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Comparative evaluations of thermofluidic characteristics of sandwich panels with X-lattice and Pyramidal-lattice cores

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ABSTRACT

This study compares the thermo-fluidic characteristics of sandwich panels with the X-lattice and the Pyramidal lattice at a given porosity and surface area density. The numerical model is validated against available experimental data at first. At a given Reynolds number in the range of 3100–5700, numerical results reveal that the X-lattice sandwich panel provides a 47–60% higher average overall Nusselt number. The special topology of the X-lattice induces counter-rotating spiral primary flow and more complex secondary flows, including one which becomes a longitudinal vortex later. The flow in the Pyramidal lattice sandwich panel is composed of a parallel primary flow and a counter-rotating vortex pair entrenched in the zone behind ligaments of the Pyramidal lattice. Compared with the Pyramidal lattice sandwich panel, endwall heat transfer of the X-lattice sandwich panel is enhanced by 75–97% and the ligaments surface heat transfer is enhanced by 85–97% at a given Reynolds number. It is also found that the friction factor of the X-lattice sandwich panel is about 2 times higher for the spiral primary flow and more complex secondary flows induced by the staggered ligaments. Finally, at a given pumping power, the cooling performance of the X-lattice is much better, too. Taking the identical fabrication method and cost into account, apparently the X-lattice is superior in engineering applications.

1. Introduction

For energy systems, thermal management is a matter of great importance. Under certain circumstances, for example, active cooling of combustion chambers of hypersonic vehicles and jet blast deflector of aircraft carriers [1–5], a heat sink is required to be able to bear the severe thermal/mechanical load concurrently [1,2,4–7]. For these situations, the sandwich panel cored with the periodic cellular material (PCMs) is one of the promising structures. It is revealed that PCMs with high specific strength/stiffness are lightweight and that the open topologies with high specific surface area makes PCMs excellent heat dissipation structures [7]. Due to these advantages, many researches have been carried out on fabrication methods of cost-effective PCMs, friendly PCMs design and mechanical/thermal performance of PCMs in the previous decades.

A cost-effective fabrication method of PCMs is the first concern. Nowadays, fabrication methods including investment casting [8], metal wire weaving [9], metal sheet folding [10–12] have been applied to prepare PCMs including those shown in Fig. 1. For investment casting, a melted parent metal is poured into a casting die, then the expendable fabricate by rapid prototyping is gasified, finally the casting is taken after cooled. The investment casting is an extremely complex process, which is suitable for low volume production of products with complex appearance [8]. Metal wire weaving literally is weaving of the helical metal wires. Unfortunately, solution to weave PCMs with complex topologies by machine is still not found [9]. For metal sheet folding, perforated or expanded metal sheet fabricated based on the target topology, is automatically folded. In view of production cost and process simplicity, metal sheet folding is the most effective process for automatic product lines [11].

Thermal and mechanical performance of PCMs is another concern reported by many researchers. Research on thermal and mechanical performance is one step behind the development of PCMs' fabrication method. Hoffmann et al. [13] did research into the thermo-fluidic characteristics of a casted Kagome metallic lattice through experiments. They found that the orientation of the lattice relative to the flow direction is one factor affecting both

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Nomenclature

a_1	model constant in Eq. (6)
$CD_{k\omega}$	a term defined in Eq. (11)
c_{pf}	specific heat of fluid (J/(kg K))
C_p	static pressure coefficient defined in Eq. (19)
E_t	turbulent kinetic energy (J)
F_1	non-dimensional blending function defined in Eq. (10)
F_2	non-dimensional blending function defined in Eq. (9)
f_H	friction factor defined in Eq. (18)
h	local heat transfer coefficient (W/(m^2 K))
H_c	height of the sandwich channel (m)
k_f	thermal conductivity of fluid (W/(m K))
k_s	thermal conductivity of solid (W/(m K))
l	length of a lattice core unit cell (m)
L	length of the sandwich panel (m)
Nu	local Nusselt number
Nu_{ave}	area-averaged local Nusselt number
Nu_H	average overall Nusselt number
p	static pressure (Pa)
P_k	production rate of turbulent kinetic energy due to fluid viscosity (J/(m^3 s)) defined in Eq. (7)
Pr_t	turbulent Prantle number
q''	heat flux applied on the outer surface of the bottom substrate (W/m^2)
Q	pumping power (W)
r	fillet radii shown in Fig. 5 (m)
Re_H	Reynolds number defined in Eq. (13)
S'	strain rate defined in Eq. (8) (1/s)
t_s	thickness of the substrate (m)
t_l	thickness of a core ligament (m)
T_f	fluid temperature in Eq. (3) (K)
T_{fb}	bulk mean fluid temperature defined in Eq. (16) (K)
T_{in}	inlet fluid temperature (K)
T_s	solid temperature in Eq. (3) (K)
T_w	wall temperature (K)
U_m	mean velocity at the inlet of the computational domain (m/s)
V_i	velocity components in 3-D Cartesian coordinate system (m/s)
V_m	velocity magnitude (m/s)
V_m/U_m	non-dimensional velocity magnitude
w	width of an X-lattice unit cell (m)
w_l	width of a core ligament (m)
W	width of the sandwich panel (m)
x_i	three components of 3-D Cartesian coordinate system (m)
x, y, z	Cartesian coordinates (m)
y^+	dimensionless wall distance
y'	minimum distance between a point to its surrounding solid wall in Eq. (9) (m)

