Study on the Effects of Channel Deployment in a S-Shaped Liquid Cooling Heat Sink for Electronic Chip Cooling

Zhihao Lu, Kai Zhang and Jinxiang Liu

Abstract The air conditioning in data center should be running in cold mode throughout the year account for amount of heat released in a relatively small space of rack. However, most of the heat in data center is released from electronic chips. Thus, the energy consumption of air conditioning will be significantly decreased if the heat released by electronic chips can be mitigated directly. Compared to the air cooling heat sink (ACHS), the cooling performance of liquid cooling heat sink (LCHS) is dramatically improved as it can remove more heat from the surface of electronic chip quickly. To further improve the cooling performance of LCHS, the effects of channel deployment are investigated in a commonly used S-shaped LCHS in this study. The numerical simulation results show that the average surface temperature of electronic chip can be reduced by 22.91 °C while the number of channels is increased from one to five.

Keywords Liquid heat sink · S-shaped · Electronic chip cooling

1 Introduction

With the development of information technology, data center is rapidly increasing in the characteristics of large-scale and high-density as essential infrastructure. The widely deployment of data center has led to an increase in heat generation which causes approximately 10 times energy consumption in the past decade [1–3]. Currently, a rack in a data center can generate a power of 2–20 kW [4, 5], requires air conditioning running in cold mode throughout the year to ensure the safe operation of the servers. However, most of the heat in the data center is released from the electronic chips [5, 6]. Therefore, the energy consumption of the air conditioning in data center will be significantly decreased if the heat released by electronic chips can be mitigated directly [7].

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The method which was most commonly used to cool the electronic chips was air cooling by using a fan [8]. Kondo and Matsushima [9] conducted a study on the forced air cooling for CPU modules with high heat dissipation. The results showed that the use of an impact pipe system for a CPU module with a fan could effectively enhance the heat dissipation of the chip surface. Marques and Kelly [10] found that the size of the air cooling heat sink (ACHS) could be reduced without affecting the heat dissipation performance by increasing the number of pin fins. However, the cooling energy of ACHS was inadequate for the high heat flux electronic chip account for a heat extent limit of 100 W/cm^2 [11]. To further improve the cooling effect of heat sinks, liquid cooling heat sink (LCHS) was focused by some researchers. Tuckerman and Pease [12] studied the heat dissipation performance of LCHS with microchannels. Their study showed that the fluid flow and heat transfer characteristics of microchannel heat sinks, which were designed for thermal control of electronic devices, were better understood through extensive theoretical and experimental studies. And then the further investigations on the optimization of numerical and geometric models for LCHS with microchannels were conducted by Ji and Peterson [13, 14]. Their studies found that the optimum parameters for the corresponding channels were different from the shapes of liquid cooling microchannel heat sinks. For the silicon liquid cooling microchannel heat sink, the optimal configuration for rectangular channel heat sinks was achieved when the number of channels approached 120 channels per centimeter. The cooling performance of LCHS was also impacted by flow rates, power inputs, material of heat sink, and type of cooling medium [7, 15, 16]. Although many efforts have been put on the improvements of cooling performance for LCHS, there still few publications focused on the effects of channel deployment on the cooling performance of LCHS.

In this study, an S-shaped LCHS was employed to investigate the effects of channel deployment on the cooling performance for electronic chips. The surface temperature distribution of the heat sink and the pressure loss in the flow channels were analyzed by using the computational fluid dynamics (CFD) simulation. The impacts of the arcuate structures' number and the cooling fluid's flow rate at the inlet on the distribution of temperature and pressure were discussed in detail.

2 Methods

2.1 Models of S-Shaped LCHS

To investigate the effects of channel deployment on the cooling performance for LCHS, three S-shaped models (i.e., with one, three, and five arcuate flow passages) were established in SolidWorks. As shown in Fig. 1, all these heat sinks had the same dimension of 60 mm $\times$ 60 mm $\times$ 6 mm (i.e., length $\times$ width $\times$ thickness). The diameter of the inner flow channel was 4 mm, and its axis was at the thickness center of these heat sinks.

