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A fault-tolerant control method of balancing valves for condenser fouling in water-cooled chillers

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Abstract

This paper proposes a fault tolerant control method for condenser fouling in water-cooled chillers. Condenser fouling is one of the common faults in water-cooled chillers that degrade its energy efficiency. Studies were conducted to develop fault detection and diagnostics (FDD) algorithms to address this issue. However, the current FDD techniques are too expensive for some faults that are not very significant such as condenser fouling, and a cheaper alternative may be needed to remove the fault impact. This study addresses this issue by proposing a control method without FDD algorithms to reduce the impact of condenser fouling in water-cooled chillers. It controls the opening of the balancing valve in the condensing water loop to adapt the chiller plant for the effectively smaller condenser. Verification of the control method is conducted by a model of a real chiller plant and comparison with the ordinary operation case is made under two different months and two fouling levels. The results show that the method can help the chiller plant to reduce the impact of condenser fouling by reducing its electricity consumption by 2.0% under normal situation and reducing the impact of fouling by 0.2 to 0.4%. However, the result is not very significant, and more studies with other control inputs are needed for more effective control methods.

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Keywords: Fault tolerant control; Chiller; Pump; Fouling; Energy retrofit; Fault Detection and Diagnostics

1. Introduction

Technologies related to fault detection and diagnostics (FDD) of building equipment are being investigated in recent years to increase the energy efficiency of buildings. Building equipment fault is one major reason why buildings do

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not operate as efficiently as designed. Typical building faults include undercharged chillers, fouled heat exchangers, poorly calibrated sensors, etc. [1]. FDD algorithms, which are mainly developed based on data-mining and rule-based techniques, help technicians to discover and remove these faults effectively and assist control algorithms to adjust the building controls to reduce the impact of the faults automatically [2, 3]. However, these algorithms are not economically viable to be used for some faults which impact is not very significant such as water-side condenser fouling [4, 5, 6]. This paper addresses this issue by proposing a fault-tolerant control algorithm that is tolerant to the impact of condenser fouling in water-cooled chillers without any FDD algorithms nor collection of model identification data that are typically required by FDD algorithms.

Nomenclature

ΔP	pressure drop [kPa]
ε	heat exchanger effectiveness [dimensionless]
F	fouling level [dimensionless]
m	mass flow rate [kg/s]
T	temperature [°C]
U	heat transfer coefficient [W/m^2-K]

Subscript

cond	condenser
des	design condition
in	inlet
out	outlet
r	refrigerant
w	water

2. Review of Condensing Water Loop and Condenser Fouling in Water-cooled Chillers

Condensing water loop in water-cooled chillers dissipates heat from the condenser of a chiller as shown in Fig. 1.

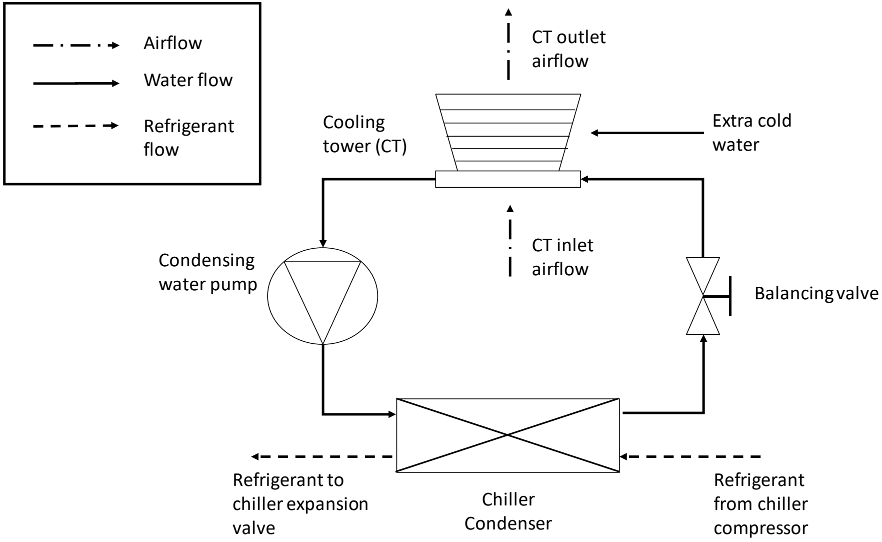

Fig. 1.Schematic of the condensing water loop of a water-cooled chiller.

Water is circulated in the loop by a pump to dissipate heat to the surroundings through the cooling tower. The opening of the balancing valve is tuned during the test and commissioning (T&C) process for a rated water flow rate in the loop and will be fixed after the T&C process. Upon fouling, dirt and contaminants accumulate at the condenser, reduce the effective size of the condenser and increase the chiller power consumption [7, 8].

