PERFORMANCE SIMULATION AND OPTIMIZATION OF EVAPORATIVE AIR-COOLED CHILLER

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ABSTRACT
It is favorable to increase the coefficient of performance of air-cooled chiller with an efficient, reliable and cost-effective method. Coupling a direct evaporative cooler with the air-cooled condenser seems to be an original solution to this problem. To determine the optimal design parameter of evaporative air-cooled chiller, which composes of an evaporative entering air cooler and a conventional air-cooled chiller, a mathematical model was developed and a new index, increase of seasonal energy efficiency rate, was proposed to evaluate the energy saving potential of the novel air-cooled chiller. The energy saving potential of the evaporative air-cooled chiller was simulated by using the hourly weather data of four typical cities in China. The influence of various factors on the energy saving potential was analyzed and it was found that there exists an optimal pad thickness which maximizes the energy saving. The optimal pad thickness varies with climate condition and face velocity. It is necessary to determine rational design parameters according to different weather condition.

KEYWORDS
Simulation, Evaporative air-cooled chiller, Energy saving, Optimization

INTRODUCTION
Currently, about 30 percent of energy consumption comes from buildings in China, and energy consumed by air-conditioning systems has accounted for 40%-60% of the total building energy consumption. Thus, energy saving and environmentally friendly air-conditioning systems in this sector are, more than ever, urgently required, especially in China.
Air-cooled chillers are widely applied in China, especially in small to medium scale commercial buildings, because no cooling towers and condenser water pumps are necessary. Another advantage of air-cooled chillers is they do not require a mechanical room for the chiller. This frees up considerable space for occupant use. However, compared with water-cooled chillers, air-cooled chillers have long been considered inefficient in providing cooling energy for air-conditioning in buildings (Chan and Yu 2002). The reason which

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results in a lower COP of air-cooled chillers than water-cooled chillers is that air-cooled condensers are designed to work at a condensing temperature of 11-14 ℃ above the dry-bulb temperature of outdoor air, while water-cooled condensers allow the condensing temperature to close to 4–6 ℃ above the wet-bulb temperature of outdoor air (Yu and Chan 2005). Therefore, a higher condenser pressure is required for air-cooled chiller than water-cooled chiller, which leads to a higher compressor power consumption and a lower refrigeration capacity. It is desirable to improve the coefficient of performance (COP) of the air-cooled chiller in order to save energy and reduce emission.

Evaporative air-cooled chiller (EACC), which composes of an evaporative entering air cooler and an air-cooled chiller, is an energy efficient air-conditioning technology and thus has a good application prospect. Energy saving potential of EACC at design weather conditions had been investigated by some researchers (Zhang and Chen 1999, You *et al* 1999, Jiang and Zhang 2006). However, a constant efficiency of evaporative cooler was considered in these researches. In addition, the energy consumption increase of condenser fan resulted by the pressure drop of evaporative cooler and the power consumption of circulating pump are ignored by these researchers.

In this paper, the principle of EACC will be introduced. In order to evaluate the energy saving potential more accurately, a mathematical model for the energy consumption analysis of EACC is developed. With the mathematical model, the factors which have effects on the energy saving potential of EACC will be analyzed and the optimal pad thickness and maximum energy saving potential will be determined with the hourly weather data of four typical cities in China. The aim of this paper is to analyze the influence of various factors on energy saving performance of EACC and to illustrate the necessity of reasonably determining the design parameter of EACC according to the different climate condition.

EVAPORATIVE AIR-COOLED CHILLER

The schematic of evaporative air-cooled chiller is as shown in Fig.1, which mainly consists of a conventional air-cooled chiller (CACC) and a direct evaporative cooler. In a conventional air-cooled chiller, ambient air directly enters the air-cooled condenser to remove the condensation heat of refrigeration system. In an EACC, a direct evaporative cooler is installed in front of the condenser to precool the entering air. The direct evaporative cooler mainly consists of a water tank, a circulating pump, a water distributor, and pad. The circulating pump draws water from the water tank and sprays it uniformly on the pad, where heat and mass transfer occurs between water and entering air and the entering air will be cooled.

