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Performance analysis of hybrid ground-coupled heat pump system with multi-functions

Tian You, Baolong Wang, Wei Wu, Wenxing Shi, Xianting Li *

Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China

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ABSTRACT

Underground thermal imbalance is a significant problem for ground-coupled heat pump (GCHP) systems that serve predominately heated buildings in cold regions, which extract more heat from the ground and inject less heat, especially in buildings requiring domestic hot water (DHW). To solve this problem, a previously developed heat compensation unit with thermosyphon (HCUT) is integrated with a GCHP unit to build a hybrid GCHP system. To improve the energy savings of this hybrid GCHP system, the HCUT unit is set to have multiple functions (heat compensation, direct DHW and direct space heating) in this paper. To analyze the improved system performance, a hotel requiring air-conditioning and DHW is selected and simulated in three typical cold cities using the dynamic software DeST and TRNSYS. The results indicate that the hybrid GCHP system can maintain the underground thermal balance while keeping the indoor air temperature within the design range. Furthermore, the HCUT unit efficiently reduces the energy consumption via its multi-functional operations. Compared to the previous system that only used HCUT for heat compensation, adding the direct DHW function further saves 7.5–11.0% energy in heat compensation (HC) and DHW (i.e., 3.6–4.8% of the whole system). Simultaneously adding the direct DHW and space heating functions to the HCUT can save 9.8–12.9% energy in HC and DHW (i.e., 5.1–6.0% of the whole system). The hybrid GCHP system with a multi-functional HCUT provides more energy savings while maintaining the underground thermal balance in cold regions that demand both air-conditioning and DHW.

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1. Introduction

1.1. The status of and problems with ground-coupled heat pump systems

The amount of energy consumed for air-conditioning (AC, including space heating and cooling) and domestic hot water (DHW) in buildings is large and continually increases with economic development and improving living standards [1]. Ground-coupled heat pump (GCHP) system has been widely applied in recent years. It always shows better performance than air-source heat pump by taking the soil as the heat source or heat link [2–4]. Compared with the coal boiler, it greatly reduces the emission of pollution [5,6].

However, for many buildings in cold regions, the heat extracted from the soil by GCHPs is significantly larger than that injected into it, and the resultant underground thermal imbalances annually decrease the soil temperature, which decreases the system performance [7–9]. If DHW is also produced via a GCHP, this thermal imbalance is aggravated. Some solutions were developed to correct the imbalance and can be classified into two categories. (1) Increase the number of or space between boreholes [10]. However, this solution simply slows down the development of the imbalance and cannot entirely eliminate the thermal imbalance; in addition, this method increases the drilling and land costs. (2) Integrate auxiliary energy, such as from solar [11–15] and fossil fuels [16], to create a hybrid GCHP system. Solar energy is renewable and costs few in operation [17,18]. However, the investment and maintenance requirements of a solar collector are high. Besides, as its performance is greatly affected by the solar radiation [19–21], the heat provided by solar collector decreases greatly in the region with less solar energy or when the day is cloudy or at night. Integrating fossil fuel auxiliaries, such as boilers, reduces the advantages of the GCHP systems particularly at high heating loads.

1.2. Hybrid GCHP systems with a heat compensation unit

Due to these shortcomings with existing solutions, a hybrid ground-coupled heat pump system with a heat compensation unit

* Corresponding author. Tel.: +86 10 62785860; fax: +86 10 62773461.
E-mail address: xtingli@tsinghua.edu.cn (X. Li).

