Study on flow and heat transfer of liquid metal in a new top-slotted microchannel heat sink

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Abstract. In order to overcome the disadvantage of large pump power required to maintain flow with the large flow resistance caused by high viscosity and high density of liquid metal in microchannel heat sink, a new top-slotted microchannel is designed in this paper. The flow and heat transfer performance of microchannel heat sink with different slot heights was studied by numerical simulation. The results show that the lowest pump power of 0.00157 W is obtained when the slot height is 0.8 mm without affecting the cooling performance of the microchannel heat sink, which is 16.5% lower than that of the traditional channel.

1. Introduction

Technical problems in thermal management are the main obstacles to reduce the size of modern electronics[1]. In recent years, with the rapid development of miniaturization and high power output electronics such as electronic chips, laser diodes, and vehicle batteries, the power consumption of electronic devices has rapidly increased, resulting in a large amount of heat accumulating[2, 3]. And in nuclear field, safety accidents happen from time to time, posing a great threat to human health and ecological environment. Great operation cost was caused because the utilization efficiency of uranium 238 in most nuclear power plants is less than 1%[4]. These problems are all closely related to the fact that huge quantity of heat generated during the operation of nuclear reactors cannot be taken away timely.

However, the traditional coolant water does not meet the demand of high-density heat dissipation because of its low thermal conductivity of ~0.60 Wm⁻¹K⁻¹[5]. A coolant with a large thermal conductivity is urgently required to obtain a large convective heat transfer coefficient in the microchannel heat sink. Therefore, liquid metal has been widely studied and used due to its excellent physical properties (thermal conductivity is about 25-70 times that of water) and unique electromagnetic drive characteristics[6-8]. However, higher pump power is needed to maintain the flow in the microchannel at the same volume flow rate because the density of liquid metal is about 6 times and the dynamic viscosity is about 2-3 times that of water[9], increasing energy consumption and limiting the cooling performance of microchannel heat sink.

In order to address this problem, the structural optimization is researched in this paper. A microchannel with an empty slot at the top is proved to be able to reduce the pressure drop and pump power.

2. Models and validation

A new top slotted microchannel heat sink is designed based on traditional microchannel, as shown in Figure 2. The overall size of the heat sink is \( W \times L = 2\text{cm} \times 2\text{cm} \), channel height \( H = 3\text{mm} \), channel
width $W_w = 0.6mm$, wall thickness between two channels $W_c = 0.4mm$, base width $t_b = 2mm$, and the slot height is $t_s$.

![Figure 1. 3D geometric structure diagram of traditional microchannel.](image)

![Figure 2. 3D geometric structure diagram of top-slotted microchannel.](image)

In order to save computing time and resources, the unit channel was studied in the numerical simulation, as shown in Figure 1 (b) and 2(b). The periodic structure grid is generated with Gambit and Fluent6.0 is employed for numerical simulation. Galinstan(21.5 wt% In, 10.0 wt% Sn and 68.5 wt% Ga), a nontoxic, nonvolatile GA alloy, which is liquid at room temperature, is selected as the liquid metal coolant and copper is applied for solid wall material. The physical parameters of galinstan is assumed to be constant as they change very small in the working temperature area[7]. The physical parameters of the materials are listed in table 1[10].

| Material  | Density (kg m$^{-3}$) | Specific Heat Capacity (J kg$^{-1}$K$^{-1}$) | Thermal Conductivity (W m$^{-1}$K$^{-1}$) | Dynamic Viscosity (kg m$^{-1}$ s$^{-1}$$\times$10$^3$) | Pr   |
|-----------|-----------------------|---------------------------------------------|------------------------------------------|---------------------------------|------|
| galinstan | 6440                  | 295                                         | 16.5                                     | 2.400                           | 0.043|
| copper    | 8910                  | 393.5                                       | 391.1                                    | -                               | -    |


The boundary conditions are set as follows. The velocity inlet boundary condition is applied for the inlet of channel, $U_i = 0.15m/s$. Pressure outlet boundary is set at the exit of channel. The constant heat flux boundary is applied at the bottom surface. The periodic boundary is applied at the left and right plane and the adiabatic boundary is assumed at other surfaces. The laminar model is selected as the flow model as the Reynolds number is less than 2300 at an inlet velocity of 0.15m/s.

