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STRUCTURE OPTIMIZATION OF FINNED WATER-COOLED HEAT SINKS FOR HIGH HEAT FLUX CHIP

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ABSTRACT

Reducing the high heat flux central processing unit temperature under a lower pressure drop has become essential to data center cooling. Based on a chip with a heat flux density of 80 W/cm^2, this study uses COMSOL Multiphysics simulation software to study the cooling effects of different structures of fin-type water-cooled radiators. This study analyzed the change in chip temperature, pressure loss in the radiator, and comprehensive heat transfer coefficient of the radiator under different flow rates by changing the area of the bottom plate, the position of the water inlet and outlet, and the gap length of the finless area. The results show that the heat dissipation effect is best when the heat sink area is close to the chip area. Additionally, it was determined that a moderate gap length has a certain optimization effect on the finned heat sink. Finally, the optimized structure for a finned, water-cooled radiator is proposed.

Keywords: fin type, water cooling, heat sink, CPU cooling, high heat flux

1. INTRODUCTION

Resent years, technologies such as artificial intelligence and cloud computing are developing rapidly. These developments create a new test of the heat dissipation capacity of data centers. The primary source of heat given off of data centers comes from the central processing unit (CPU). The quality of the cooling system affects the stability and economy of the system. The current cooling system is mainly divided into air cooling and liquid cooling [1]. Owing to their low efficiency and high noise [2], traditional air-cooled heat sinks have been unable to meet the heat dissipation requirements of high density heat flux CPUs. Meanwhile, owing to its better cooling performance and smaller volume of liquid cooling heat sinks, liquid cooling technology has become the main focus of research in the field of CPU heat dissipation with high-performance data center in recent years.

Two methods are usually used to optimize the cooling performance of a liquid-cooled radiator. One is to change the physical properties of the liquid and use different types of nanofluids; the other is to change the structure of the heat sink. Rafat et al. [3] reported that, under different Reynolds numbers, alumina nanofluids have high heat transfer performance in CPU cooling. Duangthongsuk et al. [4] dispersed silica nanoparticles with different concentrations in deionized water as a working fluid. When used in a miniature pin-fin heat sink, the heat dissipation effect is improved. Owing to the high cost of nanofluids, their higher maintenance needs and the aggregation and deposition effects of nanoparticles [5], the utility of nanofluids is still ambiguous. Instead, changing the geometry of the radiator may have great potential. Jajja et al. [6] studied the effect of fin spacing on the heat dissipation performance of the fin radiator and found that changing the fin spacing can effectively enhance the heat dissipation effect. However, this requires more pump work. Saeed et al. [7] further studied the influence of altering the fin thickness and height of the heat sink and obtained a lower reference temperature by doing so. The high cost and other shortcomings associated with the use of nanofluids encourage research into other potential solutions. Consequently, research on the influence of pure water radiator geometric factors on heat dissipation performance is of interest. Proposals

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for a high-efficiency water-cooled radiator structure continue to be a focus of current research.

Because fin-type water-cooling radiators are widely used in high heat flux chip water-cooling systems, many researchers have investigated the fluid flow and heat transfer characteristics of the fin-type water-cooling radiators. However, it is clear that few studies are investigated the effects of the area of the heat sink, the inlet/outlet locations and the gap length on heat transfer and fluid flow of the entire heat sink. Therefore, in the present study, fluid flow and heat transfer in fin-type water-cooling heat sinks with different heat sink area, different inlet/outlet locations (Type-A, B, C, and D) and different gap length are numerically studied with computational domain including the entire water-cooling heat sink.

2. GEOMETRY AND COMPUATION MODELING

2.1 *Geometry modeling*

The chip size used in this study was 25 × 25 × 5 mm^3, the heat flux density of the chip was 80 W/cm^2, and the water inlet temperature of the water-cooled radiator is 30 °C. Using the finned water-cooled radiator structure, the physical model was established, as shown in Figure 1. The structural unit is shown in Fig. 1 (a). Shown in order from bottom to top are the chip, bottom plate of the heat sink, top lid, and entrance and exit provided on the top lid. To reduce the thermal contact resistance between the chip and the bottom plate of the heat sink, a thin layer of thermal grease was applied between the two. Fig. 1(b) shows the bottom fin structure of the water-cooled heat sink. W_b, L_b, and $\mathrm{H_b}$ represent the length, width, and height of the bottom of the heat sink respectively; L_f represents the length of the fin; and $\mathrm{H_f}, \mathrm{W_f}$, and $\mathrm{S_f}$ represent the height, width, and spacing of the fins respectively. Fig. 1(c) shows an enlarged partial view of the fin.

