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Experimental performance analysis of a solar assisted ground source heat pump system under different heating operation modes

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HIGHLIGHTS

- A full scale experiment system of a solar assisted ground source heat pump is reported.
- Six cases are investigated experimentally for the system.
- The solar heat will improve the soil temperature recovery rate.
- The solar thermal storage water tank is benefit to stably operation of the system.
- Increasing the flow rate in water tank will decrease electricity consumption of the system.

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ABSTRACT

This paper presents an experimental study on the influence of operation modes on the heating performance of a solar assisted ground source heat pump system (SAGSHPS). Through experiments conducted in January, the characteristics of the SAGSHPS were investigated under different heating operation modes. The results indicate that the solar thermal could be used to accelerate the soil recovery when the heat pump unit is turned off, but the duration of solar use to recharge boreholes should be optimized according to the water temperature in the solar heat storage water tank to avoid unnecessary power consumption of the circulation pump. In addition, the solar heat storage water tank is beneficial for the stable operation of the SAGSHPS. The volumetric flow rate in the water tank has a significant impact on the electricity consumption of the SAGSHPS. From comprehensive analysis of the integral effect of the SAGSHPS under different modes, the mode in which the water tank is connected with the ground heat exchangers (GHES) in series is the recommended mode for the SAGSHPS in the coldest month in Dalian.

1. Introduction

It is estimated that the number of ground source heat pump system (GSHPS) installations has been increased four times over worldwide in the past decade [1]. However, it has been reported that the geothermal potential as a heat source or sink for the heat pump unit could be impaired under short-time continuous operation modes or long-term imbalanced-load conditions [2–6]. In the case of heating-dominated buildings, thermal heat depletion of the soil would decrease the evaporator inlet fluid temperature of the heat pump and the coefficient of performance (COP) of the installation would be decrease [7]. One of the main solutions to this problem is having a hybrid system [8] integrate the supplementary components (e.g. solar collectors) with the GSHPS.

The heat pump system, which couples geothermal and solar thermal energy, is called a solar assisted ground source heat pump system (SAGSHPS). In past decades, most studies have focused on the feasibility assessment and performance of the SAGSHPS. A system simulation approach to assess the feasibility of a ground heat pump coupled with solar thermal collectors in heating-dominated buildings was presented by Chiasson and Yavuzturk [9]. The simulation results showed that the SAGSHPS could reduce the borehole length at the design step. An experimental performance study and exergoeconomic analysis of a SAGSHPS for greenhouse heating were performed by Ozgener et al. [10,11]. The COP for the entire system was found to be 5–20% lower than the COP for the heat pump. Based on the experimental study and simulation of a ground-coupled heat pump combined with thermal solar collectors, V. Trillat-Berdal et al. [12,13] analyzed the energy-

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related behavior of the installation and obtained the best configuration(s) of the GEOSOL process in terms of energy, economic and environmental performances. H.J. Wang et al. [14,15] and X. Wang et al. [16] experimentally studied the performance of underground thermal storage in a solar-ground coupled heat pump system (SGCHPS) for residential buildings in Tianjin and Harbin, respectively. In recent years, K. Bakirci et al. [17] experimentally investigated the performance of a solar-ground source heat pump system in Turkey. The coefficient of performance of the heat pump and system were found to be in the range of 3.0–3.4 and 2.7–3.0, respectively. X. Chen and H.X. Yang [18] presented the numerical simulation of a solar assisted ground coupled heat pump (SAGCHP) system. They suggested that the optimized ratio of the borehole length to the solar collector area was 6.6 $\mathrm{m \cdot m^{-2}}$. Similar result, 7.64 $\mathrm{m \cdot m^{-2}}$, can be found in the literature [19]. E.Y. Wang et al. [20] developed a simulation model to predict the multi-year performance of a novel hybrid solar GSHPS composed of a GSHPS and a solar assisted GSHPS used in an office building. F. Busato et al. [21] reported two years of recorded data for a heat pump system combined with multiple sources, including ground heat, solar heat, and heat recovery, in a new school building. The influence of the solar heat on the operation temperatures of the source or the sink side of the heat pump in a SAGSHPS has been analyzed by P. Peter et al. [22].