Five sets of grid with 20800, 417600, 1177200, 2112000 and 3595500 cells are used for the grid independence test. The change of temperature at the centreline of the top surface is displayed in Figure 3. As can be seen, the line of 2112000 cells is almost overlap the line of 3595500 cells. The total thermal resistance is calculated by equation (1). The difference of total thermal resistance between the case with 2112000 cells and 3595500 cells is only 0.074%. Thus, the grid with 2112000 cells is chosen for present study.

The validity of the numerical simulation is verified by comparing with the result of Adeel Muhammad et al.[10]. Table 2 shows the comparison of total thermal resistance of the whole microchannel heat sink with the channel height varies from 3mm to 9mm. The maximum deviations are found to be 0.672%, 0.031%, 0.024% ,0.003% ,0.303% and 0.123%, respectively. Moreover, the pressure drop is compared with the result of Adeel Muhammad et al[10] and value calculated by theoretical correlations[11], which showed in Table 3. The maximum deviations are 2.181%, 1.635%, 1.542%, 1.603%, 1.610%, 1.655% and 0.261%, 0.557%, 1.063%, 1.654%, 2.277%, 3.520%. A great agreement can be seen effortlessly.

![Grid independence test](image)

Figure 3. Grid independence test: (a) Temperature at centreline of the top surface; (b) Partial enlarged.

| H(mm) | $R_{tot}$(K/W) Present | $R_{tot}$(K/W)Ref[10] | Diff(%) |
|-------|------------------------|----------------------|---------|
| 3     | 0.1176                 | 0.1184               | 0.672   |
| 4     | 0.1002                 | 0.1002               | 0.031   |
| 5     | 0.09154                | 0.09156              | 0.024   |
| 6     | 0.08718                | 0.08718              | 0.003   |
| 7     | 0.08504                | 0.08478              | 0.3028  |
| 9     | 0.08356                | 0.08346              | 0.1227  |

| H(mm) | $\Delta P$(Pa) present | $\Delta P$(Pa) Ref[10] | Diff(%) | $\Delta P$(Pa) Theoretical | Diff(%) |
|-------|------------------------|------------------------|---------|-----------------------------|---------|
| 3     | 348.0430               | 340.4494               | 2.181   | 347.1353                   | 0.2608  |
3. Results and discussion

In this section, the traditional microchannel and the new top-slotted microchannel with different slot heights are compared by numerical simulation. The slot height varies from 0.2mm to 1.4mm. The total thermal resistance and pump power required to drive flow are defined to be the evaluation index of the heat sink. The total thermal resistance of the heat sink

\[ R_{\text{tot}} = \frac{T_{\text{max}} - T_{\text{in}}}{Q} \]  

(1)

Where \( T_{\text{max}} \) is the maximum temperature of the whole heat sink and \( T_{\text{in}} \) is the inlet temperature of the liquid metal. The total heat generated \( Q \) can be calculated as

\[ Q = q_b \times A_b \]  

(2)

\( q_b \) is the heat flux at bottom surface, and \( A_b \) is the bottom area of the heat sink. The total thermal resistance represents the cooling capacity of the heat sink. The smaller the thermal resistance is, the lower the maximum temperature of the heat sink reaches. The pump power can be calculated as

\[ W_{\text{pp}} = n \Delta P U S \]  

(3)

Where \( n \) is the number of channel, \( \Delta P \) is the pressure drop, \( S \) is the cross-sectional area of a single channel.

3.1. Effect of the slot height on the total thermal resistance and pump power

The effect of the slot height on the total thermal resistance and pump power is shown in Figure 4. It can be seen that with the slot height \( t_s \) increases from 0 (traditional channel) to 1.4mm, the pump power increases at first and then decreases, while the thermal resistance shows the opposite.

