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Thermal performance analysis of porous-microchannel heat sinks with different configuration designs

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ABSTRACT

Three-dimensional models of porous-microchannel heat sinks (porous-MCHSs) with different configuration designs, such as rectangular, outlet enlargement, trapezoidal, thin rectangular, block, and sandwich distributions, are verified in this work. Hydraulic and thermal performances of the porous-MCHSs with various configuration designs are investigated from the pumping power, heat transfer coefficient, and temperature control effectiveness, results with Reynolds number ranging from 45 to 1350. The results reveal that the thermal performances can be improved using the porous configuration designs and can increase with a large Reynolds number. Both the sandwich and the trapezoidal distribution designs have the best heat transfer efficiency, cooling performance, and convective performance. In particular, the thermal performance of the rectangular, outlet enlargement, thin rectangular, or block distribution designs are not necessarily better than the nonporous medium for lower pumping power. In addition, adding a porous medium to the channel leads to a significant increase in the pressure drop. Among the six porous configuration designs, the lowest pressure drop was observed for a sandwich distribution design. Hence, the sandwich distribution design is the best porous-MCHS design when considering the thermal performance along with the pressure drop.

1. Introduction

A three-dimensional (3D) fluid flow and heat transfer models are proposed to investigate the effects of the configuration designs on the thermal performance of porous-microchannel heat sinks (porous-MCHSs), as shown in Fig. 1. The porous-MCHSs insert a porous metallic medium into a microchannel to raise both the surface contact area-to-volume ratio and local velocity mixing of the coolant, thereby resulting in better convective heat transfer [1,2]. The heat transfer performance of porous-MCHSs can be improved if the configurations and porosity conditions are properly designed [3–9], thus making porous-MCHSs suitable for micro-scale electronics cooling [1,2,10].

Much research has been performed to determine how the configuration design of porous channels can improve the cooling performance. The configuration designs include the rectangular duct, partially porous or rectangular channel with bypass spaces, porous plate channel, porous block, and porous-baffled channel [2,5,6,11–13]. However, comparisons between the thermal performances of different configuration designs are limited. Singh et al. examined sintered porous heat sinks for cooling high-powered compact microprocessors [1]. They determined that the thermal resistance can be reduced by 44%. Forced convection inside porous rectangular ducts was studied by Calmidi and Mahajan [3] and Haji-Sheikh et al. [4]. Zehforoosh and Hossainpour numerically investigated the laminar forced convection in partially porous channels using four different porous blocks attached to strip heat sources at the bottom wall [5]. They found that the heat transfer enhancement was nearly identical to the porous duct, whereas the total pressure drop was considerably lower. Jeng et al. experimentally determined the fluid flow and heat transfer characteristics of a porous heat sink set inside a rectangular channel with bypass spaces [6]. Tamayol et al. investigated the pressure drop in microfluidic minichannels filled with porous media formed by square arrays of microcylinders [7]. They found that the main parameters for affecting the pressure drop are the porous medium permeability and channel dimensions. Alfieri et al. performed a fundamental hydrothermal investigation on the next generation of interlayer integrated water cooled 3D chip stacks with high volumetric heat generation [8]. They observed that the local chip temperature predictions can be affected by up to 40%. The Reynolds number (Re) was found to have a strong influence on

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Nomenclature

A	base area of the heat sink (m^2)
C	Forchheimer's constant
c_f	heat capacity of the coolant (J kg^{-1} K^{-1})
c_s	heat capacity of the solid (J kg^{-1} K^{-1})
D_h	hydraulic diameter of channel (m)
f	friction factor
FOM	figure of merit
h_m	average heat transfer coefficient (W m^{-2} K^{-1})
H_c	height of channel at inlet (m)
k_e	effective thermal conductivity of the porous medium (W m^{-1} K^{-1})
k_f	thermal conductivity of the coolant (W m^{-1} K^{-1})
k_s	thermal conductivity of the substrate material (W m^{-1} - K^{-1})
K_p	permeability of porous metallic medium (m^2)
L_x	channel length (m)
L_y	height of heat sink (m)
L_z	width of heat sink (m)
Nu_m	average Nusselt number
N	number of channels
q_w	heat flux applied to bottom surface of heat sink (W m^{-2})
Q	volume flow rate of the channel cross-section (cm^3/min)
Re	Reynolds number
R_T	overall thermal resistance (K W^{-1})
T_{in}	inlet temperature of coolant (K)
T_w	local temperature along the center line of the heated wall (K)
$\overline{T}_w$	average temperature along the bottom wall (K)
$T_{w,\max}$	maximum bottom wall temperature in the heat sink (K)
u_{in}	inlet velocity of coolant (m s^{-1})
$\vec{V}$	velocity vector (m s^{-1})
W_c	width of channel at the inlet (m)
W_r	rib width (m)
Greek	
α	channel aspect ratio
β	channel width ratio
ε	porosity
Δp	pressure drop between the channel inlet and outlet (Pa)
μ_f	dynamic viscosity (kg m^{-1} s^{-1})
ρ_s	solid density (kg m^{-3})
ρ_f	coolant density (kg m^{-3})
Ω	pumping power of a channel (W)
ε_h	average heat transfer coefficient ratio
ε_{Tw}	temperature control effectiveness
Subscripts	
f	fluid phase
m	mean value
p	porous medium
s	solid phase
bf	based fluid

