Simulation-based optimization of the control strategy of variable-frequency chilled water pump in data center: A case study in Beijing

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Abstract. Reducing the energy consumption of air-conditioning system is one of the important means to improve the operation energy efficiency of data center, and the energy consumption of water pump accounts for a relatively high proportion of the energy consumption of air-conditioning system. This paper studied the reduction of operation energy consumption of water pump from the perspective of optimizing its control strategy. Based on the simulation model of the case system, this paper simulated the operation energy consumption of the chilled water pump when two control strategies (the constant DP control and the constant DT control of the main water supply-return pipeline) were used under different load demand. The calculation results show that both two control strategies can reduce the energy consumption of the chilled water pump compared with non-control, and the constant DT control is better. In addition, under two control strategies, the load distribution characteristics of system have an impact on the working state point and energy consumption of the chilled water pump.

1. Introduction

The data center is an indispensable and important facility in the era of big data, and its energy consumption has attracted much attention [1]. The total power consumption of data centers in China was over 160 billion kWh in 2018 and accounted for 2.35% of total social power consumption, which was only 83 billion kWh in 2014 [2][3]. Regarding the energy efficiency of data center, Power usage effectiveness (PUE) is currently the most influential energy efficiency indicator, defined as the ratio of the total energy consumption of data center to the energy consumption of IT equipment [4]. In the non-IT energy consumption of data center, the proportion of the energy consumption of air-conditioning system is as high as 67.8% [5][6]. Therefore, reducing the energy consumption of air-conditioning system of data center can reduce its non-IT energy consumption, thereby improving the energy efficiency of data center [7], that is, reaching a lower PUE.

The water pump is the power equipment of the transmission and distribution system in air-conditioning system. The specific adjustment action of the water pump is determined by its control
strategy, so optimizing the control strategy of water pump is an important means to reduce its energy consumption [8][9].

The control strategies of the variable-frequency chilled water pump can be mainly divided into differential pressure (DP) control and differential temperature (DT) control. Based on different control objects, the DP control can be divided into the DP control of the main water supply-return pipeline and the terminal DP control.

The constant DP control of the main water supply-return pipeline uses the DP of the most unfavorable loop under the design condition as the DP set-point. When the system is running under part load, the DP of the remote branches will be higher than the design DP, and the energy-saving effect is poor. The terminal constant DP control takes the DP of the most unfavorable branch under the design condition as the DP set-point. When the system is running under part load, the flowrate of the main pipeline will decrease, and there will be a “deficient DP” condition where the branches located upstream of the most unfavorable branch obtain available DP lower than the design DP. However, the phenomenon of overcurrent in the remote branches will not appear, so its energy-saving effect is better than the constant DP control of the main water supply-return pipeline. Based on an example project, Cao et al. [10] found that the energy-saving rates of mode-2 (frequency conversion + the constant DP control of the main water supply-return pipeline + number control) and mode-3 (frequency conversion + the terminal constant DP control + number control) in cooling and heating conditions compared with mode-1 (power frequency + number control) were 10.8%, 37.5%, 42.9% and 45.7%, respectively. Both the constant DP control and variable DP control of the main water supply-return pipeline could improve the hydraulic stability and obtain certain energy-saving rates of chilled water pump compared with non-DP control [11]. Many researchers [12-15] optimized the DP set-point of the main water supply-return pipeline of the chilled water pump. Li et al. [9] stated that the selection of control strategy should take load distribution characteristics, the design and actual condition of air-conditioning system, project operation and the technical level of staff into consideration to better meet the actual need of the system. Zhao et al. [16] stated that the variable DP control could obtain higher energy-saving rate, but the thermodynamic stability must be considered when the time interval of adjusting the DP set-point was determined.

