Research on the influencing factors of water-cooled simulation for coil heating

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Abstract: This article explores the influence of water-cooling systems on the heat dissipation factors and effects of copper coils, mainly introducing the application of water-cooling heat dissipation and its future use in large-scale computing systems such as adaptive optics. At the same time, the article also introduces centralized cooling methods and compares them one by one to prove that water-cooled heat dissipation has the strongest adaptability in adaptive optics systems. In addition, the article also introduces the algorithm used in water-cooling simulation, namely Fourier's law. This is an algorithm that can decompose the temperature effect into three directions for step-by-step calculation, and is an important part of fluid dynamics simulation.

1. Introduction

1.1 Overview of Water-cooling System for Adaptive Mirror Coil Heating

At present, the main cooling systems on the market are air cooling, droplet splashing, immersion cooling, and air cooling. Among them, air cooling and heat dissipation, as the name suggests, refers to installing a fan in the instrument to accelerate the air flow rate and achieve the goal of reducing temperature; Droplet splashing heat dissipation is achieved by spraying heat dissipation liquid onto the surface of the object being cooled, and then reducing the temperature of the object through evaporation and heat absorption; Immersion heat dissipation refers to directly immersing the object to be dissipated into non electrolyte heat dissipation liquids such as mineral oil, and achieving the purpose of heat dissipation during operation through the specific heat capacity of the liquid; Water-cooling heat dissipation is achieved by connecting water-cooled tubes to the object that needs to be cooled, and reducing the temperature through the flow of liquid [1].

Air cooling is mainly suitable for small and medium-sized instruments and equipment, where fans are installed to achieve cooling effects. Generally, air cooling is suitable for low to medium computing power computer equipment and portable computers [2].

Droplet splashing heat dissipation is mainly suitable for medium and large server base stations, and its advantages over air cooling are low noise and high efficiency. Droplet spray cooling can be applied to both data center server cooling and 5G base station cooling [3].

Immersion heat dissipation is suitable for small and medium-sized instruments, which achieves cooling by directly immersing the equipment in a non corrosive non electrolyte solution. Both data base stations and large hosts can be adapted to immersive heat dissipation [4].

Water-cooling heat dissipation is suitable for instruments of various volumes, and its installation is much simpler compared to droplet splashing heat dissipation or immersion heat dissipation. Only specialized pipes for liquid passage need to be arranged to achieve heat dissipation. Facilities such as computers and adaptive optics telescopes are particularly suitable for water-cooling heat dissipation.

In adaptive optics systems, the heating of the system mainly comes from the front end of wavefront correction. In the process of wavefront correction, the lens generates a large amount of heat, which can affect the measurement performance of the entire system and the accuracy of backend data processing. However, adaptive optics instruments themselves need to ensure the relative independence of their internal hardware to reduce the interference caused by heat. Water-cooling is the best choice in this case - it can ensure placement without changing the internal structure of the

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instrument and maximize the heat dissipation effect.

1.2 Progress of Water-cooling in Temperature Control

A water-cooled (liquid cooled) heat dissipation system must have the following components: water-cooled block, circulating liquid, water pump, pipeline, and water tank or heat exchanger. The water-cooled block is a metal block with internal water channels, made of copper or Aluminum, which comes into contact with the CPU and absorbs its heat. Therefore, the function of this part is the same as that of the air-cooled heat sink. The difference is that the water-cooled block must have a water channel for circulating liquid to pass through and be completely sealed, so as to ensure that the circulating liquid does not leak and cause electrical short circuits. The function of circulating liquid is similar to that of air, but it can absorb a large amount of heat without significant temperature changes. If the liquid is water, it is the well-known water-cooling system. The function of the water pump is to promote the flow of circulating fluid, so that the liquid that absorbs the heat of the CPU will flow out from the water-cooled block on the CPU, and the new low-temperature circulating fluid will continue to absorb the heat of the CPU.

The water pipe connects the water pump, water-cooling block, and water tank, and its function is to circulate the circulating liquid in a closed channel without leakage, so as to ensure the normal operation of the liquid cooling and heat dissipation system.

The arrangement of water-cooling tubes is crucial in water-cooling and heat dissipation, and the distribution of water-cooling tubes in instruments determines the effectiveness of heat dissipation. At the same time, the distribution, number of turns, and distribution density between the copper coils next to the water-cooled tube will also significantly affect the efficiency of water-cooling [5].

