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An optimization strategy for the control of small capacity heat pump integrated air-conditioning system

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ABSTRACT

This paper studies the optimization of a small-scale central air-conditioning system, in which the cooling is provided by a ground source heat pump (GSHP) equipped with an on/off capacity control. The optimization strategy aims to optimize the overall system energy consumption and simultaneously guarantee the robustness of the space air temperature control without violating the allowed GSHP maximum start-ups number per hour specified by customers. The set-point of the chilled water return temperature and the width of the water temperature control band are used as the decision variables for the optimization. The performance of the proposed strategy was tested on a simulation platform. Results show that the optimization strategy can save the energy consumption by 9.59% in a typical spring day and 2.97% in a typical summer day. Meanwhile it is able to enhance the space air temperature control robustness when compared with a basic control strategy without optimization.

1. Introduction

Air-conditioning (A/C) systems are widely used in buildings to provide safe and comfortable environment for building occupants. It has been shown that more than 40% of the building energy consumptions are mainly used for the heating, ventilation, and air-conditioning (HVAC) systems [1,2]. In order to reduce the energy use of A/C systems, a number of optimization controls have been developed since 1980s, reviewed by ASHRAE [3]. New developments since 2000 were surveyed by Afram and Janabi-Sharifi [4]. Generally, the basic components of optimizing A/C system framework are cost function, decision variables, and constraints [5,6].

Many optimization methods, including evolutionary algorithms [7,8], branch and bound [9,10] and simulated annealing [11,12], have been shown to be successful in minimizing energy consumption and reducing operation cost for A/C systems. However, those optimization methods focus on multi-chiller plants with large capacity [6,13] or on commercial refrigeration plants [14]. Such systems are typically characterized by continuous capacity control, for example using optimal chiller sequencing control.

This paper studies the optimization of a small-scale A/C system integrated with a ground source heat pump (GSHP). Usually, a GSHP refers to a heat pump that uses the ground as a heat source and provides heat in cold winter, but it also refers to a heat pump that uses the ground as a heat sink and provides cooling in hot summer [17]. In this study, the cooling condition of the GSHP is concerned. Such a system is one common and fast growing system for heating/cooling small-scale buildings [15,16]. Different from chiller plants with large capacity, the most common control method of small-scale GSHPs is an on/off control [18]. Many studies show that the annual efficiency of the intermittently operated heat pump may be higher than the variable-speed controlled heat pump [19,20,21]. The on/off controlled GSHP is usually controlled according to the chilled water return (CHWR) temperature (i.e., the water temperature at the inlet of the GSHP evaporator) [17]. When the CHWR temperature is higher than a pre-defined upper threshold, the compressor will be switched on; while it will be switched off when the CHWR temperature is lower than a pre-defined lower threshold. Generally, the on/off threshold is set according to the set-point of the CHWR temperature $T_{w,set}$ and the allowed width of the differential between the on and off temperature ΔT_w (see Eq. (1) for details) [22].

There are two important issues in the on/off control of GSHP in practice. One is the GSHP start-ups number per hour, which should be concerned since frequent switch on/off will speed up the wear and aging of the device [22]. Another one is the significant disturbances introduced by the on/off control on the control loops of the A/C system, which may deteriorate the stability of the control loops especially when the on/off switch is frequent [17]. Therefore,

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Nomenclature

a_0–a_3, b_0–b_1, c_0–c_3	coefficients
C	thermal capacitance (kJ/K)
c	specific heat kJ/(kg K)
c_{pw}	specific heat of water at constant pressure kJ/(kg K)
h	sampling interval (s)
J	objective function
M	mass flow rate (kg/s)
$\overline{M}$	maximum allowable bound of the mass flow rate (kg/s)
$\underline{M}$	minimum allowable bound of the mass flow rate (kg/s)
N_c	samplings in one cycle time
NTU	number of transfer units
N_{start}	allowed maximum start-ups number of the GSHP per hour
PLR	partial load ratio
Q_{HP}	cooling capacity of heat pump (kW)
$\widehat{Q}_{HP}$	mean cooling capacity over the on time during on/off cycling period (kW)
q	cooling load (kW)
$\hat{q}$	mean value of the cooling load in one GSHP on/off cycling period (kW)
T	temperature (°C)
$\overline{T}$	upper bound of the temperature (°C)
$\underline{T}$	lower bound of the temperature (°C)
T'	temperature after introducing dynamic effects (°C)
ΔT_w	width of the CHWR temperature control band (°C)
t	time (s)
UA	overall heat transfer coefficient (kW/K)
V	volume (m^3)
$\widehat{W}$	mean power consumption in one GSHP on/off cycling period (kW)

