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Mathematical Explanation and Fault Diagnosis of Low Delta-T Syndrome in Building Chilled Water Systems

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Abstract: Low delta-T syndrome often occurs in building chilled water systems, which makes systems fail to operate as efficiently as originally anticipated. Extensive studies have been conducted on the subject of low delta-T syndrome with the aims of investigating the potential causes behind and the ways to keep delta-T high. This paper addresses to explain the causes of degrading delta-T from a mathematic perspective and to analyze the impacts of important operational parameters on the delta-T quantitatively. A simplified global cooling coil model representing the relationship between the total cooling load and the total water flow rate of chilled water systems is developed, which can be used to predict the system delta-T under different load distribution and system operation conditions. It is proved mathematically that the load distribution characteristic is an important factor in influencing the system delta-T of a chilled water system. This finding explains why the system delta-T is always lower than the delta-T of individual coils, particularly under low partial load conditions. A system-level fault detection and diagnosis (FDD) method is proposed for identifying the possible causes of the low delta-T problem. A case study is conducted to validate the proposed global model and FDD method in a real building.

Keywords: low delta-T syndrome; chilled water system; global cooling coil model; mathematical explanation; fault diagnosis

1. Introduction

Centralized air conditioning systems are one of the largest energy consumers in commercial buildings [1]. Primary-only and primary-secondary are two typical types of chilled water systems, which are commonly used in existing commercial buildings. The schematic of a typical primary-secondary chilled water system is shown in Figure 1, which consists of two chilled water loops, including a primary loop and a secondary loop. In the primary loop, each chiller is connected with a primary pump, which is usually a constant speed pump to provide constant flow through the individual chiller. In the secondary loop, variable speed pumps are usually employed to allow for variable flow rate for providing required cooling demands of air-conditioning terminals. The two chilled water loops are decoupled by a bypass/balance pipeline. Normally, the flow rate of the secondary loop should be equal to that of the primary loop under full load condition and should not be larger than that of the primary loop under part load conditions [2].

However, most primary-secondary chilled water systems in practice usually fail to operate as efficiently as anticipated due to the deficit flow problem. When the deficit flow problem occurs, the required flow rate of the secondary loop exceeds that of the primary loop and causes the supply temperature increase consequently. As a result, the water temperature difference (i.e., system delta-T) that is produced by air-conditioning terminals (such as air handling units (AHU) and fan coil units (FCU)) is lower than the design value, which is referred as the low delta-T syndrome. The deficit flow problem and low delta-T syndrome may cause a series of operational problems, such as high supply temperature, over-supplied chilled water flowrate, and the increased power consumption of secondary pumps [3,4].

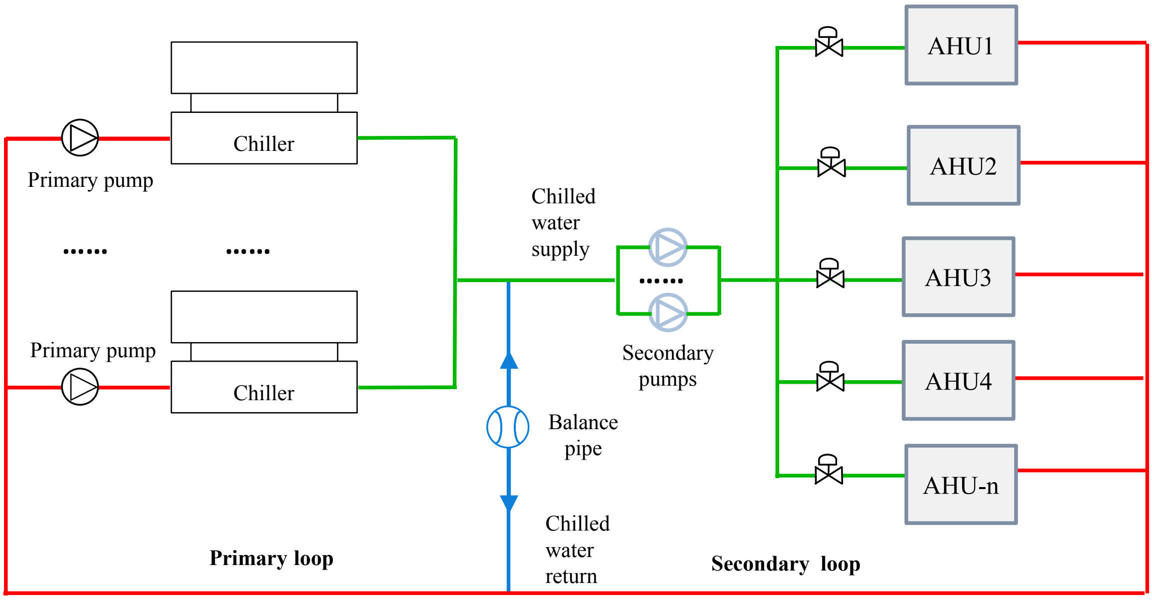

Figure 1. Schematic of a typical primary-secondary chilled water system.

