ANALYSIS OF ENERGY EFFICIENCY OF CHILLERS OPERATION AT NIGHT

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ABSTRACT

This paper is based on actual measurement weather data of recent decade in Ji’nan, P.R. China, and profile and characteristics of outdoor air wet bulb temperature are analyzed. It is found that outdoor air wet bulb temperature has an effect on the performance of chillers. Results show that the cooling capacity is increased by 9.0 percent, consumption power is reduced by 17.2 percent, and coefficient of performance is stepped-up by 31.5 percent when chillers operate at night.

Last summer, the performance of chillers in a hotel building in Ji’nan was measured. Measurement results showed good agreement with theory calculation results.

1. INTRODUCTION

Refrigeration is defined as the process of extracting heat from a lower-temperature heat source, and transferring it to a higher-temperature heat sink. Refrigeration maintains the temperature of the heat source below that of its surroundings while transferring the extracted heat, and any required energy input, to a heat sink.

A refrigeration system is a combination of components and equipment connected in a sequential order to produce the refrigeration effect. The refrigeration systems commonly used for air conditioning is a chiller of vapor compression. In chillers, compressors activate the refrigerant by compressing it to a higher pressure and higher temperature level after it has produced its refrigeration effect. The compressed refrigerant transfers its heat to the sink and is condensed to liquid form. This liquid refrigerant is then throttled to a low-pressure, low-temperature vapor to produce refrigerating effect during evaporation. The condenser is a water-cooled condenser in which the cooling water is used to remove condensing heat from the refrigerant, and cooling water is the recirculating water from the cooling tower which is evaporative cooling tower in the research project.

The chillers run in the day in the traditional air conditioning systems. The performance of chillers will change when chillers operate at night.

2. DAILY WET BULB TEMPERATURE PROFILE

Inlet temperature of cooling water has a significant effect on the performance of chillers and it depends on the wet bulb temperature of outdoor air. In general, outlet temperature of cooling tower, that is, inlet temperature of chillers is equal to the ambient air wet bulb temperature plus 3~5°C. Measured hourly wet bulb temperature of recent decade in Ji’nan in August has been analyzed and studied based on standard meteorological year [1].

Fig. 1 and Table 1 show that the average wet bulb temperature of outdoor air is 21.5°C at night, it is 23.2°C in the day and at night is 1.7°C less than that in the day. In other words, cooling water outlet temperature of cooling towers, condensation temperature of refrigerators at night is 1.7°C less than that in the day.
Table 1: Wet bulb temperature in Ji’nan August (°C)

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3. ANALYSIS OF ENERGY EFFICIENCY

A hotel building in Ji’nan has a gross space of 9200 m² (8-story). The total conditioned space is 7700 m². The building’s peak air-conditioning load is 636 kW. Piston compressors in this building are used and the refrigerant is R22. Thermal calculation of one chiller is carried out in the day and at night respectively.

With the aid of the pressure-enthalpy diagram, cooling capacity may be expressed as:

![Fig. 2: Comparison of wet bulb temperature](image)
\[ \Phi_o = V_h q_v = \eta \cdot V_h q_v = \eta \cdot V_h q_o/V_1 \] (1)

Factors that influence the \( \eta \) of the compressor include: clearance volume and compression ratio \( \eta_v \). Both factors affect the volume of reexpansion gas trapped in the clearance volume.

\[ \eta_v = 1 - c \left( \frac{P_2}{P_1} \right)^{1/m} - 1 \] (2)

Coefficient of heat effect \( \eta_h \). When vapor refrigerant enters the compressor, heat absorbed by the vapor results in a heating effect that increases the specify volume of the refrigerant and, therefore, the \( V_R \) value.

\[ \eta_h = \frac{T_v}{T_k} \] (3)

Coefficient of leakage \( \eta_l \). Refrigerant leaks through the gap and the clearance across the high- and low-pressure sides of the compressor, such as the clearance between the piston rising and the cylinder in a reciprocating compressor.

\[ \eta_l = 0.98 \] (4)

Coefficient of throttle \( \eta_\text{th} \). There is resistance when vapor refrigerant runs through suction and exhaust valves.

\[ \eta_\text{th} = 1 - \frac{1 + c \cdot \Delta P_1}{\eta_v \cdot P_1} \] (5)

By using Eqs. (2)-(5)

\[ \eta = \eta_v \cdot \eta_h \cdot \eta_l \cdot \eta_\text{th} \]

\[ = 1 - c \left( \frac{P_2}{P_1} \right)^{1/m} - 1 \right] \left( \frac{T_o}{T_k} \right) \cdot 0.98 \cdot \left( 1 - \frac{1 + c \cdot \Delta P_1}{\eta_v \cdot P_1} \right) \]

\[ = 0.98 \left( 1 - \frac{1 + c \cdot \Delta P_1}{\eta_v \cdot P_1} \right) \left( 1 - c \left( \frac{P_2 + \Delta P_3}{P_1} \right)^{1/m} - 1 \right) \left( \frac{T_o}{T_k} \right) \]

By using Eqs. (1) and (6)

\[ \Phi_o = 0.98 \left( 1 - \frac{1 + c \cdot \Delta P_1}{\eta_v \cdot P_1} \right) \left( 1 - c \left( \frac{P_2 + \Delta P_3}{P_1} \right)^{1/m} - 1 \right) \left( \frac{T_o}{T_k} \right) \frac{q_o}{V_1} \]

The following equation will be used for account shaft power.

\[ P_\text{e} = M_R \cdot \frac{W_{th}}{(\eta_1 \cdot \eta_m)} = M_R \cdot \frac{W_{th}}{\left( \frac{T_o}{T_k} \right) \cdot \eta_m} \] (8)

The effectiveness of refrigeration cycles, or coefficient of performance (COP), is one parameter that affects the efficiency and energy consumption of the chiller. The COP of a refrigeration cycle using a specific refrigerant depends mainly upon the isentropic work input to the compressor at a given condensing and evaporating pressure differential, as well as the refrigeration effect produced.

