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Energy Saving of the Variable Ice Water and Cooling Water Volume System, as Applied in Chiller Systems

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Abstract: Since the industrial revolution, overuse of energy has resulted in global warming which further leads to abnormal climate change and the counterattack phenomenon of nature has continuously caused serious disasters throughout the world. According to the statistical data of experts and scholars, fossil fuels will face depletion within 40 years. At present, 97% of the energy in Taiwan depends on imports from overseas countries and the energy crisis is closely related to society, therefore, energy saving and carbon emission reduction is an imperative subject. In Taiwan, in an ordinary office building, energy consumption of the air-conditioning system accounts for more than 60% of the total power consumption of the building, thus, effective energy-saving improvement of existing air-conditioning systems is the most direct and effective method for overall energy-saving benefits. This study aimed to improve the air-conditioning system in an office building of D plant in southern Taiwan by applying the primary variable ice water volume and variable cooling water volume system to the chiller of the air-conditioning system. The system was supported by a frequency converter, a digital controller, control strategies and other auxiliary methods. This study also analyzed and investigated the energy-saving benefit of a traditional constant water volume system. The results showed that if both the primary variable ice water volume and variable cooling water volume system were used, total energy consumption of the air-conditioning system could be saved by 16%.

Key words: Energy saving and carbon emission reduction, variable water volume (VWV), control strategy, Frequency conversion pump, constant temperature

INTRODUCTION

Taiwan has a subtropical climate. Taiwan is characterized by hot and humid summers, causing demand for air conditioning to increase which has promoted the development of refrigerating air conditioning industry. Due to the popularity of air conditioning equipment, air temperature changes are closely related to peak loads for power systems. For electric power loads, power consumption of air conditioning equipment accounts for 30% of the total power consumption during the summer. For central air conditioning systems, chillers are the primary cooling source and comprise 60% of the total power consumed by the system. Reducing energy consumption for air conditioning equipment and increasing energy use efficiency is crucial (Shih, 2004a).

For a new air-conditioning system, if the major equipment, such as the chiller, pump and air conditioning cabinet, uses high efficiency performance, it must be relatively energy-saving in overall operating costs; however, its initial setup cost is relatively high. Therefore, engineers should compare the running time, energy saving and recovery period of the equipment and carefully assess whether its economic efficiency tallies with the actual requirements. On the other hand, part of the system and devices of the established air-conditioning system are improved for energy saving, as based on the energy-saving concept and design at a lower cost which is significant and effective for the overall energy-saving benefit. In order to meet the maximum charge number demands for the system operation and considering the expandability for future use, designers of air-conditioning systems generally use the approach of over design which results in the system operating at an overly high flow rate, as well as increased energy consumption of the pump, reduced performance and efficiency of the chiller and increased operating costs. In recent years, the efficiency (Trane, 1999) obtained using a primary variable ice water volume system is highly valued and gradually applied in Taiwan. An example is the centrifugal chiller which operating capacity and flow rate of water in the heat exchanger can be minimized to about

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30% of the rated values. If the pump is applied for energy savings, an even higher energy-saving effect will be achieved.

Ice water and cooling water pumps in traditional air-conditioning system are designed by constant water volume control. It is generally considered that ice water and cooling water are needed to maintain a constant flow rate in order to ensure effective heat exchange of the heat exchanger. If the flow rate is reduced, the phenomenon of laminar flow may arise on the surface of the heat exchanger, thereby reducing the heat exchange effect. If the flow rate is too low, freeze will arise in the evaporator, resulting in the risk of ruptured copper tubes. Moreover when the flow rate is lower than a certain value and there are corrosive substances in the water, copper tube corrosion occur. However with the progress and development of the performance and control system of the chiller, some types of chillers have perfect capacity regulation mechanisms, thus, operating capacity of the chiller varies with the load demand to meet the established requirements. In addition, due to popularized applications and technical improvements of the capacity control function of the chiller, the Variable Water Volume (VWV) system is widely applied, according to the refrigerating capacity of the overall air-conditioning system which varies with the air-conditioning load demands. In other words, the higher the air-conditioning load, the higher the operating capacity of the chiller and the higher flow rate of the ice water and cooling water; and vice versa. The pump power is proportional to the cube of the flow rate of water, reducing the flow rate of water in an air-conditioning system is equivalent to reducing the pump energy consumption. Total power consumption of the pump generally accounts for about 20% of the power consumption in an air-conditioning system, therefore, if the pump is additionally equipped with a frequency converter, is supported with a control system and operating strategies (Ma and Wang, 2009; Jin *et al*., 2007) and uses as a VWV system, an energy-saving effect of the overall air-conditioning system can be realized; the power consumption of the chiller and pump can also be reduced, thus, improving their service life.

