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Performance analysis of tower-based water cooling system for data centers with different ambient temperatures and relatively humidities

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ABSTRACT

With the increase in the heat flux density of data centers, liquid cooling of data centers is becoming increasingly important. A cooling tower is typically employed in liquid cooling systems and its cooling performance is affected by ambient temperature and relative humidity. In this study, we analyze the effects of these factors on cooling performance as well as power consumption, which have previously not been studied in detail. For this purpose, we built a 4.8 kW data server cold-water system and used a fin-type water-cooled radiator for heat dissipation. The energy consumption of the cooling system under different ambient temperature and relative humidity conditions was simulated and analyzed using TRNSYS simulation software. Assuming that the chip operating temperature is 70 °C, when the ambient temperature increases from 5 °C to 30 °C, and the ambient relative humidity increases from 40 % to 80 %, the optimal primary cooling water flow and the secondary cooling water flow increase accordingly, and the corresponding energy consumption of the cooling system increases. By considering the optimal flow rates, we found that the power usage effectiveness (PUE) is in the range 1.14–1.21.

Keywords: data center, power consumption, cooling tower, ambient temperature, relatively humidity

1. INTRODUCTION

With the rapid development of information and communication technologies, the speed requirements for data processing in various industries are increasing. In addition, the integration of electronic components increases linearly, which leads to an increase in the heat dissipation of a single unit. The main heating element is the CPU chip. To ensure that the chip operates within a safe range, it must be thermally managed to satisfy the operating requirements. The energy consumption ratio of the cooling system is 40 % of the total energy consumption of the entire data center [1]. Therefore, an efficient cooling system and the thermal management of data centers is an important challenge [2]. There is an urgent need for the design and development an efficient cooling system that reduces energy consumption, while lowering the temperature of the data center.

At present, the most developed method of data center cooling is the air-cooling mode. However, with an increase in the data center scale and an increase in the heat flux density of a single unit, the traditional air-cooling method can no longer meet the large-scale cooling needs. Therefore, the water cooling mode has been favored by many researchers in recent years [3]. Two factors are mainly considered when adopting the cooling mode: optimization of the internal heat sink and optimization of the external cooling source. Heat sink optimization is mainly reflected in two aspects: shape and internal size optimization. In terms of shape optimization, Maajej [4] and Zhu [5] adopted a finned air-cooled pipe system, and a ring-shaped heat pipe, respectively. Leng [6] designed a two-layer microchannel heat sink and optimized the temperature uniformity and thermal resistance variables of the bottom wall. In terms of radiator size optimization, Minking [7] studied the effect of the height of the loose-fin array on heat transfer performance. Shwaish[8] and Jajja[9] studied the effects of fin height and fin spacing on heat dissipation performance. Kumar [10] studied the effects of the fin height, fin thickness, and inlet angle on the cooling capacity of a radiator. The research on external cold sources mainly focuses on their efficiency and energy consumption. Kanbur [11] introduced single-phase and two-phase immersion-cooling systems. Levin [12] designed a liquid immersion server and considered the structure, layout, and technical characteristics of the liquid immersion cooling system. Yang [13] proposed a hybrid cooling source operation mode by switching the traditional mechanical cooling mode, partial free cooling mode, and all free cooling mode according to the outdoor temperature. Zhang [14] introduced an integrated cooling system for mechanical refrigeration and thermosiphons. Through a review of the literature, we found that research on optimizing the combination of internal and external cooling in liquid-cooling systems remains limited. The performance of the heat sink determines the parameters of internal circulation cooling; therefore, in discussing the energy consumption of the cooling system of the data center, it is necessary to consider the type of heat sink, cooling source, internal cooling cycle of the server, and external cooling source circulation. To optimize the thermal management of the internal and external cooling of the server, it is necessary to determine the best conditions for the internal and external cooling cycles based on minimum energy consumption of the cooling system. Zhang [15] used a new type of radiator inside the cooling tower as a cold source to calculate and analyze the annual energy consumption of the cooling system; however, they did not consider the impact of ambient relative humidity on the energy consumption of the cooling system. The main objective of this study is to analyze and optimize the energy consumption of the cooling system under different ambient temperatures and ambient relative humidity when the chip is guaranteed to run at 70 °C.

