The optimal operation of cooling tower systems with variable-frequency control

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Abstract. This study investigates the energy performance of chiller and cooling tower systems integrated with variable-frequency control for cooling tower fans and condenser water pumps. With regard to an example chiller system serving an office building, Chiller and cooling towers models were developed to assess how different variable-frequency control methods of cooling towers fans and condenser water pumps influence the trade-off between the chiller power, pump power and fan power under various operating conditions. The matching relationship between the cooling tower fans frequency and condenser water pumps frequency at optimal energy consumption of the system is introduced to achieve optimum system performance.

1. Introduction

With the gradual development of frequency conversion technology, many countries have paid more and more attentions to the variable-frequency energy saving of the Chiller and cooling tower systems. At present, most of the studies are aimed at single variable research. The most is the variable condenser water flow and a small part is the variable cooling tower air volume.

The researches on variable flow of condenser water are mostly research on the influence of condenser water pump variable-frequency on the performance of the systems and the energy saving potential. Qu et al. [1] considered that the condenser water pump variable-frequency was energy saving, and has greater energy saving potential than the chilled water pump. This paper also presented a method for calculating energy saving of variable-frequency section of condenser water pump. Hu Lei [2] studied the renovation of the cooling water system in a school building. It concluded that the system with variable condenser water flow can save energy. Jiang et al. [3] analyzed the method of orthogonal test and proposed suitable control strategy of chilled water flow and cooling water flow under different conditions. Gordon et al. [4] highlighted that the condenser water flow rate could be a control variable in improving the energy performance of chiller systems.

There is little research on variable air volume of cooling tower in cooling water system. Wang et al. [5] proved that variable air volume of fan can greatly reduce the power consumption of the cooling tower and increase the COP of the system from the theoretical and experimental point of view. Chang et al. [6] introduced the method of using temperature range to replace the temperature to control the cooling tower fan. This method was applied to a practical building in Taiwan to realize the energy saving of the cooling tower. Yu et al. [7] researched on the air-cooled chiller and advanced that using condensing temperature control method instead of the pressure head control method to control the

condenser fan, which can improve the system efficiency. Ping et al. [8] highlighted that the variable-frequency control of cooling tower fan is applicable only when the chiller needs to be turned on and the wet-bulb outdoor temperature is low in winter.

Some researches showed that the cooling water system is considered as a whole for variable-frequency control of water pump and tower fan, and variable-frequency control of the fan and pump at the same time according to outdoor weather conditions and building load is better [9-12]. According to Wen et al. [13], the variation of air volume and condenser water flow need to change with the cooling tower loads and outdoor meteorological conditions. This paper also analyzed energy saving in cooling water system from the perspective of the theory. Yang et al. [14] analyzed the correlation between the factors affecting the cooling water outlet temperature of the cooling tower based on the measured data, and proposed the optimal outlet temperature control strategy. Yu et al. [15] developed a mathematical model of a system to research the influence of different control methods on energy consumption and introduced a load-based speed control method. The optimization method was applied to actual buildings and the results showed that this method can save the energy consumption and operation costs. Lu et al. [16] presented the system optimal set point through an improved genetic algorithm, and the experiment and simulation showed that the method has a great potential.

The cooling water system studied in this paper including chiller, condenser water pumps and cooling towers, but there is an energy coupling relationship between the three. The outdoor meteorological conditions and building cooling load change dynamically and the system operates under partial load most of the time. The proper control method for the system can make the system match the dynamically change and realize the maximum energy saving. It is worth promoting variable-frequency control as a standard environmental-friendly feature for condenser water pumps and cooling tower fans in systems. The aim of this paper is to assess the frequency of the cooling tower fans and condenser water pumps of typical water-cooled chiller systems in order to achieve optimum system performance at any given building load and wet- bulb outdoor temperature. This paper first presents an example chiller system serving a local office building. The model taking into account the thermodynamics and energy balance of the chiller and cooling tower are developed here for the study of the system performance under various operating conditions. A comparison of the energy consumption of the system under different variable-frequency control of the cooling tower fans and condenser water pumps. Discussion will be given on how the fans and pumps frequency can be controlled directly based on the building load and wet- bulb outdoor temperature in order to achieve optimum system performance.

