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Research Paper

A comparison between cooling performances of water-based and gallium-based micro-channel heat sinks with the same dimensions

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HIGHLIGHTS

- Thermal resistances of micro-channel heat sinks using H_2O and Ga are compared.
- Critical dimensions for equal thermal resistances between H_2O and Ga are obtained.
- 3-D and 2-D feasible regions for Ga-based micro-channel heat sinks are plotted.
- Tendencies of movement and area change of the 2-D feasible regions are obtained.

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ABSTRACT

Liquid metals are very attractive coolants for micro-channel heat sinks with a high heat flux. However, whether liquid metals can achieve a better cooling performance than water in micro-channel heat sinks of the same dimensions has not been fully investigated so far. In the present work, we compared the cooling performances between liquid gallium and water in terms of total thermal resistances of the micro-channel heat sinks. Single-variable study was first carried out and the critical values of geometrical parameters were obtained, under which the micro-channel heat sinks have the same total thermal resistance adopting water or liquid gallium as coolant. Then, multi-variable study was conducted, based on which the 3-D feasible regions (in which liquid gallium has a better cooling performance than water) were plotted in the channel width-fin width-channel height diagram. Finally, for clarity the 3-D feasible regions were transformed into 2-D ones in the channel width-fin width diagram. The overall movement and area change of the 2-D feasible region were investigated by varying one of the geometrical or operational parameters. The results obtained in this work can provide guidance for the design of micro-channel heat sinks employing liquid metals as coolant.

1. Introduction

With the rapid development of micro-electro-mechanical systems (MEMS) technique, the physical dimension of electronic chips decreases continuously and this leads to a sharp increase in its power density [1]. It is of great significance to crack the "heat barrier" problem that impedes the further development of MEMS. Therefore, highly effective compact cooling technologies are imperative for even smaller electronic devices. To date, various kinds of cooling methods, such as air cooling [2], water cooling [3], heat pipe [4–6], and thermoelectric cooling [7], have been applied for different situations.

Water-based micro-channel heat sinks have gained extensive attentions since they were firstly proposed by Tuckerman and Pease in 1981 [8]. This cooling technique has many advantages including a high heat transfer coefficient, direct integration on the substrate and negligible contact resistance. Thus, a lot of work has been carried out on the flow and heat transfer characteristics for both single-phase and two-phase flow in micro-channel heat sinks [9,10]. Many studies [11–16] had confirmed that the single-phase fluid flow and heat transfer behaviors in micro-channels were similar to those under normal scale and conventional theory [17,18] can successfully predict the flow behavior in micro-channels. However, it is also pointed out that classical correlations were inapplicable to predict pressure drop and heat transfer characteristics of two-phase flow in micro-channels [19–21]. There are other works that focused on the optimal design of micro-channel heat sinks. The thermal boundary layer redeveloping concept was used to guide the new heat sink design [22]. Approximate approaches were developed by Liu and Garimella [23] to minimize the thermal resistance of micro-channel heat sinks.

In 2002, Liu and Zhou [24] proposed that liquid metals and their

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Nomenclature

c_p	specific heat, kJ/kg·K
D_h	hydraulic diameter, mm
f	Darcy friction factor
h	convective heat transfer coefficient, W/m^2·K
h_c	microchannel height, μm
k	thermal conductivity, W/m·K
L	heat sink length, mm
m	intermediate variable ($m = \sqrt{2h/k_s W_w}$)
n	microchannel number
Nu	Nusselt number $Nu = hD_h/k$
Δp	pressure drop, kPa
q	heat flux, W/m^2
Re	Reynolds number ($Re = \rho V D_h/\mu$)
R	thermal resistance, °C/W
t	thickness of the substrate, mm
u_m	mean velocity, m/s
W	heat sink width, mm
w_c	microchannel width, μm
w_w	fin width, μm
x^*	dimensionless thermal entrance length
x^+	dimensionless hydrodynamic Entrance length

Greek symbols

α	aspect ratio ($\alpha = H/W$)
ρ	density, kg/m^3
μ	dynamic viscosity, N·s/m^2
η	fin efficiency
∞	fully developed

