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Numerical investigation of laminar flow and heat transfer in a liquid metal cooled mini-channel heat sink

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ABSTRACT

With the recent trend of miniaturization and high-power output, effective heat dissipation has become the top priority in several industrial applications. This work contributes to the novel and efficient cooling technique that utilizes the liquid metal as working fluid. A numerical analysis of laminar flow and forced convective heat transfer of Galinstan through a mini-channel heat sink exposed to a constant heat flux has been presented. A detailed parametric analysis of the influence of heat sink's geometry, and the inlet velocity on the pressure drop, pumping power and the maximum heat flux has been carried out. Optimized heat sink's dimensions and inlet velocity are obtained. Furthermore, the numerical results are compared with the analytical correlations and discussion concerning the agreement and discrepancy is made. In addition, the flow and heat transfer performance of mini-channel heat sink cooling using liquid metal, nanofluid and water are compared, which intuitively shows the advantage of using liquid metal as coolant.

1. Introduction

Recent advancements in technology have led to the trend of miniaturization and high power output, and high-density heat flux dissipation has become the main requirement in various industrial applications. Examples include electronic chip cooling, power electronics, opto-electronic devices, laser diodes, cooling of high-power light-emitting diodes (LEDs), phased array radars, vehicle batteries, concentrating photovoltaic cells, high-power microwave devices and Insulated Gate Bipolar Transistor (IGBT) modules [1–4]. Various passive and active cooling technologies have been reported in the literatures [5,6]. Among these methods, the micro/mini-channel cooling has gained a particular attention for its promising capability to remove very high density fluxes (up to 10^2–10^3 W cm^{-2}) [7–12]. Furthermore, the micro/mini-channel cooling technique possesses some advantages, such as high convective coefficient, less coolant volume and comparatively smaller cooling system size among others. In spite of numerous attempts to improve heat transfer, the maximum heat flux that can be removed is limited by the inherent thermophysical properties of coolants [12]. In recent years, liquid metals with low melting point (such as Gallium alloys) have become popular coolants due to their superior thermal conductivity, low viscosity, low toxicity, non-flammablility, high boiling point and low thermal resistance [13,14].

Many studies have been conducted to explore the applications of employing liquid metals as coolants for removing high-density heat flux [15–20]. Deng et al. [21] carried out experiments to compare the heat and flow performance of Gallium alloy and water in mini- and micro-channels. Their results show that, when working fluids are operated at high velocity, the liquid metal based micro-channel produces higher heat transfer coefficient than that of water. Tawk et al. [22] numerically and experimentally investigated the liquid metal cooled mini-channel heat sink of power electronic devices. They showed that the maximum discrepancy of temperature between numerical and experimental results was less than 7%. Luo and Liu [23] experimentally investigated the thermal performance of liquid metal based mini-channel heat sinks with different channel widths. Their results show that the heat transfer coefficient increases with the raise in the coolant's mass flow rate and the heat sink with smaller width shows better thermal performance. Zhang et al. [24] experimentally found that thermal resistance 0.077 K W^{-1} with the maximum heat flux of 1504 W cm^{-2} can be achieved using Galinstan-based mini-channel. Yang et al. [25] presented results for both water and liquid metal cooling in the micro/mini-channel heat sinks and observed that the liquid metal displays a much better thermal and flow performance in mini-channel scale. Their numerical results were also compared with different correlations, and it is noted that there is significant

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Nomenclature

P	pressure (Pa).
H	channel height (m).
f_{app}	apparent friction coefficient.
f	friction coefficient.
L	heat sink length (m).
D_h	hydraulic diameter (m).
h	heat transfer coefficient (W m^{-2} K^{-1}).
W_{pp}	pumping power (W).
U_i	velocity at inlet (m s^{-1}).
A	area (m^2).
ΔP	pressure drop (Pa).
k	thermal conductivity (W m^{-1} K^{-1}).
$\dot{m}$	mass flow rate (kg s^{-1}).
R_{tot}	total thermal resistance (K W^{-1}).
Re	Reynolds number.
Pr	Prandtl number.
T	temperature (K).
W	heat sink width (m).
c_p	specific heat capacity (J kg^{-1} K^{-1}).
W_c	channel width (m).
n	number of channel.
φ	volume fraction of nanoparticle.
A_{sf}	surface area (m^2).
Q_{conv}	convection heat transfer
u	velocity component in x-direction.
v	velocity component in y-direction.
w	velocity component in z-direction.
q_{max}	maximum heat flux (W cm^{-2}).
x_{hyd}	dimensionless axial distance for hydrodynamic entrance region.
Nu	Nusselt number.
x_t	dimensionless axial distance for thermal entrance region.
W_w	channel wall thickness (m).
q_b	bottom heat flux (W cm^{-2}).
t_b	base thickness (m).

