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Economic Analysis Based on Energy and Water Consumptions between Air-Cooling and Water-Cooling

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Cooling process is one of the most common processes in industries. There are two basic types of cooling systems, including air-cooling and water-cooling systems. Whichever is adopted, obviously energy and water consumptions should be needed. With the rapid development of social economy in China, energy-saving and emission-reduction, as well as process water conservation, become focus issues. Considering performance and economy of energy and water has reference value for reasonable choice of cooling type.
In this paper, the cooling range from 95 °C to 35 °C is considered. For dry air cooler, spray type air cooler, evaporative air cooler, and open style circulating water cooling systems, energy and water consumptions are calculated and compared under different dry bulb temperature and relative humidity conditions. Besides, under different price radio of fresh water and industrial electricity, economic analysis is performed to determine the reasonable cooling type.

1. Introduction

Heat transfer is one of the most common processes in industries. The first consideration of the whole heat exchanger network should be heat recovery, and its remaining heat will be cooled by coolers. Cooler can be classified into two categories: air cooling and water cooling.
Comparison between air cooling and water cooling is one of key issues of related researches. Shapiro et al. (1982) evaluated water-cooled and air-cooled devices, but limited to the condition of high dry bulb temperature and high relative humidity. Alhazmy et al. (2006) discussed evaporate cooling systems and direct mechanical cooling, without concern for other cooling methods. Bolotin et al. (2015) made a comparative study of typical evaporative air cooler and regenerative evaporative air cooler.
Recently, energy-saving and industrial water conservation have been the focus of research. In this paper, for dry air cooler, spray type air cooler, evaporative air cooler, and circulating cooling water systems, energy and water consumptions are calculated and compared under different dry bulb temperature and relative humidity conditions. Moreover, economic analysis is performed to select the reasonable cooling type in different price radio of fresh water and industrial electricity. This work is valuable for reasonable choice of cooling method.

2. Energy and Water Consumption of Air Cooler

2.1 Energy and Water Consumption of Dry Air Cooler

The calculation of a dry air cooler is based on ASPEN EDR. Select the module of air cooler, and then enter flows, physical property data, and chilling temperature. Choose air under different relative humidity as cooling medium, leading to data through simulation, such as static pressure drop, air outlet temperature.
The energy consumption of dry air cooler is mainly fan power, which can be computed as follows.

$$N = \frac{2.778 \times 10^{-7} \left(\Delta p_{st} + \frac{\rho_b}{2} \left(\frac{V}{900 \pi D_f^2} \right)^2 \right) V \times \left(0.98604 + 0.01435 \times 10^{-2} H_L + 2.495 \times 10^{-9} H_L^2 \right)}{\eta_1 \eta_2 \eta_3} \quad (1)$$

where N is motor power, kW; Δp_{st} is total static pressure drop, Pa; ρ_b is air density, kg·m^{-3}; V is actual wind flowrate, m^3·h; D_f is fan impeller diameter, m; η_1 is fan efficiency, whose value is taken as 0.75 in this paper;

η_2 is transmission efficiency, whose value is taken as 0.92 in this paper; η_3 is motor efficiency, whose value is taken as 0.9 in this paper; H_L, altitude, m.
Dry air cooler has no water consumption.

2.2 Energy and Water Consumption of Wet Style Air Cooler

For wet style air coolers, heat transfer is enhanced in some ways, including humidifying and spraying. According to jetting modes, it comes in several varieties: spray type air cooler, evaporative air cooler, etc. This paper chooses spray type and evaporative air cooler to calculate and analyse.
Energy consumption of a wet style air cooler comes mainly from the fan and spray water pump. In this paper, for a spray type air cooler, the head of delivery of its spray water pump is taken as 20 m, while its pump efficiency is taken as 48.5 %; for an evaporative air cooler, the head of delivery of its spray water pump is taken as 25 m, while its pump efficiency is taken as 45.5 %.
When air flowrate is about 100,000 kg/h, the film heat transfer coefficient of the shell side can be calculated.

