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Running title: Chilled Water Systems Check Valve Efficiency

Performance Enhancement of a Complex Chilled Water System Using a Check Valve: Experimental Validation

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Abstract: The large primary-secondary chilled water systems often suffer from the excess flow demand and low chilled water temperature difference, which is known as the low ΔT central plant syndrome, during operation. This paper presents an approach for experimental validation of the possible utility of a check valve (i.e., putting a one-direction check valve in the chilled water by-pass line) to solve this operational problem and enhance the overall system performance, prior to a check valve is really installed. The experimental tests were carried out on the complex central chiller plant in a super high-rise building using a simulated check valve through fully closing one of the butterfly valves in the by-pass line when the system operated with a significant excess flow demand and experienced the low ΔT syndrome. The results from the tests showed that the system operational performance can be improved when the simulated check valve was used. Compared to that without using the check valve, about 9.2% of the total energy of the chillers and secondary water pumps was saved in the test period when the simulated check valve was used.

Keywords: *Low ΔT syndrome; excess flow demand; check valve; experimental validation; energy performance*

1. Introduction

For many years, the design of chilled water plants has been dominated by the primary-secondary configurations because such systems are simple, and engineers are familiar and experienced with them [1,2]. In addition, there are some worries on the controls intended to prevent the freezing and rupturing from happening in evaporators causing nuisance shutdowns of chillers as a result of too rapid drop of chilled water flow rate [3]. However, the majority of primary-secondary systems are hard to operate efficiently since such systems are vulnerable to suffer from the low chilled water temperature difference, which is known as the low ΔT central plant syndrome [4-9]. Kirsner [4] presented that every large chiller plant serving distributed loads is afflicted with the low ΔT syndrome to some degree. Taylor [9] described that in almost every real chiller plant, ΔT falls well short of the design levels, particularly at low loads.

When the low ΔT syndrome exists, a series of operation problems will occur, such as the inability to operate the chillers with sufficient load, excess water flow demand, increase in pump energy, and either an increase in chiller energy or a failure to meet cooling demand. Therefore, the low ΔT syndrome in primary-secondary systems is a serious problem that should be avoided or mitigated.

In the last two decades, many practitioners in the HVAC&R field have devoted considerable efforts to investigating the possible causes of the low ΔT syndrome in primary-secondary systems [8-10]. The results from these efforts showed that there are many causes that may result in low ΔT problems. The common causes include the improper coil selection, improper control valve selection, coil fouling, laminar coil flow, mismatched design conditions, improper sensor calibration, the use of three-way valves, the use of improper set-points, system pressure difference above the valve shutoff head, and the occurrence of the deficit flow, etc. The results also showed that some of causes can be avoided or mitigated through proper design, control and maintenance as well as proper selection of system components, but some of them can hardly be avoided in some applications. Taylor [9] presented that some causes, 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 loads, etc., can be avoided. However, some causes, like reduced coil effectiveness, outdoor air economizers and 100% outdoor air systems, cannot be avoided.

In order to solve the low ΔT problems and achieve energy conservation, many methods with different degrees of promise have been proposed [4,6-12]. Among them, the use of a check valve, i.e., putting a one-direction check valve in the by-pass line, has received a wide attention and open discussion [1-3,6-9,12-16]. The check valve allows the surplus flow but does not allow the deficit flow and hence, can avoid the contamination of the chilled water from chillers. The major benefit related to the use of the check valve is that an additional chiller is not brought online to provide additional primary flow before the operating chillers are fully loaded [1].

Severini [1] described that his philosophy for design and operation of primary-secondary chiller plants included using a check valve, which has been proved successfully in many projects. Bahnfleth and Peyer [3] presented a parametric study using a check valve into a primary-secondary system and found that there could be a total energy saving of up to 4% and a life cycle cost saving of up to 2% of the plant, respectively. Savings occurred only when the chilled water temperature differences were less than the design value. They also pointed out that if the secondary pumps are not capable of handling the increased head and flow in the primary loop, the use of the check valve will be an unacceptable option as a retrofit. Kirsner [6] presented that the use of a check valve is a cheap and simple improvement to the primary-secondary system. It allows a plant to efficiently deal with the low ΔT syndrome while preserving the protective features of the primary-secondary design. Avery [7] installed a check valve in a real cooling plant for system retrofits and upgrading. The actual operation results showed that as much as 20% chiller plant energy and 28% annual chiller utilization hours were reduced due to the inclusion of the check valve as compared to that without using the check valve.

