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Combining a distributed flow manifold and 3D woven metallic lattices to enhance fluidic and thermal properties for heat transfer applications

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ABSTRACT

The fluidic and heat transfer capabilities of 3D woven lattice materials were reported recently under axial and bifurcated flow patterns, but three critical performance indices – pressure drop, average surface temperature and temperature uniformity – could not be optimized simultaneously using these flow patterns. Here we combine the 3D weaves with manifolds to create a novel 3D flow pattern that enhances temperature uniformity, while also maintaining low pressure drops and surface temperatures. These three properties were characterized at room temperature for a range of flow rates using water as the working fluid. Three different weaves thicknesses were investigated: 12.7 mm, 6.4 mm, and 3.2 mm, with manifold thicknesses of 12.7 mm, 19.0 mm, and 22.2 mm, respectively, to provide a constant, combined weave-manifold thickness of 25.4 mm. The properties of this new weave/manifold system are compared to those obtained using just the manifold (with no weave) and just the weave (with no manifold). Comparisons show that the addition of the weave lowers the average substrate temperature and temperature variations significantly, although pressure drop is increased. They also show that the addition of the manifold improves temperature uniformity significantly, and also lowers the average substrate temperature and the pressure drop. No specific ratio of weave to manifold thickness was found to be superior in all of the performance indices. The thermal performances are then evaluated at different pumping powers: the weave/manifold system and its distributed array flow pattern prevail. Finite element simulations were performed on a reduced and simplified model to explain the observed experimental trends, and manifold opening patterns were manipulated to demonstrate further potential property enhancements. The multiple benefits of this manifold system can be extended to common heat exchanger media beyond weaves.

1. Introduction

Recently we reported excellent fluidic and thermal properties for multifunctional 3D woven lattice materials. Due to the pore structure of these lattices, different global fluid flow patterns could be utilized to tailor various response properties, including total heat transfer, substrate temperature uniformity, and pressure drop. Specifically, we considered three flow patterns as shown in Fig. 1: axial, where fluid flows parallel to the substrate; full bifurcated, where the inlet flow is perpendicular to the substrate and turns 90 degrees to the outlet ports; and focused bifurcated, which is similar to the full bifurcated case but the inlet is concentrated over a small region [1]. Among the three applied flow patterns, we found that under the same power inputs (10.3, 20.7, and 31.0 W/cm^2) and volumetric flow rates ($1–17 \times 10^{-5}$ m^3/s), the axial flow transfers heat more effectively than the other two, while the bifurcated flow patterns provided better temperature uniformity and lower pressure drops. Thus, neither flow pattern is ideal in terms of these three properties. However, the bifurcated flow patterns have two advantages: increasing the flow rate lowers the average surface temperatures without generating the large temperature variations attendant with flow rate increases in the

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Nomenclature

ΔP	pressure drop [Pa]	ΔT	temperature variation across the surface [K]
T_s	average surface temperature [K]	X, Y, Z	Cartesian coordinates [m]

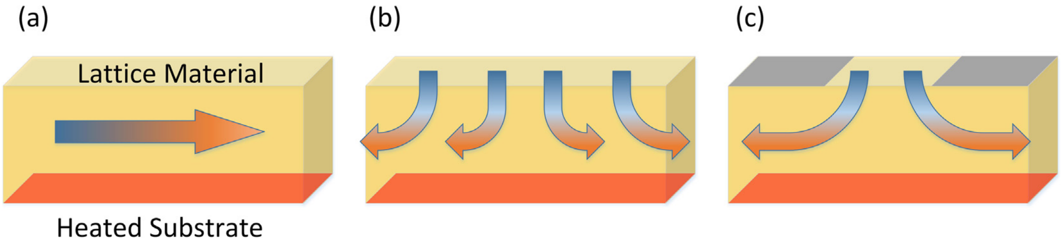

Fig. 1. Schematic of three flow patterns, (a) axial, (b) full bifurcated and (c) focused bifurcated, through the 3D woven lattice material in a previous study [1].

axial pattern, and the pressure drops in the bifurcated cases are smaller than that in the axial cases.

