

FLOW REGIMES IN FOAM-LIKE HIGHLY POROUS MEDIA

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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., filtration, heat exchange and reactors. Flow regimes, and transition from one to another, are critical for understanding energy dissipation mechanisms for flow through the foam. 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. The choice of an appropriate characteristic length for metal foam has also varied among researchers. Pressure drop characteristics such as the permeability and form/inertial drag coefficient are very divergent for metal foam. The current study is to shed some light on the above issues. In particular, a large set of experimental data for pressure drop of water flow in commercial aluminum foam having 20 pores per inch and a porosity of 87.6% was collected. The range of flow Reynolds number covered a few important flow regimes. The current data correlated very well using the friction factor based on the square root of the permeability (measured in the Darcy regime) as a function of Reynolds number based on the same length scale. 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.

INTRODUCTION

Open-cell metal foam can be manufactured from several metals and alloys, e.g., aluminum, copper, steel, nickel [1]. These highly-permeable foams have relatively high thermal

conductivity and large surface area per unit volume; their internal structure (web-like) grants forceful mixing of through fluid flow. These attributes make metal foams attractive for

NOMENCLATURE

f	[-]	permeability-based friction factor
F	[-]	Forchheimer coefficient
K	[m ²]	permeability
L	[m]	length of porous medium
p	[kPa]	static pressure
Re	[-]	Reynolds number based on permeability
u	[m/s]	average velocity

Special characters

μ	[Pa.s]	viscosity
ρ	[kg/m ³]	density neighbouring cooling inserts in the x direction

heat transfer enhancement [2,3]. Boomsma et al. [4] have shown that certain compressed aluminum 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.

Understanding various flow regimes in metal foam, and the associated pressure drop, are critical for many applications. For example, flow details directly influence convection heat transfer, chemical reaction rates, filtration effectiveness and pumping power. Fluid flow in metal foam is complex. 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.

Fluid flow in (traditional) porous media has been studied widely, e.g., [6-11]. Metal foam is different from traditional porous media: 1) it has a very high porosity (often greater than

90%), and 2) it has a web-like internal structure. 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.

The study of Beavers and Sparrow [12] is perhaps the earliest, dedicated in part to investigating pressure drop of water in nickel foam with unknown porosity and pore density. Beavers and Sparrow [12] 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. [13] used permeametry to determine the specific surface area and tortuosity of three nickel foams 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 between 5 and 10. Edouard et al. [14] 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. [15] investigated air pressure drop in six samples of aluminum foam for the purpose of obtaining a widely-applicable correlation. It was apparent that all the data lied within one flow regime (outside the Darcy regime), and does not exhibit transition. Thus the issue of flow regimes and transition was not addressed by Mancin et al. [15].

Much of the previously published data on flow in metal foam [2,16-20] contain significant disagreements on the values of the permeability and 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 [21], 2) foam sample size perpendicular to flow direction [22,23] and 3) overlooking flow regimes encountered in a given experimental data set. The same foam exhibited different values of permeability and form drag coefficient in different flow regimes, as was shown by Boomsma and Poulikakos [19] using water flow and by Dukhan and Minjeur [24] using airflow in aluminum foam.

A transition from Darcy to Forchheimer regime was identified by Boomsma and Poulikakos [19] at an average water velocity around 0.10, 0.11 and 0.07 m/s (Reynolds number based on Darcy-regime permeability, Re_K , 26.5, 22.3 and 14.2) for 10-, 20- and 40-ppi aluminum foam, respectively. In an experimental study targeting compressibility and inertia effects, Zhong et al. [22] reported departure from the Darcy regime at Re of about 0.1 for airflow in sintered metal foam. For various metal foams, Bonnet et al. [25] and Liu et al. [26] identified a transition from Darcy to Forchheimer regime.

Dukhan and Ali [27] presented none-extensive results of an experimental study of airflow through aluminum foam samples. A distinction was made between transition from Darcy to Forchheimer regimes and from laminar to turbulent flow regimes. The current work presents new set of experimental data for water flow in metal foam to establish the various flow regimes. 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 of heat and mass transport in such media.

