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Experimental investigations of the performance of a solar-ground source heat pump system operated in heating modes

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ABSTRACT

Solar-ground source heat pump system (SGSHPS) is a new type of high efficiency, energy saving and environmental protection air-conditioning technology. In this paper, experimental studies and numerical simulation on the performance of a SGSHPS operated in different heating modes were carried out. The experimental system was installed in Nanjing of China and solar collectors were coupled with ground heat exchangers (GHE) through an insulated water tank. Four operation modes including ground source heat pump (GSHP), combined operation mode, day and night alternate operation mode and solar U-tube feeding heat alternate operation mode were investigated during winter season. The heat pump performance, solar collecting performance and borehole wall temperature variations were analyzed and compared for various modes. The experimental results indicate that for the combined operation mode, the system operation efficiency during day can be improved by the assistance of solar energy, and the excess solar energy collected during day can be stored in ground by the GHE to improve the operation performance of GSHP during night. The proportions of heat source burdened by solar and geothermal energy are 43.3% and 50.2% respectively. For the alternate operation modes, the temperature resumption of ground surrounding the GHE can be well achieved due to the intermittent heat extraction of GHE or feeding solar heat into ground and thus the overall utilization efficiency of solar and geothermal energy can be improved greatly. During the whole experimental period, the average COPs are 2.37 and 2.72 for GSHP and SAHP operation mode respectively, and the corresponding parameters are 2.69, 2.65 and 2.56 for the combined operation mode, day and night alternate operation mode and solar U-tube feeding heat alternate operation mode, respectively. The average solar collecting efficiency are 43.6%, 47.3% and 38.8% for the combined operation mode, SAHP operation mode and solar U-tube feeding heat operation mode, respectively. Based on the unit modeling, a dynamic simulation program was constructed to investigate the seasonal performance of the SGSHPS operated in different heating modes, the simulation results show that the seasonal average COP are 3.67, 3.64, 3.52 and 3.48 for the combined operation, day and night alternate operation, solar U-tube feeding heat and GSHP mode, respectively. From the view of improving the overall efficiency and increasing heat source fraction of solar energy, the combined operation mode is the best.

1. Introduction

Recently, global warming has led to explore alternative technologies to convert energy in a more efficient and clean way [1–3]. Amongst those that use natural energy are ground source heat pump (GSHP) systems, which utilize temperature differences under natural conditions. GSHP systems have become increasingly popular for both residential and commercial space heating and hot water applications. The main advantage of using the ground as the system's source or sink is that this environment benefits from a relatively constant mean temperature when compared with ambient air. This can comprehensively improve the thermal performance of the system and therefore reduce operating costs. Thus, GSHP systems have been recognized to provide viable, environmentally friendly alternatives to conventional unitary systems.

Currently, there is a lot of work that has been devoted to investigating the GSHP. Adaro et al. [4] designed and evaluated a heating system for typical production greenhouse energy with

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Nomenclature

a_s	ground thermal diffusivity (m^2/s)
A_c	effective collecting area (m^2)
A_s	annual ground surface temperature amplitude (°C)
c_p	mass specific heat of water (J/kg °C)
COP	coefficient of performance (–)
GAT	ground average temperature (–)
GHE	ground heat exchanger (–)
GSHP	ground-source heat pump (–)
HDPE	high density polyethylene (–)
I_c	incident solar radiation (W/m^2)
Q_{ev}	heat extraction rate from the GHE to the evaporator (W)
Q_g	heat transfer rate of GHE (W)
Q_h	condenser load (W)
Q_s	heat storage in water tank (W)
Q_u	useful energy gain of solar collector (W)
SAHP	solar assisted heat pump (–)
SGSHPS	solar-ground source heat pump system (–)
$T_{c,in}$	inlet fluid temperature of solar collector (°C)
$T_{c,out}$	outlet fluid temperature of solar collector (°C)
$T_{con,in}$	inlet fluid temperature of condenser (°C)
$T_{con,out}$	outlet fluid temperature of condenser (°C)
$T_{ev,in}$	inlet fluid temperature of evaporator (°C)
$T_{ev,out}$	outlet fluid temperature of evaporator (°C)
$T_{g,in}$	inlet fluid temperature of GHE (°C)
$T_{g,out}$	outlet fluid temperature of GHE (°C)
$T_{s,in}$	inlet fluid temperature of water tank (°C)
$T_{s,out}$	outlet fluid temperature of water tank (°C)
T_M	annual average ground surface temperature (°C)
V_c	volume flow rate of solar collector (m^3/s)
V_g	volume flow rate of GHE (m^3/s)
V_s	volume flow rate of water tank circulation (m^3/s)
V_{ev}	volume flow rate of evaporator side (m^3/s)
V_{con}	volume flow rate of condenser side (m^3/s)
W	power consumption (W)
z	depth (m)