2. Description of the chiller and cooling tower models

The chiller and cooling tower models were developed using MATLAB. The outputs and operating variables of the chiller and cooling tower are determined by the following sets of algebraic equations through an iterative procedure. The parameters used in the modeling are described as follows: specific heat capacity of water(c_p), evaporating temperature(T_e),condensing temperature(T_c), the temperature of supply chilled water(T_{eo}), the temperature of return chilled water(T_{ei}),chilled water flow rate(m_e), the temperature of cooling water leaving the cooling tower(T_{co}), the temperature of cooling water return the cooling tower(T_{ci}), condenser water flow rate (m_c), cooling tower air flow rate(m_a), wet-bulb outdoor temperature(T_{wb}), the cooling capacity (Q_e), condenser heat rejection (Q_c), coefficient of performance of chiller ($COP_{chiller}$), chiller power consumption($W_{chiller}$), condenser water pump power consumption (W_{pump}), cooling tower fan power consumption (W_{fan}), coefficient of performance of system(COP_{system}), system power consumption (W_{system}), frequency of cooling tower fan (P_{fan}) and frequency of condenser water pump (P_{pump}). $c_1 \sim c_{14}$ are constant coefficient.

2.1. Chiller and cooling tower model

In this paper, a semi empirical modeling method is used to model the chiller. The coefficient of performance of chiller ($COP_{chiller}$) and chiller power consumption ($W_{chiller}$) are expressed by Eqs. (1)- (2) [17-18]:

$$\frac{1}{COP_{chiller}} = c_1\left(T_{ci} + c_2\left(\Delta T_c\right)^{c_3} - T_{ei} + c_4\left(\Delta T_e\right)^{c_5}\right)\left(\frac{c_6}{c_p\Delta T_e m_e} + c_7\right) \quad (1)$$

$$W_{chiller} = \frac{Q_e}{COP_{chiller}} = \frac{c_p m_e\left(T_{ei} - T_{eo}\right)}{COP_{chiller}} \quad (2)$$

According to the first law of thermodynamics and the principle of energy balance, condenser heat rejection (Q_c) is expressed by Eqs. (3):

$$Q_c = c_p m_c \Delta T_c = c_p m_c\left(T_{co} - T_{ci}\right) = Q_e + W_{chiller} \quad (3)$$

Based on Eqs. (3) ,the temperature of cooling water leaving the cooling tower (T_{co}) is given by Eqs. (4):

$$T_{co} = T_{ci} + \frac{W_{chiller}\left(COP_{chiller} + 1\right)}{c_p m_c} \quad (4)$$

The temperature of cooling water leaving the cooling tower (T_{co}) is expressed by Eqs. (5)[12]:

$$T_{ci} = T_{co} - \left(T_{co} - T_{wb}\right)\left(1 - \exp\left[c_8\left(P_{pump}\right)^{c_9}\left(P_{fan}\right)^{c_{10}}\right]\right) \quad (5)$$

As the valve position on cooling water pipe and the resistance characteristics of the cooling water pipe unchanged, the condenser water pump flow is proportional to the water pump frequency and condenser water pump power and water pump frequency is three times relationship. Similarly, the cooling tower air flow and fan power are also consistent with the law. The condenser water flow rate (m_c), the condenser water pump power consumption (W_{pump}), the cooling tower air flow (m_a) and the cooling tower fan power consumption (W_{fan}) are calculated by Eqs. (6)- (9):

$$m_c = c_{11}P_{pump} \quad (6) \qquad\qquad W_{pump} = c_{12}(P_{pump})^3 \quad (7)$$

$$m_a = c_{13}P_{fan} \quad (8) \qquad\qquad W_{fan} = c_{14}(P_{fan}{}^3) \quad (9)$$

A reference office building in Beijing is considered in order to develop the model of chiller and cooling towers. The building has 15 storeys and a total air-conditioned floor area of 38297.6 m². Table 1 summarizes the details of the chiller system studied. The constant coefficient $c_1 \sim c_{14}$ were identified from the model validation exercise.

2.2. Cooling water system

A reference office building in Beijing is considered in order to develop the model of chiller and cooling towers. The building has 15 storeys and a total air-conditioned floor area of 38297.6 m². Table 1 summarizes the details of the chiller system studied. The constant coefficient $c_1 \sim c_{14}$ were identified from the model validation exercise.
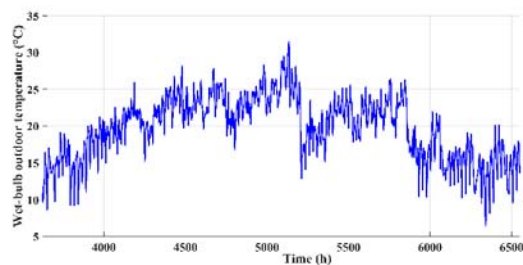
Table 1. Details of the chiller system