Taylor [9,13] presented that the use of a check valve is recommended for fixed speed chiller plants, but not recommended for variable speed chiller plants since the efficiency of variable speed chillers is high at part-load conditions. He pointed out that a disadvantage of having a check valve is that if the primary pumps are switched off and chiller isolation valves are closed while the secondary pumps are on, the secondary pumps will be deadheaded. This can be avoided by shutting off the secondary pumps whenever all primary pumps are switched off. Several authors [8,14,15] worried that the use of the check valve will destroy the philosophy of the primary-secondary designs and designers may fell uncomfortably with forcing pumps into series operation. The application guide of McQuay [8] stated that adding a check valve effectively makes the system variable primary flow during the low ΔT intervals and the system control may become more complicated. Rishel [16] presented that the low ΔT central plant syndrome is a complicated problem that may not be fixed easily using a check valve and the check valve is not suitable for all primary-secondary systems, such as for the systems utilizing special energy storage systems or water side economizers, etc.

From above studies, it can be found that there is no universal conclusion that whether the use of a check valve is a good practice and is worthy of consideration to deal with the low ΔT syndrome in a particular primary-secondary system. It is also noted that the above studies did not provide the details how the check valve can help to deal with the low ΔT problems. This paper therefore presents an experimental approach for validating whether the check valve is feasible to effectively solve the low ΔT syndrome in primary-secondary chilled water systems, prior to the real installation of a check valve. The aim of this study is to provide some useful reference for properly using the check valve if it is considered to be adopted to deal with the low ΔT syndrome in a central chiller plant. The experimental tests were carried out on the complex central chilled water system in a super high-rise building in Hong Kong. The study has been done using a simulated check valve through fully closing one of the butterfly valves in the chilled water by-pass line when the system operated with a significant excess flow demand and experienced the low chilled water temperature differences.

2. System description and operation problems

The central chilled water plant concerned in this study is a complex system in a super high-rise building in Hong Kong. This system has been designed with the primary-secondary pumping arrangement. Fig. 1 presents the schematics of this central chilled water plant, in which six identical constant speed centrifugal chillers are used to provide cooling for building occupied zones. The designed cooling capacity and power consumption of each chiller are 7230 kW and 1270 kW respectively. Each chiller is interlocked with a constant condenser water pump and a constant primary chilled water pump. The rated water flow rate of each condenser water pump is 410.1 L/s with the design power load of 202 kW. Similarly, each primary chilled water pump has the design water flow rate of 345.0 L/s with the design power load of 126 kW.

The secondary chilled water distribution system is divided into four zones and the heat exchangers are used in Zone 1, Zone 3 and Zone 4 in order to transfer the cooling energy from the chillers to high zones to avoid chilled water pipelines and terminal units from suffering extremely high pressure. All pumps in the secondary system are equipped with variable frequency drivers except that the primary chilled water pumps dedicated to the heat exchangers in Zone 3 and Zone 4 are constant speed pumps. A more detailed description of this central chilled water plant can be found in Ref. [17].

This central chilled water plant has been put into use since the middle of 2008 (i.e., Zone 1 and Zone 2 have been occupied while Zone 3 and Zone 4 are still under construction). Its operation frequently suffered from the excess flow demand and low chilled water temperature difference. Fig. 2 and Fig. 3 present the measured cooling capacity of the operating chiller, and measured water flow rate in the by-pass line and measured chilled water temperature difference in the secondary system (i.e., namely the system temperature difference) in two consecutive winter days, respectively. It can be observed that the deficit flow existed in most day time operation while the operating chillers were far from be sufficiently loaded. As shown in Fig. 2, the actual cooling capacity of the operating chiller was significantly less than that of its design value of 7230 kW, in case of the deficit flow condition. Meanwhile, as illustrated in Fig. 3, a much lower system temperature difference was resulted due to the high water flow rate, i.e., primary flow plus deficit flow, in the secondary system. Therefore, the operation of this system experienced the low ΔT central plant syndrome resulting in inefficient operation.