Greek letters

ρ	density (kg/m^3)
τ	time (s)
ω	angular frequency of annual temperature variations ($\omega = 0.00017\ h^{-1}$).
η	efficiency (–)

Subscripts

c	collector
con	condenser
ev	evaporator
g	ground heat exchanger
h	heating load
s	soil
in	inlet
out	outlet

energy-conservation measures by means of geothermal energy in the southern part of Cordoba, Argentina. The results of tests carried out during 3 years were presented. Sanner et al. [5] reviewed the development status of GSHP and underground thermal energy storage in Europe, which included GHE design and installation criteria, in situ thermal response test for the determination of ground thermal properties, thermally enhanced grouting materials and the storage of solar or waste heat. Florides et al. [6] described various types of GHE, the different calculation and performance evaluation models of GHE were presented and several models for calculating the thermal properties of vertical U-tube GHE have also been analyzed. Congedo et al. [7] discussed the main parameters that influence the performance of horizontal GHE by CFD simulations. Three different geometry configurations including linear single tube, helical tube and slinky tube have been analyzed for different working conditions and burying depth. Zhang et al. [8] presented more sophisticated mathematical models that take into account the impact of the GHE geometry as well as the groundwater movement on the heat transfer of the GHE. Lee et al. [9] introduced a GSHP integrated with a prestressed high-strength concrete pile used in the buildings foundation. Its thermal performance was analyzed through experiments in summer. Sarbu et al. [10] performed a general introduction on the GSHP and its development, and a detailed description of the surface water, ground-water, and ground-coupled heat pumps were conducted. The most typical simulation and ground thermal response test models for the vertical GHE currently available were summarized.

However, the performance of GSHP system operated in heating-dominated conditions could be impaired under short-time continuous operation or long-term imbalanced load conditions. For short-time continuous operation, the ground temperature near the GHE gradually drops due to the continuous heat extraction of GHE from ground. In turn, the lower ground temperature decreases the coefficient of performance (COP) of the heat pump. For long-term imbalanced load conditions, the annual heat extracted from and released to the ground are imbalanced, that is, the annual heat extracted from the ground greatly exceeds that released to the ground, which also results in the drop of ground temperature year by year. Thus, it might be advantageous to inject heat into the borehole to increase the ground temperature and heat pump performance. One possible way is to inject solar energy by using U-tube to ground. As a result, solar-ground source heat pump systems (SGSHPS) were proposed to broaden the application of the GSHP systems in areas with large heating demands.

The idea of SGSHPS, which combined the use of solar collector and GHE, and thus the excess solar energy collected during daytime can be saved in the ground by the GHE, was firstly put forward by Penrod [11]. Subsequently a complete procedure for designing the proposed SGSHPS were introduced [12,13]. Kjellsson et al. [14] investigated the different system configurations and control strategies of the GSHP with solar collectors. The SGSHPS with either short-term or seasonal storage were also discussed to make full use of the collected solar heat. Han et al. [15] designed and simulated a SGSHPS with latent heat energy storage tank in Harbin. Chiasson et al. [16] performed a 20-year life-cycle cost analysis to evaluate the economics of GSHP systems coupled to thermal solar collectors for six different climates in the U.S. They concluded that GSHP systems combined with solar collectors are economically viable for heating-dominated climates. Si et al. [17] presented a novel SGSHPS designed for an office building in Beijing. An operation strategy of the system in transition seasons was proposed to keep the heat pump off and connect GHE directly to fan coils. The important parameters of the system were optimized by TRNSYS and the operation strategy was shown to be feasible. Chen et al. [18,19] performed the optimization process on the TRNSYS platform by simulating the influence of solar collector area on the total borehole length and system performance. The simulating results showed that the optimized system under the specified load conditions has a collector area of 40 m^2 and a borehole length of 264 m. Pärisch et al. [20] investigated the heat pump behavior under non-standard conditions for the operation of GSHP in combination with solar collectors. The higher temperatures and varying flow rates in comparison to non-solar systems have been taken into account. The results showed that rising source temperatures do only