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Design of multifunctional lattice-frame materials for compact heat exchangers

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ABSTRACT

Structured porous materials show great potential as extended surfaces in heat-exchange applications that also require design for load-bearing capability. In particular, lattice-frame materials (LFM) are known for their superior strength-to-weight ratio; this work presents a comprehensive experimental and numerical study of fluid flow and heat transfer in porous LFMs. Flow through a periodic unit cell of the material is simulated to characterize the forced-convection performance under hydraulically and thermally fully developed conditions. The performance of LFMs with a tetrahedral ligament configuration is characterized as a function of Reynolds number in the laminar regime ($150 < Re < 1000$) in terms of Nusselt number and friction factor; the effect of porosity is studied by changing the ligament diameter. Experiments are performed for a subset of porosities to validate the numerical approach. A method is demonstrated for utilizing the simulation results, which assume perfect surface efficiency, to predict the performance of LFMs with non-ideal surface efficiency, based on the conduction resistance of the ligaments. It is shown that the thermal behavior of the ligaments closely matches that of cylindrical fins in cross flow and that this analogy can be used to calculate the overall surface efficiency. The implications of the current results on the design of compact heat exchangers using LFMs is assessed using several conventional performance metrics. Our analysis illustrates the challenges in defining any one universal performance metric for compact heat exchanger design; an appropriate performance metric must be selected that accounts for the particular multifunctional performance characteristics of interest. LFMs are shown to provide the benefits of high-porosity and high surface area-to-volume ratio of materials such as metal foams, while also incurring lower pressure drops and displaying higher structural integrity. This makes them ideal for heat exchangers in aerospace and other applications demanding such multifunctional capabilities. The characterization provided in this study readily allows LFM designs for heat exchanger applications with combined heat-transfer and pressure-drop constraints.

1. Introduction

With the continual increase in power consumption and performance demands under increasingly stringent size constraints in a variety of thermal systems, such as those deployed in electronics thermal management, waste heat recovery, and aerospace applications, there is great need for compact heat exchangers with improved heat dissipation capabilities. Over the last two decades, high-porosity metal foams have been evaluated as a potential heat-exchange medium with high surface area density, low weight, and tortuous coolant flow paths that promote flow mixing and prevent the growth of resistive thermal boundary layers. These metal foams have been investigated extensively in the literature, and simplified models [1–7] and experimental correlations [7–16] for the friction factor and Nusselt number have been developed to predict the pressure drop and heat transfer performance in forced-convection, foam-filled heat exchangers as a function of their geometric parameters. A recent review article by Zhao [17] presents an overview of thermal-hydraulic transport in high-porosity cellular ceramic and metallic foam materials. Though metal foams provide high surface-area-to-volume ratios, they suffer from low bulk thermal conductivity (*e.g.*, 2–7 W/(m K) for 90%-porosity aluminum foams in air [17–22]) and high pressure drops that limit their practical applicability in compact heat exchangers [23]. Moreover, metal foams often require additional support structures due to their low mechanical strength and stiffness [24,25].

In recent years, structured porous media known as lattice-frame materials (LFM) have received significant attention owing to their tunable, multifunctional properties. A lattice-frame

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Nomenclature

A	area, m^2
A_{fr}	channel frontal area ($H \times W$), m^2
A_t	total heat transfer surface area, m^2
c_p	gas specific heat, J/(kg K)
d	ligament diameter, mm
D_h	hydraulic diameter, Eq. (2), mm
E	friction power expended per surface heat transfer area, Eq. (16), W/m^2
f	friction factor, Eq. (5)
H	height, mm
h	heat transfer coefficient, W/m^2
j	Colburn j factor, Eq. (4)
k	thermal conductivity, W/(m K)
l	ligament length, mm
L	length, mm
Nu	Nusselt number, $Nu = \frac{hD_h}{k_g}$
p	pressure, Pa
Pr	Prandtl number ($c_p\mu/k$)
Re	Reynolds number, $Re = \frac{\rho u_\infty D_h}{\mu}$
S_x	tetrahedron longitudinal pitch, mm
S_y	tetrahedron transverse pitch, mm
St	Stanton number, $St = \frac{h}{\rho u_\infty c_p}$
T	temperature, K
u	velocity, m/s
u_∞	superficial fluid velocity, m/s
V_{uc}	total volume of a unit cell, including solid ligament and fluid space, m^3
W	width, mm
x	axial flow coordinate, mm
y	transverse flow coordinate, mm

