

Performance of an internet data center refrigeration system using an evaporative cooler

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Abstract. The traditional refrigeration method of internet data center (IDC) is mostly air refrigeration, which has undesired cooling effect and high power consumption. This study addresses this problem and proposes an evaporative air cooler (EAC) suitable for IDC. Given the high specific heat capacity of water, the evaporative condensing coil and spray device are added to the evaporative cooler to enhance the heat transfer effect. Heat and mass transfer mathematical models are established to analyze the heat transfer performance. The mathematical model is used to simulate the profile of the heat and mass transfer coefficient of the EAC with the amount of spray water and air flow. The results show that when the air flow changes from 10 to 20 kg/s, the air equivalent heat transfer coefficient increases by about 41%. When the air flow rate is 20 kg/s and the spray water volume is 0.00124 kg/(m·s), the total heat transfer coefficient is increased by about 308% compared with the case without spray water.

1 Introduction

The internet data center (IDC) is an important guarantee for the realization of emerging technologies, such as smart manufacturing, Internet +, Internet of Things and big data. IDC operates 24 hours a day, 365 days a year. The annual electricity consumption data of IDCs in China is estimated to reach the total annual power generation capacity of the Three Gorges Power Station [1]. Among the huge energy consumption of data center infrastructure, the energy consumption of cooling equipment usually accounts for about 60% of the energy consumption of the server room, and the cost caused by high energy consumption exceeds 50% of the entire operation and maintenance of the computer room [2]. In the next period of time, the scale of IDC will increase exponentially, posing greater challenges to power, cooling and other computer room infrastructure. Energy demand is also increasing.

At present, the refrigeration method of IDC is mainly air refrigeration. The air passes through the cooler under the action of the fan, and exchanges sensible heat with the working fluid flowing in the heat exchange tube of the air cooler. This refrigeration method has a natural cooling function and is easy to operate and maintain. No water needed, but the energy efficiency of refrigeration is relatively low, and the coverage area is large [3]. There is also a water-cooled refrigeration method that uses water to exchange heat of the working fluid. This type of air conditioning system is more complex, more

costly, and difficult to maintain, but it can meet the cooling and energy saving needs of large data centers. In addition, evaporative cooling technology has been developed relatively mature, but it has not been widely used for IDC refrigeration [4].

In order to solve the problems of low refrigeration efficiency, high energy consumption and large heat transfer area of traditional coolers [5], this research applies evaporative cooling technology to traditional air coolers and transforms traditional coolers. Evaporative air cooler (EAC) integrates the advantages of air cooling and water cooling, which can improve efficiency and reduce energy consumption.

2 System design

The EAC is a heat exchanger that integrates a water-cooled cooler and a cooling tower. It consists of heat exchange coil, axial fan, circulating water pump, spray device and other main components [6]. The main operation principle of the EAC is to use two cooling media, water and air, and use the latent heat of vaporization generated by the evaporation of the water film outside the tube bundle and the sensible heat of forced convection exchange between the tube bundles. The air and water film transfer the heat in the heat exchange coil. The process fluid is cooled [7]. Theoretically, the temperature of the working fluid in the coil can be reduced to close to the ambient temperature or the ambient wet bulb temperature. Its cooling temperature is 8-11 °C lower than that of air-cooled

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coolers and 3-10 °C lower than that of the water-cooled cooling system [8].

This research proposes that on the basis of the existing IDC air-cooled chillers, an EAC will replace the dry cooler as an application method for the natural cooling module, as shown in Fig. 1. The natural cooling module is composed of plate heat exchanger, water pump, EAC, etc. In actual operation, the natural cooling module is mostly operated in winter, and the mechanical cooling module is operated in conjunction with the spring and autumn transition seasons. Compared with dry coolers, EACs have the advantages of lower cooling temperature and more energy saving. The evaporative air cooler mainly uses the vaporization latent heat of water to dissipate the heat. The outlet temperature of the working fluid in the tube can theoretically reach the wet bulb temperature of the air, which is lower than the theoretical outlet temperature of the dry cooler, i.e., the dry bulb temperature [9]. Using the EAC as a natural cooling module can extend the use time during the transition season and reduce the power consumption of the compressor. The dry cooler mainly blows in air continuously through the fan to take away the heat of the fluid in the heat exchange coil, and the fan has a large output power. Although the EAC also needs a fan, under the same cooling capacity, its power is about 1/3 of that of a dry cooler, saving more than 30% of electricity [10]. The use of EACs instead of dry coolers in IDC air-cooled chillers has important practical significance.