$$h_o = 90.7\varphi_\theta G_F^{0.05+0.08N_P} B_S^{0.77-0.35N_P}\theta^{-0.35} \tag{2}$$

where h_o is film heat transfer coefficient of the shell side, W·m^{-2}·^{o}C^{-1}; G_F is air mass flowrate on the windward side, kg·m^{-2}·s^{-1}; φ_θ is fin height influence coefficient, whose value is 1; B_S is spraying intensity, kg·m^{-2}·h^{-1}; θ is temperature coefficient.
For a spray type air cooler, the calculation can be carried out in subsequent process after the inlet air is humidified. The outlet air temperature can be formulated as Eq(3).

$$t_{g2} = t_{g1} + \frac{3600Q}{W_a C_{pa}}(2.55 + 0.15N_P)\varphi_\theta B_S^{-0.54}\theta^{0.35} \tag{3}$$

where t_{g1} and t_{g2} are inlet and outlet air temperature of wet style air cooler respectively, ^{o}C; W_a is air flowrate of the wet style air cooler, kg·s^{-1}; C_{pa} is specific heat of air, kJ·kg^{-1}·^{o}C^{-1}.
The calculating formulas of fan power is the same as Eq(1), while motor power of the spray water pump is calculated as follows.

$$P_N = \frac{1.25W_A gH}{3600\eta} \tag{4}$$

where P_N is motor power of the spray water pump, kW; W_A is water flowrate, m^3·h^{-1}; g is acceleration of gravity, m·s^{-2}; H is head of delivery, m; η is pump efficiency.
Ignoring heat loss, for an evaporative air cooler, heat transferred of the hot fluid is the sum of heat absorbed by air and spray water, while its inlet air is equivalent to the ambient air. Other computational processes can refer the spray type air cooler.
For a wet style air cooler, the water consumption is the sum of evaporated water and blowdown, which accounts for 30 % of the evaporated water. The evaporated water is showed as Eq(5).

$$W_e = W_A(X_2 - X_1) \tag{5}$$

where W_e is water evaporation quantity, kg·h^{-1}; X_1 and X_2 are absolute humidity of inlet and outlet air, respectively, kg (steam)·kg (dry air)$^{-1}$.

3. Energy and Water Consumption of Open Type Circulating Water Cooling System

A circulating cooling water system can be divided into two classes: open type circulating water cooling system and full-closed circulating cooling water system. Open type is chosen to analyse because of wide using.

3.1 Energy Consumption of Open Type Circulating Water Cooling System

Circulating water pump is the basis cause of energy consumption, which can be calculated with Eq(3). In this paper, its head of delivery is taken as 15 m, while its pump efficiency is taken as 72.9 %.

3.2 Water Consumption of Open Type Circulating Water Cooling System

Water consumption of an open type circulating water cooling system mainly consists of evaporation loss, windage loss and blowdown loss, which can be formulated as follows.

$$W_m = \frac{N}{N-1}\left(-2.7778\times10^{-9}T_w^2 - 3.5714\times10^{-8}T_w + 2.0635\times10^{-5}T_w + 0.001\right)\Delta t W_r \tag{6}$$

where Δt is temperature difference of cooling water between inlet and outlet, ^{o}C; W_r is circulating water volume, m^3·h^{-1}; N is design cycles of concentration; W_m is water consumption, m^3·h^{-1}; T_w is wet bulb temperature, ^{o}C.

4. Analysis of Energy and Water Consumption During Cooling Process

4.1 Analysis of Energy Consumption During Cooling Process

Figure 1 and 2 demonstrate energy consumption of cooling methods under different relative humidity.

