Journal of Building Engineering 33 (2021) 101499

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: http://www.elsevier.com/locate/jobe

Causes of low delta-T syndrome for chilled water systems in buildings

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ARTICLE INFO

Keywords:
Low delta-T syndrome
Causes
Simulation
Analysis

ABSTRACT

Low delta-T syndrome is recognized as a typical technical problem in many chilled water systems. This syndrome typically increases the energy consumption of chilled water pumps, decreases system overall operating efficiency, and undermines occupant comfort. Although low delta-T syndrome has been widely discussed in theoretical and practical studies, these studies were not focused on systematic summaries that describe underlying reasons for the syndrome. In this study, causes of the syndrome in buildings are investigated comprehensively, through both qualitative and quantitative analyses. Firstly, a qualitative research is conducted on all issues that may cause low delta-T syndrome from three aspects, which are causes related to terminals, hydronic system design and construction, and local controls. Subsequently, a simulation platform that can simulate the dynamic features of the chilled water system is built to quantitatively analyze the effects of these causes. Finally, different causes of low delta-T syndrome are introduced into the simulation platform and the effects are analyzed. The simulation results indicate that the issues summarized all have effects on the appearance of low delta-T syndrome and increase the pump energy consumption to varying degrees. The poor valve authority and control failure of the valves are major causes for severe low delta-T syndrome.

1. Introduction

The building sector is generally acknowledged as a major consumer of energy and resources, consuming approximately 40% of primary energy in the United States and Europe and approximately 25%–30% in developing countries such as China [1]. Chilled water systems are major parts of heating, ventilating, and air-conditioning (HVAC) systems in large buildings, accounting for a large amount of building energy consumption. Low-temperature chilled water is produced by chillers, delivered to each terminal and subsequently returned to the chillers through the chilled water system, delivering cooling to the occupied spaces of buildings. It is assumed that the temperature difference (delta-T) between the supply and return chilled water will remain relatively constant, because the cooling load is directly proportional to flow rate and delta-T. However, the delta-T is significantly lower than its design value in many real applications, this phenomenon is defined as low delta-T syndrome [2].

A low delta-T is a typical syndrome of chilled water systems in buildings, and various operating parameters deviate from their design values owing to this syndrome. The syndrome imposes negative effects in the following three aspects:

1) High pump energy consumption. The pressure difference is proportional to the square of the water flow rate. Therefore, the increase in the flow rate of chilled water will result in a higher pump energy consumption.

2) Low operating efficiency of the chilled water pump. If the water flow rate differs from the design value, the operating point of the chilled water pump often deviates from the normal point, resulting in a low-efficiency operation.

3) Early startup of the chillers if flow-based control sequence is used. Large cooling plants typically have several chillers to ensure that the system can operate at high efficiencies under different partial cooling loads. When low delta-T syndrome occurs, the increase in water flow rate may cause additional chillers to start even when the cooling capacity of the chillers in operation can fully satisfy the requirements, thereby reducing the overall operating efficiency of the cooling plant.

Many studies have been conducted over the past two decades regarding the prevention and mitigation of the low delta-T syndrome. Taylor [2] provided a systematic summary of various causes of low delta-T syndrome in chilled water plants and categorized those causes into avoidable and unavoidable issues with corresponding mitigation approaches. Luther [3] proposed solutions to the problem of low delta-T from the design point and analyzed factors that decreased the delta-T of the chilled water. Apart from qualitative analysis from the perspective of

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https://doi.org/10.1016/j.jobe.2020.101499
Received 28 February 2020; Received in revised form 10 May 2020; Accepted 10 May 2020
Available online 12 June 2020

engineering practice and case studies, scholars have studied the low delta-T syndrome numerically. Wang et al. [4] used effectiveness-number of transfer units cooling coil models to study cooling coil delta-T characteristics under various conditions to diagnose the low delta-T syndrome under various loading conditions. Their results showed that model-based fault diagnosis is effective for evaluating delta-T performance and detect root causes. Henze et al. [5] developed a dynamic simulation environment and employed a coupled thermohydraulic system for a quantitative evaluation of various causes that contribute to low delta-T syndrome. Gao et al. [6–8] conducted several studies regarding the fault diagnosis of low delta-T syndrome and control strategy optimization for primary–secondary chilled water systems.

Although the low delta-T syndrome has been thoroughly studied previously, few researchers have conducted a comprehensive review on the different causes of low delta-T syndrome, and a systematic summary of the causes of this syndrome is lacking. Furthermore, most of the previous studies only involved qualitative analysis, and the effect of each factor that caused the low delta-T syndrome is still unclear. The objective of this study is to qualitatively and quantitatively study the causes of low delta-T syndrome of chilled water systems in buildings. In Section 2, a qualitative review on the causes of low delta-T syndrome is presented. The causes are categorized into three groups, which are causes related to terminals, hydronic system design and construction, and local controls. To quantitatively study the effects of different causes on low delta-T syndrome, we build an elaborated simulation platform in MATLAB, which will be described in Section 3. The platform could calculate the water flow rate and each branch's pressure drop in the chilled water system; furthermore, it could simulate the coupling and dynamic processes between the chilled water system and terminal units. In Section 4, different causes of low delta-T syndrome are introduced into the simulation platform and the effects are analyzed.

2. Qualitative analysis for causes of low delta-T syndrome

The causes of low delta-T syndrome can be categorized into three groups. Terminals are basic heat transfer units between the chilled water system and rooms; therefore, issues related to terminals should first be addressed. Additionally, the operation of chilled water systems is important. A poor system design and construction will result in low delta-T syndrome. Finally, local control is important for ensuring that the chilled water system is operating in a healthy condition. The following is a thorough qualitative analysis of causes of low delta-T syndrome from these three categories.

2.1. Causes related to terminals

In many cases, low delta-T syndrome is caused by the limited heat exchange capacity of terminals. Therefore, it is necessary to analyze the effects of various factors associated with the heat transfer of coils. Factors affecting the heat transfer characteristics of coils can be categorized into the following two categories. One is the parameters of the coil itself, such as the heat transfer exchange area, mode, and coefficient. The other is the heat transfer media parameters, such as the supply air temperature, supply chilled water temperature, air flow rate, and chilled water flow rate. The key causes of low delta-T syndrome are analyzed in this section.

2.1.1. Coil fouling

After an HVAC system is operated for a time period, the fouling of terminals' heat exchanger occurs. The fouling on the water side is characterized by the accumulation of deposit inside the coil, and that on the wind side is characterized by the accumulation of dust and rust on the fins. Therefore, to satisfy the cooling load of the room, the chilled water flow rate has to be increased considerably. Hence, the delta-T between the supply and return water decreases significantly, which is the typical symptom of low delta-T.

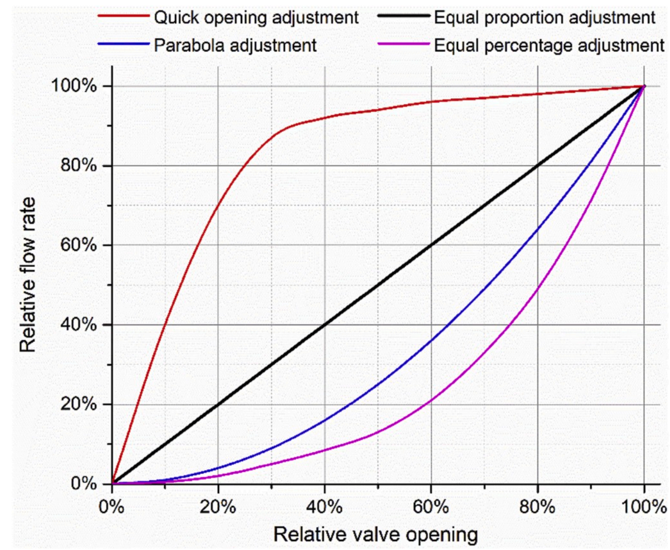

Fig. 1. Four types of valve characteristics.

2.1.2. Insufficient airflow

An HVAC system may experience insufficient air intake during operation. For example, if the filter is clogged or the coil is dirty, the wind resistance starts to increase and the amount of heat exchanged by the coil decreases. Subsequently, the cooling capacity delivered by the chilled water per unit flow rate is reduced, resulting in low delta-T syndrome.