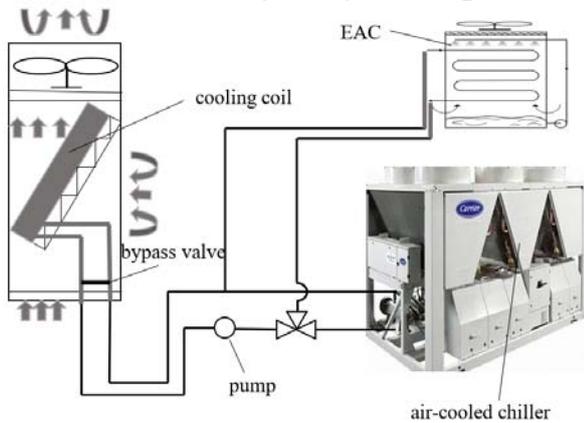


Fig. 1. Schematic diagram of the refrigeration system of IDCs using an EAC

3 Mathematical model

The working fluid flow in the tube, the water flow outside the tube and the air flow outside the tube of the EAC are counter-current flow as a whole [11]. The structures of EAC are various, and the water flow and air flow outside the tube are in a variety of mutual flow modes, but the essence of the heat and mass transfer process is basically the same, as shown in Fig. 2. The $q_{m,f}$, $q_{m,w}$ and $q_{m,a}$ shown in Fig. 2 are the flow rates of the working fluid in the tube, the spray water outside the tube, and the air flow outside the tube, respectively; t_f , t_s and t_a represent the temperature of the fluid in the tube, the spray water outside the tube, and the air, respectively; Q represents the heat transfer in the entire process; dx

represents the micro-element change along the height of the EAC.

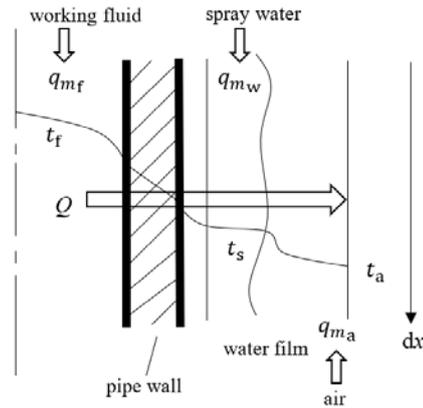


Fig. 2. Schematic heat and mass transfer of the EAC

Assuming that the working fluid flow, air flow and spray water flow at the inlet and outlet are evenly distributed, the entire heat and mass transfer process can be regarded as one-dimensional. The parameters only change in the vertical direction of the heat exchanger, and the horizontal parameters can be regarded as consistent [12]. The assumptions for the EAC are made as follows:

- (1) The air and the working fluid in the pipe flow steadily.
- (2) The heat and mass transfer interface is in equilibrium, and the heat and mass transfer process only occurs in the cooler.
- (3) In the temperature range of this study, the specific heat at constant pressure (c_p) of liquid water, water vapor, and air is a stationary number.

In Fig. 2, taking the height of the element dx as the research object, the heat and mass transfer analyses are carried out, and the heat transfer equation between the cooling water in the tube and the water film outside the tube is:

$$dQ = k_o (t_f - t_s) s dx \alpha' \quad (1)$$

where k_o is the total heat transfer coefficient from the fluid in the tube to the water film outside the tube, $W/(m^2 \cdot K)$; t_f is the temperature of the working fluid in the tube, K ; t_s is the temperature of the spray water outside the tube, K ; s is the cross-sectional area of the tube, m^2 ; α' is the heat exchange area per unit volume of the heat exchange tube, m^2/m^3 .

