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Experimental hydrodynamics of high-porosity metal foam: Effect of pore density

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ABSTRACT

Commercial open-cell metal foam has very high porosity (often greater than 90%) and a large surface area density. The open flow area is copious compared to the ligament size. These properties are exploited in many applications, e.g., heat exchanger, reactors and filters. Pressure drop, flow regimes, and transition from one to another, are indispensable for any application involving flow of a fluid through the foam, and for heat transfer rates or reaction paces. These topics are not well-agreed on 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 same can be said about flow regime boundaries. This paper presents experimental data for pressure drop for water flow in two commercial open-cell aluminium foams having 10 and 40 pores per inch (ppi). The two foams have similar porosities (88.5%). The wide range of flow Reynolds number covered all known flow regimes in porous media: pre-Darcy, Darcy, Forchheimer and turbulent. Flow regimes and transition between them were identified and compared. 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 were used. It is shown that the same foam exhibits different values of its permeability and Forchheimer coefficient in different flow regimes. A previously-tested foam having 20 pores per inch and a porosity of 87.6% was included in the comparisons. The basic finding of this study will inform numerical and analytical work concerning flow and heat transfer in foam-like highly-porous porous media.

1. Introduction

Metal, graphite, ceramic and polymeric foams enjoy numerous industrial applications. Open-cell metal foam can be manufactured from several metals and alloys [1]. Understanding various flow regimes in metal foam, transition from one to another, and the associated pressure drop, are of direct engineering interest. For example, flow details strongly impact convection heat transfer, chemical reaction rates and filtration effectiveness; they also provide an estimation of the pumping power.

Characteristics of fluid flow in customary porous media have been widely investigated, e.g., [2–8]. Open-cell metal foam has a couple of attributes that distinguish it from customary porous media: (a) it has a rather high porosity (often greater than 90%), and (b) it has a web-like internal structure with thin solid ligaments surrounding a relatively large cell. The permeability of the foam is high—in the order of 10^{-8} m^2 compared to 10^{-10} m^2 for packed spheres, as a customary porous medium. Because of these differences, care must be taken when it comes to applying well-accepted empirical results for flow in customary porous media for flow in metal foam. For example, Reynolds numbers at which transition from one flow regime to the next may not be the same for customary porous media and metal foam.

Possibly, the study of Beavers and Sparrow [9] is the earliest published work where pressure drop due to water flow in three nickel foams, of unknown porosity and pore density, was reported. These two researchers employed Reynolds number and friction factors based on permeability to treat their data, and identified a departure from Darcy regime at Reynolds number in the order of unity. For three nickel foams having 45, 60 and 100 pores per inch (ppi), Montillet et al. [10] noted a change in flow regimes at Reynolds number, based on an equivalent pore diameter, between 5 and 10. Edouard et al. [11] reviewed the literature on pressure drop in metal foam prior to 2008. They reported severe divergence among correlations for predicting pressure drop, permeability and form/inertia coefficient.

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Nomenclature

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
μ	viscosity (Pa s)
ρ	density (kg/m^3)

Mancin et al. [12] investigated air pressure drop in six samples of aluminum foam. It is apparent that all the data lied in post-Darcy regimes, and did not exhibit transition. Other published data on flow in metal foam, e.g., [13–17], contain significant disagreements on the values of the permeability and form drag coefficient, for foams with similar porosities and internal structures. There are three possible causes for the disagreements: (1) variation in foam sample size in the flow direction [18], (2) variation in foam sample size perpendicular to flow direction, [19,20], and (3) overlooking flow regimes encountered in a given experimental data set. It is now established that the same metal foam may exhibit different values of permeability and form drag coefficient in different flow regimes [11,21,22].

Studies discussing flow-regime changes in metal foam are few, e.g., [16,23,24]. A transition from Darcy to Forchheimer regime was identified by Boomsma and Poulikakos [16] 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 aluminum foam, respectively. Zhong et al. [24] reported departure from Darcy regime at Re of about 0.1 for air flow in sintered steel foam.