SYSTEM THEORY AND ANALYSIS

Energy-saving principle of the VWV system: Air-conditioning systems develop with the progress of chiller control technology. In recent years, the VWV system has been continuously applied in Taiwan, as well other countries for many years. Both its energy-saving effects and research technology has considerable achievements (Hartman, 2001). Many domestic studies have suggested that if an air-conditioning system is supported with the VWV system, a significant energy-saving effect could be achieved (Peng, 2006; Lin, 2003; Shih, 2004b). At present, a minimum flow of ice water and cooling water is used in centrifugal chillers. The T brand for instance, can be reduced to about 30% of the rated flow while the minimum permissible flow rate of water in the evaporator and condenser must follow the recommendations of the original chiller manufacturer. Only by changing the flow rate of water in the evaporator and condenser within the recommended scope, can the performance and stability of the chiller be unaffected. An example is the constant water volume system of traditional air-conditioning systems: refrigerating capacity of the evaporator is $Q_e = M_e \times \Delta T_e$, where the temperature difference ΔT_e between the inlet water and outlet water of the evaporator is a constant. When the flow rate of the ice water is constant and the chiller operates under a partial load, its refrigerating capacity Q_e is decreased and ΔT_e will be reduced accordingly. If the flow rate M_e of ice water is reduced by replacing the control strategy of constant water volume with that of variable ice water volume, then the enhanced temperature difference ΔT_e between the inlet and outlet waters, Q_e can also be maintained while the energy consumption of the ice water pump can be reduced. When the flow rate of ice water within the evaporator is decreased, the flow speed is decreased and the control valve of the load device is opened wider, thus, the pressure loss in the ice water pipeline is reduced and heat energy caused by friction and collision movement due to water flow will also be reduced. All such measures will reduce the cold energy loss caused by the ice water pump. Moreover, the higher the temperature difference of the ice water, the higher the temperature of the return water and the less cold energy loss in the ice water pipeline for cold insulation.

Similarly, the heat-sinking capability of the condenser is $Q_e = M_e \times \Delta T_e$. When the chiller load is decreased, its heat-sinking capability Q_e is reduced, thus, the practical cooling water flow becomes less, thereby, reducing the energy consumption of the cooling water pump. According to the similarity law (Eq. 1), the flow rate is proportional to the rotational speed, the head is proportional to the square of the rotational speed and the pump power is proportional to the cube of the rotational speed. Therefore, the VWV system uses a variable frequency water pump which can reduce the operating power consumption of the water pump throughout the year, as well as the energy consumption and running time of the chiller, realizing energy-saving effects of the air-conditioning system and reducing the overall operating costs.

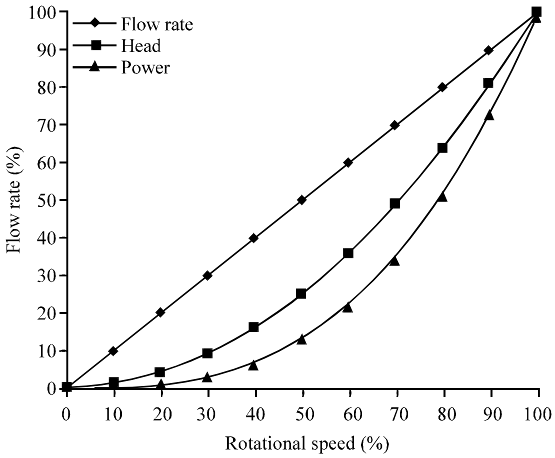

Fig. 1: Pump characteristic curve

$$\frac{Q_2}{Q_1}=\left(\frac{n_2}{n_1}\right)\ \frac{H_2}{H_1}=\left(\frac{n_2}{n_1}\right)^2\ \frac{P_2}{P_1}=\left(\frac{n_2}{n_1}\right)^3 \tag{1}$$

n: revolutions per minute (r/min), Q: flow rate(m^3/min) H: head(m) P: power (kw).