The heat transfer equation between the water film outside the tube and the air:

$$dQ = -h_m (t_s - t) s dx \alpha' - k_m (w'' - w') s dx \alpha' r \quad (2)$$

where h_m is the convective heat transfer coefficient between the air and the water film outside the tube, $W/(m^2 \cdot K)$; t is the air temperature, K ; k_m is the convective mass transfer coefficient between the air and the water film outside the tube, $kg/(m^2 \cdot s)$; w'' is the moisture content of saturated air at the temperature of the water film outside the tube, kg/kg -dry air; w' is the moisture content of the air, kg/kg -dry air; r is the latent heat of vaporization of water at the temperature, kJ/kg .

For air-water systems, the Lewis relation [13] applies. So $h_m/k_m = c_{p,a}$ holds and Eq. (2) can be rewritten as:

$$dQ = -k_m \left[(c_p t_s + w'' r) - (c_p t + w' r) \right] s dx \alpha' \quad (3)$$

$$dQ = -k_m (i'' - i') s dx \alpha' \quad (4)$$

where $c_p t_s + w'' r = i''$ is the specific enthalpy of saturated wet air at the spraying water temperature outside the pipe, kJ/kg; $c_p t + w' r = i'$ is the specific enthalpy of the air outside the tube, kJ/kg.

The heat balance of cooling water in pipe is:

$$q_{m,f} c_{p,f} dt_f = -k_o (t_f - t_s) s dx \alpha' \quad (5)$$

where $q_{m,f}$ is the mass flow rate of cooling water in the pipe, kg/s; $c_{p,f}$ is the specific heat at constant pressure of the cooling water in the pipe, kJ/(kg·K).

The heat balance of the spray water outside the pipe is:

$$q_{m,w} c_{p,w} dt_w = k_o (t_f - t_s) s dx \alpha' - k_m (i'' - i') s dx \alpha' \quad (6)$$

where $q_{m,w}$ is the mass flow rate of spray water outside the pipe, kg/s; $c_{p,w}$ is the specific heat at constant pressure of the spray water outside the pipe, kJ/(kg·K).

The heat balance of the air outside the tube is:

$$q_{m,a} di' = -k_m (i'' - i') s dx \alpha' \quad (7)$$

where $q_{m,a}$ is the mass flow rate of air outside the pipe, kg/s.

$$\text{Let } \frac{k_o s \alpha'}{q_{m,f} c_{p,f}} = a_1, \quad \frac{k_o s \alpha'}{q_{m,w} c_{p,w}} = a_2, \quad \frac{k_m s \alpha'}{q_{m,a} c_{p,a}} = a_3,$$

NTU = $\frac{k_o A}{q_{m,f} c_{p,f}} = a_1 \cdot x$, Eqs. (5)-(7) can be expressed as:

$$\frac{dt_f}{dNTU} = -(t_f - t_s) \quad (8)$$

$$\frac{dt_w}{dNTU} = \frac{a_2}{a_1} (t_f - t_s) - \frac{a_3}{a_1} (i'' - i') \quad (9)$$

$$\frac{di'}{dNTU} = -\frac{a_3}{a_1} (i'' - i') \quad (10)$$

The total heat transfer coefficient from the inner cooling water to the outer water film is:

$$\frac{1}{k_o} = \frac{1}{\alpha_f} \cdot \frac{d_o}{d_i} + \frac{\delta}{\lambda} \cdot \frac{d_o}{d_m} + \frac{1}{\alpha_w} \quad (11)$$

where $d_m = (d_o - d_i) / \ln(d_o / d_i)$ is the logarithmic average diameter of the tube; α_f is the convection heat transfer coefficient of the working fluid in the tube and the inner wall of the tube, W/(m²·K); α_w is the convection heat transfer coefficient between the outer wall of the pipe and the spray water outside the pipe, W/(m²·K); d_o and d_i are the outer diameter and the inner diameter of the heat exchange tube, respectively, m; λ is the thermal conductivity of the tube, W/(m·K); δ is the thickness of the pipe wall, m.