Greek Letters

μ	dynamic viscosity (kg m^{-1} s^{-1}).
ρ	density (kg m^{-3}).
η_f	fin efficiency.
α	channel aspect ratio.

Subscripts

b	bottom
cap	capacity
con	conduction
conv	convection
eff	effective
fr	freezing point
fd	fully developed
f	base fluid
in	inlet
nf	nanofluid
p	nanoparticle
s	heat sink solid part

deviation between the thermal resistances computed using 1-D model and the direct numerical technique for liquid metal. Zhang et al. [26] experimentally studied the Galinstan based mini-channel by varying pumping power and heating loads. They demonstrated that the system can dissipate heat power 1500 W with heat flux 300 W cm^{-2}. Moreover, it has also been proved that the loss in pressure for the mini-channel cooling with Galinstan is much lower than micro channel with water.

Although the flow of Ga alloys passing through the mini-channels has been investigated by different approaches, the influence of heat sink's geometry and the inlet velocity has not been fully investigated. In addition, study of the maximum heat flux capacity of Ga alloys in mini-channel has less been discussed. Typically, the maximum temperature of the silicon chip should be kept well below 398 K for its efficient working and reliability. Furthermore, normally the operating temperature for the electronic devices is under 343 K, since the system's reliability declines sharply along with the increase in temperature [26–28]. Considering this temperature constraint and to keep the temperature within an appropriate range, we also aim to quantitatively investigate the maximum heat flux dissipation capacity of Galinstan based mini-channel by setting the temperature's upper limit for the electronic devices as 343 K. In addition, the superior performance of liquid metal in mini-channel heat sink is intuitively demonstrated by comparing with water and nanofluid.

2. Problem statement and mathematical formulation

We consider a 3-D mini-channel with height H, width W_c, base thickness t_b and wall thickness W_w. The overall dimensions for the heat sink ($L = 2$ cm, $W = 2$ cm) are selected after considering the typical chip sizes as shown in Fig. 1.

A laminar, forced convective flow of Galinstan (21.5 wt% *In*, 10.0 wt% *Sn* and 68.5 wt% *Ga*) towards positive z-direction with a uniform inlet velocity U_i and at inlet temperature T_{in} (300 K) is considered. This kind of material is one of the most popular liquid metals used for advanced cooling application. The liquid metal exchanges heat from the bottom surface of the heat sink that is exposed to a uniform heat flux q_b (100 W cm^{-2}). Copper is considered as the heat sink material. However, attention should be paid to the corrosion/chemical incompatibility issues with the direct contact of Ga-based metals with the metallic heat sink materials [13,29,30]. One solution is to coat the copper with compatible materials like nickel, tungsten, or molybdenum [22]. Another solution is to use nonmetallic heat sink material, such as silicon. Note that the change of heat sink material also influences the overall heat and flow performance [31], which deserves to be investigated in the coming future. In all cases considered in this study, the flow's Reynolds number is less than 2300, therefore the flow is considered to be laminar. It is also assumed that the flow is in steady state and the thermal body force is neglected. All the mini-channels in the heat sink are identical, so only one channel is considered in the simulations; as shown in Fig. 1(b).

The governing equations for the fluid region can be written as follows.

Momentum equation

$$\rho\left(\vec{\mathbf{V}} \bullet \nabla \vec{\mathbf{V}}\right) = -\nabla p + \nabla \bullet \left(\mu \nabla \vec{\mathbf{V}}\right) \tag{1}$$

Continuity equation

$$\nabla \vec{\mathbf{V}} = 0 \tag{2}$$

Energy equation

$$\rho c_p\left(\vec{\mathbf{V}} \bullet \nabla T\right) = k\nabla^2 T \tag{3}$$

where $\vec{\mathbf{V}}$ is the fluid velocity, T is the temperature and p is the pressure. The symbols k, c_p, μ and ρ stand for the thermal conductivity, specific heat, dynamic viscosity and density of the coolant, respectively.

The governing equations for the solid region can be described as follows.