As can be seen from the pump characteristic curve shown in Fig. 1 when the rotational speed of the water pump is reduced from 100 to 50%, the flow rate of the water is reduced from 100 to 50% and the head is reduced from 100 to 25%, the power of the water pump is only 12.5%. Thus, in an air-conditioning system, if the VWV system is used, the rotational speed of the pump is controlled by a frequency converter, the flow rate of water is adjusted to 50% and the power of the water pump is proportional to the cube of its rotational speed in theory. In this way, only 12.5% of energy consumption is required, showing its energy-saving benefit.

EXPERIMENTAL STRUCTURE AND METHOD

VWV system control

Control method of constant temperature difference of primary variable ice water volume: Under the following control conditions: temperature of the inlet ice water T_e is 12°C, that of the outlet ice water T_e is 7°C and temperature difference ΔT_e is 5°C, the control method of constant temperature difference is applied to a primary variable ice water volume system, as shown in Fig. 2. A water temperature sensor and differential pressure sensor is installed in the inlet and outlet pipelines of the ice water and their sensor signals is transmitted to the frequency control modules. An electric two-way valve is installed in the on-site air-conditioning equipment, in order to switch the flow of ice water on and off. When the air-conditioning system operates under a partial load, in order

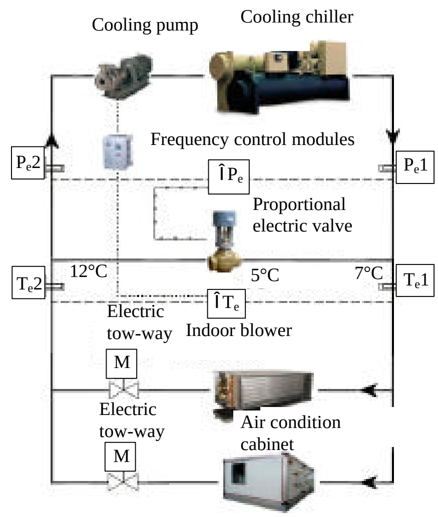

Fig. 2: System drawing of the control method of constant temperature difference of primary variable ice water volume

to maintain a minimum circulation of ice water in the chiller, a bypass pipe is installed in the ice water pipeline system, a proportional electric valve is installed in the bypass pipe and the bypass flow rate is controlled using the water pressure difference ΔP_e between the inlet and outlet ice waters. The working principle of the control system is that if the air-conditioning load is the design value, namely, both the refrigerating capacity of the chiller and on-site air-conditioning load are under the design flow of ice water, then the flow rate of ice water within the bypass pipe is 0, the ice water pump should operate at the maximum rotational speed. Under these conditions, pressure difference ΔP_e of the ice water is the given value of the proportional electric valve on the bypass pipe which controls the flow rate of ice water in the bypass pipe and the temperature difference ΔT_e between the inlet and outlet ice waters of 5°C is taken as the given controlling value variable frequency operation of the ice water pump. When the on-site air-conditioning load is reduced, as the flow rate of ice water is constant, the temperature difference between the inlet and outlet waters is decreased. As a result, the ice water pump reduces its rotational speed, thus, decreasing the flow rate of water which is restored to the established temperature difference ΔT_e. Under these conditions, if the on-site indoor blower or electric two-way valve of the air-conditioning cabinet is switched off, the pressure difference ΔP_e between P_e1 and P_e2, becomes higher and the proportional control valve will control part of the ice water to flowing through the bypass pipe in order to maintain a constant pressure difference ΔP_e of ice water.

