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Technical Note

A case study of underground thermal storage in a solar-ground coupled heat pump system for residential buildings

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ABSTRACT

This paper presents a case study of underground thermal storage in a solar-ground coupled heat pump system (SGCHPS) for residential buildings. Based on the experimental results, the operation performance is simulated by the unit modelling. The results show that the performance of underground thermal storage of SGCHPS depends strongly on the intensity of the solar radiation and the matching between the water tank volume and the area of solar collectors. Compared with the solar radiation, the variations of the water tank temperature and the ground temperature raise lag behind and keep several peaks during the day time. In the present study, the experimental efficiency of underground thermal storage based on the absorbed solar energy by the collectors reaches 76%. For the similar design of SGCHPS, it is suggested that the optimal ratio between the tank volume and the area of solar collectors should range from 20 to 40 L/m^2.

1. Introduction

The energy requirements for the space heating of buildings in winter can be supplied by the solar radiation, using different patterns of seasonal thermal storage. Earlier Bose et al. [1] studied the performance of a low-cost solar-assisted heat pump system based on the geothermal energy storage. Similar applications have been achieved extensively in Sweden, Germany, and the Netherlands [2–5].

The optimization and simulation on the solar-ground coupled heat pump systems (SGCHPS) have been paid much academic attention. For instance, Oliveti et al. [6], Ozgener and Hepbasli [7,8], Yang et al. [9] and Trillat-Berdal et al. [10] analyzed the performance of SGCHPS with different operation modes or purposes. A general goal in these efforts is to improve the energy efficiency and decrease the system investment as much as possible.

In the present study, an experimental SGCHPS is built in a residential building in the countryside of Tianjin, China. Different from the urban, the cooling load of rural residential buildings is much lower than the heating load, due to an especial climate with cool summer, cold winter and short transition seasons. A high initial ground temperature is favorable for the heat extraction by geothermal heat exchangers of GCHPS during the space heating. Without the extra heat injection into the ground in summer, the ground temperature would tend to be decreasing gradually. Thus a basic task of solar collectors in SGCHPS is to prevent such an undesired situation. The interest of this paper lies in the analysis of the preliminary experimental results. Further, based on the unit modelling, the performance of underground thermal storage of SGCHPS is simulated and its parametric effects are discussed, which are expected to be helpful for the next improvement work.

2. Experimental investigations

2.1. Overview

A general view of the experimental SGCHPS is shown in Fig. 1. It is installed in a 120 m^2 family house in Jinghai county, Tianjin (latitude 39.13° N, longitude 117.2° E). It mainly consists of the solar collection system, the underground thermal storage system, the indoor air-conditioning system, and a data acquisition system (Fig. 2).

The solar collection system includes the rooftop solar thermal collectors, a circulating pump, an 800 L water storage tank, a 50 L expansion water tank, and connecting pipes. Solar collectors are south-oriented and the tilted angle is 40°, with a 25 m^2 effective collection area. During the operation, an ON/OFF circulating controller is used. The maximum flow rate is 800 L/h. When the outlet fluid temperature of solar collectors exceeds a set value (e.g. 50 °C), the circulating pump starts, and the absorbed solar heat is transferred to the water storage tank through the coil heat exchanger. Once the temperature difference between the outlet and inlet of solar collectors is lower than a set value (e.g. 3 °C), the circulating

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Nomenclature

A	area (m^2)
A_s	surface area of the tank or amplitude (m^2 or °C)
c_p	specific heat (W/kg K)
d	bore diameter (m)
Fo	Fourier number
G	G functions
H	borehole depth (m)
I	solar radiation (W/m^2)
K_v	vegetation coefficient
M	water mass (kg)
m	mass (kg)
p	radius ratio
Q	heat energy (W)
R_{con}	heat-transfer resistance (K/W)
R_{fill}	resistance of the ground or refilled materials (K/W)
R_{pipe}	conduction resistance of pipe walls (K/W)
R_{total}	equivalent borehole resistance (K/W)
t	temperature (°C)
U_s	heat-transfer coefficient (W/m^2 K)
x	depth (m)

Greek symbols

α	thermal diffusivity (m^2/s)
λ_s	thermal conductivity (W/m K)
η	efficiency (%)
τ	time (s)