Due to the significant impact of the low delta-T syndrome on building energy performance, extensive studies have been conducted in the last two decades. Many studies focused on identifying the possible reasons of the low delta-T syndrome [5–10]. For instance, Chang [5] summarized two typical types of reasons for the low delta-T syndrome as the degradation of the heat transfer performance of coils and the coupling effect among coils. The former reason is further analyzed as a result of increased coil fouling, decreased air flow rate, and high supply temperature that is caused by a deficit flow. The later one is often caused by the use of on-off controlled water valves for the terminals. When the water valves are shut down in some coils, the chilled water flow rates of the rest coils will increase, which results in lower total delta-T of the whole system. Some studies have addressed on the diagnosis of the fouling in coils and heat exchangers, which often occurs after a long time operation [2]. One of the commonly used methods to detect fouling in coils and heat exchangers is based on the analysis of the evolution of heat transfer effectiveness over time, which has been wildly employed in some recent studies [6,7]. In addition, data-driven approaches have also gained great popularity for fouling diagnosis. For instance, Jonsson [8] proposed a non-linear physical state space model in detecting fouling in heat exchangers, which can detect fouling when the heat exchanger operates in transient states. Delmotte [9] applied a fuzzy polynomial Takagi–Sugeno representation method on the detection of the fouling occurring in a counter flow heat exchanger. Lalot [10] presented that the analysis of the evolution of the modulus of the variable computed using the lock-in technique is a simple and sensitive method for fouling detection.

Taylor [11] divided the typical causes of the low delta-T syndrome as avoidable causes and unavoidable causes. Avoidable causes are the causes that might be avoided by proper design and operation, such as improper set-point, the use of three-way valves, improper coil and control valve selection, no control valve interlock, and uncontrolled load, etc. Such causes can be considered as faults. Unavoidable causes cannot be avoided, such as reduced heat transfer effectiveness due to coil fouling, outdoor air economizers, and 100% outdoor air systems, which are not faults but the results of certain operation conditions or modes. To distinguish different causes and faults of low delta-T syndrome, some researchers proposed various fault detection and diagnosis (FDD) methods. For instance, Gao [12] presents a system-level fault diagnosis strategy for detecting and diagnosing the low delta-T syndrome of a complex air-conditioning systems involving plate heat exchangers, which can help the operators to detect the low delta-T syndrome effectively and to assess the severity level quantitatively. Some methods or strategies have also been proposed to mitigate low delta-T syndrome and deficit flow problem. Fiorino [13] recommended up to 25 practical methods, such as by proper selection of components, controls systems, piping systems, and sensor calibration to achieve a high chilled water delta-T. Kirsner [14] proposed that the use of a check valve in the bypass pipeline is a cheap and a simple measure to deal with low delta-T syndrome for a primary–secondary chilled water plants. This method was experimentally validated in a real building in Hong Kong conducted by Wang [15]. Results showed that the low delta-T conditions can be reduced effectively, and about 9.2% of total energy consumption of the chillers and secondary water pumps was saved by comparing with the case when no check valve was used.

System delta-T is an effective indicator for evaluating the overall performance chilled water distribution systems because it directly relates to system energy consumption, available cooling capacity, and system stability [12]. It is important to know whether or not the system delta-T is within acceptable ranges and to what extent it deviates from the normal values. The system delta-T is an average value of the differential temperatures produced by all individual AHU or FCU terminals, which varies with the changing of total cooling load and the load of individual terminals. Low delta-T syndrome significantly limits chiller capacities and results in inadequate cooling to the served buildings. In order to alleviate such problems, some effective measures, such as installing variable frequency drives to control the pumps at proper speeds, hydraulically decoupling the chilled water systems, and installing pressure-independent control valves to eliminate water leaking, have been proposed in practices [16,17].

Although the research on the modeling and performance prediction of individual terminals has been extensive and mature, methods that can accurately predict the system delta-T are still lacking [18]. Due to the existence of coupling effect of terminals, the system delta-T cannot be obtained by simply combining the results of individual terminals [19]. This paper therefore presents a global cooling coil model to predict the system delta-T under different load distribution and system operation conditions. It can be used to explain the low delta-T syndrome from a mathematic perspective and to diagnose the possible causes of low delta-T problem in practice for primary-secondary chilled water systems.

