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Experimental performance study of ground-coupled heat pump system for cooling and heating provision in karst region

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ABSTRACT

As a renewable energy technology, the ground-coupled heat pump (GCHP) system is gaining more and more world-wide attentions due to its advantages of energy efficiency and environmental friendliness. However, experimental studies on the GCHP system are still insufficient. In order to investigate the practical performance of GCHP system, the detailed on-site experiments were applied on a GCHP test rig located in a karst region of China. Operation parameters recorded during tests mainly include the temperature distributions of borehole at different depths, the temperature, pressure and flow rate of water circulating in the heat pump as well as the GHEs, the power consumption of the heat pump as well as circulating pumps. Consequently, the GCHP system for both cooling and heating provision was investigated by using three different operation modes – mode I (i.e. intermittent mode A), mode II (i.e. intermittent mode B) and mode III (i.e. continuous mode). Experimental results indicated that the performance of GCHP system was affected by its operation conditions and modes. Moreover, heat and cold accumulation in the ground during cooling and heating provision of the GCHP system was analyzed. The results show that the average values of $\mathrm{COP}_{\mathrm{sys}}$ for cooling and heating provision are 3.12 and 2.24, which can meet the space heating and cooling requirements of a small detached laboratory room in karst region. It is also found that the intermittent mode operation is beneficial to improving the performance of GCHP system with the fact that the $\mathrm{COP}_{\mathrm{sys}}$ increases by 23.0% when P_{rr} (the proportion of recovery time and running time) increases from 0 to 2. The $\mathrm{COP}_{\mathrm{sys}}$ of GCHP for cooling provision is 28.6% higher than which for heating provision for the reason that the cold accumulation in ground around GHEs for heating provision is more than heating accumulation in cooling provision.

1. Introduction

Ground-coupled heat pump (GCHP) is an energy utilization technology which is famous for high efficiency, energy saving and environmental protection. The application of GCHP is getting wider with the appearances of the global energy crisis and the increasing environmental problems [1]. Over the recent decades, the GCHP is receiving increasing interest because of its potential to reduce primary energy consumption and thus reduce emissions of greenhouse gases [2–4]. According to the reports of the 2005 World Geothermal Congress, from 2000 to 2005, the installed power capacity and the number of GCHP systems had increased by 198% and 272%, respectively. Moreover, the total number of the GCHP system installations had exceeded 170,000 in 33 countries by 2005 [5].

The GCHP utilizes the ground as a heat source in heating and a heat sink in cooling mode operation. In the heating mode, a GCHP absorbs heat from the ground and uses it to heat the house or building. In the cooling mode, heat is absorbed from the conditioned space and transferred to the earth through its ground heat exchanger (GHE) [6–8]. The GHE used in conjunction with a closed-loop GCHP system consists of a system of long plastic pipes buried vertically or horizontally in the ground. Generally, the ground is a more stable heat exchange medium than air. Moreover, geothermal energy is essentially unlimited and always available. Therefore, compared to conventional methods, GCHP system is an efficient alternative of conditioning residential and commercial buildings.

Abbreviations: COP, coefficient of performance; GCHP, ground-coupled heat pump; GHE, ground heat exchanger.

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Nomenclature

COP_{hp}	Coefficient of performance of the heat pump (−)
COP_{sys}	Coefficient of performance of the overall system (−)
$\cos\varphi$	Power factor (−)
C_p	Specific heat of the water-antifreeze (kJ/kg.K)
I_c	Current of the compressor (A)
I_p	Current of the circulating pump (A)
L_0	Depth of the U-pipe (m)
$\dot{m}$	Mass flow rate of the water-antifreeze solution (kg/s)
n	Number of branch pipes (−)
P_{rr}	Proportion of recovery time and running time (−)
Q_c	Average heat exchanged by the GHE (kW)
Q_E	Heat exchanged by the heat pump unit in the heating mode(i.e. GHE load, kW)
q_L	Heat flux of unit pipe length (W)
U_c	Voltage of the compressor (V)
U_p	Voltage of the circulating pump (V)
V	Volumetric flow rate of the circulating water-antifreeze in the U-pipe (m^3/s)
W_c	Power input of the compressor (kW)
W_p	Power input of the water-antifreeze circulating pump (kW)
$W_{\Sigma p}$	Total power of circulating pumps (kW)
T_{in}	Average temperature of water-antifreeze solution at inlet of GCHP (°C)
T_{out}	Average temperature of water-antifreeze solution at outlet of GCHP (°C)
ρ	Density of the circulating water-antifreeze in the U-pipe (kg/m^3)

General speaking, A GCHP system consists of a heat pump unit coupled with ground heat exchangers (GHEs). Its coefficient of performance (COP) is obviously higher than conventional air conditioning systems due to that the GCHP system uses the ground as a heat sink or source, whose temperatures keeps at a stable state throughout the year [9].

