

A Study on the Intermittent Temperature Recoverable Process of Ground Source Heat Pump Applications

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Abstract: The performance of the ground source heat pump (GSHP) used for earth energy applications in the regions where the climate changes in summer and winter are distinct is studied. The applications of the GSHP in such regions, which take the advantages that the ground source temperature is intermittently recoverable, uses renewable and sustainable energy source and has no CO₂ emissions. In the present research, the effects of the intermittence and its recoverable temperature characteristics on the GSHP performance are particularly studied. The operating experiments and numerical predictions are carried out. It is found that the temperature variations in the GSHP are related to intermittent time; the intermittence prolongs the heat transfer between the working fluid and the underground, and also increases the load of heating/cooling processes. An effective control of the intermittent process can optimise the capacity of heat exchange units so as to achieve better application of the earth energy. In addition, the control of intermittent process can decrease the number of ground heat exchangers in the GSHP system to ensure better working conditions.

Keywords: ground source heat pump, earth energy, intermittent process, renewable energy

NOMENCLATURE

c	Specific heat of the ground, $\text{kJ}/(\text{m}^3 \cdot ^\circ\text{C})$
K	Thermal conductivity of the ground, $\text{W}/(\text{m} \cdot ^\circ\text{C})$
q	Heat load of heat source, W/m
r	Distance from the borehole center line, m
r_0	Radius of the borehole outer surface, m
T	Temperature of ground at any selected distance from the center of heat source, $^\circ\text{C}$
T_0	Initial temperature of ground, $^\circ\text{C}$
α	Thermal diffusivity of ground, defined to $k/\rho c$
ρ	Density of the ground, kg/m^3
t	time, s

1. INTRODUCTION

The earth surface absorbs solar energy and deposits it into soil; thus, the earth becomes a large reservoir of renewable energy. The earth surface, as a huge collector, absorbs almost 50% of solar energy, which is the amount of much more than the human beings' requirement and is not subject to regimes and time. In addition to its renewable nature, the earth energy is also a type of clean source of energy which has no CO₂ emissions.

The ground source is ideal for heat pump used for supplying thermal energy into building. The temperature of the ground source, which very passively changes with the periodical change of the atmospheric environment, has the nature of being relatively warm in winter and cool in summer. Therefore, it can be served as a heat source in winter and a heat sink in summer to form a truly alternating

energy deposition cycle. Thus, in summer, the ground source can be used for cooling and depositing heat energy; and in winter, it can be used for heating and exporting heat energy. The development of the ground source heat pump (GSHP) was often restricted by its relatively weak capacity of heat transfer. This resulted in that a GSHP system normally requires large-scale heat exchangers and higher initial capital investment. Nevertheless, its potential for application of earth energy has drawn a great attention from the international societies and much research activities have been carried out to study and develop the GSHP [1-4].

In the present study, the authors focus on studying the effects of the intermittent and recoverable temperature characteristics of the GSHP on its operating performance typically for regions where the temperatures in summer and winter are distinctly different. Operating experiments and computational predictions for the heat transfer of fluid flowing intermittently in a buried pipe as heat exchanger and the surrounding unbounded ground are carried out.

2. EXPERIMENTAL STUDY

The experimental system was designed and set up, as shown schematically in Fig. 1, to study the heat transfer performance and the intermittent temperature recoverable process of the GSHP. The system consists of two ground heat exchangers in vertical boreholes, a heat pump, two water tanks and a piped network. The two vertical boreholes were

drilled to embed the ground heat exchangers and named as borehole 100# and borehole 200# respectively. The ground heat exchangers are type of cannula heat exchangers, in each of them one tube was first embedded into the borehole, and then the screw core tube bundles were set into the tube to form the heat exchanger. The tube for borehole 100# is of $100\text{m} \times \phi 150\text{mm}$ and the tube for borehole 200# is of $200\text{m} \times \phi 100\text{mm}$. Thermocouples as temperature sensors were located at different depth in the boreholes to measure temperatures. In borehole 100#, they were located at depth of 1.5m, 20m, 40m, 60m, 80m, and 100 metres, respectively; and in borehole 200# they were at depth of 1.5m, 20m, 50m, 80m, 110m, 140m, 170, and 200 metres, respectively. Meanwhile, 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 exits of both the cooling and heating circuits to measure water flow rate. To avoid heat loss, both the cooling and heating tanks were packaged by polyurethane foam for insulation. In addition, a multifunctional electrical meter was used to measure and record electric parameters of the GSHP system.