2. Global AHU Model for System Performance Prediction

2.1. System Total Flowrate

To predict the total required chilled water flow of all the AHUs of the system under various cooling load and working conditions, a global AHU model is developed based on the energy model of an individual AHU. Previous studies [2,19] showed that the required chilled water flowrate of an individual AHU can be determined using an empirical model, as shown in Equation (1).

$$M_{indi} = M_{des,indi} \cdot \left(\frac{t_{s1} - t_{w1}}{(t_{s1} - t_{w1})_{des}} \right)^{a_1} \cdot \left(\frac{v}{v_0} \right)^{a_2} \cdot \left(\frac{Q_{indi}}{Q_{des,indi}} \right)^{a_3} \tag{1}$$

where, M_{indi} and $M_{des,indi}$ are the required chilled water flowrate of an individual AHU under actual and design working conditions, respectively. Q_{indi} and $Q_{des,indi}$ are the cooling supply (i.e., cooling load) of an individual AHU under actual and design working conditions, respectively. t_{s1} and t_{w1} are the inlet air temperature and inlet water temperature of cooling coil, respectively. v and v_0 are the actual air flowrate and design air flowrate cross cooling coils, respectively. The coefficients (i.e., a_1, a_2 and a_3) are constant, which can be determined by linear regression method using the sample data of AHUs or actual operation data obtained from the BMS (Building Management System).

According to the configurations of the chilled water system in this study, all the AHUs are assumed to be identical and connected in parallel. As shown in Figure 2, the total required water flow of the system equals to the sum of all individual water flow rate, as described in Equation (2). Using Q_{sys} to represent the total cooling load of all the AHUs in the system, Equation (2) can then be re-written as Equation (3). Replacing the last term of Equation (3) with a temporary parameter χ, Equation (3) can then be finally expressed as in Equation (4). The physical meaning and the range of χ will be discussed in detail later.

$$M_{sys} = \sum_{i=1}^{n} M_{indi} = M_{des,indi} \cdot \left(\frac{t_{s1}-t_{w1}}{(t_{s1}-t_{w1})_0}\right)^{a_1} \cdot \left(\frac{v}{v_0}\right)^{a_2} \cdot \left(\left(\frac{Q_{indi,1}}{Q_{des,indi}}\right)^{a_3} + \left(\frac{Q_{indi,2}}{Q_{des,indi}}\right)^{a_3} + \cdots \left(\frac{Q_{indi,n}}{Q_{des,indi}}\right)^{a_3}\right) \tag{2}$$

$$M_{sys} = M_{des,indi} \cdot \left(\frac{t_{s1}-t_{w1}}{(t_{s1}-t_{w1})_0}\right)^{a_1} \cdot \left(\frac{v}{v_0}\right)^{a_2} \cdot \left(\frac{Q_{sys}}{Q_{des,indi}}\right)^{a_3} \cdot \left(\left(\frac{Q_{indi,1}}{Q_{des,indi}}\right)^{a_3} + \left(\frac{Q_{indi,2}}{Q_{des,indi}}\right)^{a_3} + \cdots \left(\frac{Q_{indi,n}}{Q_{des,indi}}\right)^{a_3}\right) \tag{3}$$

$$M_{sys} = M_{des,\,indi} \cdot \left(\frac{t_{s1}-t_{w1}}{(t_{s1}-t_{w1})_0}\right)^{a_1} \cdot \left(\frac{v}{v_0}\right)^{a_2} \cdot \left(\frac{Q_{sys}}{Q_{des,indi}}\right)^{a_3} \cdot \chi \tag{4}$$