EXPERIMENT

A schematic of the experimental setup is shown in Fig. 1. A test section was made from an aluminum pipe having an inner diameter of 50.80 mm and a length of 305 mm. Commercial open-cell aluminum foam, manufactured by ERG Materials and Aerospace foam, having 20 ppi (pores per inch) 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 50-liter tank for collecting water over a known length of time for measuring mass flow rates.

An elevated (3.5 m) plastic tank (diameter 41 cm, height 44 cm) with a network of hoses and valves, that guaranteed a constant water height of about 33 cm in the tank at all times, was used to supply water to the test section. 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 the tank. The supply line was positioned 41 cm from the bottom of the tank.

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 aluminum foam under investigation. This arrangement provided a constant water height of 33.2 cm in the tank during each experimental run. The experimental rig was able to produce and hold very low water speeds (starting at 7.6×10^{-5} m/s). For high flow rates, water was supplied to the test section directly from a water tap using switching valves and filters, which produced average velocities of up to 0.19 m/s.

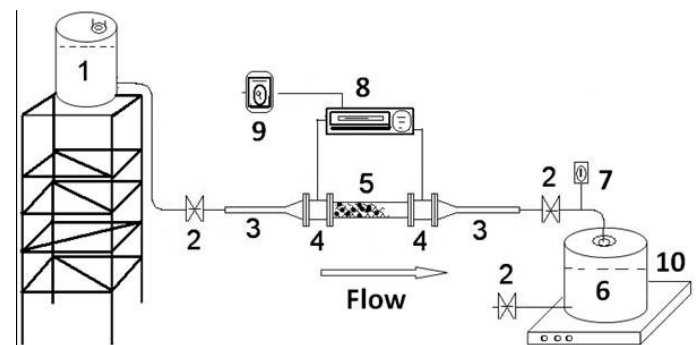


Figure 1 Schematic of Experimental Setup: 1. Supply tank, 2. Control valves, 3. Steel pipe, 4. Polyethylene tube, 5. Test section, 6. Collecting tank, 7. Air purger, 8. Carrier demodulator, 9. Multimeter, 10. Mass balance.

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 ranges. For example, diaphragms having codes 6-16, 6-22, 6-30 and 6-34, used with

the DP45 low pressure-difference sensor, were for pressure ranges 0.35, 1.4, 8.6 and 22.0 kPa, respectively. When in use, each sensor was connected to a Validyne CD15 carrier demodulator, which provided zero to 10 V DC signal. The demodulator was connected to a multimeter where the voltage signals were read. Each sensor/diaphragm combination had to be calibrated prior to its use.

For a given run, control valves were adjusted and water was allowed to flow into the foam until steady state was reached. Care was taken as to remove air bubbles from the system through the purger and/or by dismantling and reassembling parts of the set-up, as needed. At steady state and for a fixed valve opening (flow rate), water exiting the test section was captured in the collecting tank over a known period of time: approximately 1 to 1.5 minutes for high flow rates, and 3 to 4 minutes for very low flow rates. Several successive voltage readings (no less than 5) were taken during collecting a certain mass of water. These readings were recorded and averaged.

For very low flow rates, the pressure drop across the foam sample was too low to accurately measure using the pressure drop diaphragms. A known flow resistance of packed spheres was added in series with the foam. The pressure drop in the foam was obtained using two measurements at each flow rate: 1) pressure drop across the foam and the spheres, and 2) pressure drop across the spheres alone. The pressure drop in the foam was obtained by subtracting the pressure drop in the spheres from the pressure drop in the foam-sphere combination.

Uncertainty in the reported data included error in the directly-measured quantities: length, mass, time and voltage; and propagation of error in derived quantities, i.e., flow rate, pressure drop per unit length, reduced pressure drop, Reynolds number and friction factor, Figliola and Beasley [28]. The uncertainties in length and diameter of the metal foam tube were 0.33% and 0.04%, respectively. Three different mass scales were used over the range of flow rates. The precision in the low, medium and large scales were 0.01%, 0.02% and 0.008%, respectively.

