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Performance and energy efficiency analysis of data center cooling plant by using lake water source

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Abstract

A cooling plant by using lake water source was proposed to cool the space in data centers. It combines free cooling technology and variable capacity technology to remove heat and reduce energy consumption effectively. In this paper, firstly, the control strategies for this cooling plant were proposed. Then, a detailed annual energy consumption model with considering the effect of the dynamic heat dissipation characteristics of servers, lake water temperature, outdoor weather conditions, and cooling plant thermal performance, will be established to evaluate the performance and energy efficiency of this cooling plant under different load factors. The results show the mode 1 and mode 2 of this cooling plant are 67.6% and 32.4% of the year's running time, respectively. The average EER of the cooling plant under different load factor ranges from 16.8~49.3, and the average PUE value ranges from 1.11 to 1.15 under different load factors, which demonstrates this cooling plant poses higher energy efficiency than the conventional cooling plant for the data centers.

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Keywords: *Data center, Lake water source, PUE, Energy consumption*

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1. Introduction

In recent years, data centers serve as the powerful engines that pump blood through the arteries of the global economy, and the total data center energy consumption grows considerably. Among of these, data center cooling system takes account 30%~50% of the overall energy consumption[1]. In addition, the data center is an internal load dominated building, and its heat dissipation high to 4~10 kW/rack. In order to quantify the cooling efficiency, an index called PUE, the ratio between the total energy consumption of a data center and the energy consumption of the IT equipment inside, were commonly employed in the data centers. Currently, the average PUE value of 90% data centers in China is high to 1.73, and there still exists a large number of traditional data centers difficult to enhance their energy efficiency. Therefore, there is a pressing need to research and develop technology that can reduce energy consumption, increase cost effectiveness, and ensure reliability.

In order to enhance the power usage effectiveness of the data centers, several technologies and methods were proposed, as follows,1) Raise return air temperature; 2) Employ free cooling technology; 3) Implement aisle containment; 4) Apply variable capacity technology; Among of these technologies, the second method is the best candidate in improving the energy efficiency of the data centers. For example, Yahoo data center, in the Buffalo suburb of Lockport, N.Y., design open wall to allow cool air enter the building, thereby its PUE value of 1.08. Facebook data center with air side free cooling in northern Sweden operates at a PUE of 1.15. Cho et al. [2] indicated the data center by using the air side economizer or water side economizer have a significant improvement over the central chilled water system, and the PUE of the data center decreased 0.3 and 0.11, respectively. Habibi Khalaj et al. [3] compare the PUE value of the data centers by using different air side economizers, and its value decreased from an average of 1.42 to 1.22. Ling et al. [4] analyzed thermal performance of the MSHPS (water cooled multi-split heat pipe system) for data center, which have higher energy efficiency than a typical CRAC system.

The above mentioned free cooling systems are either using low dry-bulb temperature or wet-bulb temperature of outdoor air. As we all known, the outdoor air temperature largely depend on the location and climate conditions, thereby their values are not stable. However, very little information focus on the energy efficiency analysis of the data center's cooling plant by using lake water source. The lake water source can provide relative stable and enough cooling water for data center's cooling plant. In this paper, a cooling plant by using lake water source was proposed to cool the space in data centers. Meanwhile, an annual energy consumption model of this system, taking consideration of the effect of the dynamic heat dissipation characteristics of servers, lake water temperature, outdoor weather conditions, and cooling plant thermal performance, will be established to evaluate the performance and energy efficiency of this cooling plant under different load factors.