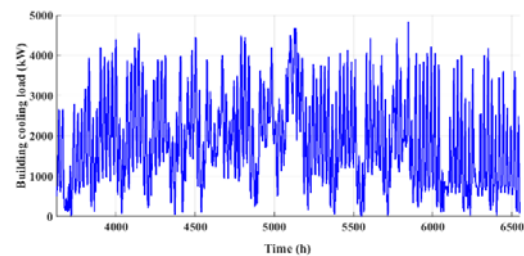| One chiller	
Nominal cooling capacity (kW)	4218
Nominal power input (kW)	741
COP at full load	5.682
Design chilled water supply/return temperature (℃)	7/12
Design chilled water flow rate (kg/s)	201.6
Design condenser water entering/leaving temp(℃)	32/37
Design condenser water flow rate(kg/s)	238.4
Chiller model parameters: $c_1 \sim c_7$	0.0079978,0.22984,0.35713,

	4.2023,0.45529,725.75,1
Two same cooling towers	
Type	Cross-flow
Heat rejection capacity (m^3/h)	500
Air mass flow rate（kg/s）	100.56
Fan motor power (kW)	15
Rated frequency	50
Cooling tower parameters: $c_9 \sim c_{10}$	-2.2589,-0.37992,0.18845
The condenser water pump parameters：$c_{11} \sim c_{12}$	2.4166,0.0006
The cooling tower fan parameters：$c_{13} \sim c_{14}$	2.0112,0.000148

3. Building cooling load simulated and typical day established

The hourly building cooling load is simulated by the energy consumption dynamic simulation software eQUEST. The simulated time selected from June 1st to September 30th in summer. The indoor design temperature of the building is 26℃and the relative humidity is 60%. The fresh air volume is 30(m^3/h • P). The indoor heat disturbance parameters are as follows: lighting power density is set to 11(W/m^2), indoor staff density is set to 4m^2/person, power density of electrical equipment is set to 20(W/m^2). Figure1 shows the hourly wet-bulb outdoor temperature in summer in Beijing. Figure 2 shows the hourly building cooling load in summer.

Figure 1. The hourly wet-bulb outdoor temperature cooling load in summer in Beijing

Figure 2. The hourly building in summer

The wet-bulb outdoor temperature and building cooling load change dynamically in summer. If considering all the conditions, it takes a lot of time and not conducives to the results showing. Therefore, a representative typical daily of wet-bulb outdoor temperature and building cooling load are constructed in this paper. This paper accumulate wet-bulb outdoor temperature and building cooling load at each clock of summer from June 1st to September 30th 8:00 to18:00 and average the results. The final results represent the entire summer each clock wet-bulb outdoor temperature and building cooling load. Typical day 8:00-18:00 hourly wet-bulb outdoor temperature and building cooling load are shown in Table 2.

Table 2. Typical day hourly wet-bulb outdoor temperature and building cooling load

time	8:00	9:00	10:00	11:00	12:00	13:00
wet-bulb outdoor temperature (℃)	19.71	20.01	20.16	20.24	20.39	20.74
building cooling load(kW)	1360.7	1657.8	2025.0	2288.9	2543.4	2809.7
time	14:00	15:00	16:00	17:00	18:00	

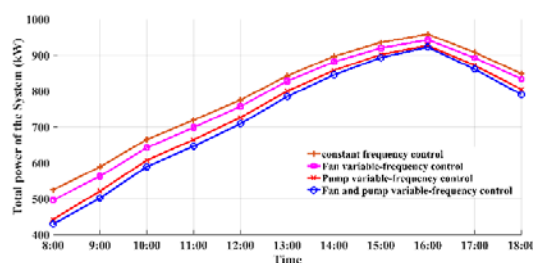|					
wet-bulb outdoor temperature (℃)	21.23	21.28	21.16	20.93	20.65
building cooling load(kW)	2968.4	3145.6	3256.6	3074.9	2838.5

4. Results and discussion

4.1. Chiller and cooling tower model

The chiller and cooling tower models were used to evaluate all the operating variables based on any given input data and constant parameters. The operating schemes shown in Table 3 are analyzed with respect to different controls of the condenser water pumps and cooling tower fans. Schemes 1 represent a constant frequency at maximum frequency configuration of the cooling tower fans and condenser water pumps. For schemes 2 to 4, variable-frequency control mode are applied to the fans and pumps. The temperature of supply chilled water (T_{eo}) and the temperature of return chilled water (T_{ei}) are set to be 7°Cand 12°C in all operating conditions.
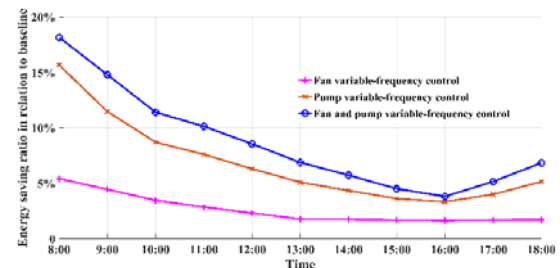
Table 3. Operating schemes of different controls of condenser water pumps and cooling tower fans