2.1.3. Extremely high chilled water supply temperature

The chilled water supply and return temperatures significantly affect the performance of chillers. If the supply water temperature is extremely high, then the energy consumption of the compressor is reduced, and the energy efficiency of the chiller is improved. However, a high supply water temperature reduces the heat exchange capacity of the terminal coils. In addition, when a primary–secondary system is used in an HVAC system, low delta-T syndrome occurs owing to backflow in the bypass pipe, specifically if the water flow of the secondary pump is higher than that of the primary pump. Owing to the presence of the bypass pipe, excess chilled water flows back through the bypass pipe and mixes with the chilled water in the primary loop. After this water mixing, the supply chilled water temperature to the coil increases, and the delta-T between the supply and return water decreases. The control valve must be further opened to increase the flow rate of the chilled water. Therefore, the low delta-T syndrome further deteriorates, and the countercurrent flow of the bypass pipe becomes increasingly severe.

2.1.4. Undersized coils

In the design and construction period of many buildings, there may be situations where coils are undersized owing to various reasons. For example, some manufacturers select coils based on the empirical formula obtained from relevant data of the test sample, which tends to overestimate the coil capacity. In other examples, some design firms would blindly copy other design samples during the selection process, resulting in selection errors. In the construction phase, some companies would directly reduce the number of the coil's rows to reduce cost. Undersized coils result in insufficient heat exchange capacity. If the coil with a smaller size than necessary is selected, then the chilled water flow rate must be increased to satisfy the cooling load.

2.1.5. Improper valves

Valves are an important control component in chilled water systems. Valves adjust chilled water flow rate by changing the opening. A valve opening is generally categorized into four types: quick opening, linear,

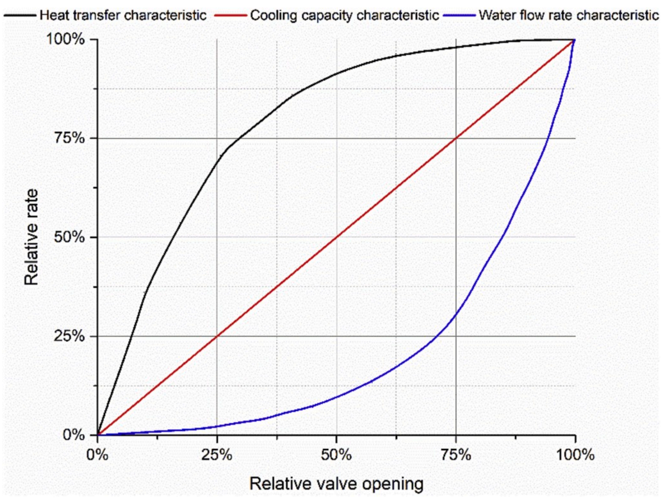

Fig. 2. Heat transfer characteristic of valve-related issues.

parabolic, and equal percentage, and its characteristic curve is shown in Fig. 1. The four valve characteristics can satisfy the requirements of different adjustment characteristics. When designing a central air-conditioning system, an equal-percentage valve is often used to control the chilled water system. The nonlinear adjustment characteristics of the coil can be compensated by the operating characteristics of the equal-percentage type valve; therefore, the problem of poor regulation can be alleviated to some extent.

However, when designing the system, if the valve is not selected appropriately, the hydraulic characteristics of the system will be affected significantly. For example, the valve opening is an important parameter to describe the operating state of the valve. The change in valve opening directly affects the water flow rate. An inappropriate valve selection can cause a significant variation in the water flow rate even when the valve opening does not fluctuate much. This problem causes negative effects, such as the inability to control the water flow rate of the terminal device and the constant fluctuation of the water flow rate around its set value. This unstable water flow rate is likely to cause the average water flow rate of the system to be higher than the real load demand over a time period, thereby reducing the delta-T between the supply and return water of the system and causing low delta-T syndrome.

2.1.6. Poor valve authority

As shown in Fig. 2, the operating curve of the coil is primarily convex. In the low valve position range, the relative cooling capacity changes significantly with a small adjustment of the valve position. The ideal valve-opening–output-cooling-capacity trend must be a straight line to accurately control the cooling output under various load conditions. Therefore, under different load conditions, the flow control valve using the equal-percentage characteristic can linearly change the control of the cooling capacity; therefore, a precise control of the cooling capacity can be achieved.

However, the flow characteristics of the valve during operation are not exactly equivalent to the flow characteristics under ideal conditions because in many chilled water systems, the valve authority has a greater effect on the valve regulation performance. The valve authority refers to the ratio of the pressure difference when the valve is fully open and that when the water flow rate reaches the design value. Only when the valve authority is 1 can a valve control the flow rate, as shown by the curves in Fig. 2. However, in the design period of the central air-conditioning chilled water system, the valve is connected with various resistance elements in the pipeline; therefore, it is impossible for the valve to exhibit the flow control demonstrated in the ideal state. In addition, although the higher valve authority can improve the quality of the flow regulation, it also increases the resistance of the water system. Excessive valve authority may pose a significant challenge to the energy-saving operation of air-conditioning systems. It is clear that the valve authority and flow rate opening curve of the valve affect the water flow rate of the coil in the selection process. If the selection is inappropriate, low delta-T syndrome will occur.

2.2. Causes related to hydronic system design and construction

2.2.1. Unbalanced water loops

In the design and construction of large hydraulic systems, the balance among loops is often neglected. The pressure drop between each branch of the loops differ vastly. These systems are often not commissioned after the construction is completed. Therefore, in the operation process, the resistance between the loops are not balanced. The unbalanced resistance in turn causes unbalanced water flow and thermal unit operations. Occasionally, the water flow rate during system operation becomes larger than the design value.

2.2.2. Oversized pumps

When selecting a chilled water pump in the design phase, the pump head is often determined by multiplying the maximum resistance of the water loop by a certain safety factor. The calculated pump head and the design flow rate are used to determine the pump size. Hence, regardless of the characteristic curve of the pump, the actual operating point of the pump is often on the lower right side of the operating point marked by the nameplate. Such an operating state will result in a large flow rate of the water system and the low delta-T syndrome.

2.3. Causes related to local controls

2.3.1. Control failure

The control of pumps and terminals are crucial for adjusting the chilled water system's water flow rate. Once the pumps or valves beyond control, the chilled water system will operate in an unsatisfactory state, in which the system cannot satisfy the building instant cooling load, and low delta-T syndrome occurs.

2.3.2. Extremely high pump pressure difference setpoint

In chilled water systems with constant differential pressure control, the value of the pressure difference is crucial in determining whether the system operates well. If the value is extremely high, then the opening of the control valve is reduced and the resistance is increased. This increases the operating energy consumption of the chilled water pump. If the value is extremely low, the pressure of some branches may be insufficient, and the water flow rate is less than the demand value, resulting in an insufficient cooling capacity to satisfy the load.

2.3.3. Improper proportional–integral–differential (PID) parameter setting

The automatic control of chilled water systems often uses the PID method. If the PID control parameters are set appropriately, the system can quickly eliminate the error and reach a stable control. However, poor settings cause many problems to the error correction of PID control. For example, increasing the proportional coefficient, the P factor, causes the system to be responsive, accelerates regulation, and reduces steady-state errors. However, if the proportional coefficient is extremely large, the numbers of overshoots and oscillations increase. The adjustment time is prolonged, and the dynamic performance deteriorates. Furthermore, an extremely large proportional coefficient will result in an unstable closed-loop system. If the supply air temperature is used as the control parameter of the water valve in the cascade control, poor parameter settings will cause the overall average flow rate to be higher than the actual demand, thereby reducing the delta-T between the supply and return water.

