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Application Analysis of Ground Source Heat Pumps in Building Space Conditioning

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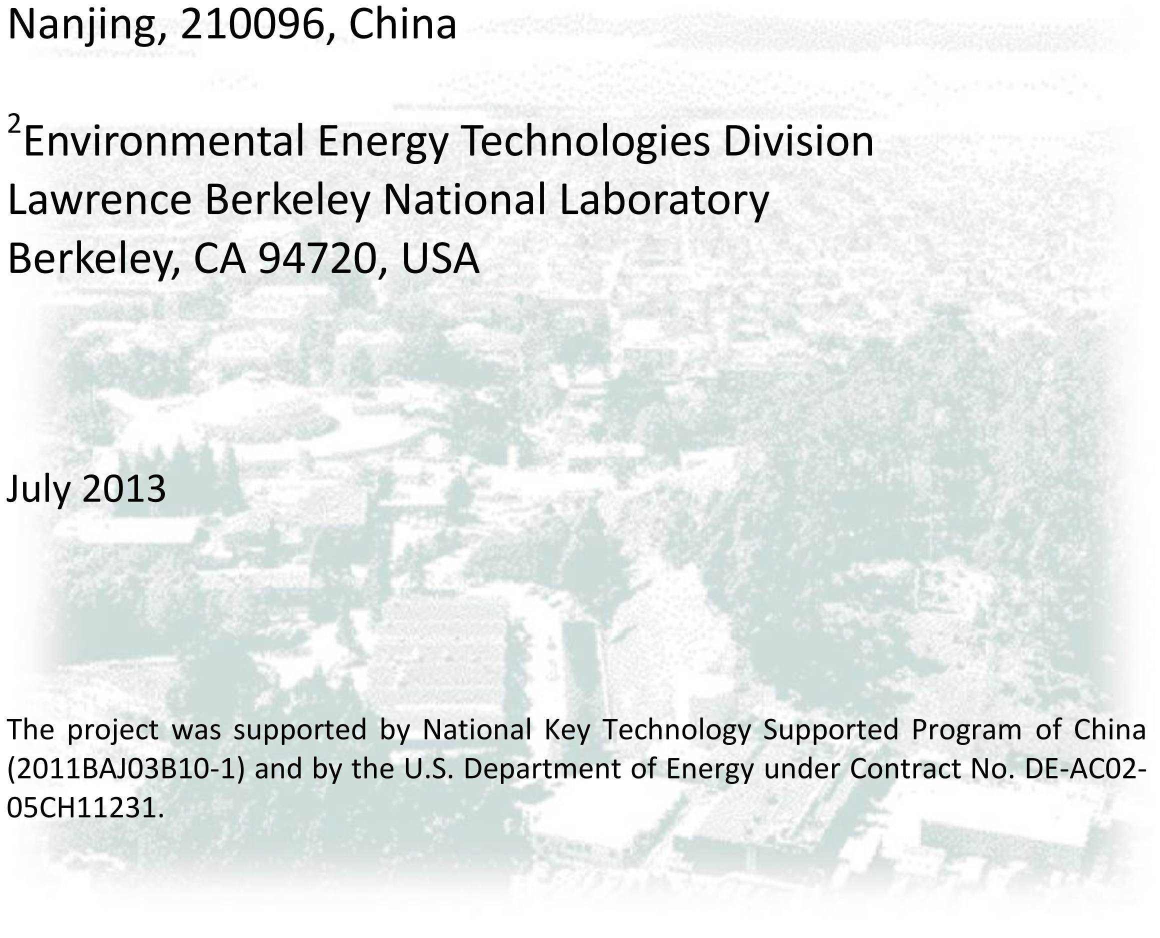

July 2013

The project was supported by National Key Technology Supported Program of China (2011BAJ03B10-1) and by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Abstract

The adoption of geothermal energy in space conditioning of buildings through utilizing ground source heat pump (GSHP, also known as geothermal heat pump) has increased rapidly during the past several decades. However, the impacts of the GSHP utilization on the efficiency of heat pumps and soil temperature distribution remained unclear and needs further investigation. This paper presents a novel model to calculate the soil temperature distribution and the coefficient of performance (COP) of GSHP. Different scenarios were simulated to quantify the impact of different factors on the GSHP performance, including heat balance, daily running mode, and spacing between boreholes. Our results show that GSHP is suitable for buildings with balanced cooling and heating loads. It can keep soil temperature at a relatively constant level for more than 10 years. Long boreholes, additional space between boreholes, intermittent running mode will improve the performance of GSHP, but large initial investment is required. The improper design will make the COP of GSHP even lower than traditional heat pumps. Professional design and maintenance technologies are greatly needed in order to promote this promising technology in the developing world.

