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Thermal equilibrium research of solar seasonal storage system coupling with ground-source heat pump

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ABSTRACT

Although GSHPs (ground-source heat pump system) have already drawn a fair amount of attention in China because of its high energy efficiency and low environmental impact characteristics, some practical problems appeared much more than the expected. COP (Coefficient of Performance) of the GSHPs decreased gradually year after year caused by imbalance energy loads especially in heating-dominated climate zones. So an experiment of solar seasonal storage coupling with GSHP was designed and implemented. In this thermal storage experiment process, a system with 1500 m solar thermal collectors and 580 sets of 120 m deep ground thermal exchangers were taken into research. Thermal equilibrium of soil was studied; relationship between solar energy radiation quantity and thermal storage quantity was discussed. Results showed that solar energy utilization efficiency achieved 50.2% and soil temperature raised by 0.21 °C. TRNSYS 16 was used to simulate thermal storage experiment, and simulation results were well matched with the measured data.

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1. Introduction

GSHPs (Ground-source heat pump system), regarded as a technology of renewable energy [1], which have a good environmental compatibility and low impact on rooms [2,3], is extensively used for heating and cooling systems in buildings [4]. But the soil temperature will decrease gradually after a certain period of operation since the temperature recovery ability of the soil is limited, which will eventually lead to the performance deterioration of heating [5]. This problem is especially obvious in cold regions, where the heat extracted from the soil by the heat pump in winter is much more than that recovered to the soil in summer [6,7]. Furthermore, the deterioration caused by thermal imbalance is even serious if there is only heating demand as in the case of many buildings in cold regions.

It is expected only 20 years reliable and environmentally friendly operation for GSHPs if there is no other special means applied to make the underground thermal balance stable and this situation is not fitting to the buildings service life, which is designed as 50 years [8]. Therefore, it is necessary to take measures to prevent the decrease of the soil temperature and deteriorate of the heating performance.

Solar thermal energy storage system can solve the above problems effectively [9]. Seasonal storage of solar thermal energy coupling with a heat pump has been the subject of many previous investigations and has also found practical applications in the past [10]. Seasonal storage of thermal energy was proposed in the U.S. during the 1960s and research projects were conducted in 1970s. In later 1970s, researchers in the north European countries also began investigating seasonal solar thermal energy storage systems [11]. Early north European experience evolved into an international collaboration on CSHPSS (Central Solar Heating Plants with Seasonal Storage). Rad [12] described a study for examining the viability of hybrid GSHPs that use solar thermal collectors as the supplemental component in heating dominated buildings. It was shown that the solar thermal energy storage in the ground could reduce a large amount of ground heat exchanger (GHX) length. Combining three solar thermal collectors with a total area of 6.81 m^2 to a GSHPs will reduce GHX length by 15%. Congedo [13] pointed out the heat fluxes transferred to and from the ground and the efficiency of the GSHPs. Lee [14] developed a model for GSHPs fitted with a variable-speed compressor and found that the adoption of a variable-speed part-load control to the GSHP in both the cooling and heating mode operations was better. Adaro [15]

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analyzed the possibility of using a constant temperature underground geothermal water source which has been studied as an economic option to solve the problems of plant freezing and plant-growth inhibition. Florides [16] described various types of ground heat exchangers, and found that simulation models may be used successfully for sizing and predicting the thermal performance of ground heat exchangers. Chen [17] analyzed operation patterns of solar-soil compound system based on state-of-the-art studies of solar-soil source heat pump compound system, and found that parallel operation pattern is better for solar-soil compound system. Chen [18] investigated four operation modes of the solar-assisted ground coupled heat pump system throughout the coldest period in winter (Dec 5th to Dec 27th) in Shijiazhuang (lat. N38°03′, long. E114°26′). He recommended using the collected solar thermal energy as an alternative source for the heat pump instead of recharging boreholes for thermal storage because of the enormous heat capacity of the earth. Stojanovic [19] presented the build-up and long-term performance test of a full-scale SAHPS (Solar-Assisted Heat Pump System) for residential heating in Nordic climatic conditions. The authors argued that with an optimized SAHPS control and operation strategy, additional use of circulation pumps and energy (electricity) could be vastly reduced. Wang [20] analyzed the performance of underground thermal storage in a SGCHPS (solar-ground coupled heat pump system) for residential building. The results show that the performance of underground thermal storage of SGCHPS depends strongly on the intensity of solar radiation and the matching up the water tank volume and the area of solar collectors. Li [21] proposed an innovative dual-mode thermochemical sorption energy storage method for seasonal storage of solar thermal energy with little heat losses. Thermodynamic analysis showed that the advanced dual-mode thermochemical sorption energy storage is an effective method for the long-term seasonal storage of solar energy. Xu [22] reports the performance of a demonstrated 2304 m^2 solar-heated greenhouse equipped with a seasonal thermal energy storage system in Shanghai. The system can operate without a heat pump, which can save electricity consumption and further enhance the solar fraction. It was found that in the first operation year, 331.9 GJ was charged, and 208.9 GJ was later extracted for greenhouse space heating.

