Energy-saving Analysis of Chilled Water System for Large Temperature Difference Air Conditioning

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Abstract. In order to analyse the energy-saving performance of chilled water system, the energy consumption of pumps in air-conditioning systems with large temperature difference is studied and analyzed theoretically. By calculating the energy consumption of each part of the chilled water system with large temperature difference, it shows that the chilled water with large temperature difference has good energy-saving effect. The influence of large temperature difference on air conditioning system is also analyzed, specific improvement measures are introduced, and some problems that should be paid attention to when choosing large temperature difference air conditioning chilled water system are pointed out. At the same time, the energy consumption of chillers and chilled water pumps is compared. Taking the total energy consumption of air conditioning unit as the objective function, the scheme of chilled water system for large temperature difference air conditioning is optimized and calculated. The results show that the optimal temperature difference between supply and return water for chilled water system of air conditioning is 7.2℃. The application situation of the scheme of chilled water system for large temperature difference air conditioning is discussed.

Keywords. large temperature difference; air conditioning system; energy consumption; energy saving.

1. Introduction

At present, the energy-saving ability of applying large temperature difference technology in air-conditioning water system has been initially affirmed, but the specific energy-saving effects of this technology and the impacts on various components of air-conditioning system are still in the exploratory stage, and there is no universal standard to measure and evaluate it [1]. In many existing literatures, scholars use various analytical methods, based on different assumptions, to analyze the performance of large temperature difference and variable flow technology of air-conditioning water system, and get some qualitative analysis results. For example, on the premise of guaranteeing the performance of chillers, the range of temperature difference between chilled water and cooling water in large temperature difference system, the law of performance and energy consumption of chillers changing with the change of chilled water flow, the law of performance change of air conditioning terminal devices caused by the change of temperature difference and flow, etc. are discussed. However, there are few studies on how much temperature difference can maximize the efficiency of the system under different conditions.

2. Methodology

Calculation method and hypothesis: Energy consumption of air-conditioning water system is mainly divided into two aspects: energy consumption of chillers and energy consumption of pumps. Under the condition of large temperature difference of chilled water, with the increase of temperature difference, the energy consumption of unit (mainly compressor) increases, while the energy consumption of chilled water pump decreases [2]. Therefore, the energy consumption of chilled water system for large temperature difference air conditioning is calculated from two aspects, chiller and chilled water pump. The calculation is based on the theory of refrigeration cycle and pump similarity, and refers to the conventional design temperature difference (7 °C/12 °C) [3]. The chiller uses R_{22} refrigerant and the condensation temperature is 40°C. Hydraulic calculation part is assumed to control specific friction to ensure that the resistance of refrigerated water pipeline does not change or change little, so the change of resistance of refrigerated water pipeline is not considered.

The calculation of energy consumption of chiller in chilled water system of large temperature difference air conditioning requires the evaporation temperature of chiller to decrease due to the decrease of chilled water outlet temperature. According to Formula (1), when the chilled water temperature is designed to be 5 °C/15 °C, the corresponding evaporation temperature and the unit cooling energy consumption of chillers are calculated.

t_0 =5°C, Δt_w =10°C are substituted in Formula (1).

$$\ln(\triangle t_w/(t_{wo}/t_o)+1) = \triangle t_w/(2.5+0.4139 \triangle t_w 0.8) \quad (1)$$

t_0 refers to the evaporation temperature (°C) of refrigerant under the condition of large temperature difference, t_{wo} is the outlet temperature of cold water, and Δt_w is the temperature difference between inlet and outlet of cold water. The evaporation temperature t_0 = 3.35 C is calculated.

When the outlet temperature of frozen water is set to 5°C, 6°C, and 7°C, respectively, the temperature difference between the supply and return water of frozen water is 6°C, 7°C, 8°C, 9°C and 10°C, respectively (Table 1).