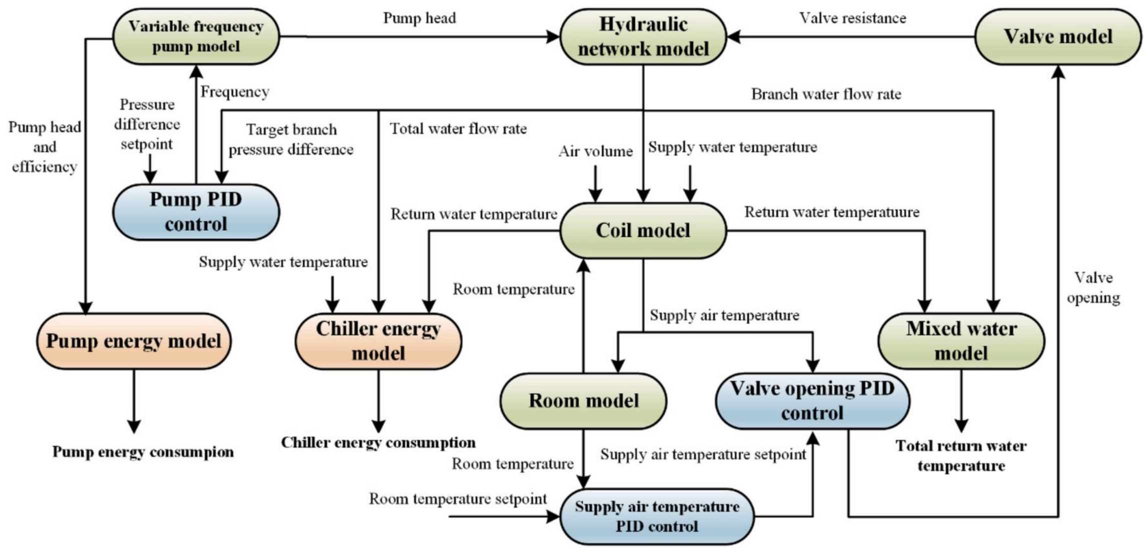

Fig. 3. Model calculation diagram.

3. Quantitative analysis through simulation

The previous section qualitatively described the potential causes of low delta-T syndrome from three aspects. It is difficult for researchers to study various causes of low delta-T syndrome in real buildings because the experimental conditions are difficult to obtain and the experimental costs are high. Therefore, we used simulation tools to create a platform on which we could simulate various causes of low delta-T syndrome and subsequently analyze them quantitatively.

3.1. Simulation procedure

To determine the effects of various causes, a simulation platform was built by coupling Matlab and EnergyPlus. Matlab was used for the detailed HVAC system simulation and the process implemented in Matlab is illustrated in Fig. 3, whereas EnergyPlus was used for the load calculation in the room model. The four-row countercurrent heat exchange coil model was obtained from the ASHRAE RP-1194 project [9, 10]. The valve model uses the valve opening as the input and the valve's resistance coefficient as the output while the equal-percentage valve type is obtained. The hydraulic network model uses the resistance coefficient (or valve opening degree) of each branch, the topology of the pipeline network, the pump head as inputs, and the water flow rate and pressure of each branch as outputs while being solved by the basic loop method [5]. The room model was obtained from Cheng et al. [11] and uses a simple harmonic to express the outdoor comprehensive temperature [12]. The variable frequency pump model uses a quadratic hydraulic head-flow rate curve and efficiency-flow rate curve. The control in the simulation adopts the incremental PID algorithm. The chiller model is based on the compression refrigerator model in EnergyPlus, and it can simulate the energy consumption of the chiller.

The room temperature and regulating valve in each branch have PID controls. The frequency of the variable frequency pump is controlled by the pressure difference. The hydraulic pipe network model can obtain the water flow rates and pressure differences of the branches. The target branch pressure difference is fed back to the pump PID controller, and the flow rate of each branch is used as the input value of the coil model at this moment. For the coil model, the calculated branch flow rate, water supply temperature, air volume, mixed air temperature of the return air and fresh air from the previous step, and the leaving temperature of water and air of each coil can be calculated. Through the simplified mixing model, the total return water temperature and the difference between the supply and return water temperatures can be obtained. The supply air temperature is calculated using the room model to obtain a new room temperature; hence, the cycle of another step is entered.

In addition to calculating the pressure, flow rate, temperature, etc.,

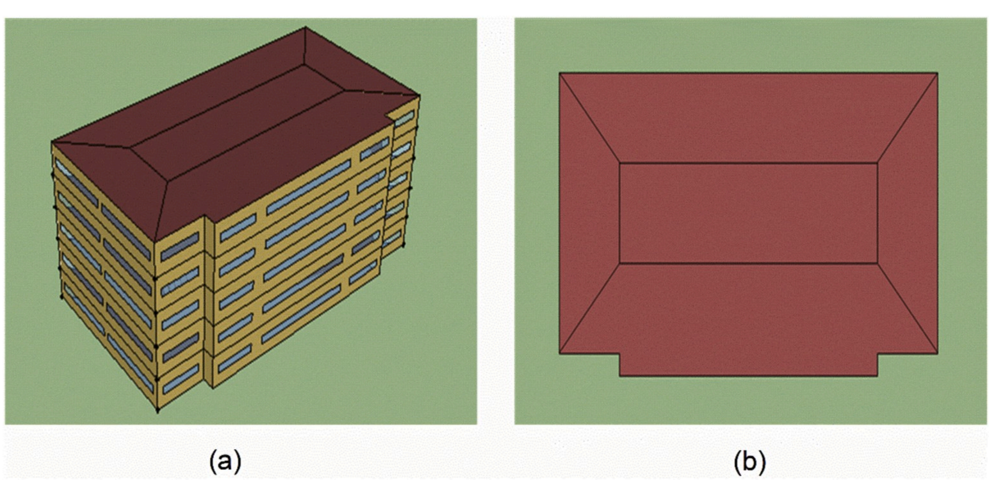

Fig. 4. Schematics of (a) building and (b) building zone.

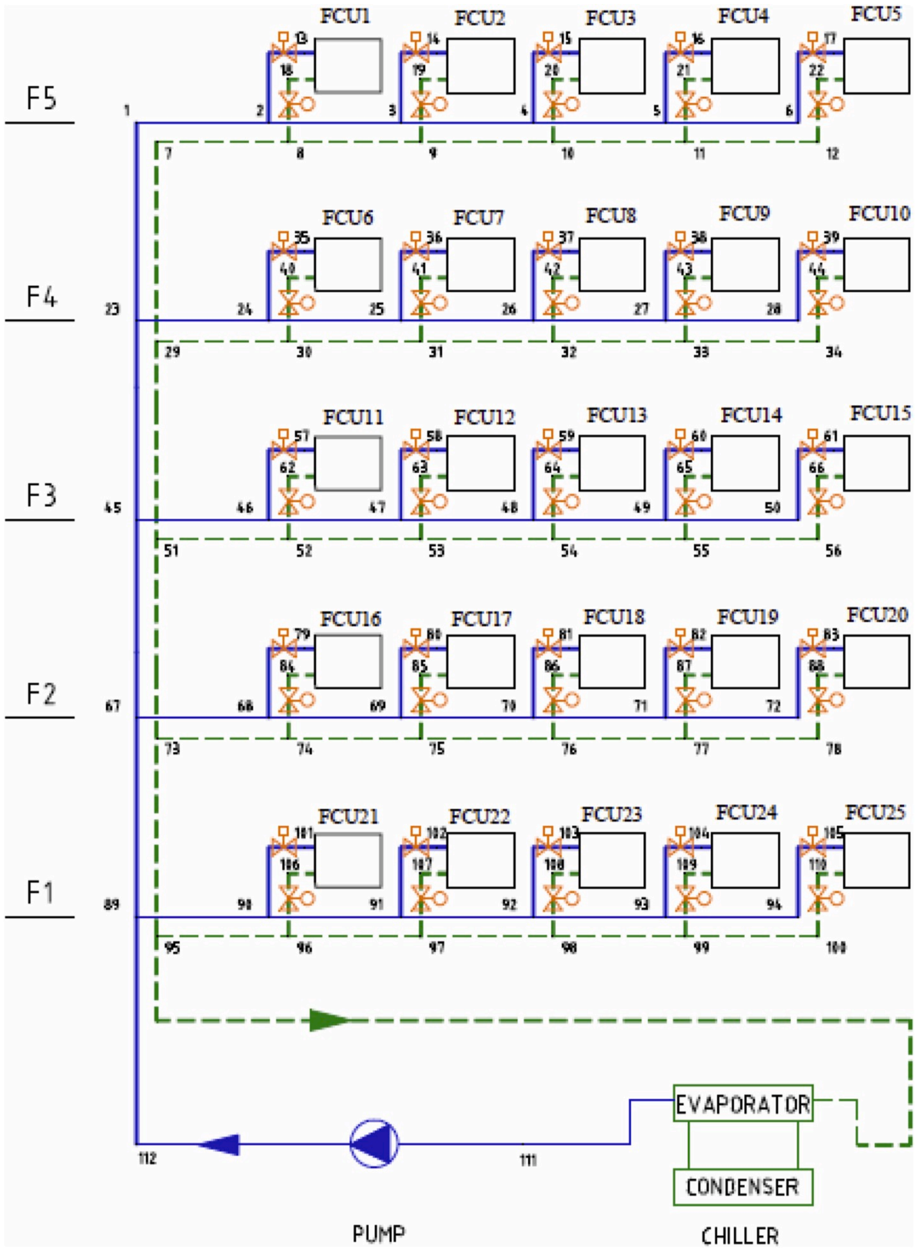

Fig. 5. Chilled water system hydraulic diagram.