3. Experimental methodology for a check valve system

In order to solve the low ΔT syndrome in this system, the possible causes, as presented earlier, were analyzed and investigated firstly. Based on the analysis and investigation, the following causes were excluded, such as coil fouling, improper sensor calibration, the use of three-way valves and the use of improper set-points. One of the possible causes would be the secondary return water mixing with the supply water from chillers, i.e., the deficit flow mixing with the primary flow.

Considering that the deficit flow is usually not good in the operation of central chilled water plants, a check valve is therefore considered to solve the low ΔT problems. As shown in Fig. 4, when the check valve is used, the chilled water distribution system behaves as it is decoupled when the primary flow exceeds the secondary flow. However, the primary and secondary pumps will be in series when the secondary flow exceeds the primary flow.

As presented earlier, the existing studies regarding to the use of check valves did not provide the details how the check valve can improve the system operational performance. To ensure sufficient degree of confidence on introducing the check valve, a test method is therefore designed and implemented to validate whether the check valve is feasible and can efficiently handle the low ΔT problems, prior to the installation of a real check valve. This test method uses a simulated check valve through fully closing one of the butterfly valves in the by-pass line when the deficit flow is observed and the system experiences the low ΔT syndrome. In order to provide the distinct difference between the systems with and without using the check valve, the test was carried out when the observed deficit flow was in the range of 40%~60% of the design flow (i.e., 345 L/s) of the primary chilled water pump. The range of 40%~60% was determined based on a long-term monitoring of the actual operation (i.e., the severity of the low ΔT syndrome, and actual building cooling demand and actual chiller cooling capacity in the low ΔT conditions, etc.) of the central chilled water plant studied. This selected range can ensure that the operating chillers have sufficient capability to provide adequate cool energy for terminal units under the given operating condition and there is no need to use an additional chiller. During the tests, the chiller control was set to manual mode and the chiller operating number was therefore maintained unchanged.

4. Results and discussion

Three repeated tests using the simulated check valve were carried out in the real building in three separate days. These three tests provided the consistent conclusions and the results presented hereafter are from the latest test carried out on 5^{th} Nov. 2009.

Fig. 5 illustrates the water flow rates in the chilled water by-pass line when the butterfly valve in the by-pass line was fully open and fully closed (i.e., using the simulated check valve) respectively. It can be found that the deficit flow existed before the simulated check valve was used. The butterfly valve was closed at 11:15am on that day and opened again at 15:15pm when the test finished. Before 13:40pm, the chilled water supply temperature set-point was set at the design value of 5.5°C and it was reset down to 5.0°C at 13:40pm. The change of the temperature set-point is to investigate whether the reduction of the temperature set-point can help to enhance the system operational performance when the chilled water plant integrated with a check valve. In the whole test period, the AHU supply air temperature set-point was set as constant of 13.0°C.

Fig. 6 shows the cool energy provided by the operating chiller (i.e., cooling capacity of the chiller) and actual measured outlet air temperature of the AHU in the typical floor before and after closing the butterfly valve in the by-pass line. It can be observed that the supply air temperature cannot be controlled at the desired set-point of 13.0°C while the operating chiller was not sufficiently loaded before the simulated check valve was used. This demonstrates that, in the low ΔT condition, the cooling provided was less than that of the cooling demanded. Once the simulated check valve was used, the operating chiller was heavily loaded and outlet air temperature of the AHU can be controlled at the intended set-point. It is worthy noticing that the response of the AHU outlet air temperature to the changes of the system from the deficit flow condition to the use of the simulated check valve was very slow and a significant time delay can be observed in Fig. 6. It is also noted that when the chilled water supply temperature set-point was reduced from 5.5°C to 5.0°C, the cool energy provided by the operating chiller increased firstly and then decreased gradually, while it is found to be reversed in terms of the outlet air temperature of the AHU, before the system reached to a relatively steady state. This illustrates that lowering down the chilled water supply temperature set-point is worth to be considered in the sequence control of chillers when a check valve is used. It is worthy noticing that the cooling capacity of the chillers illustrated in Figure 6 is not the actual building cooling load except that those supply air temperature was controlled at the desired set-point.

