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# A lightweight X-type metallic lattice in single-phase forced convection

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ABSTRACT

The superior capability of bearing thermal and mechanical loads to other types of open cellular materials has led to advances in developing new periodic cellular materials. We introduce a lightweight X-type lattice fabricated via the metal sheet folding and present its thermo-fluidic characteristics in single-phase forced convection. For fixed porosity, thermal conductivity and Reynolds number, the X-type lattice provides overall heat removal capacity up to two times higher than reference periodic cellular materials. The unique morphology of the X-type lattice results in a large scale spiral primary flow, which interacts with several secondary flows. These fluid flow behaviors and the induced complex flow mixing substantially enhance heat transfer on both the substrate and ligaments. However, the X-type lattice causes roughly three times higher pressure drop than reference periodic cellular materials for a given Reynolds number. Overall, superior heat transfer is achieved by the X-type lattice for a fixed pumping power.


## 1. Introduction

In thermal management systems, a variety of heat dissipation media have been used. The spectrum of such media includes simple two dimensional prismatic media (e.g., pin–fins [1]), stochastic cellular media (e.g., metal foams [2]) and periodic cellular media (e.g., wire-screens [3], lattice-frame materials [4] and Kagome lattices [5]). Amongst them, cellular metals including open-cell metal foams and periodic cellular materials (PCMs) are promising for multifunctional applications where simultaneous thermal and mechanical load bearing capability is required [6–10]. In particular, PCMs (Fig. 1) provide better specific strength and stiffness than stochastic ones [11]. Consequently, considerable efforts have been devoted to developing mechanically and thermally effective PCMs.

With rapid advances in manufacturing technology, different methods have been introduced to fabricate more design friendly and controllable PCMs, such as metal wire weaving [12], investment casting [13], cylinder assembling [14], and metal sheet folding [15]. In particular, metal sheet folding is considered simpler and more cost-effective [11]. Using this method, PCMs having various cell topologies (e.g., tetrahedron and pyramid) can be fabricated [11]. To fabricate a tetrahedral lattice core for sandwich construction, the perforation of a complete metal sheet to form perforated hexagonal holes is required [15], wasting a considerable amount of material. In contrast, to fabricate a pyramidal lattice (Fig. 2(a)), an alternative yet more cost-effective method of slitting and expanding a complete metal sheet has been developed to form the required diamond holes, allowing much more material to be utilized [16]. Further, half pitch shifting of the metal sheet with diamond holes has been found to form a new periodic lattice with ligaments intersecting into an "X shape," the so-called "X-type lattice;" see Fig. 2(b). Mechanically, relative to pyramidal lattice, it has been demonstrated that the X-type lattice provides approximately 30% higher peak compressive and shear strengths for a given relative density [17,18].

Morphologically, whilst LFM, Kagome and WBK lattices typically have circular ligaments (see Fig. 1); the ligaments of an X-type lattice have a rectangular cross-section (Fig. 2). Further, by changing relevant parameters of the metal sheet and moulds, the method of metal sheet folding provides more design flexibility. For a given porosity, for example, an X-type lattice having more frontal area can be easily fabricated by using a thinner metal sheet with smaller diamond holes, providing thus better heat transfer [9,19]. In comparison, for PCMs with circular cross-sectioned ligaments (Fig. 1), the variation of frontal area is always accompanied by varying porosity due to changing ligament diameter.

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**Nomenclature**

| | |
|---|---|
| $A$ | surface area ($m^2$) |
| $b_1$, $b_2$ | widths of the intersection point in Fig. 4 (m) |
| $c_p$ | specific heat of fluid (J/(kgK)) |
| $C$ | empirical constant in Eq. (9) |
| $C_p$ | pressure coefficient defined in Eq. (8) |
| $f_H$ | friction factor defined in Eq. (7) |
| $h$ | local heat transfer coefficient (W/($m^2$K)) |
| $H$ | X-type lattice core height (m) |
| $k_f$ | thermal conductivity of fluid (W/(mK)) |
| $k_s$ | thermal conductivity of solid (W/(mK)) |
| $l$ | length of a core unit cell (m) |
| $l_1$ | geometric parameter defined in Eq. (A.6) (m) |
| $L$ | length of the sandwich panel (m) |
| $n$ | empirical constant in Eq. (9) |
| $Nu$ | local Nusselt number |
| $Nu_H$ | area-averaged Nusselt number |
| $p$ | static pressure in Eq. (8) (Pa) |
| $q''$ | heat flux (W/$m^2$) |
| $r_1$–$r_3$ | fillet radii shown in Fig. 4 (m) |
| $Re_H$ | Reynolds number defined in Eq. (2) |
| $t$ | thickness of a substrate (m) |
| $t_l$ | thickness of a core ligament (m) |
| $T_f$ | bulk mean fluid temperature in Eq. (5) (K) |
| $T_{in}$ | inlet fluid temperature (K) |
| $T_w$ | wall temperature (K) |
| $U_c$ | inlet centerline velocity (m/s) |
| $U_m$ | mean inlet velocity (m/s) |
| $V_m$ | velocity magnitude (m/s) |
| $w$ | width of a core unit cell (m) |
| $w_l$ | width of a core ligament (m) |
| $W$ | width of a sandwich panel (m) |
| $x, y, z$ | Cartesian coordinates (m) |
| $y^+$ | dimensionless wall distance |