Nomenclature

A	area [m^2]
$T_{ct,o}$	oulet temperature of the cooling tower [˚C];
T_{lake}	lake water temperature [˚C];
T_s	supply air temperature [˚C];
t_{in}	intdoor air temperature [˚C];
t_o	outdoor air temperature [˚C];
K	thermal conductivity, [$W \cdot m^{-1} \cdot K^{-1}$]
P	power or heat loss [W];
Q	cooling load [W];
q	heat flux [$W \cdot m^{-2}$];
u_{server}	servers' utilization [%];

2. Description of the data center

2.1. Data center layout

Fig.1 shows the data center have two floors, the first floor mainly consists of the ancillary device room 1~4, power room, refrigeration room, and diesel engine room, etc. The second floor mainly includes IDC room 1~4, battery rooms and ancillary device rooms, etc. Among of these, the total IDC room area is about 1836 m2, as shown in Table.1. The cooling air of the IDC room 1~4 was provided by the CRAH units. For the other ancillary device rooms and battery rooms, the MSHPS was used. Due to the cooling load of these ancillary device rooms and battery rooms maintains a constant value with neglecting the effects of the outdoor weather condition in this paper, the energy consumption of the MSHPS system obtained from in-situ measurement, which is about 13.4 kW.

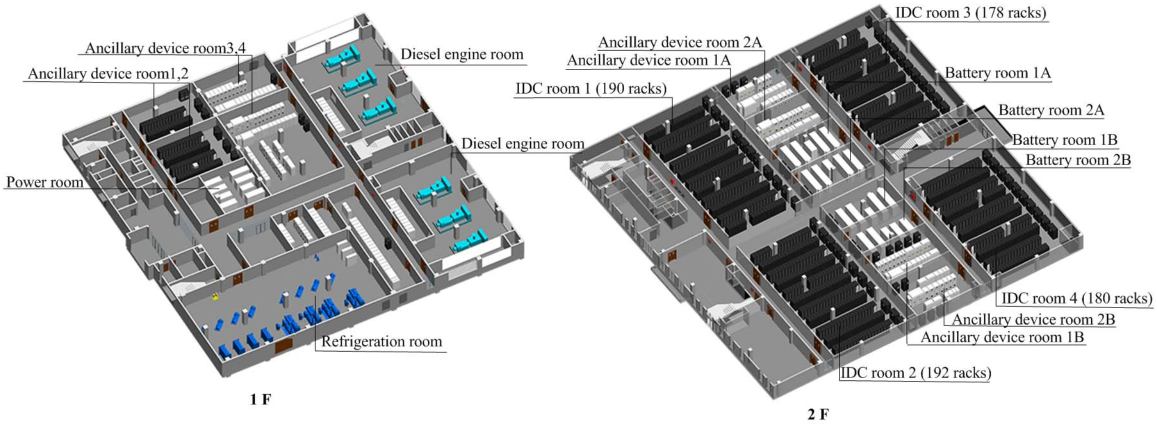


Fig.1 Layout of the data center

Table.1 The function of the IDC room

Room	IDC data room 1	IDC data room 2	IDC data room 3	IDC data room 4
Area (m^2)	473.5	473.5	440	449
Racks	190	192	178	180
CRAH	10+1	9+1	9+1	9+1

2.2. Description of the cooling plant by using lake water source

The schematic diagram of the cooling plant by using lake water source is shown on Fig.2.This system mainly consists of the cooling tower, chiller, water to water heat exchanger, cold storage tank, MSHPS, and CRAH units. The chilled water is provided jointly by a chiller and heat exchanger from lake water source. And this cooling system poses three modes: 1) free cooling (mode 1); 2) Partial free cooling (mode 2); 3) normal cooling (mode 3). The control strategies for this cooling plant are based on the lake temperature to control the valves V_1~V_8, the mass flow rates of pumps (including lake water pump, chilled water pump, and the cooling water pump) are regulated to maintain the heat exchanger hot side outlet water temperature, supply air temperature, cooling water temperature difference at the required set-point. Meanwhile, the controller changes the fan speed of the cooling tower to keep the supply cooling water temperature at the required set point. The electricity current of chiller is controlled to maintain the chilled water temperature at the required set point. And the air flow rate of the MSHPS and CRAH units to maintain to maintain the indoor air temperature in the reasonable range, as shown in Table.2. In this study, the set point for the supply chilled water temperature and supply air temperature were 15 ˚C and 24 ˚C, respectively. The low and limit of the indoor air temperature are set to 32 ˚C and 35 ˚C, respectively.