The material of the water-cooled plate affects the heat transfer performance between the waterway and the cooling water. Using materials with high thermal conductivity to make the water-cooled plate can effectively reduce the overall thermal resistance of the system. Aluminum alloy, as the most commonly used heat dissipation material, has advantages such as high thermal conductivity, low density, good processing performance, good corrosion resistance, and good physical and mechanical properties. The anti-corrosion process of Aluminum profiles is mature, which can ensure the long-term reliable use of water-cooled plates. Figure 1 illustrates the advantages of water-cooled plate cooling and points out that even if different devices use water-cooled systems, the heat dissipation effect will vary depending on the type of water-cooled system selected.

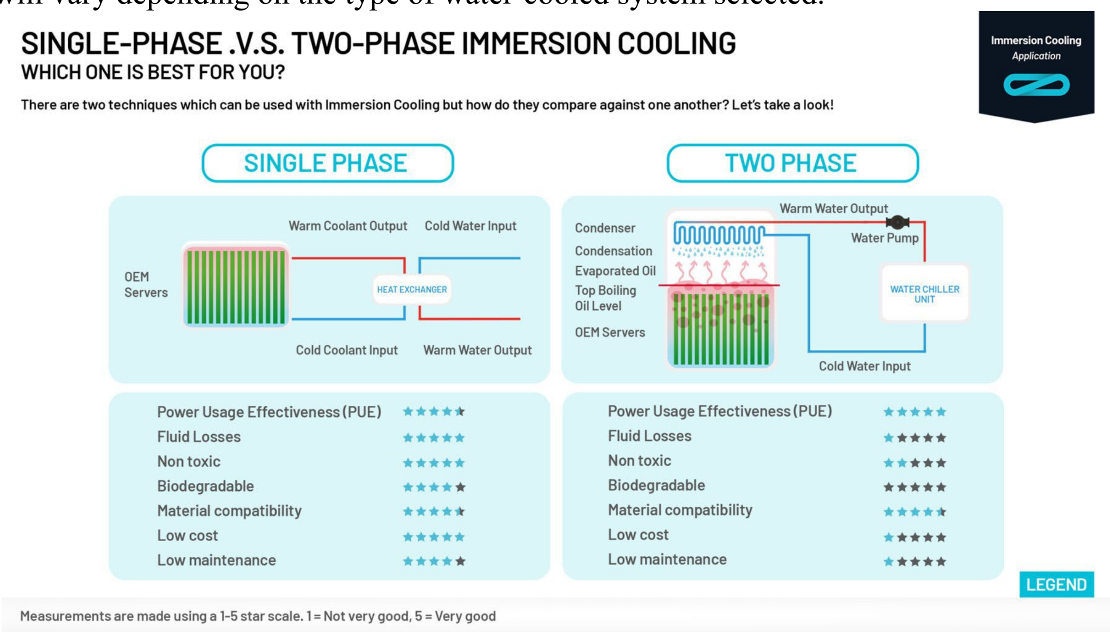

Figure 1: Energy consumption and adaptability comparison of water-cooling effect [6]

2. Models and Methods

2.1 Coil Heating and Cooling Model Based on Water-cooling

The entire modeling and simulation process uses the Fluent module in Ansys software to build the entire heat dissipation and cooling model. Firstly, create a model without water-cooling pipes and with six heating copper columns as heat sources. Use Fluent to render the model, and preliminarily infer the cloud map of natural cooling without water-cooling and heat dissipation based on the calculated observation results. Subsequently, the model with water-cooled tubes was used, and the other parameters were the same as those without water-cooled tubes. The heat dissipation effects of the two models were compared by rendering temperature cloud maps with and without water-cooled tubes [7].

