Paper ID APEN-MIT-2022_2791
Applied Energy Symposium: MIT A+B
July 5-8, 2022 • Cambridge, USA

Liquid cooling system optimization of data center server by considering monthly ambient temperature and humidity

1st Wei He
Tianjin Key Laboratory of Refrigeration Technology
Tianjin University of Commerce
Tianjin,China
weihe@tjcu.edu.cn

2nd Yuanyuan Shi
Tianjin Key Laboratory of Refrigeration Technology
Tianjin University of Commerce
Tianjin,China
shiyy@stu.tjcu.edu.cn

3rd Jifang Zhang
Tianjin Key Laboratory of Refrigeration Technology
Tianjin University of Commerce
Tianjin,China
17793503710@163.com

4th Hailong Li
Tianjin Key Laboratory of Refrigeration Technology
Tianjin University of Commerce
Tianjin,China
hailong.li@mdh.se

5th Shengchun Liu
Tianjin Key Laboratory of Refrigeration Technology
Tianjin University of Commerce
Tianjin,China
liushch@tjcu.edu.cn

Abstract— With the rapid development of big data, the scale of data center is becoming larger and larger. The heat generated by the servers in the data center is also increasing, which puts forward higher requirements for the cooling of the data center, which should have strong enough heat dissipation capacity and low enough energy consumption. This paper is committed to reducing the cooling energy consumption of the data center and reducing the PUE of the system. This paper studies a server cabinet with a power of 4.8KW. The fins indirect water-cooled radiator is used to cool the chip, and the cooling tower cold source cycle is constructed outside. In order to facilitate the research, TRNSYS software is used to model the system, and the internal modules of TRNSYS software are selected to build the system.Through TRNSYS simulation and thermodynamic calculation, the relationship between the chip temperature and the server inlet water temperature and secondary water flow is studied. The system working conditions from March to October in Tianjin are studied which all change with the change of ambient temperature and relative humidity. The results shows that the optimal cabinet inlet water temperature, primary water flow, secondary water flow, system power and PUE of the system will change accordingly with the change of ambient temperature and relative humidity. In Tianjin in each month, the range of PUE is 1.032-1.091, and the variation range of system power is 0.154 kW to 0.437kW when run at the optimal conditions.

Keywords—data center, PUE, energy consumption, ambient temperature, ambient humidity

I. INTRODUCTION

Rapid development of digital information, such as big data, Internet, and 5G, has led to the increasing demand of data centers. Increase in the size of the data center has not only increased the ability to process information, but has also led to high energy consumption and high heat generation, which increase the system temperature and further causes server or system failure. Therefore, more attention is paid to studies on data center cooling and reducing system energy consumption. Development of an efficient cooling system is necessary to reduce chip heat and energy consumption.

Data centers generally adopt reliable and mature air-cooling methods. Eduard et al. [1] integrated direct air-free cooling strategy with thermal energy storage system in data centers around Europe to study its potential. To improve the disadvantage of air cooling, Jayantha et al. [2] equipped it with an air mixer, air filter and humidifier combined the observation with the hourly temperature and humidity data of 20 meteorological stations in the major cities of Australia during the decade. This study proved that the use of air side economizers in some states has great potential to significantly save the cooling cost of data center operators. Hiroshi et al. [3] built a fresh air-cooling container data center in the suburbs of Tokyo and tested it for one year; this system annually saved 20.8% energy compared with the centers that use conventional air conditioning. However, an air-cooled system rack has a low power density, which cannot meet the demand of 30 kW+ required in super large-scale and high-performance data centers. Hence, modern studies became more focused on the liquid cooling system. Aayush et al. [4] found that water side economizers have significant energy-saving potential in most areas. Compared with the air-cooled chiller system, it can save >30% energy in some climatic areas. Howard et al. [5] established a water-cooled multi chiller cooling system for data centers, and enhanced its reliability and availability. Michael et al. [6] reintroduced water-cooling technology into its high-performance computing platform, and used water-cooled panels to cool processor modules. Manasa et al. [7] designed the cooling device with a micro rack, where each server was equipped with two cold plates to cool the CPU, while the other components were air-cooled. The study was conducted to compare the distributed and centralized coolant pumping systems. Whelan et al. [8] designed a water-cooled heat dissipation system for chip cooling. This system can cool a chip with a heating capacity of 200 W and maintain its temperature at 65 °C. Zimmermann et al. [9] found that a cooling system that uses water at 60 °C performs better, and can save up to 40% energy compared with the data center using traditional air-cooling system.