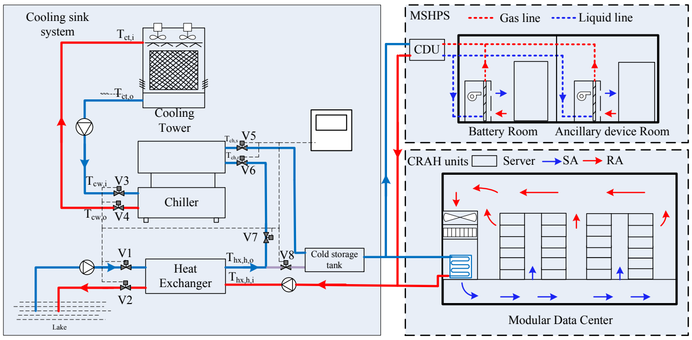


Fig.2 Schematic diagram of the cooling plant by using lake water source.

Table.2 The control strategies of the cooling plant by using lake water source

Mode	1	2	3
Condition	$Tl_{ake} \leq 13$	$13 < T_{lake} \leq 18$	$T_{lake} > 18$
Operational state	1) Valves V_3, V_4, V_5, V_6, and V_7 turn off; 2) Valves V_1, V_2 and V_8 turn on; 3) Cooling tower, chiller, and cooling water pump turn off; 4) Lake water pump and chilled water pump turn on;	1) Valve V_8 turn off; 2) Valves V_1, V_2, V_3, V_4, V_5, V_6, and V_7 turn on; 3) Cooling tower, chiller, cooling water pump, lake water pump and chilled water pump turn on;	1) Valves V_1, V_2 and V_8 turn off; 2) Valves V_3, V_4, V_5, V_6, and V_7 turn on; 3) Cooling tower, chiller, cooling water pump and chilled water pump turn on; 4) Lake water pump turn off;

2.3. Description of the cooling plant equipment

The cooling plant mainly consist of a cooling tower, a chiller, a water to water heat exchanger, a cooling water pump, a chilled water pump, a lake water pumps, several MSHPS and CRAH units. The main cooling system parameters are mainly depends on the data center cooling system design book. The nominal cooling capacity of each chiller is 4200 kW with a nominal power 581 kW. The rated air flow rate of each cooling tower is 455000 m^3/h with a nominal power 22 kW. The thermal characteristics of a plate heat exchanger taken from the technical characteristics of AIKSEN, and its UA (computed heat transfer coefficient) equal to 2878.8 kW/K. The rated mass flow rate for the cooling water pump, lake water pump, and chilled water pump are 960 m^3/h, 780 m^3/h and 860 m^3/h, respectively, and their corresponding rated power are 132 kW, 112 kW, and 160 kW, respectively. A CRAH unit includes a water to air heat exchanger and a variable fan, and its thermal technical parameters can be found in SUNRISE data center air cooler. The fan rated air flow rate and power are 32000 m3/h and 4.6 kW, respectively. The UA of the CRAH is 10.417 kW/K.

3. Annual energy consumption simulation

3.1. Data center cooling load calculation model

Consider the data center physical characteristics and the thermal dynamic characteristics of the IT equipment, the cooling load of the data center mainly comes from IT equipment, envelope, lighting, people and infiltration, etc. Among of these, the cooling load caused by people and infiltration compares to the amount generated by the IT equipment is insignificant, which can be neglected. Therefore, the total cooling load of data center can be calculated by,

$$Q(i) = KA_{envelop}\left[t_o(i) - t_{in}(i)\right] + q \cdot A + Q_{IT}(i) \qquad (1)$$

In the typical data centers, the IT equipment mainly consists of servers, power distribution units (PDUs), and uninterruptible power supplies (UPSs), etc. The servers are the greatest sources of heat generation in a data center, which is a function of their utilization[5]. Therefore, the server heat loss can be calculated by,

$$P_{servers} = \left(27.39 + 0.9027u_{server} - 0.0017462704u_{server}^2\right) \cdot P_{full} \tag{2}$$

The heat loss caused by PDUs and UPSs also can be calculated according to the reference [6].

