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Long-domain simulation of flow in open-cell mesoporous metal foam and direct comparison to experiment

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ABSTRACT

Open-cell metal foam is a class of modern mesoporous media that possesses high thermal conductivity, large accessible surface area per unit volume and high porosities (often greater than 90%). When a fluid passes through the foam, the internal structure of the foam, which is web-like, produces a complex flow field including flow reversal and vigorous mixing. All of these attributes make metal foam a very attractive core for many engineering applications, e.g. heat exchangers, filtration devices and reactors. The rather complex and intrinsically random architecture of the foam is extremely difficult to capture exactly. In this paper, we use a unit cell geometrical model to numerically investigate the flow field and pressure drop inside commercial open-cell aluminum foam. The Navier–Stokes equations are solved directly, and velocity and pressure fields are obtained for various approach velocities using a commercial numerical package. The details of the modeling process are given in this paper. The pressure drop results are compared to the Forchheimer equation, from which the permeability and form drag coefficient are calculated. Comparisons to experimental data were also carried out. The commercial foam that was used in the experiment had 10 pores per inch and porosity of 90% approximately. Air was forced to flow inside the foam using an open-loop wind tunnel. Good agreement between the modeling and experimental results are obtained for low velocities, with the agreement becoming poorer for larger velocities. The results for the low-velocity range are encouraging and lend confidence to the modeling approach, which paves the way for investigating other phenomena inside the foam, using the same unit cell, e.g. heat transfer. The limitations of the models are outlined and discussed.

1. Introduction

Mesoporous materials in general possess attractive properties, such as high surface area, tunable pore sizes and shapes, various structures, which make them prime candidates for applications in adsorption, catalysis, sensing [1,2], biotechnology [3], lithium-ion batteries and nanodevices [1,3]. Advanced applications of these materials include photoelectronic devices and fuel/solar cells [2]. Common widely-used and new mesoporous materials have been recently reviewed. Gu and Schuth [1] provided a comprehensive review of non-siliceous mesoporous oxides, including different synthesis routes. These authors also discussed composition and parameter control. A review for mesoporous titanium-oxide materials was given by Li et al. [3]. Ariga et al. [2] provided a comprehensive account of nanoarchitectonics for mesoporous materials, including recent innovations in their components and structural designs. Components included metals, alloys, biomaterials composites and carbon. Ariga et al. [2] indicated that mesoporous metals hold promise for a wide range of applications such as electronic devices and metal catalysts.

The intriguing combinations of physical and mechanical properties of mesoporous metal foams have led to increased utilization of these materials in various engineered applications. For example, the foams have been used in automotive and aerospace applications due to their high impact resistance and good strength-to-weight ratio [4]. Other applications of metal foams are found in thermal management applications, such as compact heat sinks for power electronics and compact heat exchangers. This is due to foam's huge accessible surface area and high conductivity of cell ligaments, which give good heat transfer capability [5]. Metal foam is also used in geothermal reservoirs and petroleum drilling [6]. Nickel-based foams are currently used as particulate filters in trucks, and open-cell foams with specified pore sizes have the potential to be applied in other types of fluid filtration [7,8].

Over the past 30 years more published studies have become available on the characteristics of fluid flow in metal foam. In an experimental study, Antohe et al. [7] identified two hydraulic

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Nomenclature

C	form drag coefficient (m^{-1})	u	velocity component in the flow direction (m/s)
cpi	number of cells per inch of metal foam	V	Darcy velocity (m/s)
d_1	center-to-center distance between central sphere and polar sphere (m)	V_1	overlapping volume of a polar sphere with the central sphere (m^3)
d_2	center-to-center distance between central sphere and quadrant sphere (m)	V_2	overlapping volume of a quadrant sphere with the central sphere (m^3)
D_p	pore diameter of foam (m)	V_{cube}	volume of cube surrounding a foam cell (m^3)
f	friction factor	V_{void}	void volume (m^3)
K	permeability (m^2)	Greek	
L	thickness of foam sample in the flow direction (m)	δ	uncertainty (%)
p	static pressure (Pa)	Δ	change
ppi	number of pores per inch	ε	porosity of metal foam
R	radius of any of sphere of geometrical modeling (m)	μ	kinematic viscosity of air (kg/m.s)
Re	Reynolds number	ρ	density of air (kg/m^3)

characteristics, the permeability and the inertia coefficient for air flow through 40-ppi (pores per inch) compressed aluminum foams. Two of the widely-cited experimental studies are those of Boomsma and Poulikakos [9] and Hwang et al. [4] who measured the hydraulic performance of open-cell aluminum foam. In both studies, the permeability and the inertia coefficient were determined from the Darcy–Forchheimer equation. Paek et al. [10] experimentally obtained pressure drop through aluminum foams of porosities in the range 89–96%, and used an empirical model for the friction factor as a function of the permeability-based Reynolds number.