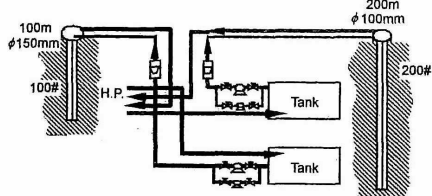


Figure 1: Experimental system

The experimental study was carried out in the Northeast City of China, Changchun, where an average day/night temperature is of 25°C in summer and -25°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 temperatures, the experimental system has been typically designed to effectively use the ground source heat energy. It is recognised that, when the heat exchanger is used for heating, the heat transfer load will result in a gradual drop of the ground thermal equilibrium temperature; and similarly, when the heat exchanger is used for cooling, the heat transfer load will result in a gradual increase of the ground temperature; as a result, the period for the ground source returning to its original thermal balance will be relatively long. This problem can be solved either by increasing the number of the boreholes for locating ground heat exchangers so as to increase the capacity of heat transfer 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 optimised by utilising 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 best suitable for cooling or heating system of the GSHP.

Three different operating periods are applied in the experiment of intermittent process. They are 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 criterions are also set up on the basis of the operating situations of the system and its supplement to decide temperature limit. For the current operating system, the ratio of stopping time to operating time is of 0.7 to 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 to be efficient.

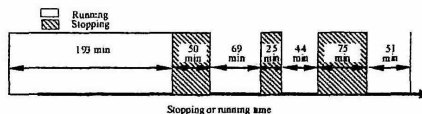


Figure 2: Intermittent process

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 respectively in the boreholes of depths of 100m and 200m. The disconnected regions indicated in the figure mean the stopping operation periods. It is obvious that the intermittent operation can recover the temperature; about $3\text{--}4^{\circ}\text{C}$ is recovered in the heating process (200# curve) and about $1.5\text{--}2.5^{\circ}\text{C}$ in the cooling process (100# curve). It is clear that the recovering is proportional to the stopping time, while the power consumption does not increase continuously. Typically, the trend of temperature changes in both the heating and cooling processes is relatively smooth, so that the evaporation temperature of heat pump 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. Thus, the earth energy is utilised more efficiently by such temperature recovering in the intermittent operation process, and as a result, the scale of the ground heat exchangers can be reduced to save the cost of initial investment.

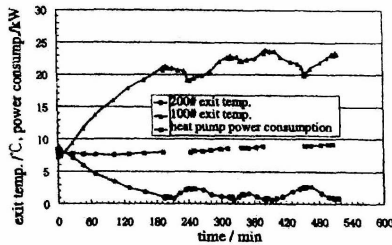


Figure 3: Exit temperature and Power consumption

Obviously, 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 on 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 at an ideal range and the scale of heat exchangers is reduced; as a result, a higher thermal efficiency of the earth energy can be achieved.

Fig. 4 shows the temperature changes during the period of intermittent process when the outside temperature is at -10°C ; the temperature variations for the boreholes with depths of 200m and 100m are recorded respectively. It is indicated that on the experimental condition, the temperature is properly controlled by the intermittent process. The lowest temperature in heating process is controlled at higher than 0.8°C ; while for a cooling process, it is controlled at lower than 27°C . Such a control of the limit of temperature changes can improve the heat change capability and ensure the heat pump work at a better working condition with improved efficiency. The results of Fig. 4 indicate that temperature is recovered sufficiently during the period of intermittent process; additionally, the instantaneous capability of ground heat exchangers is improved.

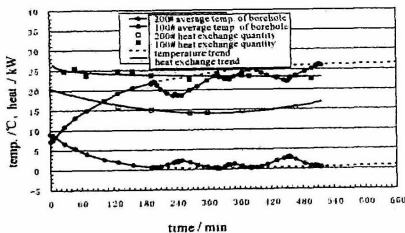


Figure 4: Trend of intermittent process

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 is relative to the ground temperature. If the distribution of ground temperature during the system operation is predicted, the system can be more properly designed, and as a result, the borehole geometry and the number of the boreholes, so as the allocation and placement of ground heat exchangers, can be optimised. Indeed, this will be also good for facilitating the GSHP, improving the COP (coefficient of performance), and reducing the initial capital investment.

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

3.1 Assumptions

The process of ground source heat transfer is firstly analysed. The process consists of the heat transfer inside and around the underground pipes. The heat transfer process in the ground is complex because it is concerned with the transport phenomena of multi-component media including invisible materials, complicated geological frame, and wet fluid movement [6-7]. To carry out the numerical calculation, following assumptions are made as: 1) the soil is homogeneous and physical property is constant; 2) the velocity of fluid flowing inside the pipe is constant at each cross section; 3) the property of material does 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 $0.2^{\circ}\text{C}/\text{m}$, it is assumed that the temperature change in vertical direction may be negligible; and 6) the heat transfer around the pipe is axisymmetry.