Scheme	Control mode	Description
1 （baseline）	constant frequency control	$P_{pump}=50$，$P_{fan}=50$
2	Fans variable-frequency control	$P_{pump}=50$，$T_{ci}-T_{wb}=3℃$
3	Pumps variable-frequency control	$P_{fan}=50$，$T_{co}-T_{ci}=5℃$
4	Fans and pumps variable-frequency control	$T_{ci}-T_{wb}=3℃$，$T_{co}-T_{ci}=5℃$

The simulation programs of the 4 control modes are established by MATLAB. Comparisons were made on how the system total power varied under various fans and pumps controls in typical day. As Figure 3 illustrates, there is no significant difference in the trend of system total power for all operating conditions at different combinations of building cooling load and wet-bulb outdoor temperature. They are increasing from 8:00 to 16:00 and have gradually decreased after reaching the maximum at 16:00. The maximum total power of the system is the control mode of Scheme 1. The total power of fans variable-frequency control mode is greater than pumps variable-frequency control mode, and the fans and pumps variable-frequency control mode is the minimum.
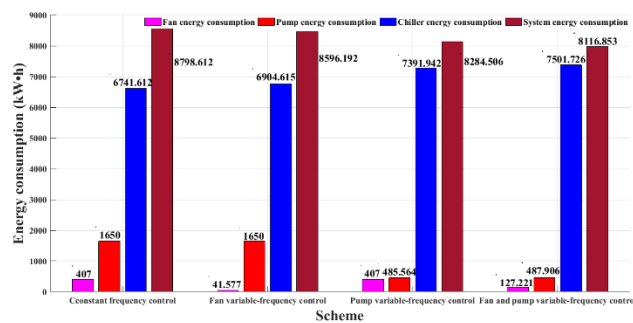

Figure 3. Total power of system in the typical day in schemes 1 to 4

Figure 4. Energy saving ratio in schemes 2 to 4 in relation to the baseline

Figure 4 shows the energy saving ratio in schemes 2 to 4 in relation to the schemes 1. The energy saving ratio could decrease by various degrees for all operating conditions when using variable-frequency control modes. The variable-frequency of fan makes full use of the advantage of the reducing

wet-bulb outdoor temperature. Therefore, the lower the temperature is, the better the energy saving effect of fans variable-frequency control mode. The condenser water flow is approximately proportional to the building load. The condenser water flow can be reduced and the pumps power can be saved when the load is reduced. Therefore, the lower the building cooling load, the better the energy-saving effect of pumps variable-frequency control mode. When the pumps and fans are variable-frequency control simultaneously, the energy consumption of the pumps and fans can be effectively reduced, so the energy saving effect of the system is best.

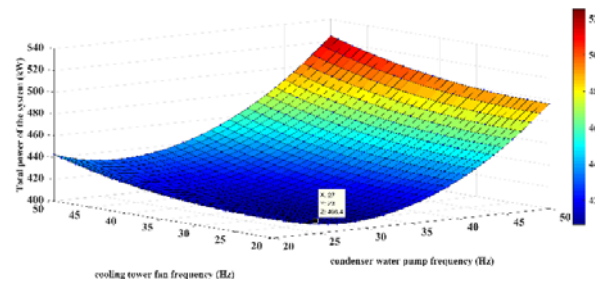**Figure 5.** Comparison of system energy consumption in schemes 1to 4

Table 4. Comparison of system energy consumption in schemes1 to 4 in the typical day

Scheme	Total energy consumption	Energy saving ratio in relation to the baseline	Energy consumption in relation to the baseline	
			fan and pump	chiller
1(baseline)	8798.612	-	-	-
2	8596.192	2.3%	-365.423	+163.003
3	8284.506	5.843%	-1164.436	+650.330
4	8116.853	7.75%	-1441.873	+760.114

As Figure 5 and Table 4 illustrates, comparing to no constant frequency control mode, the pumps and fans frequency of scheme 2 to 4 decreases. The condenser water temperature rises and the chiller power rises, but the total energy consumption of the system decreased. This is because the increase of the fans power and pumps power exceeded the reduction of the chiller power. The control mode of scheme 2 reduce the system electricity use by 2.3% in typical day, scheme 3 reduce by 5.843% and scheme 4 reduce by 7.75%.