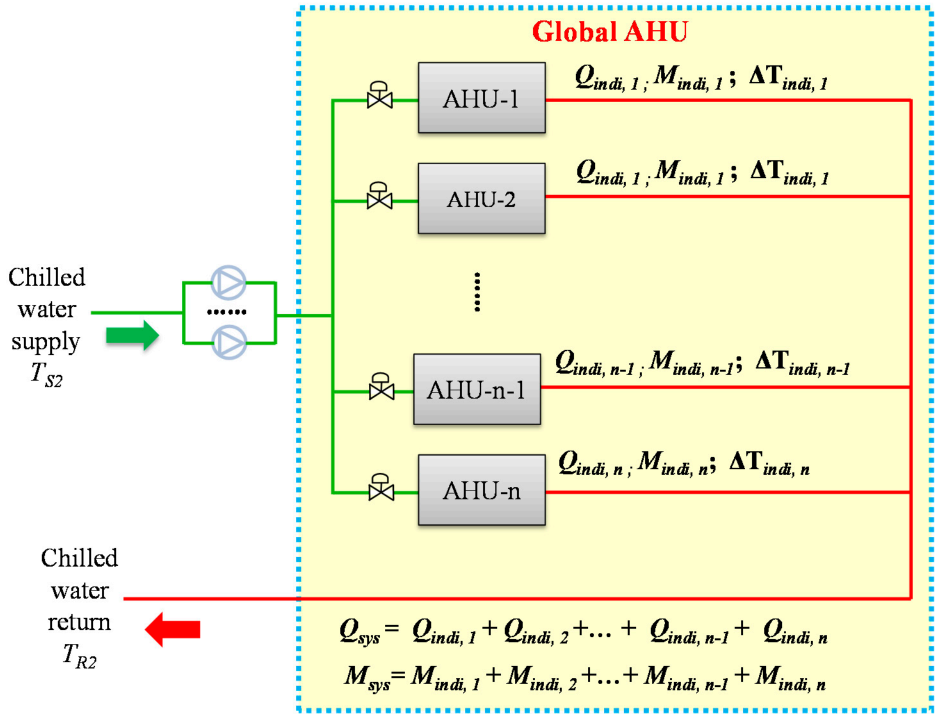

Figure 2. Scheme for development of global air handling unit (AHU) model.

2.2. System Delta-T

For cooling coils, a general relationship among cooling load, flowrate, and delta-T can be expressed in Equations (5) and (6) when it is applied to the global AHU (actual condition) and individual AHUs (design condition), respectively. Combing Equations (4)–(6), the system delta-T can be determined in Equation (7).

$$\Delta T_{sys} = \frac{Q_{sys}}{C_P M_{sys}} \tag{5}$$

$$M_{des,\,indi} = \frac{Q_{indi}}{C_P \Delta T_{des}} \tag{6}$$

$$\Delta T_{sys} = \frac{\left(\frac{Q_{sys}}{Q_{des,\,indi}}\right)^{1-a_3}}{\left(\frac{t_{s1}-t_{w1}}{(t_{s1}-t_{w1})_{des}}\right)^{a_1} \cdot \left(\frac{v}{v_0}\right)^{a_2} \cdot \chi} \Delta T_{des} \tag{7}$$

Defining the system PLR (Partial load ratio) as the ratio of system cooling load to its designed value (i.e., nQ_{des}), Equation (7) can be rewritten as in Equation (8), where β is further expressed in Equation (9).

$$\Delta T_{sys} = \frac{(\mathrm{PLR})^{1-a_3}}{\left(\frac{t_{s1}-t_{w1}}{(t_{s1}-t_{w1})_{des}}\right)^{a_1} \cdot \left(\frac{v}{v_0}\right)^{a_2} \cdot \beta} \Delta T_{des} \tag{8}$$

$$\beta = \frac{\chi}{n^{\ (1-a_3)}} = n^{\ (a_3-1)} \left(\left(\frac{Q_{indi,1}}{Q_{\mathrm{sys}}}\right)^{a_3} + \left(\frac{Q_{indi,2}}{Q_{\mathrm{sys}}}\right)^{a_3} + \cdots \left(\frac{Q_{indi,n}}{Q_{\mathrm{sys}}}\right)^{a_3} \right) \tag{9}$$

Equation (8) shows that the actual delta-T of a chilled water system is not only affected by the partial load conditions (PLR) and working conditions, but also affected by the load distribution among individual terminals (coupling effect), representing by the value of β.

2.3. Coupling Effect of Terminals

The value of β can be calculated in Equation (9) when the cooling load of each individual AHU is given. However, in practice, it is usually encountered that the load of some or even most of the individual AHUs cannot be provided. In such cases, only the range of β can be determined by considering the possible combinations of load distribution, which can be transformed as a typical nonlinear programming problem, as following:

$$\begin{cases} Min\, \mathrm{f}(\chi) \le \beta \le Max\, \mathrm{f}(\chi) \\ \mathrm{f}(\chi) = n^{\ (a_3-1)} \cdot [x_1{}^{a_3} + x_2{}^{a_3} + \cdots x_n{}^{a_3}] \\ \text{subject to :} \quad x_1 + x_2 + \cdots x_n = 1 \\ \qquad 0 \le x_1,\ x_2,\ \cdots x_n \le x_{\max} \\ \qquad\quad a_3 > 1 \end{cases} \tag{10}$$

where,

$$x_1 = \frac{Q_{indi,1}}{Q_{sys}},\ x_2 = \frac{Q_{indi,2}}{Q_{sys}},\ \cdots,\ x_n = \frac{Q_{indi,n}}{Q_{sys}},\ x_{\max} = \frac{Q_{des}}{Q_{sys}} \tag{11}$$

The value of β is always not less than 1, which indicates that the delta-T of a chilled water system should always be lower than the delta-T of individual coils due to the coupling effect among all coils [18]. As shown in Figure 3, the lower and upper limits, as well as the most typical value of β are achieved under even distribution, concentrated distribution, and random distribution, respectively. The minimal value β_{Min} = 1 is achieved when $x_1 = x_2 = x_n = 1/n$, indicating that building cooling load is evenly distributed to each individual coils. The maximal $\beta_{\mathrm{Max}} = \mathrm{PLR}^{(1-a3)}$ is achieved when building cooling load is concentrated to few coils with full load i.e., $x_{\max}$. The most commonly encountered situation in practice is random distribution, by which building cooling load is randomly assigned to all coils. In such case, the value of β appears in a narrower range. The value of β increases as the system PLR decreases, which explains why the system delta-T is more likely to deviate from the design value, particularly under low partial load conditions.

