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Running and economy performance analysis of ground source heat pump with thermal energy storage devices

Junxin Lv, Zhang Wei*, Jiaqi Zhang

Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, China

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ABSTRACT

This paper presents the thermal performance and economic analysis of a compound energy-supply system which composed of a ground source heat pump system (GSHPS) and a thermal energy storage system (TES). This system was simulated by TRNSYS and an engineering project was built for experiment, it's found that the compound system could keep the soil in a better heat balance that is more suitable for discontinuous heating and cooling constructions. From the experiment process, it's found the compound system has a higher COP than common GSHPS by 0.37 in winter and 0.04 in summer. For the price policy of off-peak electricity, the compound system could save 35.2% of the running cost in winter and 18.3% in summer than common GSHPS. In some case, the compound system could also has a lower initial investment.

1. Introduction

At present the proportion of air conditioning energy consumption accounting for 22.75% of the total energy consumption in China. Because of their high energy efficiency and stable operation capability, ground source heat pump systems (GSHPS) are attractive alternative to conventional air conditioning system. The use of geothermal energy to reduce the fuel consumption has become more and more popular [1]. GSHP installations in many countries are increasing at rates of 25–60% and greater in some cases [2]. The increasing emphasis on effective energy-saving applications in buildings has led to the utilization of unconventional techniques to meet heating and cooling demands. In the past years there have been many studies on the performance analysis of the GSHPS [3–5]. In China, the GSHP system is mostly applied in public buildings where the building load distribution is quite unbalanced. For example, in the heating season, the load in December and January is bigger than that in November and the load in morning is bigger than that in noon for the same day. The load fluctuation may result in changing the soil temperature around the borehole heat exchangers (BHE) in short time, and reducing its efficiency. Because of the load fluctuation, the heat pump (HP) units must be designed to meet the biggest building load. Also in heating-dominated buildings, the ground thermal imbalance would lead to a decrease of soil temperature and the deterioration of heating performance of the units [6–8]. That will lead to lower COP when the building load is small. To alleviate this load fluctuation, many researchers came up with ideas. To improve the performance of GSHP systems, some of the solution focus on increasing the borehole parameter, but the cost requirements is a lot. There are many studies have concentrated on improving the accuracy of the models and design method [9,10]. Studies show that project scale has a very important effect to annual heat balance of GSHP system [11]. Cui et al. [12] studied the discontinuous loads by means of numerical simulation and pointed out that the discontinuous load to GHEs for a long run is desirable and favorable for keeping GHEs at high efficiency. Some cases found hybrid GSHP system would maintain the underground thermal balance. A lot of experiment and simulation study has been finished, they found hybrid system could improve the performance of HP units and heat utilization [13,14]. In the cooling-dominated buildings, some studies present the GSHPS coupled with cooling towers to improve the performance of HP units [15–17] and some studies combined GSHPS with solar energy [18]. Study shows the discontinuous operation mode is also recommended and is feasible for commercial or residential buildings [19]. Yan Shang et al. investigated a vertical GSHPS and studied the geo-temperature variations [20]. There are also some research reported on the theoretical analysis and experimental study on thermal energy storage (TES) systems [21–25]. Wang et al. presented an experimental study of a solar-assisted ground-coupled heat pump system with solar seasonal thermal storage installed in a detached house in Harbin, which raised the soil temperature to

* Corresponding author.
E-mail address: zhang_wei@tju.edu.cn (Z. Wei).

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a higher level to increase the COP of the heat pump [26]. Durmus et al. [27] established a ground-source heat pump combined latent heat storage system and found this system had a higher COP than common GSHP system. Connolly et al. [28] studied the heat storage system from its operation strategy, the size of tank and cost, and found it could improve the system performance. Recent research shows it is necessary to combine GSHP with TES to meet the actual needs [29].

A part of these reported literatures have shown the good thermal performance of TES with some different working medium. That indicates applying the TES to GSHP system is feasible, and it's qualified to realize the load redistribution. Yet studies are mostly focused on coupling solar energy or some other devices like cooling tower with GSHP system, study on the compound system raised in this paper which combined GSHP system and TES is not enough.

In this study, a water tank used as the thermal energy storage device is directly connected with the GSHP system in the compound system. Through the simulation by TRNSYS, the influence of compound system on the soil temperature was researched, and more study on the simulated system will be carried out in the future. The experimental compound system is built to study the advantages of compound system on the running performance and economic performance.