In the literature, several researches were focused on different aspects of the GCHP system, such as design [10–12], performance [6–8,13–15] and economic analysis [16,17]. Moreover, case studies [18,19], handbooks and standards [20,21] for installation procedures of GCHP systems are also available. However, most existing studies of GCHP systems were concentrated on theoretical and simulation. Only a few of researchers investigated the practical operation performance of GCHP systems. Hwang et al. [22] investigated the actual cooling performance of a GCHP system installed in Korea in 1 day operation. And the COP of the whole GCHP system was found to be 5.9 at 65% for partial load conditions. Li et al. [23] applied experiments to investigate the operation performance of a GCHP system with conventional boreholes and foundation pile GHE. The results showed that the influence of the radius by the borehole of GHE was about 2 m. Moreover, they pointed out that the ground can be used as the heat source/sink for high energy efficiency GCHP systems. Man et al. [9] performed several detailed on-site experiments on a GCHP test rig located in temperate zone. The results indicated that the performance of GCHP system was affected by its operation conditions and modes. Pulat et al. [24] evaluated the performance of a GCHP with horizontal GHE installed in Turkey under winter climatic condition. The COP of the entire system and the heat pump unit were found to be 2.46–2.58 and 4.03–4.18, respectively. Wang et al. [25] developed a novel constant heating-temperature method for in situ thermal response test based on measurement of natural ground temperature distributions.

In summary, all the experimental studies of GCHP systems were focused on testing the GHE thermal responses and the ground thermal properties. And, the performance evaluation of GCHP system was just based on limited amount of data recorded in a short time duration. The detailed experimental study on the performance of GCHP system in karst region for different operation modes is still in the preliminary stage. In this study, a GCHP experimental test rig with comprehensive data acquisition equipments is set up according to the geological conditions of a karst region of Guilin in China. Consequently, detailed experiments on this test rig for cooling and heating provision are carried out. Several operation parameters are automatically recorded during the testing process. The parameters include temperatures of boreholes at different depths, the temperatures, pressures and flow rates of water circulating in heat pumps and ground heat exchangers (GHEs), and the power consumption of both heat pump and circulating pumps. Based on the experimental data, operation performances of GCHP system for both cooling and heating provision with different operation modes are evaluated.

2. Description of the GCHP experimental system

The GCHP experimental system was installed on the campus of Guilin University of Technology, China. And its schematic diagram is shown in Fig. 1. It mainly consists of five components, such as the GHEs, the heat pump unit, fan coil units, circulating water pumps and data acquisition instruments, which are labeled with 3, 4, 5, 1, and 7 in Fig. 1, respectively.

2.1. GHEs

In the GCHP applications, the GHEs undertake the dissipation or extraction of thermal energy from the ground. Operation of the GHEs induces simultaneous heat and moisture flows in the surrounding soils. The exchange of heat between GHEs and surrounding soils is primarily accomplished by heat conduction and to a certain degree by moisture migration. Consequently, soil types and temperature as well as moisture gradients have significant influences on the heat-exchange process [26]. Accordingly, it is essential to investigate the soil properties of the experimental site.

The experimental site was located on the campus of Guilin University of Technology (25.27°N, 110.29°E), which was at the confluence at Lijiang River II stage terrace and Pingfeng hill. The soil stratigraphy was determined through a site investigation program, which is shown as Fig. 2a. Undisturbed soil specimens were sampled (as shown in Fig. 2b) and tested in the laboratory from which the basic soil properties such as moisture density, specific gravity, water content, thermal conductivity, heat capacity, and thermal diffusivity were measured. The corresponding results, which constitute of the soil stratigraphy, are shown in Table 1. As can be seen in Table 1, the soil stratigraphy mainly consists of two major soil layers: an eluvial-colluvial red clay with thickness of approximately 9.0 m (regular font in Table 1) and an underlying carbonate bedrock to the depth of 32.0 m (bold font in Table). The result form site investigation shows that the test site was rich in karst caves and the ground water. The ground water table fluctuated between 5.0 and 6.0 m below the ground during the testing period. The average temperature across the full borehole depth was tested to be 20.7 °C.

After considering the geological conditions of the experimental site, the research objectives, and the associated installation cost, it was decided to adopt a composite ground heat exchanger system of GCHP with both horizontal- and vertical-type exchangers. As can be seen in Fig. 1, the test site was divided into 3 zones: A, B, and C. Zones A and B were installed with 10 vertical-type exchangers labeled as