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Modeling and optimization for the smart operation of a central chilled water system in a high-rise building

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Abstract. Besides meeting the cooling demands of each terminal space in a high-rise building, the smart operation of a central chilled water system is also aiming at saving more electricity. Hence, it is the key issue to distribute proper amount of chilled water to each room according to its cooling load variations, i.e. achieve hydraulic balance in the chilled water network. To save electricity consumption of both chillers and circulation pumps in operation, in this paper, a supervisory optimization model is proposed for a general chilled water system. An improved node method is also presented to simulate the hydraulic behavior of the general chilled water pipe network, which is particularly adapted for a high-rise building with faster computation speed and fine accuracy. Then the proposed model is validated in a real high-rise hotel in Shanghai. In the case study, comparing with conventional operation method (On/Off or PID control), the proposed smart operation method can save 15.4-29.3% of electricity for the chilled water system in the typical days of cooling season.

1. Introduction

Central air-conditioning system often contributes a significant proportion to the total energy consumption in buildings [1]. As the increasing number of high-rise buildings in future urban construction, the well-controlled chilled water systems have great energy saving potentials [2].

There are two main approaches to address the advanced HVAC system control, the data-driven (black-box) model or the physical based (white-box) model. Kusiak et al. proposed a data-driven approach to reduce the energy consumption of air handling units (AHU) [3]. He et al. presented three computational intelligence algorithms to optimize the performance of air conditioning system [4]. Artificial neural network (ANN) based models for predictive control and optimization of HVAC systems have already been widely adopted in recent studies [5]. The data-driven approach can save up to 8-20% energy consumption in most cases [6]. However, the black-box models cannot always ensure stable performance prediction although they show great advantages on overcoming the nonlinear characteristics of HVAC systems. On the other hand, the physical based models are also developed in early years. Wang and Jin presented an optimal control of VAV air-conditioning system with elaborated physical models [7]. Budaiwi et al. utilized the Visual DOE to give various HVAC simulation strategies [8]. To guarantee the well operation of chilled water system, Rishel presented the proper control methods on variable speed pumps [9]. Moore et al. optimized the pump operation using the control valves’ openness signals [10]. Ma and Wang employed an optimal control strategy for complex building central chilled water systems [11]. The control strategy for variable speed pumps
can save as much as 12-32% of the pump energy [12]. Zhao et al. investigated the stability of a pipe network for differential pressure control of a variable flow air-conditioning chilled water system [13]. The modeling and optimization methods in some recent studies [14,15,16,17] focusing on smart operation in the district heating networks can still be referenced to improve the energy efficiency and flexibility of a chilled water system, especially in high-rise buildings.

In this paper, an optimal model was proposed for a central chilled water system, which considered the electricity consumption of chillers and pumps, the cooling loads of customers and the hydraulic balance of water pipe network. To ensure the optimal model with fast computation speed, an improved node method is presented to simulate the hydraulic behavior of the chilled water pipe network in a high-rise building. The proposed operation is validated in a case study in comparison with conventional operation in detail.

2. Optimization model and smart operation

![Figure 1. Configuration diagram of a chilled water system.](image)

Table 1. The optimization model.

| Object function | \( \text{min}\{\text{Cost}_{\text{sys}}\} = \text{min}\left\{C_e \sum W_{ch,i} + C_e (\sum W_{pump,i} + \sum W_{pump,k}) + \sum \gamma |Q_j - Q^d_j| \right\} \) (1) |
| Decision Variable | \( T_s, M_{Ch,i}, M_{AHU,j}, M_{by} \) |
| s.t. | \( T_s^{\text{min}} \leq T_s \leq T_s^{\text{max}} \) |
| | \( 0 \leq M_{Ch,i} \leq M_{Ch,i}^{\text{max}} \) |
| | \( 0 \leq M_{AHU,j} \leq M_{AHU,j}^{\text{max}} \) |
| | \( M_{by} = \max\{0, (M_{by}^{\text{min}} - M_{AHU})\} \) |