When the internal cooling water Reynolds number $Re_f > 2300$, the correlation equation of the heat transfer coefficient of the turbulent forced convection in the tube is [14]:

$$Nu_f = \frac{f (Re_f - 1000) Pr_f}{1 + 12.7 \sqrt{\frac{f}{8}} (Pr_f^{2/3} - 1)} \left[1 + \left(\frac{d}{l} \right)^{2/3} \right] c_f \quad (12)$$

where Nu_f is the Nussel number of the process fluid in the tube, $Nu_f = \alpha_f d / \lambda_f$; λ_f is the thermal conductivity of

the process fluid in the tube, W/(m·K); Pr_f is the Prandtl number of the process fluid in the tube, $Pr_f = \mu_f c_{p,f} / \lambda_f$; μ_f is the dynamic viscosity of the process fluid in the tube, Pa·s; f is the resistance coefficient of turbulent flow in the tube, $f = (1.82 \lg Re - 1.64)^{-2}$. In this study, the working medium flows uniformly in the tube, so for liquids, $c_t = (Pr_f / Pr_w)^{0.01} = 1$, and Pr_w is the Prandtl number of the fluid at the pipe wall.

The convective heat transfer coefficient between the spray water and the outer wall of the pipe can be calculated by:

$$\alpha_w = 2012.9 (m / d_o)^{1/3} \quad (13)$$

where m is the mass flow rate of spray water outside the pipe of unit width, kg/(m·s), and $m = q_{m,w} / (NL)$, N is the number of coils per row; L is the length of the heat exchange coil, m.

Parkel and Treybal show that the correlation of the mass transfer coefficient k_m of the air-side water film to the air is [15]:

$$k_m = 0.0493 [G(1 + w_{\text{vav}})]^{0.905} \quad (14)$$

where $0.68 < G < 5$ and G is the mass flow of the minimum heat transfer section of the flow, kg/(m²·s); w_{vav} is the average mass fraction of water vapor in the air.

Heat is transferred from inner cooling water to air, including heat transfer from inner cooling water to outer water film and heat and mass transfer from outer water film to outer air. In order to facilitate the calculation of EAC, some scholars proposed to replace the mass transfer coefficient of the process from the water film outside the pipe to the air outside the pipe with the equivalent air heat transfer coefficient [10]:

$$\alpha_j = \frac{A' \beta_w \alpha_a (i'' - i_m)}{c_{p,a} (t_s - t_m)} \quad (15)$$

where A' is the coefficient related to water film temperature; β_w is the water film fluctuation coefficient; $c_{p,a}$ is the specific heat of air at constant pressure, kJ/(kg·K); α_a is the convective heat transfer coefficient of air flowing through the cluster of smooth tubes, W/(m²·K); i_m is the average enthalpy of the air outside the tube, kJ/kg; t_m is the average temperature of the air outside the tube, K; and

$$\alpha_a = 0.88 \frac{c \lambda_a Re_a^m Pr_a^{0.3}}{d_o} \quad (16)$$

where λ_a is the thermal conductivity of air; Re_a the Reynolds number of air; Pr_a is the Prandtl number for the air; c and m are the correlation constants.

Then the total heat transfer coefficient of cooling water to air in the pipe is

$$\frac{1}{k'_o} = \frac{1}{\alpha_f} \cdot \frac{d_o}{d_i} + \frac{\delta}{\lambda} \cdot \left(\frac{d_o}{d_m} \right) + \frac{1}{\alpha_w} + \frac{1}{\alpha_j} \quad (17)$$

4 Results and discussion

Outside the EAC tube is spray water and air flow, while inside the tube flows cooling water. Therefore, the thermal performance of EAC is co-influenced by spray water, air flow and inner cooling water [16]. In this study,

parameters influencing the fluid in the EAC, such as inlet and outlet temperature, remain basically unchanged, and their influences on the EAC can be temporarily ignored. The influence of spray water and air flow on its thermal performance is considered.