Table 1. Evaporation thermometer with different outlet temperature of chilled water and temperature difference between supply and return water

t_0°C	$\triangle t_w = 6$	$\triangle t_w = 7$	$\triangle t_w = 8$	$\triangle t_w = 9$	$\triangle t_w = 10$
t_{wo} = 5°C	3.08	3.16	3.23	3.29	3.35
t_{wo} = 6°C	4.08	4.16	4.23	4.29	4.35
t_{wo} = 7°C	5.08	5.16	5.23	5.29	5.35

As the temperature of chilled water changes from 7°C/12°C to 5°C/15°C, the evaporation temperature is decreased by 1.65 °C (5-3.35=1.65 °C) [4]. The decrease of evaporation temperature leads to the increase of energy consumption of water chillers.

$$P/Q_0 = (h_2 - h_1)/(h_1 - h_4) \circ (1/\eta_C) \diamond \eta_m \quad (2)$$

η_C indicates the total efficiency of refrigeration compressor, η_c =0.65～0.72; η_m suggests the driving efficiency of motor, and coupling direct drive is η_m =0.98.

According to the theoretical cycle of water chiller with R_{22} and condensation temperature of 40°C, the energy consumption per unit refrigeration capacity of water chiller can be obtained from the enthalpy diagram when t_0 = 3.35 °C, h_1 = 406.57 kJ/kg, h_2 = 431.82 kJ/kg, and h_4 = 249.67 kJ/kg [5].

$$P/Q_0 = (431.82 - 406.57)/(406.57 - 249.67)/(1/0.7 \times 0.98) = 0.2253\,kW/kW \quad (3)$$

The energy consumption per unit refrigeration capacity of water chiller at each evaporation temperature is calculated (Table 2).

Table 2. Energy meter of unit refrigeration capacity of water chiller at various evaporation temperatures

t_0°C	h_1 kJ/ kg	h_2 kJ/kg	h_4 kJ/kg	η_C	η_m	P/Q_0 kW/kW
3.08	406.48	431.95	249.67	0.7	0.98	0.2274
3.16	406.51	431.92	249.67	0.7	0.98	0.2268
3.23	406.53	431.89	249.67	0.7	0.98	0.2263
3.29	406.55	431.85	249.67	0.7	0.98	0.2258
3.35	406.57	431.82	249.67	0.7	0.98	0.2253
4.08	406.83	431.49	249.67	0.7	0.98	0.2197
4.16	406.86	431.46	249.67	0.7	0.98	0.2191
4.23	406.88	431.43	249.67	0.7	0.98	0.2186
4.29	406.9	431.39	249.67	0.7	0.98	0.2181
4.35	406.92	431.36	249.67	0.7	0.98	0.2176
5.00	407.15	431.06	249.67	0.7	0.98	0.2126
5.08	407.18	431.03	249.67	0.7	0.98	0.2120
5.16	407.21	431	249.67	0.7	0.98	0.2114
5.23	407.23	430.96	249.67	0.7	0.98	0.2109
5.29	407.25	430.93	249.67	0.7	0.98	0.2104
5.35	407.27	430.9	249.67	0.7	0.98	0.2109

Tables 1 and 2 show that the unit refrigeration power consumption of chillers is decreased with the increase of the outlet temperature of chilled water, and decreased with the increase of the temperature difference between chilled water supply and return water [6]. However, the change of outlet temperature of chilled water and temperature difference between supply and return water will lead to the change of refrigeration capacity, which has great influence on the terminal device. Therefore, based on the premise of constant refrigeration capacity, the power consumption of chillers is analyzed according to the refrigeration capacity under the conventional temperature difference (7°C/12°C). According to the logarithmic mean temperature difference formula, the logarithmic mean temperature difference changes very little when the average temperature of the refrigerated water supply and return level is constant. The temperature of the refrigerated water supply and return water is 7.0 °C/12.0°C, 6.5°C/12.5°C, 6.0°C/13.0°C, 5.5°C/13.5°C, 5.0°C/14.0°C, and 4.5°C/14.5°C, respectively [7]. Evaporation temperature and unit energy consumption of the chiller are calculated and the results are shown in Table 3.

