Energy and Buildings 75 (2014) 181–188

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Water flow rate models based on the pipe resistance and pressure difference in multiple parallel chiller systems

Handong Wang

M&E School of Shenzhen Polytechnic, Guangdong Province 518055, China

ARTICLE INFO

Article history:
Received 7 October 2013
Received in revised form
27 December 2013
Accepted 5 February 2014

Keywords:
Multiple parallel chillers
Water flow rate
Pressure difference
Model
Pipe resistance coefficient

ABSTRACT

To obtain the total and partial water flow rates of multiple parallel chillers, flow rate models are theoretically proposed based on the fundamentals of fluid dynamics using a real cooling plant with multiple parallel chillers as the prototype. These models reveal the inherent relationship among flow rate, pressure difference, and pipe resistance coefficients. After the model coefficients are determined theoretically and experimentally, both the total and partial flow rates of the multiple chillers are determined. The prototype system is subjected to two kinds of experiments, short-time and long-time experiments, to investigate the effect of resistance coefficients and pressure difference on the accuracy of the models. The two experiments show that the models are accurate in determining the flow rates of chilled water and cooling water in the prototype system. Some characteristics of the models are also discussed briefly.

1. Introduction

The cooling load of chillers is a key parameter in the optimal control, performance evaluation, and fault detection and diagnosis (FDD) of air conditioning systems. As such, it should be determined properly. The cooling load of chillers is closely related to the flow rate and inlet-outlet temperature difference of chilled water flowing through the chillers. Thus, the proper determination of the flow rate of chilled water in air conditioning systems is one of the key problems in the above-mentioned processes. In modern buildings, multiple parallel chillers are usually used to supply adequate and flexible cooling loads to meet the requirements of air conditioning. Thus, obtaining the actual flow rate of chilled water flowing through each chiller in a cooling plant with multiple parallel chillers becomes a very important task for engineers or researchers in optimizing the operation control or analyzing the energy efficiency of each chiller. It also helps improve the efficiency of air conditioning systems.

Considerable research on the optimal control, performance evaluation or modeling, and FDD of various chillers is related to cooling loads or chilled water flow rates. Reddy et al. [1] presented a comparative study on the suitability of four different chiller performance models used for online automated FDD. In their study, the four chiller performance models are related to the chiller cooling loads. Saththasivam et al. [2] utilized the simple thermodynamic model (STM), also known as Gordon and Ng Universal Chiller model, to detect and diagnose some of the common faults in centrifugal chillers. In STM, the cooling load is chosen as a model variable. Chang et al. [3] used practical measurement data to compare the accuracy of the ASHRAE and XY models [4] of chillers. In their study, both models were related closely to the cooling load or chilled water flow rate of the system.

Many other chiller models are also related to the cooling load or chilled water flow rates, such as those in the studies of Beitelmal and Patel [5], Gordon et al. [6], and Lee and Lu [7]. Some empirically based models, such as the simple linear regression model [8], bi-quadratic regression model [8], multivariate polynomial regression model [1,9], Gordon–Ng universal model [10], Gordon–Ng simplified model [6], and Lee's simplified model [11], directly depend on the cooling load of the chiller.

Yu and Chan [12] used data envelopment analysis (DEA) to facilitate the benchmarking of the energy performance of a system containing five sets of chillers, pumps, and cooling waters. The scale and technical and overall efficiencies defined in DEA were calculated based on the correlation between the output-system coefficient of performance (COP) and the input load factors and temperatures of chilled water and condenser water. In their work, the chillers were connected in parallel manner, and a fixed flow rate of chilled water passing through each chiller was adopted [13,14].

Powell et al. [15] proposed a novel technique of solving a dynamic optimal chiller loading problem by considering all chillers as a single optimal chiller. In their study, a static optimal chiller

E-mail address: zlwhd@szpt.edu.cn

http://dx.doi.org/10.1016/j.enbuild.2014.02.017
0378-7788/

Nomenclatures

D,d	pipe diameter, m
h_l	energy loss of the chilled water, mH_2O
l	pipe length, m
p	pressure, Pa
Q	water flow rate, m^3/s
S	pipe resistance coefficient, s^2/m^5
S_{z01}	sum of the resistance coefficients of pipes MK and LN in Fig. 1, s^2/m^5
$S_{z01,c}$	sum of the resistance coefficients of pipes M'K' and L'N' in Fig. 1, s^2/m^5
S_{zx}	resistance coefficient of the chilled water branch pipe of x chiller(s) in Fig. 1, s^2/m^5
$S_{zx,c}$	resistance coefficient of the cooling water branch pipe of x chiller(s) in Fig. 1, s^2/m^5
v	velocity of chilled water, m/s
x	sequence sign of working condition of operating chiller(s), $x = 1, 2, 3, 12, 13, 23, 123$ (1 stands for chiller 1 and 12 stands for chillers 1 and 2 and so on)
z	installation height of pressure transducers, m
γ	volume-weight of chilled water, N/m^3

