Experiment and simulation of temperature characteristics of intermittently-controlled ground heat exchanges

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Abstract

Because of poor heat transfer coefficients of soil/rock, ground source heat pumps (GSHP) or underground thermal energy storage (UTES) systems always occupy a large area and need many ground heat exchangers. This initial energy investment is so heavy that it cannot be used on a large-scale. Intermittent operation can reduce the extreme temperatures around the ground heat exchangers (GHEs) and keep the temperature in reasonable range. The aim of this study is to implement an experiment and develop a dynamic model of hydronic heating systems of GSHP in order to get a more fair comparison of energy efficiency between continuously controlled and intermittently controlled systems. Factors such as thermal inertia, temperature levels and lag time are also considered to see how they affect the efficiency. It is shown that temperature variation is related to the intermittent period and that intermittence prolongs the heat transfer without reaching at an utmost temperature (operation limitation). An effectively controlled intermittent process can optimize the capacity of heat exchange units so as to achieve better application of the ground energy. Additionally, the intermittent control can decrease the number of GHEs of GSHP and UTES systems and keep better working conditions.

1. Introduction

The earth surface absorbs solar energy and deposits it into ground; thus, the ground becomes a large reservoir of solar energy. The amount absorbed by the earth’s surface is much more than the human-being’s requirement and is not subject to regime and time. In addition to its renewable nature, ground source energy is environment friendly and has no CO₂ emissions.

Ground source energy is an ideal energy source for heat pumps. The temperature of the ground which changes along with the atmospheric environment, is relatively warm in winter and cool in summer. Therefore, it can serve as a heat source in winter and a heat sink in summer. That is the ground source energy can be used for cooling and depositing heat energy in summer; and it can be used for heating and exporting heat energy in winter. As we know, the ground can also be used actively as a heat pool for the seasonal underground thermal energy storage (UTES) system.

The development of the ground source heat pump (GSHP) and UTES has been limited by its relatively poor capacity of heat transfer. This results in the GSHP or UTES system normally requiring large-scale heat exchangers and higher initial capital investment.

Nevertheless, their potential for application of ground energy has drawn great attention from the international societies and much research has been carried out for both their study and development [1,2]. It has been shown that the intermittent process in the ground heat exchangers is a feasible way to promote heat extracted from and rejected to the ground.

Because a poor heat transfer coefficient exists in the underground soil/rock, GSHP or UTES systems must always occupy a big area and necessitate many ground heat exchangers. Additionally, the initial cost of the GSHP or UTES systems is so high that it is not practical for them to be used widely [3]. The intermittent control concept is in accordance with the operation character of extracting heat from and rejecting heat to the earth based on the principle of the ground temperature restoration.

Stevens provided a numerical simulation of intermittent convection heat for ground source heat pump design. A finite-difference model was used to calculate the heat transfer between a liquid flowing intermittently in a buried pipe. This model used the intermittence factor to evaluate its effect. It was found that the average heat transfer over the active part of the cycle is always higher for any intermittent case than for the continuous case [4,5].

Cui et al. [6] 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 [6]. Recently the results showed that the
discontinuous operation mode and the alternative cooling/heating modes can effectively alleviate heat buildup in the surrounding soil. The operation modes can ultimately improve the system performance. Therefore, the discontinuous operation mode (i.e., operating during daytime while shut down at night) is also recommended and feasible for commercial or residential buildings.

Over the decades many researchers [3,7,8,9] concentrated on the development of GHEs to improve and enhance the heat transfer. In this paper, the authors aim to study the underground temperature characteristics of the ground surrounding borehole. Specifically, temperature recovery will be analyzed while exploring the intermittent process of every GHE borehole, with the ultimate goal of both making better use of GHE in GSHP and UTES and maintaining better functioning of GSHPs.

2. Experimental study

The experimental system was designed and set up, as shown in Fig. 1, to study the heat transfer performance and the intermittent temperature restoration process of the GSHP. The system consists of two ground heat exchangers in vertical boreholes, a heat pump, two water tanks, and a pipe network. The two vertical boreholes, named as borehole 100# and borehole 200# respectively, were drilled to embed the ground heat exchangers. The ground heat exchangers are cannula type, in each of them one tube was first embedded into the borehole, and then screw core tube bundles were set into the tube to form the heat exchanger. The tube for the borehole 100# is 100 m × Φ 150 mm and the tube for the borehole 200# is 200 m × Φ 100 mm. Thermocouples were located at different depths in the boreholes to measure temperature. In borehole 100#, they were located at depths of 1.5 m, 20 m, 40 m, 60 m, 80 m, and 100 m; and in borehole 200#, they were located at depths of 1.5 m, 20 m, 50 m, 80 m, 110 m, 140 m, 170, and 200 m. In addition, the temperatures at the inlet and exit of each ground heat exchanger, at the evaporator and the condenser of the heat pump, were also measured. Two flow meters were installed at the exit of the cooling and heating circuits to measure water flow rate. To avoid heat loss, both the cooling and heating tanks were installed with polyurethane foam. In addition, a multifunctional electrical meter was used to measure and record the electric parameters of the GSHP system.