Table 3. Unit refrigeration energy consumption meter for water chillers

t_1/t_2°C	t_0°C	h_1 kJ/kg	h_2 kJ/kg	h_4 kJ/kg	η_C	η_m	P/Q_0 kW/kW
7.0/12.0	5.00	407.15	431.06	249.67	0.7	0.98	0.212 6
6.5/12.	4.58	407.01	431.26	249.67	0.7	0.98	0.215 8
6.0/13.0	4.16	406.86	431.46	249.67	0.7	0.98	0.219 1
5.5/13.5	3.73	406.71	431.66	249.67	0.7	0.98	0.222 4
5.0/14.0	3.29	406.55	431.85	249.67	0.7	0.98	0.225 8
4.5/14.5	2.85	406.4	432.052	249.67	0.7	0.98	0.229 1

The calculation of pump power consumption in chilled water system of large temperature difference air conditioning is known from the literature that the water temperature difference doubles and the required water flow will be reduced by half for the same load. When two pumps convey the same fluid and rotate at the same speed, according to the similarity theory, the relationship among pump head, flow rate and power is as follows:

$$\text{Indenter: } H'/H = (W'/W)^{2/3} \tag{4}$$

$$\text{Power: } N'/N = (W'/W)^{5/3} \tag{5}$$

In the above formulas, H is the indenter of the pump, m; W is the flow rate of the pump, kg/s; N is the power of the pump, kW; the superscript ' represents the parameter of large temperature difference. When W = 50%, it is possible to get:

$$\mathrm{H} = 0.5^{2/3}H = 0.63H, \mathrm{N} = 0.5^{5/3}N = 0.315, \triangle N = N' - N = (1 - 0.315)N = 0.685N.$$

According to the calculation results, the energy consumption of chilled water pump is reduced by 68.5% by using water system with large temperature difference and the energy consumption of converted unit cold energy is as follows:

$$\begin{aligned} \triangle H/Q_0 &= 0.685N/Q_0 \\ &= (0.685\rho WH \times 9.81 \times 10^{-3})/1000\eta_P\eta_m WC \triangle t \\ &= 6.72\rho H/(10^6\eta_P\eta_m WC \triangle t)\ kW/kW \end{aligned} \tag{6}$$

In the formula, ρ is the density of water, ρ= 1 000 kg/m^3, H is the indenter of the pump, m; W is the flow rate of the pump, kg/s; Q_0 is the refrigeration capacity; Q_0 = WCΔt, kW; C is the specific heat of water, C = 4.186 8 kJ/kg *°C; Δt suggests the temperature difference of chilled water, °C; η_p is the total efficiency of centrifugal pumps, η_p = 0.60-0.92; η_m is the efficiency of motor drive, η_m = 0.98 for direct coupling drive. Substituting the relevant data into Formula (6), the following formula is obtained:

$$\triangle N/Q_0 = (6.72 \times 1000H)/(10^6 \times 0.8 \times 0.98 \times 4.4868 \times 5) = 4.09 \times 10^{-4}H\ kW/kW$$

Under the conventional temperature difference (7°C/12°C), the energy consumption of the pump is about 10%-15% of that of the compressor, which is calculated by 12%. According to the unit refrigeration energy consumption of the chiller under the conventional temperature difference in Table 3, the unit refrigeration energy consumption of the pump under the conventional temperature difference can be calculated. In other words, based on the pump energy consumption of $0.2126 \times 12\% = 0.0255\,kW/kW$, the unit refrigeration energy consumption of the pump under the conventional temperature difference can be calculated according to the reduction ratio of the energy consumption of the pump.

When the temperature difference between chilled water supply and return water is taken as 6°C, 7°C, 8°C, 9°C and 10°C, the changes of the energy consumption of the pump are shown in Table 4.

Table 4. Changes of energy consumption of chilled water pump with temperature difference between supply and return water

t_1/t_2°C	$\triangle t_W$°C	W'/W	N'/N	$\triangle N$%	N′ / Q_0 kW/kW
7.0/12.0	5	1.000	1.000	0.0	0.0255
6.5/12.5	6	0.833	0.738	26.2	0.0188
6.0/13.0	7	0.714	0.571	42.9	0.0146
5.5/13.5	8	0.625	0.457	54.3	0.0117
5.0/14.0	9	0.556	0.375	62.5	0.0096
4.5/14.5	10	0.500	0.315	68.5	0.0080

3. Results and discussion

3.1. Energy-saving analysis of chilled water system for large temperature difference air conditioning
The sum of energy consumption and energy consumption of chillers and pumps after changing temperature difference and inlet temperature of chilled water are shown in Table 5.

