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THERMOHYDRAULIC PERFORMANCE OF LIQUID METALS BASED MICROCHANNEL HEAT SINK USING NUMERICAL APPROACH

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Abstract—The continuous miniaturization of microchips in semiconductor industries has been posing a challenge on microscale thermal management systems for removal of high heat flux. Traditional air-cooling methods cannot meet the demands for heat dissipation for integrated circuits. In this regard, microchannel heat sinks constitute an innovative cooling technology as it manifest attributes, such as high surface–to–volume ratio, high heat dissipation capabilities, and lower coolant requirements. Due to such inherent advantages, microchannel heat sinks have received considerable attention, since the pioneering study of Tuckerman and Pease. Hence, in the present work, various liquid metals are employed as coolant in order to quantitatively evaluate the thermal and hydraulic performance of a microchannel heat sink. A three-dimensional model of microchannel heat sink is developed for numerically analyzing heat transfer and fluid–flow characteristics with determination of temperature field in both solid and liquid regions, along with pumping power for coolant flow. The present study employs liquid metal – Gallium and its alloys and compared with traditional coolant (water).

Keywords-microchannel heat sink; liquid metals; gallium; conjugate heat transfer

I. INTRODUCTION

The development of integrated electronic circuits and miniaturization implies an increase in heat generation, thereby raising the requirement for effective and compact heat removal. For instance, the new generation of computer chips can dissipate heat flux as high as 100 W/cm^2. Although an isolated ship dissipating 100 W could be cooled by forced air-convection, an array of such chips presents a serious cooling problem. Furthermore, investigations have revealed that over 50% of the failure in electric devices is caused by overheating [1]. Thus, a serious challenge of effective thermal management is persistent in micro-electronic devices.

To overcome such issues, Tuckerman and Pease first proposed the concept of microchannel heat sink [2]. Since then, microchannel heat sink has leaped as a promising cooling technology due to several favorable characteristics – high heat dissipation rate, compact arrangement and ease of integration onto microchips, and lower coolant inventory.

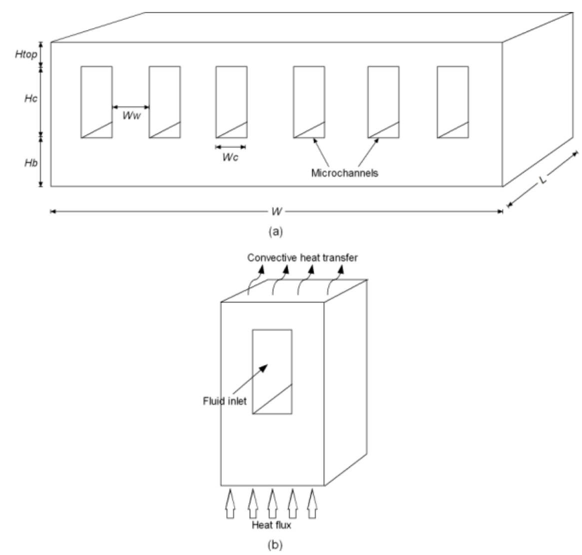

Figure 1 Schematic representation of (a) Microchannel heat sink, and (b) computational domain utilized for numerical analysis

The thermal and hydraulic performance of a single-phase heat transfer of a microchannel heat sink is determined by various parameters, such as geometric configuration, flow rate of working fluid, and thermophysical properties of both fluid and substrate. In the early stages, different cross-section for microchannel were analyzed to evaluate the heat transfer performance [3]–[7]. Perret *et al.*, [3] evaluated rectangular, diamond, and hexagonal microchannel and the results indicated that rectangular microchannel showed the least thermal resistance. In this regard, Ginnasegaran *et al*. [5] numerically examined rectangular, trapezoidal, and triangular microchannel and rectangular microchannel showed the highest cooling performance, followed by trapezoidal and triangular Therefore, rectangular microchannel are currently widely used due to its high transfer performance. microchannels. Consequently, optimization of a rectangular microchannel was conducted using numerical experiments by Ryu *et al*. [8], in order to minimize the thermal resistance, which is the performance parameter for a heat sink.