To improve properties beyond those reported for these ordinary flow patterns, we focus here on modifying the bifurcated flow pattern with a manifold to overcome its two main disadvantages. One is that a large portion of the fluid enters and exits the 3D weave near its edges in bifurcated flow and does not interact sufficiently with the weave to facilitate forced convection between the heated solid and the cooling fluid. A manifold combined with a thinner weave forces more of the fluid flow towards the heated substrate, thereby enhancing heat transfer. Another is that the maximum and minimum temperatures of the heated substrate occur at the center and the edges of the bifurcated flow pattern, respectively, meaning that temperature variations scale with the lateral dimensions of the flow pattern. The use of periodic manifolds can reduce the scale of the bifurcated flow and thereby minimize temperature variations, while also accommodating large substrates. Thus, we argue that the combination of a thin metallic weave and a manifold provides the ability to tune local temperature variations for any size substrate while also providing superior fluidic and thermal properties.

Earlier studies have shown that continuous jet impingement of a liquid or gas onto a surface is more effective at removing heat from that surface than forced convection [2–4]. High-speed jet impingement on a component surface creates a thin boundary layer and enables superior heat transfer. Macro and micro-scale jets [2] have been studied with multiple fluids and flow schemes and they have been used to quench metals and to cool turbine blades. Many practical applications employ an array of jets that typically maintains a more consistent surface temperature and can cool very large areas compared to a single jet. Recently, Motakef et al. described the achievement of heat transfer coefficients of 500,000 and 20,000 W/m^2 K with sub-millimeter, microjet arrays using water and air, respectively [3].

While jet impingement devices have shown tremendous success [4], most of these studies have been performed with the jets spraying fluid onto a substrate through an empty spacing so as to quantify parameters such as heat transfer coefficients or Nusselt numbers while changing variables such as Reynolds number, jet diameter, radial position, wall-to-nozzle spacing, etc. [5,6]. By inserting a heat exchange medium, such as a metallic weave, between the jets and the heated substrate, heat transfer can be enhanced further. The solid ligaments of the weave provide high heat conduction and more surface area for improved heat convection, and the local, regular pores enhances fluid mixing. Here we present fluidic and thermal studies of a combined heat exchange system that includes a plastic flow manifold and a 3D Cu weave. The manifold is designed so that the return or exhaust fluid flow does not interfere with the impinging jets, and its thickness is increased from 12.7 mm to 19.0 mm and then to 22.2 mm while the thickness of the weaves is decreased from 12.7 mm to 6.4 mm and then to 3.2 mm to maintain a constant total system thickness of 25.4 mm. We then perform finite element simulations on a reduced and simplified model to study the trends observed in the experiments. For comparison, we also report on the use of only the flow manifold for cooling. Pressure drops, average surface temperatures, and temperature variations are reported and are compared to earlier data for axial and full bifurcated flow patterns within the same Cu weaves. Finally, methods for optimization of the manifold are suggested to improve the system's performance and one example of adjusting the manifold opening pattern is reviewed.

2. Experimental procedures and simulation setup

A schematic of the fluid flow patterns and photographs of the 3D printed plastic flow manifolds are shown in Fig. 2. The coolant first flows through an array of inlet channels that are shown in Fig. 2c and span the manifold's full thickness. Then the coolant flows through the weave and impinges on the heated substrate as an array of high velocity jets (blue[1] arrows in Fig. 2a). Next the coolant returns through the weave and enters a second set of channels shown in Fig. 2d. These exhaust channels are located between the inlet channels on the bottom surface of the manifold (Fig. 2d) and span only its bottom lip. Thus, the heated, exhaust coolant flows within the hollow structure towards the periphery of the flow manifold where it is collected and eventually leaves via the smaller faces on the right and left of the manifold (orange arrows in Fig. 2a). Alternatively, one could adjust the outlet piping allowing the heated coolant to exit the manifold through the larger faces on the front and back, or through both sets of faces. The localized exhausting of each jet to the center of the manifold minimizes cross-flow between neighboring jets within the weave and near the heated surface. This increases cooling efficiency and also allows the performance of a single jet to be replicated over a large area.

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[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.