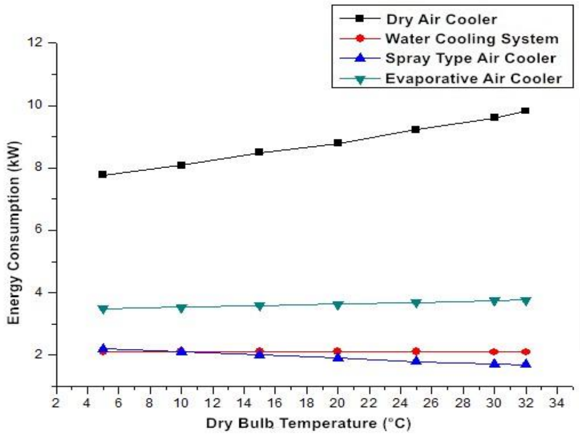

Figure 1: Relationship between T_w and energy consumption when relative humidity is 0.4

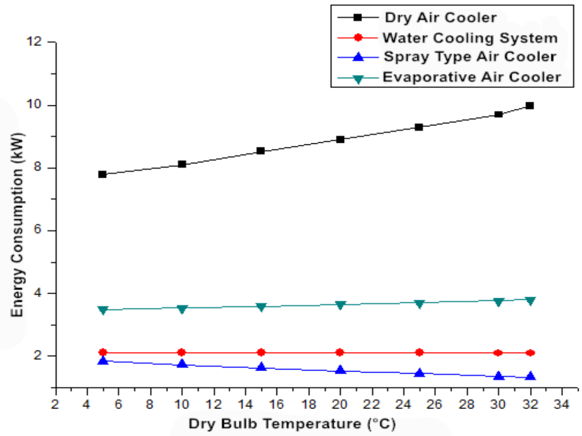

Figure 2: Relationship between T_w and energy consumption when relative humidity is 0.6

As is shown in Figure 1, when the dry bulb temperature is below 12 ºC, the open type circulating water cooling system has the lowest energy consumption; when the dry bulb temperature is above 12 ºC, the spray type air cooler has the lowest. In this case, the dry air cooler has the highest energy consumption. Figure 2 shows that the energy consumption of spray type air cooler is the lowest one, followed by the open type circulating water cooling system and evaporative air cooler; that of the dry air cooler is also the highest.

Since the specific heat of air is much smaller than that of water, dry air cooler needs more air, under the same cooling duty, leading to higher energy consumption caused by fan. Compared with spray type air cooler, evaporative air cooler needs less spray water and more air, while fan power occupies a larger proportion in energy consumption than power of spray water pump, so it requires more energy consumption.

The inlet air temperature can be reduced to about its wet bulb temperature by wet style air cooler. Under lower relative humidity, energy consumption of a spray type air cooler is close to that of an open type circulating water cooling system. Under certain relative humidity, the higher the dry bulb temperature is, the smaller the difference in temperature between dry bulb and wet bulb is, so that the cooling capacity of a spray type air cooler is lower, with higher energy consumption, and vice versa. Under higher relative humidity, the difference in temperature between dry bulb and wet bulb is relatively small, so a spray type air cooler has lower cooling capacity than an open type circulating water cooling system, while its energy consumption is higher.

4.2 Analysis of Water Consumption During Cooling Process

Under different relative humidity, water consumption of these cooling methods can be seen in Figure 3 and 4.

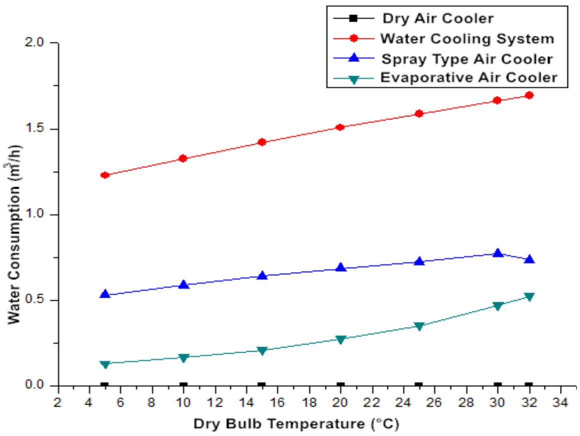

Figure 3: Relationship between T_w and water consumption when relative humidity is 0.4