3.2. Cooling plant component model

In this study, the performance and energy efficiency of the cooling plant for the data center will be analyzed. Fig.3 depicts the heat and energy flow schematic diagram of the cooling plant by using lake water source with three modes. To investigate the annual operating and energy consumption of this cooling plant, several mathematical models of the main components in the system, including water cooled chiller, cooling tower, pumps, water to water heat exchanger, and the CRAH unit, will be developed. In this study, the thermal performance and power consumption of the water cooled chiller and cooling tower were simulated by using the Energy Plus water chiller model and water cooling tower model [7], respectively. The pumps and fans of this system were variable speed are regulated to satisfy the set point requirement, which can be calculated according to the pump and fan law. For the water to water heat exchanger, the heat transfer model was established by using ε-NTU method[8]. The heat transfer performance of the water to air CRAH units was predicted by the cross flow heat exchanger with both fluid unmixed model.

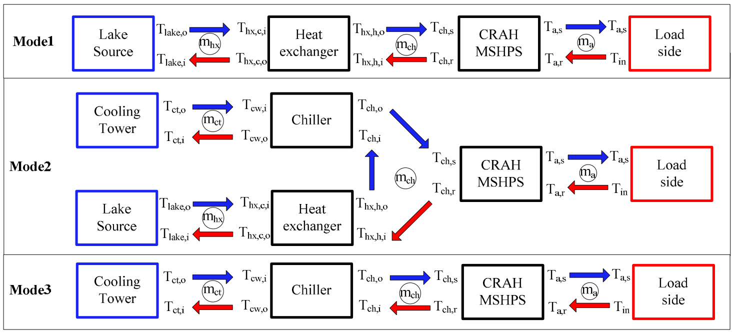


Fig.3 The heat flow schematic diagram of the cooling plant with three modes

4. Results and discussion

4.1. Location, weather and lake water data

In this study, this data center located in Dongjiang lake, Chenzhou city, southeast Hunan province, China, which is in the hot summer and cold winter zone. The maximum dry-bulb and wet bulb temperature are37.4 ˚C and -2.2 ˚C, respectively. And the minimum dry-bulb and wet bulb temperature are 28.1 ˚C and -2.29 ˚C, respectively. Fig.4 shows the lake water temperature of Dongjiang lake which obtained from the test results of Dongjiang station in 2013~2015. The water temperature less than or equal to 13 ˚C takes account 32.3%, 66.7%, and 66% in 2013, 2014 and 2015, respectively. The water temperature for these three years is less than 18 ˚C. It's clear that the cooling plant can utilize free cooling mode (mode 1) or partial free cooling mode (mode 2) throughout the year. And this annual energy consumption simulation model employed the year of 2015 lake water temperature.