2. METHODOLOGY

2.1 System construction

A data center cooling system consisting of a server cabinet with total 4.8 kW load and a water-cooling system with cooling tower taken. The server cabinet includes 12 chips of each has a thermal power of 400 W. and the water-cooled fin-type heat sink is located on the top of each chip. The system equipment and coupled water circulations are shown in Fig. 1. Two water cycles were connected by a plate-type heat exchanger in a countercurrent manner. The water on the side of the cooling tower was called primary cooling water (run by Pump-1), while the water on the side of the server cabinet (run by Pump-2) is called secondary cooling water. The q_{v1}, q_{v2}, $T_{server,in}$, and T_{atm} denote the primary water flow rate, secondary water flow rate, water inlet temperature of the server, and water supply temperature of the chiller, respectively. The fin-type water-cooled heat sink structure is taken, where, L_b=115 mm, W_b=78 mm, and H_b=3 mm refer to the length, width, and height of the bottom plate, respectively. L_f =72.6 mm, W_f =0.8 mm, H_f =3.5 mm, and S_f =0.45 mm express the length, width, height of one fin, and the space between two fins, respectively.

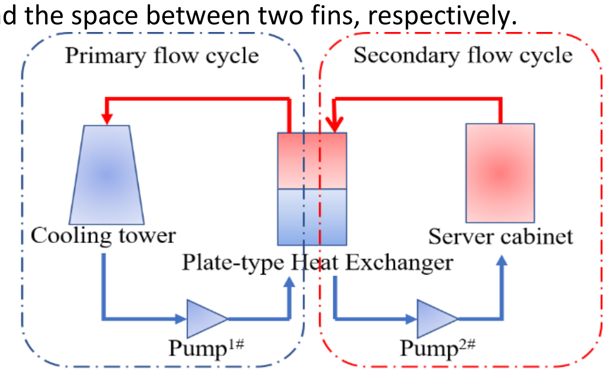

Fig. 1 Schematic of data center cooling system

2.2 Modeling

According to Fourier's law, for a one-chip water-cooling unit, the chip temperature can be expressed by the following equation:

$$T_{chip} = T_f + Q \cdot R_{total} \quad (1)$$

where R_{total} (K W^{-1}) is the total thermal resistance, and Q (kW) denotes the thermal power from one chip, which is a constant value of 400 W in this study. T_f (°C) represents the average temperature of the fluid.

According to the heat transfer mechanism, the total thermal resistance between the coolant and hot chip can be classified as follows: the contact thermal resistance R_{cont} (K W^{-1}), which appears at the interface surface between the heat sink plate and chip; conduction thermal resistance R_{cond} (K W^{-1}), which appears in the heat sink plate; and convection thermal resistance R_{conv} (K W^{-1}) caused by water fluid flow. Therefore, R_{total} can be calculated as follows:

$$R_{total} = R_{cont} + R_{cond} + R_{conv} \quad (2)$$

The three thermal resistances are calculated by the following equations:

$$\begin{cases} R_{cont} = \delta_s / \left\{ L_f \left[(n-1) S_f + n * W_f \right] \lambda_s \right\} \\ R_{cond} = H_b / \left(W_b L_b \lambda_c \right) \\ R_{conv} = 1 / \left\{ h \left[L_f S_f (n-1) + 2\eta_f L_f H_f (n-1) \right] \right\} \end{cases} \quad (3)$$

Where δ_s =1.5 mm and λ_s =4.5 W m^{-1} K^{-1} are the thickness and thermal conductivity of the thermal grease, respectively; n =38 is the number of fins in one heat sink; h is the heat transfer coefficient when water flows through the heat sink, and η_f is the fin efficiency; λ_c =400 W m^{-1} K^{-1} is the thermal conductivity of copper.

To calculate and compare the cooling system efficiency, the power consumed by the IT equipment and cooling system was considered as the total power consumption. Other parts power consumptions, such as power supply, distribution, and auxiliary equipment were excluded. Therefore, the power usage effectiveness (PUE) was applied to evaluate the air conditioning system in a data center as follows [17]:

$$P_{system} = P_{chiller} + P_{pump1} + P_{pump2} \quad (4)$$

$$\text{PUE} = (P_{IT} + P_{system})/P_{IT} \quad (5)$$

where P_{system} denotes the total power consumption of the cooling systems, and PIT refers to the power consumption of the IT equipment. $P_{chiller}$, P_{pump1}, and P_{pump2} contribute to the power consumption of the chiller, power consumption of Pump-1, and power consumption of Pump-2, respectively.

TRNSYS was applied to calculate the power consumption in the entire cooling system under various working conditions. A constant load of 4.8 kW was input into the model. The inlet and outlet temperatures and the power consumed by each equipment could be calculated by the temperature modules and power consumption modules in the software automatically by inputting the equipment and fluid parameters.