As shown in figure 1, a chilled water system is often composed of three parts: source side, pipe network and user side. To reduce energy consumption and fulfill the cooling demand simultaneously, the chilled water system should operate with the help of an optimization model so that the optimal results are used to update the set-points of key parameters of chillers, pumps and valves. Then the chilled water system can eventually achieve sound performance as expected. See figure 1, the supply/return water temperature from/to the source side is \( T_s/T_r \); the chillers are considered to provide the same supply temperature, \( T_s \). The total circulating mass flow rate is \( M_{Ch} \). The individual mass flow rate of each chiller is \( M_{Ch,i} \), where the subscript \( i \) is the index of chiller. The mass flow rate through the bypass is \( M_{by} \). The supply/return water temperature to/from the user side is \( T_{s,AHU}/T_{r,AHU} \); The total circulating mass flow rate is \( M_{AHU} \). The individual mass flow rate of each terminal user is \( M_{AHU,j} \), where the subscript \( j \) is the index of terminal user. The primary pump is indexed in accordance with \( i \); the secondary pumps are indexed with subscript \( k \). Then, the optimization model is proposed as Table 1.
The total cost on electricity consumption of the chillers and pumps are involved in the first and second terms of formula (1). $C_e$ is the price of unit electricity. The third term $\sum \gamma |Q^d_j - Q^a_j|$ is in particular proposed for the energy fulfilment extent of users that refer to the gap between the demanded cooling energy $Q^d_j$ and the actual supplied cooling energy $Q^a_j$. The penalty factor $\gamma$ is designed to balance the “importance” of the gap.

The decision variables are $T_s$, $M_{Ch,i}$, $M_{AHU,j}$ and $M_{by}$, respectively. As considering the well insulation of chilled water pipes, $T_{s,AHU} = T_s$. Suppose the reasonable operation range of $T_s$ is 5-11°C. The return water temperatures, $T_r$ and $T_{r,AHU}$, are measured from onsite meters. Therefore, $T_r$ and $T_{r,AHU}$ are already known as input data for the proposed model. The mass flow rates, $M_{Ch,i}$, $M_{AHU,j}$ and $M_{by}$, are adjusted by the valves’ openness and rotation speed of secondary pumps.

3. System model

The chilled water system model is composed of three parts: source model, user model and pipe network model.

For the user, the main function of user model is to predict the current cooling demands $Q^d_j$. It may be written as,

$$Q^d_j = F_j^d(T_{indoor}, T_{outdoor}, T_{set}, V_{room}, \cdots) \tag{2}$$

where $T_{indoor}$, $T_{outdoor}$ and $T_{set}$ are the indoor temperature, outdoor temperature and the set temperature by the resident. $V_{room}$ is the volume of room. The subscript $j$ is the index of user.

For a general AHU, the actual cooling energy transported to the users can be written as follows,

$$Q^a_j = F_j^a(AU_{AHU,j}, \phi_{AHU}, T_{s,AHU}, M_{AHU,j}, T_{in,air,j}, M_{air,j}) \tag{3}$$

where $AU_{AHU,j}$ is the heat transfer capacity of AHU. $\phi_{AHU}$ is the efficiency of AHU. $T_{in,air,j}$ and $M_{air,j}$ are the inflowing temperature and flow rate of air. The supply temperature and flow rate of chilled water, $T_{s,AHU}$ and $M_{AHU,j}$, are decision variables. In practice, the function $F_j^a$ can be got from the characteristic curve provided by the manufacturer or from the regression curve of the operation data. With available $Q^d_j$ and $Q^a_j$, the third term of the objective function (1) can be figured out.

For source, the electricity consumption of a chiller (indexed with $i$) can be calculated as,

$$W_{ch,i} = \frac{Q_{ch,i}}{\text{COP}_{ch,i}} \tag{4}$$

$$\text{COP}_{ch,i} = \frac{1}{EIR^r \cdot \phi_{EIR} \cdot \phi_{PLR}} \tag{5}$$

where $W_{ch,i}$ is the electricity consumption of chiller. $Q_{ch,i}$ is the dispatched cooling load of chiller. $EIR^r$, $\phi_{EIR}$ and $\phi_{PLR}$ are the regressed factors.

The total energy load of all chillers can be estimated from the sum of energy demand of users and the thermal losses in the pipe network, which is given as,

$$Q_{ch}^{tot} = \sum Q^d_j + Q_{pipe}^{loss} \tag{6}$$

Then the chilled water supply temperature $T_s$ can be estimated as,

$$T_s = T_r - \frac{Q_{ch}^{tot}}{M_{Ch,i} \cdot C_p} \tag{7}$$

The electricity consumption of primary pumps can be given as,

$$W_{pump,i} = P_i \cdot \frac{M_{Ch,i}}{\rho \cdot \eta_i} \tag{8}$$
where $P_i$ is the pressure head of pump; $\eta_i$ is its efficiency; $\rho$ is the density of chilled water.

