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Experimental studies on a ground coupled heat pump with solar thermal collectors for space heating

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ABSTRACT

This paper presents experimental studies on a solar-assisted ground coupled heat pump (SAGCHP) system for space heating. The system was installed at the Hebei Academy of Sciences in Shijiazhuang (lat. N38°03′, long. E114°26′), China. Solar collectors are in series connection with the borehole array through plate heat exchangers. Four operation modes of the system were investigated throughout the coldest period in winter (Dec 5th to Dec 27th). The heat pump performance, borehole temperature distributions and solar colleting characteristics of the SAGCHP system are analyzed and compared when the system worked in continuous or intermittent modes with or without solar-assisted heating. The SAGCHP system is proved to perform space heating with high energy efficiency and satisfactory solar fraction, which is a promising substitute for the conventional heating systems. It is also recommended to use the collected solar thermal energy as an alternative source for the heat pump instead of recharging boreholes for heat storage because of the enormous heat capacity of the earth.

1. Introduction

In recent years, a lot work has been done to incorporate renewable applications into residential and commercial buildings. This concern is prompted by the ever-aggravating energy demand and global warming all over the world. In China, buildings are expected to account for more than 35% of the national energy use by the year 2020, where heating, ventilation and air-conditioning systems will contribute more than 65% of the consumption [1,2]. Geothermal heat pump systems with vertical/horizontal heat exchangers, known as ground coupled heat pump (GCHP) systems, are considered relatively efficient for heating, air-conditioning or hot water supply. Because underground soil temperature is rather constant compared with ambient air, the ground is regarded as an ideal renewable energy-source for the heat pump system. However, geothermal potential as heat source or sink could be impaired under short-time continuous operation or long-term imbalanced-load conditions, which has been observed and discussed by many researchers [3–6]. As a result, solar-assisted ground coupled heating (SAGCHP) systems were proposed to broaden the application of the GCHP systems in areas with large heating demands.

Since 1956 when the SAGCHP was introduced [7], simulation studies were carried out by many researchers. Zaheer et al. proposed a design criterion for solar-assisted heat pump systems based on modeling and optimization [8]. Investigations on different system configurations and control strategies of the GCHP with solar collectors were performed by Kjellsson et al. [9]. The SAGCHP systems with either short-term or seasonal storage were also discussed to make full use of the collected solar heat. Zongwei Han et al. designed and simulated a solar-assisted ground-source heat-pump (SAGSHP) heating system with latent heat energy storage tank (LHEST) in Harbin [10].

Up to now, most researchers focused on the simulative or theoretical studies on the SAGCHP system, while a few researchers investigated practical operation performance by experiments. Onder Ogzener et al. [11,12] performed space heating operations of a solar-assisted ground-source heat-pump system for a greenhouse in Turkey. The heating coefficient of the heat pump (COP_{hp}) is between 2.00 and 3.13 depending on weather conditions. Solar-assisted heating was proved to be necessary in order to secure

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the temperature requirement in the greenhouse. Experimental studies were performed for a solar-ground source heat pump (SGSHP) system with a vertical double-spiral coil (VDSC) ground heat exchanger (GHX) by Bi et al. [13,14]. The COPs of the two heating modes including an SSHP (solar energy-source heat pump) and a GSHP (ground-source heat-pump) were 2.73 and 2.83, respectively. The SSHP mode showed better collecting efficiency compared with the solar direct heating systems. V. Trillat-Berdal et al. [15] presented the operational results of a solar-assisted heat pump system for providing space heating and hot water to a private residence. During the system operation, energy injected into the ground can recover 34% of the heat extracted for heating in winter, and the heat pump's coefficient of performance (COP) in heating mode had an average value of 3.75. A SAGCHP system with floor heating terminals was studied by Wang et al. [16]. The solar fraction of the system reached to 49.7% in the heating period and the soil temperature was increased to a higher level due to the seasonal storage after the whole year operation. However, the temperature ascent was controlled within a reasonable range to preserve the soil thermal balance. Similar results of the SAGCHP system with seasonal storage could also be observed in the studies conducted by Huajun Wang et al. [17,18]. Recently, Bakirci et al. [19] performed experimental investigation on a solar-ground source heat pump system during the heating period of a cold region in Turkey. The heating efficiency of the system as well as economic analysis proved its applicability in residential heating, but detailed underground thermal reactions caused by the system operation were not reported.