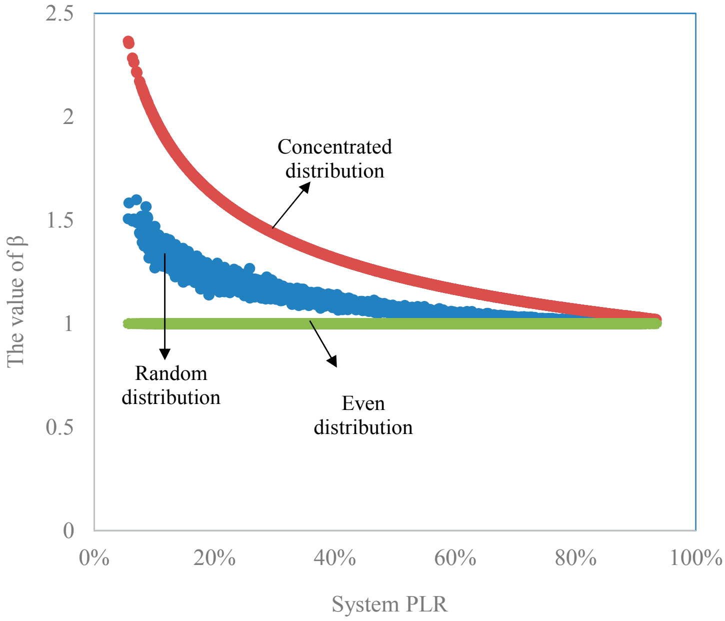

Figure 3. The value of β (coupling effect) under three types of load distribution conditions.

3. Fault Detection and Diagnosis of Low Delta-T Syndrome

3.1. Fault Detection

For detecting whether the low delta-T syndrome existed in a chilled water system, the measured temperature difference of the entire system is compared to the predicted value using Equation (8). The low delta-T syndrome can be detected if the measured system delta-T is even lower than the minimal value of predicted delta-T under random distribution after the impact of measurement uncertainties is deducted, as shown in the following inequality.

$$\Delta T_{sys\_Meas} < \mathrm{Min}(\Delta T_{sys\_pred}) - \Delta T_{uncer} \tag{12}$$

3.2. Fault Diagnosis

There are a lot of faults that can result in low delta-T syndrome, which can be classified into two categories: "heat transfer deterioration" faults and "improper water flowrate" faults. "Heat transfer deterioration" faults cause low system delta-T by deteriorating the heat transfer performance of AHU coils, including coil fouling, improper selection of components, and improper control of system (such as the reduced air flowrate, increased chilled water temperature). By contrast, "improper water flowrate" faults cause low delta-T by increasing the water flowrate, including control valve malfunction, the use of three-way valves, and deficit flow in by-pass line. When different faults occur, the performance map of system delta-T are also different, which can be used to identify the faults behind. As shown in Figure 4, when the air flowrate of AHUs is reduced to 60% of the design value, the system delta-T is reduced significantly under all partial load conditions. Under ultra-low PLR conditions (e.g., PLR < 15%), the system delta-T is basically proportional to building load (i.e., system PLR), which reflects that the system almost operates with the constant (minimum) flowrate.