Control method of constant temperature difference of variable cooling water volume: Air-conditioning systems operate under partial load and traditional constant cooling water volume systems run in a state of a high flow rate and low temperature difference, resulting in unnecessary energy consumption of the cooling pump. The cooling pipeline system is simple and the cooling pump consumes more energy than the ice water pump, thus, if a variable flow system control is used, more energy-saving benefits would be realized. When a control method of a constant temperature difference is used in the variable cooling water volume system, as shown in Fig. 3, a water temperature sensor must be installed in the inlet and outlet pipelines of the cooling water which sensor signals are submitted to the frequency control modules. The control conditions and set values are as follows, temperature of the cooling water inlet T_e2 is 32°C, that of the cooling water outlet T_e1 is 37°C and temperature difference ΔT_e is 5°C. Its control system and working principle are as follows; when the on-site air-conditioning load is reduced, the temperature difference ΔT_e between inlet water and outlet water is decreased as the cooling water flow is constant. Under these conditions, the rotational speed of the cooling pump is decreased, in order to reduce the flow rate of water and return to the given temperature difference ΔT_e. If the air-conditioning load becomes higher, the temperature difference ΔT_e between the cooling water inlet and outlet becomes larger and rotational speed of the cooling pump is increased to improve the flow rate of water and maintain the given temperature difference ΔT_e.

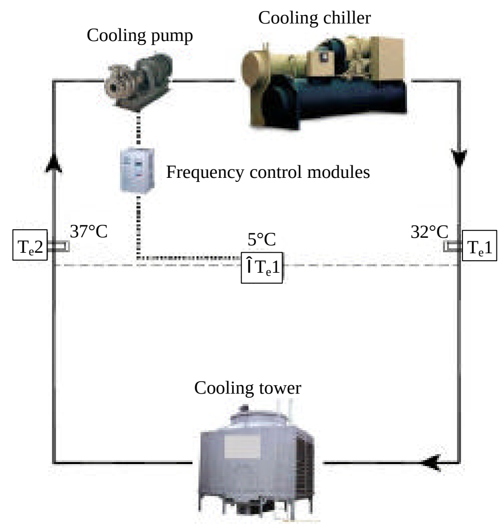

Fig. 3: System drawing of the control method of constant temperature difference of variable cooling water volume

A case of VWV system improvement

Analysis of a practical case: In this study, the case is an office building with 5 stories, from basement level 1 up to the 4th floor, in D plant in southern Taiwan. Its spatial usage is an executive office and a clean room. The air conditioner has a total area of about 6600 m^2 and is in use 24 h a day. The main equipment of the air-conditioning system includes a centrifugal chiller of 500 RT with a rated power consumption of 303 KW, a cooling pump and a standby pump, each with the rated power consumption of 37 KW and an ice water pump with the rated power consumption of 30 KW. The on-site pneumatic conveying device is an air-conditioning cabinet and an indoor blower where ice water is controlled at a temperature of 7°C/12°C and the cooling water t is controlled at a temperature of 32°C/37°C.

The on-site air-conditioning system operates for all executive offices and the clean rooms during daily business hours and for clean rooms at night, a constant water volume design is used in both ice water and cooling water systems. Therefore, when the air-conditioning system operates under partial load, the situation of excessively low temperature difference between inlet and outlet and overhigh flow rate easily arise in pipeline systems of ice water and cooling water result in unnecessary energy consumption.

Analysis of energy-saving benefits: Figure 4 and 5 show the energy consumption changes of the chiller before improvements when the operation is controlled by constant volume systems of ice water and cooling water. When the outdoor unit of the air-conditioning system operates under partial load, power consumption of the chillers of both constant volume systems are reduced with the decreases air-conditioning load and the ice water pump and cooling pump maintain constant power consumptions due to the constant water volume system.

Figure 6 and 7 show the energy consumption changes of the chiller before improvements when operation is controlled by variable water volume systems of the ice water pump and cooling pump. When the outdoor unit of the air-conditioning system operates under high load, power consumptions of the ice water pump and cooling pump of both VWV systems are enhanced with the increased power consumption of the outdoor unit and reduced with the decreased power consumption of the outdoor unit when the outdoor unit of the air-conditioning system operates under partial load.

