Numerical Study of Performance of a Micro Chip Cooler

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Abstract

A three dimensional simulation model of a grooved micro chip cooler was developed to study the performance of the cooler working under steady condition. A comparison among five different physical models was given based on the computational results of temperature and thermal stress. Meanwhile, two different materials, \textit{i.e.} copper and silicon nitride compound, were introduced to investigate the effect of material on the capability of the cooler. The results indicate that a copper cooler has better cooling capacity though its internal stress is higher than that of a compound one. The cooling capacity is enhanced by splitting the original rectangular channel into two identical smalls. Moreover, the small channels should be arranged in the parallel direction so as to achieve not only a lower temperature but also a lower thermal stress. The thermal stress should be considered in future study.

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Keywords: micro chip cooler; performance; temperature; thermal stress

1. Introduction

With continuous improvement of electric components, more heat is generated during the cause of work, which demands a high-performance cooling system. Micro chip coolers with high heat transfer coefficients, compact volumes, high heat transfer areas per unit volume, are suitable for the cases, such as cooling microelectronic units and aerospace devices, with special requirements on the size and cooling capacity of heat exchange equipments. The study of a compact, light, and stable micro cooling device is a concern and extensive researches have been carried out [1-14]. Both experimental [1-6] and numerical efforts have been conducted to find the operational principle and improvement of performance of such devices [7-14].

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Here the research object is a grooved micro chip cooler (MCC) and a three-dimensional model based on the finite element software ANSYS is developed to simulate the steady heat transfer process. The profiles of temperature and thermal stress of the cooler working under stable condition are obtained. Then the cooling capability of five different structured coolers is analyzed. Also the effects of different materials, including copper (Cu) and silicon nitride compound (SiNₓ), are considered. The existing researches are mainly focused on the temperature of the coolers, however, the internal thermal stress is not discussed before. Here, in addition to the temperature, the stress is considered, which is essential for long-term stability of the coolers. The efforts are referable for further study of micro heat exchangers.

2. Numerical Model

1. 2.1 Physical model

As shown in Fig. 1, a micro chip cooler with eight rectangular channels is the research object (case 1). Set case 1 as the standard model, the dimensions and structures of the other models are changed based on this model, such as the height and the width of the channel are reduced in case 2 and 3, respectively. More attention should be drawn to case 4 and 5, which are shown in Fig. 2 and 3, respectively, the original channels are split and the new structure is differently rearranged. The dimensions of five different models are listed in table 1.

![Fig. 1 The physical model of case 1](image1)

![Fig. 2 Structure of case 4 (parallel flow)](image2)  ![Fig. 3 Structure of case 5 (cross flow)](image3)
Table 1 Dimensions of the coolers

<table>
<thead>
<tr>
<th>Case #</th>
<th>Lch (mm)</th>
<th>Wch (mm)</th>
<th>Hch (mm)</th>
<th>W (mm)</th>
<th>W1 (mm)</th>
<th>δ1 (mm)</th>
<th>δ2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>0.4</td>
<td>2</td>
<td>6</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>0.4</td>
<td>1.6</td>
<td>6</td>
<td>0.3</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>0.3</td>
<td>2</td>
<td>6</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>4/5</td>
<td>6</td>
<td>0.4</td>
<td>1</td>
<td>6</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

2.2 Governing equations

The heat transfer of the MCC is governed by Eq. (1) and the boundary conditions are shown in Fig. 4. Here some simplifications are adopted: 1) the convection condition is used in the channel. \( T_f \) is the temperature of cooling fluid and \( h \) is the convection heat transfer coefficient; 2) heat flux \( q \) is determined by the contact surface area and chip power; 3) the other boundaries are treated as adiabatic walls; 4) the bonded layer is a part of the MCC and made in the same material as the cooler body; 5) the cooling fluid is water with a fixed temperature of 30 °C; 6) the contact resistances are neglected; and 7) the cooling water velocity is 0.005 mm/s and the chip heating power is 5 W.

![Fig. 4 Boundary conditions](image)

\[
\frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) = 0
\]  

(1)

The convection heat transfer coefficient, which is defined as

\[
h = \frac{Nu \cdot \lambda}{d_n}
\]

(2)

Where \( d_n \) is the hydraulic diameter of the channel. \( Nu \) is determined by \( Re, Pr \), and the channel dimensions. Here, Eq. (3) is employed to evaluate \( Nu \).

\[
Nu = 1.86 \left( Re \cdot Pr \right)^{1/3} \left( \frac{d_{ch}}{L_{ch}} \right)^{1/3}
\]

(3)

Moreover, there is thermal stress within the MCC under working condition. Also a deformation is found, the relationship between stress and strain is determined by the thermo-elastic equation, \textit{i.e.} Eq. (4) and (5).

\[
\sigma_i = 2G\varepsilon_i + \frac{\mu}{1 + \mu} \Theta - 2Ga\Delta T
\]

(4)

\[
\tau_y = G\gamma_y
\]

(5)
The subscripts: \(i=1, 2, \) and \(3\) refers to \(x, y, \) and \(z\) direction, respectively, nevertheless \(i \neq j\). Meantime, the displacements of every side of the models are assumed to be zero.