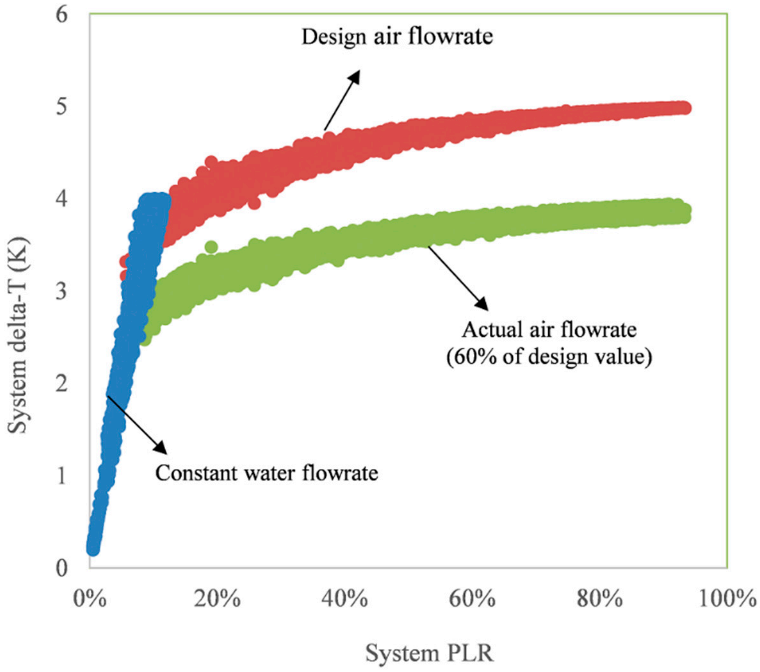

Figure 4. Performance map of system delta-T under typical faults.

4. Application Case Study in a Real Building

In this section, a case study is presented to illustrate how to apply the proposed diagnosis method to identify the potential causes of low delta-T syndrome of the centralized air-conditioning system in a real building. This building is a 12-story educational building with a basement that is located in Hong Kong. Its net floor area is 25,750 m^2 and it is mainly used for administration, teaching, research, and exhibitions. Space cooling is provided by the air-conditioning system throughout the year and the daily schedule started at 7.30 a.m. and ended at 11.00 p.m. The concerned chilled water system consists of five identical chillers, five primary chilled water pumps (constant speed), and five secondary chilled water pumps (variable speed), with a similar configuration, as shown in Figure 1. A total of 60 similar AHUs in the same series are used in the air-conditioning system to provide cooled air for indoor thermal comfortable control. As provided in Table 1, a number of important operation parameters of the air-conditioning system, such as temperatures and flow rate, are monitored by the BMS, which provide sufficient data for supporting the implementation and validation of the developed method. As shown in Figure 5, all of the coefficients for describing the performance of individual AHUs are identified (a_1 = 1.245, a_2 = 0.64 and a_3 = 1.1896) by linear regression method using the actual operation data obtained from the BMS in three days for given AHUs [19].

Table 1. Monitored operational data from BMS for case study.

Measurement Parameters	Location	Sensors	Interval
Total water flowrate	Main return pipe	Electromagnetic flowmeter	10 min
Bypass flowrate	Balance pipe	Electromagnetic flowmeter	10 min
Return water temp (primary)	Primary main pipe	Temperature data logger	5 min
Supply water temp (primary)	Primary main pipe	Temperature data logger	5 min
Return water temp (secondary)	Secondary main pipe	Temperature data logger	5 min
Supply water temp (secondary)	Secondary main pipe	Temperature data logger	5 min

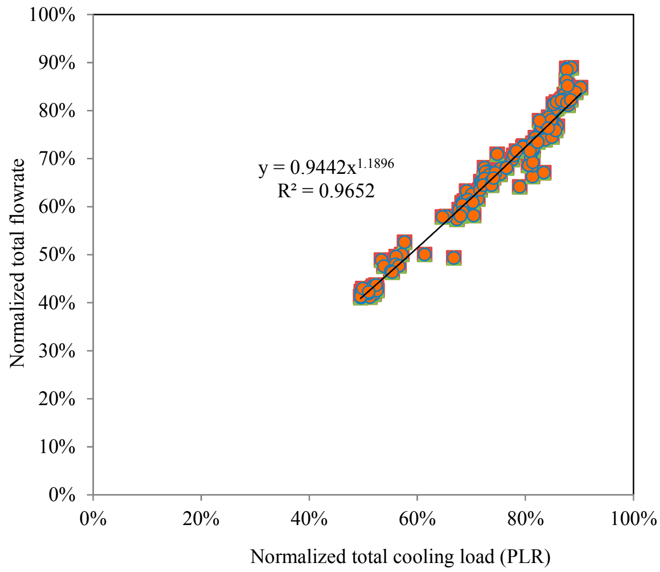

Figure 5. Parameter identification of AHU using operational data of three days.

The design delta-T of this chilled water system is 5 °C when the temperature of supply chilled water and indoor air temperature are maintained at 7 °C and 23 °C, respectively. However, some faults that cause the working conditions of the system to deviate from the design conditions may lower the system delta-T in actual operations. The system delta-T of four conditions (including fault-free and actual condition) under different part loads is presented in Figure 6. The part load ratios are based on the actual cooling load of the building, as measured by the BMS in October 2015.