Greek letters

ρ_w	water density (kg/m^3)

Subscripts

a	air
cd	condenser
cl	cooling water
cyc	one cycle time
down	lower threshold
ev	evaporator
fan	fan
GS	ground source heat exchanger
HP	heat pump
in	inside or inlet
k	current time instant
l	total cooling load
min	minimum
off	off
on	on
out	outlet
pump	pump
rated	rated
re	return
sen	sensible heat load
set	set value
soil	soil
sup	supply
sys	system
up	upper threshold
w	chilled water

both issues should be taken into account when studying the energy efficiency of a GSHP integrated A/C system.

However, current relative studies did not consider both issues. For example, Corberan et al. [17] studied the on/off control of a GSHP integrated A/C system and showed that the energy consumption of the GSHP reduces when the set-point of the CHWR temperature increases. Madani et al. [24] compared three common methods to control an on/off controlled GSHP system and showed that the degree–minute method achieves the lowest energy use. Cervera-Vázquez et al. [25] proposed an energy optimization strategy for a GSHP system and showed that a higher chilled water temperature set-point leads to more frequent on/off of the heat pump [22]. As the compressor on/off cycling frequency depends on the on/off threshold, Beghi and Cecchinato [22] proposed an adaptive control to deal with the similar problem. In their study, ΔT_w and $T_{w,set}$ are regulated to improve the energy efficiency rating (EER) of the chiller based on the estimated cooling load subject to the allowed maximum number of compressor start-ups per hour. However, in their algorithm, the energy consumption of the air side system was not considered.

In this paper, a strategy is proposed for a GSHP-integrated A/C system to minimize the overall system energy consumption subject to the allowed GSHP maximum start-ups number per hour specified by customers. Two steps are necessitated. Firstly, the water volume inside the chilled water loop is checked whether it is enough to satisfy the allowed GSHP maximum start-ups numbers per hour at the designed condition (i.e. ΔT_w and $T_{w,set}$ are the rated values). If not, a water tank is added to increase the water volume to the required minimum volume. Secondly, ΔT_w and $T_{w,set}$ are optimized to minimize the overall system energy consumption according to the system operating load condition without violating the allowed GSHP maximum start-ups number and degrading the indoor temperature control performance.

2. System description and control Issues

2.1. System description

The GSHP-integrated central A/C system is illustrated in Fig. 1, where the GSHP is controlled by an on/off capacity controller C1. The cooling water is provided by a ground source heat exchanger (GSHE). The water flow rate in both the chilled water side and the cooling water side is constant. The supply air is conditioned by an air handle unit (AHU), which consists of the fresh air from outdoor and the returned air from the conditioned space. When the GSHP is on, the water is chilled down and delivered to the AHU to cool down the supply air. The supply air temperature is not under control and will vary with the variation of the chilled water supply temperature, which oscillates following the on/off operation of the GSHP. The supply air flow rate is controlled by a variable frequency drive (VFD) fan according to the room temperature measurement and its set point. The room is a common A/C zone, and its temperature is controlled by a bilinear feedback controller C2 [26,27], which tracks the set-point by regulating the supply air flow rate. Details are referred to the reference [23].

2.2. Water volume and its influence on system performance

It is known that the water volume inside the chilled water loop affects the on/off frequency of the compressor when the system operates at partial load. Generally at the same load condition, the