Greek symbols

α_1–α_3	model constants in Eq. (12)
β_1–β_3	model constants in Eq. (12)
β'	model constants in Eq. (4)
Δp	pressure drop (Pa)
σ_{k1}–σ_{k3}	model constants in Eq. (12)
$\sigma_{\omega 1}$–$\sigma_{\omega 3}$	model constants in Eq. (12)
ε	porosity
μ_f	dynamic viscosity of fluid (Pa s)
μ_t	turbulent viscosity defined in Eq. (6) (Pa s)
ρ_f	density of fluid (kg/m^3)
ρ_{SA}	surface area density (m^2/m^3)
ω	turbulent frequency (1/s)

Abbreviations

OA	orientation A
PCMs	periodic cellular materials

pressure drop and heat transfer tremendously. Through experiments and numerical simulations, the pioneer, Kim et al. [14–17] thoroughly discussed the forced convective heat transfer mechanisms of a casted tetrahedral metallic lattice as shown in Fig. 1. Joo et al. [1] and Feng et al. [18] investigated heat transfer characteristics of a wire-woven bulk Kagome (WBK) lattice. They concluded that the WBK lattice thermally exceeds the casted Kagome lattice at identical porosity. Gao et al. [19,20] introduced a composite tetrahedral lattice and explored its thermal performance for electronics cooling. They also developed relevant analytical models for engineering design based on their research. Yan et al. [4,5,11,21] introduced an X-type metallic lattice and investigated its flow characteristics and heat transfer mechanisms through experiments and numerical simulations. For a given porosity, they drew the conclusion that the overall thermal performance of the X-type lattice outperforms other reference lattices because of the unique spiral primary flow and three types of second flows. Zhao et al. [22] developed a woven lattice by weaving copper wires orthogonally and investigated the influence of weaving pattern and flow configurations on the thermal performance.

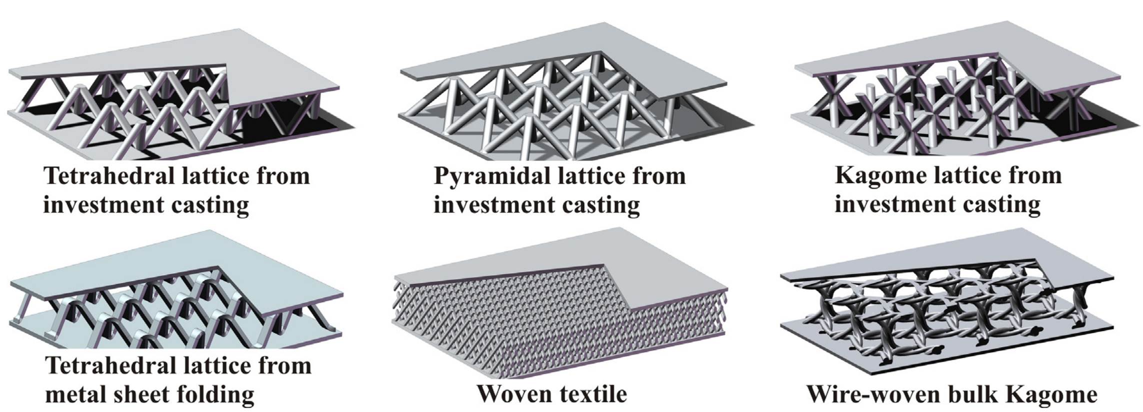

Fig. 1. The sandwich panels cored with the metallic lattices fabricated with different methods to bear mechanical and thermal load concurrently.