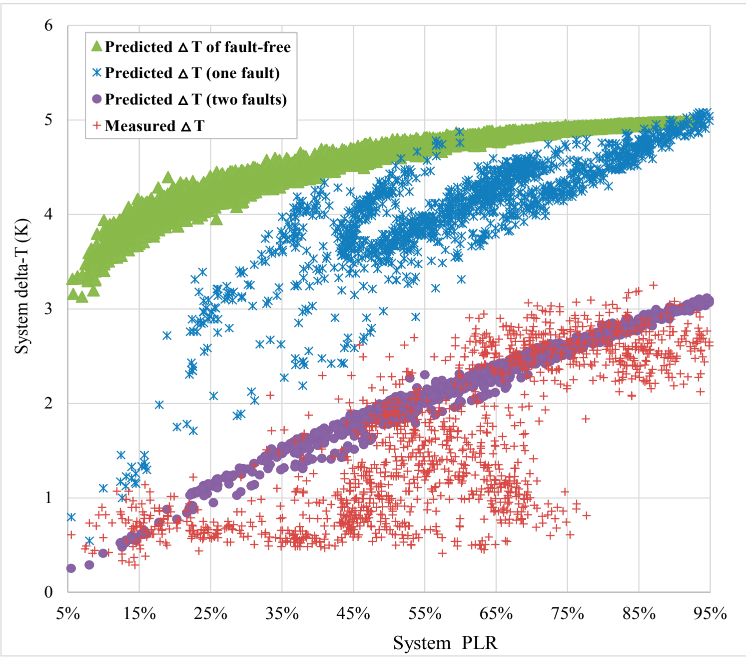

Figure 6. Predicted and measured system delta-T under part load conditions.

The predicted ΔT of fault-free is the system delta-T calculated in Equation (8) by assuming that the system is operated as intended (i.e., no fault is occurred). It can be observed that the system delta-T decreases along with the decrease of PLR. Due to the influence of load distribution among individual terminals, the value of the predicted system ΔT with the same PLR is different, which is reflected in Figure 6 as a performance band curve with a certain width. The predicted ΔT (one fault) is the calculated system delta-T by assuming that the system is operated only with one fault that the actual supply temperature of the chilled water deviate from the value of set-point. As shown in Figure 7, the measured supply temperature of the chilled water system is often higher than 7 °C, which causes the system delta-T to be lower than the value of fault-free.

However, if only such one fault occurs, then the system delta-T should appear within the data area of star-shaped (*) rather than within the data area of measured ΔT. In other words, in addition to the fault of the high supply water temperature, there should be other faults that cause the measured system delta-T (denoted with +) to be much lower than the predicted value. It can be observed that the measured system delta-T is almost always lower than 3 °C. Particularly, the delta-T is even lower than 1 °C when the PLR is lower than 45%. According to our experiences and previous studies [14,15], one of the most likely causes of such poor performance is the deficit-flow in bypass pipe. Based on the actual flowrate of the secondary loop and the bypass pipe, which are recorded by BMS and shown in Figure 8, the predicted ΔT of two faults (i.e., the fault of high supply water temperature and the fault of deficit flow occur simultaneously) is estimated. As shown in Figure 6, the predicted delta-T of two faults agrees well with the measured value, which indicates that the fault of high supply water temperature and the fault of deficit flow are the main causes of poor performance of the concerned chilled water system. By the eliminating of two such faults, the system delta-T should be increased significantly and located within the range of predicted ΔT of fault-free.

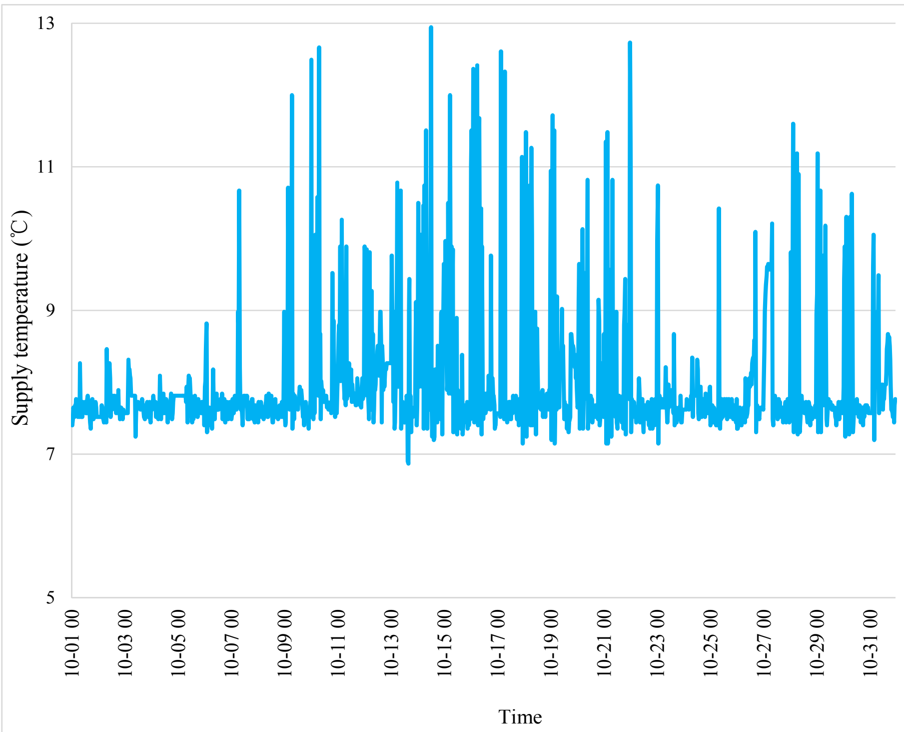

Figure 7. Actual supply temperature of the chilled water system.

