Design of Heat Sink in Power Electronic Device Using Liquid Metal

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Abstract. Most converter valves of IGBT modules use a water-cooling system. The cooling technology of water cooling system is mature and has considerable advantages. However, higher power density power electronics lead to greater cooling power. With the improvement of the heat dissipation power of power electronic devices, the traditional water cooling system will gradually fail to meet the heat dissipation requirements of power electronic devices, and new cooling systems need to be developed. In this paper, based on the existing traditional water-cooling system model, numerical simulation analysis technology is used to compare and analyze the different cooling materials (copper, aluminum) and cooling medium (water, liquid metal) under the working conditions. For deionized water and liquid metal, the heat dissipation effect is compared and analyzed, which shows that the heat dissipation performance of the heat dissipation system using copper and liquid metal is greatly improved. Based on this, the model of liquid metal heat dissipation system is proposed. Compared with the traditional cooling model, it shows its superiority in heat dissipation performance with highest temperature decreased by 20.4%.

Keywords: Liquid metal; power electronic device; heat dissipation technology.

1. Introduction
In recent years, the UHV DC transmission market has developed rapidly. The DC converter valve is the core equipment of UHV DC transmission engineering and is the core functional unit for AC/DC conversion. The cooling effect of the valve water cooling system in the valve body will directly affect the commutation performance of the converter valve. The poor heat dissipation of the converter valve component will not only cause the component to be overheated and damaged, but also cause the DC system to be shut down in severe cases [1].

The currently widely used cooling system is a water-cooled system, but there are shortcomings such as leakage of the cooling line, aging of the material, fouling of the water supply electrode and sealing ring, resulting in a large proportion of unplanned outages [2]. Liquid metal has high thermal conductivity, low viscosity, easy to evaporate and leak, and has stable physical properties. It has better heat dissipation capacity, safer structure and material properties, and more efficient circulation system than traditional air-cooled heat dissipation system and liquid cooling system.

Liu Jing of the Institute of Physics and Chemistry of the Chinese Academy of Sciences in China first proposed a computer chip heat dissipation method using a low melting point metal or its alloy as a cooling flow medium [3]. This is a new concept introduced in the field of chip thermal management.
Foreign researchers have not reported the use of liquid metal radiators on converter valves or other power electronics systems, but have done some work on other civil liquid metal materials and radiator applications [4]. Coolaboratory Inc. of Germany has developed a liquid metal thermal paste with a melting point of 10 °C and a liquid metal thermal pad with a melting point of 58°C to achieve superior thermal conductivity than conventional silicone materials [5]. In 2005, Nanocooler of the United States developed a circulating heat sink based on gallium-based liquid metal, claiming that its heat dissipation efficiency reached 100W/cm² and the heat transfer efficiency reached 20W/(Kcm²) [6]. When a liquid metal heat sink is applied to a power electronic device, the fluid physical properties of the liquid metal are special due to its complicated structure. Therefore, how to construct an accurate theoretical model and select the appropriate physical parameters for theoretical simulation of the radiator system is a difficult point for the successful implementation of liquid metal radiators. It is necessary to carry out conditions such as the material of the radiator, the position of the inlet and outlet, and the wall surface. Reasonable choice.

In this paper, based on the existing traditional water-cooling heat dissipation system model, the numerical simulation analysis technology is used to replace the heat-dissipating working fluids with deionized water and liquid metal, and the heat dissipation effect is compared and analyzed, and the optimal scheme of the heat dissipation system is given. The heat dissipation performance of liquid metal cooling system and traditional water cooling system is compared and analyzed. The heat dissipation performance of liquid metal cooling system is much better than that of traditional water cooling system.

2. Heat Dissipation System Calculation Model

This paper constructs a simulation model suitable for the heat dissipation system of power electronic devices. Through the simulation analysis of the traditional water-cooled cold plate and the liquid metal technology cooling system under the same conditions, the optimal solution of the heat dissipation system is selected to provide reference for the system heat dissipation performance improvement. The simulation in this chapter is divided into two parts: the original cold plate structure, the simulation analysis of different cooling medium (water, liquid metal), different cold plate materials (copper, aluminum) (structure 1, as shown in Fig. 1(a)), comparative analysis of the impact of different cooling fluids and cold plate materials on the heat dissipation performance of the heat dissipation system; using liquid metal cooling system, combined with the simulation analysis of the optimized cold plate structure (structure 2, as shown in Fig. 1(b)), compared with the traditional water cooling, illustrates the superiority of the heat dissipation performance of the liquid metal cooling system.