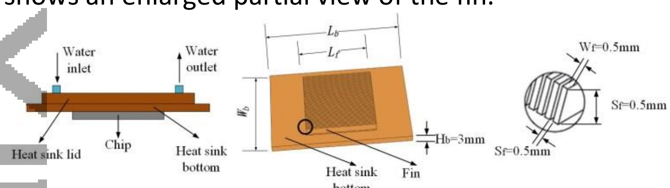

Fig 1 Finned water cooling heat sink (a) Water cooling unit (b) Heat sink bottom fin structure (c) Partial enlarged view of fin

2.2 *Computational modeling*

This study used COMSOL multiphysics to solve the conjugate heat transfer problem presented by different geometries of heat sinks. The equations for continuity, momentum, and energy in steady-state form are, respectively, expressed as follows:

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (1)$$

Momentum equation:

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\eta\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (2)$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\eta\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \quad (3)$$

$$\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial x}+\eta\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (4)$$

Energy equation:

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (5)$$

The pressure drop produced by a finned water-cooled radiator:

$$\Delta p = p_{in} - p_{out} \quad (6)$$

Here, p_{in} represents inlet pressure, and p_{out} represents outlet pressure.

The convective heat transfer coefficient for a finned water-cooled radiator is

$$h = mc_p\frac{(T_{out}-T_{in})}{A(LMTD)}. \quad (7)$$

Here, *A* is the heat exchange area of the radiator, c_p is the specific heat capacity at a constant pressure, *m* is the mass flow of water, T_{in} is the temperature of the inlet water, T_{out} is the temperature of the outlet water, and *LMTD* is the logarithmic mean temperature difference.

$$LMTD = \frac{(T_b-T_{in})-(T_b-T_{out})}{\ln\left(\frac{T_b-T_{in}}{T_b-T_{in}}\right)}. \quad (8)$$

Here, T_b is the average temperature of the bottom plate of the radiator.

To balance the heat transfer performance and the flow resistance performance, the comprehensive heat transfer coefficient was used as follows [8]:

$$\eta = h/\Delta p \quad (9)$$

2.3 *Model validation*

In order to verify the numerical simulation results, a chip cooling system based on fin-type water-cooling radiators was built. Use the same working conditions as the experiment for numerical simulation. The comparison between numerical simulation results and experimental results are shown in Figure 2. Comparing the experimental results and the simulation results, the maximum absolute temperature difference between the simulation results and the experimental results is 3.2°C, and the relative error is 11%. This verifies the accuracy of the simulation.

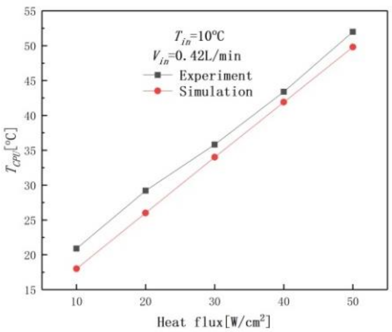

Fig 2 Numerical simulation and experimental comparison

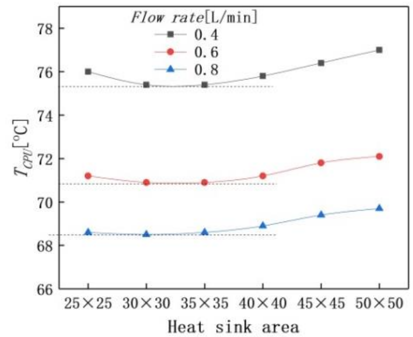

Fig 3 CPU temperature of different area radiators

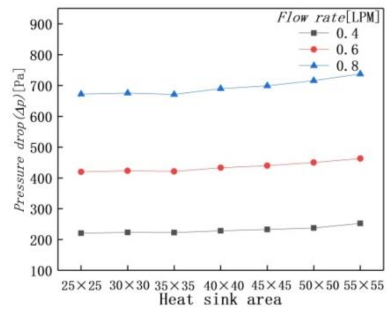

Fig 4 Pressure drop of different area radiators

3. RESULTS

3.1 Influence of the radiator area

The heat transfer area is altered by changing the floor area of the radiator structure, as shown in Figure 1. The heat transfer performance and flow resistance performance of the radiator can then be analyzed.