This experimental study was carried out in the Northeast City of Changchun, China, where the average day/night temperature is 23 °C in summer and −20 °C in winter.

Due to the fact that the heating and cooling processes of the ground heat exchangers are often affected by the changes of the ground thermal equilibrium temperature, the experimental system has been designed to effectively use the ground source energy. It is recognized that, when the heat exchanger is used for heating, the heat transfer load will cause a gradual drop of the ground thermal equilibrium temperature; and similarly, when the heat exchanger is used for cooling, the heat transfer load will cause a gradual increase of the ground temperature. As a result, the period for the ground source to restore to its original thermal balance will be relatively long. This problem can be solved either by increasing the number of boreholes for installing ground heat exchangers so as to decrease the load of a single exchanger or by enhancing heat transfer so as to control temperature variation and to increase the capacity of heat exchangers. In addition, the system can be controlled and optimized by utilizing the temperature recoverable characteristics of the intermittent operating process and increasing the rate of heat energy deposited in the earth. Considering the fact that a heat pump system normally does not operate continuously, the intermittent performance should be most suitable for cooling or heating systems using the GSHP.

Three different operating periods were applied in the experiment of intermittent process. They were 25 min, 50 min, and 75 min, respectively. A criterion for stopping the test operation is set up in the experiment to ensure that the exit temperature of the ground heat exchanger is not lower than 0.8 °C. Other criteria are also set up on the basis of the operating situations of the system and its supplement, which decides temperature limit. For the current operating system, the ratio of stopping time to operating time is 0.7–1.7, as shown in Fig. 2. In contrast, it is known that the ratio for a conventional heating/cooling system is at about 2 [5]. Indeed, it is very important to choose a reasonable ratio to make the temperature recovering more efficient.

The exit temperature of two ground heat exchangers and the power consumption of heat pump are shown in Fig. 3. The heat exchangers are located in the boreholes of depths of 100 m and 200 m respectively. The disconnected regions shown in the figure illustrate periods when no operation was taking place. It is obvious that the intermittent operation can recover the temperature; about...
3–4 °C is recovered in the heating process (200# curve) and about 1.5–2.5 °C in the cooling process (100# curve). Additionally, it is indicated that the recovering is proportional to the stopping time, during which the power consumption does not increase continuously. Typically, the trend of temperature variation in both heating and cooling processes is relatively smooth, so that the evaporation temperature of heat pumps in winter can be kept at a higher temperature and the condensation temperature in summer can be kept at a lower temperature; this ensures the system to work at high efficiency. Therefore, the ground energy is utilized more efficiently by intermittent operation process, and the scale of the ground heat exchangers can be reduced to save the cost of initial investment.

As the data shown clearly, the intermittent process can change the trend of the ground source temperature evolution by increasing or decreasing the thermal equilibrium temperature, so that the heat pump system can work at an ideal condition. Meanwhile, the power consumption is affected by the temperature distribution in the borehole. To ensure the system to run at high efficiency, the temperature in the vertical boreholes is controlled during the long-period of operation. Through a reasonable control of intermittent process, the temperature variation is then limited in an ideal range and the scale of heat exchangers is reduced; as a result, a higher thermal efficiency of the ground energy can be achieved.

Fig. 4 shows the temperature changes during the period of intermittent process when the ambient temperature is about -10 °C. As the data shown clearly, the intermittent process can change the trend of the ground source temperature evolution by increasing or decreasing the thermal equilibrium temperature, so that the heat pump system can work at an ideal condition. Meanwhile, the power consumption is affected by the temperature distribution in the borehole. To ensure the system to run at high efficiency, the temperature in the vertical boreholes is controlled during the long-period of operation. Through a reasonable control of intermittent process, the temperature variation is then limited in an ideal range and the scale of heat exchangers is reduced; as a result, a higher thermal efficiency of the ground energy can be achieved.

3. Model description

It is important to understand how the temperature is distributed around the ground heat exchanger. In general, the performance of the GSHP system depends on the ground temperature. If the distribution of the ground temperature during the system operation can be predicted, the system can be more properly designed, and as a result, the borehole geometry and the number of the boreholes, as well as the allocation and placement of ground heat exchangers, can be optimized. Overall, the GSHP can be better utilized, improving the COP (Coefficient of performance), and reducing the initial capital investment.

