International Journal of Heat and Mass Transfer 77 (2014) 114–123

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Metal foam hydrodynamics: Flow regimes from pre-Darcy to turbulent

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ARTICLE INFO

Article history:
Received 24 February 2014
Received in revised form 4 May 2014
Accepted 9 May 2014
Available online 5 June 2014

Keywords:
Porous media
Flow regimes
Metal foam
Friction factor
Permeability
Characteristic length

ABSTRACT

Metal foam is a relatively new class of porous media. The internal morphology of the foam is composed of connected cells each having many ligaments that form a web. In addition, metal foam has very high porosity (often greater than 90%) and a large surface area density. These properties are exploited in many applications, e.g., heat exchanger, reactors and filters. Flow regimes, and transition from one to another, are critical for understanding energy dissipation mechanisms for flow through the foam, and for heat transfer or reaction rates. While this topic is well studied in traditional porous media, e.g., packed beds, it is not well understood for foam-like porous media such as metal, graphite and polymeric foams. Pressure drop parameters such as permeability and form/inertial drag coefficients are very divergent for metal foam. The choice of an appropriate characteristic length for metal foam has also varied among researchers. In the current study a large set (88 points) of carefully-obtained experimental data for pressure drop of water flow in aluminium foam having 20 pores per inch and a porosity of 87.6% was collected. The range of flow Reynolds number covered all known flow regimes in porous media from pre-Darcy to turbulent. Flow regimes and transition between them were identified and compared to their counterparts in traditional porous media and to what is available for metal foam. The current data correlated very well using the friction factor based on the square root of permeability (measured in the Darcy regime) and the Reynolds number based on the same characteristic length. It is shown that the same foam exhibits different values of its permeability and Forchheimer coefficient in different flow regimes. The finding of this study can help in numerical and analytical work concerning flow and heat transfer in foam-like porous media.

1. Introduction

Man-made porous media, e.g., packed spheres and metal, graphite, ceramic and polymeric foams are highly exploited in many engineering applications. Open-cell metal foam can be manufactured from several metals and alloys, e.g., aluminium, copper, steel and nickel [1]. These highly-permeable foams have relatively high thermal conductivity and contain high surface area per unit volume; their internal structure (web-like) grants forceful mixing of through fluid flow. For liquid flow in metal foam, dispersion – an added mechanism of transport – is considerable. All these attributes make metal foams attractive for heat transfer enhancement, e.g., in electronics cooling [2], and in gas–liquid and liquid–liquid compact heat exchangers [3]. Boomsma et al. [4] have experimentally proven that, at the same pumping power, certain compressed aluminium foam heat exchangers generated thermal resistances that were two to three times lower than commercially available heat exchangers. Mahjoob and Vafai [5] published a synthesis of fluid and thermal transport models for metal-foam heat exchangers, and introduced a performance factor for assessing the enhanced heat transfer and pressure drop penalty simultaneously, which showed superior performance of such heat exchangers.

In applications requiring flow of liquid or gas in metal foam, e.g., heat exchangers and filters, Understanding various flow regimes in metal foam, and the associated pressure drop, are critical. For example, flow details directly influence convection heat transfer, chemical reaction rates and filtration effectiveness, as well as the required pumping power.

The internal structure of metal foam drastically influences the flow field by destroying boundary layers and compelling the fluid to travel through winding tortuous paths. In order to understand the pressure drop penalty, one must first understand the characteristics of flow regimes in metal foam and the processes of energy dissipation in each regime, as well as the transition from one regime to another.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.05.017
0017-9310/

Nomenclature

a	constant, Eq. (8)
b	constant, Eq. (8)
f	permeability-based friction factor = $\frac{(\Delta p/L)\sqrt{K}}{\rho u^2}$
F	Forchheimer coefficient (dimensionless)
K	permeability measured in Darcy regime (m^2)
L	length of porous medium (m)
p	static pressure (kPa)
Re	Reynolds number based on permeability $= \frac{\rho u\sqrt{K}}{\mu}$
u	average velocity (m/s)

Greek

Δ	change
ε	porosity
μ	viscosity (Pa s)
ρ	density (kg/m^3)

Fluid flow in (traditional) porous media has been the subject of numerous studies, e.g., [6–12]; and has been covered in several books, e.g., [13]. Open-Cell metal foam is different from traditional porous media in two regards: (1) it has a very high porosity (often greater than 90%), and (2) it has a web-like internal structure with the solid ligaments being relatively thin compared to cell size. These two attributes endows the foam with high permeability—in the order of 10^{-8} m^2 compared to 10^{-10} m^2 for packed spheres. Hence, one must be careful not to simply expect well-accepted empirical results for flow in traditional porous media to be valid for flow in metal foam. For example, values of Reynolds number corresponding to transition among flow regimes in traditional porous media may or may not be easily extrapolated to metal foam.