*Greek symbols*

| | |
|---|---|
| $\alpha, \beta$ | included angles shown in Fig. 4 (°) |
| $\Delta p$ | pressure drop (Pa) |
| $\varepsilon$ | porosity |
| $\mu$ | dynamic viscosity of fluid (Pa s) |
| $\rho$ | density of fluid (kg/$m^3$) |
| $\rho_{SA}$ | surface area density ($m^2/m^3$) |

*Abbreviations*

| | |
|---|---|
| OA | orientation A |
| OB | orientation B |
| PCM | periodic cellular material |

This study aims to investigate single phase forced convective heat transfer in an X-type lattice, and compare its performance with other types of PCMs. A series of experiments and numerical simulations are conducted to gain physical insight into its overall and detailed thermo-fluidic characteristics. Particular focus is placed upon revealing the distinctive forced convective flow features associated with the unique morphology of the X-type lattice and their effects on local and overall heat transfer.

## 2. Experimental details

### 2.1. Test apparatus

With reference to Fig. 3, the test rig consists of an air supply system, a test section and a data acquisition system. Air at ambient conditions is drawn into a rectangular channel by a centrifugal fan. The test channel, having width $W$ and height $H$, is made from low-conducting acrylic plates. Before the test sample, a honeycomb is inserted in a long parallel passage having length 48$H$ (not shown in Fig. 3). The sample, a sandwich panel with X-type lattice core, is inserted in the test section with the inner surfaces of the substrates flush with the channel inner surfaces.

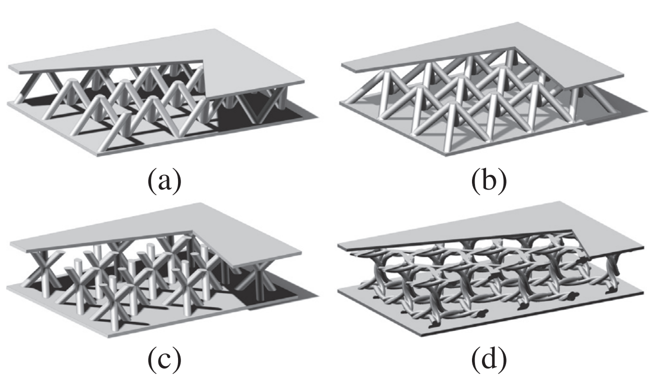


**Fig. 1.** Sandwich panels with (a) tetrahedral core (also called "lattice-frame material" (LFM)), (b) pyramidal core, (c) Kagome core and (d) wire-woven bulk Kagome (WBK) core.

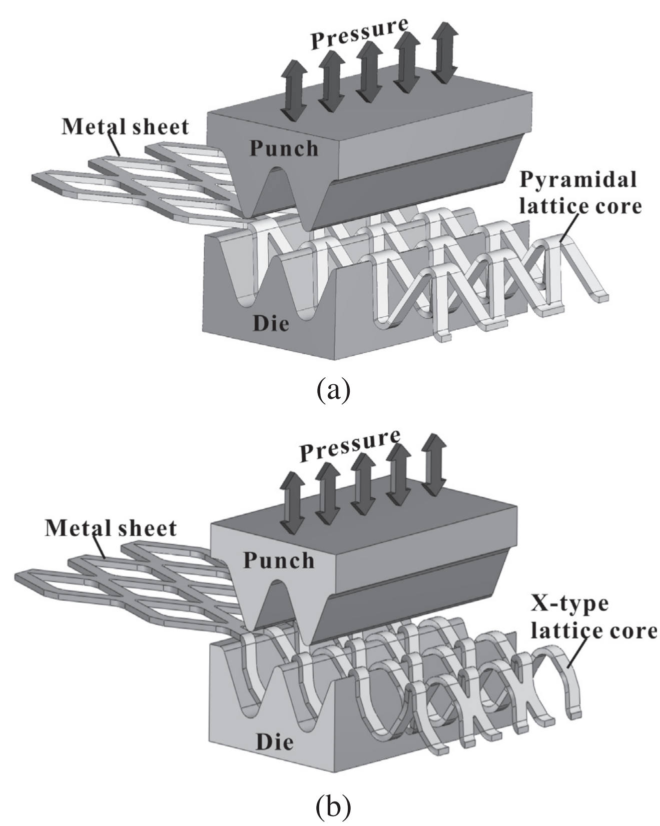


**Fig. 2.** Fabrication of (a) pyramidal and (b) X-type lattice by metal sheet folding.