In engineering practice, most of air-conditioning systems have the operation phenomenon that the DT of the main water supply-return pipeline is low. Low DT was one of the main factors that affect the actual operation energy efficiency of chilled water system [17]. However, the low-load condition under the constant DT control may cause the system flowrate to be lower than the minimum allowable flowrate of chiller [18]. In order to ensure the safe operation of the chiller, this paper optimizes the constant DT control, that is, when the flowrate on the user side decreases to the minimum allowable flowrate of the chiller, the constant DT control is changed to the constant flowrate control on chiller side, and the water pump also operates at a constant flowrate.

In summary, both the constant DP control of the main water supply-return pipeline and the constant DT control have certain energy-saving effect. Taking a data center as case, the difference of energy consumption of the two control strategies under different load demand is discussed.

2. Case information

In this study, the case building is a six-story data center building in Beijing. The cooling source is chiller, and the terminal is water cooled computer room air handler (CRAH). Two independent subsystems are used in the case system, which are alternate for each other to ensure the safety of the IT equipment in data rooms. The schematic diagram for the case system is shown in figure 1, and table 1 shows the basic parameters of the main equipment of the case system.

The control strategy of the variable-frequency chilled water pump is the constant DP control of the main water supply-return pipeline. The variable-frequency water volume of the chilled water pump needs to meet the minimum allowable flowrate of the chiller so that its variable range is from the minimum allowable flowrate to the design flowrate. When the water volume decreases to the minimum
allowable flowrate, the chilled water pump runs at a constant flowrate, i.e the minimum allowable flowrate.

![Schematic diagram of the case system.](image)

Table 1. Basic parameters of main equipment.

| Equipment                          | Characteristics                                                                 |
|------------------------------------|---------------------------------------------------------------------------------|
| Chiller-1/2                        | Centrifugal, Rated cooling capacity: 4898 kW, Rated power: 849 kW, Minimum flowrate in the evaporator side: 210.6 m³/h |
| Chilled water pump-1/2              | Variable frequency, Flowrate: 760 m³/h, Head: 46 mH₂O, Power: 132 kW           |
| Chiller-4/5                        | Centrifugal, Rated cooling capacity: 4505 kW, Rated power: 716 kW, Minimum flowrate in the evaporator side: 130 m³/h |
| Chilled water pump-4/5              | Variable frequency, Flowrate: 650 m³/h, Head: 46 mH₂O, Power: 110 kW           |
| CRAHs                              | Return air control, Adjustable water volume and supply air volume               |

3. Simulation model

3.1 Hydraulic calculation model

The hydraulic calculation model of the chilled water pipe network is expressed as equation (1) as follow:

\[ H = SG^2 \]  

\[ S = S_j + S_g \]  

Where \( H \) is the total pressure drop of the pipe network, \( S \) is the total resistance of the pipe network, \( G \) is the total flowrate of the pipe network, \( S_j \) is the total resistance of equipment and pipelines on the cooling source side, \( S_g \) is the total resistance of equipment and pipelines on the user side.
When the user load changes, $S_g$ changes greatly, while $S_j$ is almost unchanged. In order to simplify the calculation model, the change of $S_j$ is ignored when calculating $S$, i.e taking $S_j$ as a constant for calculation.

The resistance of the equipment is calculated according to equation (3) as follow:

$$S_e = \frac{\Delta P_{es}}{G_{es}^2}$$  \hspace{1cm} (3)

Where $S_e$ is the resistance of the equipment, $\Delta P_{es}$ is the pressure drop of the equipment under rated condition, $G_{es}$ is the flowrate of the equipment under rated condition. Equation (3) is applicable to the resistance calculation of the chiller and CRAH.

3.2 Energy consumption calculation model

The curve fitting formula of flowrate $G_P$ and head $H_P$ at a certain pump-frequency is shown in equation (4) as follow:

$$H_P = a_1G_P^2 + a_2G_P + a_3$$  \hspace{1cm} (4)

Where $H_P$ is the head of one pump, $G_P$ is the flowrate of one pump, $a_1$, $a_2$ and $a_3$ are fitting coefficients.

