] experimentally investigated flow and thermal aspects for water transport through and annulus filled with aluminum foam and heated externally with a constant heat flux. The wall temperature and the local Nusselt number were given as functions of axial location, at only four axial locations. Thermal development was obvious, but concrete conclusions were difficult to ascertain due to the limited number of data points.

Nield et al. [22] analytically investigated thermal entry length for the case of a circular-tube porous media subjected to constant heat flux assuming local thermal equilibrium between the solid and fluid phases in the porous medium. They ignored hydrodynamic development in the analysis. Nonetheless, this is the closest case to the problem investigated in the current paper. A comparison of the results of the current study to those presented in [22] will be given below.

The thermal entry length, as well as the effect of thermal development, is often ignored in metal foam heat transfer studies. In the current study, direct measurements of wall, inlet and outlet temperatures for water flow inside heated, commercial open-cell aluminum foam are presented. The foam cylinder tested is