As the area of the radiator increases, the radiator's area of heat transfer increases, as does its thermal resistance. Therefore, the radiator area must be optimized such that it has a larger heat transfer area and a smaller thermal resistance. Here, we compare the temperature characteristics of the CPU of radiators of different areas and under different flow rates; the results are shown in Figure 3. An excessively high chip temperature will affect the performance of the chip by degrading or even leading to the failure of the chip. To avoid this situation, it is particularly important to control the maximum temperature of the chip. Therefore, the chip temperature shown in the figure is the highest temperature of the chip surface. As shown in Figure 3, the chip temperature decreases significantly with an increase in the inlet water flow. With the gradual increase in the size of the heat sink, the chip temperature changes in line with expectations, showing a trend of first decreasing and then increasing. The optimal radiator size under different flow rates is slightly different, but the optimal side length of the radiator bottom plate is concentrated between 25 mm and 35 mm. Figure 4 shows the pressure drop for radiators of different areas. For radiators of different areas, the pressure drop increases with an increase in the inlet water flow; this trend does not vary under different flows. In addition, the pressure drop gradually increases with an increase in radiator area. However, when the side length of the radiator bottom plate is less than 35 mm, the pressure drop does not change significantly.

Therefore, when the heat sink area is close to the chip surface area, the heat sink has the best heat dissipation effect. In other words, this arrangement produces a lower chip temperature and heat sink pressure drop.

3.2 Influence of import and export methods

For this study, the layout of the water inlet and outlet in the radiator was changed. The four inlet and outlet arrangements are shown in Figure 5 and referred to as Type-A, Type-B, Type-C, and Type-D.

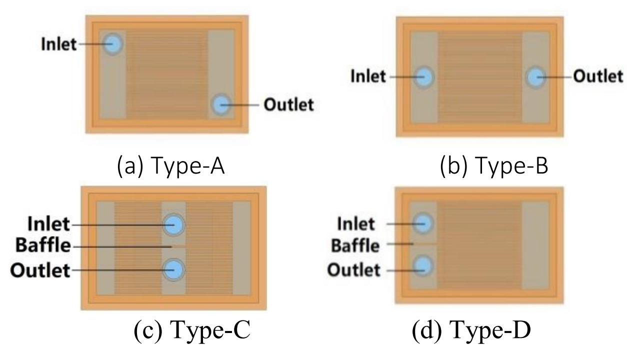

Fig 5 Arrangements of the four inlet and outlet methods

A radiator with an area of 30 × 30 mm^2 was chosen. Figure 6 shows the chip temperature of the radiator using different inlet and outlet arrangements. As also shown in the figure, different inlet and outlet methods have little effect on temperature. Figure 7 shows the influence of the different inlet and outlet arrangements on the comprehensive heat transfer coefficient of the radiator. It can be observed from the figure that the comprehensive heat transfer coefficient of the Type-C radiator is significantly higher than that of other radiators.

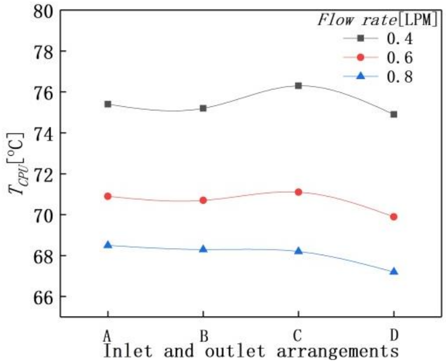

Fig 6 Temperature of radiator chip using different inlet and outlet arrangements

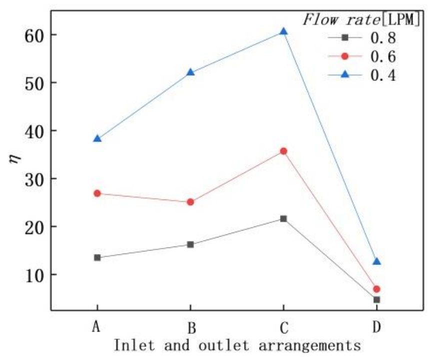

Fig 7 Comprehensive heat transfer coefficient of radiators using different inlet and outlet arrangements

3.3 Influence of baffle position

There is a baffle in the middle of the Type-C radiator. The presence and location of a baffle also affects the heat dissipation performance of the radiator. The influence of different baffle positions on the heat dissipation performance of the Type-C radiator is studied here. Fig. 8 shows five types of baffle positions. From the previous analysis, we can observe that the trends in parameter changes under different flow rates are basically the same, so the calculation below only selects one flow rate for further analysis.

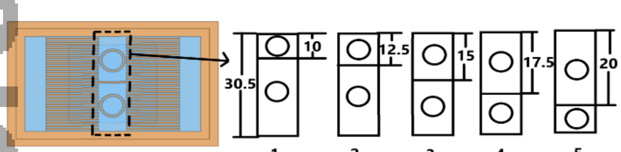

Fig 8 Baffle position of Type-C

Figure 9 shows the chip temperature, the pressure drop of the radiator and the comprehensive heat transfer coefficient at different baffle positions of the Type-C radiator when the water flow rate was 0.8 L/min. As shown in the figure, the maximum chip temperature decreases as the baffle position moves down. The pressure loss shows a trend of first decreasing and then increasing; because of this, position 3 is the location where the pressure loss of the baffle is the smallest. Considering the overall heat transfer and flow resistance characteristics of the radiator, Figure 9 also shows the comprehensive heat transfer coefficient of the radiator at different baffle positions. It can be observed that the comprehensive heat transfer coefficient η of the radiator at position 3 is the largest.