However, specific investigations for the effect of operating modes on the performance of the SAGSHPS are relatively scarce. Based on the simulation studies of different configurations and control strategies of the GSHPS combined with solar collectors, five operation modes of the SAGSHPS were performed by Kjellsson et al. [23]. They concluded that the utilization of solar thermal energy should be first directed to the heat pump and then to the borehole. Chen et al. [24] investigated four operation modes of a SAGSHPS for space heating, in which the system worked in the continuous or intermittent modes with or without solar assisted heating. They also recommended that solar thermal energy, as an alternative source for the heat pump, is more beneficial than recharging boreholes for heat storage. Lazzarin [25] studied two arrangements of dual source heat pump systems: air source heat pumps combined with solar collectors; and ground source heat pumps coupled with solar collectors. A higher COP could be achieved when the solar system was connected in series with the heat pump compared to using the solar system as a dual source for the heat pump. The performance of the solar heat storage water tank in a SAGSHPS was not investigated in their research. Although Yang et al. [26] conducted a numerical simulation of the performance of a solar-earth source heat pump system with or without water tank in an alternate or combined mode, the experimental validation could not be given. Thus it is necessary to provide more practical data for the SAGSHPS with a solar heat storage water tank to improve the flexibility and stability of this system as well as to validate the feasibility of this system.

In this paper, a solar assisted ground source heat pump system with a 1 $\mathrm{m^3}$ solar heat storage water tank and 9 single U-type ground heat exchangers, installed at Dalian University of Technology in China, is reported. The compositions of the SAGSHPS and the conversion of the various operating modes are described. To investigate the feasibility of using solar thermal to accelerate underground soil recovery, a special case of using solar energy to recharge the boreholes is designed for the condition when the heat pump unit is turned off at night. Based on the experimental results of the SAGSHPS under different heating operation modes, the performance of the SAGSHPS and the GSHPS are analyzed and compared. Finally, the best operation mode for the SAGSHPS is recommended in the coldest month in Dalian.

2. Description of the experiment system

2.1. Components of the SAGSHPS

The schematic of the SAGSHPS is shown in Fig. 1. The main equipment of the SAGSHPS includes heat pipe evacuated tube collectors (HPETC), solar heat storage water tank (SHSWT), ground heat exchangers (GHEs), heat pump unit (HPU) and air handling units (AHU). The main parameters of the device are presented in Table 1.

2.2. Data measurement system

According to the test parameters, test data can be divided into four categories: temperature, flow rate, power, and solar radiation.

The PT100 temperature sensors designed by Tsinghua Tongfang Company are used to test the pipeline temperature at the inlets and outlets of the evaporator, the GHEs, the solar collectors and the SHSWT. There are 9 boreholes with a single U-type tube (W1–W9) and 1 borehole without a single U-type tube (M1), which is 2.8 m away from the GHE W1 and can be used to test the soil temperature near the ground heat exchanger, for the SAGSHPS, as shown in Fig. 2(a). To test the borehole wall temperature at different depths of the boreholes, the GHEs (W1 with the depth of 75 m, W3 with the depth of 50 m and W4 with the depth of 25 m) and a borehole (M1) are studied in detail. The PT100 temperature sensor distributions in W1, W3, W4 and M1 are shown in Fig. 2(b). The range of the temperature sensors is from −25 °C to +100 °C,and the permissible error is ±0.3 °C. The measured temperature data are transmitted to the computer and saved automatically through a data logging device from Luban software at a time interval of 5 min.

The Rotameter flow meters with ranges of 0–6300 l/h and 0–630 l/h and an accuracy grade of 1.6% are utilized for volumetric flow rate testing.

The power consumption of the compressor is measured by a digital multimeter, for which the current range is from 0 to 20 A, with an accuracy grade of 1%, and the voltage range is from 0 to 600 V, with an accuracy grade of 2%. The measured flow rate and the power data are recorded manually at a time interval of 5 min.

Solar radiation is measured by a portable automatic weather station with an outdoor temperature range of −50 °C to +80 °C and a permissible error of ±0.1 °C and a solar radiation range of 0–2000 W and an accuracy grade of ±5%. The measured solar radiation data are recorded automatically at a time interval of 5 min.

2.3. Uncertainty analysis

In this experiment, uncertainty analysis of error estimations for both measured and calculated parameters is carried out. The measured parameters are discussed in Section 2.2. The calculated parameters include the heat absorption from the evaporator (Q_e), the power consumption of the compressor (W_{com}), the $\mathrm{COP_{hp}}$ (coefficient of performance of the heat pump), the $\mathrm{COP_{sys}}$ (coefficient of performance of the entire system), the useful solar heat (Q_{sc}), the efficiency of the solar collectors (η_{sc}), the heat supply from the solar heat storage water tank (Q_{wt}), the solar fraction (f_{sc}), the extracted heat from the ground heat exchangers (Q_g), the geothermal fraction (f_g) and the soil temperature recovery rate (r_{st}), which are calculated by Eqs. (1)–(11).

$$Q_e = c_w \dot{m}_{\mathrm{we}} (T_{\mathrm{ei}} - T_{\mathrm{eo}}) \tag{1}$$