Energy and Buildings 108 (2015) 127–136

Contents lists available at ScienceDirect

Energy and Buildings

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

Space temperature control of a GSHP-integrated air-conditioning system

Jiajia Gao [a], Gongsheng Huang [b], Xinhua Xu [a,*]

[a] Department of Building Environment & Energy Engineering, Huazhong University of Science & Technology, Wuhan, China
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong, China

ARTICLE INFO

Article history:
Received 4 July 2015
Accepted 14 August 2015
Available online 6 September 2015

Keywords:
Ground source heat pump
Air-conditioning system
Bilinear control
Robustness
Variable frequency drive

ABSTRACT

This paper presents a method which combines the bilinear control technique with a set-point reset technique to control the space temperature when its cooling is provided by a GSHP equipped with an on/off capacity control, aiming to (i) improve the robustness of the space temperature control by taking account of load uncertainty; and (ii) to reduce the frequency of the GSHP on/off cycling by using the indoor space temperature set-point reset. When the GSHP is on, a smaller space temperature set point is used; while the GSHP is off, a larger set point is used. The proposed control was tested on a simulation platform, which consists of a ground source heat exchanger, a GSHP, an air-handling unit (AHU) and a middle-sized room. The test results show that the proposed control method is able to achieve a good control performance and has the potential to be applied to a real GSHP integrated air conditioning system to improve the robustness of space temperature control and simultaneously reduce the on/off frequency of the GSHP.

1. Introduction

Ground source heat pump (GSHP) is a central heating and/or cooling system that transfers heat to or from the ground, which is considered as the most widely used ‘green’ heating, ventilation and air-conditioning (HVAC) system with an estimate of 1.1 million ground-source heat pumps installed worldwide before 2005 [1,2]. It becomes one of the common and fast growing systems for heating/cooling the buildings worldwide [3,4].

To improve the efficiency of a GSHP, capacity control is always adopted, and there are two control methods that have been developed and practiced: on/off control and variable capacity control. Many studies show that the variable-speed controlled heat pump may not improve the annual efficiency compared to the intermittently operated heat pump ([5,6]; Zhao et al., 2003). Therefore, the most common method for capacity control is still the on/off control, especially in small-scale systems [7]. In the on/off control, the compressor of the heat pump is switched on or off according to the estimated discrepancy between building heating/cooling demand and heat pump capacity. Normally, this discrepancy is denoted by the chilled water return (CHWR) temperature. The compressor will be switched on when the CHWR temperature is higher than a pre-defined threshold and it will be switched off when the CHWR temperature is lower than a pre-defined threshold [8]. It should be noted that the pre-defined switch-on threshold should be larger than the switch-off threshold in cooling mode. A larger difference can lead to a less frequent on/off operation during part-load operation.

The on/off capacity control of the heat pump compressor has its own disadvantages. It is well-known that GSHPs are normally sized to cover the peak load, but they may work at part load condition during most of the time. This will lead to a frequent on/off switch of GSHPs when the on/off capacity control is used. A frequent on/off operation of the compressor will fasten the aging and degradation of the compressor and shorten the life of the heat pump. A typical way to avoid excessive cycling of the compressor is to size the heat pump to cover the base load (say 60% of the peak load) and to use a back-up heater/cooler to cover the left peaks [5,9]. However, for an existing GSHP integrated air-conditioning (A/C) system, it is not cost-effective to resize the GSHP.

Another important issue is that the on/off capacity control will introduce significant disturbances on the control loops of the GSHP integrated air-conditioning (A/C) system, especially when the on/off switch is frequent [8]. In such a case, the performance of the space temperature control will be deteriorated, and the thermal comfort of the conditioned space may be affected (for example when during the transient the indoor temperature may be outside of the thermal comfort range). Besides, it is possible that as

* Corresponding author.
E-mail address: bexhxu@hust.edu.cn (X. Xu).