Keywords: Ground source heat pump (GSHP), coefficient of performance (COP), building, energy saving, developing world

1. Introduction

The awareness of climate change and environmental pollution issues is increasing dramatically in the past decade. The interests of adopting alternative energies to improve energy efficiency and reduce environmental risks are growing rapidly. Geothermal energy utilized by ground source heat pumps (GSHP, also known as geothermal heat pump) becomes a new and promising energy source lying right beneath our feet. It is environmentally friendly, low life-safety risk and has low maintenance cost（Bayer et al, 2012; Capozza,et al. 2012; Kharseh et al. ,2011; Lund et al, 2011; Staffell,et al. 2012）.

Heat pumps use electricity to move heat from one cold (source) location to the warm location (sink), providing desired thermo environment for people, food, manufacture, and so on. A typical heat pump system consists of the heat source or sink, heat pump units and indoor heating and air conditioning terminal systems. The GSHP is one of these heat pumps, which uses soil or ground/underground water as its heat source or sink to extract heat from soil during winter and inject heat into soil during summer. Because of the relatively constant underground temperature (higher than the air temperature during winter and lower than the air temperature during summer), the GSHP theoretically has higher energy efficiency compared to the conventional air-air or air-water heat pumps. The ground heat exchanger (GHE) is an important part of the GSHP system. It could be soil, ground water or underground water. For soil GSHP, the orientation of GHE can be either horizontal or vertical. Compared to the horizontal GHE, vertical GHEs occupy less space and can accommodate large air temperature fluctuation (Capozza,et al., 2012; Staffell,et al., 2012; Yang et al., 2010; Yuan et al., 2011)

The first concept of using ground as the heat source for heat pumps was recorded in a Swiss patent published in 1912 by Heinrich Zoelly (Ball and Hodgett, 1983; Rawlings and Sykulski, 1999; Yu et al., 2008). . It was not used in practice due to technology difficulties and the low efficiency of heat pumps during that time. In 1945, the first GSHP system prototype was used for space heating in the United States (Rawlings and Sykulski, 1999). However, commercial GHSPs were not developed until after the first oil crisis in 1973 (Rawlings and Sykulski, 1999). Afterwards, theories and applications of GSHP received strong interests from a number of developed countries including the United States, Sweden, Germany, Switzerland, and Austria. This technology started being accepted by other parts of the world after 2000. It was estimated that a total of 2.76 million GHSPs had been installed worldwide during 2010, which doubled the number reported for 2005, and the estimated installation capacity of GSHP is approximately 33,000 MW and the annual energy use is 200 TJ for 2010 (Lund et al., 2011).

The countries with large GSHP installation capacity include United States, China, Sweden, Germany and Netherland (Lund et al, 2011). China started researching GSHP in 1980s, but did not adopt this technology in commercial applications before the beginning of the 21st century. The GSHP developed rapidly after 2004 with strong support from the China government in order to reduce the carbon emissions. The GSHP technology was included in a number of national laws, for example the “People’s Republic of China Renewable Energy Law” issued in 2006 and the “People’s Republic of China Energy Saving Law” revised in 2008 (Xu, 2011) . The capacity of installed heat pump increased from 383 MW to 5210 MW, the total area adopting GSHP systems was 140 million m^2 and the annual growth rate was greater than 30% between 2004 and 2009 (Lund et al, 2011; MOST, 2011).

Heat accumulation or cold accumulation will occur when the GSHP system is not properly designed, especially when the heating and cooling load is unbalanced. For the building located in warm areas where heating load is larger than the cooling load, heat will be injected into the ground leading to the increase of ground temperature and fluid temperature entering heat pumps. This makes the GSHP efficiency decrease, eventually makes the heat pump halt. The cold accumulation may appear when the heating load is larger than the cooling load. This drawback can be overcome by increasing the total length of the ground heat exchanger (GHE) and the space between boreholes. Some hybrid methods combined with solar energy or cooling tower were used to solve these problems. However, they increased the complexity of running and maintaining GSHP.

The accurate prediction of long term soil temperature distribution when the GSHP is running can improve the design of the GHE. Previously, some models were developed to predict the soil temperature distribution, such as the analytical solution of line source theory, the analytical solution of cylindrical source theory and numerical solutions (Lu and Chen, 2010; Yang et al., 2010; Yuan et al. 2012). Analytical solutions can deliver accurate results in a timely manner. However, they only suit single boreholes. Numerical simulation methods are widely used in engineering projects to investigate long-term temperature distribution of soil for multiple boreholes and to predict the heat pump performance. There is still a lack of models to integrate both the GSHP performance and the soil temperature distribution. In this paper, we present a novel model integrating these two perspectives. We aim to evaluate the performance of GSHP under different running modes and cooling/heating loads using this model.