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Nomenclature

C	specific heat of water, kJ/kg °C
P	power consumption, kW
Q	heat capacity, kW
T	time for domestic hot water production, h
m	number of people
q	normal DHW demand, L/(person d)
t	temperature, °C
Greeks	
ρ	density, kg/L
Abbreviations	
COP	coefficient of performance
AC	air-conditioning (including space heating and cooling)
HC	heat compensation
DHW	domestic hot water
GCHP	ground-coupled heat pump
GCHP-AC	ground-coupled heat pump unit providing air-conditioning
GCHP-DHW	ground-coupled heat pump unit providing domestic hot water
HCUT	heat compensation unit with thermosyphon
HCUT–GCHP	ground-coupled heat pump system integrated with heat compensation unit with thermosyphon
Subscripts	
C	cooling
DHW	domestic hot water
H	heating
TH	thermosyphon mode
P	heat pump mode
c	cold water
ci	condenser inlet
ei	evaporator inlet
h	hot water

(called HCUT–GCHP) was previously proposed [22–24]. This system integrated a heat compensation unit containing a thermosyphon (HCUT) with a traditional GCHP system to compensate heat to the soil during non-heating seasons. The principle of the proposed system is shown in Fig. 1, where the solid line stands for a traditional GCHP system providing AC, and the dashed line represents the heat compensation (HC) circuit with HCUT [23].

A HCUT combines a thermosyphon and an air source heat pump to transfer heat from the air into the soil during warm seasons. In the thermosyphon mode, the compressor does nothing, and the unit is driven by natural temperature differences between the ambient air and ground, which produces a high COP. The heat pump mode also has a higher COP than traditional air-source heat pumps and a larger heat capacity than the thermosyphon because of the high air temperature during non-heating seasons and low water temperature available for heat compensation [23].

The previous simulation verified this system can maintain the thermal balance of the soil with high energy efficiency compared to the "boiler + split air-conditioners" commonly used in cold regions [23].

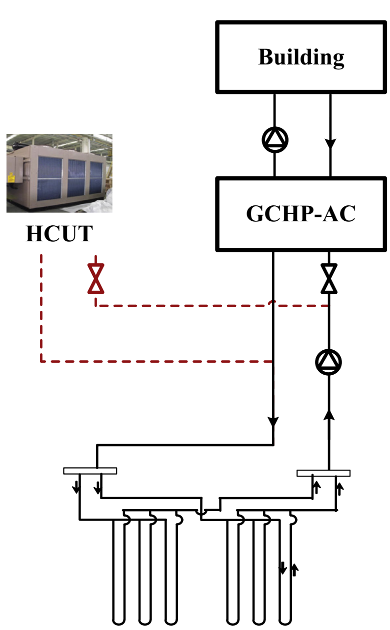

Fig. 1. Schematic of the HCUT–GCHP system.

1.3. Objectives

The previously reported HCUT unit was only used for heat compensation during non-heating seasons. In actuality, many buildings that use GCHP systems also require DHW, such as hotels and residential buildings. For such buildings, producing DHW using a GCHP unit over an entire year significantly increases the difference between the heat extracted from and injected into the soil relative to a building without DHW; therefore, the HCUT must compensate for more heat. The pump energy consumption will be large using the previously described HCUT–GCHP system because the heat is first stored in the soil from the air by the HUCT before being pumped out by the GCHP unit for DHW. Thus, the heat experiences a round trip that wastes pumping power.

In this work, the HCUT operates using multiple functions heat compensation, direct DHW during the non-heating season, and direct space heating during the beginning and end of the heating season when the heat load is relatively low. In this manner, the system energy requirements were reduced further via the multi-functionality of the HCUT unit. This work explains the principle and operating strategy for systems with different HCUT functionalities and investigates the operating performance via dynamic simulation.

2. Methodology

2.1. Principles of hybrid GCHP systems with multiple functions

In addition to heat compensation, the HCUT unit can be made to operate with multiple functions to enhance the hybrid GCHP system performance. A hybrid GCHP system with multiple functions for a building in a cold region requiring DHW is shown in Fig. 2, and the system operates in different circuits according to the differing seasonal demands.

A schematic diagram for heating, cooling and DHW production by the GCHP unit is shown by the solid line in Fig. 2(a). It illustrates that the GCHP-AC and GCHP-DHW units simultaneously provide space heating and DHW, respectively, during the heating season and the GCHP-AC unit provides space cooling during the cooling season. To maintain the underground thermal balance, the HCUT

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