With the \( t_s \) increases continuously while \( t_s > 0.4 \text{mm} \), the flow resistance becomes smaller and the pump power continues to decrease and then becomes lower than that of traditional channel. The total thermal resistance of the heat sink shows the trend of decreasing first and then increasing with the increase of \( t_s \), the total thermal resistance becomes higher than that of traditional channel while \( t_s \geq 1.0 \text{mm} \). Therefore, under the condition of the cooling performance of the heat sink does not decrease, the pump power reaches the minimum value while \( t_s =0.8 \text{mm} \), reaching 0.00157W, which is 16.5% lower than the traditional microchannel. The pump power of 0.00157W is obtained for designed heat sink without deteriorating the cooling performance (the total thermal resistance of top-slotted microchannel heat sink is lower than the traditional one) when \( t_s =0.8 \text{mm} \), which is 16.5% lower than the traditional microchannel heat sink.

| \( t_s \) | \( T_{\text{max}} \) | \( T_{\text{in}} \) | \( Q \) | \( W_{\text{pp}} \) |
|---|---|---|---|---|
| 4 | 331.3371 | 325.9176 | 1.6360 | 333.2295 | 0.5712 |
| 5 | 322.8046 | 317.8277 | 1.5418 | 326.2355 | 1.0628 |
| 6 | 317.2210 | 312.1348 | 1.6033 | 322.4668 | 1.6537 |
| 7 | 313.2827 | 308.3297 | 1.6097 | 320.4183 | 2.2777 |
| 9 | 308.0951 | 302.9963 | 1.6550 | 318.9398 | 3.5199 |
3.2. Effect of slot height on the temperature at the centreline of exit along y-axis

The temperature distribution at the centreline of exit is studied in this section. Figure 5 shows the change of temperature at the centreline of exit along y-axis. In the solid region (y ≤ 2mm), when \( t_s > 0.8 \text{mm} \), the temperature increases significantly and become higher than the traditional channel with the increase of \( t_s \), which results in the local temperature being too high and the cooling performance is weakened. This is consistent with the results obtained in section 3.1. In the fluid region (2mm ≤ y ≤ 5mm), the temperature decreases with the increase of y, and as \( t_s \) gets larger, the temperature goes down faster, and the fluid temperature close to the top of the heat sink become lower. This is caused by the increase of volume flow rate of liquid metal when \( t_s \) increases.

3.3. Effect of slot height on the velocity at the centreline of exit along y-axis

The velocity distribution at the centreline of exit is studied in this section. Figure 6 presents the change of velocity at the centreline of exit along y-axis. It can be noted that the speed increases significantly with the increases of y while \( t_s > 0.4 \text{mm} \), and the y-coordinate of turning point decreases with the
increase of $t_s$. At the position far away from the cavity ($y<3\text{mm}$), the velocity decreases as the slot become higher. That is to say, in the channel area far away from the slot, the fluid slows down due to high viscous resistance of liquid metal and forming a thermal-protective layer, resulting in poor cooling performance. This explains the cause of obvious deterioration of cooling performance while $t_s > 0.8\text{mm}$. Although the flow velocity of fluid slows down far away from the slot when $t_s < 0.8\text{mm}$, the velocity increases and more heat can be taken away due to the increase of the cross-sectional area of the channel. Thus, the cooling performance is improved.

![Figure 6. Effect of slot height on the velocity at the centreline of exit along y-axis.](image)

4. Conclusion
Flow and heat transfer characteristics of liquid metal galinstan in a new top-slotted microchannel are studied in this paper. It is found that designing a slot at the top of the channel reduces the pump power as compared to the traditional microchannel. With the increase of slot height $t_s$, the pump power decreases, and the total thermal resistance decreases first and then increases. While $t_s > 0.8\text{mm}$, the fluid slows down due to the high viscous resistance of the metal fluid and forming a thermal-protective layer in the channel area far away from the slot, resulting in poor cooling performance. The lowest pump power of 0.00157W is obtained when $t_s=0.8\text{mm}$ without affecting the thermal performance of the microchannel heat sink, which is 16.5% lower than that of the traditional channel.

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