3.2 The method

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

$$\frac{1}{\alpha} \frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r} \frac{\partial \theta}{\partial r} \quad (r_0 < r < \infty) \quad (1)$$

$$-2\pi r_0 k \frac{\partial \theta}{\partial r} = q \quad (r = r_0, \theta > 0) \quad (2)$$

$$\theta = 0 \quad (r > r_0) \quad (3)$$

Where, surplus temperature $\theta = T - T_0$.

A finite element software is employed to solve 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 the actual situation and reach a

high accuracy. The grid is designed to be dense around the cylinder heat source (borehole) because the temperature changes more sharply there, but be sparse or loose far from the central heat source (borehole).

4. RESULTS

4.1 Ground Temperature

Calculations for ground temperature distribution around the ground heat exchangers at different operating conditions are carried out. The different operating conditions refer to different intermittent operating cycles. These include that, during a heating process, the operation was cut off for two hours (2-hour-off), then was carried on for another one hour (1-hour-on); or 1-hour-off, then 2-hour-on; or 0.5-hour-off and 1-hour-on, etc. The depth of boreholes for testing is different, which is at 50m, 100m, and 200m, respectively. The diameter of the boreholes is also different, which is of 100mm and 200mm, respectively. In addition, the heat exchange load is of 5kW and 10kW, respectively. Figs. 5~7 show the calculation results of temperature variation of different cases at different position in radial direction.

Fig. 5 shows the temperature variation around the vertical borehole and the heat exchangers; the borehole depth is of 100 m. The ground temperature changes for the heat exchanger operating cycle of 1-hour-off and 2-hour-on is shown in Fig. 5a; Fig. 5b 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 Figs. 5a & b respectively represents the results at different radial positions as A: R=0cm, B: R=3cm, C: R=8.5cm, D: R=28.4cm, E: R=49cm, and F: R=80cm. It is obvious that the temperature variation of the different operation tactic is quite identical. For example, curve-A in Fig. 5a shows more violent fluctuation than that in Fig. 5b. This is due to the former has a shorter period to recovery the ground temperature and longer period to release heat energy to the ground than the latter situation.

Fig. 5a ($q=5\text{ kW}$, operating: 1-hr-off, then 2-hr-on)

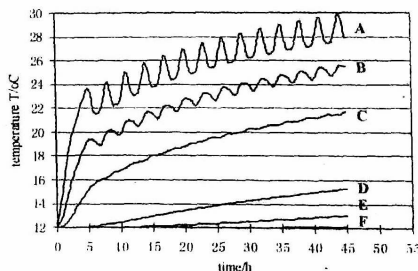


Fig. 5b: ($q=5\text{ kW}$, operating: 2-hr-off, then 1-hr-on)

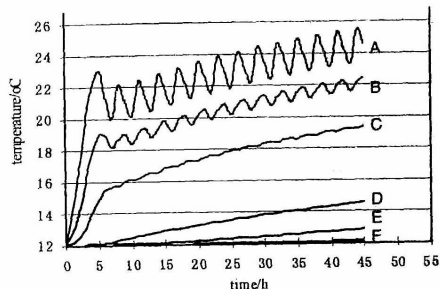


Figure 5: Temperature change in 100# borehole

However, the trend of ground temperature variation in both situations of Figs. 5a & b is balanced to a certain temperature after a few hours. If the dots of the top temperature of the curve are jointed together, the trend line is convergent, and this is consistent with the experimental results. However, comparing with the test results, the calculated results need much longer to be convergent because the exchanging heat is invariable in the modelling, but in actual operating condition the heat is variable usually decreasing during the period of operation.

Similar to Fig. 5, Fig. 6 also shows the comparison of the ground temperature variation for different operating conditions, but the depth of the borehole is 200 meters, two times of the depth of the borehole discussed in Fig. 5. Fig. 6a shows the data of 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 respectively represents the results at different radial positions as A: R=0cm, B: R=3cm, C: R=8.5cm, D: R=28.4cm, and E: R=49cm. 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 increase of cylindrical surface area. For example of curve-E (R=80cm), the ground temperature is rarely changed and affected. Based on the analysis and calculation for the ground heat exchanger operating at different conditions, the available range of heat transfer can be estimated in the intermittent process. In Figs 5 & 6 the range is an area of radius of R=1m. For a further identification, the condition of longer period stopping and shorter period re-start operation cycle was selected. As shown in Fig. 6b it results in the smaller influence range about R=0.4m.

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 radial direction is smaller. This is because the heat transfer intensity of 5kW/200m is lower than that of 5kW/100m. Nevertheless, Figs. 5 and 6 indicate that the effect of the intermittent process (off/on cycle) on the variation of ground temperature is obvious. The recovery of

initial underground state takes place even though at different data of the conditions.