Table 5. Comparison of energy consumption change between water chiller and pump under large temperature difference

t_1/t_2℃	$\triangle t_W$℃	P / Q_0 kW/kW	N′ / Q_0 kW/kW	W / Q_0 kW/kW
7.0/12.0	5	0.2126	0.0255	0.238 1
6.5/12.5	6	0.2158	0.0188	0.234 6
6.0/13.0	7	0.2191	0.0146	0.233 7
5.5/13.5	8	0.2224	0.0117	0.234 1
5.0/14.0	9	0.2258	0.0096	0.235 4
4.5/14.5	10	0.2291	0.0080	0.237 1

Comparing the data in the above table with that in the conventional temperature difference (7℃/12℃), the reduction $\Delta N/Q_0$ kW/kW of energy consumption per unit refrigeration capacity of pumps under large temperature difference is calculated, and the increment $\Delta P/Q_0$ kW/kW of energy consumption per unit refrigeration capacity of chillers is also computed. The difference between the reduction of energy consumption of pumps and the increment of energy consumption of chillers is $\Delta W/Q_0 = \Delta N/Q_0 - \Delta P/Q_0$ kW/kW (Table 6).

Table 6. Contrast of pump energy consumption reduction and unit energy consumption increment under large temperature difference

t_1/t_2℃	$\triangle t_W$℃	P / Q_0 kW/kW	N′ / Q_0 kW/kW	W / Q_0 kW/kW
7.0/12.0	5	0.0000	0.0000	0.0000
6.5/12.5	6	0.0032	0.0067	0.0035
6.0/13.0	7	0.0065	0.0109	0.0044
5.5/13.5	8	0.0098	0.0138	0.0040
5.0/14.0	9	0.0132	0.0159	0.0027
4.5/14.5	10	0.0165	0.0175	0.0010

3.2. Result analysis
According to the above table, the energy consumption of chillers and chilled water pump is compared, and it is concluded that the system has the best energy saving when t_{wo} = 5.9 ℃ and Δt_w = 7.2 ℃. The calculation shows that the evaporation temperature of refrigerant is 4.07 ℃. The energy consumption per unit mass refrigeration capacity of water chiller is only 0.007 1 kW/kW higher than that of nominal refrigeration capacity, the flow of chilled water is reduced by 30.5% and the corresponding energy consumption of chilled water pump is reduced by 45.5%. At the same time, when t_{wo} = 5.9 ℃ and t_w = 7.2℃, in order to ensure energy-saving operation of the system, it is required that at this time, $\Delta N/Q_0 > \Delta P/Q_0$. According to Formula (6), $\Delta N/Q_0 = 2.72 * 10^{-4}$ H is calculated, i.e. $2.72*10^{-4}$ H >0.007 1 kW/kW, and the pump lift needs H > 26.1 m. That is to say, the energy-saving effect of the system can be achieved only for projects with pump lift greater than 26.1 m, and for high-rise buildings, the energy-saving effect of the system will be more obvious.

4. Conclusion

First, the chilled water system of large temperature difference air-conditioning has a great influence on the energy consumption of refrigerating units and air-conditioning units, but its operation has its applicable scope. Only when the reduction of energy consumption of refrigerated water pump is greater than the increment of refrigerator energy consumption can its energy saving be of practical significance.

Second, the technology of large temperature difference of chilled water in air conditioning reduces the circulating water volume, energy consumption of chilled water pump, operation cost of water system and initial investment.

Third, the results of energy consumption analysis of large temperature difference air-conditioning water system show that when the pump head is greater than 26.1 m, the temperature difference between supply and return water of air-conditioning chilled water is 7.2℃ and the outlet temperature of chilled water is 5.9℃, and the large temperature difference air-conditioning water system has the best energy-saving effect.

Fourth, when using the system, it is necessary to balance the initial investment and operation cost of the system in order to make a reasonable choice.

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