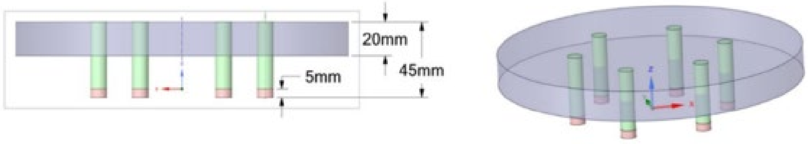

Figure 2: Structure diagram of heating coil for waterless cooling tube

As shown in Figure 2, there is no water-cooled cooling pipe installed in the heat dissipation coil. The diameter of the Aluminum plane is 200mm and the thickness is 20mm. Six heating copper columns are evenly distributed on the plane. The diameter of the heating copper pillar is 10mm, and the thickness of the heating point at the lower end is 5mm, generating 1W of heat. By calculation, it can be concluded that the volume of a single copper pillar is approximately 3.925 × 10 ^ (-7) cubic meters, and the heat generated by each cubic meter of copper pillar is 2.55 × 10 ^ (-7) W.

In the simulation, the heating and thermal conductivity effects of the copper pillar tend to be rationalized, so the temperature difference generated by the upper and lower heating coils of the copper pillar will also be more significant, which will be more pronounced under the water-cooling heat dissipation effect.

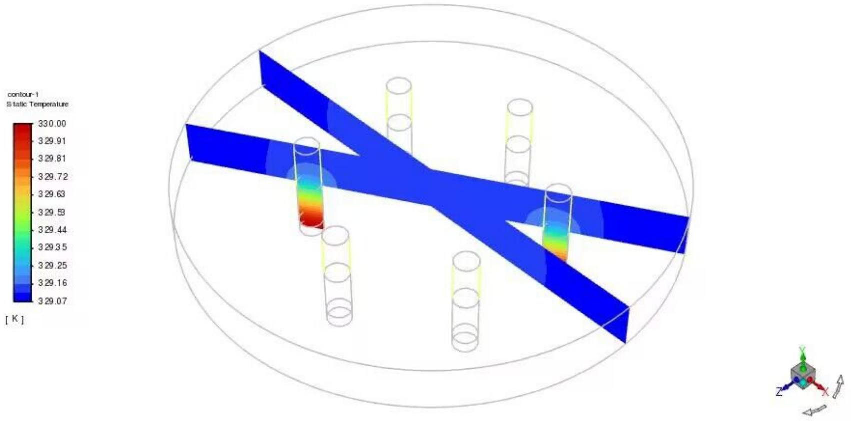

Figure 3: Temperature difference diagram of copper coil heating up and down without water-cooled pipeline

In this case, the water-cooling pipeline of the simulated adaptive optics device does not have water flow. As shown in the figure, the thermal conductivity and thermal conductivity of the copper column are good, which can ensure a significant temperature difference between the top of the copper column and the coil when the coil below heats up.

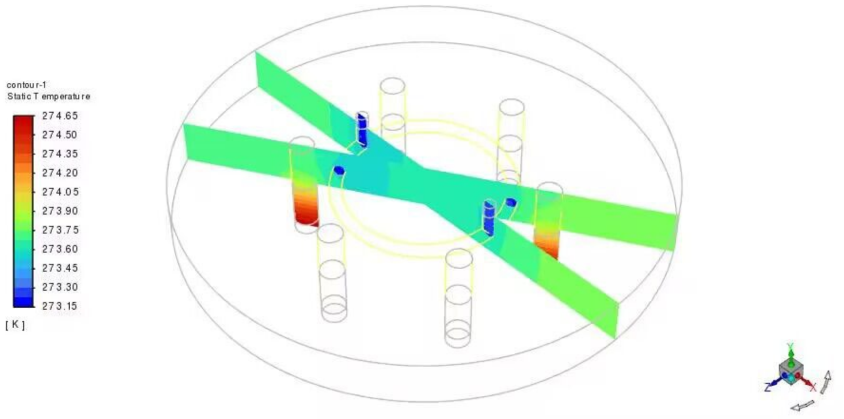

Figure 4: Temperature difference diagram of copper coil heating under water-cooled pipeline

Figure 3 is the temperature difference diagram of a copper coil heating up and down without a water-cooled pipeline. As shown in Figure 4, this is the effect of adding water-cooling pipes. The liquid in the water-cooling pipes is water with a temperature of 273 Kelvin, and the phase transition of water due to temperature is not considered during the water-cooling process. The model's boundary conditions are a room temperature of 293 Kelvin and a convective heat transfer coefficient of 2. In this model, the section of the water-cooling pipe intersects the copper column for cooling. The structure of the water-cooling pipe is shown in the following figure 5:

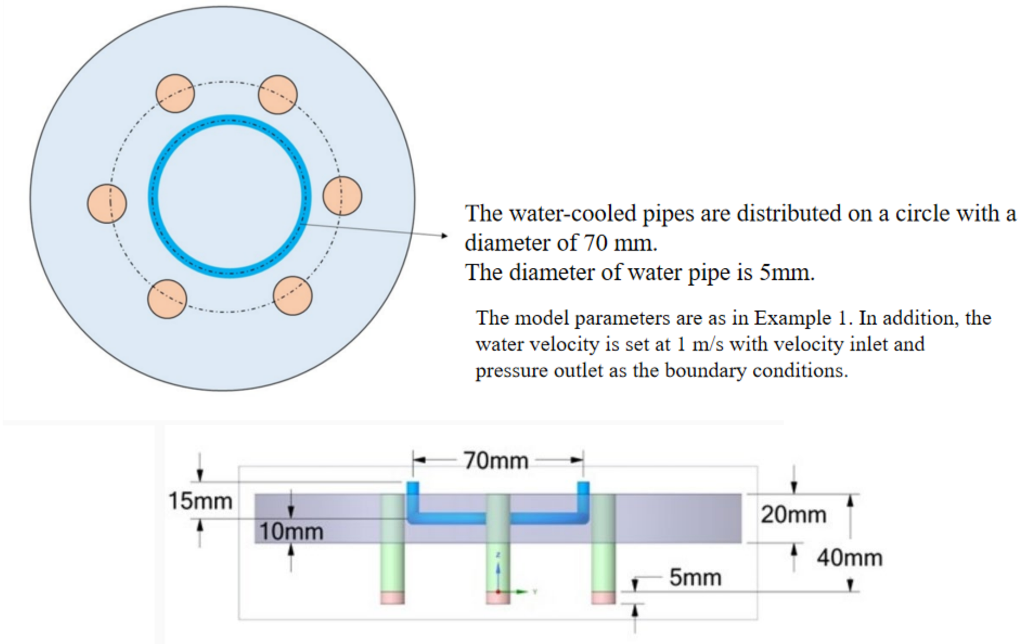

Figure 5: Distribution diagram of water-cooled pipes and heating copper columns structure

The water-cooled pipes are evenly distributed on a circumference with a diameter of 70mm. The diameter of the water-cooled pipes is 5mm, and the water flow velocity in the water-cooled pipes is one meter per second.

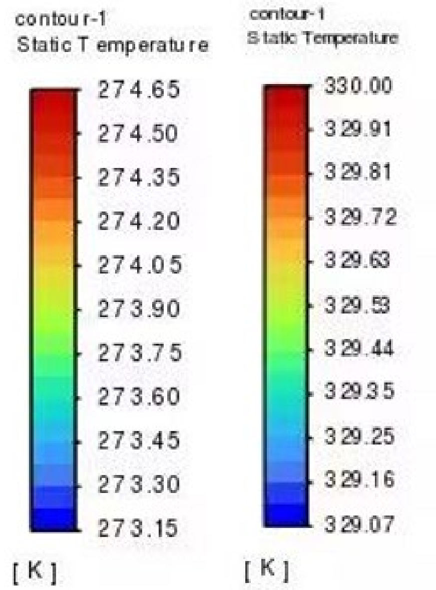

Figure 6: Comparison of temperature cloud maps and heat dissipation of copper coils with and without water-cooling

As shown in Figure 6, the maximum and minimum temperatures of the upper and lower ends of the copper column vary depending on the critical temperature with or without water-cooling. Nevertheless, the temperature difference between the upper and lower surfaces of the copper column with water-cooling is much greater than that without water-cooling. This is due to the higher specific heat capacity of water in the water-cooling system, which can absorb the temperature of the copper column while ensuring that its own temperature is minimally affected by the absorbed heat.

2.2 Introduction to Finite Volume Method

The finite volume method, also known as the finite volume method or the control volume method, is a commonly used numerical algorithm in computational fluid dynamics. The finite volume method is based on integral conservation equations rather than differential equations, which describe each control volume defined by the computational grid. The finite volume method focuses on constructing discrete equations from a physical perspective. Each discrete equation is an expression of the conservation of a certain physical quantity on a finite volume. The derivation process is clear in terms of physical concepts, and the coefficients of the discrete equation have certain physical meanings, ensuring that the discrete equation has conservation properties.