Compared to traditional porous media, the literature on fluid flow in metal foam is significantly less sizable. The study of Beavers and Sparrow [14] is one of the earliest, if not the earliest, dedicated in part to investigating pressure drop of water in three nickel foams. No mention of the porosity or pore density (number of pores per inch) was provided. Beavers and Sparrow [14] employed Reynolds number and friction factors based on permeability to plot their data, and identified a departure from Darcy regime at Reynolds number of order unity. Montillet et al. [15] used permeametry to determine the specific surface are and tortuosity of three nickel foam having 45, 60 and 100 pores per inch (ppi). There was a noticeable change in flow regimes at Reynolds number, based on an equivalent pore diameter, between 5 and 10. Edouard et al. [16] reviewed the literature on pressure drop in metal foam. They reported severe divergence of available correlations in terms of predicting pressure drop, permeability and form/inertia coefficient.

Mancin et al. [17] investigated air pressure drop in six samples of aluminium foam for the purpose of obtaining a widely-applicable correlation. From inspection of their pressure drop data, it is apparent that all the data lied in post-Darcy regime, and did not exhibit transition. Naturally, the issue of flow regimes and transition was not addressed by Mancin et al. [17].

Much of the previously published data on flow in metal foam, e.g., [2,18–22], contain significant disagreements on the values of the two pressure drop parameters, i.e., the permeability and the form drag coefficient, for foams with similar porosities and internal structures. These discrepancies are attributed to three possible causes: (1) foam sample size in flow direction used by various researchers [23], (2) foam sample size perpendicular to flow direction, [24,25], and (3) overlooking flow regimes encountered in a given experimental data set, along with the fact that the same foam exhibited different values of permeability and form drag coefficient in different flow regimes, as was shown by Boomsma and Poulikakos [21] using water flow and by Dukhan and Minjeur [26] using air flow in aluminium foam.

The literature containing flow regime changes in metal foam is limited. It also seems that flow-regime transitions were encountered happenstance. A transition from Darcy to Forchheimer regime was identified by Boomsma and Poulikakos [21] at an average water velocity around 0.10, 0.11 and 0.07 m/s (Reynolds number based on Darcy-regime permeability, Re 14.2, 22.3 and 26.5) for 10-, 20- and 40-ppi aluminium foam, respectively. In an experimental study targeting compressibility and inertia effects, Zhong et al. [24] reported departure from Darcy regime at Re of about 0.1 for air flow in sintered steel foam. For various metal foams, Bonnet et al. [27] and Liu et al. [28] identified a transition from Darcy to Forchheimer regime.

Dedicated studies purposely geared toward establishing various flow regimes in metal foam, and transition among them, are almost none-existent. Dukhan and Ali [29] presented results of an experimental study of flow through aluminium foam samples. A distinction was made between transition from Darcy to Forchheimer regimes and from laminar to turbulent flow regimes. The data in [33] was not extensive and the working fluid was air.

The current work presents new set of experimental data for water flow in metal foam to establish various flow regimes, and to assess the behavior of pressure drop in each regime. Such information has not been available in the literature, to the best knowledge of the authors. Understanding flow regimes and their boundaries can directly aid in modeling–numerical and analytical – of flow in metal foam; and it can assist in interpreting and cognizing heat and mass transport in such media.

2. Experiment

A schematic of the experimental setup is shown in Fig. 1. At the heart of the set-up, there is a test section made from an aluminium alloy (6061-T6) pipe having an inner diameter of 50.80 mm, a wall thickness of 6.35 mm and a length of 305 mm. Commercial aluminium foam (6101-T6 alloy), manufactured by ERG Materials and Aerospace, having 20 ppi and a porosity of 87.6% was brazed to the inside surface of the tube.

The test section was connected to two 51.4-mm-diameter 200-mm-long polyethylene tubes at its two ends using specially-designed flanges. Pressure taps were drilled on these tubes. The outlets of the Polyethylene tubes were connected to stainless steel pipes 32 mm in diameter and 110 cm in length. A hose and a valve were used for connecting the outlet of one steel pipe to a 50-liter tank for collecting water over a known length of time for measuring mass flow rates.

An elevated plastic tank (diameter 41 cm, height 44 cm) with a network of hoses and valves, that guaranteed a constant water height (33.2 cm) in the tank at all times, supplied water to the foam in the test section. To increase potential energy, and thus achievable flow rates, this supply tank was elevated 3.5 m from ground level via a platform. Heavily-filtered tap water was supplied to the tank using a 1.27-cm hose. Four 1.90-cm outlet houses were attached to the tank at a height of 36.3 cm from the bottom of