the platform must calculate the energy consumption of the chiller and pump. With the calculated delta-T, flow rate, evaporator leaving water temperature, and condenser entering water temperature, the energy consumption of the chiller can be calculated. The pump energy consumption can be calculated using the flow rate, pressure, and efficiency of the variable frequency pump.

3.2. Building case

A five-floor official building in Shanghai was selected as the target building for simulation; the height of each floor was 4.5 m and each floor was categorized into five areas, i.e., four outer areas and one inner area, as shown in Fig. 4(a) and (b). The chilled water system was modeled as a primary pump variable flow system and the pressure difference was 12 m H_2O for the index circuit. The hydraulic design of the building is shown in Fig. 5; the baseline model achieved hydraulic balance after commissioning. To consider hydraulic coupling between the terminals, each fan coil unit was used for the corresponding zone's cooling load. The temperature control range of each zone was 24 °C-26 °C. Detailed information regarding the simulated building is shown in Tables 1 and 2.

The model described in this section is a baseline model with no faults. Because the comfort temperature fluctuation is approximately 0.5 °C, a deviation within ±0.5 °C is considered stable. The control system maintains the indoor temperature at the setpoint in around 1 h. Based on the model, the operation of the target building's chilled water system during the operating hours of the building from 10:00 to 18:00 in the summer was simulated.

As shown in Fig. 6(a), the air-conditioning control system stabilized the zone temperature to within 24 ± 0.5 °C in 0.5 to 1 h. Owing to the rapid change in the cooling load, the valve opening fluctuated such that the supply air temperature reached the setpoint, as shown in Fig. 6(b). It is clear that the change in the valve opening is consistent with the change in the load, and the control system operates well.

As shown in Fig. 7(a)(b), the total water volume of the main pipe and the delta-T of the system fluctuate significantly with the load. The delta-T between the supply and return water under a large load is smaller than

Table 1
The simulated building's main envelop information.

Structure	Material	Thickness (mm)	Thermal conductivity (W/m·K)	Density (kg/m^3)	Specific heat capacity (J/kg·K)
Roof	Insulation mortar	20	0.08	400	1045.8
	Expanded perlite	50	0.16	400	1170
	Reinforced concrete	200	1.74	2500	920
	Lime mortar	20	0.93	1800	1050
Exterior wall	Granite	20	3.49	2800	920
	Insulation mortar	20	0.08	400	1045.8
	Cement mortar	30	0.93	1800	1050
	Concrete block	200	0.68	1300	537.8
	Lime mortar	25	0.93	1800	1050
Window	Glass	6	/	/	/
	Air layer	13	/	/	/
	Glass	6	/	/	/
Ground	Lime mortar	25	0.93	1800	1050
	Reinforced concrete	350	1.74	2500	920
	Lime mortar	20	0.93	1800	1050
Floor	Lime mortar	20	0.93	1800	1050
	Reinforced concrete	80	1.74	2500	920
	Lime mortar	20	0.93	1800	1050
Interior wall	Lime mortar	20	0.93	1800	1050
	Reinforced concrete	80	1.74	2500	920
	Lime mortar	20	0.93	1800	1050

Table 2
The simulated building's equipment information.

Equipment	Item	Value
Chiller	Number	1
	Rated cooling capacity (W)	703300
	COP	7.03
	Resistance coefficient (m/(L/s)^2)	0.000369
Pump	Number	1
	Rated water flow rate (L/s)	28
	Rated pump head (m)	28
	Rated power (kW)	10.2
	Rated speed (r/min)	980
	Resistance coefficient (m/(L/s)^2)	0.0015
Fan coil unit	Number	25
	Design air flow rate (m^3/s)	1.86
	Design water flow rate (L/s)	1.32
	Design delta-T (°C)	6
	Valve authority	0.5

that when the load is small, whereas the water flow shows the opposite trend. The simulation results show that under a good control and no obvious hard faults, the general trend of delta-T of the supply and return water is similar to that of the single coil curve. It is noteworthy that the total water volume and the total delta-T of the main pipe fluctuated significantly during certain time periods. This was because the load change was increasing during this period, which increased the coupling between the fan coil units.

As shown in Fig. 7 (c)(d), the energy consumptions of chiller and pump are positively correlated with the load and change with the load. At 10:00, when the power is turned on, the surge of power consumption of the chiller and the pump is large owing to the large cooling load. In 17:00–18:00, after the operating hours, the power consumption is small, which is consistent with the actual situation.

4. Quantitative analysis for causes of low delta-T syndrome

Based on the simulation platform built in Section 3, we introduced various causes of low delta-T syndrome into the target simulated building; subsequently, the quantitative results of the effects of various causes on low delta-T syndrome were obtained.

4.1. Causes related to terminals

4.1.1. Coil fouling

After a long use period, fouling could appear inside and outside the coils. The fault of the coil fouling of the terminal was simulated by reducing the heat transfer coefficient of both the water and air sides by 20%. The simulation results are shown in Figs. 8(a) and 9(a). The temperature change and the total pipe water flow rate in each area increased slightly. The weighted average delta-T of the supply and return water was 4.85 °C, with a decrease of 23%. The average energy consumption of the pump was 10.2 kW, with an increase of 38.27%. The average energy consumption of the chiller was 678.4 kW, which was consistent with that of the baseline model.

Coil fouling and some fouling problems in the terminals together with the effect of coil fouling on the overall HVAC water system were considered. The simulation results are shown in Table 3 below. It is clear that a single coil fouling failure did not affect the operation of the overall water system. However, if the unit fouling degree reached a certain amount, it would affect the energy consumption of the water system.

4.1.2. Insufficient airflow

The circulating air volume of each unit in the model was set to 90% of the original reference model to obtain the simulation results under the fault conditions, as shown in Figs. 8(b) and 9(b) below. The weighted average delta-T of the water system decreased to 5.29 °C, a decrease of 16.13%. The average energy consumption of the pump increased by 8.95 kW, an increase of 21.23%. The average daily energy consumption of the chiller was 664.7 kW, a decrease of 3.15%. The indoor temperature fluctuations in various regions were stable, but the water flow in the main pipe fluctuated significantly.

4.1.3. Extremely high chilled water supply temperature

As the supply chilled water temperature was reset, the delta-T between the supply and return water changed as well. The simulation results from increasing the chilled water supply temperature from 6 °C to 7 °C are shown in Figs. 8(c) and 9(c). The indoor temperature in each area and the main water flow rate fluctuated significantly. The weighted average delta-T of the water system decreased to 5.8 °C, a decrease of 8.24%. The average energy consumption of the pump increased to 8.85 kW, an increase of 19.95%. The average energy consumption of the chiller was 686 kW, which was slightly lower than that of the benchmark model. Although the pump energy consumption increased under warm chilled water, the chiller energy consumption decreased.