Other pressure drop studies targeting various important effects have appeared. The issue of different flow regimes in metal foam and how they should be identified was presented by Dukhan and Ali [11], while the fact that the same foam can exhibit different flow properties in different flow regimes was discussed by Dukhan and Minjeur [12]. The effect of confining wall on the pressure drop through metal foam was investigated by Dukhan and Ali [13] and Dukhan [14], while the effect of foam length in the flow direction (or size effect) was obtained by Dukhan and Patel [15].

The internal structure of metal foam results in a rather complex flow field, which includes flow recirculation at the back of the foam's solid fibers and unsteady flow structures. Interactions between the surface of the solid matrix and the fluid are not yet well understood by oversimplified numerical approaches or macroscopic empirical correlations. Detailed numerical analysis at the pore level can assist in better understanding intricacies of this complex flow field.

For studying the flow field inside metal foam in detail, the Navier–Stokes equations can be solved inside and around the pores and the ligaments of the foam. In order to solve these equations, an idealized geometrical model of the internal microstructure of the foam is indispensable. Such model must be realistic in terms of being able to capture the foams' morphological parameters to the greatest extent possible. These parameters include shape and diameters of actual foams' cell and open windows, shape and thickness of foam's ligaments, specific surface area and porosity. This is a difficult task indeed. Actually, the difficulties associated with developing predictive geometrical models is the prime reason for the fact that a lot of metal foam research is conducted at the macroscopic level as opposed to the detailed microscopic or pore level. The microscopic approach for studying fluid flow (and heat transfer) in porous media, where pore-scale level analysis is conducted, captures the intricate details of the foam structure and fluid–solid interactions. This approach is computationally expensive; however, computational time can be reduced by symmetry in the physical domain where symmetry is found.

The past few years have seen several studies on numerical simulation of transport in metal foam using commercial packages. Perhaps the primary cause for the low fidelity of some of numerical analyses for metal foam simulation using these packages is the inadequacy of physical and/or geometrical modeling of the foam. All commercially-available simulation packages have modules that are based on packed beds or granular media representation of all porous media having porosities in the range 30–60%. For metal foam the porosity is typically greater than 90%, and the internal structure of the foam is web-like. Other noticeable issues with numerical simulation of metal foam include a lack of a validation strategy.

Numerous studies have attempted to model the geometry of the highly porous metal foam by defining a representative elementary volume (REV) that captures the relevant characteristics of these materials in fluid flow and heat transfer. One of the early attempts is that of Du Plessis et al. [16] who presented geometrical modeling of the fluid dynamics in reticulated foams such as aluminum foam with high porosity. Their REV was based on a set of rectangular prisms. They provided good predictions of pressure drop, permeability and form drag coefficient as functions of the foam's structural characteristics (density, pore size, tortuosity and cell size). The predictions compared well with experimental data for flow of water in 40-, 60- and 100-ppi foam with porosity range between 92% and 96%.

To model a significant foam domain numerically would require a lot of time and computational power. This issue can be overcome by investigating a single 'repeating' cell representing the structure of open-cell metal foam. Boomsma et al. [17] captured more intricate details of the foam structure in their model. Their idealized foam unit cell was a tetrakaidecahedron (14-sided polyhedra having 12 pentagonal and two hexagonal faces, and two pentagonal dodecahedra). Their 'periodic' unit consisted of eight such cells. The cross section of ligaments was shaped triangularly. Laminar, incompressible flow was then simulated utilizing these unit cells along with periodic boundary conditions. Their numerical pressure drop results were lower than experimental results by up to 25%, which was explained by the presence of wall effects.

Krishnan et al. [18] carried out a direct pore-scale simulation of pressure drop and heat transfer in open-cell metal foam using a single unit cell. Their ideal unit cell was a body center cube (BCC) created by assuming the void pore to be spherical, with windows located at the vertices and the center of the unit cell. They assumed a fully-developed flow and periodicity. Their predicted thermal conductivity, pressure drop and heat transfer coefficient compared well with experimental correlations for foam porosity of 94%.