Subscripts

a	ambient or equation coefficient
a0, a1, a2	equation coefficients
b	equation coefficient
c	solar collector
g	ground
in	inlet
loss	heat loss
m	average
out	outlet
s	water tank
w	pipe wall
∞	far field

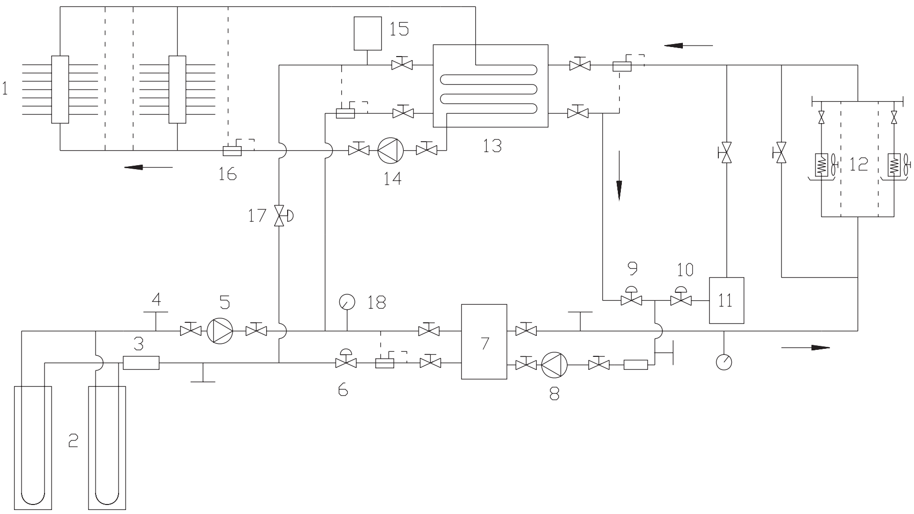
pump stops. For the winter operation, the water–antifreeze mixture (35% glycol solution with the freezing point of −21 °C) is considered for use.

The underground thermal storage system includes four geothermal heat exchangers, a DMR-020 type heat pump unit, and two circulating pumps. The maximum flow rate of circulating pumps is 1800 L/h. The rated cooling and heating capacity of heat pump unit are 11 kW and 10.45 kW, and the corresponding input powers are 2.2 kW and 2.7 kW, respectively. Geothermal heat exchangers are composed of double U-shaped high-density polyethylene pipes (HDPE) with the nominal outer/inner diameter of 32/25 mm. The diameter and depth of each borehole are 220 mm and 50 m, respectively. The borehole configuration is square, with an equal spacing of 2 m. In order to measure the ground temperature variation, six Pt1000-type temperature sensor with ±0.1 °C accuracy are embedded at the depth of 3 m, 5 m, 10 m, 20 m, 35 m, and 50 m of each borehole. Before the installation, all sensors are calibrated by XLR-1 type constant-temperature water bath with ±0.01 °C accuracy.

The indoor air-conditioning system includes four FP-68LMY type fan-coil heat exchangers mounted at a front room and three bedrooms. The rated air output, cooling and heating capacity of fan-coil units are 680 m^3/h, 3.87 kW and 6.35 kW, respectively. Besides the ground temperature sensors, data acquisition system also includes several GRP-type calorimeters, which can record in a timely manner the accumulated heating or cooling energy. Each calorimeter consists of one flow meter with the minimum flow rate of 0.05 L/h and two Pt1000 temperature sensors with ±0.1 °C accuracy. All power consumptions are recorded by the wattmeter.

2.2. Operation modes

Based on the requirements of residential owners, four operation modes are designed in the present SGCHP system. Operation modes



1: solar collectors 2: geothermal heat exchangers 3: water filter 4: temperature sensor
5: circulating pump (P1) 6: valve (V1) 7: heat pump unit 8: circulating pump (P2) 9: valve (V2)
10: valve (V3) 11: auxiliary tank 12: indoor coil pipes 13: water storage tank
14: circulating pump (P3) 15: expansion tank 16: calorimeter 17: valve (V4) 18: pressure meter

Fig. 1. Principle diagram of SGCHPS.