Fig. 7 presents the comparison of the total power consumption of chillers and secondary water pumps in the test period by using the simulated check valve with that in a similar working condition during the same time period with the deficit flow, resulting in frequent needs of an additional chiller in operation. It can be found that the energy consumption reduced significantly when the simulated check valve was used as compared to that without using the simulated check valve. The average energy saving due to the use of the simulated check valve in this particular comparison was about 9.2% of the total energy consumption of both the chillers and secondary water pumps. The savings will be significantly greater than the above mentioned value if the additional energy of a condenser water pump, a primary chilled water pumps as well as the cooling towers due to the operation of one more chiller is included.

As mentioned above, when the system operated without using the simulated check valve, if an additional chiller is put into operation, significant more energy will be consumed but cool energy provided will be adequate. On the other hand, the cool energy provided may be inadequate if an extra chiller is not used. As a result, a poor indoor thermal comfort will be caused.

The annual energy saving due to the use of the check valve in the complex system studied was estimated by comparing it to that without using the check valve. Table 1 summarizes the annual energy consumption of chillers and pumps (i.e., including constant speed pumps and variable speed pumps) as well as their total energy consumptions when the system operated in two different configurations respectively. Compared to that without using the check valve, about 317200 kWh (0.94%) total annual energy of the chiller plant (including chillers and pumps) can be saved when the system equipped with a check valve. The energy saving is mainly achieved due to the use of less number of chillers and less number of constant speed pumps. The energy consumption of cooling towers was not estimated here. Their actual energy consumption is strongly dependent on the ways used to sequence control of cooling towers, as the cooling towers are equipped with variable speed fans.

It is worthwhile to point out that the annual energy consumption of the system without using the check valve was calculated through 'calibrated simulations'. The annual energy consumption of the system with the check valve was roughly estimated based on the current frequency of the low ΔT syndrome monitored and the actual savings achieved in the test periods. It is estimated that, for the system without using the check valve, there is a total of 115 days in each year that the system will suffer from the low ΔT syndrome and result in an additional chiller and its dedicated constant water pumps in operation. The duration of the low ΔT syndrome in each day is three hours. If a check valve is used, about 211250 kWh chiller energy and 105950 kWh pump energy will be saved in above assumed low ΔT periods. The annual energy consumption of the system with the check valve presented in Table 1 is the difference between the annual energy consumption of the system without using the check valve and the energy savings resulted in the above low ΔT periods due to the use of the check valve.

The results from above tests illustrated that when the system operated with a excess water flow demand and low chilled water temperature difference, either an inadequate cool energy (without switching on an additional chiller) or an increase in energy consumption (an additional chiller is put into operation) will be resulted. However, the operating chillers cannot be loaded sufficiently. When the system equipped with a check valve, it can ensure the operating chillers to be loaded sufficiently before an additional chiller is put into operation, which can therefore enhance the overall system performance and reduce the chiller utilization hours. As presented earlier, when a check valve is used, one issue to be concerned is that the secondary water pumps should have capacity of handling the increased pressure drop and water flow in the primary loop . This is often not a big problem in practice since the design of the secondary water pumps is usually somewhat oversized.

Based on the above tests, the installation of a check valve was recommended to the building owner. The building owner has accepted the recommendation and a check valve is being considered to be installed in the concerned building.

5. Conclusion

This paper presented an approach for experimentally validating the feasibility of using a check valve in the chilled water by-pass line to deal with the low ΔT syndrome encountered in primary-secondary chilled water systems, prior to the practical installation of a real check valve. The experimental tests were carried out in a real building using a simulated check valve through fully closing the butterfly valve in the by-pass line. The results show that the check valve can help the operating chillers to be sufficiently loaded before an additional chiller is used. Compared to that without using the check valve, about 9.2% of the total energy consumption of the chillers and secondary water pumps was saved in the test period when the simulated check valve was used.