Figure 8 and Table 1 show the comparison between the total energy consumption changes and energy-saving

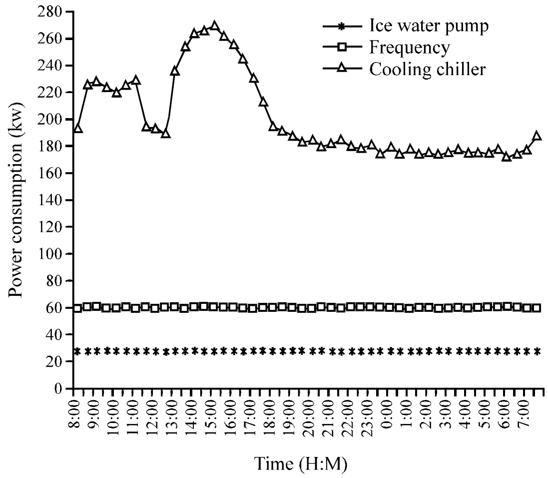

Fig. 4: Energy changes of the constant ice water volume system and chiller

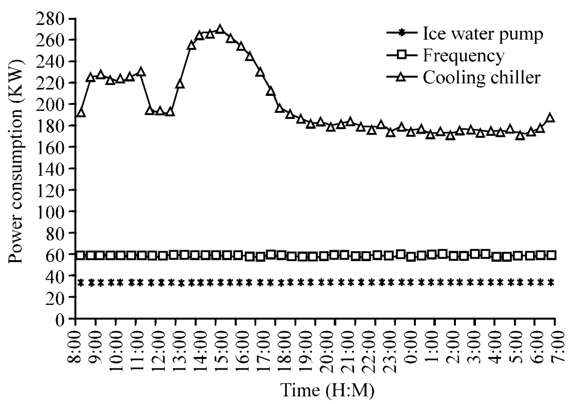

Fig. 5: Energy consumption changes of the constant cooling water volume system and chiller

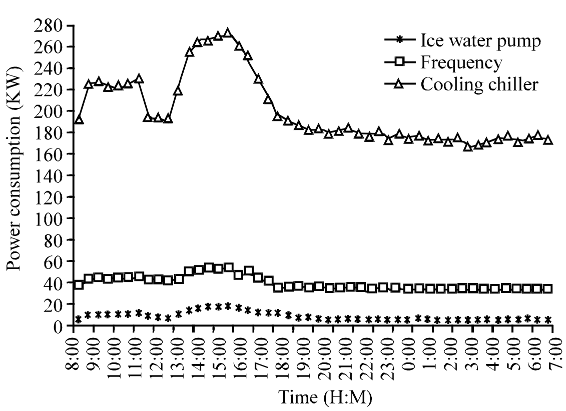

Fig. 6: Energy consumption changes of the variable ice water volume system and chiller

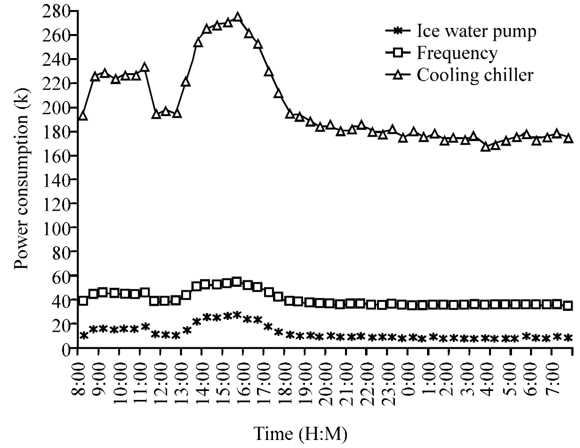

Fig. 7: Energy consumption changes of the variable cooling water volume system and chiller