4.1.4. Undersized coils

The number of rows in the coil model was reduced in the dynamic model to reduce the cooling capacity by approximately 10%. The simulation results under this situation is shown in Figs. 8(d) and 9(d). The indoor temperature oscillated, and the water flow of the main pipe fluctuated significantly. The weighted average delta-T of the water system decreased to 5.22 °C, a decrease of 17.2%. The average energy consumption of the pump increased by 10.1 kW, at 36.36% daily. The average energy consumption per day of the chiller was 679.23 kW,

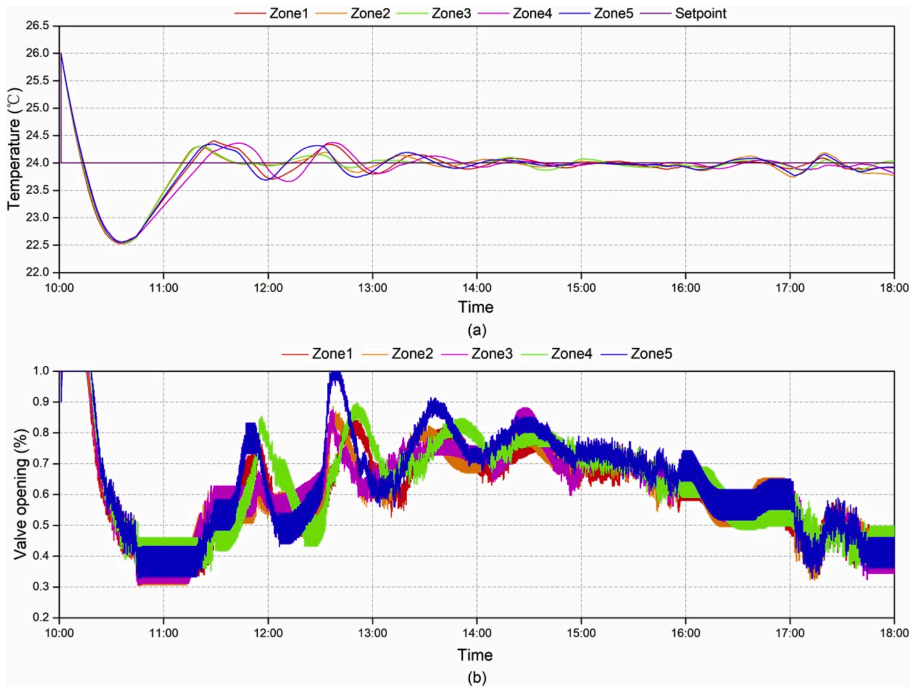

Fig. 6. (a) Temperature variation diagram (b) Valve opening variation diagram.

which was slightly lower than that of the baseline model.

4.1.5. Improper valves

As described previously, the control valve in the terminal coil affects the total delta-T of the water system. The parameters of the valve include valve authority and valve curve. Ideally, HVAC systems should use proportional valves to control flow. However, linear valves are more typical owing to their low cost. The proportional water flow characteristic of the baseline model was replaced by that of the linear valve in this simulation. The simulated results are shown in Figs. 8(e) and 9(e). The weighted average delta-T of the water system was 6.12 °C, with a decrease of 2.8%. The pump average energy consumption per day was 7.4 kW, which was consistent with that of the baseline model. The average energy consumption of the chiller was 685.1 kW, which was slightly higher than that of the baseline model.

4.1.6. Poor valve authority

The valve authority of all valves in the reference model changed from 0.5 to 0.1, and the simulation results are shown in Figs. 8(f) and 9(f). The indoor temperature of each room fluctuated, and the room was extremely cold for the occupants. The weighted average delta-T of the water system decreased to 4.87 °C, a decrease of approximately 22.69%. The pump average energy consumption per day was 10.93 kW, which was 32.48% higher than that of the baseline model. The average energy consumption of the cold machine increased to 735.01 kW, an increase of 7%.

Although the energy consumption of the pump did not increase significantly, the room temperature was extremely low. In addition, the total delta-T differed from that of other faults. The total delta-T of the system under a partial load was lower than that under a high load, as shown in Fig. 8(f). This was because the water valve was adjusted to a small opening value under a partial load, and the water valve could not be adjusted accurately to the required valve position at a small opening value because the passing water flow rate was extremely large.

4.2. Causes related to hydronic system design and construction

4.2.1. Unbalanced loops

The hydraulic balance problem is difficult to solve for water systems. This simulation resets the coefficient of the partial balance valve of the hydraulic system and adjusts the ideal hydraulic state under the design condition of the reference model to the state of hydraulic imbalance. As is shown in Figs. 10(a) and 11(a), over time, the indoor temperature in each room stabilized, and the fluctuations in the total water flow rate increased and became unstable. The weighted average delta-T of the water system decreased to 6.28 °C. The average energy consumption of the pump was 7.46 kW, an increase of 1%. The average energy consumption of the chiller increased to 686.6 kW a day, which was consistent with that of the baseline model.

4.2.2. Oversized pumps

Engineers tend to oversize the pumps with a safety factor. Consequently, the pressure head and flow rate of the pumps become extremely large. In the simulation, the pump was increased by a factor of 1.5 compared with that in the reference model. The simulation results are shown in Figs. 10(b) and 11(b). As shown, the indoor temperature fluctuations and the total water flow fluctuations of the respective regions increased slightly. The weighted average delta-T of the water system decreased to 6.27 °C. The average energy consumption of the pump during the day was 7.57 kW, an increase of 2.53%. The average energy consumption of the chiller increased to 686.6 kW in one day. Because the variable frequency water pump can adjust the rotational speed according to the control pressure difference, the trend of the water pump valve opening degree is the same as that in the reference model.

4.3. Causes related to local controls

4.3.1. Valve control failure

In many cases, the terminal's valve is often beyond control. We simulated two situations, in which two terminals were stuck in full opening and full closing. In addition, we simulated cases where all terminals were stuck in full opening and the valve opening was 0.5.