As for pressure drop measurements, two sensors were used (each with various diaphragms): DP15 and DP45 with accuracy of $\pm 0.25\%$ and $\pm 0.5\%$ of full scale, respectively. Sensor DP45 with diaphragm 3-24 which could measure up to 2200 Pa was used to obtain data in the Pre-Darcy regime. The uncertainty in the pressure drop sensors was reported by the manufacturer and included effects of linearity, hysteresis and repeatability. The following average estimates were obtained: for the pre-Darcy region, the uncertainty in the pressure drop had a minimum of 0.49% and a maximum of 1.56%. For all other flow regimes the uncertainty in the measured pressure drop had a minimum of 0.13% and a maximum of 1.01%. Uncertainty in other derived parameters is reported in the results section.

RESULTS

Figure 2 is a plot of the pressure drop over length vs. Darcy velocity. The behaviour in this plot is typical for pressure drop in porous media: the pressure drop increases in quadratic fashion with velocity. Quadratic curve fit of the data with a high correlation factor R^2 is shown on the plot.

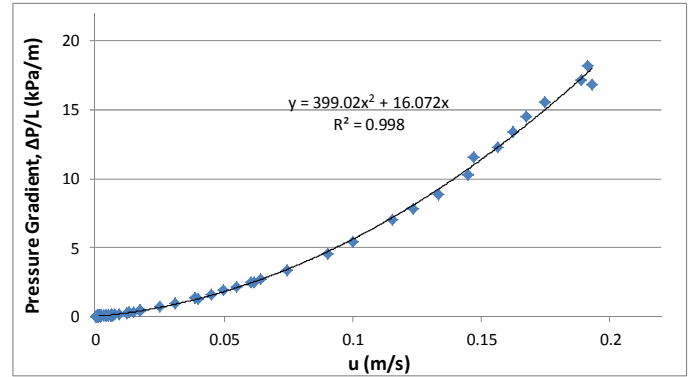


Figure 2 Pressure drop per unit length versus Darcy velocity

The second-order Forchheimer equation is::

$$\frac{\Delta p}{L} = \frac{\mu}{K} u + \frac{\rho F}{\sqrt{K}} u^2 \quad (1)$$

where Δp is the static pressure drop, L is the length of the porous medium in the flow direction, μ is the fluid viscosity, and the superficial or Darcy velocity u is calculated by dividing the mass flow rate through the porous medium by the cross-sectional flow area and the density of the fluid ρ . The permeability of the porous medium, K , has units of area and the dimensionless inertia drag coefficient F is, known as the Forchheimer coefficient, is believed to be universal, or at least fixed, for a given class of porous media, [20,21,29]. Both K and F strongly depend on the internal structure of the porous medium. By comparing the curve-fit equation of Fig. 2 to the Forchheimer equation, values of the permeability and Forchheimer coefficient are obtained as $4.42 \times 10^{-8} \text{ m}^2$ and 0.070, respectively. These values are listed in Table 1.

Table 1

Permeability and Forchheimer coefficient in various flow regimes

	Darcy	Forchheimer	All
Permeability $\times 10^8 (\text{m}^2)$	4.75	5.14	4.42
Forchheimer Coefficient	NA	0.079	0.070

The choice of dependent variable of Fig. 2, while common among some researchers, completely hides various flow regimes. The Forchheimer equation can be divided by the average velocity u , as was done by some researchers [2,15,19]:

$$\frac{\Delta p}{Lu} = \frac{\mu}{K} + \frac{\rho F}{\sqrt{K}} u \quad (2)$$

This is a linear equation; and plotting the reduced pressure drop $\Delta p/Lu$ versus velocity can clearly show various flow regimes. The choice of the actual average velocity as an independent variable provides a physical value of this variable, and hence an immediate sense of magnitude of how low or high the water

velocity should be in various flow regimes. Fig. 3 is a plot of $\Delta p/Lu$ versus u for all the experimental data. Various flow regimes are discernable where clear changes in the slope of the reduced pressure drop data.