Greek symbols

ε	porosity
ϕ	ligament angle of inclination
ρ	gas density
μ	gas dynamic viscosity
η_f	fin efficiency
η_o	overall surface efficiency

Subscript

avg	average
i, j	index
g	gas
f	fin
s	solid

material consists of a periodic network of cylindrical ligaments of constant cross section, unlike stochastic metal foams which typically have ligaments that vary in diameter along their length. This periodicity and homogeneity gives LFMs an advantage over stochastic metal foams by allowing optimization of the ligament configuration and diameter for specific applications and requirements [26]. With advances in additive manufacturing technologies, LFMs can be fabricated with small-scale feature sizes and three-dimensional ligament arrangements in a variety of possible configurations including square, diamond, tetrahedral, kagome, and pyramidal lattice structures [27–29]. In addition to these different configurations, researchers have also explored various materials (*e.g.*, metal, carbon fiber, and composites) to address a range of multifunctional needs. Xiong et al. recently reviewed these LFM structures and their potential applications [30]. Multifunctional load-bearing and effective heat dissipation capabilities have the potential to reduce the volume and weight of heat exchangers because LFMs do not require the separate support and stiffening structures needed by metal foams [31]. This is especially advantageous in aerospace applications where heat exchangers are often used as structural elements [32]. We review below previous studies that investigate pressure drop and convective heat transfer in tetrahedral LFMs.

Lattice-frame materials were first investigated as structural components that provide high compressive strength and resistance to plastic buckling [31,33–37]; subsequently, they have been considered as potential convective heat transfer media. Lu et al. compared LFMs against prismatic cores, woven metal textiles, metal foams, and traditional louvered fins [28]. For a load-bearing heat exchanger, LFMs and prismatic core structures outperformed all other options based on a comparison of the heat transferred per unit temperature difference and pressure drop. Using this same metric, Krishnan et al. [38] found the overall performance of LFMs to be approximately three times larger than that of stochastic metal foams at similar porosities. In a series of experimental studies by Kim and co-workers [39–41], the pressure drop and heat transfer characteristics of compact heat exchangers composed of tetrahedral LFMs were measured. Local wall temperature measurements revealed the formation of vortices within the structure and that the corresponding local heat transfer coefficients were sensitive to subtle variations in the ligament vertex locations and inclination angles. Owing to their superior mechanical and convective transport characteristics, lattice-frame materials are a viable alternative to stochastic metal foams for heat-exchange applications. Past work has investigated transport in LFMs using either numerical or experimental approaches that analyze the influence of microstructural variations over a limited range. However, the successful adoption of LFMs for heat exchanger design requires an understanding of the particular application needs to which their pressure drop and heat dissipation characteristics can be tailored; singular performance metrics typically considered in past work cannot be used for such tailored design.

In this work, we characterize the performance of lattice-frame materials as a function of porosity using several conventional performance metrics to delineate the specific applications for which they are a suitable heat-exchange medium. We use an integrated simulation and experimental validation approach to systematically investigate the effect of porosity on pressure drop and forced convection heat transfer in LFMs. We also validate a simplified correction factor to account for the finite surface efficiency, which can be used to predict the thermal performance for materials of different thermal conductivity based on the simulation data. Finally, we analyze the results with a focus on the implications of each performance metric on heat exchanger design using LFMs.

2. Lattice-frame material geometry

Lattice-frame materials consist of a periodic network of cylindrical ligaments. We investigate a specific tetrahedral lattice configuration with its ligaments organized in the shape of a tetrahedron, as shown in Fig. 1a. In the tetrahedral LFM considered, an equilateral triangular base forms the bottom of each structural unit with cylindrical ligaments arising from each vertex. These three ligaments define the vertical edges of the tetrahedral structure,