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Analytical and numerical prediction of heat transfer and pressure drop in open-cell metal foams

Mo Bai, J.N. Chung*

Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32611, USA

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ABSTRACT

Enhanced cooling methods are needed for advanced power systems. A promising method is using an open-cell metal foam to improve the heat transfer rates. However, the pressure drop induced by the metal foams is relatively higher and thus becomes a critical issue in engineering applications. The focus of this research is the modeling and simulation of heat transfer enhancement and corresponding pressure drop.

A simplified analytical model based on diamond-shaped unit cells has been developed to predict the heat transfer capability of a foamed channel. The heat transfer rates predicted by the analytical model have been compared with available experimental data from other researchers and favorable agreements have been obtained. To evaluate the pressure drop in metal foams, a unit-cell CFD model was built using software package Fluent. The model is based on a structure of sphere-centered open-cell tetrakaidecahedron, which is very similar to the actual microstructure of an aluminum metal foam. Flow patterns and grid independence are investigated and simulation results are shown to agree well with experimental data.

1. Introduction

The open-cell foam is one type of porous media and it is emerging as an effective material for heat transfer enhancement, due to its large surface area to volume ratio, high thermal conductivity, and intensified fluid (coolant) mixing. Fig. 1 shows typical metal foams.

The use of open-cell foam to enhance heat transfer has been investigated widely. Koh and Stevens [1] used a stainless steel cylindrical annulus to experiment with the heat transfer enhancement by open-cell foam filler. They found the heat flux increased to more than 2 folds for a constant wall temperature case and the wall temperature dropped to about one third for the constant heat flux case. Hunt and Tien [2] utilized foam-like material and fibrous media to enhance forced-convection for potential application to electronics cooling. Their results showed that a factor of two to four times enhancement is achievable as compared to laminar slug flow in duct. It is believed that the enhancement is mainly due to the micro turbulent mixing in the pores and super heat transfer through high thermal conductivity porous structure.

However, open-cell foams also generate large pressure drops because of the extensive micro-scale mixing. Leong and Jin [3] performed experiments to investigate the pressure drop from oscillating flow through metal foams. They found the flow's Reynolds number has very significant effect on pressure drop. Kim et al. [4] experimentally investigated the relation between flow friction factor and heat transfer in an asymmetrically heated foamed channel. Yuan et al. [5] investigated the heat transfer enhancement and pressure drop in an annular channel with nickel foams. They found that, under the same pressure drops, the heat transfer rate provided by foamed channel is enhanced by as much as 170%, when compared with conventional open channel.

Many researchers investigated open-cell foams by numerical methods, both analytical and computational. Lu et al. [6] simplified the random microstructure of metal foams to cubic unit cell and investigated their friction and heat transfer properties analytically. However, the model oversimplifies the metal foam structure and its prediction of heat transfer leads to overestimates. Krishnan et al. [7,8] carried out direct simulations of the transport phenomenon in open-cell metal foam by analyzing a single unit-cell structure. They performed CFD simulations and obtained good agreement with experimental data on Nusselt number and friction factor. Yet, this model is only suitable for foams with porosity greater than 0.94, due to the geometrical limitation of the body-centered cube model. Chung et al. [9] developed a unit-cell structure based on Kelvin's

* Corresponding author.
E-mail addresses: gatormo@gmail.com (M. Bai), jnchung@ufl.edu (J.N. Chung).

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