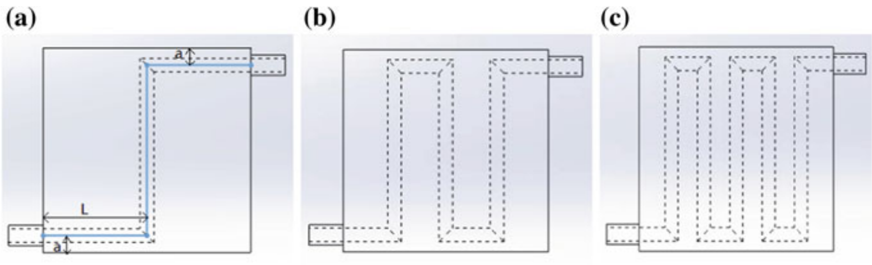


Fig. 1 Structure of S-shaped LCHS: **a** one arcuate flow channel; **b** three arcuate flow channels; **c** five arcuate flow channels

The flow channels were evenly distributed within the heat sink, and the inlet and outlet were deployed at opposite ends of the heat sink, respectively. The diameters of inlet and outlet pipes were also 4 mm, and the thickness of pipe wall was 1 mm. The distance between the internal flow channels would be different when the number of arcuate structures was changed. The detailed parameters were listed in Table 1, in which n was the number of arcuate structures and *R* was the radius of the flow channel.

2.2 Numerical Simulation

After completing the establishment of these S-shaped LCHS models, the models were simplified and repaired by Geometry (i.e., Design Model, DM) under the Ansys Workbench platform. Then these resulting "clean" models were imported into Ansys Icepak for numerical calculation. The models were also meshed in Ansys Icepak, and the mesh type was selected as the Mesh-HD. This mesh type was not only suitable for meshing the SolidWorks model, but also could be used to mesh the geometry into multiple levels. In order to obtain a more uniform and independent grid, the meshing levels of the heat sink and channels were configured as level 3. And the meshing levels of heat source, inlet, and outlet were configured as level 2. The number of mesh generated for these three heat sinks (i.e., with one, three, and five arcuate flow channels) were 1,318,478, 1,532,977, and 1,790,378 meshes, respectively. The mesh quality was checked by using the specified parameters in Ansys Icepak of face alignment, volume, and skewness [17], which was satisfied the threshold of Mesh-HD method.

Table 1 Detailed parameters of the flow channels for the heat sinks

Case	*n*	*L* (mm)	*a* (mm)	*R* (mm)
1	1	30	5	2
2	3	15	5	2
3	5	10	5	2

For the advantages of relatively cost-effective and suitable for most electronic cooling conditions, the zero equation was applied in these models. And the governing equations were given as follows [17]:

Momentum conservation equation:

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla p + \nabla.(\bar{\bar{\tau}}) + \rho\vec{g} + \vec{F} \tag{1}$$

where p is the static pressure; $\bar{\bar{\tau}}$ is the stress tensor; $\rho\vec{g}$ is the gravity; and $\vec{F}$ is the source term caused by other forces such as friction.

Energy equation of fluid and solid region:

$$\frac{\partial}{\partial t}(\rho h) + \nabla.(\rho h\vec{v}) = \nabla.[(k + k_t)\nabla T] + S_{\mathrm{h}} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h) = \nabla.(k\nabla T) + S_{\mathrm{h}} \tag{3}$$

where ρ is the density; T is the temperature; k is the molecular thermal conductivity; k_{t} is the thermal conductivity caused by turbulence; and S_{h} is the bulk heat source term, including all defined heat source terms.

The boundary conditions for each heat sink were same as each other, which was introduced in Table 2.

3 Results and Discussion

3.1 Comparison of Temperature Distribution

The temperature distributions for the three heat sinks mentioned above were shown in Fig. 2. As shown in these figures, the peak temperature was decreased with the increase number of the arcuate flow channels. And the peak temperatures were 72.02, 41.71, and 34.71 °C while the number of arcuate flow channels was one, three, and five. Furthermore, the distribution of temperature would be more uniform when the number of arcuate flow channels was increased. However, the relationship between the peak temperature and the number of arcuate flow channels was non-linear. The effect on the temperature distribution would be decreased while the

Table 2 Boundary conditions

Item	Parameter
Inlet fluid temperature	20 °C
Heat sink material	Aluminum
Heat flux of heat source	10 W/cm^2
Inlet flow rate	2.0 m/s

