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Experimental flow in various porous media and reconciliation of Forchheimer and Ergun relations

Nihad Dukhan [a,*], Özer Bağcı [b], Mustafa Özdemir [b]

[a] Department of Mechanical Engineering, University of Detroit Mercy, Detroit, MI 48334, USA
[b] Makina Fakültesi, Istanbul Technical University, Gümüşsuyu, 34437 Istanbul, Turkey

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ABSTRACT

Flow characteristics and pressure drop in traditional porous media, e.g., packed beds of spheres, and in modern man-made fibrous media, e.g., metal foam, are critical in many naturally-occurring and engineered applications. Pressure drop parameters such as permeability and form/inertial drag coefficients reported in the literature are very divergent for both classes of porous media. The choice of an appropriate characteristic length; and the selection of a way for correlating pressure drop data have also varied among researchers. In the current study a large set of experimental data for pressure drop of water flow in three different porous media was collected. The porous media were packed spheres of 1 mm, packed spheres of 3 mm and aluminum foam having 20 pores per inch. The porosity of both sets of packed spheres was practically the same at about 35%, while the porosity of the foam was 87.6%. The internal structure of the two classes (packed spheres and foam) of porous media investigated here are markedly different. The range of flow velocity covered Darcy, Forchheimer and turbulent flow regimes. It is shown that the same porous medium exhibited different values of permeability in different flow regimes. The widely-used equations of Ergun and Forchheimer for the post-Darcy regimes were revisited. An apparent difference between the two famous equations was presented and explained. The two equations were reconciled using the hydraulic radius theory, and the fact that the same porous medium exhibits different values of its permeability in different flow regimes. The multipliers of the viscous term and the inertial/form drag term in the post-Darcy regimes were shown to be connected. The square root of the permeability determined in the Darcy regime is shown to be appropriate length scale for defining and correlating the friction factor and the Reynolds number.

1. Introduction

Porous media exist naturally, e.g., sand and rocks and can be constructed, e.g., packed spheres and metal, graphite and ceramic foams. Human-made porous media are highly exploited in engineering applications. Open-cell metal foams, for example, can be manufactured from several metals and alloys [1], and can have high permeability, porosity and thermal conductivity as well as large surface area per unit volume. The internal structure of metal foam is composed of cells made up by connected ligaments; such structure causes vigorous mixing of through flowing fluid. All these attributes make these foams attractive for heat transfer enhancement [2], as well as for reactors and filters.

Understanding various flow regimes and the associated pressure drop behavior in porous media is critical as it directly influences convection heat transfer, chemical reaction rates and filtration effectiveness, as well as the required pumping power in these applications. Fluid flow in traditional porous media has been the subject of numerous studies, e.g., [3–6]; and has been covered in books, e.g. [7–9].

Open-cell foam differs from traditional porous media: (1) it has very high porosity (for metal foam greater than 90%), and (2) it has a web-like open structure. The foam thus has high permeability-in the order of 10^{-8} m^2 compared to 10^{-10} m^2 for packed spheres, as an example. The study of Beavers and Sparrow [10] is one of the earliest works dedicated in part to investigating pressure drop of water in three nickel foams. They 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. All of their data was clearly in the post-Darcy regime. Montillet et al. [11] determined the specific surface area and tortuosity of three nickel foam having 45, 60 and 100 pores per inch (ppi). The ppi is obtained by counting the number of open windows

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* Corresponding author. Tel.: +1 313 993 3285.
E-mail address: nihad.dukhan@udmercy.edu (N. Dukhan).

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Nomenclature

a	constant, Eq. (20)
b	constant, Eq. (20)
A	constant, Ergun equation
B	constant, Ergun equation
c_1	coefficient, Eq. (15)
c_2	coefficient, Eq. (23)
d_{par}	particle diameter (m), Ergun equation
f	permeability-based friction factor $= \frac{(\Delta p/L)\sqrt{K}}{\rho u^2}$
F	Forchheimer coefficient (dimensionless), Forchheimer equation
K	permeability measured in Darcy regime (m^2)
K_F	permeability measured in Forchheimer regime (m^2)
K_t	permeability measured in turbulent regime (m^2)
L	length of porous medium (m)
p	static pressure (kPa)
Re	Reynolds number based on Darcy permeability $= \frac{\rho u\sqrt{K}}{\mu}$
u	average velocity (m/s)
Greek	
δ	uncertainty
Δ	change
ε	porosity
κ	Carman–Kozeny constant
σ	surface area of the solid particle per unit volume (m^{-1})
μ	viscosity (Pa s)
ρ	density (kg/m^3)

in a length of one inch of the foam. Here 'windows' means open areas surrounded by connected ligaments (polyhedra). So a foam cell has many windows. There was a noticeable change in flow regimes at Reynolds number (based on an equivalent pore diameter) between 5 and 10.