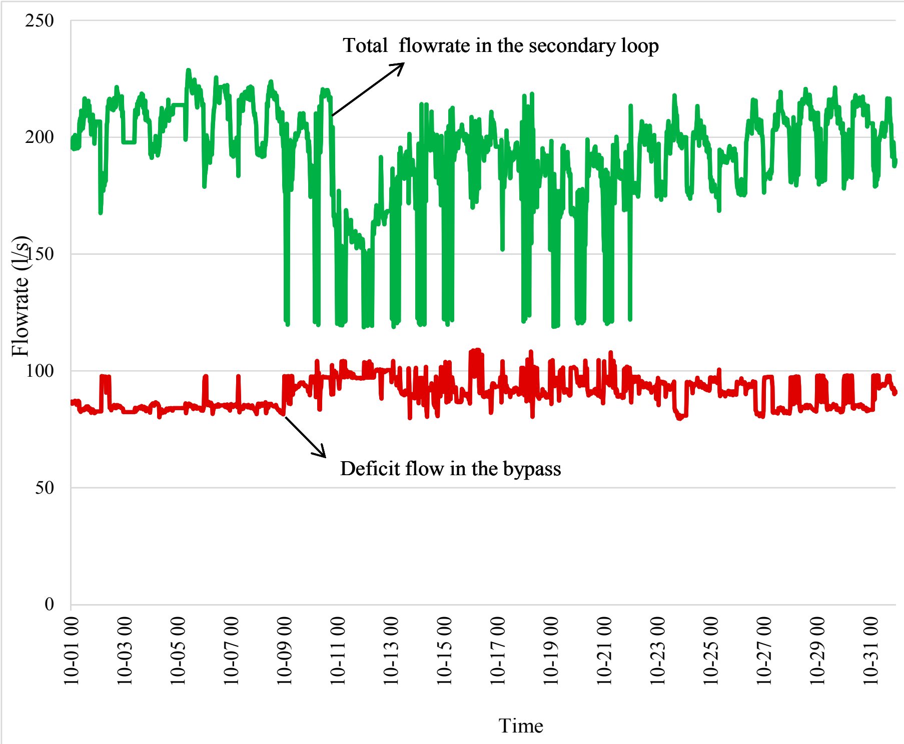

Figure 8. Actual flowrate in the secondary loop and in the bypass pipe.

5. Conclusions

This paper presents a mathematical explanation for the typical low delta-T syndrome in most building chilled water systems and proposes a fault detection and diagnosis method that is based on such an explanation. A simplified global cooling coil model is developed to predict the system delta-T under different load conditions. A case study is conducted to implement and validate the proposed FDD method in a real building. The major conclusions of this study are drawn, as follows.

- The developed global AHU model can be used to predict the system delta-T under different load distribution and system operation conditions, which provides an effective indicator to evaluate the overall performance of the entire chilled water system.
- The load distribution among individual terminals (coupling effect β) plays an important role in determining the system delta-T of a chilled water system. Under random load distribution, the system delta-T should always be lower than the delta-T of individual coils due to the coupling effect, particularly under low partial load conditions.
- The developed global AHU model and the proposed FDD method is implemented and tested in a real building, which validates that the proposed method can effectively identify the possible faults of high supply chilled water temperature and t deficit flow, by comparing the predicted ΔT of different combinations of faults with the measured data of delta-T.

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Nomenclature

AHU	air handling units
BMS	building management system
C_p	constant pressure specific heat capacity
Delta-T	water temperature difference
FDD	fault detection and diagnosis
FCU	fan coil units
M	chilled water flowrate
N	number of the AHUs
PLR	partial load ratio
Q	cooling supply
ΔT	temperature difference
t_{s1}	coil inlet air temperature
t_{w1}	coil inlet water temperature
v	actual air flow rate
v_0	design air flow rate
x	ratio to total load
χ	temporary parameter
β	coupling effect
Subscript	
indi	individual
des	design condition
sys	system
p	atmospheric pressure
means	measured value
pred	predicted value
uncer	measurement uncertainties
Superscripts	
a	constant coefficient

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