The finite volume method divides the calculation area into a series of control volumes [8], and integrates the differential equation to be solved for each control volume to obtain a discrete equation. The basic idea is to divide the calculation area into grids and have a non repeating control volume around each grid point. The differential equation (control equation) to be solved is integrated for each control volume to obtain a set of discrete equations. The unknown variables are the dependent variables on the grid points. In order to obtain the integral of the control volume, it is necessary to assume the variation law of the value of φ, which is the generalized variable, between grid points. From the perspective of the selection method of the integration region, the finite volume method belongs to the subdomain method of the weighted residual method. From the perspective of the approximation method without known solutions, the finite volume method belongs to the discrete method using local approximation. In short, the subdomain method plus discretization is the basic method of finite volume method.

The core of the finite volume method lies in the method of regional discretization, which essentially replaces the original continuous space with a finite number of discrete points. The implementation process of the finite volume method for region discretization is to divide the calculated region into multiple non overlapping subregions, i.e., the computational grid, and then determine the node positions and control volumes represented by each node in each subregion [7].

2.3 Specific process of finite volume method for model solving

Whether it is the continuity equation, momentum equation, or energy equation, they can all be written as the following general formula. The governing equation for one-dimensional problems:

$$\frac{d(\rho u\varphi)}{dx} = \frac{d\left(\frac{\tau d(\varphi)}{dx}\right)}{dx} + S \tag{1}$$

In the equation, ϕ is a generalized variable that can be a physical quantity to be solved for, such as velocity, temperature, or concentration. τ is the generalized diffusion coefficient corresponding to ϕ, and S is the generalized source term; ρ represents the density of the simulated object, and u represents the flow velocity of the simulated object.

Figure 7 is the solving process of finite volume method. When using the finite volume method to establish discrete equations, conservation forms must be used. The main steps of applying the finite volume method to solve the convection diffusion problem corresponding to the equation are as follows:

1) Generate a computational grid within the computational area, including nodes and their control volumes.

2)Integrate the conservation type control equation on each control volume (using the interpolation formula for the unknown variable Φ and its derivative at the interface, i.e. discrete format), and obtain the discretized algebraic equation system about the unknown variables at the nodes.

3) Solve algebraic equations to obtain the value of Φ for each computing node.

The process of finite element model simulation using the Fluent module in Ansys is as follows [9]:

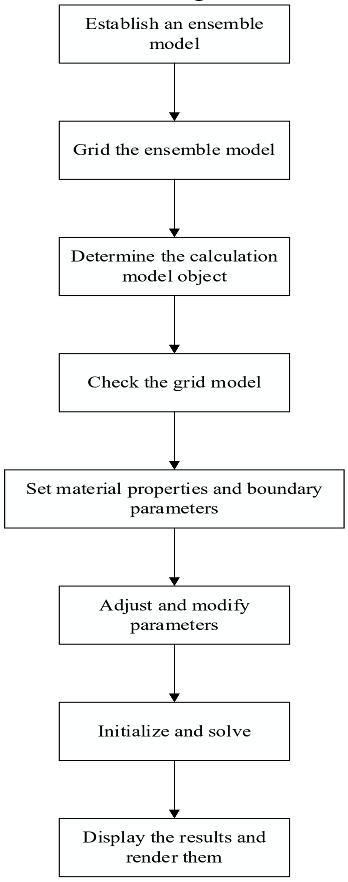

Figure 7: Solving process of finite volume method

3. Challenges and Future Development of Coil Heating Water-cooling

3.1 Challenge Analysis

(1) The adaptive mirror diameter is getting larger and the coil heat generation is increasing

As the diameter of the adaptive mirror increases, the computing power of the adaptive optics system will also significantly increase. However, due to the large amount of heat generated during its operation, the heat generation of the copper pillars in the system will also significantly increase. In the case where the distribution of cylinders and the spacing between each cylinder are the same, a water-cooling system with only one circle around the centre is definitely not enough.

We can arrange circular water-cooled tubes between every two layers of heating coil copper columns and double cross water-cooled tubes to ensure that the copper columns distributed on the outermost ring can also receive heat dissipation effects close to the centre.