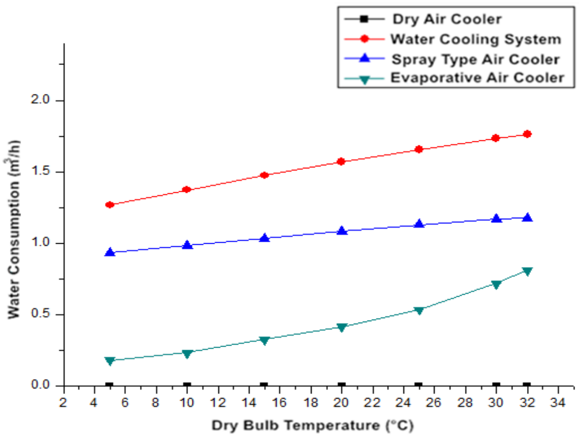

Figure 4: Relationship between T_w and water consumption when relative humidity is 0.6

Figure 3 and 4 show that an open type circulating water cooling system has the highest water consumption; water consumption of a spray type air cooler is higher than that of an evaporative air cooler. This is because open type circulating water cooling system needs much water for cooling due to evaporation loss, windage loss and blowdown loss; a spray type air cooler requires more spray water than an evaporative air cooler, causing higher water consumption.

5. Economic Analysis of Cooling Process

To a great extent, economic analysis of cooling processes depends on price of fresh water and industrial electricity. The price in different important industrial cities of China is given in Table 1, obtained from China Statistical Yearbook 2015.

The price radio of fresh water and industrial electricity is set as the variable, the scattering plots curves of price radio and annual total cost are drawn, and then the curves are fitted to analyse. ASPEN EDR and the Economics module in ASPEN PLUS are used to determine the cost of those cooling methods. Depreciation for plant assets adopts double-declining-balance method.

Table 1: Price of fresh water and industrial electricity in different cities of China and its radio

City	Price of electricity (CNY/kWh)	Price of fresh water (CNY/m^3)	Price radio (kWh/m^3)
Nanchang	0.66	2.37	3.60
Wuhan	0.63	2.35	3.70
Harbin	0.59	2.40	4.05
Chengdu	0.60	2.70	4.50
Fuzhou	0.62	3.00	4.82
Yinchuan	0.48	2.60	5.43
Nanjing	0.66	3.60	5.45
Shanghai	0.73	5.00	6.89
Urumqi	0.38	2.70	7.07
Hangzhou	0.45	3.90	8.69
Shijiazhuang	0.59	5.33	9.10
Jinan	0.65	5.95	9.19
Chifeng	0.51	4.90	9.61
Lanzhou	0.25	2.53	9.96
Xi'an	0.57	5.80	10.17
Average	0.56	3.68	6.59

5.1 Economic Analysis of Water Cooling Process in 5 ºC

The relationship between the price radio and annual total cost at 5 ºC is shown in Figure 5 and 6, when the relative humidity has a value of 0.4 and 0.6.

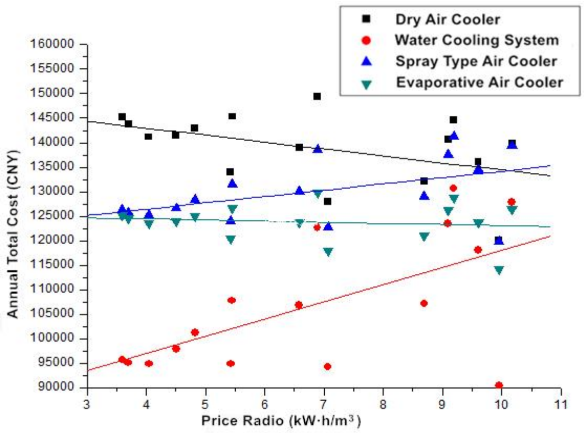

Figure 5: Relationship between price radio and annual total cost at 5 ºC when relative humidity is 0.4

