Performance of a Small-Scale Direct-Expansion GSHP System During the Winter Operation

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ABSTRACT
This paper designs a small-scale experimental direct-expansion ground source heat pump system for space heating. It uses R22 as the refrigerant, consisting of four 20m-deep single U-tube copper ground heat exchangers in clay soils. Its preliminary operation performance and energy efficiency in the heating mode is tested. Results show that the design of the present DX-GSHP system is reliable and effective. During the heating period, when the heating capacity of the indoor coil fan is 6.41kW, the room temperature varies from 18ºC to 20ºC even if the door is opened or closed frequently. The average COP of the heat pump and the whole system are 3.12 and 2.88, respectively, and the average heat-transfer rate of GHEs per depth is 54.4W/m. The present results can provide guides for further improvement on the design of DX-GSHP systems in future.

1. Introduction
In recent years, ground source heat pumps (GSHPs) developed rapidly as an energy-efficient technology for space cooling and heating of buildings. GSHPs use the ground as a heat source or sink through a closed loop of horizontal or vertical ground heat exchangers (GHEs)[1]. Usually, according to the fluid type through the GHEs, GSHP systems can be divided into two categories, namely the secondary loop GSHP (SL-GSHP) and the direct expansion GSHP (DX-GSHP). For the former, water or a water-antifreeze solution is used as an intermediate working fluid to move heat energy between the ground and the buildings. For the latter, however, the refrigerant is circulated in the closed loops of copper tubes buried in the ground. That is to say, the GHEs function as the evaporator. By eliminating the intermediate heat exchanger, the refrigerant temperature in DX-GSHPs is closer to the ground temperature, which lowers the heat pump’s required compression ratio and reduces its size and energy consumption. Also, a shorter ground loop can be used because of the high heat transfer efficiency of copper tubes [2].

Compared with SL-GSHPs, the present DX-GSHPs are still at an initial stage due to some potential design and environmental impacts including compressor starting, oil return, refrigerant leakage, and metal corrosion [3]. For example, DX-GSHPs are not frequently used for urban buildings in China. In spite of this, their advantages in the construction and operation costs are still attracting great interest to residential buildings in rural areas, having a promising market potential. For example, Wang et al. [4] performed an experimental evaluation of a DX-GSHP system with three 30m-deep single U-shaped GHEs in sandy soils. They found that the coefficient of performance (COP) of the heat pump and the whole system was 3.55 and 3.28, respectively, when the heating capacity was about 6.43 kW. With the background above, the present work is carried out to build up an experimental DX-GSHP system in clay soils for space heating of a guard room, and test the actual operation performance and energy efficiency in winter. The present results can provide useful guides for further improvement on the design of DX-GSHP systems in the future.

2. Experimental Investigation
An experimental DX-GSHP system has been installed in Jinzhou (38.02ºN, 115.07ºN), located in the northern China, as shown in Figure 1. The annual average ambient temperature is 12.4ºC, and the average ground temperature at 20-40m depth is 14.1ºC. The object building is a guard room with the total area of 30m², and because of no insulation for external walls, the heating load is estimated as a high value of about 240W/m². An indoor coil fan is installed with a maximum heating capacity of 8.05kW under the input power of 75W. As shown in Figure 2, the DX heat pump unit consists of a compressor (JT95 type), a four-way valve (STF-0408 type), a double-pipe condenser (155CS030 type), an electronic expansion valve (30D85 type), a high/low pressure liquid receiver, an oil separator, a drying filter, two inspection glasses, and other control parts. The rated heating capacity and the input power of the compressor are 9.02kW and 2.78kW, respectively.
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R22 is used as a refrigerant, and the refrigerant charge is about 7.5 kg, which also depends on the layout of the corresponding ground system.

For the ground system, four 20m-deep boreholes dilled in clay soils are arranged in a square pattern with uniform spacing 6 m. Four single U-shaped copper tubes are used as the evaporator and connected in parallel with the DX heat pump unit. The diameter and wall thickness of the copper tubes are 12.7 mm and 1 mm, respectively. According to previous studies [5], choosing a smaller copper tube diameter is favorable for increasing the flow rate of refrigerants, guaranteeing oil return during the heating operation. In order to avoid the thermal short-circuit, several special support legs are installed on the copper tubes. Fine sand is refilled after installation. In order to measure the variation in ground temperature during the heating period, two sets of Pt1000 temperature sensors are installed. The first set includes three sensors buried at 4 m depth, their distances from borehole #1 are 1 m, 2 m, and 3 m, respectively.

The heat transfer rate \( Q \) of the coil fan can be calculated by

\[
Q = m c_p (t_j - t_c)
\]

where \( m \) is the flow rate, \( c_p \) is specific heat, and \( t_j \) and \( t_c \) are the inlet and outlet fluid temperature in the coil fan, respectively.

The average heat-transfer rate \( q \) of GHEs as a function of depth can be calculated by the energy balance principle. It can be expressed as

\[
q = 0.25 \left( Q - P_c \right) / H
\]

where \( P_c \) is the power consumed by the compressor, and \( H \) is the borehole depth.

