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Experimental Thermal and Fluid Science 30 (2006) 329–336
Experimental Thermal and Fluid Science
www.elsevier.com/locate/etfs

Measurement and correlation of friction characteristic of flow through foam matrixes ☆

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Received 2 September 2004; accepted 27 July 2005

Abstract

A correlation of friction characteristic was developed based on the measured pressure drop of air through foam matrixes. The pressure drops of seven types of aluminum foams with different porosities and pore densities were measured. The Reynolds number based on the equivalent spherical diameter of the foam ranged from 32.05 to 1289.32. The range of porosity was 0.87–0.958. A empirical equation was developed to correlate the dimensionless pressure drop with the dimensionless flow velocity for all seven types of aluminum foams. The empirical correlation agreed well with experimental data. According to the empirical correlation and the measured data, the pressure drop introduced by foam matrixes was much lower than that by granular matrixes at the same Reynolds number. The relationship between the friction factor and *Re* of foam matrixes follows the trend of granular matrixes and can be classified into three regimes: $Re < 30$, $f_k \propto \frac{1-\varepsilon}{Re}$; $30 < Re < 300$, $f_k = 22\frac{1-\varepsilon}{Re} + 0.22$; $Re > 300$, the value of f_k approaches 0.22.

Keywords: Porous media; Foam; Pore diameter; Pressure drops; Transport properties

1. Introduction

Due to their augmented heat- and mass-transfer characteristics, the transport phenomena in porous media have been of continuing interest for the past two centuries. The augmented heat- and mass-transfer characteristics of porous media have led to numerous applications. For example, porous media can be applied to solar-receiving devices, high-efficiency heat exchangers, energy-storage units, ceramic processing units, electronic coolers, catalytic reactors, and others. In the applications of high-efficiency heat exchangers, electronic coolers, and catalyst supports, ceramic and metal porous materials with high thermal conductivity in the reticulated form of foam are usually adopted for heat- and mass-transfer enhancement. For example, metal-foam heat sinks made of copper or aluminum have proven to be appropriate for the cooling of high-power electronic components, with excellent thermal performance under conditions of forced convective cooling [1–3]. Chao et al. [1] reported the thermal performance of a thermally enhanced plastic ball grid array (PBGA), which incorporated a heat slug in a package with a metal-foam heat sink on the top of the package. The measured results indicated a significant improvement in power dissipation when a commercial pin-fin sink was replaced by an aluminum foam heat sink under forced convective cooling conditions. Chou and Yang [2] also showed the superior thermal cooling performance of aluminum foam sinks. At the air speed of 3.6 m/s, the overall heat-transfer coefficient of the aluminum foam with 91.4% porosity was reported to be 25% higher than that of a conventional finned array. In Lee et al.'s [3] work, a dissipating power of 100 W for a 1 cm^2 chip with an aluminum-foam heat sink and a low

☆ This work represents a part of the results obtained under contract number NSC-89-2212-E-194-023 sponsored by the National Science Council, Taiwan, ROC.
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doi:10.1016/j.expthermflusci.2005.07.007

Nomenclature

Abbreviations

D_p equivalent spherical diameter of porous media, m
d_p mean pore diameter, m
F inertia coefficient, dimensionless
f_k friction factor, defined in Eq. (7), dimensionless
K permeability, m^2
L length of the test section, m
P pressure, N/m^2
PPI pores per inch, pore/inch
Re Reynolds number based on the equivalent spherical diameter of porous media, dimensionless
S_v surface area per unit volume of solid phase, m^{-1}
u velocity of the fluid, m/s
x X-coordinate, m

Greek symbols

ρ density, kg/m^3
μ viscosity, Pa s
ε porosity, dimensionless

power muffin fan was demonstrated. Richardson et al. [4] indicated that foams had extensive pore tortuosity that enhanced turbulence mixing and transport. These features suggested significant advantages of foam materials in catalytic processes limited by mass or heat transfer. The study of Pestryakov et al. [5] revealed that the catalysts beds with foam structure were superior to traditional catalyst beds with a granular or a honeycomb structure because that the catalyst beds with foam structure had better structural stability, higher permeability and filtering ability, and better isotropy of mechanical properties when the solid density were the same. In addition, the three-dimensional cellular structure of foam materials provided a turbulent mode of fluid motion. This increased the extent of active surface utilization and the catalyst efficiency.

Although foam materials offer the aforementioned merits, they usually cause significant pressure drops. It is therefore important to fully understand the pressure-drop characteristic of foam materials when applying these types of materials to any system. Hunt and Tien [6] measured pressure-drop characteristic of seven different types of highly porous foams. They deduced the permeability and inertia coefficient of the Forscheimer equation [7] for the foams from experimental data. Lee and Howell [8] also analyzed the pressure-drop characteristic of ceramic foams. Du Plessis et al. [9] measured six sets of pressure-drop data for Newtonian fluids (water and aqueous solution of glycerol) flowing through metal foams. Richardson et al. [4] performed a series of pressure-drop experiments on foam as catalyst supports.

Based on the literature survey of relevant studies it is noted that no general equation has been proposed for the calculation of the pressure drop through different foam matrixes. In order to develop such a general equation, experience could be learned from the study of granular beds. During the past eight decades, a considerable amount of experimental work has been performed on pressure drops through beds of granular solids. Following an extensive review of works done by Ergun [10], Macdonald et al. [11], Kuo et al. [12], and Jones et al. [13], have developed various general equations for granular porous media. To construct a generalized equation for foam matrixes, similar to those for granular media [10–13], a characteristic length namely the equivalent spherical diameter (D_p) of a foam material needs to be determined for the calculation of the dimensionless pressure drop and velocity, namely f_k and Re. Unfortunately, due to the complexity of the geometric shape of foam materials, there is no consensus on how to determine the characteristic length. Several approaches have been proposed to tackle this problem. Du Plesis et al. [14] constructed a model that used three mutually orthogonal duct sections in a cubic unit cell to estimate D_p. Smit and Du Plessis [9,15] used representative unit cells as basic elements to determine D_p. In Ref. [15] Smit and Du Plessis studied the pressure drop of non-Newtonian fluids flowing through metal foams. These proposed models are specific to special cases and require strict assumptions. Meanwhile, various characteristic lengths, such as the square root of the permeability [16], the ligament diameter [17], and the pore diameter [18], etc. were proposed, but none of these characteristic lengths, due to the complex geometry of foam materials, can be used to obtain a general flow friction correlation for foam materials with different pore densities and porosities.

Richardson et al. [4] proposed a generalized experimental procedure for the estimation of mean pore diameter (d_p), which consequently led to a reliable determination of the equivalent spherical diameter (D_p). It is suggested here that mean pore diameter (d_p) is used as the characteristic length of foam materials because imaging analysis can be used to take measurements.

In this study, a series of experimental tests was conducted to determine the flow friction characteristic of metal foam. Seven types of aluminum foams with different porosities and pore densities were tested. An empirical equation was developed to correlate the dimensionless pressure drop (f_k) and flow velocity (Re) for all seven types of aluminum foams. The empirical correlation was compared with available experimental data.