Numerical analysis has been regarded as an effective way to simulate complex experiments to save time and money. Numerical experiments can also extend beyond the limitation of experiments and predict and design a hypothetical system under any working conditions. In the present study, in parallel with the experimental test, the intermittent process of the ground heat exchange is studied numerically by finite element software.

3.1. Assumptions

Initially, the process of ground source heat transfer is analyzed. This process involves the heat transfer inside and around the underground pipes, and is complex as it is concerned with the transport phenomena of multi-component media, including invisible materials, complicated geological formations, and moisture and heat migration [10]. To carry out the numerical calculation, the following assumptions are made: 1) the soil is homogeneous and its physical properties are constant; 2) the velocity of liquid flowing inside the pipe is constant at each cross section; 3) the property of the pipes and ground materials do not change with temperature; 4) the effect of the wet movement in the ground on heat transfer is negligible; 5) as the temperature difference between top and bottom of the vertical borehole for ground heat exchanger is usually only about 0.2 °C/m, it is assumed that the temperature change in the vertical direction may be negligible; and 6) the heat transfer around the pipe is in axis-symmetrical.

3.2. The method

Based on the assumptions mentioned above, a one-dimensional transient cylindrical model with a heat source is used to solve the temperature distribution around the underground pipe.

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \theta}{\partial r} \right) = \frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r} \frac{\partial \theta}{\partial r} \quad (r_0 < r < \infty)
\]
Where, surplus temperature \( \theta = T - T_0 \).

Finite element software ANSYS is employed to resolve the transient temperature field around the vertical heat exchanger pipe. The element type and the grid density were selected to be variable according to the sensitivity of temperature quantity, so that the calculation can adapt to the actual situation and reach a high level of accuracy. Because the temperature changes more sharply around the cylinder heat source (borehole), the grid is designed to be more dense in that area, while it is more sparse farther away from the central heat source.

4. Results

4.1. Ground temperature

Calculations are performed for ground temperature distribution around the ground heat exchangers under different operating conditions. The different operating conditions refer to different intermittent operating cycles. These calculations include that, during a heating process, the operation was off for 2 h (2-hour-off), then on for another 1 h (1-hour-on); or 1-hour-off and 2-hour-on; or 0.5-hour-off and 1-hour-on, etc. The depth of boreholes for testing varies between 100 m and 200 m. The diameter of the boreholes is varies between 100 mm and 200 mm and the heating loads are 5 kW and 10 kW, respectively. Figs. 5–7 shows the calculation results of temperature variation of different cases at different position in radial direction.

Fig. 5 shows the temperature variation around the vertical boreholes and the heat exchangers at a borehole depth 100 m. The ground temperature changes for the heat exchanger operating cycle of 1-hour-off and 2-hour-on are shown in Fig. 5a, b shows the temperature variation for the cycle of 2-hour-off and 1-hour-on. The temperature curves A, B, C, D, E and F in Fig. 5a and b represent the results at different radial positions as A: \( R = 0 \) cm, B: \( R = 3 \) cm, C: \( R = 8.5 \) cm, D: \( R = 28.4 \) cm, E: \( R = 49 \) cm, and F: \( R = 80 \) cm respectively. The data shows that the temperature variation of the different operation modes is nearly identical. However, curve-A in Fig. 5a shows more violent fluctuation than that in Fig. 5b. This is due to the fact that the former situation has a shorter period to recover the ground temperature and longer period to release heat energy to the ground than the latter situation.

It should be noted that the trends of ground temperature variation in both situations of Fig. 5a and b become balanced to a certain temperature after a few hours. In comparison with the test results, the calculated results need much longer to be convergent because the exchanged heat is variable in the modelling, but in actual operating condition the heat is variable–usually decreasing–during the period of operation, as shown in Fig. 4.

Similar to Figs. 5 and 6 shows the comparison of ground temperature variation for different operating conditions, but the depth of the borehole is 200 m, two times of the depth for the borehole discussed in Fig. 5. Fig. 6a shows the data of the heat exchanger cycle of 1-hour-off & 2-hour-on, and Fig. 6b is the result of 2-hour-off & 1-hour-on. The temperature curves A, B, C, D, and E in Fig. 6 represent the results at different radial positions as A: \( R = 0 \) cm, B: \( R = 3 \) cm, C: \( R = 8.5 \) cm, D: \( R = 28.4 \) cm, and E: \( R = 49 \) cm respectively. In general, it is predictable that the temperature fluctuation gets smaller with the distance in radial direction; the temperature curves become relatively smooth as the heat flux from the heat exchanger to the ground decreases with the increment of cylindrical surface area. For example, looking at curve-F (\( R = 80 \) cm), the ground temperature is rarely changed and affected. Based on the analysis and calculation of the ground heat exchanger operating at different conditions, the available range of heat transfer can be estimated in the intermittent process. In Figs. 5 and 6 the range is an area of radius of \( R = 1 \) m. For further evidence, the condition of longer period stopping and shorter period re-start operation cycle was selected. As shown in Fig. 6b, this combination results in the smaller influence range of about \( R = 0.4 \) m.