3. RESULTS AND DISSCUSION

3.1 Effect of ambient relatively humidity

To maintain chip operation within a safe temperature range, cooling water is required to remove the generated heat. The parameter settings of the cooling water have a certain relationship with each other, including the flow of the primary cooling water, the flow of the secondary cooling water, and the temperature and relative humidity of the environment. In order To study the influence law between various parameters, we assume that the operating temperature of the chip is 70 °C and study the system energy consumption of the water-cooling system under different working conditions, and optimize the working condition parameters.

Fig. 1 shows the primary and secondary cooling water flows required to ensure the working temperature of the chip when the ambient temperature of the cooling system is 15 °C under different cabinet inlet water temperatures and relative humidities. As shown in the figure, the influence of the cabinet inlet water temperature on the required secondary cooling water flow is much greater than that on the required primary cooling water flow. As the inlet water temperature of the cabinet increased, the required secondary cooling water flow increased significantly, and the higher the temperature, the greater was the increase. At a certain ambient temperature, the required primary cooling water flow is also affected by the inlet water temperature of the cabinet and relative humidity of the environment. As the inlet water temperature of the cabinet increased, the required primary cooling water flow showed a decrease first followed by an increase, with a minimum primary cooling water flow. When the inlet water temperature of the cabinet remained unchanged, the required primary cooling water flow gradually increased as the relative humidity of the environment increased. The ambient relative humidity also affected the minimum inlet water temperature of the cabinet. As the ambient relative humidity increased, the minimum inlet water temperature of the cabinet gradually increased. In other words, a lower ambient relative humidity enables a lower cabinet inlet water temperature. As the relative humidity of the environment increased, the minimum required primary cooling water flow also increased.

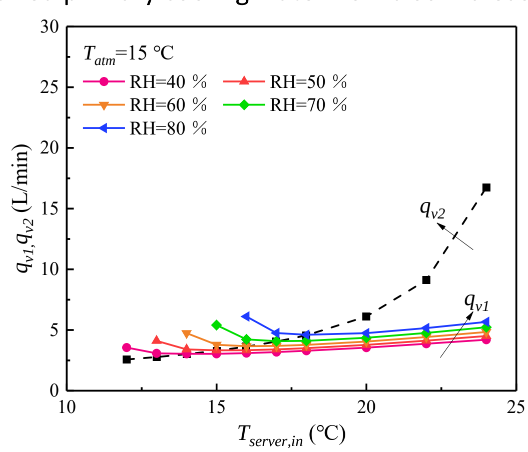

Fig.1 Effect of relative humidity and cabinet inlet water temperature on cooling water flow at T_{atm} = 15 ℃

The power consumption values of the cooling system corresponding to Fig. 1 are shown in Fig. 2, from where it can be observed that when the relative humidity of the environment is constant, the power consumption of the cooling system increased rapidly after the inlet water temperature of the cabinet increased beyond 18 °C. The main reason is that the increase in the secondary cooling water flow rate is too fast at this time, resulting in an increase in the energy consumption of the secondary pump; thus, the total energy consumption of the system increased rapidly. When the inlet water temperature of the cabinet is fixed, the total power consumption of the cooling system increased gradually with an increase in the relative humidity of the environment. The energy consumption of the stage pump was determined. With the increase in the inlet water temperature of the cabinet, the power consumption decreased first and then increased. The optimal cooling water working condition parameters were obtained at the minimum point of total energy consumption. Taking the relative humidity of the environment to be 80 % as an example, the optimal cabinet inlet water temperature $T_{server,in,opt}$ was 17 °C. Combined with Figure 1, the corresponding optimal primary water flow $q_{v1,opt}$ was 4.75 L/min, and the optimal secondary water flow was 4.75 L/min. The flow rate $q_{v2, opt}$ was 4.04 L/min.

Fig. 3 shows the optimal cooling water condition parameters ($T_{server,in,opt}$, $q_{v1,opt}$, $q_{v2,opt}$) corresponding to the minimum system power consumption under different relative humidity conditions at T_{atm} = 15 °C It can be seen from the figure that with the change in the relative humidity of the environment, both the optimal primary cooling water flow and the optimal secondary cooling water flow increase constantly, but the growth rates between the two tend to be consistent. For every 10 % increase in ambient relative humidity, the optimum cabinet inlet water temperature increases by 1° C.