The above studies are regarded to be one sided as the working conditions and thermal management of the whole system were not fully considered. It is necessary to study the energy consumption and thermal management of the system from its perspective. Previously, we had carried out a similar study on the thermal management optimization of the whole system, mainly focusing on the influence of partial load and safety chip temperature based on finned cold plate radiator and cooling tower cold source under a given constant ambient temperature [10], and also studied the influence of ambient temperature on the whole system [11]. However, the influence of relative humidity on the system was not considered. Relative humidity varies greatly throughout the year and significantly impacts the cooling performance of the cooling tower, and needs more detailed study. This paper establishes a cooling system, which is mainly composed of a finned indirect radiator, cooling tower, and water pump. The system has two coupled water cycles. The external primary water cycle is completed by the cooling tower, and the internal secondary water cycle is completed by the finned indirect radiator on the cabinet server. Optimization conditions of the internal and external cooling system were studied. Additionally, the local climate in Tianjin, both the ambient temperature and relative humidity, were considered to understand the optimal operating conditions of the system, and better study the thermal management of the system to reduce its energy consumption.

II. METHOD

A. System construction

A cooling system was established for the data center to improve its energy efficiency. It consisted of a server cabinet with a total load of 4.8 kW and a water-cooling system with an air-cooled chiller. The server cabinet includes 12 chips with a thermal power of 400 W each. Each chip was equipped with a finned water-cooled radiator on top to dissipate the chip heat. The system equipment and the coupled water cycle are shown in Fig. 1. The device contained two coupled water circulation systems, connected by a plate heat exchanger. Primary and secondary cooling water were exchanged through a plate heat exchanger, where the heat exchanger works in counter-current. The external primary cooling water circulation was installed on the cold source side) and the internal secondary cooling water circulation was located on the server side of the data center.

The experiments were cumbersome to be conducted in real system; therefore, we simulated them to obtain more experimental data in this system. TRNSYS (Transient System Simulation Program) is a transient system simulation program, from which we built a data center cooling simulation system based on the thermal and power model, (Fig. 1). The system consists of a cooling tower module, two cooling water pump modules, a plate heat exchanger module, a server module, three result display modules, and two power calculation modules. The length, width, and height of the base plate were L_b = 47 mm, W_b = 33 mm, and H_b = 2 mm, respectively (Fig. 1). The length, width, height, and spacing between two fins were L_f = 30 m, W_f = 0.5 mm, H_f = 3.5 m, and S_f = 2 mm, respectively.

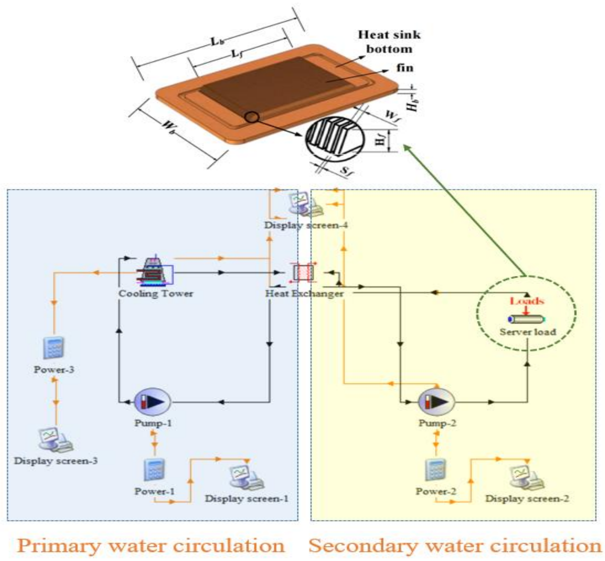

Fig.1 Schematic of data center cooling system in TRNSYS model and fin-type water cooled heat sink structure

After setting the load in the software, the temperature and power consumption modules can automatically calculate the inlet and outlet water temperatures and power consumption of each equipment by inputting equipment and fluid parameters. In the simulation system, 400 W is input in the load module setting to represent the thermal power of the server cabinet. After this, given the secondary water flow, the system can be balanced by adjusting the primary water flow to obtain the corresponding optimal cabinet inlet water temperature, system power, and power usage effectiveness (PUE).

