Energy and Buildings 42 (2010) 203–209

Contents lists available at ScienceDirect

Energy and Buildings

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

Economic benefits of optimal control for water-cooled chiller systems serving hotels in a subtropical climate

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ARTICLE INFO

Article history:
Received 27 July 2009
Received in revised form 25 August 2009
Accepted 25 August 2009

Keywords:
Water-cooled chiller
Cooling tower
Economic analysis
Optimum control

ABSTRACT

A water-cooled chiller system in an air-conditioned hotel can take up about one-quarter of the total electricity consumption and considerable amounts of water in the heat rejection process. This paper evaluates operating cost savings of a chiller system integrated with 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. It is estimated that applying load-based speed control to the cooling tower fans and condenser water pumps could reduce the annual system electricity use by 8.6% and operating cost by 9.9% relative to the equivalent system using constant speed fans and pumps with a fixed set point of 29.4 °C for cooling water temperature control. The ways to implement this advanced control for system optimization are discussed.

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1. Introduction

Hotels play an important role in sustaining the economic growth of Hong Kong. Yet they constitute one of the major energy end users in the commercial sector because of their round-the-clock operation. A previous survey [1] indicated that the overall electricity consumption in the hotel segment increased from 443 to 921 GWh (a 108.2% increase) from 1988 to 2000. With the increasing supply of local hotels, it was estimated that their electricity demand could grow by 36.8 GWh per annum over the period of 2001–2005 [2]. One possible way to moderate the increasing electricity demand is to improve the energy performance of air-conditioning systems which account for around half of the total electricity consumption. According to studies on the electricity consumption of 16 local hotels [3,4], their energy use intensity (EUI—the annual electricity consumption in kWh per unit floor area of a building in m^2) varied widely from 198 to 926 kWh/m^2 with an average of 406 kWh/m^2. For hotels with central air-conditioning plants, water-cooled chiller systems with cooling towers are commonly used to provide cooling energy in the form of chilled water to maintain the thermal conditions required for indoor areas. The operation of chillers and cooling towers leads to the peak electricity demand and accounts for about half of electricity consumption for air conditioning. Moreover, cooling towers rely on evaporation of water in the heat rejection process, leading to considerable water consumption when the chillers are operating.

Variable speed technology has long been considered a standard energy-efficient feature to enhance the energy performance of chiller systems. Hartman [5] launched the equal marginal performance principle (EMPP) to assist in optimizing the performance of chiller systems in which variable speed drives (VSDs) are applied to all the chillers, condenser water pumps and cooling tower fans. Yet the all-variable speed arrangement is seldom considered in system design and VSDs are applied solely to the secondary loop pumps and cooling tower fans in most systems. Variable flow of chilled water is increasingly used to reduce energy use, given that pump energy can be saved when the primary pumps deliver less flow to their dedicated chillers at part load conditions. The successful application of variable-primary flow depends on how the flow and chiller capacity can be adjusted to match changing load conditions [6]. This application is subject to the design of the chilled water distribution circuit and the airside cooling coils are required to be furnished with two-way control valves in order to allow the flow of chilled water to drop under the reduced load conditions. For a constant air volume system requiring high latent cooling capacity, the potential of reducing the chilled water flow rate under part load conditions is rather limited and so are the pump energy savings.

Gordon et al. [7] and Hydeman et al. [8] developed chiller models to study variations of chiller COP (coefficient of performance) at different condenser water flow rates. No analysis was

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doi:10.1016/j.enbuild.2009.08.016

made on the trade-off between the chiller power, tower fan power and condenser water pump power under the reduced flow conditions. Also no control regime was given on how the condenser water flow should vary in response to the chiller load and wet-bulb conditions. Variable speed control is increasingly applied to cooling tower fans to reduce their cycling frequency and allow better heat rejection control with decreased fan power [9]. The dynamic characteristics of cooling towers with the varying heat rejection airflow impose more complications in system optimization. Lu et al. [10] presented a model-based optimization strategy for the condenser water loop of a chiller system. The strategy involved minimizing the total power of the chillers, condenser water pumps and cooling tower fans, taking into account the interaction between the varying air flow rate and condenser water flow rate for a given heat rejection rate. The influence of the condenser water entering temperature on both the chiller power and cooling tower performance was analysed. Yet they did not explain the control logic of the condenser water pump and cooling tower fan for system optimization.