The curve fitting formula of flowrate $G_P$ and efficiency $\eta$ at a certain pump-frequency is shown in equation (5) as follow:

$$\eta = b_1G_P^2 + b_2G_P + b_3$$  \hspace{1cm} (5)

Where $\eta$ is the efficiency of one pump, $b_1$, $b_2$ and $b_3$ are fitting coefficients.

The input power of one pump is calculated according to equation (6) as follow:

$$P_P = \frac{\gamma G_P H_P}{3600 \times 1000 \eta}$$  \hspace{1cm} (6)

Where $P_P$ is the input power of one pump, $\gamma$ is the volumetric weight of the liquid transported.

3.3 Calculation cases

This paper focuses on the analysis of two control strategies (figure 2 and figure 3). Table 2 shows the 30 calculation cases selected in this paper. The water supply temperature is 10 ℃. The DP set-points of subsystem I and II are 168 and 165 kPa, respectively. The DT set-point is 6 ℃.

![Figure 2](image)

**Figure 2. Control principle diagram of the constant DP control of the main water supply-return pipeline.**

![Figure 3](image)

**Figure 3. Control principle diagram of the constant DT control.**

**Table 2. Calculation cases under the constant DP control of the main water supply-return pipeline and the constant DT control.**

| DP cases | DT cases | Total Cooling load ratio (%) | Cooling load ratio of each room (%) | Load distribution |
|----------|----------|-----------------------------|-------------------------------------|------------------|
| DP-90    | DT-90    | 90                          | 90                                  | Load distribution-1 |
4. Results and discussion

4.1 The influence of control strategy

When keeping the load ratio of each room and the total load ratio the same, the energy consumption of the chilled water pump using the constant DP control of the main water supply-return pipeline and the constant DT control under the same load demand is shown in figure 4. As shown in figure 4, whether using the constant DP control or the constant DT control, the energy consumption under part load is lower than the energy consumption under full load, and the energy consumption under the constant DT control is lower. The following takes subsystem I as an example to analyze the reason of the difference in energy consumption.

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**Figure 4.** Comparison of energy consumption of the chilled water pump under two control strategies and the same load demand.

**Figure 5.** Comparison of the working state point of the chilled water pump of subsystem I under different control strategies.

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*F1, F3, F4, F5 and F6 represent all the rooms on the first, third, fourth, fifth and sixth floor respectively.*
Figure 6. Comparison of the working flowrate and head of the chilled water pump of subsystem I under different control strategies and the same load demand.

Figure 5 shows the change of the working state point of the chilled water pump under different load ratio. The intersection of the control curve of the control strategy and the characteristic curve of the chilled water pipe network is the working state point of the chilled water pump, and point A is the working state point under the design condition. Figure 6 illustrates the working flowrate and head of the chilled water pump under different load ratio. The flowrate under the constant DP control and the constant DT control will decrease as the load decreases, and the relationship of the flowrate under the same load ratio is: the constant frequency control > the constant DP control > the constant DT control. The decrease of the working flowrate will cause changes in the operating number of the chilled water pump. Under the constant frequency control, the constant DP control and the constant DT control, when the operating number of pump changes from 2 to 1, the corresponding load ratios are 40%, 50% and 60%, respectively, and the corresponding working state points of the chilled water pump are points D, B and C in figure 5, respectively. The head under the constant DP control and the constant DT control will also decrease as the load decreases, while the head under the constant frequency control is basically unchanged, and the value is larger. Therefore, compared with the constant frequency control, both the constant DP control and the constant DT control achieve energy-saving operation of the chilled water pump by using smaller flowrate (i.e larger DT) and smaller head.

4.2 The influence of load distribution characteristic
The chilled water pipe network will have different hydraulic characteristic under different load distribution. This paper analyzes the working state point and energy consumption of the chilled water pump under four kinds of total load ratio and three kinds of load distribution (load distribution-1: the same ratio, load distribution-2: near-end is smaller, and remote-end is larger, load distribution-3: near-end is larger, and remote-end is smaller). The calculation result of the hydraulic characteristic of the chilled water pipe network of subsystem I is shown in table 3.