It is worthy noticing that the check valve is not feasible for every project. When a check valve is taken into consideration, other potential causes, such as improper sensor calibration, and the use of improper set-points, etc, which can be easily handled, should be corrected firstly. A well understanding of the system configuration and potential limitations is also essential. In order to increase the degree of confidence by using the check valve, the experimental validation by using the simulated check valve is worth and practical to be considered.

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Figure Captions

Fig. 1 Schematics of the central chilled water plant

Fig. 2 Measured cooling capacity of the operating chiller in two winter days

Fig. 3 Measured water flow rate in the by-pass line and temperature difference in secondary system in two winter days

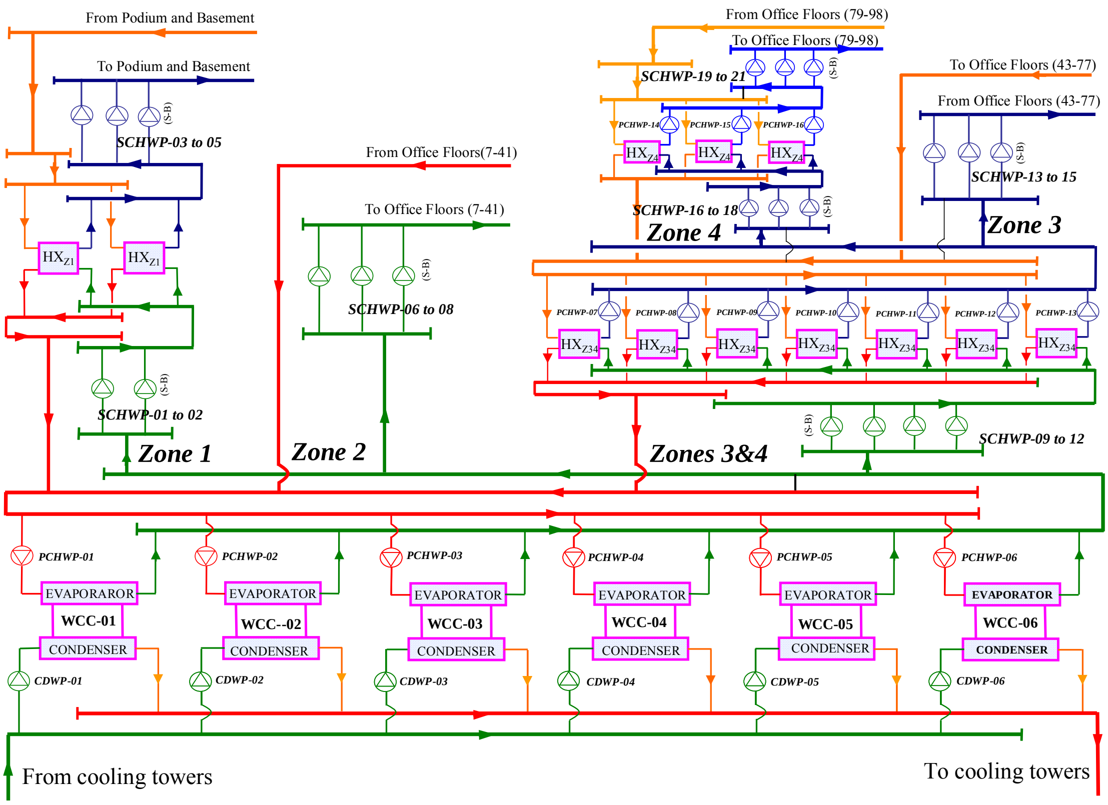
Fig. 4 Illustration of the system with a check valve

Fig. 5 Water flow rate in the by-pass line before and after using the simulated check valve

Fig. 6 Comparison of the chiller cooling capacity and AHU outlet air temperature before and after using the simulated check valve