2. Methods

2.1 Model description

This paper focuses on the vertical underground GHE, which is being widely used in China. Multiple boreholes were placed as array as shown in Figure 1. The borehole was put in node of the rectangle mesh. The distance between boreholes was between 3 m and 6 m in China according to the national standard (MOHURD, 2010). Figure 1 shows the layout of boreholes in two dimensions of 5 by 5 multi pipes.

The heat transfer around vertical multi-pipe in soil is governed by soil thermal properties, distance between boreholes, cooling and heating load, local weather data, and etc. Assumptions made are listed below:

(1) The initial soil temperature is uniform;
(2) The soil properties are constant;
(3) The influence of air temperature and subsurface seepage flow is excluded;
(4) The vertical heat transfer is excluded. The problem can be simplified as two dimensions.

Based on above assumptions, the governing equation can be described as shown below.

$$\frac{\partial t}{\partial \tau} = \alpha\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2}\right) + \frac{q}{\rho c} \tag{1}$$

in which t is the soil temperature (^{o}C), τ is time (s), α is the soil thermal diffusivity (m^2/s), ρ is the density of the soil (kg/m^3), c is the specific heat capacity (J/(kg$*^{o}$C)), and q is the heat source (W/m^3).

Initial condition:

When $\tau = 0$, $t(x,y,\tau) = t_0$, where t_0 is the initial soil temperature (^{o}C), τ is time (s). Equation (1) can be discretized in space and time. The implicit algorithm was employed to discretize time to make results insensitive to time step.

Boundary conditions:

(1) The constant temperature was set as the measured soil temperature at the boundary of computing domain (see Figure 1). The distance between the outside borehole and the computing boundary is 10 m, which is twice of the distance between boreholes.
(2) At the borehole node, the heat source q (W/m^3) was set to $\frac{\varphi}{\Delta x \Delta y}$, where $\Delta x, \Delta y$ is the grid distance of the node where the borehole is located, φ is set as the heat exchange per meter between circulating water and soil (W/m). At other locations, q is set to 0. It can be obtained based on the cooling or heating load and the performance of GSHP shown in Equation (2) and (3) below.

For cooling load:

$$\varphi = [CL * (1 + \frac{1}{COP})] / l \tag{2}$$

For heating load:

$$\varphi = [HL * (1 - \frac{1}{COP})] / l \tag{3}$$

where CL is the cooling load (W) in the summer and HL is the heating load (W) in the winter, l is total length of boreholes (m), COP is the coefficient of performance. It is the ratio of the heating or cooling output by a heat pump over the electrical energy consumed.

Different heat pumps, different condensation temperatures and evaporation conditions lead to different COP values. Heat pump manufacturers normally publish one single COP value for one model for standard conditions. Some manufactures may publish several COP values for one model under various conditions of supply/return chilled and cooling water temperature. The industry-average data can be calculated using the following equation (Staffell et al., 2012):

$$COP_{GSHP} = 0.000734\Delta T^2 - 0.150\Delta T + 8.77 \tag{4}$$

where ΔT is temperature difference between the heat pump heat source and the heat sink, and it should be between 20 ^{o}C and 60 ^{o}C.

The default supplied/returned chilled water to in the building temperature is 7 ^{o}C /12 ^{o}C in summer, which means the average source temperature in summer is 9.5 ^{o}C. The supplied/returned heat water temperature distributed to the building is 45 ^{o}C /40 ^{o}C in winter, which means average sink water temperature in winter is 42.5 ^{o}C. The COP value of GSHP depends on the water from the ground heat exchanger. The average sink water temperature in the summer and the source water temperature in the winter can be calculated based on the average temperature of water going into and going out of the GHE, which can be obtained by conservation equations below.

$$T_{out} = 2(\varphi \cdot R_S + T_S) - T_{in} \tag{5}$$

$$T_{in} = \frac{\varphi l \Delta \tau}{\rho c_w l_w} + T_{out} \tag{6}$$

where T_{out} is the inlet water temperature of the ground heat exchange (^{o}C), T_{in} is the outlet water temperature of the ground heat exchange (^{o}C), C_W is the specific water thermal mass (J/[kg·^{o}C]), l_w is the water flow rate (m^3/s), T_S is the soil temperature adjacent to boreholes, which can be obtained using Equation (1), R_S is the thermal resistance between circulating water and soil adjacent to boreholes including convective thermal resistance between circulating water and pipe wall, pipe thermal resistance and backfilled materials thermal resistance (m ^{o}C/W), T_S is the soil temperature adjacent to boreholes (^{o}C). The efficiency of the GSHP system and the soil temperature can be calculated by solving Equations (2) to (6). Iterations need to be done because these equations are coupled.

2.2 Model validation

Beier et al. carried out an experiment to obtain reference data sets for vertical borehole ground heat exchanger (Beier, et al. 2011). A sandbox of 18 (m) × 1.8 (m) × 1.8 (m) with a borehole at the center were constructed for measurements. The experimental data and detailed experimental setup information are available in the supplementary of the paper (Beier, et al. 2011). These results were used for model validation in our study.

