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Performance enhancement of air-cooled chillers with water mist: Experimental and analytical investigation

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ABSTRACT

This paper investigates how water mist evaporative pre-cooling can be applied to air-cooled chillers to improve the chiller efficiency by on-site experimental studies. There is a lack of detailed experimental studies on the application of water mist system on air-cooled chillers. The experiment was conducted on a chiller plant with water mist system in a subtropical climate. The experimental results showed that the dry bulb temperature (DBT) of entering condenser air with water mist pre-cooling could drop by up to 9.4 K from the ambient air temperature, and the approach could be as low as 0.5 K. A thermal effectiveness of up to 0.91 was obtained in using the water mist system. The pre-cooled condenser air enabled a drop of the condensing temperature by up to 7.2 K, and the chiller coefficient of performance (COP) could be improved in varying degrees by up to 18.6%. This study demonstrates that the water mist system coupled to air-cooled chillers is an energy-efficient and environment friendly technique, which has significant potential to improve the efficiency of air-cooled chillers and reduce the electricity demand for the commercial and industrial sector.

1. Introduction

Large commercial buildings in Hong Kong typically require cooling year round, and centralized water chillers are commonly used for providing space cooling. The operation of chillers accounts for about 40% of the annual total energy use in commercial buildings in a subtropical climate [1,2], which contributes considerable greenhouse gas emissions. The chiller efficiency is a matter of concern, which is subjected to influence by the heat rejection method, load ratio, external conditions and compressor efficiency. Air-cooled chiller systems are commonly used in commercial buildings due to its flexibility, the ease of installation, the simplicity of operation and maintenance, especially for the cities with water shortage problem. Compared with water-cooled chillers, air-cooled chillers are generally energy inefficient. The deficient performance of air-cooled chillers is mainly due to the traditional operation under head pressure control (HPC), whereby minimal condenser fans are staged to control the condensing temperature to float around a high set point of 50 °C. The use of HPC is due to a convention that the proper function of thermostatic expansion valves needs a high pressure differential of at least 690 kPa to control refrigerant flow properly. The use of electronic expansion valves enables the required differential pressure to be as low as 290 kPa for ensuring compressor lubrication [3]. Under such control strategies, the condenser fan power can be minimized, but the compression efficiency becomes lower and the compressor power remains high, which causes a considerable decrease in COP when the chillers operate under part load conditions. It is, therefore, desirable to increase the chiller COP through improving the operational control of their components. Some researchers have stated the opportunity to lower the condensing temperature to improve the operating efficiency of air-cooled chillers [2,4,5].

As condenser fans force ambient air to condense and slightly subcool the refrigerant, the extent of the condensing temperature drop is constrained by the dry bulb temperature (DBT) of ambient air. Evaporative cooling can pre-cool the ambient air before entering the condenser, which is effective for improving the performance of air-cooled chillers. This concept is enhanced at present in consideration of energy saving and environmental protection.

Refrigeration systems with evaporative condensers have been applied for years. For the evaporative condensers, ambient air is drawn or blown through a porous wetted surface with a film of cool water. The air stream is cooled by the evaporation of water, and its DBT drops to approach its wet bulb temperature (WBT). With

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a reduction of entering condenser air temperature, the condensing temperature is lowered, which results in a decrease of the compressor power of air-cooled chillers. However, additional fan power is required for the evaporative condenser to draw or blow air through the porous surface, which trades off the reduction of compressor power partly. Zhang et al. [6] indicated that the application of evaporative pre-coolers could improve the COP of air-cooled chillers by 14.7% under the climatic conditions of Tianjin in China. According to a simulation study [7], a 1.4–14.4% decrease in chiller power was achieved when an air-cooled reciprocating chiller with an evaporative pre-cooler operated under HPC. However, this technology has some adverse effects including the risk of mineral deposits and corrosion of the condenser coils, which will reduce the cooling efficiency with time.

An alternative for evaporative condenser is to install a water mist system to pre-cool the air entering condensers. The water mist pre-cooling system is not a new concept, and it has been applied successfully in the industries [8–10]. However, the application of water mist pre-cooling associated with a chiller system is uncommon. The water mist system has advantage over the evaporative condenser because, firstly, it has no additional air pressure loss through the wetted media and hence no additional fan power will be incurred. Although the water mist pump will operate to deliver water at a high pressure of around 70 bars, the water flow rates are very low and hence a small amount of power to drive the high pressure pumps is the only additional power to be considered. Secondly, it is simple and convenient to install a mist system, which is advantageous in retrofitting for the existing hundreds of thousands of air-cooled chillers. Due to the remarkable advantage of water mist system, it is expected to be widely applied. Yu and Chan [11] studied the application of water mist system by simulation. There is a lack of field investigations on air-cooled chillers with water mist system. This paper aims to conduct an experimental study on the energy performance of air-cooled chillers with water mist pre-cooling system via on-site measurement under various operating conditions. The enhancement of chiller COP with water mist system is evaluated, which is necessary for developing and designing more efficient systems.