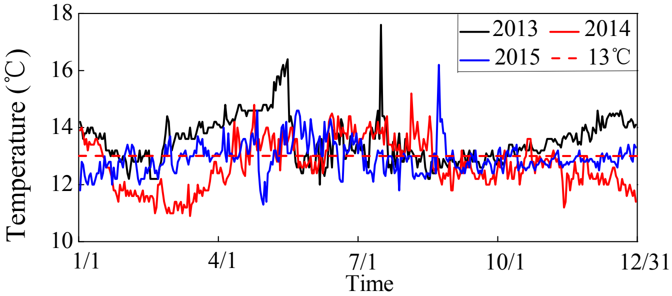


Fig.4 Water temperature of the Dongjiang lake in 2013~2015

4.2. Energy consumption under different load factors

The load factor of the data center influence on the power consumption of each component in the cooling plant. Four simulations with four different load factors were conducted, which is 25 %, 50 %, 75 % and 100 %. The load factor of 25%, 50% , 75% and 100% refer to the racks in IDC room 1, IDC room 1~2, IDC room 1~3 and IDC room 1~4 are installed servers, respectively. Fig.5 depicts different modes runs ratio for each month during the year according to the control strategies. The ratio of free cooling mode (mode 1) decreased with increasing of the average lake water temperature. In April, May, and June, due to the average lake water temperature increased, the system works on free cooling mode (mode 1) less than 50% of the whole time, while the system works on partial free cooling mode (mode2) for the rest of time. Fig.6 shows that the energy consumption distribution of each component for every month under different load factors. As expected, the total energy consumption of each month strongly varies with the average lake water temperature. At low load factor (25% and 50%), the changing trends in the energy consumption of the CRAH units fluctuates within a range, while the energy consumption of the CRAH units maintains at a stable value at higher load factors. This is because of that the indoor air temperature was controlled in a range, the air flow rate of the CRAH fans change rate under low load factor is relative large compare to that of under high load factor. That means the energy consumption of the CRAH fans is more sensitive to the indoor air temperature under low load factors. For different load factors, the energy consumption of the chilled pump and MSHPS vary the same trend. The energy consumption variation of the chiller, cooling water pump, cooling tower, lake water pump increased with decreasing of the run hours of the mode 1.

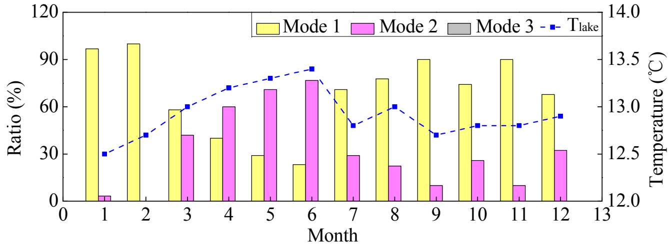
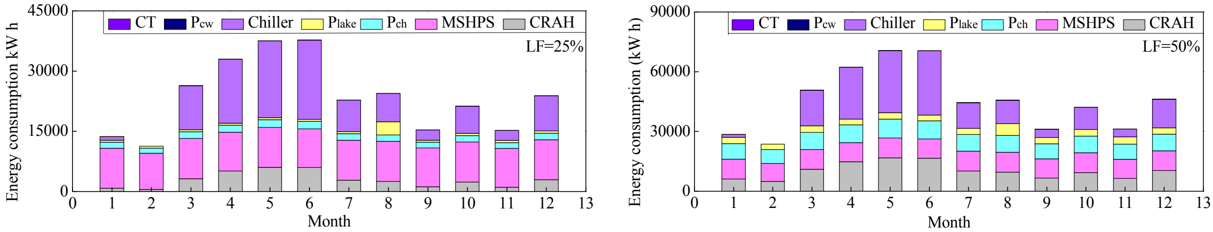
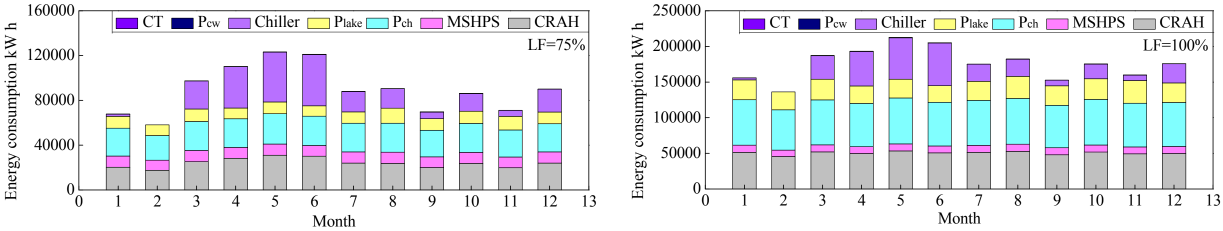


Fig.5 Different modes runs ratio during the year



(a) (b)



(c) (d)

Fig.6 Energy consumption distribution of each component for every month under different load factors