the development length and the micropin structure was found to have good cooling capability. Wan et al. [10] proposed a novel thermal management method for high-power light-emitting diodes (LEDs) using a porous micro heat-sink system. The predicted results showed that the thermal performance of the LED chips can be effectively improved. They also found that increasing the liquid velocity enhances the average heat transfer coefficient and overall pressure loss of the heat sink increases with increasing inlet velocity. Turbulent forced convection heat transfer inside a rectangular channel with porous baffles periodically arranged on the top and bottom of the channel walls was investigated by Yang and Hwang [11]. They found that the ducts with porous-type baffles experienced a lower friction factor and enhanced the heat transfer relative to the smooth channel. The forced convection heat transfer inside the channels filled with sintered bronze media was experimentally and numerically examined by Jiang et al. [12,13]. Their results showed that the heat transfer inside the sintered porous-channel was better than the non-porous channel. Ould-Amer et al. [14] found that the insertion of porous materials between the heat-generating blocks increased the average Nusselt number up to 50% and reduced the maximum temperatures within the heated block. Hetsroni et al. experimentally determined the heat transfer and pressure drop inside a rectangular channel with sintered porous stainless steel inserts of different porosities to cool mini-devices [15]. They found that the porosity could negatively influence the heat transfer. Tzeng and Jeng reported that the cooling performance of heat sink with uncompressed porous media was better than the compressed media [16]. The effects of bead particle size on the efficiency of heat exchange between the fluid and the solid phases of the heat sink were experimentally determined by Tzeng et al. [17]. They found that for smaller particle sizes, the overall wall temperature distribution was prominent. The forced convection inside a rectangular microchannel filled with or without a porous medium was analytically examined by Hooman [18]. The expressions for the friction factor and Nusselt number were proposed in terms of key parameters. Yucel and Guven numerically analyzed the laminar forced convection inside a channel with a porous medium on the bottom wall [19]. They found that a channel with a high thermal conductivity porous cover can significantly enhance the heat transfer from the solid blocks. Venugopal et al. experimentally determined the potential of a simple, inexpensive porous insert developed specifically for augmenting the heat transfer from the heated walls of a vertical duct under forced-flow conditions [20]. They found that the average Nusselt number increased 4.52 times compared with a clear flow when a porous material with porosity 0.85 is employed. Convective heat transfer inside a channel partially filled with a porous medium was examined by Aguilar-Madera et al. [21]. Their results showed that the thermal performance can be improved by either increasing the size of the porous insert or by ensuring that mixing inside the

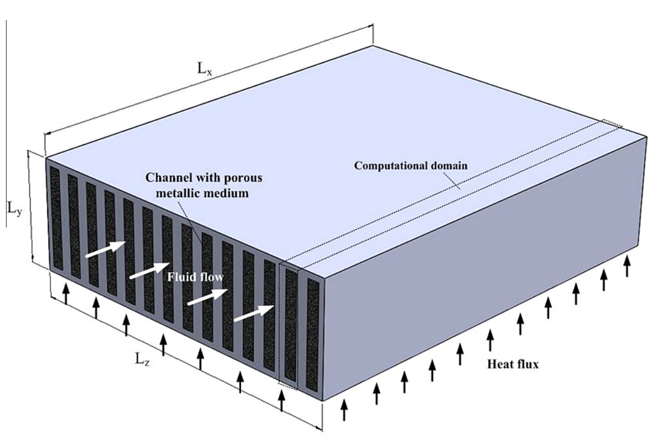

Fig. 1. Schematic diagram of a porous-MCHS.