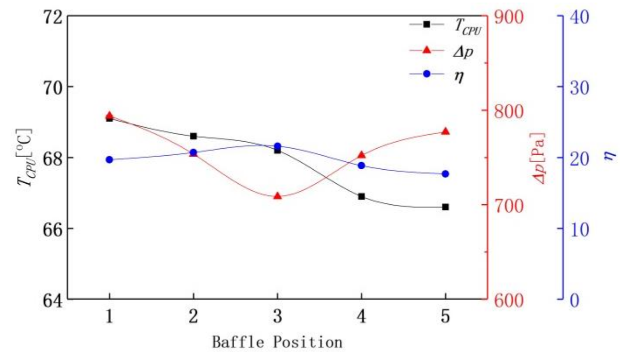

Fig 9 Chip temperature, pressure drop and comprehensive performance coefficient at different baffle positions of the Type-C radiator

3.4 Effect of gap length

There are gaps at both ends of the Type-C radiator, as shown in Figure 10. Water passing through the gap of the radiator changes the flow direction. This generates a vortex area in the radiator gap, which will disturb the fluid and improve the performance of the radiator. The length of the gap can affect the heat dissipation effect of the radiator. Here, we study the effect of different gap lengths on the heat dissipation performance of Type-C radiators with baffle position 3.

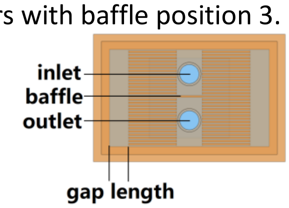

Fig 10 Gap length of Type-C radiator

Figure 11 shows the temperature, pressure drop and comprehensive performance coefficient diagram of radiators with different gap lengths. It can be observed from the figure that the chip temperature basically does not change. The pressure drop decreases with an increase in the gap length, and the downward trend gradually tends to be flat. When the gap length exceeds 6 mm, increasing the gap length does not significantly change the pressure loss. Moreover, an excessive increase in the gap length noticeably increases the production cost of the radiator. Considering the overall heat transfer and flow resistance characteristics of the radiator, when the gap length exceeds 6 mm, increasing the gap length does not significantly change the comprehensive performance coefficient. Therefore, a gap length of 6 mm is appropriate, as this allows for the achievement of an acceptable heat dissipation effect while keeping the manufacturing cost of the radiator down.

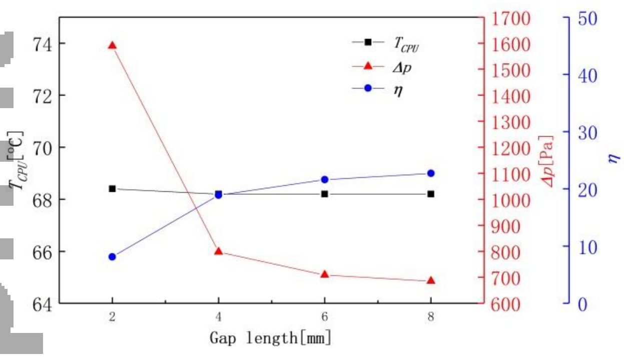

Fig 11 Temperature, pressure drop and comprehensive performance coefficient of the Type-C radiator with different gap lengths

4. CONCLUSION

The COMSOL Multiphysics numerical simulation was used to study the cooling effect of differently structured finned heat sinks based on a chip with size of 25 × 25 × 5 mm^3 and high heat flux density of 80 W/cm^2. The heat transfer and flow resistance performance of the radiator were studied by examining the impact of differently sized floor areas, inlet and outlet methods, and tail length. The following conclusions were drawn:

(1) The optimal radiator size varies slightly depending on flow rate. For radiators of different sizes, as the radiator area gradually increases, the pressure loss also shows a gradual upward trend. Considering the optimal structure of the bottom plate, the side length should be between 25 and 35 mm.

(2) Four types of inlet and outlet structures were compared, of which it was determined that Type-C can obtain the best heat dissipation performance. In addition, the comprehensive performance is the highest for Type-C when the middle internal baffle arrangement was used and the gap length was 6 mm.

(3) After optimization, the heat dissipation performance is greatly improved. Moreover, the improvement method is simple, the cost is low, and the maximum heat dissipation capacity is obtained with a small flow loss. It is suitable for the cooling of high heat flux density CPU.

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