2. 2.3 Properties of materials

The properties of copper and silicon nitride compound are given in table 2.

Table 2 Physical parameters of different material

<table>
<thead>
<tr>
<th>Item</th>
<th>(\rho) (kg/m(^3))</th>
<th>(C_p) (J/kg·K)</th>
<th>(\lambda) (W/m·K)</th>
<th>(E) (10(^11)Pa)</th>
<th>(\mu)</th>
<th>(\alpha) (10(^6)/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>8930</td>
<td>386</td>
<td>400</td>
<td>1.08</td>
<td>0.32</td>
<td>17.5</td>
</tr>
<tr>
<td>SiNx</td>
<td>2400</td>
<td>703</td>
<td>163</td>
<td>3.10</td>
<td>0.26</td>
<td>4.68</td>
</tr>
</tbody>
</table>

3. Results and Discussion

As shown in Fig. 5, the variation of the width or height of the rectangular channel leads to change of hydraulic diameter, affects the heat transfer coefficient and thus results in the updating of temperature field. It is noticed that the cooling effect is enhanced by splitting the original channel into two identical small channels. And the temperature of a copper cooler is always lower than that of a compound one thought their variations are similar. By analyzing case 1, 2, and 3, it is found the cooling ability improves as the aspect ratio \((H_{ch}/W_{ch})\) of channel decreases.

Fig. 6 indicates that both thermal stress and the temperature of the cooler vary similarly due to the change of channel dimensions. On the other hand, the stress of a compound cooler is much smaller than that of a copper one. Moreover, the stress is also affected by the arrangement of the channels. Though the difference of temperature between case 4 and 5 is negligible, the difference of stress is notable. As far as the copper cooler is concerned, the maximum stress of a parallel flow condition (~68 MPa) is about 30 MPa greater than that of a cross flow condition. However, there is only 2.5 MPa increment in stress for the compound cooler. The fact reveals that thermal stress is not only associated with the temperature gradient but also associated with the elastic ratio and thermal expansion coefficient. Although the computational results of internal stress are evidently smaller than the ultimate strength of the material, the reality of strength should be taken into consideration during the research and development procedure.

Fig. 5 The maximum temperature of coolers

Fig. 6 The maximum thermal stress of the coolers
4. Conclusions

Based on the three dimensional heat transfer analysis of a micro chip cooler, the conclusions are reached: 1) the copper cooler has a better cooling capability which is characterized with low and uniform temperatures due to its excellent thermal conductivity. Whereas, the silicon nitride compound cooler are not with a good conductivity results in high and non-uniform temperatures; 2) profile of thermal stress is opposite to that of the temperature. The compound cooler has low stress which ensures a long term operation period; and 3) once the channel is split into smaller channels, the cooling capacity is enhanced. However, attention should be paid to the arrangement of the small channels. The parallel flow model (case 4) is better than the cross flow mode (case 5) since the former can not only lower the temperature but also reduce the internal thermal stress, which is significant for a long stable service life.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p$</td>
<td>specific heat, J/kg·K</td>
</tr>
<tr>
<td>$d_h$</td>
<td>hydraulic diameter of the channel, m</td>
</tr>
<tr>
<td>$E$</td>
<td>the Young’s modulus, Pa</td>
</tr>
<tr>
<td>$G$</td>
<td>shear modulus, Pa</td>
</tr>
<tr>
<td>$H_{ch}$</td>
<td>height of the channel, m</td>
</tr>
<tr>
<td>$h$</td>
<td>convection heat transfer coefficient, W/m²·K</td>
</tr>
<tr>
<td>$L_{ch}$</td>
<td>Length of channel, m</td>
</tr>
<tr>
<td>$Nu$</td>
<td>Nusselt number</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$q$</td>
<td>heat flux, W/m²</td>
</tr>
<tr>
<td>$Re$</td>
<td>Renault number</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature, K</td>
</tr>
<tr>
<td>$T_f$</td>
<td>temperature of cooling fluid, K</td>
</tr>
<tr>
<td>$W$</td>
<td>width of the model, m</td>
</tr>
<tr>
<td>$W_{ch}$</td>
<td>width of the channels, m</td>
</tr>
<tr>
<td>$W_f$</td>
<td>spacing of the channels, m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Greek symbols</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>temperature rise, K</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>coefficient of expansion, K·¹</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>shear strain, m¹</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>gap between hot surface and channels, m</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>thickness of bonded layer, m</td>
</tr>
</tbody>
</table>
$\Theta$ volumetric strain

$\lambda$ thermal conductivity, W/m·K

$\mu$ Poisson ratio

$\rho$ density, kg/m$^3$

$\sigma$ normal stress, Pa

$\tau$ shear stress, Pa

3. Acknowledgements

The work of this paper was performed under the grant No. SLG09001 sponsored by Shanghai Municipal Education Commission.

References