Graves [11] reformulated the Gordon–Ng model [7] in order to optimize a system designed with two chiller-pump pairs and one cooling tower. The chiller model was coupled with an Ntu-effectiveness (Ntu—no. of transfer units) model [12] for evaluating the cooling tower performance. Drawing on the chiller–tower interaction, the modified model was used to analyse how the system COP varied with the changing condenser water flow. Yet the tower model discounted the water loss due to evaporation, and a single NTU value was assumed to represent the tower performance at different water and airflow rates. Two correlations were identified to facilitate near-optimal system operation: one was the linear relationship between the cooling water set point and wet bulb (an analogy to the fixed approach method); another was the linear relationship between the tower fan speed and pump speed. Benton et al. [13] developed a regression model to represent the improved cooling tower simulation algorithm (CTSA). The algorithm simply indicated the cooling tower approach (cooling water leaving temperature subtracted from wet-bulb temperature) as a dependent variable of the wet-bulb temperature, range (temperature difference of cooling water), condenser water flow and fan power. It remains to be ascertained how to evaluate an optimal set point for cooling water temperature or the optimal fan speed control in response to dynamic characteristics of cooling towers at part load operation.

The aforementioned studies have demonstrated important modelling techniques to analyse chiller system performance and some insights on optimizing the control of chiller and cooling tower systems with variable speed control for condenser water pumps and tower fans. Yet none of the reported models are comprehensive enough to assess power relationships of chillers, condenser water pumps and cooling towers together with water consumption in the heat rejection process, with regard to various control methods of cooling towers and condenser water pumps. Furthermore, most of the studies focus only on electricity sayings without considering the likely trade-off between water and electricity savings.

More quantitative figures and economic analysis are considered necessary in order to reap the potential benefits of applying optimization technologies to chiller systems. The objective of this study is to investigate the economic benefits of a water-cooled chiller system with the following energy-efficient technologies: variable speed control of cooling tower fans; a constant approach; a fixed and low cooling water leaving temperature; variable condenser water flow. These technologies are adaptable to most existing chiller systems with minor modifications. This paper first describes a hotel and its chiller system. The method to simulate hourly building cooling loads is presented. A sophisticated chiller system model was used to analyse how the system COP varies with different technologies and to predict the annual electricity and water consumption of the chiller system. An assessment was made on the water and electricity cost savings resulting from the individual and mixed uses of the technologies. The significance of this study rests on providing more quantitative analysis to promote water-cooled chiller systems with optimal operating strategies in order to boost their environmental performance in terms of annual electricity and water consumption, and, at the same time, to reduce their operating costs.

2. Evaluation of hourly cooling loads of the hotel

Table 1 summarizes the features of the hotel to be modelled. The features were compiled into a building description file for the multi-zone model in the simulation program TRNSYS 15 [14] used

Table 1
General information about the hotel and its air-conditioning systems.

General		
Gross floor area (GFA) (m^2)	52,020	
Total air-conditioned area (m^2)	45,540 (87.5% GFA)	
U-values of wall/window/roof (W/m^2 °C)	1.9/5.4/0.7	
Shading coefficient of glass	0.55	
Area	Guestrooms	Shops and restaurants
Area per floor (m^2)	2,010	2640
Air-conditioned area per floor (m^2)	2,010	1560
Number of floors	18	6
Cooling temperature set point (°C)	24	22
Relative humidity (%)	50	50
Ventilation rate (L/s/person)	7.5	5
Occupancy (m^2/person)	18	5
Equipment power density (W/m^2)	12	50
Lighting power density (W/m^2)	18	35
Air-conditioning system operating hours		
Monday–Friday	0100–2400	0800–2300
Saturday	0100–2400	0800–2300
Sunday	0100–2400	0800–2300
Air side system details		
Type of air handling units	Fan coil units (FCUs)	CAV AHU and FCUs
Chilled water flow control	2-way valve	2-way valve
Chiller plant operating hours (all days)	0100–2400	

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