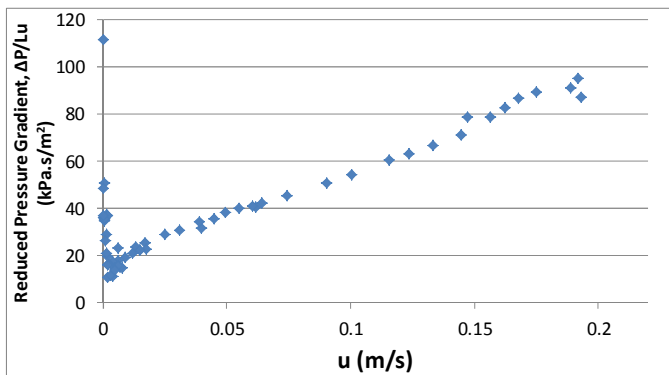


Figure 3 Reduced pressure drop versus average velocity. Uncertainty in reduced pressure drop is 1.11% in the pre-Darcy regime and 0.70% in all other regimes.

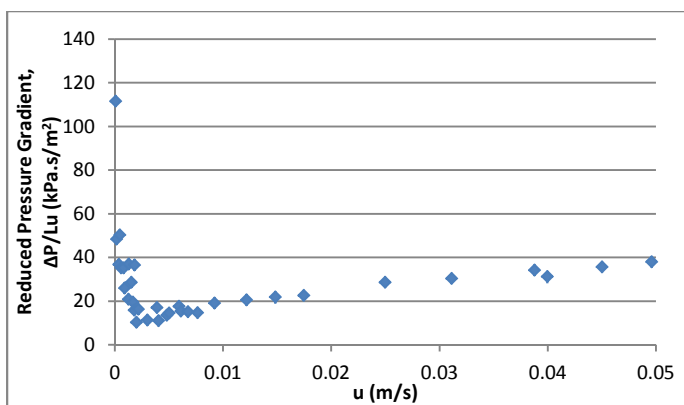


Figure 4 Reduced pressure drop versus average velocity: Darcy and pre-Darcy regimes. Uncertainty in reduced pressure drop is 1.11% in the pre-Darcy regime and 0.70% in Darcy regime.

There is a clear change in the behavior of the pressure drop around 0.02 m/s. For higher velocities, the reduced pressure drop increases linearly with the velocity indicating that Eq. (2) is satisfied, and that the data in this range is in the Forchheimer regime. In this regime, a permeability value of $5.14 \times 10^{-8} \text{ m}^2$ is obtained by fitting a straight line to the experimental data in this regime. The Forchheimer coefficient obtained is 0.079, which is very different from 0.55—the value well-accepted for packed sphered porous media. In the Forchheimer regime, flow energy dissipation becomes the sum of viscous and form (and inertia) drags. Boundary layers begin to develop near solid boundaries inside the porous medium and they become pronounced and an inertial core appears, [6]. Kinetic energy degradation begins due to pore constrictions (open flow area reduction) and flow direction changes (to go around the ligaments of the foam). Nonetheless, the flow remains laminar and steady. The additional drags are captured by the term that has a second-order dependence on velocity in Eq. (2).

For extremely low velocity, a pre-Darcy regime is identified in Fig. 3 and expanded in Fig. 4. The pre-Darcy regime is not clearly understood and, to the knowledge of the authors, has never been presented in metal foam literature, most likely due to experimental difficulties in accurately measuring the rather small flow rates and pressure drops associated with it. According to Fand et al. [7], in this regime a fluid may exhibit non-Newtonian behaviour; and small counter currents along the pore walls in a direction opposite to the main flow direction may occur. The pre-Darcy seems to extend up to about a velocity of 0.007 m/s, after which the Darcy regime begins. The purely viscous Darcy regime is identified by a constant value of the reduced pressure drop, which is identified by a horizontal line corresponding to

$$\frac{\Delta p}{Lu} = \frac{\mu}{K} \quad (3)$$

which is a slightly modified form of famous Darcy relation. This Darcy regime prevails for slow flow (creeping or seepage flow); and the pressure drop is solely due to viscous drag due to flow over the surfaces of the solid phase of the foam. Because of low momentum, the flow engulfs and attaches to the surfaces of the ligaments of the foam. As such, wakes and inertial cores are non-existent, and the actual geometry of the internal structure of the foam is exposed and is directly ‘experienced’ by the flowing fluid. The permeability in this regime is obtained as $4.75 \times 10^{-8} \text{ m}^2$.