B. Modeling and calculation

1) Heat dissipation model of chip water-cooling unit

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

$$T_{chip} = T_f + Q \cdot R_{total} \tag{1}$$

where R_{total} (K/W) is the total thermal resistance, and Q (kW) is 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, total thermal resistance between the coolant and hot chip can be classified as follows: the contact thermal resistance R_{cont} (K/W), which appears at the interface between the heat sink plate and chip; conduction thermal resistance R_{cond} (K/W), which appears in the heat sink plate; and convection thermal resistance R_{conv} (K/W) caused by water fluid flow. Fig. 2 shows the schematic diagram of the thermal resistance network model of the chip water cooling and heat dissipation unit structure.

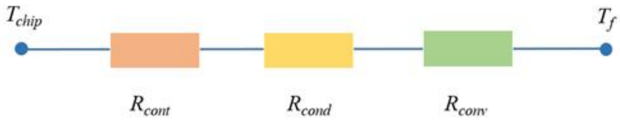

Fig.2 Thermal resistance model

Therefore, R_{total} can be calculated as follows:

$$R_{total} = (T_{chip} - T_f)/Q = R_{cont} + R_{cond} + R_{conv} \quad (2)$$

where the contact thermal resistance R_{cont} can be considered as a constant fixed value of ~0.052, estimated after multiple experimental verification.

h is the heat transfer coefficient when water flows through the heat sink (wm^{-2}k^{-1}) and η_f is the fin efficiency.

The conductivity resistance R_{cond} is calculated by:

$$R_{cond} = H_b/(W_b L_b \lambda_c) \quad (3)$$

where λ_c = 400 W/mK is applied as the thermal conductivity of copper.

The convection resistance R_{conv} is calculated by:

$$R_{conv} = 1/\left\{h\left[L_f S_f (n-1) + 2\eta_f L_f H_f (n-1)\right]\right\} \quad (4)$$

where h is the heat transfer coefficient when water flows through the heat sink (wm^{-2}k^{-1}), n represents the number of fins, and η_f is the fin efficiency, which is calculated using

$$\eta_f = \tanh\left(\sqrt{2h(L_f+W_f)/(\lambda_c L_f W_f)}H_f\right)/\left(\sqrt{2h(L_f+W_f)/(\lambda_c L_f W_f)}H_f\right) \quad (5)$$

2) Power consumption model of the cooling system

Energy consumption of the data center consists of the energy consumption of an IT, a refrigeration system, power supply and distribution system, and other equipment. Among them, energy consumption of the IT and refrigeration system equipment account for ~85%. To simplify the simulation, energy consumption of the power supply and distribution system equipment and other equipment was ignored, and only that of the IT and refrigeration system equipment were considered.

To calculate and compare the cooling system efficiency, power consumed by the IT equipment and cooling system was considered as the total power consumption. Power consumptions of the other parts, such as power supply, distribution, and auxiliary equipment were excluded. PUE was applied to evaluate the air conditioning system in a data center as follows:

$$P_{system} = P_{chiller} + P_{pump1} + P_{pump2} \quad (6)$$

$$\text{PUE} = (P_{IT} + P_{system})/P_{IT} \quad (7)$$

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

III. Results and Discussions

To reduce the power consumption of the data center and estimate its optimal operation condition, further research was carried out in the above simulation system.

A. Optimal working condition analysis

Owing to the numerous information storage devices in the data center, we designed 12 chips, each with a thermal power of 400 W. Therefore, during simulation, the problem of the chip, especially its temperature safety, should be considered. Too high or too low chip temperature will affect its working efficiency. Consulting the large number of data, the safe temperature of the chip was set at 70 °C. This section describes how to optimize the cooling water system to meet this safe temperature for chip operation and reduce energy consumption and PUE of the server cabinet cooling system.