Although Fig. 6 shows the similar characteristic and trend of ground temperature variation to Fig. 5, the intensity of heat transfer is much lower and the influent extent of temperature variation in a radial direction is smaller. This is because the heat transfer intensity of 5 kW/200 m is lower than that of 5 kW/100 m. Nevertheless, Figs. 5 and 6 indicate that the effect of the intermittent process (off/on cycle) on the variation of ground temperature is apparent. The recovery of the initial underground state takes place even though the data represent different conditions.

4.2. The effect of borehole depth

The difference between Figs. 5 and 6 is that they represent different borehole depths; the latter represents the temperature variation for the heat exchanger borehole depth of 200 m, which
is twice as deep as the heat exchanger borehole represented in Fig. 5. Although they have the same heat output of 5 kW, the latter surface heat flux is only half of the former. From the results of the calculations, it can be seen that the range of temperature fluctuation is in inverse relationship to the depth of the heat exchanger borehole. Thus, the deeper the borehole, the lower the temperature fluctuation will be. With smaller temperature variation, the temperature recovery for a deep borehole will be relatively weaker. Therefore, it can be assumed that higher heat flux can result in a higher grade of temperature distribution around the ground heat exchanger and more violent temperature fluctuation. This means that, to satisfy the need for ground heat transfer, a deeper borehole for heat exchangers may be a better choice. In this case, the heat load for the borehole will increase while the initial cost of the GSHP can be relatively low.

4.3. The effect of cycle ratio and intermittent period

The effect of the cycle ratio and intermittent period on the GSHP operation was studied by simulation. In the first simulation, the experimental test for the GSHP was run at the cycle ratio of 0.5, but in different intermittent period. For example: one operating cycle is 0.5-hour-off and 1-hour-on cycle, and another is 1-hour-off and 2-hour-on cycle; these are shown in Fig. 7a and 7b, respectively. The temperature curves A, B, C, D and E shown in Fig. 7a and 7b represent the results at different radial positions as A: $R = 55$ cm, B: $R = 25$ cm, C: $R = 13$ cm, D: $R = 4$ cm, and E: $R = 0$ cm respectively. Fig. 7 shows that the temperature around the heat exchangers decreases greatly after 5 h of operation; this is because these are cases of extracting heat energy from the ground.

Fig. 7a shows a process for a short period time 0.5 h, in which the temperature recovery is not very significant, but the lowest temperature is higher than that in Fig. 7b. The falling trend of temperature variation is actually controlled by selecting the cycle ratio and the intermittent period; meanwhile, the temperature can also become balanced by the selection.

It should be mentioned that in the above results, all simulations were performed under the same condition of 5 h operation before any intermittent operation is applied. If a measurement was taken before 5 h, the temperature variation would be difficult to identify. Therefore, the pre-operating period, 5 h, is another key to control the ground temperature in order to get better performance of the GSHP.

In large size ground heat pump system, such as Jiuhua Resort & Convention Center, there are hundreds of boreholes some of which are on while the rest are off. Therefore, the performance is improved with intermittent period control strategy.
5. Conclusion

(1) A long period of time is needed to both diffuse the heat and prevent its increase during an underground heat transfer. Such an interval of time can reduce the extreme temperature surrounding ground heat exchangers (GHEs) and achieve a temperature restoration. The temperature variation is related to intermittent time and the intermittence prolongs the heat transfer without reaching an extreme temperature (operation limitation). An effective control of the intermittent process can result in better application of the ground energy.

(2) The intermittent process cannot only change the trend and the degree of ground temperature but also change the balanced temperature. The appropriate mode and condition of intermittently controlled ground temperature can serve as an ideal heat pump working condition, which includes a lower condenser temperature or higher evaporator temperature in the GSHP system. It has been found that intermittent interval (stopping or running time), heat exchange load and previous running time are important factors regarding the optimization of the GSHP system. They will become the key factors for control strategies in the operation of GHEs of GSHP and UTES.

(3) When used in comparison with experimental results, modelling analysis was an efficient way to both decrease experimental scale and solve engineering problems of GSHPs in the intermittent process. The finite element software was also used to predict and analyze various conditions. In general, this work will serve as a basis for further study and application of the intermittent process in the future. The intermittent process will be profitable for GSHP, but needs further development.

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