As pointed out in the study of Bhattacharya et al. [14], there are many industrial and engineering applications that involve fluid flow in metal foam. Some of these applications exploit the high surface area of metal foams to obtain wide catalytic surfaces, compact heat exchangers and heat sinks. In the literature, not only experimental but also numerical research studies involving fluid flow can be found [15].

Fluid flow in foam continue to appear in the literature [25,26]. However, dedicated studies purposely geared toward establishing various flow regimes in metal foam, and transition among them, are almost non-existent. Some information regarding flow regime and transition for water flow in metal foam having 20 pores per inch has been recently published [22]. The current work presents new set of experimental data for water flow in metal foam having 10 and 40 pores per inch, and thus complement the results of [22] and establishes the effect of pore density on flow regimes and transition among them. Understanding flow regimes and their boundaries can directly aid in modeling- numerical and analytical- of flow in metal foam; and it can inform design and interpretation of heat and mass transport in metal foam.

2. Experiment

A schematic of the experimental setup is shown in Fig. 1. Two test sections were employed in this experiment. Each was made form an aluminum alloy pipe having an inner diameter of 50.80 mm, a wall thickness of 6.35 mm and a length of 325 mm. Commercial aluminum foam (6101-T6), manufactured by ERG Materials and Aerospace, was brazed to the inside surface of the pipe. In one case the foam had 10 ppi, while in the other the foam having 40 ppi.

The 10-ppi-foam test section was connected to two 50.80-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 period of time for measuring mass flow rates.

An elevated plastic tank (41 cm in diameter, 44 cm in height) with a network of hoses and valves, that sustained 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 the 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 hose. Four 1.90-cm outlet houses were attached to the tank at a height of 36.3 cm from the bottom of the tank. The supply line to the tank was positioned 41 cm from the bottom of the tank (3.7 cm higher than the four outlet hoses).

To supply constant-pressure flow to the porous medium, one end of another 1.90-cm hose was connected at 3.1 cm from the bottom of the tank, while the other end was connected to the plumbing containing the test section under investigation. This arrangement provided a constant water height of 33.2 cm in the tank during each experimental run. The flow rate provided by the tank was practically constant (less than 4 % variation). For high flow rates, a 2-hp pump (Standard Model No. TS268) was used. Water speed ranged from about 7.6×10^{-5} to 0.62 m/s.

The pressure drop was measured by two Validyne pressure-differential sensors, model DP15 and DP45. Each sensor could accommodate diaphragms having different thicknesses - each suitable for a certain pressure-difference range. For example,

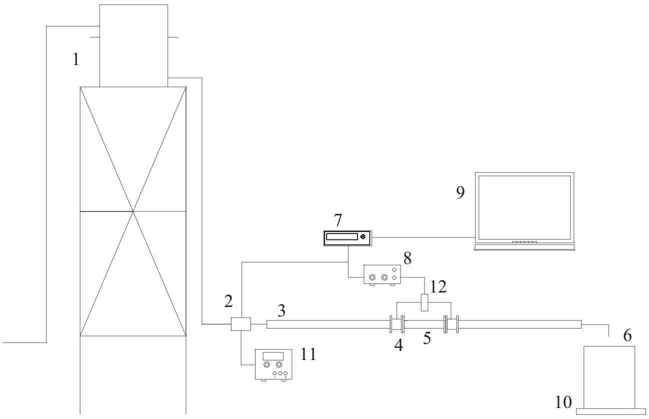

Fig. 1. Schematic view of the complete experimental setup: 1. Constant-height supply tank, 2. Magnetic flow meter, 3. Steel pipe of 32-mm in diameter, 4. Polyethylene tube, 5.Test section, 6. Collecting tank, 7. Data logger, 8. Carrier demodulator, 9. Computer, 10. Mass scale, 11. DC power supply, 12. Differential pressure sensor.