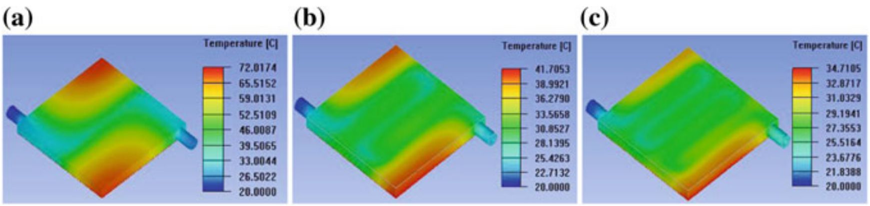
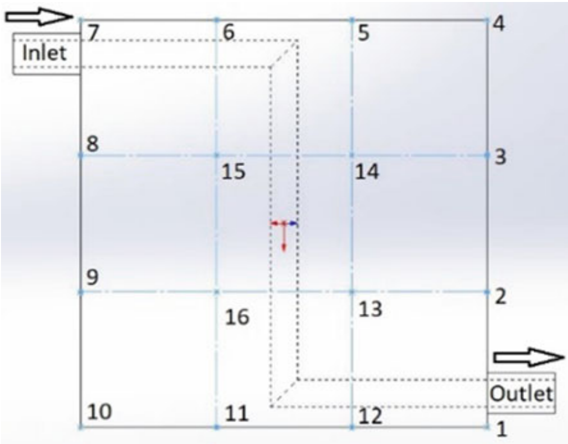


Fig. 2 Temperature distribution of S-shaped LCHS: **a** One arcuate flow channel; **b** three arcuate flow channels; **c** Five arcuate flow channels

Fig. 3 Deployment of reference points for calculating the average temperature



number of arcuate flow channels was increased. It also indicated that the changes on the peak temperature would be small while the number of arcuate flow channels was increased to a certain extent.

The average temperature was also adopted to indicate the effect of channel deployment on the cooling performance of S-shaped LCHS. The temperatures of reference points in Fig. 3 were selected to calculate the average temperature for the three Cases in Table 1, and the detailed temperature was listed in Table 3.

From Table 3, the average temperatures were 53.61, 34.88, and 30.70 °C while the number of arcuate flow channels was one, three, and five. And the effect of channel deployment on the average temperature was similar to that on peak temperature. In other words, the average surface temperature would be decreased as the number of arcuate channels increased.

3.2 *Analysis of Pressure Loss in the Flow Channel*

With the increasing of the number of arcuate channels, the length of the flow channel was also increased which would cause the increase in the pressure loss.

Table 3 Detailed temperatures of reference points

No.	t (°C)			No.	t (°C)		
	n = 1	n = 3	n = 5		n = 1	n = 3	n = 5
1	33.60	29.76	28.73	9	68.79	40.69	33.12
2	56.58	39.00	33.78	10	71.96	41.45	33.77
3	67.74	41.45	34.52	11	59.44	31.21	29.10
4	70.23	41.65	35.66	12	35.84	33.06	29.62
5	57.14	31.72	30.03	13	50.51	33.55	29.66
6	35.17	31.77	28.58	14	56.10	33.54	29.85
7	31.19	27.48	26.36	15	49.81	32.00	28.52
8	55.87	37.02	31.35	16	57.80	32.65	28.62

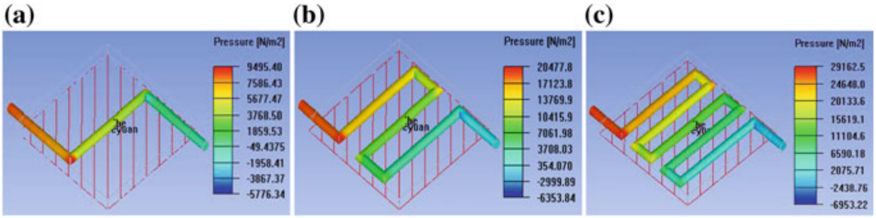


Fig. 4 Pressure distribution of S-shaped LCHS: **a** one arcuate flow channel; **b** three arcuate flow channels; **c** five arcuate flow channels

As shown in Fig. 4, the internal flow channels' pressure losses of these three heat sinks were 15.27, 26.83, and 36.12 kPa. Compared to the heat sink with one arcuate channel, the pressure loss was increased by 75.7% for three arcuate channels, and 136.5% for five arcuate channels. Different to the effect on the temperature distribution, the pressure loss would be increased with the increasing number of arcuate channels linearly. It also meant that the pressure loss would still significantly increase even though the impact on the temperature distribution was small when the number of arcuate flow channels was increased to a certain extent.

The direct impact of the increase in pressure loss was the increase in pump power demand, and the pump power demand could be calculated by Cai and Long [18]:

$$N = g \times Q \times H/\eta \tag{4}$$

where N is the pump power; g is the gravitational acceleration, 9.81; H is the head loss; Q is the mass flow rate; and η is the pump efficiency which was usually taken a value of 0.85.