Fig. 7 Comparison of power consumptions of chillers and secondary pumps between with and without using the simulated check valve

Table 1 Estimated annual energy saving when using a check valve



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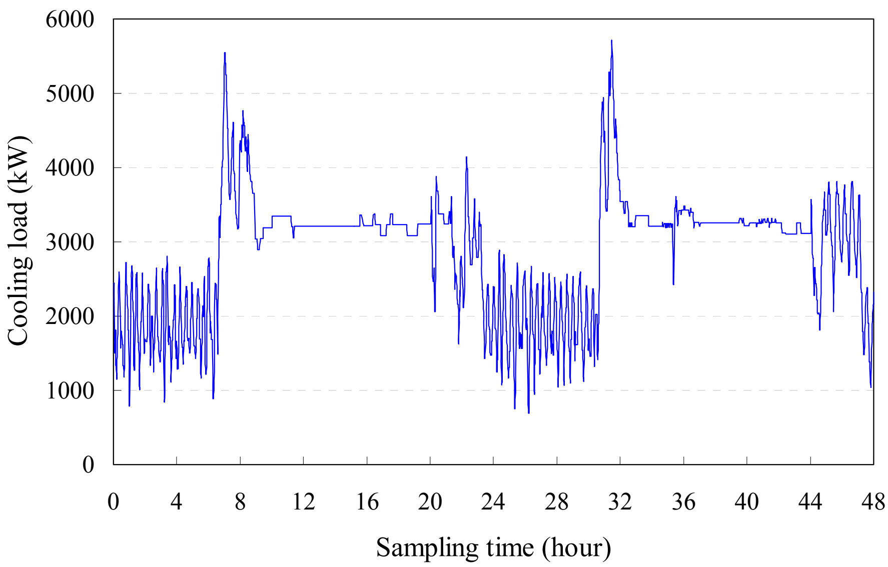

Fig. 2 Measured cooling capacity of the operating chiller in two winter days

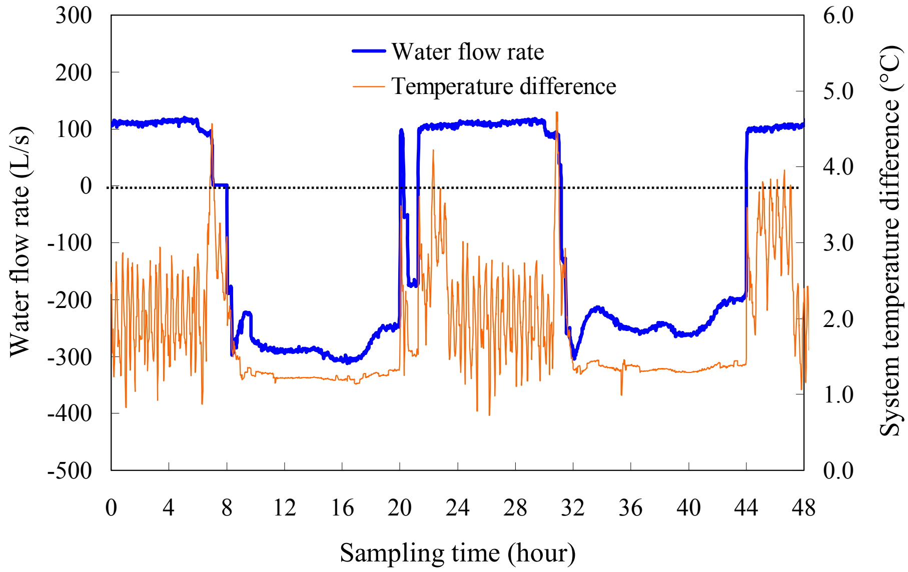

Fig. 3 Measured water flow rate in the by-pass line and temperature difference in secondary system in two winter days