Above analysis shows that researches have been carried out to solve the problems caused by soil-thermal-imbalance. But the thermal equilibrium research for solar seasonal storage system coupling with GSHP is limited to a certain extent. This paper developed the calculation method for thermal equilibrium. Relationship between solar energy radiation quantity and thermal storage quantity was discussed. And simulation approach used for solar energy storage coupling with GSHP suitable for the heating-dominated climate zones in transition season was presented in this paper.

2. System description

SGSHPs (Solar-ground-source heat pump system) was divided into two independent sub-system in this paper. One is thermal storage system, the other is GSHP heating system. Thermal storage system only runs in the summer or transition season, and the heat pump heating system only runs in winter. This system is mainly composed of four parts: solar collector, water tank, ground thermal exchangers and ground temperature measurement system which can measure and record the soil temperature in different depths automatically. Heating system is mainly composed of soiling heat source heat pump unites and the consumer, shown in Fig. 1.

When thermal storage system was operated in summer, water in the solar collector is heated by receiving solar radiation and is pumped to the water tank by pumps A which are controlled by automatic controller. Then the hot water is pumped to ground thermal exchangers by Pump B to exchange thermal energy with soil. Valve 1, 2, 3, 4, 5, 6 were turned on and valve 7 and 8 were turned off in this situation.

When GSHPs was operated in winter, valve 1, 2, 3, 4, 5, 6 were turned off and valve 7 and 8 were turned on. Stored heat was extracted by buried pipe for building heating.

2.1. Energy equilibrium equation

It is important to research energy transfer process of the SGSHPs, which has great significance for calculating the thermal storage quantity by buried pipe. Temperature of the water input and output of the water tank was measured to calculate the storage heat quantity in experimental period.

Energy equilibrium equation for the thermal storage process can be described as follows:

$$Q_{wt} = Q_{se} - Q_{bp} - Q_d \tag{1}$$

$$Q_{se} = \sum_{i=1}^{n} \overline{R_i} A \tau_i' \tag{2}$$

$$Q_{bp} = \sum_{i=1}^{n} \left(\overline{t_{gi}} - \overline{t_{hi}}\right) L_i \tau_i c_p \rho \tag{3}$$

where, Q_{wt} – Heat quantity of water tank, J;
Q_{se} – Heat quantity of solar collection, J;
Q_{bp} – Thermal storage quantity by buried pipe, J;
Q_d – Dissipated heat quantity, J; Considering Q_d accounts for the proportion of total energy in the experimental process, its value is zero.
$\overline{t_{gi}}$ – Average temperature of supply water, °C;
$\overline{t_{hi}}$ – Average temperature of return water, °C;
L_i – Flow rate of Pump B, m^3/s;
τ_i – Running time of Pump B or thermal storage time, s;
c_p – Specific heat at constant pressure of the water, J/(kg °C);
ρ – Density of water, kg/m^3;
$\overline{R_i}$ – Average intensity of solar radiation, W/m^2;
A – Area of the solar collector, m^2;
τ_i' – Time of solar energy collection, s.

2.2. Main components parameters

Experimental platform located in the new campus of Tianjin Polytechnic University in Tianjin, China. Tianjin belongs to cold area, where winter is long and cold; summer is hot. Annual sunshine hours are 2500–2900 h and the average daily solar radiation intensity is 13.36 MJ/m^2. During the summer, GSHPs was not operated because most teachers, students and staff went on holidays. GSHPs was only used for heating air conditioning for 181,501 m^2 with heating load 14,460 kW and domestic hot water load 3500 kW.

Solar energy collectors are totally 1500 m^2 area, 553 sets, 145 cm × 187 cm in size, with 25 solar collecting tubes in each set. The tube is called vacuum solar energy collecting tube, 5.1 cm diameter.

Water tank, 4.16 m × 2.17 m × 2.66 m in size, is used as a temporary energy storage device and is of some advantages. With this tank, the dramatic change of the water temperature caused by unstable solar intensity or unstable pump running can be avoided, and the water tank also has a preferable thermal insulation effect.

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