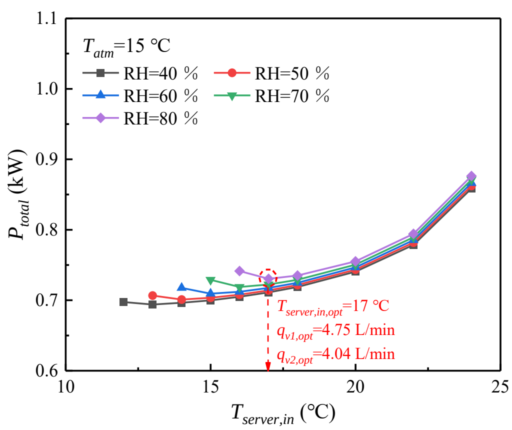

Fig.2 Power consumption with variation in ambient relative humidity and cabinet inlet water temperature at T_{atm} = 15 °C

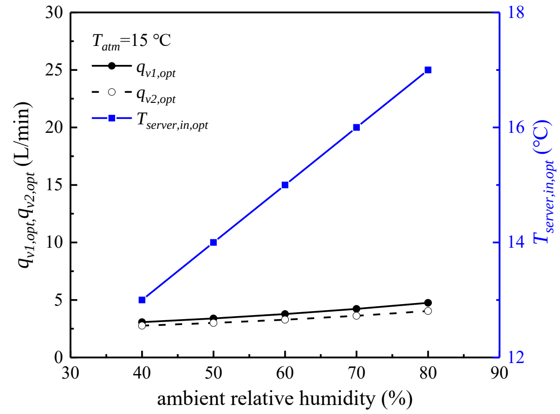

Fig.3 Optimal cooling water flow and cabinet inlet water temperature for different ambient relative humidities at T_{atm} = 15 ℃

3.2 Effect of ambient temperature

The previous analysis was for an ambient temperature of 15 °C. Here we analyze the influence of different ambient temperatures on the system performance. The minimum power consumed when the cooling system operates under different ambient temperatures and relative humidities is shown in Fig. 4. As can be seen from the figure, when the relative humidity of the environment remained unchanged, the energy consumption of the cooling system increased with an increase in the ambient temperature. For constant ambient temperature, the energy consumption of the cooling system increased gradually with the increase in the ambient relative humidity mainly because the primary cooling water absorbed heat from the plate heat exchanger, and then released the heat to the environment through the cooling tower. When the relative humidity of the environment increases, the heat release effect is very poor, and the heat exchange rate can only be accelerated by increasing the cooling water flow; therefore, the energy consumption of the first-stage pump increased, and the total energy consumption increased. In addition, under different ambient relative humidities, the maximum ambient temperature for normal operation of the system is different. When the relative humidity is high, the system can operate normally only at a lower ambient temperature, and when the relative humidity is low, a higher ambient temperature is needed for normal operation of the cooling system.

The optimal primary cooling water flow rate and optimal secondary cooling water flow rate of the system corresponding to the minimum energy consumption values in Fig. 4 are shown in Fig. 5 and Fig. 6. It can be seen from Fig. 5 that at constant relative humidity of the environment, with an increase in the ambient temperature, the optimal primary cooling water flow also increased gradually, which is mainly due to the decrease in the temperature difference between the water and the environment, but the heat exchange between them remaining constant. In order to meet the requirements, the cooling water flow can only be increased once. When the relative humidity of the environment increases, the moisture content in the ambient air increases, and its heat absorption capacity per unit time decreases, so the primary cooling water flow rate must increase to provide effective cooling.

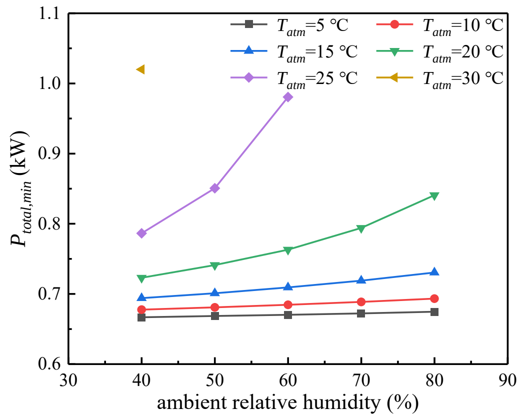

Fig.4 Minimal energy consumption at different ambient temperatures and ambient relative humidities