4.2 The Effect of Borehole Depth

The difference between Figs. 5 and 6 is that they have a different borehole depth, and the latter represents the temperature variation for the heat exchanger borehole depth of 200 meters, which is twice as deeper as the heat exchanger borehole represented in Fig. 5. Although they have the same heat output of 5 kW, the later surface heat flux is only half of the former. Based on the calculation results, it can be seen that the range of temperature fluctuation is inverse to the depth of the heat exchanger borehole. The deeper of the heat exchanger borehole, the lower temperature fluctuation will be. With lower level of 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 higher grade of temperature distribution around the ground heat exchanger and more violent temperature fluctuation or restoration. This means that, with satisfying the need of ground heat transfer, a less depth of borehole for heat exchangers may be a better choice. Although this may increase the operating heat load, the initial cost will be relatively low.

Fig. 6a: ($q=5$ kW, operating: 1-hr-off, then 2-hr-on)

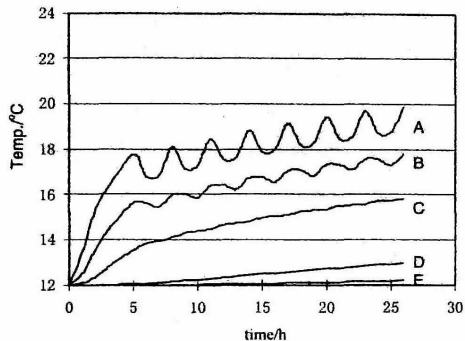


Fig. 6b: ($q=5$ kW, operating: 2-hr-off, then 1-hr-on)

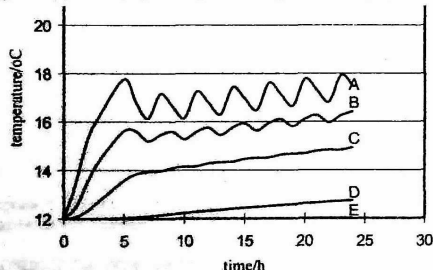


Figure 6: Temperature change in 200# borehole

4.3 The Effect of Cycle Ratio and Intermittent Period

The effect of the cycle ratio and intermittent period on the GSHP operation is studied. In the first place, the experimental test for the GSHP was run at the same cycle ratio which was set as 0.5 but in different intermittent period, such as operating cycle of 0.5-hour-off, then 1-hour-on cycle, and 1-hour-off, then 2-hour-on cycle; these are shown in Figs. 7a and 7b, respectively. The temperature curves A, B, C, D and E shown in Figs. 7a and 7b respectively represents 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. Fig. 7 shows that the temperature around the heat exchangers decreases greatly after five hours of operation; this is because these are the cases of absorbing heat energy from the ground.

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

It should be mentioned that in above results, all cases were selected at the same condition of operating for 5 hours before taking any measurement. If a measurement was taken shorter than 5 hours, the temperature variation would be difficult to be identified. Therefore, the pre-operating period, saying 5 hours, should be another key of controlling the ground temperature to get better performance of the GSHP.

Fig. 7a ($q=10$ kW, operating 0.5-hr-off and 1-hr-on)

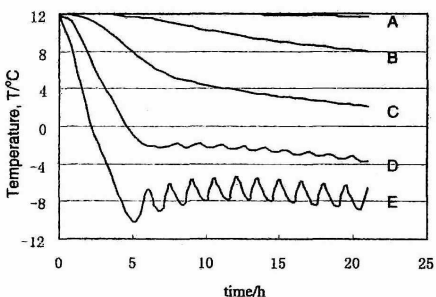


Fig.7b: ($q=10$ kW, operating 1-hr-off and 2-hr-on)

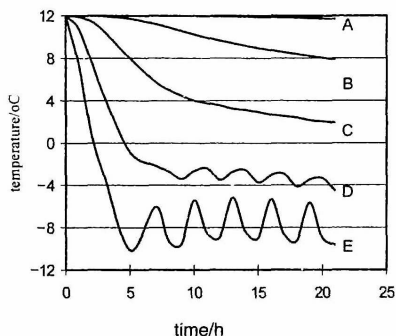


Figure 7: same ratio with different region

5. CONCLUSION

The intermittent process can not only change the trend and the degree of ground temperature but also adjust the balanced temperature. Correctly selecting reasonable case and condition of ground temperature can serve as ideal GSHP working conditions. In an intermittent process of the GSHP application, the parameters, such as time cycle (off/on), borehole depth, borehole diameter, heat exchange load, previous running time, stopping or running time and cycle ratio are important factors to optimize GSHP system and to utilize the earth energy sufficiently. They will become the key of operating and control strategies of GSHP.

Comparing with experimental results, modelling analysis is a way to decrease experimental scale and an efficient method to solve engineering problems of GSHP in the intermittent process. This method can also predict and analyze various condition in the finite

element software. This work is a basis for further study and application of the intermittent process in the future. The intermittent process will be profitable for the ground energy utilization in heating and cooling systems of GSHP, and it also needs further development.

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