For pipe network, the hydraulic modeling of pipe network is treated as a conventional fluid network based on the Graph Theory, which have been elaborated in the previous studies [17,18].

To accelerate the numerical convergence of hydraulic calculation, the vertical pipes and horizontal pipes can be treated separately. After only several iterations, the whole hydraulic calculation can often be done completely. The improved node method can be briefly summarized as figure 2. The thermal modeling of pipe network can refer to the quasi-static modeling of district heating systems [17].

![Figure 2](image2.png)

**Figure 2.** The improved node method.

4. **Case study**

The chilled water system in a high-rise building (a hotel in Shanghai, China) with 25 floors is demonstrated to validate the proposed optimization model. The schematic diagram of the chilled water system is shown in figure 3. There are 6 identical chillers and primary pumps on the roof of the building. The chiller’s rated cooling capacity is 865.6 kW, its rated power consumption is 245.2 kW. The designed supply/return water temperature is 7/12°C. The primary pump’s rated volume flow rate is 164.0 m$^3$/h, rated water head is 20.0 H$_2$O m. There are 12 identical secondary pumps with rated volume flow rate as 82.0 m$^3$/h and rated water head as 60.0 H$_2$O m. Besides the local climate records and history energy consumption data, the number, area and facilities of the rooms in each floor have also been checked as input data for the cooling load prediction. The hotel’s total cooling load curves of the three typical days in June, July and August are shown in figure 4. The conventional and proposed operations of chilled water system in these typical days are simulated to compare the energy saving effects.

In conventional operation, the return water temperature of the chiller is set to 12°C; the flow rate of the secondary pumps is set to follow the design flow rate of the peak load in a day. The chillers are set to follow the return water temperature by On/Off control. In the proposed operation, the supply water temperature of the chiller and the flow rate of the pumps are adjusted by the proposed model. The chillers are set to follow the cooling load variation by variable frequency control. The electricity price of the chillers and pumps are 0.80 CNY/kWh; the penalty factor in proposed model equation (1) is set to 80.0 CNY/kWh.
The electricity consumptions of the conventional and proposed operation in the typical days in June, July and August are illustrated in figure 5, 6 and 7, respectively. Comparing to that of the conventional operation, the electricity of the proposed method can be saved as much as 29.3% in the typical day of June, 16.9% in July and 15.4% in August, respectively. The control strategy of the proposed operation which follows tightly the cooling demand can be more flexible than that of the conventional operation. The proposed operation shows more advantage in June, when the cooling load is nearly half of that in August. The system COPs of the conventional and proposed operations in the typical days in June, July and August are shown in figure 8. Obviously, the system COP can reach 3.43 in the typical day of June, which is the highest value in three typical days. The enhancement of the proposed operation on system COP almost reaches as much as 1.0 higher in comparison with that of the conventional operation in the typical day of June. The system COPs are 3.10 and 2.92 in the typical day of July and August, which also show much better performances by the proposed operation.

**Figure 4.** The predicted cooling loads of the typical days in June, July and August.

**Figure 5.** The electricity consumption in a typical day of June.

**Figure 6.** The electricity consumption in a typical day of July.

**Figure 7.** The electricity consumption in a typical day of August.

**Figure 8.** COPs of the conventional and proposed operations.
5. Conclusions
The chilled water system is vital important for electricity saving in operation of a central air-conditioning system. To fulfill the cooling demands of the high-rise building efficiently, optimal control strategies should be elaborately developed. In this study, a smart operation method is proposed for the chilled water system in a high-rise building. The main conclusions are summarized as follows.

(1) A new optimization model is proposed with consideration of less electricity consumption of chillers and pumps while still fulfilling the varied cooling demands of building. The optimization model can be convenient to adjust the supply water temperature of chillers, the rotation speed of secondary pumps and the openness of the throttle valves.

(2) An improved node method is presented to accelerate the computation speed of hydraulic calculation of the pipe network in a high-rise building. By treating the vertical pipes and horizontal pipes separately, the hydraulic calculation of chilled water pipe network in a high-rise building can be converged in several iterations.

(3) The proposed operation method is validated in a 25-floor hotel in Shanghai. In the case study, comparing with that of the conventional operation method (On/Off control on the chillers, PID control on the return water temperature), the electricity of the smart operation method can be saved as much as 29.3% in the typical day of June, 16.9% in July and 15.4% in August, respectively. The system COPs of the smart operation are 3.43, 3.10 and 2.92 in the typical days of June, July and August, respectively. The performance of the chilled water system can be improved significantly by the proposed operation.

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