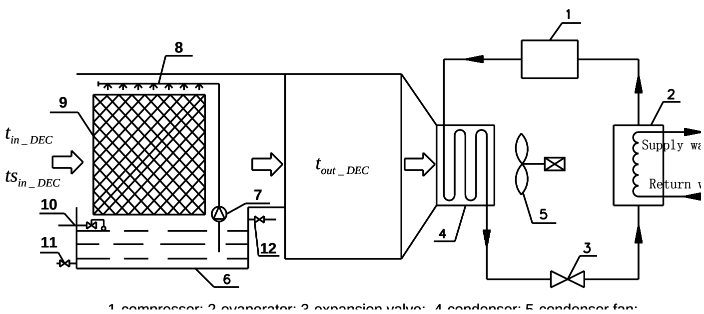

Figure 1. Schematic of EACC

MATHEMATICAL MODEL

DIRECT EVAPORATIVE COOLER

Performance of direct evaporative cooler can be expressed by a saturating efficiency, or called as direct evaporative cooling efficiency, which is defined as

$$\eta = (t_{in\_DEC} - t_{out\_DEC})/(t_{in\_DEC} - ts_{in\_DEC}) \quad (1)$$

where, t_{in_DEC} and t_{out_DEC} are, respectively, the entering and leaving air dry-bulb temperatures of the direct evaporative cooler in ℃; ts_{in_DEC} is the entering air wet-bulb temperature of direct evaporative cooler in ℃. The entering air dry-bulb and wet-bulb temperatures of direct evaporative cooler equal to that of ambient air. The saturating efficiency varies with the performance of pad, the thickness of pad, and face velocity. It can be computed by Eq. (2) (Wu *et al* 2009).

$$\eta = 1 - \exp(-\alpha \frac{\delta}{v^n}) \quad (2)$$

where, δ is the pad thickness in m; v is the face velocity in m/s. α and n are the performance parameters which vary with the material and structure of pad.

AIR-COOLED CHILLER

For a given air-cooled chiller, its performance is influenced by the entering water temperature and flowrate of evaporator, the entering air temperature and flowrate of condenser, and the rotary velocity of compressor. If the entering water temperature and flowrate, the entering air flowrate, and rotary velocity keep constant, the cooling capacity and power consumption of a air-cooled chiller will mainly vary with the entering air dry-bulb temperature of condenser. That is

$$Q_{ACC} = a_0 + \sum_{i=1}^{4} a_i (t_{in\_ACC})^i \quad (3)$$

$$P_{ACC} = b_0 + \sum_{i=1}^{3} b_i (t_{in\_ACC})^i \quad (4)$$

where, Q_{ACC} is the cooling capacity of air-cooled chiller in kW; P_{ACC} is the power consumption of chiller in kW, which includes the compressor power and the condenser fan power; $a_i (i = 0 \sim 4)$ and $b_i (i = 0 \sim 3)$ are constant coefficients; t_{in_ACC} is the entering air dry-bulb temperature of condenser in ℃. For a conventional air-cooled chiller, t_{in_ACC} is the dry-bulb temperature of ambient air. But, t_{in_ACC} equals to the leaving air dry-bulb temperature of direct evaporative cooler, t_{out_DEC}, for an EACC.

EVALUATION INDEX

Energy efficiency rate (EER) is usually used for assessing the performance of chiller. For conventional air-cooled chiller, its EER can be computed by

$$EER_{CACC} = Q_{CACC} / P_{CACC} \tag{5}$$

where, Q_{CACC} and P_{CACC} are, respectively, the cooling capacity and power consumption of conventional air-cooled chiller, which can be calculated by using Eqs. (3) and (4). However, for a EACC, its EER should be determined by Eq. (6).

$$EER_{EACC} = Q_{EACC} /(P_{EACC} + \delta P_F + P_P) \tag{6}$$

where, Q_{EACC} and P_{EACC} are, respectively, the cooling capacity and power consumption of EACC, which can also be calculated by using Eqs. (3) and (4). But for this case, the entering air temperature of condenser in Eqs (3) and (4) should be the leaving air dry-bulb temperature of direct evaporative cooler, t_{out_DEC}. δP_F is the additional power consumption of condenser fan in kW resulted by the pressure drop of the direct evaporative cooler. P_P is the power consumption of circulation pump of direct evaporative cooler, kW. δP_F and P_P can be determined by Eqs. (7) and (8), respectively.

$$\delta P_F = G_F \delta p_F /(1000\eta_F) \tag{7}$$

$$P_P = G_P \rho_W H_P g /(1000\eta_P) \tag{8}$$

In Eqs. (7) and (8), G_F is air volume flow-rate of condenser fan in m^3/s. δp_F is the pressure drop of direct evaporative cooling pad in Pa. G_P is the water volume flow-rate of circulating pump in m^3/s. ρ_W is the density of water in kg/m^3. H_P is the circulating pump head in unit of m. g is the gravitational acceleration in m/s^2. η_F and η_P are, respectively, the efficiency of condenser fan and circulating pump, which are assumed to be 80% in this paper. The flowrate of circulating pump, G_P, can be determined by Eq. (9).

$$G_P = \mu G_F \rho_A / \rho_W \qquad (9)$$

where, ρ_A is the density of air in kg/m^3. μ is the rate of water flowrate to air flowrate required by direct evaporative cooler, which is usually 0.4. The pressure drop of direct evaporative cooling pad varies with the pad thickness and the face velocity, which can be calculated by

$$\delta p_F = \beta \delta v^2 \qquad (10)$$

where, β is a constant related with pad.