(2) How to ensure the uniformity of temperature distribution

The thermal conductivity of materials significantly affects the distribution of temperature. In general, under the ideal conditions given in the previous text, where the copper pillars are completely identical, uniformly distributed, and have the same heat generation, the uniformity of temperature can be judged by the degree of uniformity of thermal conductivity. In the case of uniform thermal conductivity, the uniformity of temperature distribution can also be guaranteed. The Fourier formula used to calculate the thermal conductivity coefficient is expressed as follows:

$$Jr = -\kappa \frac{dT}{dx} \tag{2}$$

Where x represents the direction of heat flux

Jr represents heat flux, which is the heat transfer rate in the x-direction per unit area perpendicular to the transport direction

T represents temperature

K represents thermal conductivity, which is an inherent property of matter and cannot be easily changed

This formula indicates that the relationship between thermal conductivity q and temperature gradient is proportional, but the direction of heat flow is opposite to the direction of temperature gradient.

The partial differential equation here is not only considered in the x-direction in practical applications, but is generally elevated from one-dimensional to two-dimensional or even three-dimensional. In this case, the formula for the thermal conductivity coefficient can be written in the following form:

$$Jr = -\kappa \frac{\partial T}{\partial r} = -\kappa \nabla T = -\kappa * \left(\vec{i} \frac{\partial T}{\partial x} + \vec{j} \frac{\partial T}{\partial y} + \vec{k} \frac{\partial T}{\partial z} \right) \tag{3}$$

In this formula, $\frac{\partial T}{\partial r}$ is decomposed into three different directions, and partial differential differentiation is performed on the heat transfer that occurs in each direction.

Another example that confirms Fourier's law is the concept of hot gas, which is created from the mechanical motion of matter. From the perspective of microphysics, the appearance of any heat is the result of irregular motion of molecules. Therefore, we can link the mechanical motion of molecules with phenomena in thermal conductivity, thus linking microphysics and macrophysics. When studying Brownian motion, the irregular and uninterrupted motion of molecules is analogized through the conservation of mechanical energy to derive the formula for calculating internal energy; Similarly, in the study of heat conduction, we can approximately describe the heat generated during the irregular motion of molecules as a particle called a hot gas.

(3) Intelligent temperature control

The temperature control system needs to be equipped with a temperature detection system and a temperature control system. The temperature detection system in the equipment will be responsible for the temperature of the entire system and provide real-time feedback on temperature changes; At the same time, the temperature control system will make a judgment based on the temperature feedback from the temperature detection system, determine whether the temperature has risen to the point where it needs to be cooled down, and proceed with the cooling process. Through an intelligent temperature control system, the temperature of the entire device can be controlled within a stable range while ensuring that power consumption is minimized [9].

3.2 Future Development Trends

Immersion cooling and water-cooled cooling will become the mainstream cooling methods in the operation of large-scale instruments in the future. For large computers, immersion cooling can effectively and quickly reduce the large amount of heat generated during operation due to high power; For large instruments similar to adaptive optics, water-cooled cooling is clearly more suitable [10].

(1) Temperature control of water-cooled partition

In an ideal situation, water-cooling systems are generally equipped with temperature detection systems to detect temperature changes during water-cooling operation. In order to ensure a constant temperature throughout the system, a temperature control alarm system should also be added while cooling the device with water [17]. By installing temperature sensors in the water-cooling system to monitor temperature changes in real time, the temperature can be controlled during the circulation process of the water-cooling system, but abnormal temperature values may still occur during this process. Therefore, it is best to pair the adaptive water-cooling system with a constant temperature system to ensure that the water-cooling system is minimally affected by temperature fluctuations caused by the ambient temperature. In such a situation, the water-cooling system of adaptive optics will become more complex, and the temperature control system will also occupy a certain volume. In order to ensure the cooling effect of water-cooling, the original ideal design required more water-cooling pipes and higher power refrigerators to ensure the effectiveness of the water-cooling cycle and to minimize the temperature drop in the shortest stroke.

(2) Optimization of water-cooled pipeline structure

In order to ensure that in practical application, even in the presence of a constant temperature system, the water-cooled pipeline needs to be arranged more compactly. It can be modified from the original double cross shape to a double cross and two circular rings, so that water can flow over a longer distance in the same area, effectively improving the efficiency of water-cooled heat dissipation.