When the valves of all fan coil units were always fully open, the

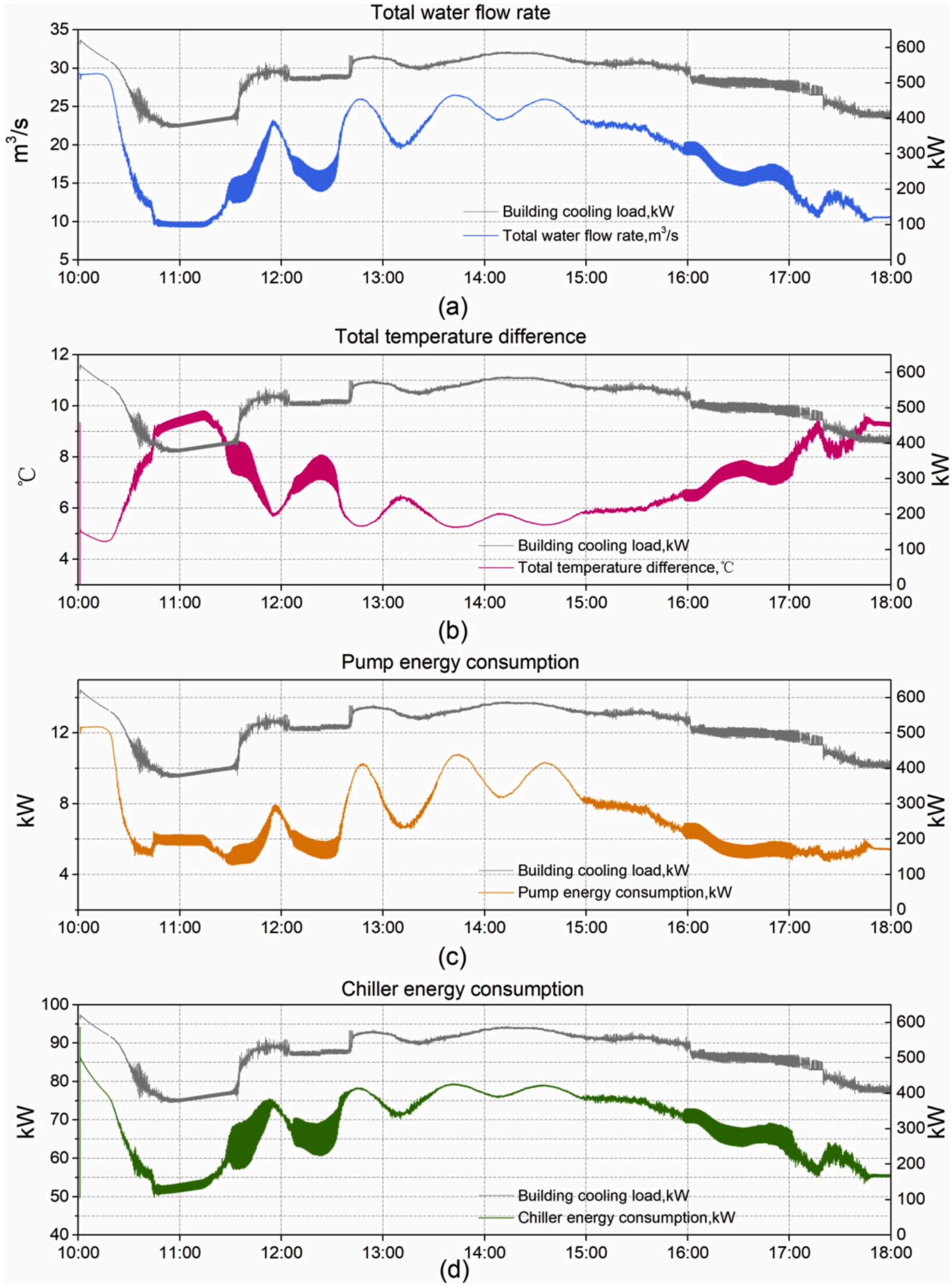

Fig. 7. Chilled water system parameter chart.

indoor temperature fluctuations in the zones increased and the zones' cooling capacity was extremely large. The weighted average delta-T of the water system was 4.51 °C, a decrease of 28.5%. The average energy consumption of the pump was 12.32 kW, an increase of 66.9%. The average energy consumption of the refrigerator increased to 743.44 kW, an increase of 8.32%. As shown in Fig. 12(c), the average delta-T under a partial load was slightly smaller than those at medium and high loads.

When the valves' opening degree of all fan coil units was set to 0.5, the indoor temperature fluctuations in the zones increased, the fluctuation of the total water volume increased, and the cooling capacity in the room was insufficient, as shown in Figs. 12(d) and 13(d). Because the valves could not be adjusted in this situation, the weighted average delta-T of the water system increased to 8.49 °C.

When the valves of some terminals were always fully open, the indoor temperature fluctuations in the area increased, and the fluctuation of the total water volume increased. The weighted average delta-T of the water system was 6.22 °C, which was a slight decrease. The average energy consumption of the pumps and chiller was 7.41 kW and 687.2 kW, respectively, which increased slightly.

When the valves of some terminals were closed, the indoor temperature fluctuations in the area were the same as those of the baseline model. However, the fluctuation of the total water volume increased. The weighted average delta-T of the water system was 6.29 °C, which was consistent with that of the baseline model. The average energy consumption of the pump was 7.36 kW, which was a slight decrease. The average energy consumption of the refrigerator decreased to 674.3 kW, a decrease of 1.75%. It was clear that some of the valves that were stuck at a small opening imposed little effect on the average delta-T of the water system.

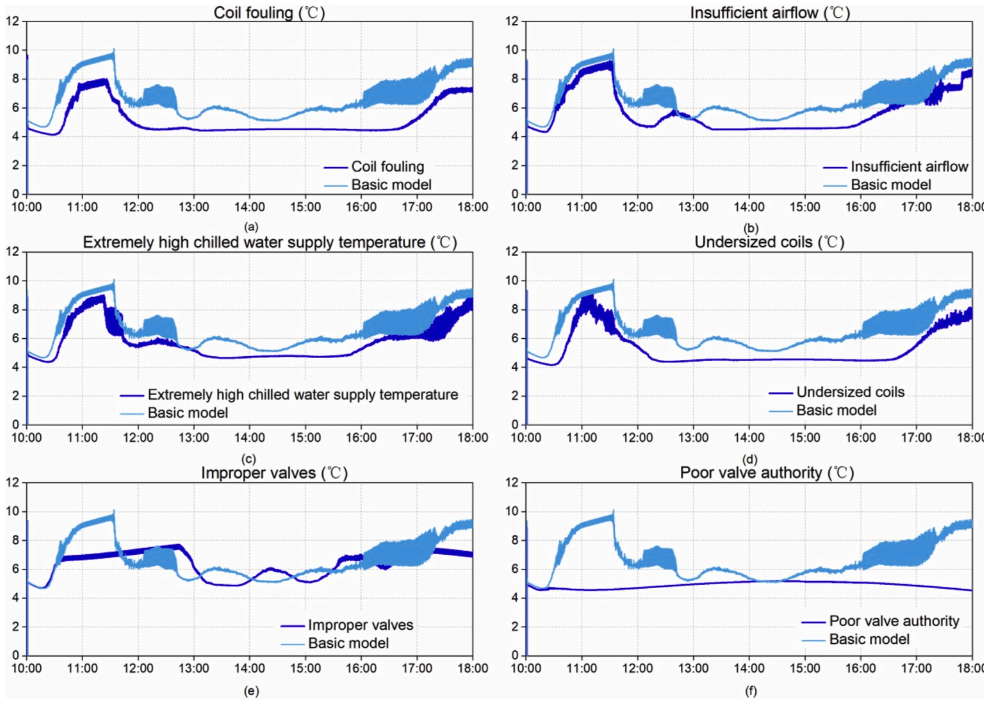

Fig. 8. Comparison of weighted delta-T under different faults
(a) Coil fouling (b) Insufficient airflow (c) Extremely high chilled water supply temperature
(d) Undersized coils (e) Improper valves (f) Poor valve authority.

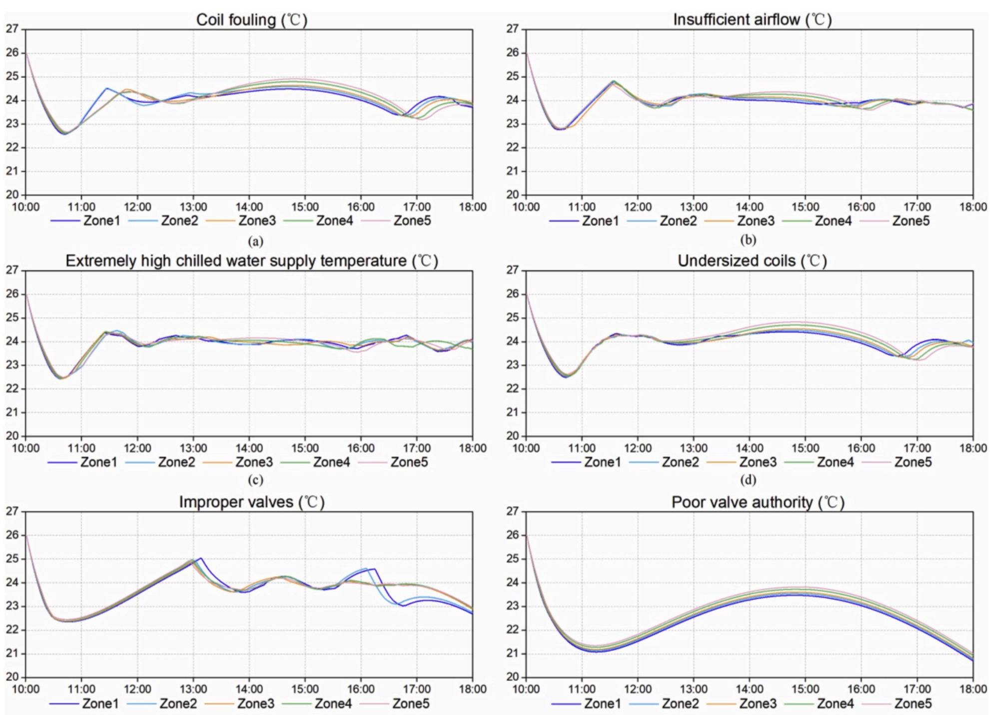

Fig. 9. Temperature fluctuation diagram of zones 1–5
(a) Coil fouling (b) Insufficient airflow (c) Extremely high chilled water supply temperature
(d) Undersized coils (e) Improper valves (f) Poor valve authority.

4.3.2. Pump control failure

Variable frequency pumps often operate at a fixed frequency or at several frequency positions. This simulation canceled the frequency control of the variable frequency water pump, and the frequency was set to 50 Hz. The simulation results of the water system are shown in Figs. 12(e) and 13(e). The indoor temperature fluctuations in the zones increased, and the valve's opening degree was smaller than that of the reference model for a long time. The weighted average delta-T of the

Table 3
Effect of different number of terminals' fouling on various parameters of water system.