The air mass flow contributes to the convective mass transfer and convective thermal efficiency between the water film outside the tube and the air, and thus it can influence the thermal performance of the EAC. Eq. (14) is employed to calculate the change of mass transfer coefficient from water film outside the tube to air when the mass flow rate of the minimum heat transfer section is $G = 1.2\text{-}5 \text{ kg}/(\text{m}^2\cdot\text{s})$ [17], as shown in Fig. 3. It can be seen that there is almost a linear relationship between air flow and convective mass transfer coefficient, and convective mass transfer coefficient increases with the increase in air flow. The larger the air flow rate, the stronger the convective heat transfer and convective mass transfer between the water film outside the tube and the air.

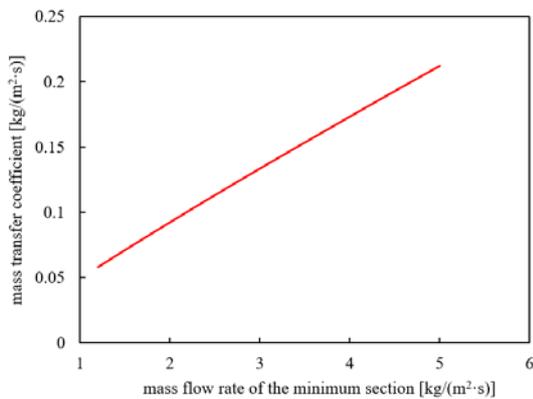


Fig. 3. Influence of air flow on convective mass transfer coefficient

Eq. (15) is employed to calculate the variation of the equivalent heat transfer coefficient of air outside the tube when the air flow rate is 10-20 kg/s, as shown in Fig. 4. It can be seen that with the increase in air flow rate, the air equivalent heat transfer coefficient also increases. When the air flow rate increases from 10 to 20 kg/s, the air equivalent heat transfer coefficient increases from 33.09 to 46.80 W/(m²·K).

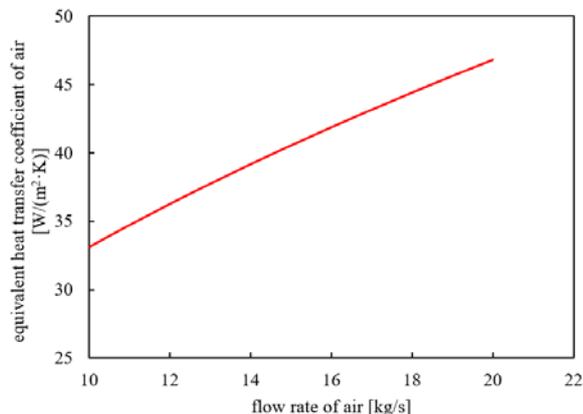


Fig. 4. Influence of air flow on equivalent air heat transfer coefficient

The amount of spray water influences the convective

heat transfer coefficient between the water film outside the tube and the outer wall of the tube, thus influencing the thermal performance of the EAC [11]. Eq. (13) is employed to calculate the change of the convective heat transfer coefficient between the water film outside the tube and the outer wall of the tube, and Eq. (11) is used to calculate the change of the total heat transfer coefficient between the cooling water inside the tube and the water film outside the tube, as shown in Figs. 5 and 6. When the spray water quantity per unit width changes from 0.002 to 0.006 kg/(m·s), the convective heat transfer coefficient from the water film outside the tube to the outer wall of the tube increases from 1013 to 1454 W/(m²·K), and the total heat transfer coefficient k_o from the cooling water inside the tube to the water film outside the tube increases from 841 to 1109 W/(m²·K). Numerically, the local convective heat transfer coefficient is greater than the total heat transfer coefficient. For a certain range of spray water volume, with the increase in spray water volume per unit width, the turbulence of liquid film outside the tube is intensified, and then, the heat transfer is enhanced.