Figure 2 shows the comparison between the measured and the predicted water temperature flow into and out of GHE. Figure 3 shows the comparison between the measured and the predicted soil temperature at different locations (various distances to the borehole). The experimental data and model prediction results are in good agreement. The temperature difference between the experiment and the prediction is within 1 ^{o}C. This temperature difference becomes smaller as time goes. These results indicate that our model can accurately predict the water and soil temperature over the course of 50 hours.

2.3 Background information for model simulation

The soil initial temperature is 17.6 ^{o}C, the thermal conductivity is 1.537 W/(m·^{o}C), the specific heat capacity is 2156 J/(kg·^{o}C), and the soil density is 1871 kg/m^3. These values were retrieved from field measurements of soil thermal properties in Nanjing, China. A total of 25 boreholes with each borehole 50 m in depth are arrayed as shown in Figure 1. To investigate impacts of the heat balance, daily running mode and the space between boreholes, the following scenarios were modeled as listed in Table 1.

3. Results and discussion

3.1 The impact of heat balance

Heat or cold accumulation substantially influences the heat pump efficiency and performance. Unbalanced heat injected into soil in the summer and extracted from soil in the winter may lead to heat or cold accumulation. In our study, four different scenarios were simulated to demonstrate the heat balance as shown in Table 1.

- Scenario 1 (50 kW, 0 kW). The GSHP only runs in the summer and the cooling load of the building is 50 kW. The heat injected into soil will change with the COP as shown in Equation (2), which is larger than cooling load. If COP = 4, the total injected heat will be 62.5 kW, and the heat exchange between soil and borehole is 50 W/m.
- Scenario 2 (50 kW, -40 kW). The GSHP runs in the summer with the cooling load of 50 kW and in the winter with the heating load 40 kW. In the winter, heat extracted from soil is less than the heating load as seen in Equation (3). If COP = 4, the ratio of heat injection in the summer and heat extraction in the winter is 1.8.
- Scenario 3 (40 kW, -50 kW). The GSHP runs in the summer with the cooling load of 40 kW and runs in the summer with the heating load of 50 kW. The ratio of heat injection in the summer and extraction in the winter is 1.25 when COP = 4.
- Scenario 4 (0, -50 kW). The GSHP only runs in the winter with the heating load of -50 kW. The summer running period is from the beginning of June to the end of August and the winter running period is from the beginning of November to the end of January.

Figure 4 shows the results of the four simulation scenarios. The heat accumulation or cold accumulation was detected when the building only has cooling loads or heating loads. For a ten-year running period, the soil temperature for scenario 1 and scenario 4 increased to 39.1 ^{o}C and decreased to 6.9 ^{o}C, respectively. The GSHP system will not be able to perform properly when soil temperature increased to 39.1^{o}C and decreased to 6.9 ^{o}C. This is for the GSHP running for 3 months during each year. Running for a longer period will make the heat or cold accumulation issue even more severe. For Scenario 1, the average soil temperature increased rapidly in the cooling period when heat was injected into soil, and the temperature decreased slowly in the other period. When the soil temperature increased, the soil recovery speed increased as well due to the increment of the temperature difference between the soil around boreholes and the soil further. The same phenomenon is observed in scenario 4. When the heat flux ratio was close to 1 as scenario 3, the average soil temperature fluctuated with the initial soil temperature.

Figure 5 shows the temporal variation of the calculated COP values. In general, the COP value of scenario 1 and scenario 4 slightly decreased year by year. The COP values of scenario 3 were relatively constant. The COP values for scenario 2 in the summer decreased year by year while it increased year by year in the winter, which is because of the increase of the soil temperature. These results indicate that the annual heat balance is very important for GSHP. The GSHP installed in buildings with both cooling and heating loads perform better compared to those in buildings with only cooling or heating load.

3.2 The impact of daily running mode

The daily running mode could change the performance of the GSHP and the soil temperature distribution. The heat pump efficiency is governed by the temperature difference between the heat pump heat source and the heat sink as shown Equation (4). Four modes were chosen to compare the impact of daily running mode on the soil temperature, including the scenario 5 (8 hr, 16 hr) running 8 hr per day, the scenario 6 (10 hr, 14 hr) running 10 hr per day, the scenario 7 (12 hr, 12 hr) running 12 hr per day, the scenario 1 (24 hr, 0 hr) running continuously for 24 hr per day. The cooling loads for these four scenarios are at 50 kW.