Because the temperature and humidity of ambient air are variable during a year, EER of chiller is not constant. Thus, the annually operation performance of air-cooled chiller can not be accurately represented by the EER under a given weather condition. A new index, seasonal energy efficiency rate (SEER), is used for assessing the annually operation performance of air-cooled chiller, which is defined as

$$SEER = (\int EER dt)/(\int dt) \approx (\sum_{cooling\,season} EER \Delta t)/(\sum_{cooling\,season} \Delta t) \qquad (11)$$

To evaluate the energy saving potential of EACC compared with conventional air-cooled chiller, a new index, named as increase of seasonal energy efficiency rate (ISEER), is defined as

$$ISEER = (SEER_{EACC} - SEER_{CACC}) / SEER_{CACC} \qquad (12)$$

where, $SEER_{CACC}$ and $SEER_{EACC}$ are, respectively, the SEERs of conventional air-cooled chiller and EACC. Obviously, the greater ISEER is, the greater the energy saving potential of EACC is, compared with conventional air-cooled chiller. Therefore, ISEER can be used for assessing the energy saving potential of EACC under a given weather condition. If ISEER is larger than zero, it means that the EACC is more energy-saving than a conventional one and vice versa.

SIMULATION AND OPTIMIZATION

SIMULATION CONDITIONS

In this paper, performance data of a typical conventional air-cooled chiller manufactured by a famous air-conditioning company in Guangdong Province of China is used for analyzing the energy saving potential of the combination of direct evaporative cooler and conventional air-cooled chiller. The rated cooling capacity of this air-cooled chiller is 347kW with a supply water temperature of 7℃ and a return water temperature of 12℃. The volume flowrate of condenser fan is 30m^3/s. Taking advantage of the experimental data from manufactory, the constant coefficients in Eqs. (3) and (4) were fitted by the least squares method, which are a_0=440, a_1=1.8, a_2=0.15, a_3=3.7×10^{-4}, a_4=1.2×10^{-5}; b_0=110, b_1=2.3, b_2=6.9×10^{-2}, b_3=-3×10^{-4}. A kind of stripe pad developed by Munters AB is used for direct evaporative cooler. This pad consists of specially impregnated and corrugated cellulose paper sheets with different flute angles and thus has a high evaporation efficiency while still operating with a very low pressure drop. The performance parameters of pad in Eqs (2) and (10) are also fitted by using the performance data from manufactory, which are α=22.84, n=0.263, and $\beta = 179.65$. It is estimated that the circulating pump head is about 10m.

The hourly weather data of four typical cities, Beijing, Shanghai, Lhasa and Urumchi, are used for analyze the effects of pad thickness and face velocity on performance of EACC. The weather data comes from reference (Information Center of China Meteorological Administration 2005). In the simulation, only when the outdoor dry-bulb temperature is higher than 25℃ will be considered. Otherwise, cooling is no need.

SIMULATION OF THE ENERGY SAVING POTENTIAL OF EACC

Besides weather condition, the factors which have effect on the energy saving potential of EACC include the thickness of pad, δ, and face velocity, v. Fig. 2 shows the variation of ISEER with pad thickness and face velocity at four typical cities, Beijing, Shanghai, Lhasa, and Urumchi.

As can be seen from Fig. 2, both pad thickness and face velocity have great influence on energy saving potential of evaporative air-cooled chiller, and the effects are different at the four cities because of their different weather features. For given climate condition and pad thickness, the ISEER increases with the decrease of face velocity. The higher the face velocity is, the shorter the stay time of entering air in pad is. The heat and mass transfer between entering air and water is not completed, and thus resulting in a higher leaving air temperature.

Pad thickness has dual effects on energy saving potential of EACC. On one hand, the staying time of air in pad gets longer and thus a higher cooling efficiency with the increase of pad thickness. On the other hand, the pressure drop of pad increases and thus a larger power consumption of condenser fan with a thicker pad layer. Just as shown as Fig. 2, for a given face velocity, the ISEER increases at first and reduces then as pad layer gets thick. This variation is more obvious for a lower face velocity.

