Equivalent particle diameter and length scale for pressure drop in porous metals

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Abstract

The internal architecture of metal foam is significantly different from that of traditional porous media. This provides a set of challenges for understanding the fluid flow in this relatively new class of materials. This paper proposes that despite the geometrical differences between metal foam and traditional porous media, the Ergun correlation is a good fit for the linear pressure drop as a function of the Darcian velocity, provided that an appropriate equivalent particle diameter is used. The paper investigates an appropriate particle diameter considering the physics of energy dissipation, i.e. the viscous shear and the form drag. The above approach is supported by wind tunnel steady-state unidirectional pressure drop measurements for airflow through several isotropic open-cell aluminum foam samples having different porosities and pore densities. For each foam sample, the equivalent particle diameter correlated well with the surface area per unit volume of the foam. This was also very well valid for previous porous metal pressure drop data in the open literature.
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1. Introduction

Metal foams initially became commercially available in the early 1980s, and in 1990s, they have been considered by the academic enterprise. The recent development of a variety of processes for producing them at lower cost, with improved properties, has increased their applications. See for example Zhou et al. [1], Ashby et al. [2], Crosnier et al. [3] and Khayargoli et al. [4]. Recently, Azzi et al. [5] have demonstrated the feasibility of using metal foam between the combustor and the turbine section of a turbo-jet engine in order to increase the overall efficiency. They also have measured the pressure drop for air flow in metal foam in the compressible flow regime for the first time.

There is a crucial need for accurate evaluation of the pressure drop and flow characteristics for achieving the improved performance and efficiency in designs utilizing metal foam. Fluid flow in a porous metal travels through tortuous passages with random disruptions. Such flow contains complex effects such as lack of boundary layers, recirculation and turbulence. Hwang et al. [6] and Lage et al. [7] indicated that the geometric complexity of metal foam structure prevents exact solutions of the transport equations inside the pores.

Seguin et al. [8] provided experimental characterization of flow regimes in various porous media, while Decker et al. [9] provided detailed experimental characterization and numerical modeling of the heat and mass transport in highly porous nickel–chromium alloy foam. They indicated that fluid flow models for packed beds did not apply to metal foam, but they contained and described all the relevant transport effects.

Crosnier et al. [3] studied the pressure drop in 20- and 40-ppi aluminum foam and 20-ppi stainless steel foam using air. All the porosities were above 90%. They stated that the larger the pore diameter the higher the permeability K and the smaller the pressure drop; and that the smaller the pore size, the higher the surface area and thus the higher the mechanical energy dissipation. The permeability

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Nomenclature

A	empirical constant in Eq. (2) (dimensionless)
B	empirical constant in Eq. (2) (dimensionless)
C	form drag coefficient (m^{-1})
c	inertia coefficient (dimensionless)
$f_\sigma = \left(\frac{\varepsilon^3}{1-\varepsilon}\right)\frac{(\Delta p/L)(1/\sigma)}{\rho V^2}$	kinetic friction factor (dimensionless)
K	permeability (m^2)
L	thickness of foam sample in the flow direction (m)
p	static pressure (Pa)
ppi	number of pores per inch
$Re_\sigma = \frac{\rho V (1/\sigma)}{\mu}$	Reynolds number based on surface area density (dimensionless)
V	Darcian velocity (m/s)

Greek symbols

α	empirical coefficient in Eq. (3) (dimensionless)
β	empirical coefficient in Eq. (3) (dimensionless)
δ	uncertainty (%)
ε	porosity (%)
μ	kinematic viscosity of air (kg/m s)
ρ	density of air (kg/m^3)
σ	surface area per unit volume of foam (m^{-1})

and the form drag coefficient were functions of the porosity, the pore size, the surface area and the solid structure of the foam.

Khayargoli et al. [4] studied the relationship between the permeability and the structural parameters for airflow in nickel and nickel–chromium foams. As the pore size decreased, the surface area increased creating additional flow resistance. K increased and C decreased with increasing the pore diameter, but did not show any clear correlation with the porosity.

Tadrist et al. [10] experimentally determined K and C, and used an Ergun-type relation between the pressure drop and the velocity in aluminum foam. Kim et al. [11] carried out systematic experiments to study the friction and the heat transfer characteristics of porous fins in a plate-fin heat exchanger using water. They determined the permeability using the Forchheimer model and correlated the friction factor with the Reynolds number, the Darcy number and the geometry.

Paek et al. [12] experimentally determined the permeability and the form drag coefficient for water flow through aluminum foam in the porosity range of 89–96%. At a fixed porosity, as the cell size decreased, the surface area-to-volume ratio increased which increased the resistance to the flow and thus lowered the permeability and increased the pressure drop. Noh et al. [13] reported on the pressure loss in an annulus filled with aluminum foam.

Bhattacharya et al. [14] provided analytical and experimental results for the permeability and the friction coefficient for aluminum foam. They represented the foam by a two-dimensional array of hexagonal cells, and proposed models for the inertia coefficient and the friction factor. K increased with the pore diameter and the porosity, while the friction factor depended only on the porosity. They used the Forchheimer equation to describe the pressure drop in the foam for air and water separately.

Du Plessis et al. [15] provided a geometrical model for the fluid dynamics in metal foam. Fourie and Du Plessis

[16] enhanced the above model by developing expressions for the characteristic dimension as a function of the cell size and the porosity. The characteristic dimension correlated well with the cell size.

Despois and Mortensen [17] presented a microstructure-based model for the permeability of porous metal, and used pure aluminum foam saturated with water and glycerin separately, to validate the model. The Darcy-regime data showed a strong dependence of the permeability on the square of the pore size.

Boomsma et al. [18] modeled the flow in aluminum foam using a periodic unit of eight cells. The Reynolds number based on the pore diameter was more applicable than the permeability based Reynolds number for metal foams. The surface area controlled the viscous drag which was the dominant factor for the pressure drop in the foam.

Few researches used three-dimensional X-ray computed tomography to investigate the microstructure of metal foam. Olurin et al. [19] indicated that it was unclear how to precisely characterize the microstructure and the internal architecture of the foam, and that there was no simple standard experimental technique for such characterization. Scheffler et al. [20] studied 20-ppi aluminum foam's morphology and reported that the pores were nearly sphere-like. The ligament diameter showed a maximum at 0.25 mm (0.009 in.) and the cell size showed a bimodal distribution with maxima at 0.75 and 1.9 mm cell diameter.

Zhou et al. [1] investigated the microstructure and macrostructure of aluminum foam using a combination of optical and scanning electron microscopy. They noted that the cells in 10-, 20- and 40-ppi foam were elongated, and that the actual structure was somewhat different from the tetra-kaidecahedron model that has been used to describe the cells. They recorded significant variations in both the face size and the ligament length. In addition, metal foam contained numerous closed-cell faces.

For some heat transfer and mechanical applications, metal foam needs to be compressed to lower porosities.