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A system-level fault detection and diagnosis method for low delta-T syndrome in the complex HVAC systems ☆

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HIGHLIGHTS

- System-level FDD method for diagnosing the low delta-T syndrome.
- The faults concerning AHUs system and heat exchangers system degradations are identified.
- Reference models are developed using less measurements points while holding high prediction accuracy.
- *t*-Statistics based adaptive thresholds are introduced to mitigate the measurement and model fitting uncertainties.
- Quantitatively evaluate the system delta-T.

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ABSTRACT

Low delta-T syndrome widely exists in the existing air-conditioning systems and results in increased energy consumption. This paper presents a system-level fault detection and diagnosis method (FDD) to detect and diagnose the low delta-T syndrome resulted from the performance degradation of AHUs system and plate heat exchanger system in a complex HVAC system. Performance indices are introduced to characterize the health status (normal or faulty) of the system. Reference models are developed to generate the benchmarks of the performance indices under fault-free conditions. In order to mitigate the impact of the model fitting uncertainty of the reference models and the measurement uncertainty of the performance indices, adaptive thresholds are adopted using *t*-statistic approach to identify the health conditions of the performance indices. The proposed method was validated in a dynamic simulation platform built based on a real complex HVAC system studied. The results show that the proposed FDD strategy can successfully detect the low delta-T syndrome, identify the related faults and quantitatively evaluate of the faults severity.

1. Introduction

Heating ventilating and air-conditioning (HVAC) systems are the major energy consumers in the commercial buildings [1]. Currently, the primary–secondary chilled water systems still dominate in the existing commercial buildings. A typical primary–secondary chilled water distribution system consists of two loops: the primary loop and the secondary loop. In the primary loop, each chiller is associated with a constant speed primary pump to ensure the constant flow through the individual chiller. In the secondary loop, variable speed pumps are employed to achieve variable flow rate according to the cooling demands of the terminal Air-Handling Units (AHUs). The two loops are decoupled by a bypass pipeline. In the high-rise commercial buildings, complex primary–secondary chilled water systems are normally employed, which utilizes multiple plate heat exchangers as the heat transfer station for delivering cooling from low floors to higher levels to avoid extremely high static pressure. Normally, the flow rate of secondary loop should be equal to that of the primary loop under full load condition and should be less than that of primary loop under part load conditions.

However, in practical applications, many primary–secondary chilled water systems do not work as efficiently as expected due to the excessive secondary flow demand, which causes deficit flow problem (i.e., the required flow rate of secondary loop exceeds that of the primary loop). When the deficit flow problem exists, the system water temperature difference (delta-T) produced by the air

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handling terminals is much lower than the design value, which is known as the low delta-T syndrome [2–4]. The deficit flow problem and low delta-T syndrome may cause a series of operational problems, such as the high supply water temperature to terminal units, the over-supplied chilled water and the increased energy consumption of the secondary pumps. Kirsner [2] pointed out that the low delta-T chilled water plant syndrome exists in almost all large chilled water systems.

The low delta-T syndrome is one of the critical operation problems degrading the building energy performance, which was frequently studied in the last two decades [5–15]. Many possible reasons of the low delta-T syndrome have been studied [6–9]. Taylor [7] summarized some typical causes that causing the low delta-T syndrome. Some causes can be avoided, such as improper set-point or controls calibration, the use of three-way valves, improper coil and control valve selection, no control valve interlock, and uncontrolled process load, etc. While some causes cannot be avoided, such as reduced coil effectiveness (e.g., fouling), outdoor air economizers and 100% outdoor air systems. Gao [9] presented a case study on diagnosing the low delta-T problem resulted from the deficit flow that frequently occurred in the chilled water system of a super high-rise building. The improper set-point of outlet water temperature on the secondary side of heat exchangers is finally diagnosed as the fault that resulted in the deficit flow and low delta-T syndrome.