It is clear that the same foam exhibits different permeabilities and Forchheimer coefficients in different flow regimes. It is also clear that when using the whole data set to calculate the permeability and the Forchheimer coefficient, significantly different values for these properties are obtained. Dukhan and Minjeur [24] have shown that K calculated from the Forchheimer equation was different from the one obtained in the Darcy regime for airflow in the same aluminum foam.

Equation (2) can be manipulated to yield the non-dimensional relation:

$$f = \frac{1}{\text{Re}} + F \quad (4)$$

where $f = (\Delta p/L) \sqrt{K}/\rho u^2$ and $\text{Re} = \rho u \sqrt{K}/\mu$. The square root of the permeability is utilized as a length scale in these non-dimensional variables. Since the same foam exhibits different permeabilities in various flow regimes, a question arises as to which permeability should be used. Kececioglu and Jiang [8] stressed that the appropriate characteristic length for packed spheres ought to be the square root of the permeability, not the sphere diameter. Boomsma and Poulikakos [19] indicated that Reynolds number based on Darcy-regime permeability was the preferred parameter to indicate transition from Darcy to Forchheimer, since it gave the least divergent values for the three types of metal foam in their study.

Beavers and Sparrow [12] confirmed this relation between f and Re for nickel foam; Zhong et al. [22] for sintered stainless-steel foam; while Paek et al. [30], Liu et al. [26] and

Mancin et al. [15] confirmed this relation for aluminum foam. Dukhan [31] obtained a similar relation via analysis of Darcy flow including Brinkman viscous term. As for the coefficient F , it varies among researches: Beavers and Sparrow [12] obtained a value of 0.07; Paek et al. [30] 0.105 and Zhong et al. [22] between 0.41 and 0.75.

The experimental data of the current investigation is plotted in the format of Eq. (4) in Fig. 5. The classical behavior of the friction factor as a function of Reynolds number is displayed: the friction factor is generally inversely proportional to the Reynolds number.

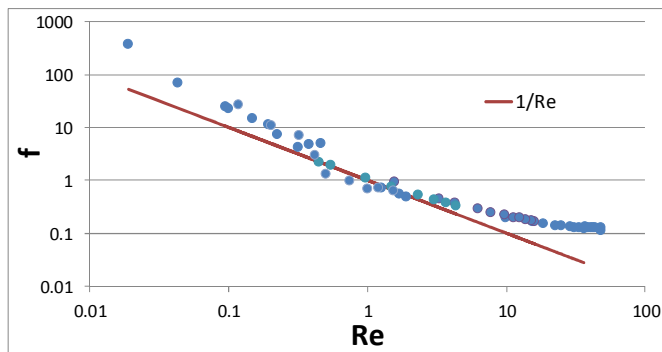


Figure 5 Permeability-based friction factor versus permeability-based Reynolds number

Flow regimes are identified again by comparing the experimental data to $1/Re$. According to Eq. (4) and for the Darcy regime, the data must follow the curve $1/Re$; departure from this function signifies the end of the Darcy regime. The departure is seen to occur close to Re between 1 and 10.

While the behavior of the reduced pressure drop as a function of velocity seems to be unusual in the pre-Darcy regime, Fig. 3, the behavior is easily discernable in the friction factor f versus Reynolds number Re plot, Fig. 5. Kececioğlu and Jiang [8] stated that in the pre-Darcy regime, the pressure drop seemed to be inversely proportional to the Reynolds number. This statement was based on experimental data obtained by these researchers for flow in packed spheres. In essence f is inversely proportional to Re , as seen in Fig. 5.

CONCLUSION

Results for water flow in high-porosity metal foam were presented. Various flow regimes were identified starting with pre-Darcy and ending with Forchheimer. It was difficult to decide with certainty that there was a transition to the turbulent flow regime. The same metal foam was seen to exhibit different values of permeability and Forchheimer coefficient in different flow regimes. Using the square root of the permeability, measured in the Darcy regime, as a length scale for defining Reynolds number and the friction factor was seen to correlate the pressure-drop data very well. The friction factor in the pre-Darcy regime seemed to be a function of the reciprocal of the Reynolds number.

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