![Figure 1. Heat dissipation system simulation model diagram.](image-url)

The system model in structure 1 is composed of heating element, liquid cooling plate and cooling machine; the system model in structure 2 is composed of heating element, liquid cooling plate, liquid metal circulation system and heat exchanger. The liquid metal is cooled from the heat exchanger and sent to the cold plate (the metal block in which the pipe is buried) through the electromagnetic pump. The heat generating component is mounted on the cold plate, and the heat is carried away by the flowing liquid metal. The heated liquid metal enters the heat exchanger again, and is convectively transferred to the cooling water through the pipe wall. After being cooled, it enters the electromagnetic pump. The water inlet temperature in the heat exchanger is 50°C, and the flow rate is 2.385×10⁻⁴m³/s. The
The electromagnetic pump used to drive the flow of liquid metal is set to the parameters of the liquid metal tube circulation line and no longer appears in the simulation analysis. The structure of the heat exchanger of structure 2 is complex and fine, and the overall simulation of the system is not easy to obtain ideal results. In this chapter, the heat exchanger is separated and analyzed separately, and the conditions and results are related to the whole system to obtain the overall system performance parameters. The heating elements in Structures 1 and 2 are used as heat sources, two on the top and bottom, each having a calorific value of $Q = 1kW$, and the thermal contact surface with the cold plate is a circular surface having a diameter of 75 mm.

At the same time, in the simulation calculation, the calculation is more accurate and the calculation is more convenient. This paper makes the following assumptions for the simulation.

a) The heating element is an area heat source with uniform heat flux density, and the contact between the heating element and the liquid metal cold plate The thermal resistance is small and difficult to measure, so it is not considered in the simulation calculation.

b) The flow rate of the liquid metal flowing out from the electromagnetic pump is uniform.

c) The outer surface of the cold plate and the outer surface of the heat exchanger are insulated.

d) System The structure has been simplified a little to increase the quality of the mesh and improve the calculation accuracy.

3. Analysis of Heat dissipation System Calculation Results

3.1. Calculation Result Analysis of Structure 1

In the simulation analysis of structure 1, the inlet temperature and the cooling medium flow rate are the same, and the heat dissipation performance of different cooling working materials (water and liquid metal) and different cold plate materials (copper and aluminum) is compared. Kind of working conditions. After reaching stability, the temperature cloud diagram for different situations is shown in Fig.2 The heat transfer performance are shown in Table 1.

![Temperature Cloud Diagram](a) water and aluminum (b) liquid metal and aluminum (c) water and copper (d) liquid metal and copper

**Figure 2.** Temperature cloud of structure 1.
Table 1. Heat transfer performance of structure 1.

|                        | Water and Al | Liquid metal and Al | Water and Cu | Liquid metal and Cu |
|------------------------|--------------|---------------------|--------------|---------------------|
| **Chip case temperature(°C)** | 73.6~82.8 (79.2) | 65.0~71.1 (68.5) | 67.7~73.6 (71.4) | 59.3~62.9 (61.4) |
| **Flow path temperature(°C)** | 54.7~69.3 (63.0) | 50.1~55.6 (53.2) | 56.4~66.7 (61.9) | 50.3~55.2 (53.3) |
| **Average convective heat transfer coefficient(W/(m²K))** | 9569 | 65789 | 9657 | 65789 |
| **Total heat exchange area (m²)** | 0.019 | 0.019 | 0.019 | 0.019 |
| **Total thermal resistance(K/W)** | 1.41×10⁻² | 0.845×10⁻² | 1.02×10⁻² | 0.485×10⁻² |

The values in parentheses in the table are average values. Using the calculation results in Table 1, the heat dissipation performance comparison of the four working conditions is shown in Fig. 3.

Figure 3. Thermal resistance and maximum temperature under 4 working conditions.

It can be seen from the above results that in the case where aluminum is used for the cold plate material and water is used for the cooling medium, the maximum temperature of the heat source surface is 82.8°C, which is close to the actual situation. Due to the contact thermal resistance of the contact surface between the cold plate and the heating element and the thermal resistance of the heating element itself, the maximum temperature of the heating element is slightly higher than this temperature, and the working state is required when the temperature of the casing does not exceed 90°C. Relatively dangerous, and the long-term work of the components again under temperature, will have a certain impact on its work stability and life.

Comparing the above data, it can be seen that under the same boundary conditions, using liquid metal as the cooling medium, the maximum temperature of the heat source surface can be reduced by 10.7~11.7°C, and the heat dissipation performance is improved obviously. Moreover, using copper as the cold plate material, the maximum temperature of the surface of the heat source can be lowered by 8.2 to 9.2°C, and the heat dissipation performance is more obviously improved when the liquid metal is used as the cooling medium.

It can be seen from Fig. 3 that when the cold plate material is aluminum, liquid metal is used as the cooling medium, and the total thermal resistance is reduced by 40%; when the cooling medium is water, copper is used as the cold plate material, and the total thermal resistance is used. The decrease was 27.7%; when the cooling medium was liquid metal, copper was used as the cold plate material, and the
total thermal resistance decreased by 42.6%. It can be seen that when the cooling medium is water, the convective heat transfer resistance of the total heat resistance of the system accounts for a large proportion; when the cooling medium is liquid metal, the total thermal resistance of the system is the thermal resistance of the cold plate itself. It has a large proportion. When the cooling medium is liquid metal, if the inlet temperature of the cold plate is 52.9 °C, the maximum temperature of the system is increased by 2.9 °C, but the maximum temperature is still 7.8~8.8 °C lower than the original system. The heat dissipation performance will be improved after the structure and flow rate are optimized accordingly. The system uses liquid metal as the cooling medium to improve the heat dissipation structure, and the maximum temperature of the system can be reduced by at least 14.1%. In the use of liquid metal cooling fluid to improve the heat dissipation structure of the system, in order to obtain better heat dissipation and optimal system structure, the structure and material of the cold plate should be improved at the same time. In addition, in order to be a liquid metal circulation system, the configuration of medium pressure drop and convective heat transfer performance is optimized, and the flow path size and flow rate of liquid metal are also changed.