The compound energy supply system put forward is composed of a heat storage device and a common GSHPS. The compound system uses low-price electricity to store energy in the heat storage device that would be used to satisfy the load in the next day. This compound system which could redistribute the building load controlled by changing the operation strategy has the following advantages:

(1) Reduce installed capacity of ground source heat pump units.
(2) Improve the efficiency of the heat pump units.
(3) Extensive applied building types with good prospect.

The compound system and common system were simulated with TRNSYS software to determine their effect on soil heat imbalance and an experiment project was established for an office building in Tianjin, China. The experiment process is established to study its operation and economy performance compared to common GSHP system.

2. Simulation process

Firstly, the system model was built up with TRNSYS. As Fig. 1 shows the model is mainly composed of heat pump, water pump, flow diverter, flow mixer, BHE and energy storage tank. There are 4 circulations involved in the compound system, circulation 1 is the heat pump energy supply process, circulation 2 is water tank energy supply process, circulation 3 is energy storage process, and circulation 4 is BHE circulation.

2.1. Simulation method

The models for a common GSHPS and a compound system including a thermal energy storage system (TES) and a GSHPS were built, and the performance of these two system were compared in this paper. In the compound system, the TES and the GSHPS were in series. In simulation process, we used time control and temperature control to manipulate these systems. In order to ensure that the soil temperature was only influenced by the two systems, the weather data, working condition parameters of borehole heat exchanger and so on were remained the same.

The heating season was set to start from November 15th to March 15th of the next year, and the cooling season is set from June 15th to October 15th. The working time was set from 8:00 to 18:00. The energy storage process start from 23:00 in the evening to the next morning in 6:00. If the water temperature reaches 15 °C in heating season or 5 °C in cooling season in this period, the energy storage process will stop. In the beginning of working day, the TES system was on first, the exoergic progress starts from 8:00, when the average water temperature in the tank reaches 38 °C in the heating season, or 12 °C in the cooling season, the exoergic progress stops. Then the heat pump will start to satisfy the building load. The total load in heating season was designed larger than in cooling season so that there will be heat imbalance in the soil. That means the heat quantity would accumulate in the soil and result in temperature rise after long-time running. Then both long-term and short-term running were simulated and the temperature variation of these two systems were compared.

In the simulation progress, the method of soil temperature computation was based on g-function method. This method combines analytical method and mathematical method to solve the soil temperature distribution [30,31]. The soil temperature was decided by iterating 3 parts including global temperature, local solution, steady-flux solution.

2.2. Simulation results

2.2.1. Experimental data validation

In the simulation process, parameters of the buried pipe, water flow and building load are designed according to the experimental parameters in order to make the simulation process close to the actual working condition as much as possible. To verify the accuracy of the simulation, a part of the experimental data and simulation data was compared, as shown in Fig. 2.

As shown in the figures, the inlet and outlet water temperature trend of changes in the simulation is close to the experiment data. As the typical meteorological year data was used in the simulation, there would be differences with the actual temperature that would affect the load file and external temperature of soil and water tank. Because the on-off of the heat pump used in the simulation combined time control and temperature control, it could also affect the on-off of the pumps and heat pump. So in some short period, there could be some reasonable fluctuation of the outlet and inlet water temperature of the BHE. But in the long term the temperature difference is mostly under 2 °C.The operation of the simulation system seems in a reasonable condition, which can be concluded that the simulated system is workable.

2.2.2. Comparison of soil temperature

To study the effects on soil temperature of the compound system, the average temperature of the whole storage volume was gained in TRNSYS. Fig. 3 shows the average temperature in a heating season of the compound system and common system, as we can see, in the full-season running, the compound system gets a relatively small soil temperature fluctuation than common GSHPS. After the first-season running, the soil temperature of the compound system changes from 16 °C to 14.6 °C, while it's 12.7 °C for common GSHPS.

In the long term comparison, the soil temperature range in 10 years of these two systems were compared in order to find the long-term-operation influence of the compound system on soil temperature.

Fig. 4 shows the trend of average soil temperature under these two different systems after ten-years running, as Fig. 4(a) appears, the average temperature of the compound system has a smaller range of variation than the common system. And in heating season the range is getting larger as a result of the larger load. Fig. 4(b) shows that running under 10-years, the heat imbalance results in continuous temperature drop of the storage volume, but the mean