4.2. Optimum frequency control for system optimization

The simulation results showed that the energy consumption of the cooling water system under the pumps and fans variable-frequency control simultaneously is less than that of the pumps or fans variable-frequency control individually. For any given building cooling load and wet-bulb outdoor temperature, when the condenser water pumps and the cooling tower fans variable-frequency simultaneous, the total energy consumption of the system will have a unique minimum value, which is the best operating condition of the system. Taking the total energy consumption of the system as the objective function, a three-dimensional relationship surface between the energy consumption and the two variables can be found. Figure 6 shows the relationship between the total energy consumption of the system with the frequency of fan and pump at typical day 8:00. The total energy consumption of the system have a unique minimum value and correspond to the unique pump frequency and fan frequency.
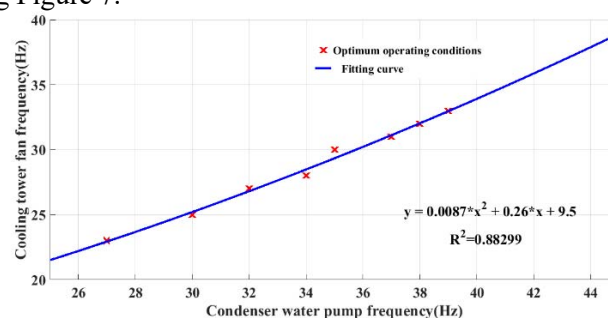
Figure 6. The relationship between the total energy consumption of the system with the frequency of fan and pump at typical day 8:00.

The minimum energy consumption and the corresponding frequency of pump and fan at each clock of the typical day is obtained by calculated. Table 4 shows the minimum total power of the system and the corresponding frequency of pump and fan for the given building cooling load and wet-bulb outdoor temperature at 8:00 to 18:00 of typical day. These points are the optimal operating conditions of the system.

Table 5. Summary of the optimal operating conditions of typical days at various times

time	minimum total power（kW）	pump frequency (Hz)	fan frequency (Hz)
8:00	394.94	27	22
9:00	473.35	29	25
10:00	570.77	32	27
11:00	643.31	34	28
12:00	717.33	36	30
13:00	803.29	37	31
14:00	864.83	38	32
15:00	919.75	39	33
16:00	949.54	40	34
17:00	887.02	39	33
18:00	808.72	37	32

To perform optimum frequency control for the cooling water system, it is essential to have a dedicated controller which controls the frequency of pumps and fans based on signals of wet-bulb outdoor temperature and the building cooling load. As Table 5 illustrates, for the typical day of different conditions, when the building cooling load and the wet-bulb outdoor temperature rises, the minimum power value of the system and the corresponding frequency of the fans and pumps rise at the same time. It can separate the pump frequency and fan frequency as a two-dimensional function relation. The relationship between the optimal condenser water pump frequency and the cooling tower fan frequency is shown in the following Figure 7.

Figure 7. Relationship between the pump frequency and the fan frequency under optimum operating conditions

The relationship between the pump frequency and the fan frequency can be obtained by regression analyzed. The relationship is expressed by Eqs. (10):

$$P_{fan} = 0.0087 \times (P_{pump})^2 + 0.26 \times P_{pump} + 9.5$$

$$(20\,\text{Hz} < P_{fan} < 50\,Hz, \text{Integer})$$

$$(20\,\text{Hz} < P_{pump} < 50\,Hz, \text{Integer})$$

(10)

This equation describes the relationship between the frequency of the condenser water pump and the cooling tower fan at the optimal operating condition of the system.

5. Conclusions

This paper presents a comparison of the energy consumption of the system under different variable-frequency controls of the cooling tower fans and condenser water pumps. Discussion on how the fan and pump frequency can be controlled directly based on the building cooling load and wet-bulb outdoor temperature in order to achieve optimum system performance. Thermodynamic chiller and cooling tower models are developed to investigate how the energy vary for a system operating under various controls of condenser water pumps and cooling tower fans. The optimum operation of the system can be achieved simply and directly by the optimum frequency control under which the frequency of the tower fans and condenser water pumps is regulated as a function. The findings of this research highlight the need to widen the use of variable frequency drives with speed control for water-cooled chiller systems serving air-conditioned buildings in order to enhance their sustainability.

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