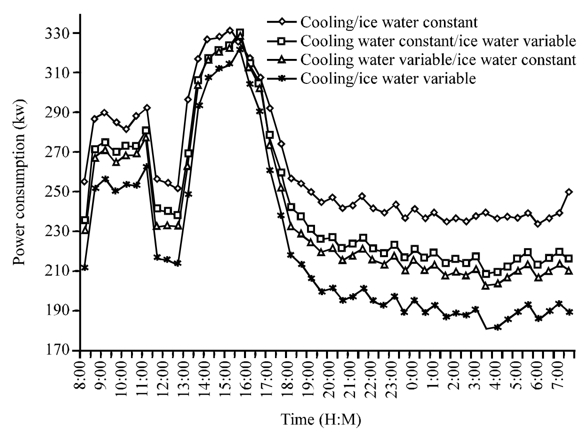

Fig. 8: Total energy consumption changes of the air-conditioning system when a constant/ variable water volume system is used

benefits of an air-conditioning system when a constant/variable ice water volume system and a constant/variable cooling water volume system are used. When both a constant ice water volume system and a constant cooling water volume system are used, the ice water pump and cooling pump operate at rated power, thus, the total energy consumption of the air-conditioning system is the highest. When both a variable ice water volume system and a variable cooling water volume system are used, operations of the ice water and cooling pumps vary with the load of the air-conditioning system. In particular, the energy-saving effect is most significant when the air-conditioning system operates under partial load, total energy consumption of the air-conditioning system can be saved by about 16%. It can be seen that the VWV system is characterized by

Table 1: Comparison of the energy-saving benefit when a constant/variable water volume system is used

System	Cooling/ice water constant	Cooling water constant /ice water variable	Cooling water variable /ice water constant	Cooling/ice water variable
Cooling water inlet/outlet (°C)	32.3/35.2	32.2/35.3	37.1/32.1	37.2/32.2
Ice water inlet/outlet (°C)	10.6/7.2	12.1/7.2	10.3/7.1	12.2/7.1
Consumption of chiller (ΣKWH/day)	4, 824.5	4, 832.7	4, 853.3	4, 751.1
Consumption of cooling pump (ΣKWH/day)	845.2	848.5	3.4.1	323.1
Consumption of ice pump (ΣKWH/day)	652.6	229.6	655.3	216.7
Consumption of chiller/ pump (ΣKWH/day)	6, 322.3	5, 910.8	5, 812.7	5, 291.0
Consumption of energy-saving (ΣKWH/day)	-	411.5	509.6	1, 031.3
Brnefit of energy-saving (%)	-	6.51%	8.06%	16.31%

significant and high energy-saving benefits, as compared to the constant water volume system.

RESULTS AND DISCUSSION

From installation to the end of the service life of an air-conditioning system, its operating cost accounts for about 70% of the overall costs and its future operating cost depends on the design and application of energy saving. In recent years, due to wide applications of the VWV system, air-conditioning systems have become an effective energy-saving measure. In this study, energy-saving improvement of the VWV system with constant temperature difference between ice water and cooling water in air-conditioning systems, is studied and concluded, as follows:

- If a VWV system is used, it is recommended to mainly use an improved constant water volume system which is characterized by easy implementation, significant energy-saving effects and short recovery period
- The water volume in load equipment of an on-site air-conditioning system, such as the air-conditioning cabinet and indoor blower, must be balanced in order to avoid affecting the functional performance of the on-site air-conditioning system, due to the reduced flow rate of ice water when the air-conditioning system operates under partial load
- It is recommended to set parameters of the pressure difference and temperature difference of the variable ice water volume system according to the actual on-site operational requirements. Decreased pressure difference and increased temperature difference within the permissible range helps to improve energy-saving benefits
- When a VWV system is used and the air-conditioning system operates under partial load, decreased ice water and cooling water volumes result in decreased COP value of the outdoor unit, however, the practical influence is little
- When both a variable ice water volume system and a variable cooling water volume system are used, maximum energy-saving benefits will be achieved. Moreover, they also have the most significant impact on the performance and stability of the outdoor unit
- A VWV system can achieve energy-saving effect; if it can match the operating characteristics of the chiller, an even higher energy-saving effect could be attained

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