Applied Thermal Engineering 113 (2017) 435–448

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Evaluation of the design of chilled water system based on the optimal operation performance of equipments

Xing Fang, Xinqiao Jin *, Zhimin Du, Yijun Wang, Wantao Shi

School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

HIGHLIGHTS

- An evaluation method of the design of chilled water system is proposed.
- The optimal operation performance of chilled water system and equipments are set up.
- Operation matching degree is defined to evaluate the design of chilled water system.
- The evaluation method can point out the optimal design for chilled water system.

ARTICLE INFO

Article history:
Received 18 January 2016
Revised 19 April 2016
Accepted 6 November 2016
Available online 11 November 2016

Keywords:
Chilled water system
Design
Optimal operation performance
Operation matching degree

ABSTRACT

Central air-conditioning system is usually designed according to the peak load, and improper design is a popular problem. Commonly, when the central air-conditioning system is improperly designed, the operation performance of each equipment in the system will be deviated from its optimal operation performance. In order to evaluate the effects of the design of a central air-conditioning system on the operation performance of equipments and the system, this paper proposes an evaluation method based on exergy analysis. A chilled water system of a central air-conditioning system serving a building in Changsha of China is used as the study object. Based on exergy analysis, the optimal operation performance of the chilled water system and each equipment under specific load condition are obtained by maximizing their exergy efficiencies respectively. The evaluation index - *operation matching degree of equipment* is defined as the ratio of its exergy efficiency under system's optimal operation performance to its maximum exergy efficiency. And the *operation matching degree of system* is defined as the product of the *operation matching degrees* of all equipments in system. According to the frequency distribution of year-round load conditions, the *annual operation matching degree of system* is obtained, which is used to evaluate the design of chilled water system for a long term's operation. Eight alternative designed chillers and three alternative designed chilled water pumps are introduced to verify the evaluation method. By comparing the *annual operation matching degrees* of chilled water system in different designs, the optimal design of chilled water system is pointed out.

1. Introduction

Central air-conditioning system has been widely used in modern buildings to provide acceptable indoor thermal comfort. As reported by the literatures, the energy amount consumed by air-conditioning system accounts for over 40% of the total energy consumption in buildings [1]. Therefore, improving the operation performance of central air-conditioning system can substantially decrease the building energy consumption. In general, under specific load condition, the operation performance of air-conditioning system is mainly affected by two kinds of factors: control condition and design condition. Control condition refers to the control strategies applied in the air-conditioning system. Design condition refers to the size and configuration of air-conditioning system. Commonly, the control condition and the design condition can be changed to improve the operation performance of air-conditioning system. In recent years, many researchers have proposed related optimal control strategies to improve the operation efficiency of air-conditioning systems.

Fan et al. [2] presented an optimal load allocation control strategy for a multi-chiller system based on probability density

* Corresponding author at: Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, No. 800, Rd. Dong-Chuan, Dist. Min-Hang, Shanghai 200240, PR China.

E-mail address: xqjin@sjtu.edu.cn (X. Jin).

http://dx.doi.org/10.1016/j.applthermaleng.2016.11.053
1359-4311/

Nomenclature

W	energy consumption (kW)
I	exergy destruction (kW)
F	exergy fuel (kW)
P	exergy product (kW)
η	exergy efficiency (%)
Φ	operation matching degree (%)
E	exergy (kW)
COP	coefficient of performance
PLR	part load ratio
Q	cooling load (kW)
T	temperature (°C)
G	water flow rate (kg/s)
c_w	specific heat capacity of water (kJ/kg K)
CAP	rated cooling capacity (kW)
H	head of pump (m)
ρ	density (kg/m^3)
CL	building cooling load (kW)
f	frequency (%)
λ	speed ratio of pump
n	operating speed of pump (r/min)

Subscripts and superscripts

sys	system
ct	cooling tower
cdp	cooling water pump
ch	chiller
chp	chilled water pump
ex	exergy
equ	equipment
AHU	air handling unit
c	condenser
e	evaporator
chw	chilled water
cdw	cooling water
in	inlet
out	outlet
ave	average
0	dead state
set	set-point
db	dry bulb
r	representative
peak	peak
des	designed

distribution of cooling load ratio. The results showed that the optimal control strategy could save more power consumption of chillers than the original sequence control strategy. Ma et al. [3] proposed a model-based supervisory and optimal control strategy for central chiller plants to enhance their energy efficiency and control performance. The optimal strategy was formulated using simplified models of major components and the genetic algorithm (GA). Lu et al. [4] presented a systematic approach in optimizing the overall energy consumption of a centralized Heating, Ventilation and Air-conditioning (HVAC) system which consisted of indoor air loops and chilled water loops. Kusiak et al. [5] developed a multi-objective optimization model to minimize the energy consumption of a HVAC system while maintaining the corresponding IAQ (indoor air quality) within a user-defined range. Wang et al. [6] presented an adaptive optimal control strategy for online control of complex chilled water systems to enhance the operation performances. Test results showed that the strategy had enhanced control robustness and reliability, and saved significant energy consumption of chilled water pumps when compared with conventional methods.

On the other hand, the proper design is another key issue to reduce the energy consumption and improve the operation performance of air-conditioning system [7]. Seo et al. [8] used an optimal design method for the HVAC system in apartment using a genetic algorithm, and examined the possibility for the energy conservation of designed HVAC system. The results showed that this proposed method was significantly capable of determining optimal system design for saving energy in apartment house. Sun et al. [9] proposed a multi-criteria system design optimization for net zero energy buildings (NZEBs) under unspecificties. The study results showed that the peak cooling load unspecificty approximately followed a normal distribution and it needed to be well considered for the sizing of the air-conditioning system. Yu et al. [10] provided insights into how a chiller plant should be designed to enable the chillers to operate frequently with maximum performance. The results showed that unequally sized chillers should be installed in a chiller plant to enable the chillers to operate more frequently near the full load with improved performance.

Although sophisticated knowledge and skills are used in improving the design conditions of air-conditioning systems, energy consumption and initial cost are two main concerned factors for researchers. However, few studies addressed the problem that whether the operation performance of designed equipment can be close to its optimal operation performance in long-term's operation. In conventional design method, the air-conditioning equipment is designed according to the peak building cooling load [7], and oversized equipments are commonly selected in the design of central air-conditioning systems [11]. The oversizing of air-conditioning equipment usually deteriorates the operation performance of the equipment because of the part-load operation [12]. Therefore, for an air-conditioning equipment, when it is improperly sized, the operation performance of the equipment will be deviated from its optimal operation performance. Furthermore, for a central air-conditioning system including many equipments, such as chillers, cooling towers, water pumps and AHUs, the improper sizing of equipments will result in the improper design of the system, which makes the operation performance of all equipments deviated from their optimal operation performance.

In order to evaluate the effects of the sizing of equipment on the operation performance of equipments and the system, this paper proposes a new evaluation index - "*operation matching degree*" to represent the deviation ratio of the operation performance of equipment from its optimal operation performance. The evaluation method based on *operation matching degree* is divided into three steps. Firstly, exergy analysis and optimization method (PSO algorithm [13]) are applied to obtain the optimal operation performance of a chilled water system and each equipment under specific load condition. Secondly, based on the optimal operation performance of chilled water system and equipments, the *operation matching degrees* of each equipment and the system under specific load condition are obtained. Thirdly, the frequency distribution of year-round load conditions is analyzed, and the *annual operation matching degree* of the chilled water system is obtained to evaluate the design of system in long-term's operation. For validating the evaluation method, an actual air-conditioning system is introduced and 35 alternative designs of chilled water system are