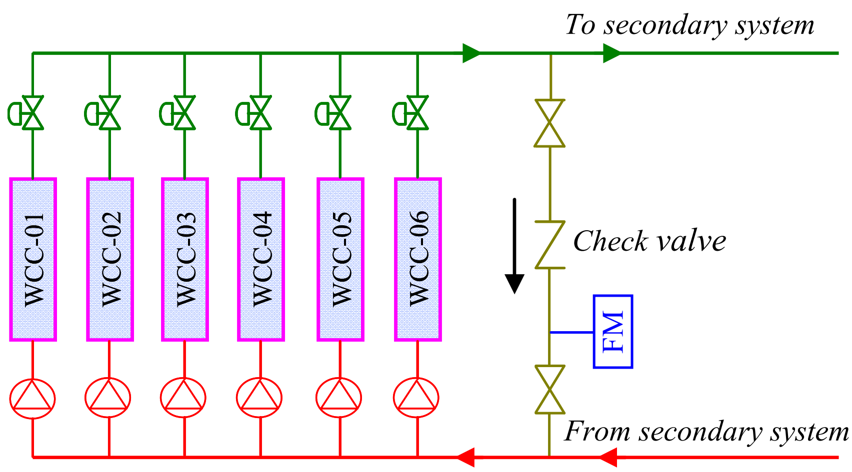

Fig. 4 Illustration of the system with a check valve

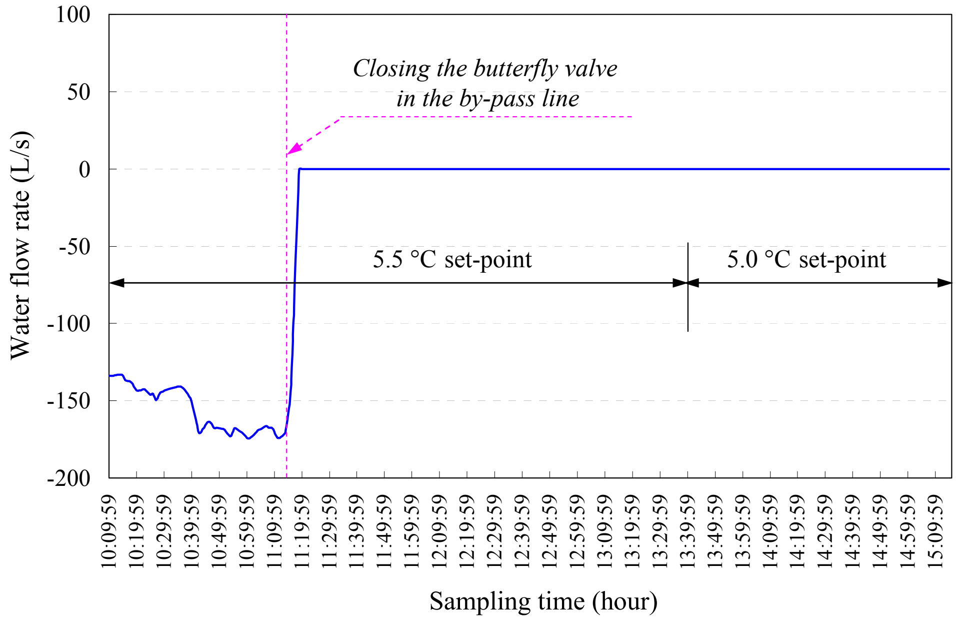

Fig. 5 Water flow rate in the by-pass line before and after using the simulated check valve