Edouard et al. [12] reviewed the literature on pressure drop in metal foam, and reported severe divergence of available correlations in terms of predicting pressure drop, permeability and form/inertia coefficient. Mancin et al. [13] investigated air pressure drop in six samples of aluminum foam for the purpose of obtaining a widely-applicable correlation. From inspection of their pressure drop data, it was apparent that all the data lied in a post-Darcy regime with no apparent transition.

In general, published data on flow in traditional porous media, [5,6]; and in foam [2,14–18] contain significant disagreements on the permeability and the form drag coefficient, for media with similar internal structures. In the case of foam, these discrepancies are attributed to few possible causes: (1) foam sample size in flow direction used by various researchers [19], and (2) foam sample size perpendicular to flow direction, [20,21]. For both foam and traditional porous media, the following two reasons for discrepancies may be add: (1) overlooking flow regimes encountered in a given experimental data set, along with the fact that the same porous medium exhibits different values of permeability and form drag coefficient in different flow regimes, as has been shown by Boomsma and Poulikakos [17] using water flow and by Dukhan and Minjeur [22] using airflow in aluminum foam, and (2) issues with adopted correlations for treating pressure-drop data. The current study will shed some light on the last two issues.

In the post-Darcy regimes where inertial effects are significant, two equations are invariably used to describe pressure drop as a function of average velocity; Forchheimer and Ergun equation. Other seemingly different correlations may be traced back or manipulated to fit the basic forms of these two equations.

Forchheimer postulated his empirical equation using analogy with pipe flow, [23]. The equation was also arrived at using analytical derivation, [23–27].

The construction of Ergun equation was based on modeling the space between packed beds of spheres as parallel capillaries, with multipliers as correction factors to account for the geometrical difference between flow paths in packed spheres and parallel capillaries, [28]. Ergun equation can be obtained by superimposing the Blake–Kozeny equation for 'laminar' flow, and the Bruke–Plummer equation for 'turbulent' flow, [29]. de Plessis [30] analytically derived a momentum transport equation for fully-developed flow in porous media that was similar to Ergun equation.

The current work presents new set of experimental data for water flow in two different classes of porous media: packed spheres and metal foam. The data were collected in the same experimental set-up and covers Darcy and post-Darcy regimes. Permeability and drag coefficient are determined in each flow regime. The widely-used equations for pressure drop in porous media, Forchheimer and Ergun equations are revisited; and a way of reconciling them using the hydraulic radius theory of Kozeny–Carman is proposed. To the best knowledge of the authors, such reconciliation has not been clearly presented in the literature.

2. Experiment

A schematic of the experimental setup is shown in Fig. 1. A test section can be changed to house three porous media. Two packed-spheres porous media were formed by filling a stainless steel (AISI 304) pipe having an inner diameter of 51.4 mm and a length of 304 mm. The packing was for mono-size stainless steel balls of 1 mm or 3 mm in diameter (actual average diameters were 1.14 mm and 3.03 mm), one at a time. Two wire meshes (0.6 mm open widows) were installed at both ends of the test chamber in order to keep the balls in place. The pipe was vigorously shaken after it was filled in order to ensure that the spheres were uniformly packed with no excessive voids. The porosities were 35.0% and 35.5% for the 1- and 3-mm spheres, respectively. The third porous medium was made from aluminum alloy (6061-T6) pipe having an inner diameter of 50.80 mm and a length of 305 mm. Commercial aluminum 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.

At both sides of the test section, 51.4-mm-diameter 200-mm-long Polyethylene tubes that housed pressure taps were

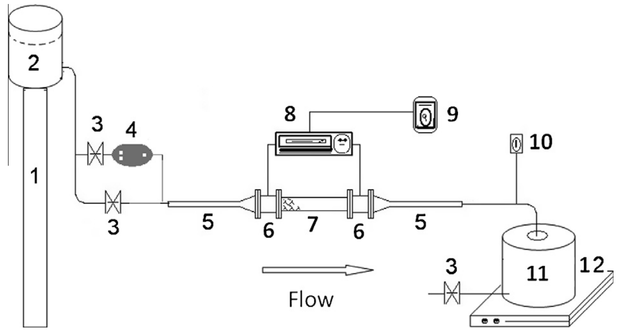

Fig. 1. Schematic of experimental setup: 1. Platform, 2. Constant-height supply tank, 3. Control valves, 4. Pump, 5. Steel pipe, 6. Polyethylene tube, 7. Test section/porous medium, 8. Carrier demodulator, 9. Multimeter, 10. Air purger, 11. Collecting tank, 12. Mass scale.