4. Analysis of Calculation Results of Liquid Metal Heat Dissipation System (Structure 2)
The simulation calculation is carried out by using structure 2, the cold plate material is copper, and the heat dissipating working medium is liquid metal, and the cold plate material in structure 1 is aluminum, and the heat dissipating working medium is water working condition (conventional heat dissipating system). The analysis of the liquid metal heat dissipation system of structure 2 is divided into two parts: heat source, cold plate, electromagnetic pump, liquid metal circulation line; heat exchanger (heat exchange between liquid metal and water tank). The two parts of the conditions and results are interrelated. After reaching stability, the temperature cloud diagram of structure 2 is shown in Fig. 4. The system streamline diagram is shown in Fig. 5. The comparison analysis of structure 2 (copper and liquid metal) and structure 1 (aluminum and water) is shown in Table 2.
Table 2. Heat transfer performance of structure 1.

|                                      | Liquid metal cooling system (structure 2) | Traditional cooling system (structure 1) |
|--------------------------------------|------------------------------------------|------------------------------------------|
| Chip case temperature(℃)            | 58.3~65.9(63.1)                          | 73.6~82.8(79.2)                          |
| Flow path temperature(℃)            | 53.0~63.9(59.3)                          | 54.7~69.3(62.0)                          |
| Liquid metal temperature(℃)         | 52.9~59.3(56.2)                          | ——                                       |
| Cooling water temperature (°C)       | 50.0~52.4(51.0)                          | 50.0~52.4(51.0)                          |
| Cold plate convection heat transfer coefficient(W/(m²K)) | 52282                                    | 9569                                     |
| Cold plate heat exchange area(m²)    | 0.012                                    | 0.019                                    |
| Total thermal resistance(K/W)        | 0.605×10⁻²                               | 1.41×10⁻²                                |

A comparison of the heat dissipation performance of the liquid metal heat dissipation system and the original heat dissipation system is shown in Fig. 6. HEA is short for heat exchange area, thermal resistance is short for MT is short for maximum temperature. The cold plate volume decreases 83%, the total HEA decreases 37%, the total TR decreases 57%, and the MT decreases 14%.

Figure 6. Comparison of heat dissipation performance of liquid metal heat dissipation system.

It can be seen from the above structure that after the system is added to the liquid metal heat dissipation system, the maximum temperature of the heat source surface can be lowered by 16.9 °C (see Table 2), and the heat dissipation performance is improved. In the original system, the two thermal resistances are relatively large. After adding the liquid metal heat dissipation system, the two thermal resistances are reduced, the overall thermal resistance distribution of the system is relatively uniform, and the heat flow channel is good, so the heat dissipation effect is obviously improved. It can be seen from Fig. 6 that after the liquid metal heat dissipation system is used in the system, the total thermal resistance is reduced by 57.1%, the cold plate volume is reduced by 82.2%, and the heat dissipation performance is improved when the heat exchange area is reduced.

After the system uses a liquid metal heat dissipation system, the total pressure drop of the liquid metal circulation system is 53 kPa, and the water pressure drop is 2.68 times larger than the original structure. The liquid metal circulation system uses an electromagnetic pump, and its pumping power is larger than that of a conventional water pump. The system pressure drop and flow rate can be realized. If the system
uses a secondary heat dissipation system that incorporates liquid metal, the heat dissipation water needs to increase the pressure drop when the flow rate is constant.

In summary, the system uses liquid metal as the heat-dissipating working medium and improves the original structure. The maximum temperature can be reduced by 20.4%, and the total thermal resistance is reduced by 57.1%. At the same time, the structure and material of the cold plate, the size of the flow channel and the flow rate are both the shape of the cold plate has been reduced by 82.2%. However, the pump used in the system cooling water circulation needs to increase the pump pressure without changing the flow rate.

5. Conclusions

In this paper, different heat dissipation working fluids and cold plate materials and improved systems using liquid metal are simulated for the traditional heat dissipation system, and comparative analysis is carried out. It can be seen from the simulation results that although the heat dissipation method of the conventional heat dissipation system requires a margin of about 8 °C for the operating temperature of the converter valve to cope with the heat generated by the transient working state of the power electronic device, it still has certain danger. The cold plate material, the heat-dissipating working medium and the structure have improved the heat-dissipating effect of the original structure to varying degrees. Among them, copper is used as the cold plate material, and the liquid metal is used as the heat-dissipating working medium to have the best heat dissipation performance. Moreover, the liquid metal heat dissipation system after the application of the improved cold plate structure has a significant improvement on the overall thermal resistance and heat dissipation performance of the system, and is more suitable for application in power electronic devices.

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