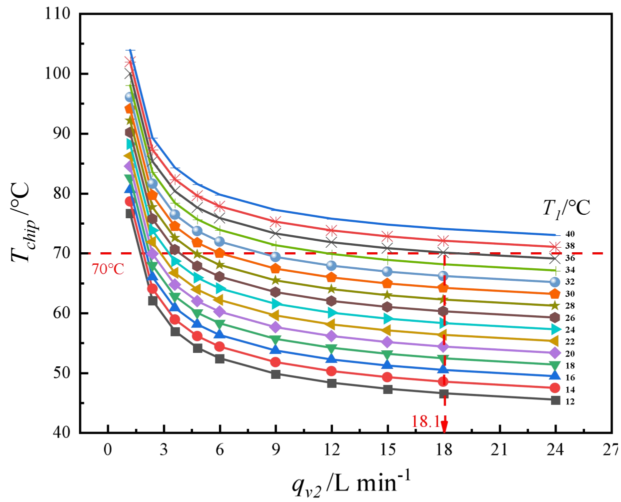

Fig.3 Change in chip temperature with secondary cooling water flow rate for different water inlet temperature.

Through TRNSYS simulation and thermodynamic calculation, it was observed that the chip temperature (T_{chip}) is related to the server inlet water temperature (T_1) and water flow of the secondary cooling water (q_{v2}) (Fig. 3). The chip temperature increased with the decrease in server inlet water temperature for a constant secondary water flow rate. For a constant server inlet temperature, with continuous increase of the secondary water flow, the chip temperature first decreases sharply, and then gradually, and stabilizes after 18.1 L min^{-1}. Each water inlet temperature contained a minimum secondary water flow to maintain the safe temperature, and the minimum water flow required increased with the increase of water inlet temperature. However, when the inlet water temperature rises above 38°C, the water flow cannot meet the temperature requirements of the safety chip. Therefore, corresponding to the determined safety chip temperature, the maximum inlet water temperature was limited.

Additionally, each available inlet temperature had a corresponding minimum cooling water flow. A smaller flow denoted a smaller pump power consumption, and better energy-saving.

B. Effect of ambient relative humidity and temperature

The average monthly ambient temperature and relative humidity data of Tianjin was studied for a year (Fig. 4)., based on which the system was simulated to find ways to improve its energy efficiency. When the ambient temperature was too low, it caused problems, such as dehumidification or humidification in the data center. The ambient temperature in January, February, November, and December was <5 ℃; hence, the working conditions in these months were not considered in this study.

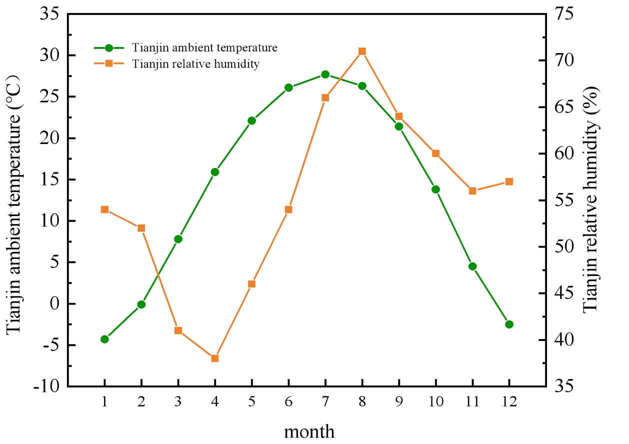

Fig.4. Average ambient temperature and relative humidity in Tianjin in 12 months

The maximum water inlet temperature of the cabinet can reach 36 ℃ to ensure the normal operation of the system (Fig. 3). However, considering the maximum flow of the pump, the maximum inlet water temperature of the cabinet should be set to 34 ℃. The monthly ambient temperature (>5 ℃) and relative humidity in Tianjin was input into the system (Fig. 4) and the inlet temperatures of several cabinets floating in the ambient temperature accessories in the simulation system constantly adjusted the system to obtain the control signal of target pump 1, the primary water flow, the optimal inlet temperature of the cabinet corresponding to the ambient temperature, and the system power to calculate the system PUE according to the power system.