Number of fouling coils	System weighted delta-T (°C)	Chiller energy consumption (kW)	Pump energy consumption (kW)	Pump energy efficiency (%)
0	6.30	686.31	7.38	65.14
1	6.22	686.23	7.51	53.41
5	5.88	685.40	7.95	55.00
10	5.54	683.72	8.55	56.00
25	4.85	678.40	10.21	57.91

water system was 6.17 °C, a decrease of 2.18%. However, the average energy consumption of the pump for one day was 11.64 kW, an increase of 57.69%. The average energy consumption per day of the chiller increased to 685.38 kW, which was consistent with that of the baseline model.

4.3.3. Extremely high pump pressure difference setpoint

The setpoint of the pressure difference for the pump control is often extremely high in many buildings. The pressure setpoint of the reference model was increased by 1.5 times in this simulation, and the results are shown in Figs. 12(f) and 13(f). The indoor temperature fluctuations in the zones increased slightly, the fluctuation of the total water volume increased, and the valve opening degree was smaller than that of the reference model for a long time. The weighted average delta-T of the water system was 6.22 °C, a decrease of 1.38%. The average energy consumption of the pump during the day was 8.47 kW, an increase of 14.76%. The average daily energy consumption of the chiller increased slightly.

4.3.4. Improper PID parameter setting

Tuning the PID parameters is crucial for the operation of the water system. A poor PID parameter setting often causes overshoots, and the room temperature may be extremely low or the air volume may be insufficient. In this simulation, the proportional coefficient in the PID controller corresponding to the reference model supply air temperature setpoint was increased by 1.5 times, and the simulation result is shown in Fig. 14. The indoor temperature fluctuations in the zones were the same as that of the baseline model. The weighted average delta-T of the water system was 6.28 °C, with a slight decrease. The average energy consumption of the pumps and chiller was the same as that of the baseline model.

4.4. Results summary

The effects of different causes are summarized in Table 4. From the simulation results, we can see that problems related to terminals, hydronic system design and local controls all have effects on the appearance of low delta-T syndrome to varying degrees. Fouling, small valve authority and all valves keep fully open are three major causes for severe low delta-T syndrome. For problems related to hydronic system design, because the variable frequency water pump could be adjusted according to the control pressure difference, the low delta-T syndrome in this simulation is not severe. Only in the case that all valves keep opening at 0.5, cooling capacity is insufficient, valves could not be adjusted and the weighted average delta-T of the water system increased. In addition, the simulated cases of low delta-T syndrome all increased the pump energy consumption to varying degrees. Since the simulation was based on only a single chiller, the low delta-T syndrome caused a decrease of the chiller energy consumption and the total energy consumption in some cases. For cases of small valve authority and all valves keep fully open, the total energy consumption increased a lot. It is noteworthy that the poor

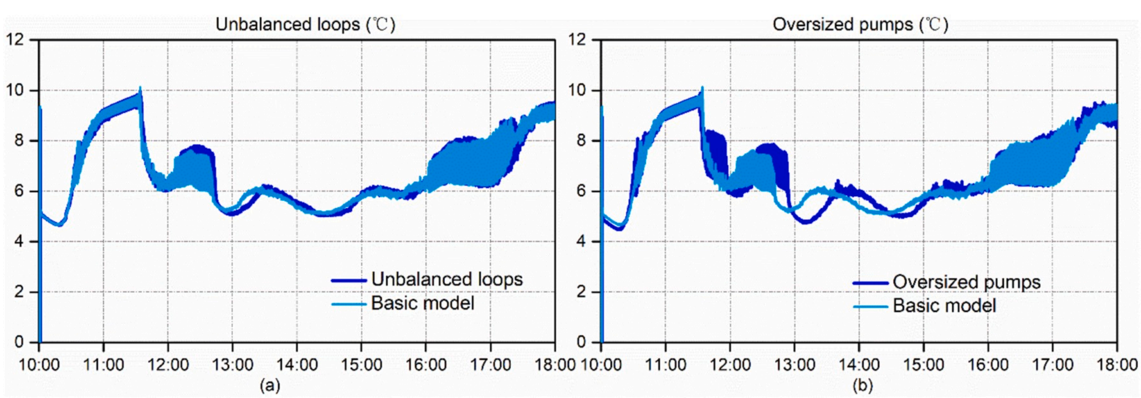

Fig. 10. Comparison of total delta-T under different faults(a) Unbalanced loops (b) Oversized pumps.

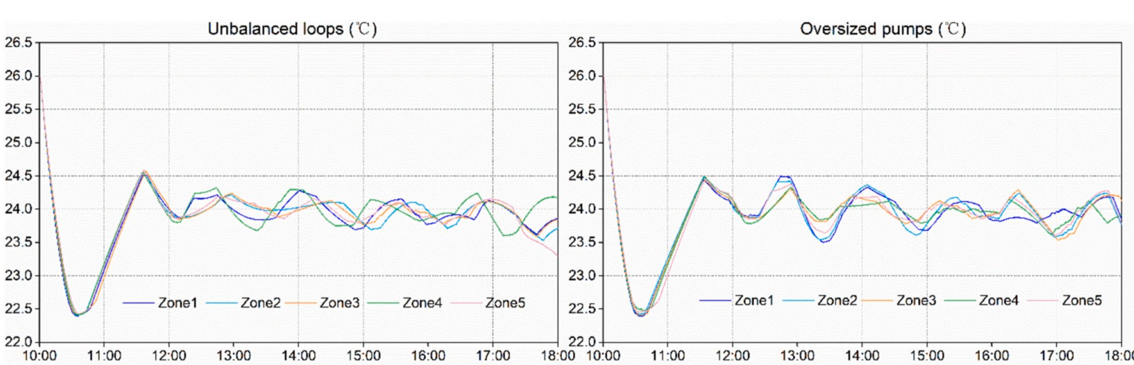

Fig. 11. Temperature fluctuation diagram of zones 1–5(a) Unbalanced loops (b) Oversized pumps.

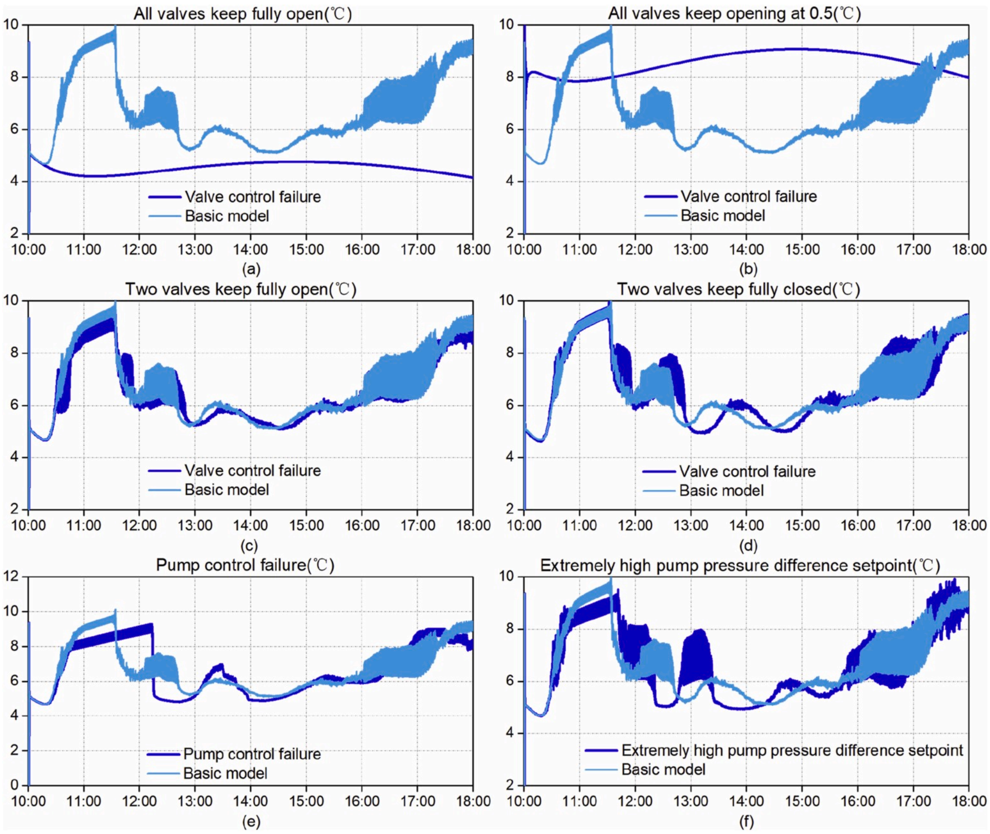

Fig. 12. Comparison of total delta-T under different faults
(a) All valves keep fully opened (b) All valves keep opening at 0.5
(c) Two valves keep fully opened (d) Two valves keep fully closed
(e) Pump control failure (f) Extremely high pump pressure difference setpoint.