Furthermore, the recent advancement for high heat-flux application is to use liquid metal, such as Gallium and its alloys as coolant, which has proved to have significantly more heat carrying capacity compared to traditional coolant (water) [9], [10]. However, such liquid metals must be evaluated on thermal and hydraulic basis. Hence, in the present work, we develop a three-dimensional model of microchannel heat sink and employ liquid metals to assess the thermal and hydraulic characteristics.

II. Physical Model

The schematic diagram of a typical microchannel heat sink is illustrated in Figure 1. It consists of a substrate, top plate and side walls which are made from oxygen-free copper. The geometric parameters pertaining to the microchannel is mentioned in Table I. Furthermore, slots are present in the substrate which acts a microchannel for water and liquid metals to flow. The thermophysical properties of working fluids and microchannel are mentioned in Table II.

TABLE I. GEOMETRIC PARAMETERS OF MICROCHANNEL HEAT SINK (MM) [11]

W	***H***	***L***	W_c	H_c	W_w	H_{top}	H_b
10	7.62	44.8	0.5888	0.713	0.236	1.270	5.637

TABLE II. THERMOPHYSICAL PROPERTIES OF WATER, LIQUID METALS (GALLIUM AND ITS ALLOYS) AND SUBSTRATE (COPPER)

Material	**Density (kg/m^3)**	**Specific heat (J/kg-K)**	**Thermal conductivity (W/m-K)**	**Viscosity (Pa-s)**
Water	996.56	4180.6	0.60950	0.00085374
Ga [10]	6093	381.5	29.4	0.0018
GaIn [10]	6280	326	29.4	0.0018
Ga68.5In21.5Sn10 [9]	6440	295	16.5	0.0024
Ga68In20Sn12 [12]	6363.2	335	24.89	0.00222
Copper [11]	8933	385	401	-

III. Methodology

In the present section, the numerical set-up is presented. First the description related to grid generation is mentioned, followed by the assumptions for the relevant simplification of the problem, and the governing equations. Furthermore, the boundary conditions imposed on the grid are also described.

A. Grid Generation

For the present study, structured grid was adapted. As the modelling of microchannel heat sink is multi-body problem (see section II), the entire computational domain was sliced such that we obtain a system of blocks, such that the mesh performed on each bock is independent of other blocks. Such slicing enables us in customization of mesh on the edges of each block, thereby generating structured mesh. Several grids were created in order to perform the mesh-sensitivity analysis. Such analysis helps in identifying the optimum mesh such that the thermal and hydraulic parameters obtain can be under considerable limits (*W*: 50, *H*: 90, *L*: 220).

B. Governing Equations

Before proceeding with the governing equations, a few assumptions, as listed below, were employed for the conjugate heat transfer phenomenon. Such assumptions for a microchannel heat sink are based on its operating conditions.

- The flow is incompressible, steady, and in laminar conditions
- Due to forced-convection in a microchannel, the influence of gravity is neglected
- The modes of heat transfer are conduction and convection, the effect of radiation is neglected
- The effect of viscous dissipation is negligible
- Thermophysical properties for substrate are constant

Based on the assumptions above, the continuity, momentum, and energy equations for fluid in the microchannel are as follows

$$\nabla\vec{V} = 0, \tag{1}$$

$$\rho_f\left(\vec{V}\cdot\nabla\vec{V}\right) = -\nabla p + \nabla\cdot\left(\mu_f\nabla\vec{V}\right), \tag{2}$$

$$\rho_f c_{p,f}\left(\vec{V}\cdot\nabla T\right) = k_f\nabla^2 T. \tag{3}$$

The heat conduction equation for the solid region is as follows:

$$k_s\nabla^2 T_s = 0. \tag{4}$$

where, V is the velocity of working fluid (m/s), p refers to the pressure of fluid (Pa), T_s and T_s indicates the temperature of fluid and solid regions (K), respectively. The thermophysical properties – ρ_f, $c_{p,f}$, k_f, μ_f are the density (kg/m^3), specific heat (J/kg-K), thermal conductivity (W/m-K), and dynamic viscosity (Pa-s), respectively of working fluid.

C. Boundary Conditions

Considering the hydraulic boundary conditions, a uniform velocity is applied at the channel inlet and no-slip boundary condition is considered at the walls of heat sink.

For the thermal boundary conditions, a uniform heat flux of magnitude 100 W/cm^2 is imposed at the bottom surface of the substrate (eq. (4)), convection at the top surface of the substrate (eq. (5)) and adiabatic conditions at the rest of the walls,

$$-k_s\frac{\partial T}{\partial z} = q''_{bottom} \tag{4}$$

$$-k_s\frac{\partial T}{\partial z} = h_{conv}\left(T_{top} - T_\infty\right) \tag{5}$$

where h_{conv} is the convective heat transfer coefficient which is estimated at 10 W/°C-m^2 [13]. T_∞ is the ambient temperature of 25 °C. Adiabatic boundary conditions are applied to all other boundaries of the solid region.

IV. Results and Discussion

A. Validation

In order to check the accuracy of the present results in predicting thermal and hydraulic performances, we compared the obtained temperature difference and pressure drop values with that available in literature, as shown in Figure 2 and Figure 3. For the purpose of comparison, viscosity is considered to be temperature-dependent and implemented using eq. (5) [14]. Furthermore, all the walls are treated as thermally insulated. It is evident that the result of the present model is matching closely with the reference works.

$$\log\left\{\frac{\mu_f(T_f)}{\mu_f(20°C)}\right\} = \frac{20-T_f}{T_f+90}\left\{1.2378-1.303\times10^{-3}\left(20-T_f\right)+3.06\times10^{-6}\left(20-T_f\right)^2+2.55\times10^{-8}\left(20-T_f\right)^3\right\}$$
(5)

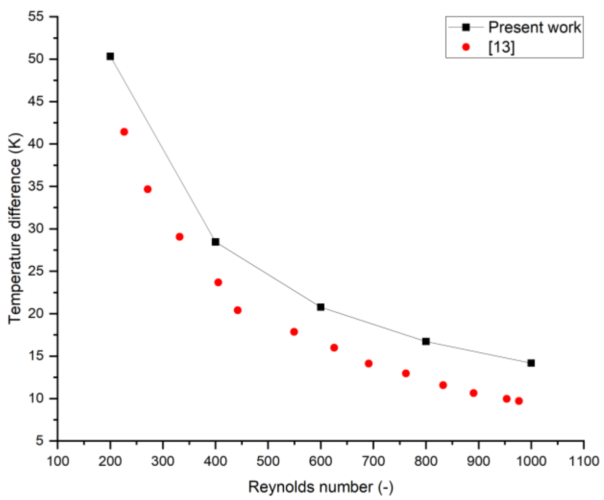

Figure 2. Comparison of temperature difference v/s Reynolds number for present model and reference experimental work

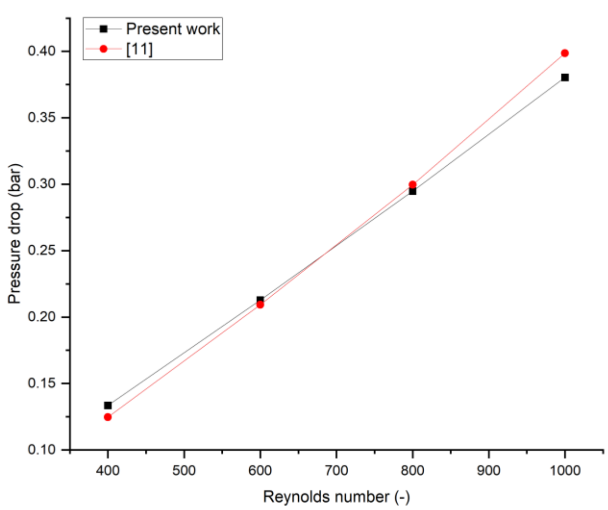

Figure 3. Comparison of pressure drop v/s Reynolds number for present model and reference numerical work