At the end of the 3-month period (2100 hours), the average soil temperature around boreholes for scenario 5, 6, 7, 1 increased from initial soil temperature, i.e. 17.6 ^{o}C to 18.7 ^{o}C, 18.9 ^{o}C, 19.2 ^{o}C, 20.8 ^{o}C, respectively, as shown in Figure 6. The soil temperature distributions at the end of the 3-month period in all four modes are shown in

Figure 7. For continues running mode (Scenario 1(24 hr, 0 hr)), both the average soil temperature and the maximum temperature near boreholes are much higher compared to the intermittent running modes (Scenario 5-7). For intermittent running modes, longer running period will result in higher soil temperature, higher GHE outlet water temperature. Figure 8 shows the water temperature variation at the outlet of the GHE during operation. At the end of the 3-month running period, the water temperatures at the inlet of the GHE are 43.2 ^{o}C, 43.9 ^{o}C, 44.6 ^{o}C, and 49.6 ^{o}C for the four scenario, respectively. Through heat transferring to the soil, the water temperatures at the outlet of the GHE is 39.7 ^{o}C,40.3 ^{o}C,41.0 ^{o}C and 45.8 ^{o}C for the four scenarios, respectively. The COP values for the four scenarios decreased from 4.65 to 4.34, 4.27, 4.20 and 3.80, respectively, as shown in Figure 9. With the stop period increasing, the GSHP efficiency increased. At the end of the 3-month operation period, the COP value of Scenario 5 is 0.5 higher than Scenario 1. As the running period increases, the difference between the two COP values increases as well. These results indicate that the intermittent operation mode is suitable for the GSHP. Longer stop time will help soil temperature recovery.

3.3 The impact of boreholes

The number of boreholes (or the total length of boreholes) and the space between boreholes influence the efficiency of the GSHP. Large space between boreholes will help soil temperature recover quickly. Four scenarios are simulated and shown in Table 1. For the scenario 1, the space between boreholes is 5 m. For the scenario 8, the space between boreholes is 1 m, and other conditions are the same as the scenario 1. For the scenario 9, the space between boreholes is 3 m, and the other conditions are the same as Scenario 1. For the scenario 10, the space between boreholes is 7 m, and other conditions are the same as the scenario 1. For the scenario 11, the space between boreholes is 5 m, and there are 7*7 (total 49) boreholes. Other conditions are the same as the scenario 1.

It is found that when the space between boreholes is 1 m (scenario 8), the average soil temperature increases to 46.2 ^{o}C in 30 days. The inlet water and outlet water (to the GHE) temperatures are 72.0 ^{o}C and 67.8 ^{o}C, respectively. The heat pump system may not be able to work properly in such high temperature. For scenario 1 and scenarios 9-11, the calculated COP value was shown in Figure 10. When the space between boreholes increases, the COP increases as well. These results suggest that enlarging the space between boreholes can help the soil temperature recovery and increase the efficiency of the GSHP. The efficiency of the scenario 11 is higher compared to the scenario 10, and they occupy nearly the same area. The scenario 11 has larger number of boreholes, which make its efficiency higher, but the initial investment cost also increases.

The GSHP has the potential to save energy. It requires proper design and operation. The installation cost for the GSHP (especially for the GHE) is high. These factors limit its wide application in developing countries. As discussed earlier, the GSHP is suitable for buildings with similar cooling load in the summer and the heating load in the winter, and runs in the intermittent operation mode. When the cooling load and the heating load for buildings are unbalanced, the system requires larger number of boreholes and wider space between boreholes. The initial investment cost will then increase. So one needs to balance the energy saving and the initial investment. When operation parameters deviate from design parameters, the performance of GSHP will be substantially restricted. If sufficient safety margin is given, the initial investment will increase dramatically and more space is needed.

4. Conclusions and perspectives

In this paper, a novel model was developed and verified to integrate the GSHP performance equation and the soil temperature distribution. The model was used to evaluate the impact of heat balance, daily running mode and boreholes on the performance of the GSHP. Results show that the GSHP is suitable for buildings with balanced cooling and heating loads, which can keep the soil temperature relatively constant for a long operation period. When the heating and cooling loads are not balanced, extending the length of boreholes and the space between boreholes may overcome this drawback. However, large amount of initial investment and space are needed. The intermittently running mode can improve the efficiency of the GSHP, and it needs fewer boreholes. Professional design and maintenance technology are required in order to run the GSHP properly.

In China, the GSHP is treated as an application method using the renewable geothermal energy. The initial investment of GSHP is higher than the traditional heat pump. The application of the GSHP is mainly determined by the government financial encouragement and the price of power. Being supported by the “People’s Republic of China Renewable Energy Law” issued in 2006 and the “People’s Republic of China Energy Saving Law” revised in 2008, the GSHP is widely adopted. The GSHP is included in the standard of green buildings in China. Nowadays, there are a large number of companies getting involved in the GSHP field. The competition will help reduce the cost. As we discussed above, the GSHP is more effective in heating, compared to traditional air source heat pump and more suitable to be applied in the zones with balanced heating and cooling load. So it is widely used in northern China (the cold climate zone) and eastern China (cold winter and hot summer climate zone). The GSHP occupies large underground space, which makes it difficult to be adopted in old cities.