4.3. Energy efficiency under different load factor

Fig.7 depicts EER of the cooling plant during the year under different load factors. With increasing of the load factor, the cooling load of the data center increase. In order to satisfy the cooling requirement of the data center, the mass flow rate of the chilled water, lake water and cooling water, the electric current of the chiller, and the air flow rate of CRAH units increased, which cause the energy consumption of the cooling plant increased (as shown in Fig.6). And the relationship between the total energy consumption and load factor is not a linear, and its growth rate increased. However, the cooling load of the data center increased with increasing of the load factor, and the increase rate maintains at a relative stable value. Therefore, the EER for the cooling plant decreased with increasing of the load factor. As shown in Fig.8, the average EER of the cooling plant under different load factors ranges from 16.8~49.3, which is much higher than the conventional cooling plant (it usually ranges from 3~8), even higher than the cooling plant by using the water-side economizer (it usually ranges from 3.5~10.5) or air-side economizer (it usually ranges from 4.3~13.2) [2]. This cooling plant by using lake water source with high energy efficiency, which fully show this cooling plant has a high energy saving potential for data center by using natural cooling source.

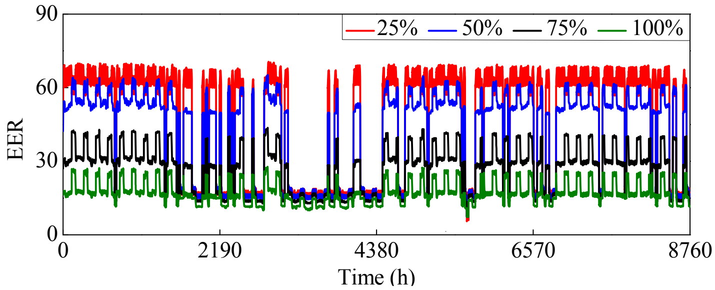


Fig.7 The EER of the cooling plant during the year under different load factors

Fig.8 demonstrates that the data center's PUE value under different load factors. For different load factors, the range of PUE value during the year is in 1.08~1.39, and its average value ranges from 1.11 to 1.15. At the time of 5664 h, the lake water temperature is higher to 16.2 ˚C, which cause the PUE value obtain the maximum value under different load factors. Table.3 shows the average PUE value under different running modes for different load factor. At mode 2, the PUE value is higher than that of at mode 1. This is because of that the lake water source can only provide partial cooling capacity for data center, and the water chiller system provides the rest of cooling capacity. Due to the water chiller system with variable frequency drive technology, the PUE value of the mode 2 increased not much. Consequently, it is clear that the cooling plant by using lake water source can successfully enhance the power usage effectiveness of the data center.

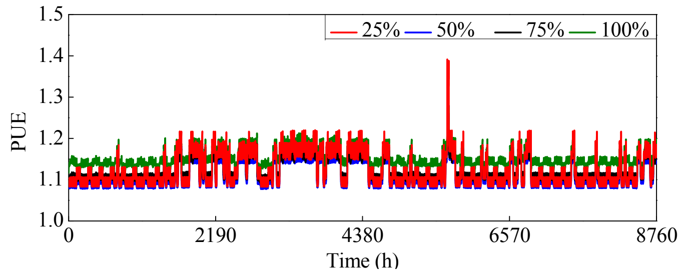


Fig.8 The PUE value for the data center during the year under different load factors

Table.3 The average PUE value under different running modes for different load factors

Load factor	25%	50%	75%	100%
Mode 1/Mode 2	1.1/1.17	1.09/1.15	1.11/1.16	1.14/1.18
Total	1.12	1.11	1.12	1.15

5. Conclusions

Data centers are growing rapidly across the world with the development and demand of information and communication technology, which cause their massive energy consumption problem attract considerable interest from industry and academia. The cooling plant by using lake water source is an effective method to reduce the energy consumption of the data centers, and its performance and energy efficiency was analyzed in this paper. The following conclusions are obtained:

1) The ratio of free cooling mode decreased with increasing of the average lake water temperature. For the whole year, the mode 1 and mode 2 takes account 67.6 % and 32.4 %, respectively. For different load factors, the total energy consumption of each month strongly varies with the average lake water temperature.

2) The average EER of the cooling plant under different load factor ranges from 16.8~49.3, which is much higher than the other cooling pant for data center. And the average PUE value ranges from 1.11 to 1.15, which illustrates that the cooling plant by using lake water source can successfully enhance the energy efficiency of the data center.

In the future, further simulations will be conducted to optimize the control parameters, which is able to achieve the minimum energy consumptions.

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