In the TRNSYS simulation system, first the load was input in the system, followed by input of the average ambient temperature and relative humidity in Tianjin for May in the cooling tower module, and the corresponding control signal at the cabinet inlet water temperature of 17 ℃ in pump 2. Each control signal corresponded to a fixed water flow. The control signal of pump 1 was then adjusted so that the output temperature corresponds to the previously selected cabinet inlet water temperature, and the system power and PUE was recorded. The primary and secondary water flow corresponding to the inlet water temperature of different cabinets in May are shown in Fig. 5, and the system power and PUE corresponding to the inlet water temperature of the different cabinets in May are shown in Fig. 6. The above simulation was then repeated according to the inlet water of other cabinets at 17, 19, 21, 23, and 25 ℃. After calculation, the system power and PUE value were compared, and the minimum system power and cabinet inlet water temperature corresponding to PUE were selected as the best cabinet inlet water temperature. The optimal cabinet inlet water temperature in May was 19 ℃, the corresponding primary water flow was 2.23 L min^{-1}, the secondary water flow was 2.46 L min^{-1}(Fig.5), the system power was 0.1845 kW, and the PUE was 1.0384 (Fig. 6). In this system, for a fixed ambient temperature and relative humidity, a corresponding optimal cabinet inlet water temperature, optimal system power, and PUE were estimated. When the ambient temperature was low and the relative humidity was not too high, the values of system power and PUE were low, and the system showed good energy consumption.

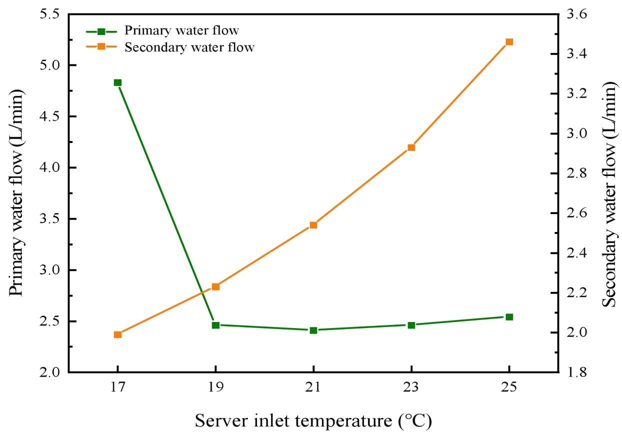

Fig.5 Primary water flow and secondary water flow corresponding to different cabinet inlet temperatures in Tianjin in May

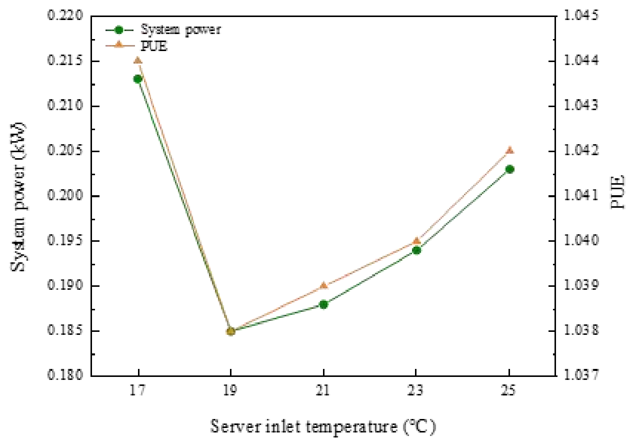

Fig.6 System power and PUE corresponding to different cabinet inlet temperatures in Tianjin in May

Fig. 7 shows the best primary and secondary water flow and the best cabinet inlet temperature in Tianjin in different months. We observed that the optimal cabinet inlet water temperature in each month changed with the change in ambient temperature and relative humidity. When the ambient temperature and relative humidity were low, the optimal cabinet inlet water temperature also decreased. During summer, the ambient temperature and relative humidity in Tianjin rises, and the best inlet water temperature of the cabinet will also rise. Correspondingly, the primary and secondary water flow also show this change. This can be explained by the fact that as the temperature rises, more water is needed to cool the chip.

