Numerical Simulation and Performance Test of Multi-heat Resource Water Cooling System

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Abstract. It is hard to obtain the performance of the whole traction converter water-cooling system with different shape and route connecting tubes. In order to get the performance effectively and rapidly, the numerical simulation method is adopted to do that. The flow rate to every water-cooling heat sink is acquired through simulation analysis. Based on the flow rate, the temperature distribution of water-cooling heat sink has been investigated, and also the temperature variation of water-cooling system. The results show that the temperature difference between water-cooling heat sink is less than 1℃ under the same inlet flow rate. With the purpose of verifying the accuracy and correctness of the numerical simulation method, the performance test also has been done. The difference of performance result between numerical simulation and test is below 6%, which demonstrates the accuracy and feasibility of numerical simulation method. Comparing with test, the numerical simulation method can greatly improve the design efficiency and save human and financial resources.

1. Introduction

With the development of heavier duty and higher power of electrical locomotive, the power loss of Insulated Gate Bipolar Transistor (abbreviation, IGBT) used is increasing. The traditional air cooling, oil cooling methods become more difficult to meet the cooling requirement of traction converter. The water-cooling method has the advantage of radiating effect, safety, environmental protection and energy saving. So it is quickly and widely applied in traction converter cooling system of high power electrical locomotive.

Practices for recent years indicate that 55% IGBT damage is caused by excess temperature. The permanent damage of IGBT will make the traction converter stop working, which finally influence the safety and stability of locomotive operation. Naturally, how to design a satisfied cooling system becomes one of the hot and difficult problems in the course of traction converter design. After consulting related document made to be public, it is found that researchers pay more attention on the characteristics and thermal design of applied cooling system, not about performance research on water cooling system of traction converter. Bernet [1] did research on the main characteristics of cooling system of high power traction converter applied and gave the main characteristics of the latest water cooling converter series. Hoffmann [2] compared the technical characteristics of different cooling system used in traction converter at present and turned his attention on inner water-cooling system, finally gave out the work mode of system and some problem needed to consider. Sykes [3] discussed...
the working principle of air cooling system through the design course of converter of Hongkong metro. Chen [4] explained the structure and principle of water cooling system applied in static synchronous compensator and proved the cooling system could meet the cooling requirement of high power converter by test. Yazan [5] gave theoretical analysis and research on evaporative cooling system of CRH2 motor train unit traction converter and designed gravity heat pipe cooler that meets the practice operation requirement.

Traction converter is consist of multiple converter and inverter units. Each unit is cooled by a water-cooling heat sink. In order to make the traction converter work reliability, the cooling water is required to flow into each different water-cooling heat sink evenly or flow into the water-cooling heat sink working for modules with the highest power dissipation. Besides units, the water-cooling system includes many connecting tubes with different shape and route. So it is difficult to obtain the performance of the whole system by theoretical calculation. This paper takes the water-cooling system used in one high power locomotive traction converter as analytic target and do some research on the performance through numerical simulation method by Fluent software. As the result, the flow distribution, temperature distribute of each water-cooling heat sink and the temperature rise of the system are gained. Comparing with test, this method can greatly improve the design efficiency of traction converter and save human and financial resources.

2. Composition of water-cooling system

The whole system includes eight big water-cooling heat sinks, two small water-cooling heat sinks, main pipes and distributive pipes. Eight big water-cooling heat sinks work for eight big converter units (numbered 1~8) respectively. Two small water-cooling heat sinks work for two small inverter units (numbered 9~10) separately. Eight big IGBT modules are mounted on the each big water-cooling heat sink. The power dissipation of each big IGBT module is about 1500W. Three small IGBT modules are mounted on the each small water-cooling heat sink. the power dissipation of each small IGBT module is about 1200W. The rated inlet flow of system is 180L/min. The maximum designed flow is 270L/min. The cooling water flows into system from inlet, then go through main pipes and distributive pipes, then gets to 10 water-cooling heat sinks, finally mingles at the main outlet pipe and flows out of the system. The height of the cooling system is about 1.8m. The whole system is showed as Fig. 1.

Each water-cooling heat sink is consist of many grooves, its inner structure is shown as Fig. 2, the morphological structure of water-cooling heat sink mounted with IGBT modules is shown as Fig. 3
3. Establishment of numerical model

3.1. Model selection and boundary conditions establishment
The final flow state of cooling medium is turbulence, so k-ε model is used to do the numerical research [6]. The cooling medium is 25°C pure water, its thermophysical parameters are following: density 998.2 kg/m³, thermal conductivity 0.599W/m-K, specific heat capacity 4183 J/kg-K, dynamic viscosity $1.004 \times 10^{-3} \text{kg/m} \cdot \text{s}$ [6]. Considering the influence of gravity on the height of water-cooling system, the acceleration of gravity in vertical direction is set to be 9.81m/s². Inlet boundary conditions is set to be velocity boundary conditions, and outlet boundary conditions is set to be pressure boundary conditions. In order to guarantee the accuracy of calculation result, the convergence criterion is set to be $10^{-6}$.