Table 3. The hydraulic characteristic of the chilled water pipe network of subsystem I under different load distribution.

| Total cooling load ratio (%) | Load distribution | $S$ of subsystem I (Pa/(m$^3$/h)$^2$) | Total cooling load ratio (%) | Load distribution | $S$ of subsystem I (Pa/(m$^3$/h)$^2$) |
|-----------------------------|------------------|--------------------------|-----------------------------|------------------|--------------------------|
| 50                          | 1                | 0.556                    | 70                         | 1                | 0.373                    |
| 50                          | 2                | 0.595                    | 70                         | 2                | 0.390                    |
| 50                          | 3                | 0.531                    | 70                         | 3                | 0.358                    |
| 60                          | 1                | 0.441                    | 80                         | 1                | 0.328                    |
| 60                          | 2                | 0.479                    | 80                         | 2                | 0.338                    |
| 60                          | 3                | 0.401                    | 80                         | 3                | 0.321                    |

Table 3 shows that under the same total load ratio, affected by the opening of the electric control valve of different branches, the relationship of the total resistance of the chilled water pipe network ($S$)
is: load distribution-2 > load distribution-1 > load distribution-3. Taking the total load ratio = 60% as an example, figure 7 illustrates the changes of the working state point of the chilled water pump under different kinds of load distribution and different control strategies.

As shown in figure 8, the relationship of the working flowrate and head of the chilled water pump is: load distribution-3 > load distribution-1 > load distribution-2. As shown in figure 9, the relationship of the energy consumption of the chilled water pump is: load distribution-3 > load distribution-1 > load distribution-2. In addition, when the total load ratio is 60%, if the constant DP control is used, the energy consumption of the chilled water pump under load distribution-2 is significantly lower than that of load distribution-1 and load distribution-3 by more than 50%, 70% and 80%; if the constant DT control is used, the energy consumption of the chilled water pump under load distribution-1 and load distribution-2 is significantly lower than that of load distribution-3 by more than 50%, 70% and 80%. Under the same total load ratio and different kinds of load distribution, the working flowrate of the chilled water pump will be different, which will also involve the number control of chilled water pump. Under the constant DP control, when the total load ratio of subsystem I is 60%, the operating numbers of chilled water pump under load distribution-1, load distribution-2 and load distribution-3 are 2, 1 and 2, respectively. Under the constant DT control, the operating numbers are 1, 1 and 2, respectively. This is also the reason for the above-mentioned difference in the energy consumption at a total load ratio of 60%. Therefore, under the same total load ratio, different load distribution may also affect the operating number of chilled water pump.

Figure 7. Total load ratio = 60%, comparison of the working state point of the chilled water pump under three kinds of load distribution of subsystem I.

Figure 8. Comparison of the working flowrate and head of the chilled water pump of subsystem I under two control strategies and different load demand.
5. Conclusions

Based on the simulation model of the case system, this paper simulated the operation energy consumption of the chilled water pump when the constant DP control of the main water supply-return pipeline and the constant DT control were used under different load demand. According to the analysis of the calculation results, the following two conclusions are drawn:

1) Compared with the constant frequency control, both the constant DP control and the constant DT control of the main water supply-return pipeline achieve energy-saving operation of the chilled water pump by using smaller flowrate (i.e. larger DT) and smaller head, and the constant DT control is better.

2) Regardless of whether the constant DP control of the main water supply-return pipeline or the constant DT control is adopted, the load distribution of the system has an impact on the working state point and energy consumption of the chilled water pump. Under the same total load ratio, the hydraulic characteristics of the chilled water pipe network under different load distribution are different. The total resistance of the chilled water pipe network of the case system is greatly affected by the load of near-end, so the relationship of $S$ is: load distribution-2 > load distribution-1 > load distribution-3, which further affects the working state point and energy consumption of the chilled water pump. Therefore, the relationship of the working flowrate, head and energy consumption of the chilled water pump is: load distribution-2 < load distribution-1 < load distribution-3. In addition, under the same total load ratio, different load distribution may also affect the operating number of the chilled water pump.

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