The GSHP concept has not been fully accepted in other developing world. The application of GSHP worldwide is controlled by many factors including climate, initial cost, technology, financial support from government and the power price. The GSHP is not suitable for the area where the cooling load is much higher than the heating load. Even when the climate favors, considering the initial investment and appropriate technologies, it needs great financial support and policy encouragement from the government. Therefore, the GSHP is difficult to be widely adopted in the developing world.

Acknowledgements

The project was supported by National Key Technology Supported Program of China (2011BAJ03B10-1). The contents in this work are solely the responsibility of the authors and do not necessarily represent the official views of Department of Energy (DOE).

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Table 1 Different Scenarios for evaluate GSHP performance.

Scenario ID	Period	Running time (hr)	Cooling load/heating load (kW)	Space (m)	Number of borehole
1	Jun-Aug (Summer)	24	50/0	5	5*5
2	Jun-Aug (Summer) Nov-Jan (Winter)	24	50/-40	5	5*5
3	Jun-Aug (Summer) Nov-Jan (Winter)	24	40/-50	5	5*5
4	Nov-Jan(Winter)	24	0/-50	5	5*5
5	Jun-Aug (Summer)	8	50/0	5	5*5
6	Jun-Aug (Summer)	10	50/0	5	5*5
7	Jun-Aug (Summer)	12	50/0	5	5*5
8	Jun-Aug (Summer)	24	50/0	1	5*5
9	Jun-Aug (Summer)	24	50/0	3	5*5
10	Jun-Aug (Summer)	24	50/0	7	5*5
11	Jun-Aug (Summer)	24	50/0	5	7*7

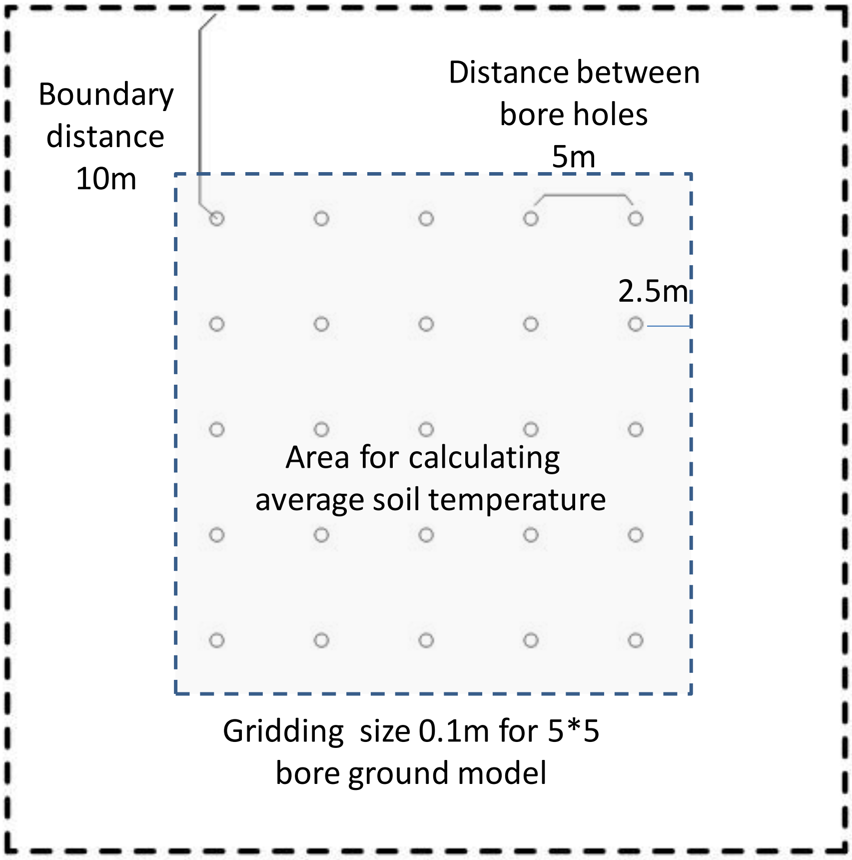


Figure 1. The demonstration of computation area and array of boreholes.