The COP of chillers is also defined as:

\[ \text{COP} = \frac{\Phi_o}{P_\text{e}} \] (9)

Experimental fitting formulas of calculation cooling capacity and shaft power are derived from references [2-6] in order to simplify the calculation.

\[ \Phi_0 = a_1 \cdot \exp\left[ b_1 (t_o + b_2)^2 + b_3 (t_k + b_4)^2 + b_5 (t_{l} + b_6)^2 \right] \]

\[ P_\text{e} = a_2 \cdot \exp\left[ c_1 (t_o + c_2)^2 + c_3 (t_k + c_4)^2 + c_5 (t_l + c_6)^2 \right] \]

Since refrigerant in the chillers is R22, these coefficients are respectively as follows:

\[ a_1 = 2362.01, \quad b_1 = -3.066017 \times 10^{-4}, \]
\[ b_2 = -46.12189, \quad b_3 = -1.616698 \times 10^{-4}, \]
\[ b_4 = 6.534695, \quad b_5 = -1.762319 \times 10^{-4}, \]
\[ b_6 = -6557.827. \]
\[ a_2 = 280.1342, \quad c_1 = -3.160405 \times 10^{-4}, \]
\[ c_2 = 7.454992, \quad c_3 = -2.049994 \times 10^{-4}, \]
\[ c_4 = -73.58168, \quad c_5 = -5.494057 \times 10^{-4}, \]
\[ c_6 = -53519.666. \]

It is over-simplified to assume that the condensing temperature drops by the same amount as the wet bulb temperature in Fig. 3. 1→2→3→4→1 is the rating condition in the day, the condensation temperature is 40 °C and the evaporation temperature is 5°C. 1→2′→3′→4′→1 is the rating condition at night, the evaporation temperature is still 5°C, and the condensation temperature is 38.3 °C which is 1.7°C less than that in the day.
Table 2: Comparison of chillers performance in the day & at night

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<th>Night</th>
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<th>ΔΦ_0 / Φ_0 (%)</th>
<th>ΔP_e / P_e (%)</th>
<th>ΔCOP / COP (%)</th>
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<td>31.5</td>
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</table>

Last summer, the cooling capacity and shaft power of the chiller were measured. The cooling capacity is known after the rate of flow, inlet temperature and outlet temperature of chilled water are surveyed. Shaft power is known with the help of dynamometer. Calculation of cooling capacity and shaft power is carried out by using Eqs. (10) and (11) after evaporative and condensing pressures are gauged because evaporating and condensing temperature result from evaporating and condensing pressure.

Table 2 indicates that the cooling capacity is increased by 9.0 percent, shaft power is reduced by 17.2 percent, coefficient of performance is stepped-up by 31.5 percent when chillers operate at night.

In addition, the operation efficiency of chillers is greatly increased since they run with peak load, the times of chillers stops are reduced at night.

4. ANALYSIS AND DISCUSSION

Wet bulb temperature in outdoor air changes hourly and average wet bulb temperature of 10 years at night is 1.7°C less than that in the day in Ji’nan, P.R. China.

The wet bulb temperature is the primary parameter that affects the performance of the cooling tower, and so wet bulb temperature has greatly an effect on the performance of chillers. The cooling capacity and coefficient of performance are increased, and energy consumption is reduced at night.

Because energy situation is now very serious, so it is right time that chillers operate at night as far as possible. The development of operation method is very important and has a bright future.

NOMENCLATURE

t_e evaporation temperature, °C
t_k condensation temperature, °C
Φ_0 cooling capacity, kW
P_e shaft power, kW
COP coefficient of performance
T_e evaporation temperature, K
T_k condensation temperature, K
q_o mass refrigerating capacity, kJkg^{-1}
V_1 specific volume, m^3kg^{-1}
W_th work of compression, kJkg^{-1}
M_R mass rate of flow of refrigerant, kgs^{-1}
b constant
m expansion index number
c relative clearance volume
P_1 suction pressure, Pa
ΔP_1 suction pressure difference, Pa, ΔP_1 = P_1 - P_o
P_2 exhaust pressure, Pa
ΔP_2 exhaust pressure difference, Pa, ΔP_2 = P_k - P_2
η_m friction efficiency, %
P_o evaporation pressure, Pa
P_k condensation, Pa
V_R actual induced volume of suction vapor at suction pressure, m^3
V_h theoretical displacement of compressor, m^3
η volumetric efficiency, %
η_l compression efficiency, %
η_v cleance volume and compression ratio
η_h coefficient of heating effect
η_l coefficient of leakage
η_p coefficient of throttle

REFERENCES