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Research Paper

Thermal-hydraulic performance of metal foam heat exchangers under dry operating conditions

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HIGHLIGHTS

- Metal foam heat exchangers have been built using open cell aluminum foams with different pore sizes.
- The impact of foam cell geometry on the thermal hydraulic performance of metal foam heat exchanger has been evaluated.
- The existing performance modeling approaches for metal foams have been evaluated for applications.
- New correlation for friction factor and colburn j factor have been established based on physically measureable parameters.

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ABSTRACT

High porosity metal foams with novel thermal, mechanical, electrical, and acoustic properties are being more widely adopted for application. Due to their large surface-area-to-volume ratio and complex structure which induces better fluid mixing, boundary layer restarting and wake destruction, they hold promise for heat transfer applications. In this paper, the thermal-hydraulic performance of open-cell aluminum metal foam heat exchanger has been evaluated. The impact of flow conditions and metal foam geometry on the heat transfer coefficient and gradient have been investigated. Metal foam heat exchanger with same geometry (face area, flow depth and fin dimensions) consisting of four different type of metal foams have been built for the study. Experiments are conducted in a closed-loop wind tunnel at different flow rate under dry operating condition. Metal foams with a smaller pore size (40 PPI) have a larger heat transfer coefficient compared to foams with a larger pore size (5 PPI). However, foams with larger pores result in relatively smaller pressure gradients. Current thermal-hydraulic modeling practices have been reviewed and potential issues have been identified. Permeability and inertia coefficients are determined and compared to data reported in open literature. On the basis of the new experimental results, correlations are developed relating the foam characteristics and flow conditions through the friction factor *f* and the Colburn *j* factor.

1. Introduction

Recent advances in manufacturing techniques have made possible a broader use of metal foams and metal matrix composites (MMCs) for heat transfer applications. They are characterized by the size of the windows (or pore diameter) which correlates to the nominal pore density (usually as pores per inch—PPI), the strut diameter and length, and the porosity ε (volume of void divided by the total volume of the solid matrix and void). Some of the length scales for metal foams are defined in Fig. 1.

Metal foams have attractive properties for heat transfer applications and have been used for thermal applications in cryogenics, combustion chambers, geothermal systems, petroleum reservoirs, catalytic beds, compact heat exchangers for airborne equipment, air cooled condensers and compact heat sinks for power electronics. Despite manufacturing and implementation issues, these materials hold promise both for heat exchangers and heat sinks [1]. The open porosity, low relative density, high thermal conductivity of the cell edges, large accessible surface area per unit volume [2–6], and the ability to mix the cooling fluid contribute to making the metal foam thermal management devices efficient, compact, and light-weight. If metal foams are to be widely used in thermal systems, their pressure-drop and heat transfer characteristics must

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Nomenclature

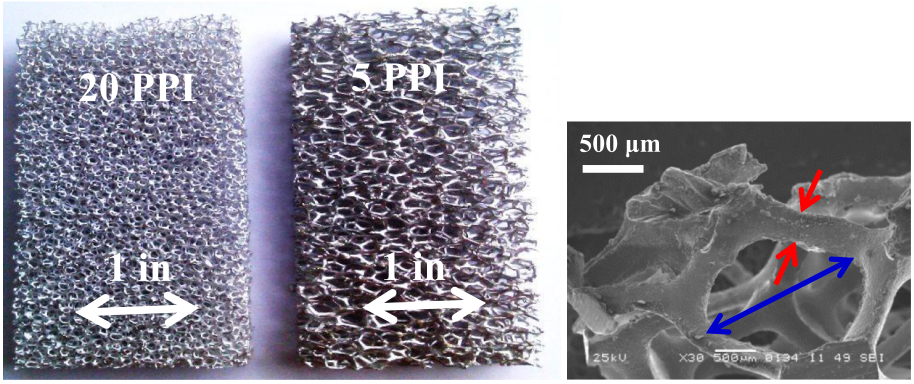
A	area (m^2)
C	inertia/friction coefficient(m)
c	specific heat (J/kg K)
D	diameter (m)
F	correction factor for LMTD
f	friction factor
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
j	Colburn j factor
K	permeability (m^2)
k	thermal conductivity (W/m K)
L	length (m)
LMTD	Log-mean temperature difference (K)
Pr	Prandtl number
$\Delta P/L$	pressure drop per unit length (Pa/m)
q	heat transfer rate (W)
R	bonding resistance (K/W)
Re	Reynolds number based on average pore diameter (Fig. 1)
T	temperature (K)
U	overall heat transfer coefficient (W/m^2 K)
V	face velocity (m/s)

Subscripts

a	air
ave	average
b	base, bond
c	coolant, characteristic
eff	effective
f	fin
fo	foam
fr	frontal
fl	fluid
h	hydraulic
i	inlet
min	minimum
o	outlet
li	ligament
p	pore
s	solid

Greek letters

Δ	difference
ε	porosity
ρ	density (kg/m^3)
μ	kinematic viscosity (N s/m^2)
η_0	overall surface efficiency
η_f	fin efficiency



(a) (b)

Fig. 1. Definition of length scale for metal foams (a) 20 and 5 PPI and (b) pore diameter (blue), strut diameter (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

be available to potential users in terms that fit into the current design methods. This paper focuses on the experimental analysis of pressure drop and heat transfer for air flow in metal foams heat exchangers with different pore size, geometry and base metal.

2. Literature review

Metal foams are a relatively new class of materials. Due to their recent emergence and complex structure, they are not yet completely characterized. Interest in using them in contemporary technologies makes the need for fully characterizing them more urgent. Central to this need is an accurate evaluation of the flow characteristics to assist in making the trade-off analysis between the increased heat transfer and the associated increase in the pressure drop for foam heat exchanger and heat sink designs. Extensive reviews of the topic of the fluid flow in the porous media in general can be found in the open literature [7–9].

Seguin et al. [10] experimentally investigated the flow regimes in various porous media. The onset of the turbulent flow regime was found to occur at a Reynolds number equal to 470. The Reynolds number was defined based on the pore diameter of metal foams. Lage et al. [11] reviewed Darcy's Law [12] and argued that the ratio between the form and the viscous forces should be used to mark the transition from the linear to the quadratic flow regimes of the pressure drop behavior. They concluded that the transition is material specific and depends on the internal geometry of the porous medium. Several researchers conducted experimental and numerical studies to determine the permeability and inertia coefficient for the flow through the open cell metal foams