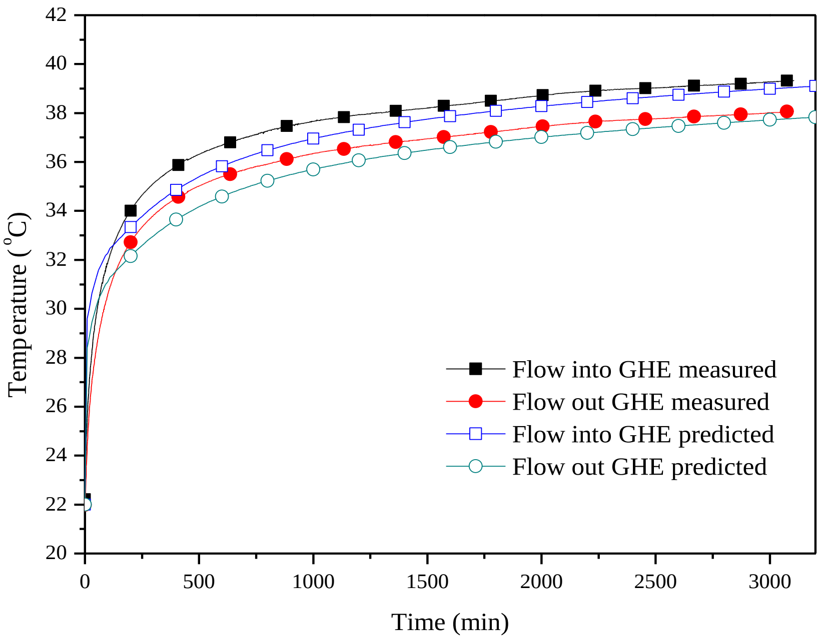


Figure 2. Comparison of the measured and the predicted water temperature going into and going out of the GHE.

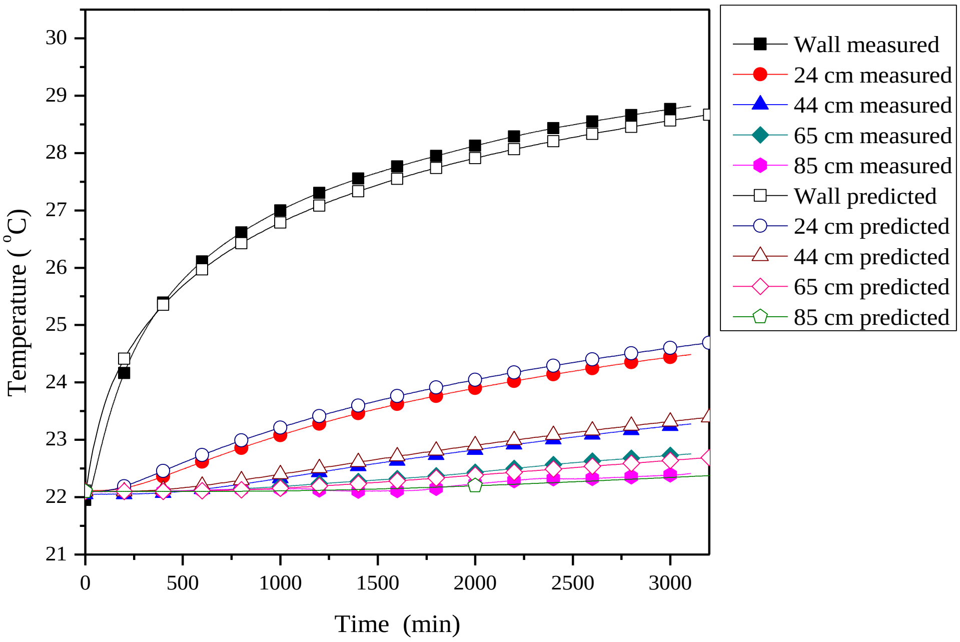


Figure 3. Comparison of the measured and the predicted soil temperature at different locations.