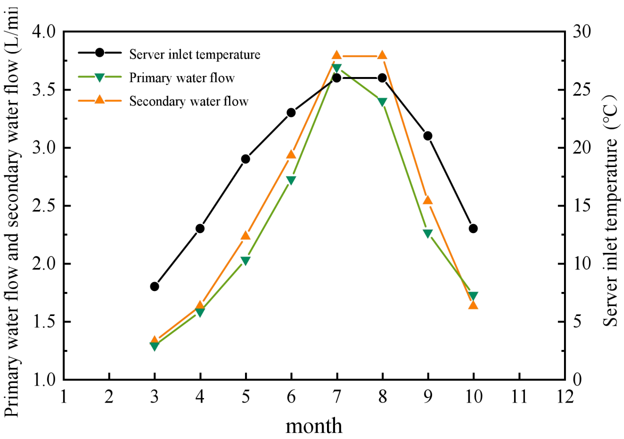

Fig.7 Optimal primary and secondary water flow and optimal cabinet inlet water temperature in different months in Tianjin.

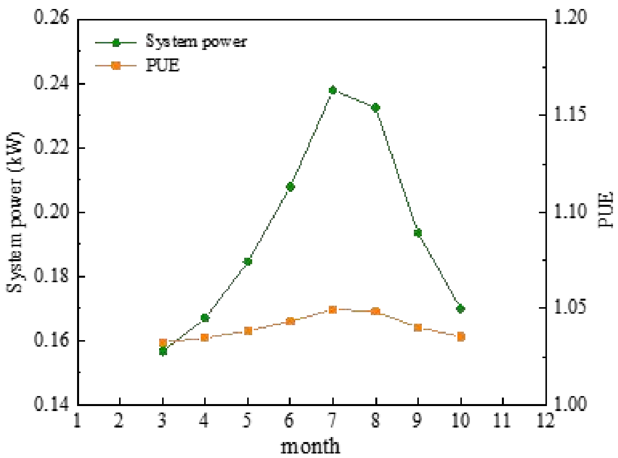

Fig.8 Optimal system power and optimal PUE in Tianjin in different months.

Fig. 8 shows the optimal system power and optimal PUE in Tianjin in different months. The inlet water temperature of different cabinets was calculated corresponding to a month, the values of power and PUE were compared, and the cabinet inlet water temperature with the lowest power and PUE was selected as the best cabinet inlet water temperature. PUE has become an internationally accepted measure of power efficiency in data centers. PUE value refers to the ratio of all energy consumed by the data center to the energy consumed by the IT load. The closer the PUE value is to 1, the lesser energy will be consumed by a data center. Power and PUE also changes with the month in Tianjin, owing to the effects of the ambient temperature and relative humidity (Fig. 8). They decrease during low ambient temperature and relative humidity. During summer, the ambient temperature and relative humidity in Tianjin rise, increasing the power and PUE. The PUE varies between 1.032 and 1.091, and the power of system varies between 0.154 and 0.437 kW (Fig. 8).

C. Effects of different relative humidity

As the relative humidity in Tianjin increases from 38 to 81 %, we calculated the optimal cabinet inlet water temperature corresponding to the ambient temperature in Tianjin from 40 to 80 % relative humidity, as well as other corresponding parameters of the system, such as primary water flow, secondary water flow, system power, PUE, etc. We found that with the increase of relative humidity in Tianjin, the maximum ambient temperature gradually decreases under the condition of maximum cabinet inlet water temperature of 34 ℃.

For example, when the relative humidity was 40%, the cabinet inlet water temperature was 34 ℃ , and the ambient temperature that can be met was 43 ℃. When the relative humidity was 80%, the ambient temperature became 33 ℃. We found a significant influence of the relative humidity on system working conditions.