Subscripts

cond	conduction
conv	convective
cal	caloric
cr	critical
o	overall
s	solid
t	total

alloys with low melting points can be used as coolant for the cooling of computer chips. An overall review on chip cooling using liquid metals or their alloys was presented by Ma et al. [25]. Miner and Goshal [26] carried out analytical and experimental work on liquid metal flow in a pipe. Their results indicated that the heat transfer coefficient is enhanced in both laminar and turbulent regimes compared to water. Goshal et al. [27] used a GaIn alloy-based heat sink in a cooling loop and achieved a thermal resistance of 0.22 K/W for the entire system. Hodes et al. [28] used a first-order model to predict the optimum geometry for water-based and Galinstan-based heat sinks in terms of minimum thermal resistance. It was shown that for fixed heat sink width, micro-channel height and pressure drop, when the heat sink length was 10 mm, the optimum values of micro-channel width and fin width were 49 μm and 14 μm for water, while the corresponding optimum values were 336 μm and 21 μm for Galinstan, respectively. It was also indicated that in their optimized configurations, Galinstan can reduce the overall thermal resistance by ~40% compared to water. Zhang et al. [29] carried out a follow-up work and they reported the experimental data of Galinstan-based mini-channel heat sink. A thermal resistance as low as 0.077 K/W was achieved and a maximum heat flux of 1504 W/cm^2 was reached in their experiment. These studies show that liquid metals could enhance the convective heat transfer due to their superior thermophysical properties.

It is known from Ref. [28] that the optimal channel widths of Galinstan-based heat sinks are hundreds of micrometers, which are much larger than the counterparts of water-based heat sinks (tens of micrometers). Thus, a question rises naturally: whether liquid metals can achieve a better cooling performance than water in heat sinks consisting of micro-channels of the same dimension? Unfortunately, this has not been fully investigated so far. Therefore, in the present work we employed a thermal resistance model, in which both hydrodynamic and thermal entry effects are taken into account, to calculate the total thermal resistance of water-based and gallium-based micro-channel heat sinks of the same dimensions. Both single-variable and multi-variable studies were carried out. Critical values of geometrical parameters were obtained, under which the micro-channel heat sinks adopting water or liquid gallium as coolant have the same total thermal resistance. In addition, feasible regions in which liquid gallium has a better cooling performance than water were plotted.

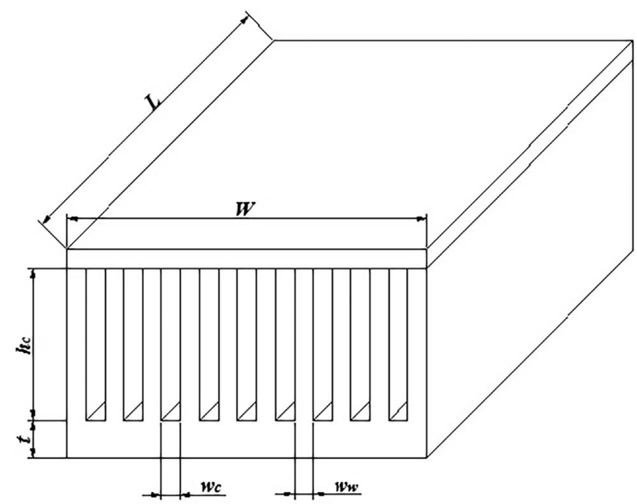

Fig. 1. Schematic of the rectangular micro-channel heat sink under consideration.

2. Mathematical model

2.1. Thermal resistance model with consideration of entry effects

The rectangular micro-channel heat sink under consideration is schematically depicted in Fig. 1, where L, W, h_c, w_c, w_w and t represent the length and width of the heat sink, height and width of the micro-channel, fin width, and substrate thickness, respectively. Silicon is chosen as the solid material. The lid (i.e., top plate) is assumed to be insulated. The bottom surface of heat sink is exposed to a constant heat flux q. Numerous micro-channels (the number of channels $n = W/(w_c + w_w)$) are accommodated in parallel. Comparing to the overall heat sink dimension, the widths of an individual micro-channel and intervening fins are typically small. The liquid flow in the micro-channels is assumed to be laminar.

The overall thermal resistance of the heat sink, R_o, consists of three components [23]:

$$R_o = R_{cond} + R_{conv} + R_{cal} \tag{1}$$

(1) R_{cond} is the thermal resistance due to the substrate conduction: