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Hydrothermal Performances of Liquid Cold Plates

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Abstract - The effect of the number of channels in a liquid cold plate (CP) on the cooling capability of the CP was investigated through three-dimensional simulation of laminar flow and heat transfer. Serpentine channels with rectangular cross sections were implemented inside a copper plate, and the number of channels varied from one to three at a fixed cross section. The cooling performance was characterized by the maximum temperature ($T_{\max}$) and the temperature variation (ΔT) across the heating surface. Results were described at different flow rates and pumping powers (P_P) to provide a better insight on the practical applications of the CPs. Although an increase in the pressure drop and P_P are the consequences of increasing the number of channels, reducing the flow rate can potentially lower the P_P in a CP with more channels. It was found that at either a given flow rate or a given P_P, the $T_{\max}$ of a CP is reduced monotonically by increasing the number of channels. While the opposite trend to the $T_{\max}$ was obtained for the ΔT, the difference between ΔT across different CPs was negligible. CPs with increased number of channels are promising thermal management systems for high heat flux applications if their fabrication complexity is resolved using advanced manufacturing processes.

***Keywords*:** Thermal management; Active cooling; Liquid cold plate; Pumping power; Maximum temperature.

1. Introduction

Liquid cold plates (CPs) are among the most widely used active cooling technologies due to their high cooling capacity, low weight, compactness, and long durability [1]. A CP consists of a series of channels implemented inside a highly thermal conductive metal plate and carries a coolant to exchange heat with a heat source [2]. Hydrothermal analysis of cold plates has been extensively investigated under a wide range of design parameters; however, the available performance data in literature is mainly specific and applicable to the design parameters and operating conditions of their corresponding research. As a result, due to lack of generalized correlations and data to describe hydrothermal performances of CPs, detailed research is still required. This paper aims to investigate the thermo-fluid characteristics of customized CPs with an increased number of channels in a fixed cross section. Unlike passive cooling systems, active cooling systems require external power such as a pump for their operation. Pumping power (P_P), the power required to drive the flow across the cooling system, is one of the key design parameters of an active cooling system. Generally, an increase in P_P may hinder the use of the cooling system regardless of its capability to improve thermal performance [3]. In this study, the effects of increasing the number of channels of a CP at a fixed cross section on its heat transfer capability and P_P are investigated.

2. Problem Description and Computational Procedure

Fig. 1 illustrates the CPs studied in this work. In total, three CPs made of copper, with one, two, and three serpentine channels with rectangular cross-sections are considered. The channels have zero thickness because it is assumed that they are grooved inside the copper plate. The cross section of the channels plus the distance between adjacent channels is 6 mm × 6 mm; therefore, the channel width in Fig. 1(d) is equal to 6, 2.5, and 1.33 mm in CPs with N=1, N=2, and N=3, respectively, which "N" stands for the number of channels. Also, the channel height is equal to 6 mm in all designs. A channel is classified based on its hydraulic diameter (D_h), and is identified as a conventional channel and a minichannel with 3 mm $< D_h$, and 200 μm $< D_h \leq$ 3 mm, respectively [4]. Therefore, the CPs with N=1 and N=2 are conventional channels while the CP with N=3 is a minichannel. Liquid water is the coolant, and it enters the inlet(s) at a temperature of 22 °C and exits from the outlet(s). By assumption of a steady and incompressible flow as well as constant properties for both the fluid and solid, the governing equations to simulate the flow and heat transfer are as follows:

Continuity: $$\nabla . \boldsymbol{u} = 0 \tag{1}$$
Momentum conservation: $$(\boldsymbol{u}.\nabla)\rho\boldsymbol{u} = -\nabla p + \mu\nabla^2\boldsymbol{u} \tag{2}$$
Energy conservation (fluid): $$\boldsymbol{u}.\nabla T_f = \frac{\lambda}{\rho c_p}\nabla^2 T_f \tag{3}$$
Energy conservation (solid): $$\nabla^2 T_s = 0 \tag{4}$$

where ρ, u, p, μ, λ, c_p, and T_f are the fluid density, velocity, pressure, viscosity, thermal conductivity, specific heat, and temperature, respectively, and T_s is the solid temperature. Flow rates and temperature are set at the inlet, and zero axial gradients for all the variables are imposed at the outlet. The remaining surfaces are walls with a no-slip boundary condition. A constant heat flux equivalent to 120 W is applied at the top-surface of the CP (i.e., heating surface). The remaining exterior surfaces are insulated. The simulations are performed for a wide range of flow rates that maintained laminar flow in the channels. A grid structure with 260,618 computational cells is selected through a grid independence test since by increasing the number of cells beyond 260,618, the changes in the magnitude of heat transfer coefficients and friction coefficients are negligible. The transport equations are solved using Ansys Fluent.

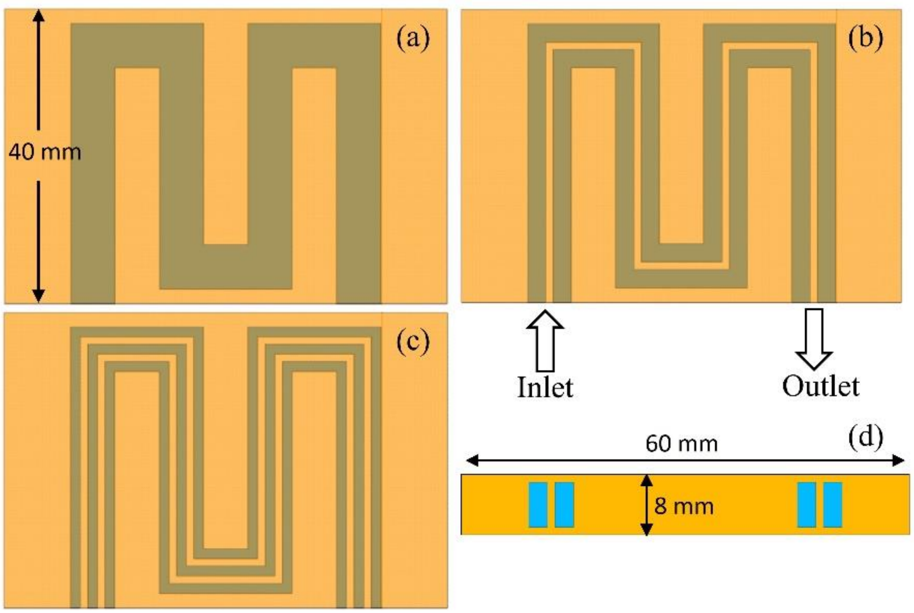

Fig. 1: Top view of the CPs with (a) N=1, (b) N=2, (c) N=3. (d) Front view of the CP with N=2. The dimensions are in mm.

3. Results

The maximum Reynolds number in the simulations is 1936, which indicates the flow to be laminar throughout the simulations. Fig. 2 illustrates the maximum temperature ($T_{\max}$) and the temperature variation (ΔT) across the heating surfaces at different flow rates. The flow rates varied from 0.3 to 0.7 LPM (liter per minute) for all CPs. For a given CP, increasing the flow rate corresponds to increased sensible heat, which results in a monotonic decrease in both $T_{\max}$ and ΔT across the heating surface. At a fixed cross section, an increase in the number of channels leads to a higher surface area to volume ratio, which results in a higher thermal performance (i.e., lower $T_{\max}$) [5]. At a given flow rate, an increase in the number of channels from one to two and one to three reduces the $T_{\max}$ by ~ 4.2 °C and ~ 6.7-7.0°C, respectively. Based on Fig. 2(b), although ΔT had an opposite trend from that of $T_{\max}$, the difference among ΔT in various CPs is negligible. The maximum ΔT across the heating surface of the CPs with N=1, N=2, and

N=3 is less than 3.9°C, 4.6°C, and 4.8°C, respectively, which indicates the maximum difference in ΔT among all CPs is below 0.9°C. Fig. 3 compares the temperature distributions over the heating surfaces of the three CPs at 0.7 LPM.

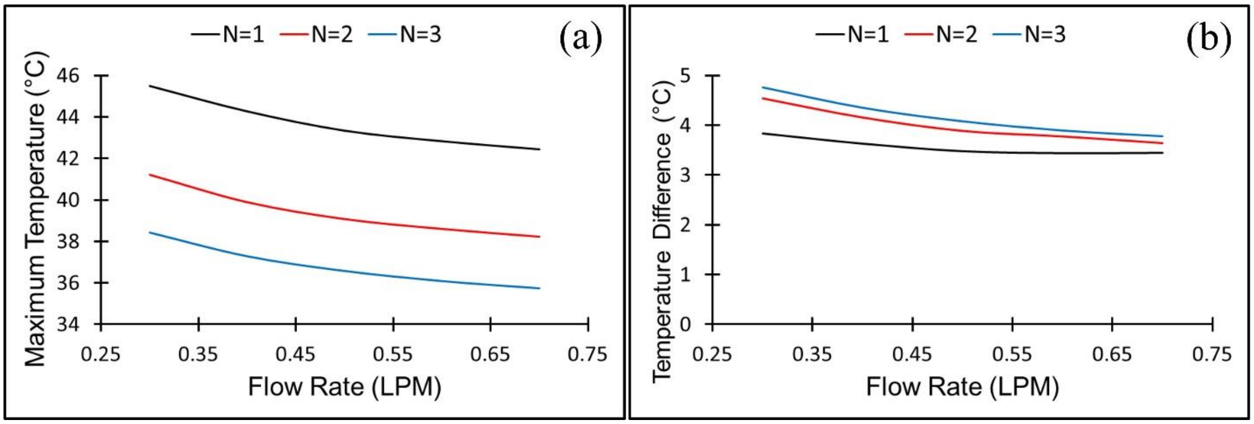

Fig. 2: (a) Maximum temperature, and (b) temperature variation across the heating surface at different flow rates.

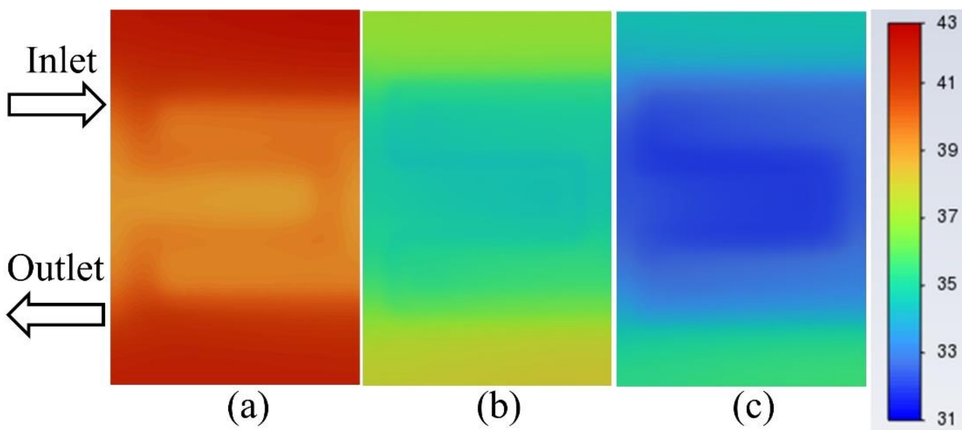

Fig. 3: Temperature distribution (in °C) over the heating surface of CPs with (a) N=1; (b) N=2; (c) N=3. Flow rate: 0.7 LPM.

P_P is calculated as follows [6]:

$$P_P = \Delta p \times \dot{V} \tag{5}$$

where Δp and $\dot{V}$ are the pressure drop across the channel and the total volume flow rate, respectively. In a CP with multiple channels, Δp through all channels is the same due to the parallel flow across the CP. Therefore, since the overall lengths of individual serpentine channels vary from each other in a CP with multiple channels, the flow rate inside each channel should be different to maintain the same Δp among all channels. However, due to the negligible differences in the lengths of various channels of a CP with multiple channels in this study, the same inlet flow rate was assigned for the individual channels for simplicity. Since this results in a slightly different Δp among various channels of a CP, the maximum Δp was used to calculate the P_P for an individual CP.

At a given cross section, increasing the number of channels leads to a smaller hydraulic diameter and, in turn, a higher Δp across the channel. However, at a given flow rate, a larger number of channels corresponds to a lower flow rate inside each channel due to dividing the total flow rate in more channels. As a result, despite an increased Δp, lower flow rates could potentially reduce the P_P. To present cooling performances of CPs in a more applicable way, $T_{\max}$ and ΔT across the heating surfaces are described as functions of P_P in Figs. 4(a) and 4(b), respectively. The results cover a different range of flow rates inside the range of laminar regime for each CP. Since the flow remains in a laminar regime for a wider range of flow rates inside the channels of a CP with more channels, the flow rates were not increased for the CP with N=1 in Fig. 4.

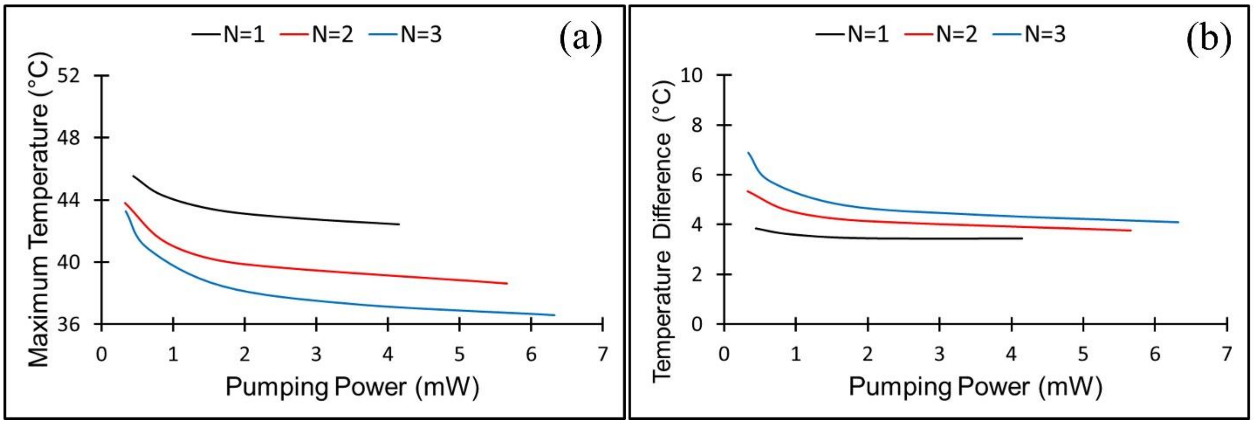

Fig. 4: (a) Maximum temperature, and (b) temperature variation over the heating surface at different pumping power.

For a given CP, an increase in P_P corresponds to a larger flow rate, which results in an increased sensible heat. As a result, a monotonic decrease in $T_{\max}$ of the heating surface is expected by increasing the P_P. The interesting conclusion from Fig. 4(a) is a considerable and monotonic reduction in the $T_{\max}$ of a CP at a given P_P by increasing the number of channels. As a result, if the fabrication complexity of a CP with multiple channels is addressed by leveraging advanced manufacturing technologies, it can be an effective thermal management system in high heat flux applications.

Although the trend of ΔT across the heating surfaces (shown in Fig. 4(b)) is opposite to that of the $T_{\max}$ at a given P_P, the difference in ΔT among various CPs is not significant. Especially, by increasing P_P, as it corresponds to an increased sensible heat, the differences in ΔT across heating surfaces of various CPs become negligible.

4. Conclusion

Three-dimensional simulations were performed to investigate the hydrothermal performances of CPs with different numbers of channels. It was found that at either a given flow rate or a given P_P, an increased number of channels results in a monotonic and substantial reduction of the $T_{\max}$ of the CP. While there was not a significant difference between the ΔT among various CPs in this study, the ΔT showed an opposite trend compared with that of the $T_{\max}$.

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