B. Heat Transfer Performance

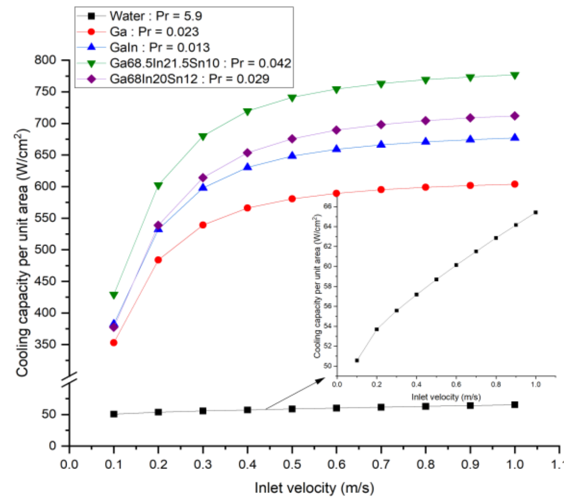

Figure 4. Cooling capacity per unit area v/s inlet velocity for water and Gallium based liquid metals

To evaluate the heat transfer performance, the cooling capacity per unit area for various inlet velocity is utilized as shown in Figure 4. It is evident that Gallium and its alloys shows superior cooling capacity compared to water. The relative enhancement in cooling capacity enhancement. between water and Ga is ~597% at an inlet velocity of 0.1 m/s. Thus, the incorporation of liquid metal significantly increases the heat carrying capacity compared to traditional fluid (water). Furthermore, it can be observed that for higher velocity (>0.5 m/s), the slope of the graph stabilizes and thus yields a nearly constant cooling capacity for each liquid metal. Thus, keeping such trend in mind, the circulation of liquid metal at low flow rates would be beneficial.

C. Hydraulic Performance

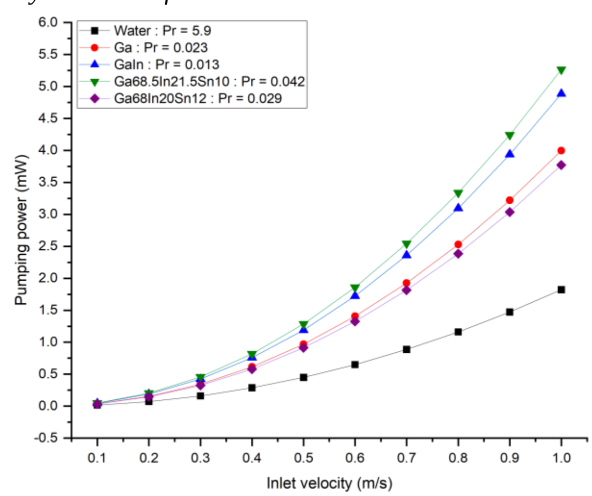

Figure 5. Pumping power v/s inlet velocity for water and Gallium based liquid metals

To evaluate the hydraulic performance for the circulation of working fluid, the pumping power for various inlet velocity is utilized, as shown in Figure 5. It is evident that when Gallium and its alloys have marginally increased the pumping power requirement. The relative increases in the pumping power between water and $Ga_{68}In_{20}Sn_{12}$ is ~107% at an inlet velocity of 1 m/s. Moreover, at low inlet velocity (<0.3 m/s), the pumping power for water and liquid metals starts to coincide. Furthermore, it can be observed that the increase of inlet velocity further increases the difference between the pumping powers for liquid metal and water.

V. Conclusion

The present work employed liquid metals – Gallium and its alloys and compared the thermohydraulic performances with that of water. The recommendations from the present work are as follows:

- Incorporation of Gallium and its alloys significantly enhances the cooling capacity, however, such increases come with the penalty of pressure drop.
- The circulation of liquid metal should be maintained at low inlet velocity (<0.4 m/s). The benefit for such approach would be two-fold, which comes from the following reasons. First, at higher inlet velocity the cooling capacity per unit area stabilizes and second, the increase in inlet velocity constantly increases the pumping power requirement. Thus, at low rate, the advantage of liquid metal can be favorably utilized in enhancing the heat transfer rate per unit area and lowering the pumping power requirements.

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