To model the effect of condenser fouling, the pressure drop and heat transfer coefficient across the condenser should be changed according to the condenser fouling level as in Equations (1) and (2) [7].

$$\Delta P_{cond} = \Delta P_{cond,des}\left(\frac{m}{m_{des}(1-F)}\right)^2 \tag{1}$$

$$U_{cond} = U_{cond,des}(1-F) \tag{2}$$

3. New Fault Tolerant Control Method

The proposed control method aims at adjusting the condenser water flow rate to minimize the increase of power consumption of the chiller plant due to condenser fouling. Condenser fouling reduces the effective size of a condenser, and the condensing water pump provides too much flow to the chiller. An adjustment of the flow can shift the operating point to a new optimum where the total power consumption of the chiller plant (e.g. the chiller, the condensing water pump and the cooling tower) becomes smaller than the original scenario. In this study, a control method which changes the water flow rate by maintaining the condenser heat exchanger effectiveness at its design value is proposed. During the chiller plant operation, the heat exchanger effectiveness can be calculated according to Equation (3) [9].

$$\varepsilon_{cond} = \frac{T_{w,cond,out} - T_{w,cond,in}}{T_{r,cond,in} - T_{w,cond,in}} \tag{3}$$

To maintain the heat exchanger effectiveness at its design value, the opening of the balancing valve in Fig. 1 is controlled to change the water flow rate across the condenser. A proportional-integral (PI) controller would calculate ε_{cond} by the measured condenser temperature and change the valve opening to maintain ε_{cond} at its design condition. Since the control method does not contain any FDD algorithms, the method will be used at all times regardless of the fouling level in the condenser. Hence the success of the algorithm depends on the following two criteria:

- if the algorithm maintains the energy efficiency of the chiller plant during the normal operation;
- if the algorithm reduces the impact of condenser fouling under faulty conditions.

To examine if the method matches these criteria, the algorithm is tested in a scenario modeled by a building simulation software. Its effects on the chiller plant performance under various fouling levels are simulated and are compared with a reference case which the opening of the balancing valve is fixed at its design value. If the energy use of the building cases with the method is lower than that of the reference case, the method would be considered to be effective at tolerating condenser fouling in water-cooled chillers.

4. Test Scenario

The test scenario was conducted by modeling of a part of a chiller plant in a 490m tall building [10]. The model consists of a 7,230kW chiller, a 202kW single-speed condensing water pump, a 500mm balancing valve and two variable-speed cooling towers with a total rated fan power at 250kW. Its specification is listed in Table 1.

Table 1. Specification of the equipment in the chiller plant.

Chiller		Balancing valve		Pump		Cooling tower	
Cooling capacity	7230kW	Diameter	500mm	Rated speed	50Hz	Motor power	250kW per tower
Rated power consumption	1346kW	Range of valve opening	0.15 to 0.34	Rated pressure difference	408kPa	Rated heat rejection rate	5234kW
Refrigerant	R134a	Range of pressure drop	1.7 to 364kPa	Rated power consumption	202kW	Minimum water flow rate	125L/s
Rated condenser mass flow rate	410.6L/s	Rated pressure drop	40kPa				
Rated condenser pressure drop	108kPa	Valve opening at design	0.34				

The range of valve opening is limited so that the flow rate will not be too large to burn the motor current or too small for unreliable operation [11].

The information is used to create the model of chiller plant which consists of two parts: the pressure drop model and the thermal model.

The pressure drop determines the water mass flow rate in loop based on the pressure drop models of the pump, the balancing valve, the condenser and the rest of the condensing water loop. The pressure drop model of the pump is created based on a quadratic equation of the pressure with water mass flow rate from its specification data, and the pressure drop models of the other components are created based on basic pipe flow models and the relationship between pipe flow and their opening area [12].

The thermal model uses the water mass flow rate, the ambient condition and the cooling load of the chiller to determine the total power consumption of the chiller plant. The chiller model is a semi-empirical chiller model which models the physics of both the water and the refrigerant flow [13], the pump model comes from the Type 743 model in building simulation software TRNSYS 16 [14] and the cooling tower model is a simplified heat exchanger effectiveness model [15]. Both the pressure drop model and the thermal model are adjusted by Equation (1) and (2) for the impact of condenser fouling to the chiller plant performance.

To compare the fault tolerant control algorithm and the normal operation which the balancing valve opening is fixed, a parametric study is conducted by simulating the monthly performance of the building under the conditions in Table 2.