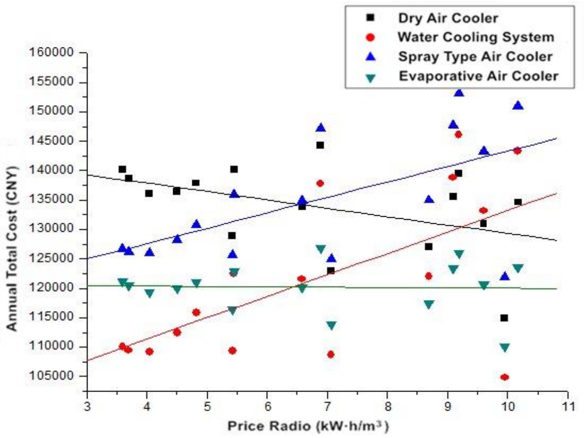

Figure 6: Relationship between price radio and annual total cost at 5 ºC when relative humidity is 0.6

Under lower relative humidity, according to Figure 5, the open type circulating water cooling system has the lowest annual total cost. Under higher relative humidity, from Figure 6, when the price radio is lower than 6.5, the annual total cost of the open type circulating water cooling system is also the lowest; when the price radio is higher than 6.5, that of the evaporative air cooler is the lowest, because its energy consumption is lower than that of the dry air cooler, while its water consumption is lower than that of the evaporative air cooler.

5.2 Economic Analysis of Water Cooling Process in 15 ºC

Figure 7 and 8 represent the relationship between the price radio and annual total cost at 15 ºC, under the condition that the value of relative humidity is 0.4 and 0.6.

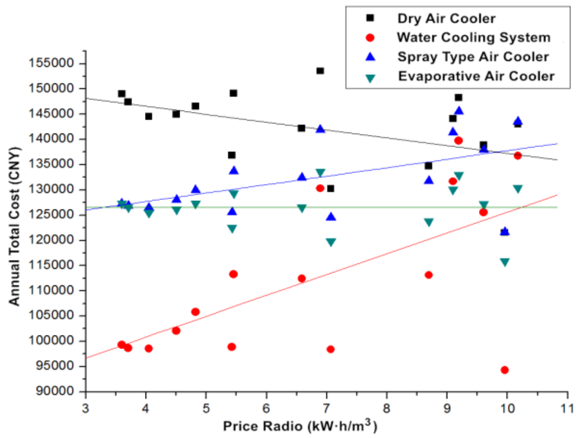

Figure 7: Relationship between price radio and annual total cost at 15 ºC when relative humidity is 0.4

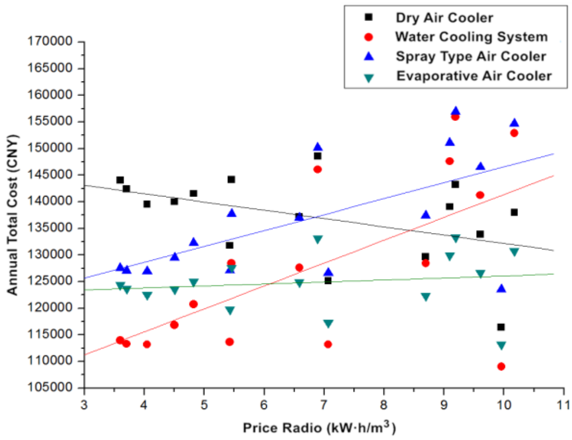

Figure 8: Relationship between price radio and annual total cost at 15 ºC when relative humidity is 0.6

As is shown in Figure 7, under the condition that the value of relative humidity is 0.4, when the price radio is lower than 10.4, the annual total cost of the open type circulating water cooling system is the lowest; when the price radio is higher than 10.4, that of evaporative air cooler is the lowest. From Figure 8, under the condition that the value of relative humidity is 0.6, when the price radio is lower than 6.2, the open type circulating water cooling system has the lowest annual total cost; when price radio is higher than 6.2, the evaporative air cooler is the best choice. There is no doubt that in terms of economic performance, water cooling is more advantageous. Additionally, since, to some extent, the evaporative air cooler has advantages of water cooling and air cooling, it has the lowest annual total cost when relative humidity is comparatively higher.