IV. CONCLUSIONS

In this study, a TRNSYS simulation system was established based on 12 data center cooling system. To study the minimal system power and PUE, we established an internal and external double circulation cooling water system. during simulation, different ambient temperature and relative humidity significantly impacted the working conditions of the system. The following conclusions were obtained:

(1) The safety temperature of the chip was set at 70 ℃ and the maximum water temperature of the cabinet was 34 ℃. The results based on this showed that the ambient temperature has significantly impacted the operating conditions of the system. At high temperature, the system required more power to cool the chip. Therefore, the primary water flow, secondary water flow, system power, and PUE of the system increased. These values decreased with fall of the ambient temperature.

(2) We studied the operating conditions of the system when the relative humidity was 40–80 %. The results showed that a higher relative humidity indicated a lower ambient temperature that can be met by the maximum inlet water temperature of the cabinet. Under the same ambient temperature, with the decrease of relative humidity, the cabinet inlet water temperature corresponding to the ambient temperature gradually decreased, which further decreased the power and PUE of the system.

(3) We studied the impact of the monthly average ambient temperature and relative humidity on the working conditions of the system from March to October in Tianjin. The research showed that the working conditions of the system were significantly

affected by climatic conditions. In summer, when the ambient temperature and relative humidity are high, the primary water flow, secondary water flow, system power, and PUE of the system increase. When the ambient temperature and relative humidity decrease, these values also tend to decrease.

ACKNOWLEDGEMENT

The authors are grateful for financial support from TianjinNatural Science Foundation (No.18JCZDJC97100), the National Natural Science Foundation of China (51806152) and the International Cooperation Program of the Ministry of Science and Technology of China (2017YFE0198000).

REFERENCES

[1] Oró, Eduard, and Jaume Salom. "Energy model for thermal energy storage system management integration in data centres." Energy Procedia 73 (2015): 254-262.

[2] Siriwardana, Jayantha, Saliya Jayasekara, and Saman K. Halgamuge. "Potential of air-side economizers for data center cooling: A case study for key Australian cities." Applied Energy 104 (2013): 207-219.

[3] Endo, H., Kodama, H., Fukuda, H., Sugimoto, T., Horie, T., & Kondo, M. ."Effect of climatic conditions on energy consumption in direct fresh-air container data centers." Sustainable Computing: Informatics and Systems 6 (2015): 17-25.

[4] Agrawal, Aayush, Mayank Khichar, and Sanjeev Jain. "Transient simulation of wet cooling strategies for a data center in worldwide climate zones." Energy and Buildings 127 (2016): 352-359.

[5] Cheung, Howard, and Shengwei Wang. "Reliability and availability assessment and enhancement of water-cooled multi-chiller cooling systems for data centers." Reliability Engineering & System Safety 191 (2019): 106573.

[6] Ellsworth Jr, M. J., Goth, G. F., Zoodsma, R. J., Arvelo, A., Campbell, L. A., & Anderl, W. J. "An overview of the IBM power 775 supercomputer water cooling system." (2012): 020906.

[7] Sahini, M., Kshirsagar, C., Kumar, M., Agonafer, D., Fernandes, J., Na, J., ... & Soares, M."Rack-level study of hybrid cooled servers using warm water cooling for distributed vs. centralized pumping systems." 2017 33rd Thermal Measurement, Modeling & Management Symposium (SEMI-THERM). IEEE, 2017.

[8] Whelan, B. P., R. Kempers, and A. J. Robinson. "A liquid-based system for CPU cooling implementing a jet array impingement waterblock and a tube array remote heat exchanger." Applied Thermal Engineering 39 (2012): 86-94.

[9] Zimmermann, S., Meijer, I., Tiwari, M. K., Paredes, S., Michel, B., & Poulikakos, D. (2012). "Aquasar: A hot water cooled data center with direct energy reuse." Energy 43.1 (2012): 237-245.

[10] He, W., Ding, S., Zhang, J., Pei, C., Zhang, Z., Wang, Y., & Li, H. (2021). "Performance optimization of server water cooling system based on minimum energy consumption analysis". Applied Energy, 303, 117620.

[11] He, W., Zhang, J., Li, H., Liu, S., Wang, Y., Lv, B., & Wei, J. "Optimal thermal management of server cooling system based cooling tower under different ambient temperatures." Applied Thermal Engineering 207 (2022): 118176.