3.2. Grid partition of model
Firstly, we use the strong three-dimensional modeling function of Pro/E software to establish the physical model of water-cooling heat sink. Then import physical model into the pre-processing module Gambit of Fluent [7-8], finally adopt Gambit to divide grid. The IGBT modules are welded by multilayer materials, including AlSiC base plate, solder layer, copper layer, AlN layer, chip, insulating materials and so on. The thickness of each layer is different.

The width of grooves of inner water-cooling heat sink is 4mm. The dimension of model grids can’t be too small, or it will exceed the calculation capacity of table computer station; but it also can’t be too big, or it will be difficult to catch the information of flow field and calculate the temperature field of IGBT modules. According to the practical experience, we know it will exceed the calculation capacity of table computer station if we divide grids of pipes, cooling water, AL body of water-cooling heat sink and each layer of IGBT modules to be 2mm and 10mm to the left region.

In order to catch the flow field information among the grooves more accurately under present computer resource, Author adopts the following method to divide grids and simulating calculate: firstly, divide the grids on fluid region into 2mm, shown as Fig.4 and work out the flow rate that flow into each water-cooling heat sink; then, divide the grids on each water-cooling heat sink and each layer of IGBT component into 0.5mm shown as Fig.5 and Fig.6. Taking the flow rate calculated above as input condition, the accurate temperature field distribution can be figured out.
4. Result and analysis of numerical simulation

4.1. Simulation result and analysis of water-cooling system flow field

The simulation results of flow field include flow velocity distribution and pressure distribution. Fig. 7 shows the simulation result of system pressure under the inlet flow rate at 180L/min. From it, it is easy to know the system pressure loss is 29.34kPa.

Fig. 8 shows the simulation result of flow velocity, which tells that the flow velocity of cooling water in the main pipes is not even, the maximum flow velocity appears at the bend of pipe system and the minimum flow velocity appears at the end of main inlet pipe and main outlet pipe because they are blind.

![Fig. 7 Pressure distribution of main pipes section](image1)

![Fig. 8 Flow velocity distribution of main pipes Section](image2)

Although the distribution cloud picture can show the flow status of cooling water in different position intuitively, the average inlet flow velocity value of each water-cooling heat sink is difficult to get accurately. So the inlet flow velocity value of each water-cooling heat sink under the inlet flow rate at 180L/min and 270L/min is extracted from cloud picture shown as the Table 1. From the Table 1, we can know that the inlet flow velocity of NO.3 water-cooling heat sink is maximum because it is nearest to the system outlet and suffers from minimum resistance. The inlet flow velocity of NO.8 water-cooling heat sink is minimum because it is at the end of the system inlet and at the bottom of the system, suffering from the most influence of gravity. The velocity of No.9 and No.10 have little difference because the cooling system layouts symmetrically and both of them are almost at the same position.
Table 1. Average inlet flow velocity of heat sink

| Serial number of modules | 180L/min average inlet flow velocity (m/s) | 270L/min average inlet flow velocity (m/s) |
|--------------------------|-------------------------------------------|-------------------------------------------|
| 1                        | 1.47                                      | 2.21                                      |
| 2                        | 1.44                                      | 2.16                                      |
| 3                        | 1.5                                       | 2.26                                      |
| 4                        | 1.5                                       | 2.24                                      |
| 5                        | 1.48                                      | 2.23                                      |
| 6                        | 1.48                                      | 2.22                                      |
| 7                        | 1.45                                      | 2.18                                      |
| 8                        | 1.42                                      | 2.13                                      |
| 9                        | 1.83                                      | 2.73                                      |
| 10                       | 1.84                                      | 2.74                                      |

4.2. Simulation result and analysis of water-cooling system temperature field

Through above flow field analysis, we get average inlet flow velocity of each water-cooling heat sink under rated flow rate and maximum design flow rate. For the big converter units, we choose No.8 unit with the minimum flow velocity to do further analysis and its temperature distribution result is shown as Fig.9. The maximum surface absolute temperature is 63.7°C. The maximum temperature appears on the IGBT modules in the same side.

![Temperature field distribution under the flow velocity at 1.42m/s](image)

Meantime, taking the No.3 converter unit with the maximum flow velocity to analyze, its maximum surface absolute temperature amounts to 63°C. Analysis above on the two big converter unit are both under the inlet flow rate at 180L/min. Because the water-cooling heat sinks used in the 8 big converter units are the same. The value and distribution of power dissipation of IGBT modules amounted on the water-cooling heat sink are the same too. So the surface absolute temperature of No.3 and No.8 converter unit can be deemed to the maximum and minimum temperature value for 8 water-cooling heat sink used for the big converter units under the inlet flow rate at 180L/min. The temperature difference among the water-cooling heat sinks used for big converter units is only 0.7°C.