Then, the pump power demand was derived from Eq. (4) as 442.70×10^{-3} W for one arcuate channel, 777.84×10^{-3} W for three arcuate channels, and 1047.17×10^{-3} W for five arcuate channels. Compared to the deployment of one arcuate channel, the pump power demand was also increased by 75.7% for three arcuate channels, and 136.5% for five arcuate channels. It also meant that the energy consumption for the liquid circulation in the flow channels of heat sink would be increased as the number of arcuate flow channels increased. Thus, the effect of pressure loss on the pump power demand also should be considered while increasing the number of arcuate structures to obtain a lower surface temperature.

3.3 Effects of Flow Rate on Temperature and Pressure Distribution

The flow rate also has a great impact on the cooling performance of LCHS. Thus, the effects of the flow rate on the cooling performance were analyzed by using the S-shaped LCHS with five arcuate flow channels. As shown in Fig. 5, the peak temperature of the heat sink was decreased to 32.33 and 30.98 °C, resulting in a reduction of 6.9 and 10.9% when the inlet flow rate was increased to 3.0 and 4.0 m/s. And the pressure loss in the flow channels of the heat sink was increased to 76.42 and 131.26 kPa, which were 111.6 and 263.4% higher to that in Case 3 (Fig. 6). Thus, it should be considered carefully to improve the cooling performance by increasing the flow rate while the number was increased to a certain extent.

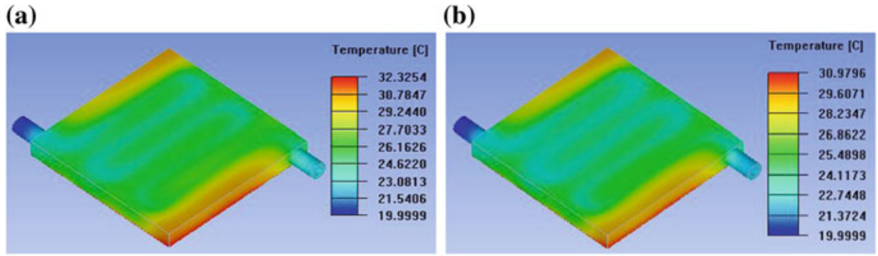


Fig. 5 Temperature distribution of S-shaped LCHS with 5 arcuate flow channels: **a** the inlet flow rate was 3.0 m/s; **b** the inlet flow rate was 4.0 m/s

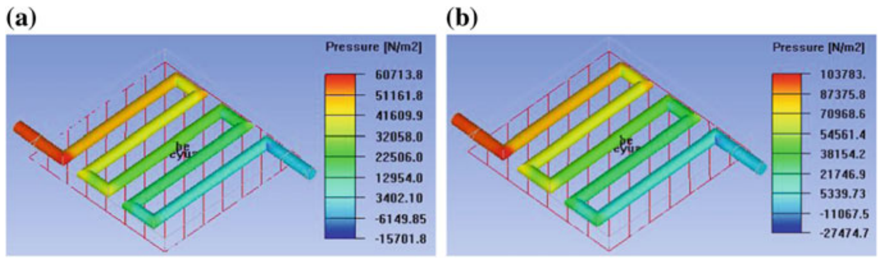


Fig. 6 Pressure distribution of S-shaped LCHS with 5 arcuate flow channels: **a** the inlet flow rate was 3.0 m/s; **b** the inlet flow rate was 4.0 m/s

4 Conclusions

This study investigated the effects of the channel deployment (i.e., number of arcuate flow channels) on the heat sink's surface temperature and the pressure loss in the flow channels based on a commonly used S-shaped LCHS. And then the impacts of the inlet flow rate on the distribution of temperature and pressure were discussed in detail. The main conclusions were as follows:

The peak temperatures/average temperatures were 72.02/53.61 °C, 41.71/34.88 °C, and 34.71/30.70 °C while the number of arcuate flow channels were one, three, and five, respectively.

Compared to the heat sink with one arcuate channel, the pressure loss or pump power demand was increased by 75.7% for three arcuate channels, and 136.5% for five arcuate channels.

The improvement in the temperature distribution was limited by increasing the arcuate flow channel number or the flow rate while the number was increased to a certain extent. However, the pressure loss would be continuously increased with the increasing of the arcuate flow channel number.

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