According to the above introduction, it can be clearly seen that the SAGCHP technology needs more experimental results to verify the theoretical and simulative results. Among limited experimental studies, detailed experimental study on the performance of the SAGCHP system for different operational modes to provide space heating in cold areas of China (Cold areas in China should be the regions where the averaged air temperature of the coldest month is lower than −3.0 °C, the number of months of which the averaged air temperature is higher than 10 °C is not more than 5, and the average yearly temperature does not exceed 5.0 °C [20]) is still not available. In this paper, an experimental test rig with comprehensive data acquisition equipment installed at Hebei Academy of Sciences in China is reported. Based on experimental data and relevant theories, thermal responses of the borehole and heating performances of the system under different working modes are estimated and analyzed. Consequently, the application potential of the SAGCHP in the cold area of China is verified and preferable utilization method of solar thermal energy will also be discussed.

2. System description

The SAGCHP experimental system is developed inside the renewable energy laboratory of the Academy. A schematic diagram of the system and the solar collector are shown in Fig. 1 and Fig. 2. The system consists of five main components, i.e. the ground heat exchanger (GHE), the water-to-water heat pump unit, fan coils, circulating water pumps and evacuated-tube solar collectors.

- **The ground heat exchanger (GHE)**: In the GHE, five single U-tubes in parallel were buried in the boreholes with 5 m interval and 21 m depth. High-density polyethylene (HDPE) tubes with 32 mm outside diameter and 25 mm insider diameter are used with water as heat transfer fluid. In order to prevent surface water penetration and potential groundwater contamination, all boreholes are completely backfilled by grout mixed with drilling mud, cement and sand in specific proportions. According to the geological report, the on-site geological conditions are: clay layer from surface to 28 m deep and pebble gravel layer from 28 m to 40 m deep. The thermal conductivity and diffusivity of soil around the boreholes are estimated to be 1.9 (W/m K) and 0.71×10^{-6} (m^2/s), respectively.
- **The heat pump unit**: The heat pump utilized in this experimental system is a water-to-water heat pump DNQWSR-4 manufactured by Lu Huan Company with R22 as refrigerant. The rated heating capacity is 4.6 kW with load side inlet water temperature of 40 °C.
- **The fan coil units**: Two series-connected fan coil units (Model: FP-12.4LMZ; Production of GRAD) provide space heating for a single room of 36 m^2 area. The total rated air flow rate is 2500 m^3/h.
- **Solar collectors**: Four evacuated solar collector modules are mounted on the top of the laboratory building. Each module is composed of 25 pipes with 1800 mm length and 70 mm diameter. Solar collectors with gross area of 13.6 m^2 facing south are installed with 0° azimuth angle and 38° tilt angle (about the local latitude).
- **The circulating water pumps**: The water circulating loops consist of a GHE side loop, a fan coil side loop and a solar side loop. The circulating pumps chosen for the GHE and the fan coil side loops are constant-speed pumps with maximum head of 5 m and maximum flow rate of 65 l/min (Model: LRS40-6; Produced by Tianfeng Company). The solar loop circulating pump is a constant-speed pump with maximum water head of 9 m and maximum flow rate of 95 l/min (Model: LRS40/9; Produced by BaiYi Company).

3. Measurement and uncertainty analysis

3.1. Data acquisition system

The data acquisition system consists of the temperature measurement system, the flow rate measurement equipment, the power consumption measurement system and the solar radiation measurement equipment.

- **Temperature system**: 6 Pt100 sensors are buried together with the GHE to measure the temperature distribution at the center of the boreholes according to Fig. 3. Additional 6 identical three-wire Pt100 temperature sensors are installed at the water pipelines' inlets and outlets of the evaporator, the condenser and the solar collector array. The Pt100 sensors (Model: WZP-201) could be applied to the temperature range of −50–100 °C and the accuracy grade is 0.5%.
- **Flow rate system**: Because the SAGCHP system works with constant flow in all the water circulating loops, the flow rate is recorded by an ultrasonic flow meter (Model: JTLL-II). The equipment could be applied to fluids with the temperature range from −40 °C to +160 °C and the pipeline diameter from 50 mm to 1500 mm. The accuracy grade is 1.0%.
- **Power system**: The operational power consumption of three circulating pumps and the compressor in the heat pump can be measured by equipment consisting of current transformers and tri-phase active power transmitters with an accuracy grade of 0.2%.
- **Solar system**: The total solar radiation on the inclined surface of solar collectors could be recorded by a pyranometer (Model: TBQ-2) with a sensitivity of 7 $\mu V/Wm^{-2}$ and range of 0–2000 W/m^2.

Data transmitted from the flow meter and the pyranometer could be logged by their implanted commercial hardware and software, while the temperature and the power consumption