Some studies focused on dealing with the low delta-T syndrome and deficit flow problem [10–15]. Among the studies, Fiorino [10] indicated strongly that a higher delta-T could be achieved by proper application of cooling coils, controls systems, distribution pumps, and piping systems. Up to 25 practical methods are recommended to achieve high chilled water delta-T ranging covering component selection, sensor calibration, and configurations of distribution systems. Gao [15] presented a fault-tolerant control strategy for secondary chilled water pump systems to mitigate the low delta-T problem. The strategy modulates the speed of the secondary pumps to ensure the water flow of secondary loop not exceed that of the primary loop while still maintaining highest possible delivery capacity of cooling to terminals. Kirsner [4] analyzed the advantage the use of check valve in the bypass line and thought that installing check valve in the bypass line is a cheap and a simple improvement to primary–secondary design of chilled water plants that allows a plant to deal with low delta-T syndrome. Wang [12] presented an approach that experimentally validated the feasibility of using a check valve in the chilled water bypass line to solve the low delta-T syndrome. Results showed that about 9.2% of total energy consumption of the chillers and secondary water pumps was saved in the test case when compared with the case when no check valve used.

The existing studies demonstrate that low delta-T syndrome widely existed in the primary–secondary chilled water system and the elimination of this problem can improve the energy efficiency of the chilled water system. Therefore, the delta-T of the overall system is an essential indicator that indicates the healthy status of the entire chilled water system. Lower system temperature difference means excessive chilled water is delivered and more energy is wasted. It is very important to monitor and diagnose whether or not the system temperature difference is in normal conditions and to what extent it deviates from the normal values. However, some challenges have to be addressed when diagnosing the system temperature difference. The system temperature difference is an average value of the differential temperatures produced by individual AHUs. The system temperature difference will vary with the changing of total cooling load and each AHU's load. Because there are no enough sensors (e.g., water flow rate, return water temperature) for individual AHUs in most of the existing HVAC systems, there would be difficult to diagnose the temperature difference of each AHU separately. Actually, in real applications, a slightly lower system delta-T is hard to be identified by the operators until it is worsened to be highly lower than the normal value (e.g., delta-T is 2–3 °C) after a long time. Therefore, it is necessary to detect and identify the lowered temperature difference as soon as possible so that less energy can be wasted. It is also import to find the causes that result in the lowered temperature difference.

Among the possible causes, the reduced effectiveness of cooling coils or/and heat exchangers is one of the major causes, which inevitably occurs after a long operating time. For instance, when the performance of the cooling coil is degraded, such as coil fouling, the heat transfer effect between the inlet air and inlet water is significantly decreased. More chilled water is required and the water temperature difference produced by the coil is decreased when handling the same cooling load. Some existing studies have paid efforts on the diagnosis of the fouling in coils and heat exchangers [16–19].

Unlike the existing studies focusing on the diagnosis of fouling in individual cooling coils or heat exchangers, this study therefore provides a system-level fault detection and diagnosis (FDD) method for detecting and quantitatively diagnosing the low delta-T syndrome in the complex HVAC system involving plate heat exchangers. This system-level FDD method pays more attention to the healthy status of the water temperature difference of the AHUs system and plate heat exchanger system as a whole, respectively. The temperature differences of both the AHUs system and heat exchanger system will be detected and evaluated quantitatively. Performance indices are also developed to identify the faults concerning the degraded AHUs and plate heat exchangers, which are the two main causes for the low delta-T syndrome.

Three major innovative works are involved in this study. First, the proposed method is based on the system-level, which is cost-effective and needs a small amount of measurement sensors when compared to the component-level method. Second, load ratios of individual AHUs are introduced as the drive variables to enhance the prediction accuracy of reference models for the water temperature difference of AHUs system, which considers the time-varying load distribution of individual AHUs with high nonlinearity. Third, adaptive thresholds are introduced to enhance the detection ratio using the *t*-statistic approach for mitigating the uncertainties from the measurements and model fittings. This method is evaluated on a simulated dynamic system constructed based on a real system in a high-rise building in Hong Kong.

Since the primary constant–secondary variable chilled water systems are still the typical configurations in the existing building HVAC systems, the FDD method presented in this paper is developed and customized based on a high rise building in Hong Kong. Therefore, this paper firstly introduces the case study building and then the method proposed. This paper is organized as follows: Section 2 gives a brief description of the studied building and HVAC system. The formulation of the FDD strategy is then introduced in Section 3. Section 4 describes the FDD method validation and discussion. The last section is the conclusion.

2. Building and system description

The central cooling system concerned in this study is a complex primary–secondary chilled water system in a super high-rise building in Hong Kong [20]. The building is about 490 m high with approximately 321,000 m^2 floor areas, consisting of a basement of four floors, a block building of six floors and a tower building of 98 floors. As shown in Fig. 1, this central chilled water plant employs six identical constant speed centrifugal chillers to provide chilled water for air handling units in the building. The rated cooling capacity and power consumption of each chiller are 7230 kW and