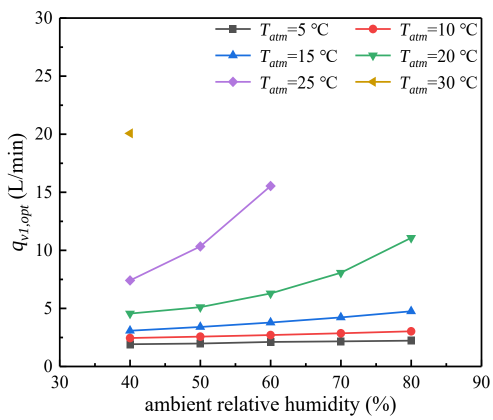

Fig.5 Optimal primary cooling water flow at different ambient temperatures and ambient relative humidities

As shown in Fig. 6, as the ambient temperature increased, the secondary cooling water flow also gradually increased. This is mainly because the ambient temperature affects the primary cooling water flow, but the heat exchange capacity of the plate heat exchanger is constant; therefore, it will indirectly affect the cabinet inlet water temperature, which leads an increase in the secondary cooling water flow.

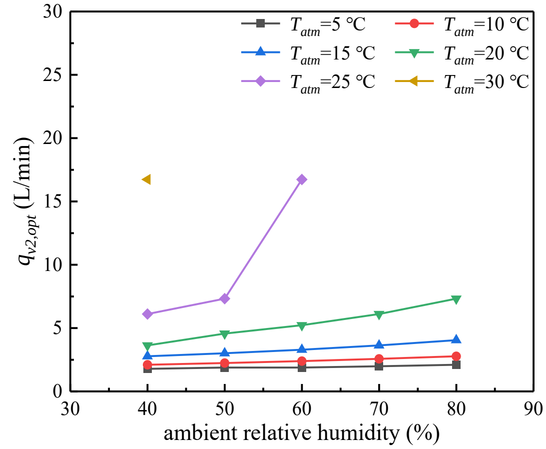

Fig.6 Optimal secondary cooling water flow at different ambient temperatures and ambient relative humidities

Fig. 7 shows the PUE value of the cooling system corresponding to Fig. 4. As is evident from Fig. 7, as the ambient temperature and ambient relative humidity increase, the PUE value of the cooling system also increases gradually. For temperatures higher than 20 °C, the sharp increase is mainly due to the large increase in the energy consumption of the cooling system. By contrast, when the ambient temperature is low, the difference between the PUE of the cooling system at different ambient relative humidities is small. The smaller the energy consumption of the cooling system, the smaller the PUE; therefore it the cooling tower can be operated when the ambient temperature and relative humidity are low, resulting in minimum power consumption safe operation of the chip. Given the range of ambient humidity and temperature, when the system operating conditions are optimally designed, the achievable PUE range is 1.14–1.21.

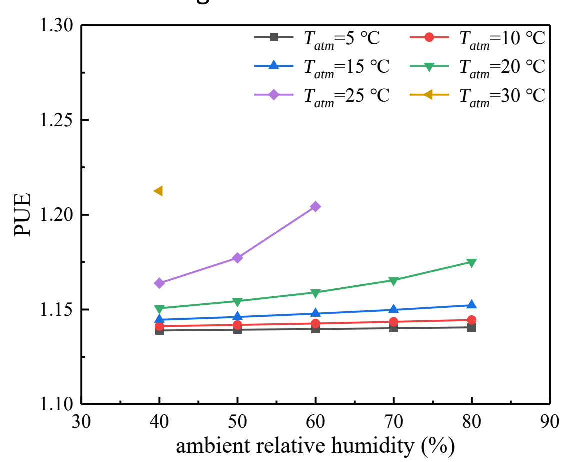

Fig.7 Minimal PUE at different ambient temperatures and ambient relative humidity

4. CONCLUSIONS

Taking the safe operating temperature of the chip at 70 °C as an example, a performance analysis of data center water cooling systems with different ambient temperatures and relative humidities based on the cooling tower was performed. The main findings are as follows:

(1) When the ambient temperature and ambient relative humidity remain unchanged, there is minimum power consumption, and optimal primary and secondary cooling water flows can be obtained. By contrast, when the relative humidity of the environment increases, the optimal primary cooling water flow gradually increased, resulting in an increase in the optimal secondary cooling water flow. For a relative humidity of 80 %, the optimal rate of primary water flow was 4.75 L/min, that of secondary water flow was 4.04 L/min, and the optimal cabinet inlet water temperature was 17 °C.

(2) When the relative humidity remains unchanged, both the optimal primary and secondary water flow rates increase with an increase in the ambient temperature, and the system energy consumption also increases. The results indicated that the PUE ranged between 1.14–1.21 when the ambient temperature and relative humidity were in the ranges of 5–30 °C and ambient relative humidity 40–80 %, respectively.

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