2. Water mist system

Fig. 1 illustrates a schematic of a typical water mist system, which comprises of a high pressure pump, a filter unit, atomization nozzles, high pressure and low pressure tubing. The high pressure pump can operate to deliver water at a high pressure of around 70 bars, and the water is forced through micro nozzles at very high pressure to create a water mist of 10 micron sized droplets. When the tiny water droplets are sprayed into the atmosphere, they quickly absorb the heat in the environment and evaporate, and then the air temperature decrease due to evaporative cooling effect. When the water mist system is coupled to an air-cooled chiller, the temperature of the entering condenser air will drop, which results in lowering the condensing temperature and pressure. With the decrease of the condensing pressure, the compressor power is reduced and the chiller performance is improved.

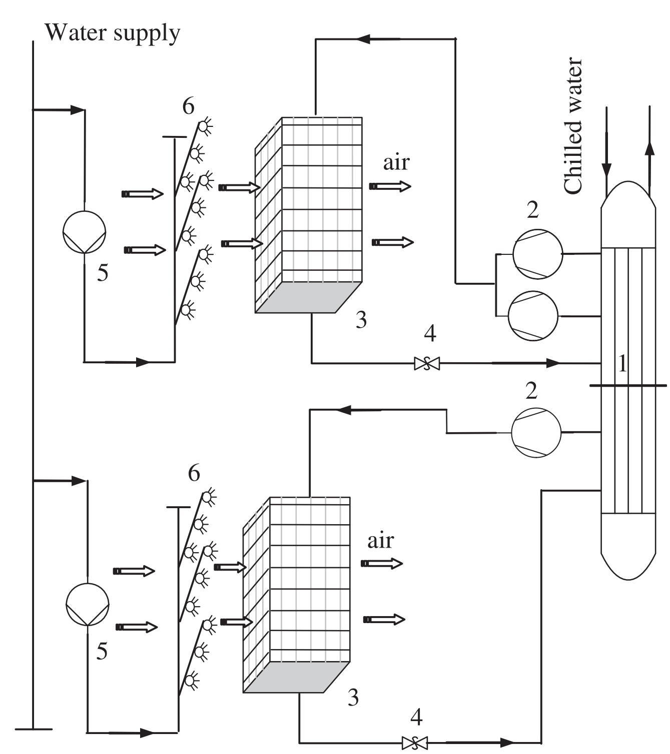
3. Experiment setup

The main objective of this study is to evaluate experimentally the performance of air-cooled screw chillers with or without water mist system. This involved measurements of the temperature, flow rate, pressure, power and other parameters related to the chiller performance. With the aid of a data logging system, data of related parameters can be continuous recorded and compiled for further analysis.

3.1. Description of the chiller and the water mist system

In this study, a chiller plant installed in an institutional complex comprising of three identical screw chillers connected in parallel was investigated. Each chiller has two refrigeration circuits, namely circuit A and circuit B, using refrigerant R134a. The chiller is equipped with one compressor for circuit A and two compressors for circuit B. The nominal cooling capacity of the studied chiller is 705 kW, rated under the operating conditions of entering condenser air temperature at 35 °C and entering/leaving chilled water temperatures at 12 °C/7 °C. The rated power of the studied chiller is 242 kW. The condensers comprise of 10 identical condenser fans arranged with a total airflow rate of 53.45 m^3/s, including four fans serving circuit A and six fans serving circuit B. The fan speed is 15.8 r/s, and each fan consumes a power of 2.4 kW.

The air-cooled screw chiller plant has been installed to provide space cooling for some years. In order to improve the chiller efficiency, water mist systems were installed in July 2009. Each chiller is served by a separate water mist system comprising of two water mist circuits, as shown in Fig. 1. The two water mist circuits contain high pressure pumps at rating of 0.75 kW and 1.25 kW dedicated for refrigeration circuits A and B, respectively. The flow rate of the high pressure pumps are 2 l/min and 4 l/min at 1500 rpm for circuit A and circuit B, respectively, discharging through a total of 58 nozzles. According to the layout of the condenser coil, the nozzles are evenly distributed in front of the entire condenser surface to ensure better evaporative effect. The DBT and relative humidity (RH) of entering condenser air were measured with a data logger system, and the other variables related to chiller performance were recorded by the building management system (BMS). Fig. 2 shows the experimental setup of the air temperature and RH sensors at the inlet to the condensers of the studied air-cooled screw chiller. A



1. Evaporator 2. Compressor 3. Condenser 4. Expansion valve 5. High pressure pump 6. Nozzles

Fig. 1. Schematic of the water mist system.