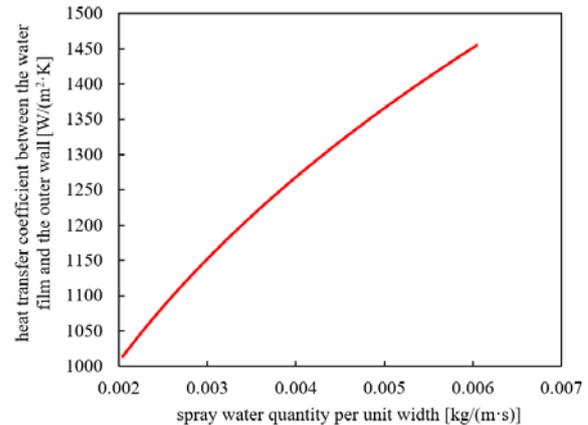


Fig. 5. Influence of spraying water on the local heat transfer coefficient for the water side of the water-tube interface

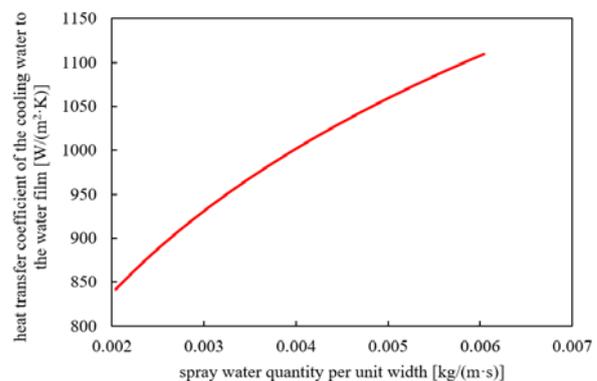


Fig. 6. Influence of spray water on the total heat transfer coefficient of the cooling water in the tube to the water film

In this study, EAC is applied to IDC refrigeration system instead of dry cooler. EAC removes latent heat of vaporization by the evaporation of spray water, while dry cooler removes heat by the forced air flow across the heat exchange tube bundle. The biggest difference between EAC and dry cooler lies in whether the heat

exchange tube bundle is sprayed with water [18]. Therefore, it is necessary to investigate the heat transfer performance of EAC and dry cooler under the same flow rate of air. The variation of total heat transfer coefficient under different air flow rates is shown in Fig. 7. With the increase in spray water quantity and air flow rate, the total heat transfer coefficient increases. The total heat transfer coefficient without spray water is less than that with spray water. Therefore, it is verified numerically that EAC has better heat transfer performance than the dry cooler.

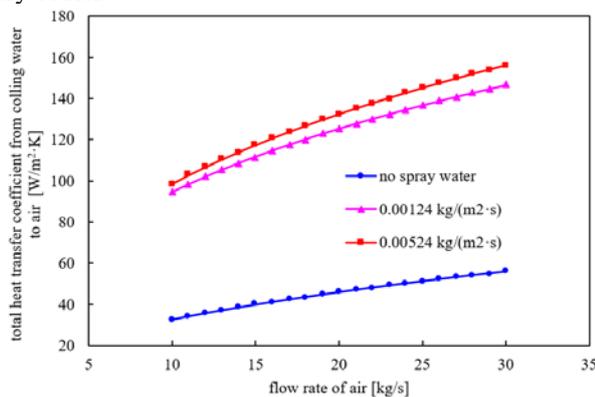


Fig. 7. Influence of air flow rate on the total heat transfer coefficient under different flow rates of spray water

5 Conclusion

A new IDC refrigeration system using EAC is proposed in this study. EAC is applied to IDC air-cooled chiller with natural cooling module instead of dry cooler. The heat and mass transfer models of EAC are established and the thermal performance is analyzed.

With the increase of air flow rate, the mass transfer coefficient and air equivalent heat transfer coefficient between spray water and air outside the tube also increase. When the air flow rate changes from 10 to 20 kg/s, the air equivalent heat transfer coefficient increases from 33.1 to 46.8 W/(m²·K).

With the increase in spray water, the convective heat transfer coefficient from the outer wall of the tube to the spray water outside the tube and the total heat transfer coefficient from the cooling water inside the tube to the water film outside the tube also increase. The total heat transfer coefficient of water without spraying is smaller than that of water with spraying. When the air flow rate is 20 kg/s, the total heat transfer coefficient is 46.3 W/(m²·K) without spray water and 188.86 W/(m²·K) with spray water volume of 0.00124 kg/(m²·s).

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