Then, the thermal performance analysis will be done under the inlet flow rate at 270L/min. As above, taking the No.8 unit with the minimum flow velocity to do the research, the highest surface temperature is 57.4°C when the inlet flow velocity is 2.13m/s. For the No.3 unit, the highest surface temperature is 56.9°C when the inlet flow velocity is 2.26m/s. In a similar way, the surface absolute temperature of No.3 and No.8 converter unit can be deemed to the maximum and minimum temperature value for 8 water-cooling heat sink used for the big converter units under the inlet flow.
rate at 270L/min. The temperature difference among the water-cooling heat sinks used for big converter units is only 0.5°C.

For the water-cooling heat sink used in the small converter units of system, because of small difference of flow velocity, we can choose randomly No.9 converter unit to do the analysis. The temperature distribution result is shown as Fig.10. The highest surface temperature is 62.2°C. the temperature is well-distributed.

![Fig. 10 Temperature field distribution under the flow velocity at 1.83m/s](image)

According to the analysis above, under the same inlet flow velocity, the temperature rise difference caused by the difference of flow velocity is less than 1°C, which can prove that the temperature-uniforming performance of the whole water cooling system and the design of pipe system is very reasonable.

For different inlet flow rate, the inlet flow rate 270L/min is bigger one third than the inlet flow rate 180L/min, it causes temperature difference about 6.1°C on No.3 converter unit and 6.3°C on No.8 converter unit. The result shows that the increase on flow rate only leads to limited influence on the radiating effect. New efficient method need to be found to improve the radiating effect of water-cooling heat sink.

4.3. Temperature rise analysis of the whole cooling system

The temperature difference between inlet temperature and the highest temperature decides the temperature rise of the whole system. From the analysis of part 4.2, The highest temperature point of cooling system must occurs at the water-cooling heat sink used for big converter unit with the minimum flow velocity or the water-cooling heat sink used for small converter unit with the minimum flow velocity. When the inlet flow rate is 180L/min, the highest temperature point of big converter unit is at No.8 unit, the highest temperature is 63.7°C. The highest temperature of small converter unit is 62.2°C. The temperature rise of the whole cooling system equals to 38.7°C which is calculated by 63.7°C minus inlet temperature 25°C.

5. Test research and result analysis

The test system shown as Fig.11 is used to test the flow resistance of the water cooling system. Firstly, adopting the test system shown as Fig.11(a) to gain the pressure P1 of the whole water cooling system .Then, using the test system shown as Fig.11(b), to get the pressure P2 of the pipe system .The pressure dropΔP of the whole cooling system can be calculated as following formula: ΔP = P1 – P2.
We use infrared radiation thermometer to test the surface temperature of water-cooling heat sink. The highest temperature appears at the water-cooling heat sink used for No.8 converter unit.

During the course of test, the pressure gauges tells the pressure loss of the whole water cooling system is 30.71kPa. The infrared radiation thermometer tells the temperature rise of the whole cooling system is 36.6 ℃.

From the contrastive analysis, the result of numerical simulation fits in nicely with the results of test. The deviation ratio of pressure loss is only 4.7% and the temperature rise deviation ratio is only 5.7%, which verify the feasibility and accuracy of numerical simulation method.

6. Conclusion
(1) Using the numerical simulation method, the maximum flow velocity is measured as 1.5 m/s on the water-cooling heat sink used for No.3 converter unit under the inlet flow rate as 180L/min. The pressure loss of the whole cooling system is 29.34kPa. The test result of pressure loss is 30.71kPa. the result deviation ratio is only 4.7%.

(2) The temperature of the whole cooling system is well-distributed. When the inlet flow rate is 180L/min, the temperature difference among the water-cooling heat sinks used for big converter units is 0.7 ℃; When the inlet flow rate is 270L/min, the temperature difference among the water-cooling heat sinks used for big converter units is 0.5 ℃.

(3) When the inlet flow rate is 180L/min, the temperature rise of the whole cooling system is 38.7 ℃ gained through numerical simulation method and 36.6 ℃ gained by test. the result deviation ratio is only 5.7%.

Through the above contrastive analysis of the result gained from numerical simulation method and test, the numerical simulation method can calculate accurately the performance of the designed water-cooling system. Before this method is used in this field, in order to get the performance of the designed system, the only way is to produce a set of water-cooling system to test. If the result is not very good, the engineers will redesign the system. So repeatedly, it wastes abundant man power and material resources. Now the engineers can get the performance results through the computer simulation rather than test in the real system, which can greatly improve the design efficiency and save man power, physical and financial resources.
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