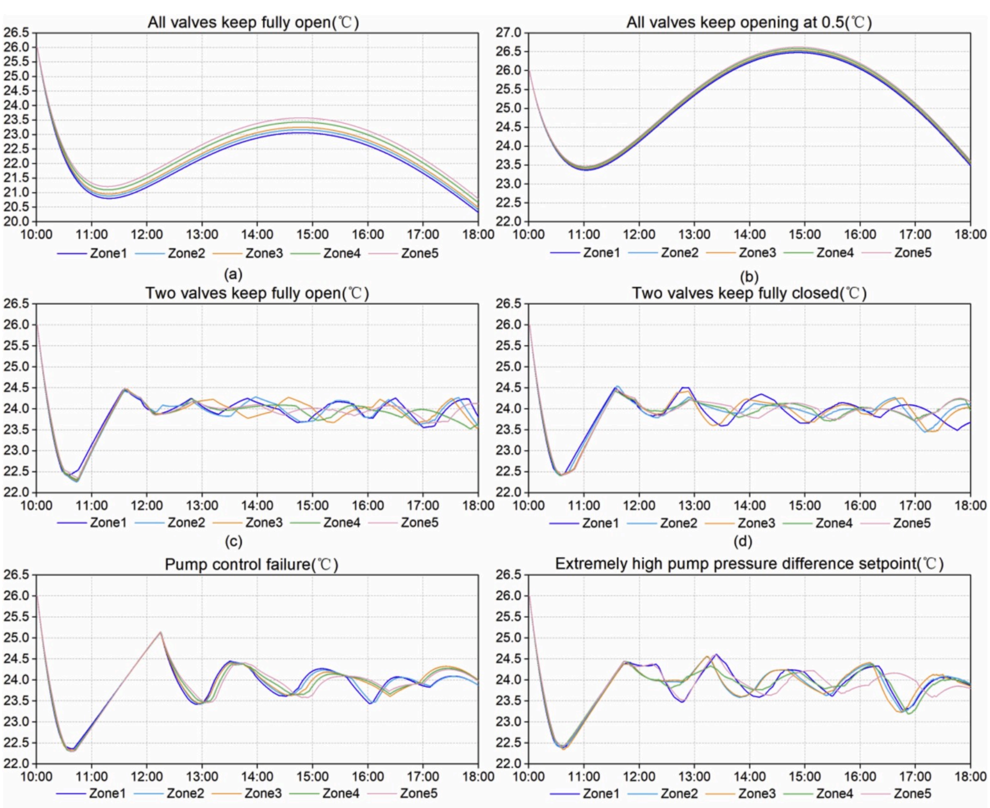

Fig. 13. Temperature fluctuation diagram of zones 1–5
(a) All valves keep fully open (b) All valves keep opening at 0.5
(c) Two valves keep fully open (d) Two valves keep fully closed
(e) Pump control failure (f) Extremely high pump pressure difference setpoint.

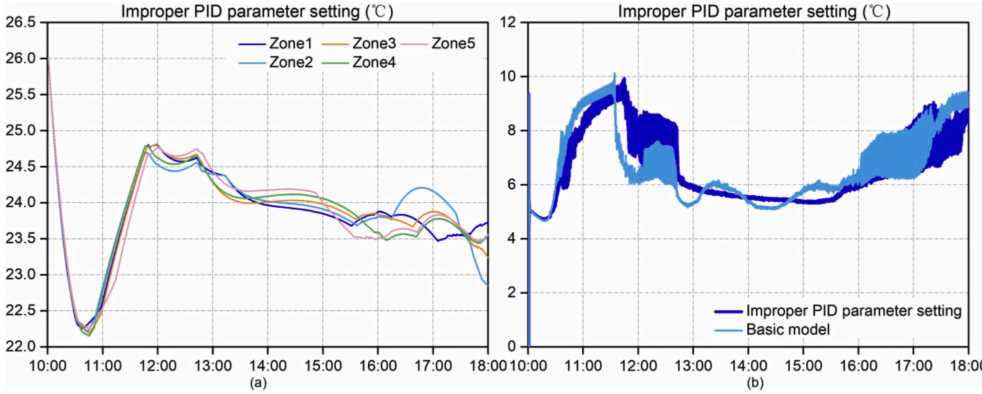

Fig. 14. Improper PID parameter setting
(a) Indoor temperature fluctuation (b) Total system delta-T.

Table 4
Quantitative effects for different causes of low delta-T syndrome.

Causes		System weighted delta-T		Chiller energy consumption		Pump energy consumption		Total energy consumption	
		Deviation (%)	Direction	Deviation (%)	Direction	Deviation (%)	Direction	Deviation (%)	Direction
Related to terminals	Basic model	–	–	–	–	–	–	–	–
	Fouling	23.02	↓	1.15	↓	38.35	↑	0.73	–
	Insufficient airflow	16.03	↓	3.15	↓	21.27	↑	2.89	↓
	Undersized coil	17.14	↓	1.03	↓	36.45	↑	0.63	–
	High chilled water supply temperature	8.25	↓	0.02	–	19.92	↑	0.23	–
	Different valve selection	2.86	↓	0.82	–	0.27	–	0.81	–
	Small valve authority	22.70	↓	7.09	↑	48.10	↑	7.53	↑
Related to system design	Hydraulic imbalance	0.32	↓	0.04	–	1.08	↑	0.05	–
	Oversized pump	0.48	↓	0.04	–	2.57	↑	0.07	–
Related to local control	Two valves keep fully open	1.27	↓	0.22	–	0.41	–	0.22	–
	Two valves keep fully closed	0.16	–	1.75	↓	0.27	–	1.73	↓
	All valves keep fully open	28.41	↓	8.32	↑	66.94	↑	8.95	↑
	All valves keep opening at 0.5	34.76	↑	5.89	↓	30.62	↓	6.15	↓
	No pump control	2.06	↓	0.14	–	57.72	↑	0.48	–
	High pump control pressure difference setpoint	1.27	↓	0.12	–	14.76	↑	0.28	–
	PID parameter setting	0.06	–	0.36	–	0.60	–	0.35	–

authority selection and control failure of the valves are significant causes for severe low delta-T syndrome and the result of high total energy consumption.

5. Conclusions

In this paper, various causes of low delta-T syndrome are investigated and simulated from a holistic perspective. The main conclusions are as follows:

- Low delta-T syndrome is primarily caused by three types of problems at different levels. Decline of heat transfer capacity performance and poor flow regulation of valves are common problems at terminal level. Hydraulic imbalance and poor pump selection are two major causes at hydronic systems level. Inappropriate adjustment in system operation control parameters leads to failed local control.
- Simulation results successfully quantify effects of various causes at terminals and hydronic system. Fouling, small valve authority and stuck open valves are three major causes for severe low delta-T syndrome. Low delta-T syndrome is not severe if the variable frequency water pump could be adjusted according to the control pressure difference. The poor authority selection and control failure of the valves are significant causes for severe low delta-T syndrome, which leads to high total energy consumption.

The qualitatively and quantitatively study of these causes provide a reference for building maintenance staff to avoid low delta-T syndrome in design and operation period.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mingkun Dai: Methodology, Software, Data curation, Writing - original draft. **Xing Lu:** Conceptualization, Methodology, Investigation, Resources. **Peng Xu:** Methodology, Supervision, Writing - review & editing.

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