http://dx.doi.org/10.1016/j.enbuild.2015.08.031
0378-7788/

Nomenclature

$a_0 - a_1, b_0 - b_1$	coefficients
CT	timer
c_{pw}	specific heat of water at constant pressure {kJ/(kg K)}
e	tracking error of the space air temperature (°C)
F	frequency (Hz)
$\bar{F}$	maximum allowable bound of the frequency (Hz)
$\underline{F}$	minimum allowable bound of the frequency (Hz)
G	moisture content (g/kg)
M	mass flow rate (kg/s)
N_c	timer threshold
NTU	number of transfer units
Q_{other}	heat transfer from the doors, glass curtain and the above steel structure floor (kW)
q	cooling load (kW)
$\underline{q}$	lower bound of the cooling load (kW)
R	thermal resistance (m^2 K W^{-1})
T_r	space air temperature actual set point (°C)
$T_{r,set}$	space air temperature nominal set point (°C)
T'	temperature after introducing dynamic effects (°C)
ΔT	small change of the space temperature set point (°C)
t	time
V	space volume (m^3)
W	power consumption (kW)
W_{lo}	constant portion of the electromechanical losses (kW)
C	thermal capacitance (kJ/K)
c	specific heat {kJ/(kg K)}
h_1	sampling interval (s)
$Mass$	mass of the space air (kg)
N_w	length of a moving window
Q	heat transfer rate (kW)
$\bar{q}$	upper bound of the cooling load (kW)
T	temperature (°C)
UA	overall heat transfer coefficient (kW/K)
v	volume flow rate (m^3/s)

Greek letters

α	coefficient
ρ	fluid density (kg/m^3)
γ	user-defined parameter
α_1, α_2	coefficients
ε	heat transfer effectiveness
ζ	parameter on the cooling load (kW)

Subscripts

a	air or air side
cd	condenser
cl	cooling water
com	compressor
fr	fresh air
in	inside or inlet
oc	occupant
out	outlet
s	supply air
w	water or water side
ahu	air handle unit
ch	chilled water
$coil$	cooling coil
ev	evaporator
im	internal mass
k	current time instant
ou	outside surface
r	radiation
si	ith wall
z	zone

the GSHP on–off capacity control and the space temperature control interact with each other, the deteriorated space temperature control performance may fasten the frequency of the GSHP on/off operation. In current literature, very few studies can be found to deal with this problem.

This paper, therefore, proposes a method to address the issue of space temperature control of a GSHP-integrated A/C system. Different from previous studies that aims to avoid excessive cycling of the heat pump by sizing the capacity of a GSHP to cover the base load (not the full load), the proposed method will consider the integrity of the GSHP on/off control and the space temperature control, which can avoid excessive cycling of the heat pump (at low load condition) and simultaneously to enhance the robustness of space temperature control by reducing the disturbances introduced by the on/off capacity control of the GSHP.

The A/C system considered in this study is a variable-air-volume (VAV) system. It is well-known that in a VAV A/C system, the space temperature variation is a bilinear process suffering from load uncertainties [10]. The space temperature is determined by the outdoor weather condition (such as outdoor temperature and solar radiation), the indoor load condition (such as lighting, electrical appliance and occupants) and the amount of cooling provide by the A/C system [12]. The space temperature control, normally by a thermostat, aims to maintain the room temperature at a desirable set point. Aiming at improving the robustness of the space temperature control, researchers developed a number of control strategies for the VAV A/C systems, such as model-based predictive control [11,12], robust infinite control [13] and many other controls listed in Ref. [14]. Notably, a bilinear control was developed by Huang [10], and its application in a typical VAV A/C system has shown that this control can significantly improve the robustness of the space temperature control [15].

The proposed method combines the bilinear control technique with a set-point reset technique to control the space temperature when its cooling is provided by a GSHP equipped with an on/off capacity control, aiming to (i) improve the robustness of the space temperature control by taking account of load uncertainty [15]; and (ii) to reduce the frequency of the GSHP on/off cycling by using the indoor space temperature set-point resetting. When the GSHP is on, a smaller space temperature set point is used (which should be set according to a thermal comfort handbook such as ASHARE handbook 2011), which will not affect the thermal comfort. When the GSHP is off, a larger set point is used, which will not affect the thermal comfort as well. The paper is organized as follows. At the beginning, a typical building A/C system and its models are described. Then, the proposed control method and its algorithm are illustrated. Finally, the test platform and the testing results as well as the application issues are presented.

2. System description

The considered GSHP-integrated A/C system is illustrated in Fig. 1, where the GSHP is controlled by an on/off capacity controller, *i.e.* the GSHP will be switched on and provide full cooling capacity when the CHWR temperature, measured by a temperature sensor, is higher than a pre-defined threshold; while it will be switched off and no cooling/heating is provided when the CHWR temperature is lower than a pre-defined threshold. When the GSHP is on, the