Greek symbols

λ	on-way resistance coefficient
Δp	pressure difference, $\Delta p = p_{in} - p_{out}$, Pa
ξ	local resistance coefficient

Subscripts

1,c	cooling water of Chiller 1 in Fig. 1
3,c	cooling water of Chiller 3 in Fig. 1
e	experimental result
in	inlet
m	modeling result
out	outlet
x	chilled water at x working condition
x,c	cooling water at x working condition

loading problem was solved as a sub-problem to obtain the optimal total power required at each time interval. Gordon and Ng developed a thermodynamic chiller performance model [16], in which the cooling load is pre-measured to obtain the regression coefficients of the model.

Chang presented research results on optimal chiller loading, in which the part load ratios (the load on a chiller divided by its rated capacity) of each chiller were set as equal to one another [17].

Lu et al. [18] proposed a systematic approach in optimizing the energy consumption of the overall system rather than that of the individual component. For multi-chiller systems, the study adopted Stoecker's model related to the cooling load to express the relationship among the power consumption of chillers and other related parameters.

Yu and Chan [19] evaluated the savings on the operating cost of a chiller system integrated with the optimal control of cooling towers and condenser water pumps. A sophisticated chiller system model was used to ascertain how different control methods influence the annual electricity and water consumption of chillers operating for the cooling load profile of a reference hotel. Chiller sequencing was implemented, under which all the running chillers carried the same part load.

Chang [20] proposed a method of using dynamic programming to solve the optimal chiller sequencing problem and eliminate the deficiencies of conventional methods. In Chang's study, the COP of a centrifugal chiller is a function of its partial load ratio (PLR) for a given wet-bulb temperature. The COP function of the *i*th chiller unit is expressed as a second-order polynomial of PLR*i*, determined from the flow rate and temperature difference of chilled water flowing through the *i*th chiller.

In the studies mentioned above, the flow rate of chilled water in each chiller was usually determined by measuring on-field or from the database of the products. However, Chang et al. [21] proposed a novel method of obtaining the flow rate of chilled water. They applied regression analysis to establish the relationship between the flow rate and differential pressure by modeling experimental data. They specifically used such relationship in interpreting the flow rate of an air conditioning water system to establish a low-cost alternative flow rate interpretation, in which information was obtained more conveniently. They installed pressure transmitters and paddle wheel flow meters on the condenser side of the chiller and an air handling unit on the inlet and outlet ends of the pump of a small air conditioning system to model the relationship between the differential pressure and flow rates through actual operation data. In their experimental results, the differential pressure obtained to interpret the flow rate had a high accuracy, with an error value of less than 2%. However, they provided only the regression model of the chilled water flow rate of a single chiller and not the theoretical explanation.

To the author's knowledge, no research has been conducted yet on the determination of the actual distribution of chilled water in multiple parallel chillers. In most studies, chilled water is usually considered as evenly distributed in the operating chillers [13,14,17,19,22,23]. However, this assumption does not apply in most of the actual cooling plants. If the cooling loads distributed in each chiller of the multiple parallel chillers are even, then the flow rates of chilled water flowing through each chiller should be the same under the given identical temperature difference. This situation very seldom occurs in real cooling plants, especially when the system is not carefully adjusted. This claim has been proven by our on-field measurements in many actual cooling plants. Thus, the assumption of the even distributed of chilled water in multiple parallel chillers is just an ideal. It cannot help to accurately analyze or diagnose the performance of each chiller in real cooling plants. However, the assumption still plays a positive role in determining the optimal performance of a cooling plant. It can be used to conduct the optimal control design and so on.

Measuring the flow rate of chilled water of each chiller is difficult or even impossible in many real cooling plants. Most of the chilled water pipes connecting each chiller to the main pipe do not have enough straight pipe length. Most flow meters require that the straight pipe length should be at least 10 and 5 *D* for upstream and downstream, respectively, where *D* is the diameter of the measured pipe. For example, if a branch pipe is a DN250 pipe with an inner diameter of 0.259 m, the required upstream and downstream straight pipe lengths are 2.59 and 1.30 m, respectively. Thus, the total straight pipe length should be at least 3.89 m without any parts causing local resistance. A proper place for the installation of flow meters is not easy to find in many cooling plants. If a flow meter is improperly installed on the pipe without enough straight length, the measured flow rate causes great error and misdirects the analysis or diagnosis of the chiller performance. Our measurement results show that the relative error can reach 30% when a supersonic flow meter is installed in a chilled water pipe with DN250 and straight length of 2.8 m. Thus, the accurate determination of the water flow rates of pipes without enough straight length should be handled carefully.

This study proposes a novel method of determining the actual distribution characteristic of water flow rates in multiple parallel chillers by combining the pipe resistance coefficients and online pressure difference. First, with a real air conditioning system in