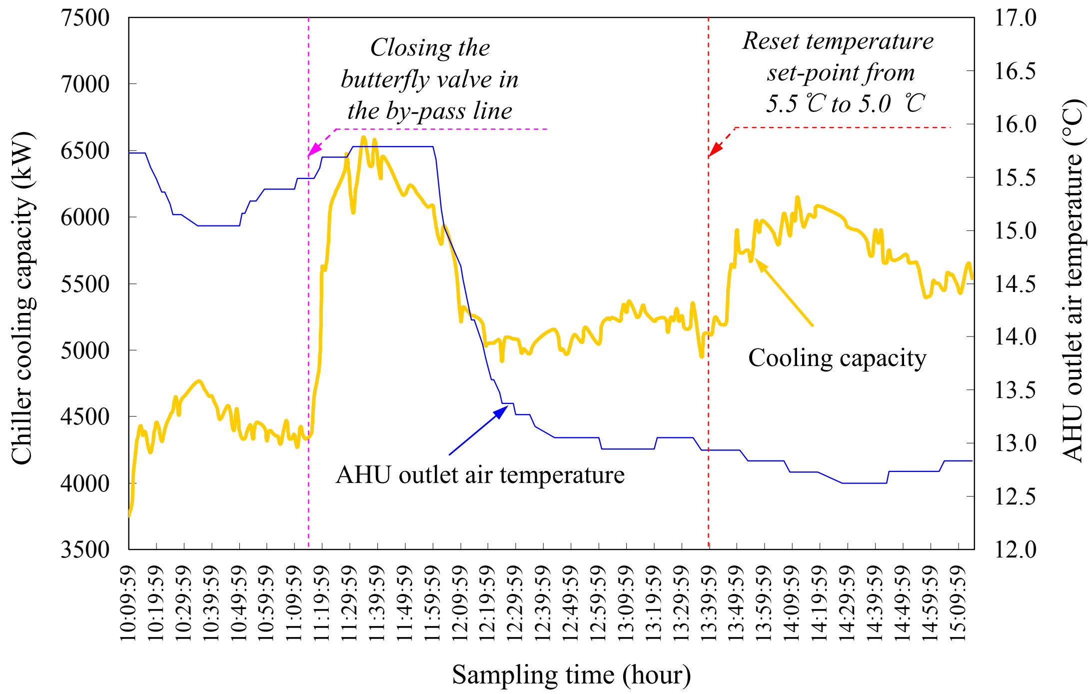

Fig. 6 Comparison of the chiller cooling capacity and AHU outlet air temperature before and after using the simulated check valve

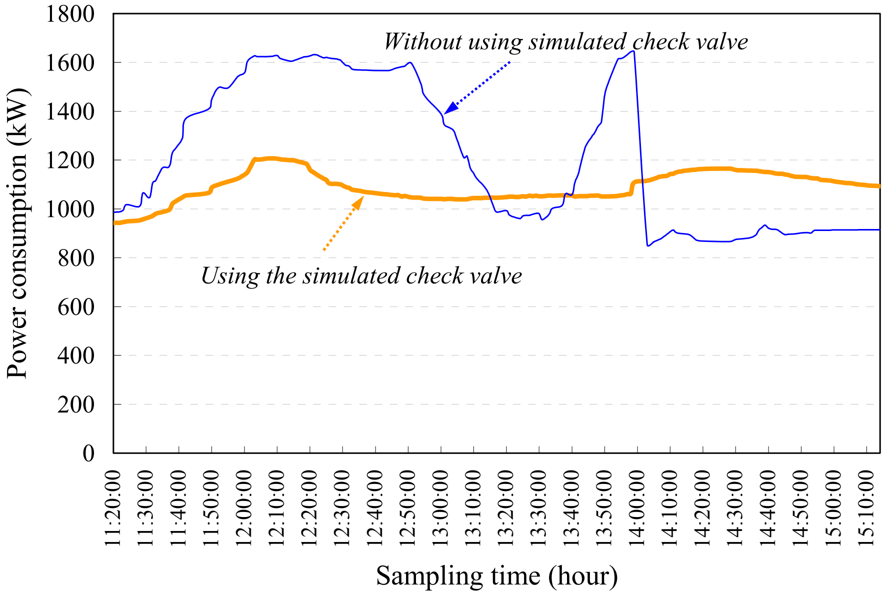

Fig. 7 Comparison of power consumptions of chillers and secondary pumps between the systems with and without using the simulated check valve

Table 1 Estimated annual energy saving when using a check valve

System configuration	Energy consumption			Energy Saving			
	Chiller	Pump	Total	Chiller	Pump	Total	
	kWh	kWh	kWh	kWh	kWh	kWh	%
Without using the check valve	24567965	9270556	33838521	-	-	-	-
With the check valve	24356715	9164606	33521321	211250	105950	317200	0.94