The COP of the whole DX-GSHP system can be evaluated by

\[
COP = Q / \left( P_c + P_f + P_m \right)
\]

where \( P_f \) and \( P_m \) are the power consumed by the coil fan and the circulating pump, respectively.

3. Results and Discussion

Figure 3 shows the variations of water temperatures and pressures during the starting process of the experimental DX-GSHP system. It can be seen that the intake and exhaust pressure of the compressor varies smoothly, and the whole system can reach a relatively steady state after 15 min. After a number of field tests, there are few problems like starting process. In particular, the problem of insufficient oil return does not occur in this experiment during long term operation. This indicates that the design of the present DX-GSHP system is reliable and effective.

Figure 4 and 5 show the test performance of the present DX-GSHP system on two typical operation days. It can be seen that when the ambient temperature ranges from -7.2 °C to 0.2 °C on the first typical day, the average supply and return water temperature of the coil fan at the average flow rate of 1.75 m³/h
From the point of view of heat extraction, the average heat-transfer rate of GHEs per depth is calculated as 54.4 W/m. According to previous tests on the conventional HDPE GHEs, the heat extraction rate usually ranges from 25 to 35 W/m for single U-tubes, and 35 to 45 W/m for double U-tubes [6-7]. On the other hand, according to the European standard EN 15450 (Heating System in Buildings – Design of Heat Pump Heating Systems), when the operation period ranges from 1800-2400h, the specific heat extraction rate of GHEs should range from 50 to 60 W/m for normal underground and water-saturated sediment. By comparison, the present DX-GHEs have an obvious advantage on the ground heat transfer. In addition, the European standard also states that the COP should lie within the range of 3.5 to 4.5 when used for heating a building. This is really a great challenge for the design of DX-GSHP systems around the world. Despite this, in northern China this kind of small-scale DX-GSHP system is very suitable for common rural residential buildings with a total area of 100-150 m². For these buildings, the heating load usually ranges from 6 to 12 kW, requiring about 4-8 geothermal boreholes, which is easily accepted by rural home owners. At present, DX-GSHP systems have been recommended by the national GSHP standard as an option for space cooling and heating of rural buildings.

Figure 6 shows ground temperature variation at 4 m depth. It can be seen that with an increasing heat extraction for spacing heating in winter, the ground temperature decreases gradually. The ground temperature near the GHEs drops very quickly. In this experiment, the natural ground temperature drop is only 2.6 °C, but the ground temperature drop caused by heat extraction at 1m, 2m and 3m is 4.4 °C, 3.5 °C, and 3.4 °C, respectively. This indicates that when the distance from the GHE exceeds 2 m, the ground temperature drop is affected by natural seasonal varieties. Thus, the results of the experiment indicate a recommended spacing between two GHEs at least 4 m. Generally, an increasing spacing is helpful for heat extraction in winter and heat injection in summer, but excessive spacing can unnecessarily increase construction cost.

Objectively speaking, the design of DX-GSHP systems is complex, and its actual operation performance can be influenced by many factors. For example, we find in this experiment that an
unbalanced flow through four GHEs may cause an inadequate ground heat transfer, thereby lowering the COP. Backfilling is another crucial factor. If the boreholes are not backfilled compactly, an increased thermal resistance may decrease greatly the heat transfer rate, leading to an undesired increase in the power consumption of the compressor. Optimal backfilling materials with higher thermal conductivity should be developed. From the point of view of environmental impacts, the use of alternative refrigerants (e.g., R134a, R410a, R407c, carbon dioxide, etc.) is also a promising approach to improving performance [8]. In addition, we find that the winter performance of DX-GSHP systems depends greatly on the natural ground temperature. Generally, a higher ground temperature is favorable to achieving a higher COP. For example, according to the experimental results by Yang et al. [9], the average COP of the DX-GSHP system reached 4.72 when the average ground temperature was 19.0°C in sandy rocks in southern China. In term of the present DX-GSHP system, although the present COP seems to be low, there is still room for improvement. For instance, an updated scroll compressor, alternative refrigerants and optimal backfilling materials can be taken into consideration.

The present results can provide useful guides for the design of DX-GSHP systems under similar geological conditions. In future work, we will continue to improve the present experimental system to obtain higher energy efficiency, and a higher COP is expected to be reached.

4. Conclusions

This paper tests the actual performance of a small-scale DX-GSHP system in clay soils for space heating. The design of the present DX-GSHP system is reliable and effective. During the heating period, when the heating capacity of indoor the coil fan is 6.41kW, the room temperature varies from 18°C to 20°C. The average COP of the heat pump and the whole system are 3.12 and 2.88, respectively, and the average heat-transfer rate of GHEs is 54.4W/m. The reasonable spacing between two adjacent GHEs should range from 4 to 6m in clay soils. The backfilling quality of geothermal boreholes, as well as the natural ground temperature, determines to a great extent the actual operation performance of DX-GSHP systems. The present DX-GSHP systems have a promising potential application for rural residential buildings in northern China.

References