Table 2. Variables being changed in the parametric study.

Control method	The proposed control method and fixed valve opening
Weather and chiller load	January and July from typical weather data in Hong Kong [16] and the building management system (BMS) data of the building in 2015 [10]
Fouling level	0%, 10% and 20%

5. Results and Discussion

5.1. Comparison of control methods based on the chiller plant performance under normal operation

Simulation results show that the electricity consumption of the chiller plant under the proposed control method is lower than that of the operation with a fixed valve opening by 2.1% and 2.0% in January and July respectively. To understand the cause of the reduction, the change of the balancing valve opening on 3rd July is studied as shown in Fig. 2.

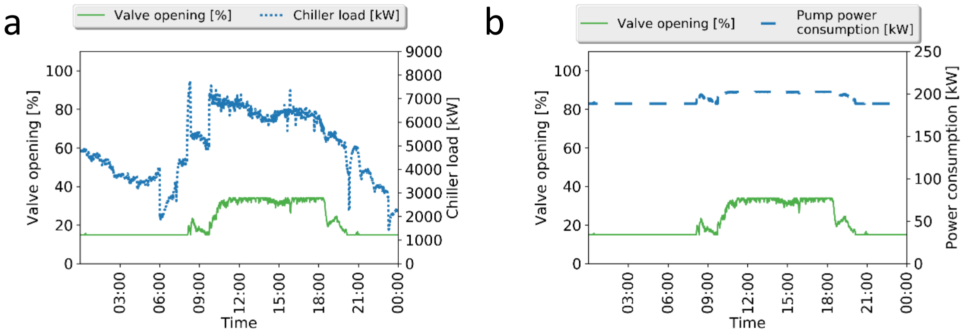

Fig. 2. Changes of balancing valve opening on 3rd July without condenser fouling using the proposed control method with (a) chiller load and (b) total power consumption of the chiller.

Fig. 2 illustrates how the valve opening changes with chiller load due to the proposed control method in Equation (3). The opening of the valve is smaller than its rated value (0.34) most of the time because the chiller load is much smaller than its rated cooling capacity (7,230kW). This results in a lower pump power consumption as shown in Fig. 2(b) in most cases and hence a lower total power consumption than the reference case with a fixed valve opening. Similar results are also found on the other days of the 2-month simulation. This shows that the control method does not deteriorate the performance of the chiller plant under normal operation.

5.2. Comparison of the control methods based on the chiller plant performance under fouling conditions

The effect of fouling to the performance of the chiller plant under different control methods and fouling levels are compared in Table 3.

Table 3. Changes of electricity consumption due to fouling for cases using different control methods.

Control methods	Month	Fouling at 10%	Fouling at 20%
Fixed valve opening	January	0.24%	0.50%
	July	0.73%	1.63%
Proposed control method	January	0.22%	0.48%
	July	0.51%	1.24%

Table 3 shows that the changes of the electricity consumption due to fouling is reduced by 0.2 to 0.4% when the proposed control method is used, showing that the proposed control makes the chiller plant more tolerant to the impact of condenser fouling.

The cause is related to the distribution of power consumption under two different control methods as shown in Table 4.

Table 4. Distribution of power consumption of different components in the condensing water loop under fouling under the design condition of the chiller plant.

Equipment	Rated condition without fouling	Fixed valve opening with 20% fouling	Proposed control method with 20% fouling
Chiller	1839.1 kW	1948.2 kW	1972.2 kW
Pump	202.5 kW	199.8 kW	187.3 kW
Cooling tower	120.2 kW	112.1 kW	82.1 kW
Overall	2161.8 kW	2260.1 kW	2241.6 kW

Table 4 shows the same trend of the component power consumption under both control methods. Upon fouling, the chiller power consumption increases and the power consumption of pump and cooling tower decreases. However, the proposed control method lowers the water flow rate further to reach an operating point where the drop of power consumption of the pump and cooling tower compensates some increase of chiller power consumption. Hence the total power consumption of the chiller plant is reduced.

6. Conclusions and future work

To conclude, this study proposes a new control method which aims at reducing the impact of condenser fouling without the use of any FDD algorithms is proposed. A simulation is conducted to examine its effectiveness, and the results show that the proposed control method reduces the chiller plant power consumption by 2.0% and reduces the impact of condenser fouling by 0.2 to 0.4%. Although the proposed control method helps the water-cooled chiller tolerate condenser fouling, the result is not very significant and more work such as the optimal control of the pump and compressor speed may be needed to make a more effective fault tolerant control.

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