The following points need to be considered in the structural design of optimized water-cooled pipelines

(a) Adding circuits: After preliminary planning of the water flow channel design, numerical simulation revealed that the heat dissipation efficiency did not meet the requirements and the thermal resistance was high. In this case, adding circuits can be considered, such as changing from single cycle to double cycle, or even more, to enhance heat transfer

(b) Balanced water-cooling area: Try to evenly cover the contact surface of the flow channel passing through the heat source. In the same area, the longer the fluid travels, the more significant the heat dissipation effect. Therefore, a spiral shape may be a good choice

(c) Avoiding short circuits: When the inlet and outlet are very close, the rib structure of the waterway design is often used to extend the waterway and distribute it directly below the heat source, avoiding direct water flow from the inlet to the outlet

Modifying the heat exchange components of the liquid cooling system while retaining the water-cooled pipes, the internal heat exchange groove structure of the heat exchange components will affect the efficiency of liquid cooling heat dissipation, and the different internal flow channel designs will greatly affect the heat dissipation effect [11].

In the structural design of water-cooled plates, the following points need to be considered:

(a) Heat transfer performance requirements: Under the setting of flow rate and inlet and outlet water temperature difference, achieve the temperature rise target of the heat source, as well as the thermal resistance target of the radiator, and the requirements for its heat transfer performance

(b) Strength and pressure requirements: Some projects may require special instructions on the surface pressure and overall stress situation of the water-cooled plate due to the usage environment and installation requirements inside the system

(c) Anti corrosion requirements: Liquid cooling medium flowing in the channel for a long time will be affected by high temperature, which will aggravate the damage of metal materials, and even block them, affecting the heat dissipation efficiency

(d) Leak prevention requirements: The design of the cover plate, upper and lower end faces, sealing strips, and even welding methods can all achieve leak prevention measures

(e) Low-cost requirement: Reduce the costs caused by pump pressure, working hours, etc. from the dimensions of production and processing feasibility, material selection, process complexity, flow resistance, thermal resistance, etc

(3) Media with higher thermal conductivity

For the heat transfer medium of water-cooled heat dissipation, both the coolant and the metal heat transfer plate are extremely important. The thermal conductivity of the coolant will affect the total heat that can be transferred by the liquid per unit time, while the heat transfer plate will affect the efficiency of the entire water-cooled heat dissipation process. Both are indispensable [12].

For general water-cooled heat dissipation, deionized pure water is generally used as the coolant, which is inexpensive, environmentally friendly, and pollution-free [14-15]. However, the disadvantage is that pure water is extremely susceptible to contamination by other solutes during operation. Once contaminated, it is difficult to maintain its insulation state. Therefore, once it leaks, it will cause irreversible losses.

Mineral oil heat dissipation is also feasible. It is inexpensive and insulating, but it is easy to decompose and prone to spontaneous combustion at high temperatures. The actual risk caused by it may be much greater than that of pure water [16].

Fluorinated liquid is currently the mainstream heat dissipation liquid, which is insulating and not easy to burn, but compared to it, its price is the most expensive.

For water-cooled thermal conductive materials, Aluminum alloy and copper are both excellent thermal conductive materials. Aluminum alloy has a high thermal conductivity, low density, and lower cost compared to copper, making it a good material for water-cooled plates. At the same time, Aluminum products have strong corrosion resistance and mature anti-corrosion processes, which can ensure the reliability of water-cooled plates in long-term operation [13].

4. Conclusion

In adaptive optics, water-cooled heat dissipation is an essential part of wavefront distortion correction to ensure the normal operation of the instrument [18-19]. Compared with other heat dissipation methods, it has higher efficiency and better heat dissipation effect. Water-cooling has significant heat dissipation effects in large instruments such as adaptive optics, and may supplement copper coil heat dissipation in future laptops and other small devices to achieve better results. By installing a water-cooled cooling system, the temperature generated during the operation of the adaptive telescope can be significantly reduced to correct wavefront distortion, thereby ensuring the accuracy of the data provided by the instrument during operation and data analysis. The water-cooling system set in adaptive optics ideally achieves the best cooling effect when using Aluminum alloy as the cooling plate and fluorine liquid as the heat dissipation liquid; However, when considering temperature regulation, it is necessary to add a temperature control system on top of the water-cooling system. Therefore, most of the Aluminum alloy plates used in adaptive optics are paired with purified water.

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