5.3 Economic Analysis of Water Cooling Process in 25 ºC

When the value of relative humidity is 0.4 and 0.6, Figure 9 and 10 demonstrate the relationship between the price radio and annual total cost at 25 ºC.

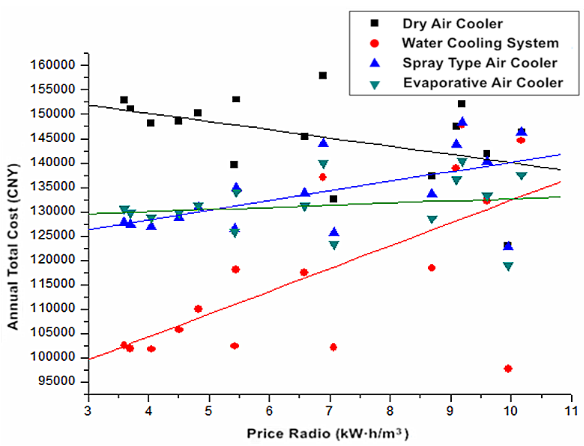

Figure 9: Relationship between price radio and annual total cost at 25 ºC when relative humidity is 0.4

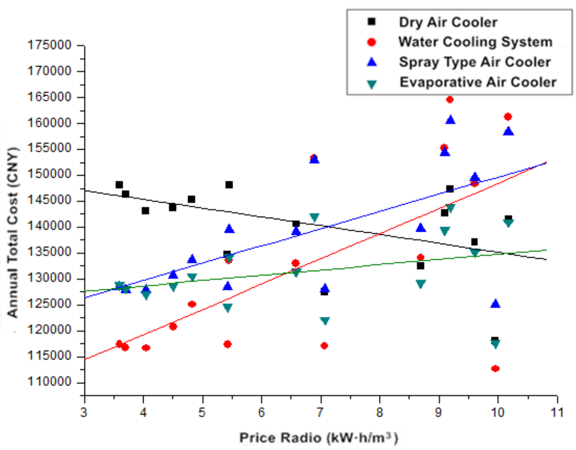

Figure 10: Relationship between price radio and annual total cost at 25 ºC when relative humidity is 0.6

According to Figure 9, under lower relative humidity, when the price radio is lower than 10, the open type circulating water cooling system has the lowest annual total cost; when the price radio is higher than 10, so does dry air cooler. As is shown in Figure 10, under higher relative humidity, when the price radio is lower than 6.5, the annual total cost of the open type circulating water cooling system is the lowest; when price radio is between 6.5 and 10.2, that of the evaporative air cooler is the lowest; when price radio is higher than 10.2, the dry air cooler is the best choice. Water cooling is favourable with a lower price radio, and a higher price radio leads to lower annual total cost of air cooler. Besides, the evaporative air cooler combines advantages of both water cooling and air cooling, which is dominant when price radio is in the middle.

6. Conclusions

In this paper, dry air cooler, spray type air cooler, evaporative air cooler and open style circulating water cooling system are calculated and compared.

Among these cooling methods, a dry air cooler has the highest energy consumption. Energy consumption of an open type circulating water cooling system is the lowest under the condition of lower dry bulb temperature and relative humidity. When the dry bulb temperature is higher and relative humidity is lower, or when the relative humidity is higher, a spray type air cooler has the lowest energy consumption. A dry air cooler has no water consumption, while an open type circulating water cooling system has the highest water consumption. Furthermore, water consumption of an evaporative air cooler is lower than that of a spray type air cooler.

The price radio of fresh water and industrial electricity exerts tremendous influence on economy of cooling methods. The dry air cooler is the best choice where the price radio is higher, while the open type circulating water cooling system should be chosen where the price radio is lower. Additionally, where the price radio is in the middle, the evaporative air cooler has the lowest annual total cost under the condition of higher dry bulb temperature. Restricted to the cooling medium, the dry air cooler might not cool hot fluid into lower temperature, which can be solved in the way of following by water cooling.

Acknowledgments

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