Weather condition has influence on energy saving potential of EACC, too. Fig. 2 shows EACC has greater energy saving potential in Urumchi than in the other cities. Compared with the others, the energy saving potential in Shanghai is the minimum. The reason is that

Urumchi, a northwest city of China, has a dry and hot climate in summer while Shanghai, a southeast city of China, has a humid and hot climate in summer. Therefore, EACC is more favorable for dry and hot climate like Urumchi.

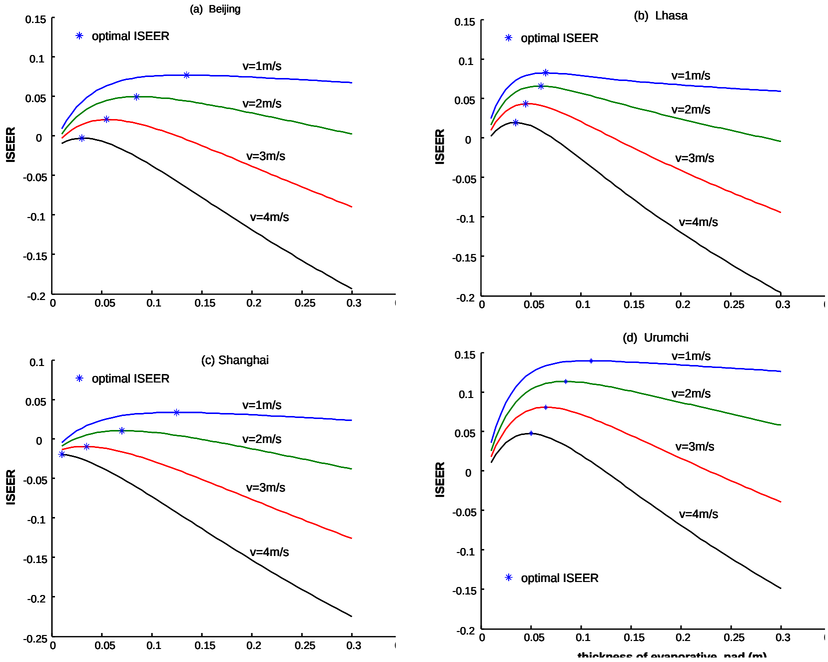

Figure 2. Simulation result of energy saving potential of EACC

OPTIMIZATION OF PAD THICKNESS

From above analysis, rational selection of face velocity and pad thickness is the key for design of EACC. It can be seen from Fig. 2 that EACC is not always more energy-saving than conventional air-cooled chiller. For example, when face velocity is higher than 2m/s, the EACC may consume more energy than conventional air-cooler chiller in Shanghai. Even in Urumchi the ISEER may be lower than zero if the face velocity is high and pad is thick. Therefore, EACC should be optimally designed and not a simple combination of direct evaporative cooler and air-cooled chiller. Otherwise, more energy may be consumed.

If only the energy saving is considered, a lower face velocity is better. However, a lower face velocity requires a larger frontal area of evaporative cooling pad, and thus a larger volume of chiller and a higher cost. Usually, a face velocity of 1~2m/s is reasonable.

Table 1. Optimization result of EACC (v=1m/s)

City name	Optimal pad thickness (mm)	Optimal ISEER （%）
Beijing	δ=135	7.7
Lhasa	δ=65	8.2
Shanghai	δ=125	3.4
Urumchi	δ=110	14.0

It can be found from Fig. 2 that there exists a pad thickness which maximizes the energy saving of EACC for given weather condition and face velocity. It is called optimal pad thickness. The optimal pad thickness reduces as face velocity increases. Table 1 shows the computation results of the optimal pad thickness for a face velocity of 1m/s. The optimal ISEER is the ISEER at the optimal pad thickness. From Table 1, the optimal pad thicknesses for various cities are different. Therefore, when an EACC is adopted, an optimal pad thickness should be determined according to the climate condition of the location where the chiller will be installed. It can also be found an energy saving of about 14.0% can be achieved in Urumchi while that is 3.4% in Shanghai.

CONCLUSIONS

Combining the air-cooled chiller with direct evaporative cooler can decrease the entering air temperature of condenser and thus improve the performance of air-cooled chiller. The energy saving potential of EACC is concerned with the face velocity and pad thickness besides the climate condition. For given climate condition, the energy saving potential reduces with the increase of face velocity. There exists an optimal pad thickness which maximizes the energy saving potential of EACC. The optimal pad thickness reduces as face velocity increases. In general, EACC has a greater energy saving potential in dry and hot climate than in humid and hot climate. Therefore, EACC is especially suitable for dry and hot climate like that of west and north of China. To maximize the energy saving potential, an EACC should be reasonably designed according to the climate condition.

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