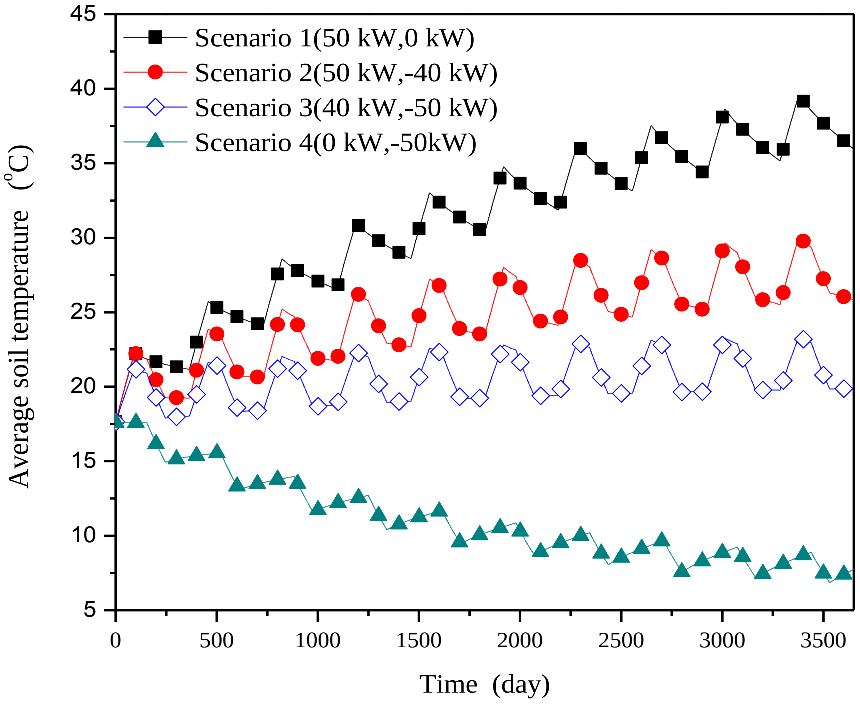


Figure 4. The temporal variation of soil temperatures over the course of ten years with four different heat flux ratio.

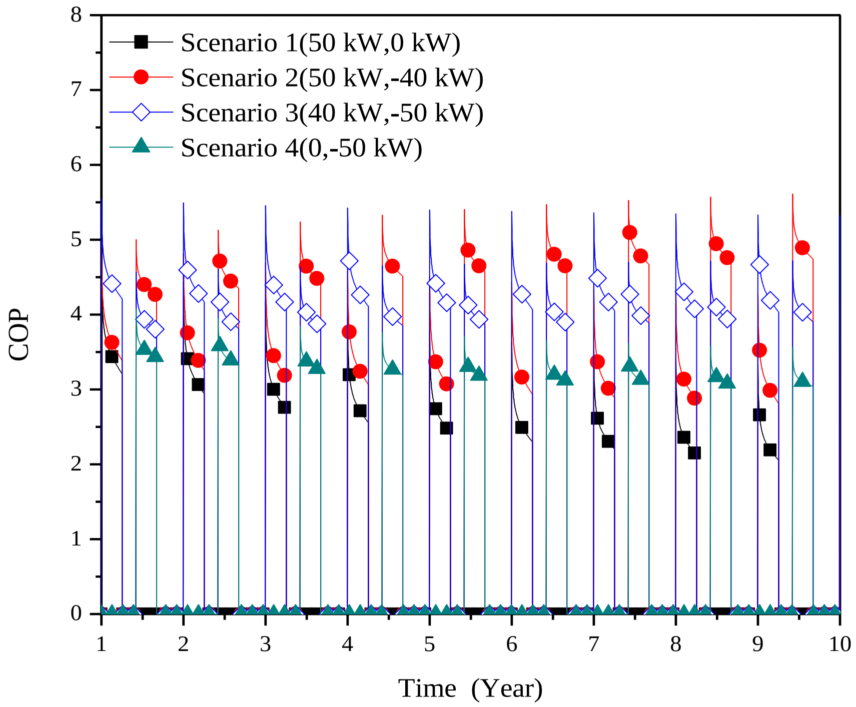


Figure 5 . COP variation in 10 years with different heat flux ratio

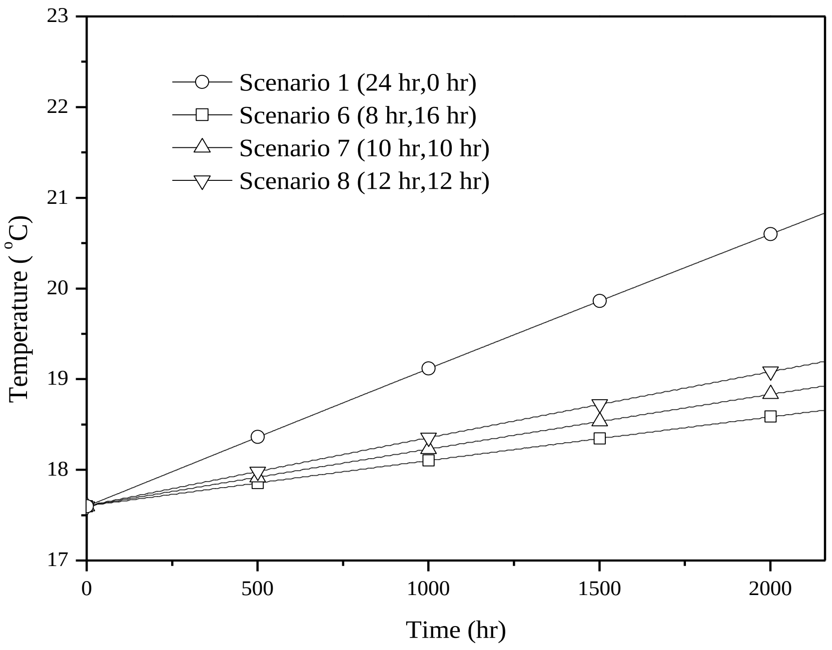
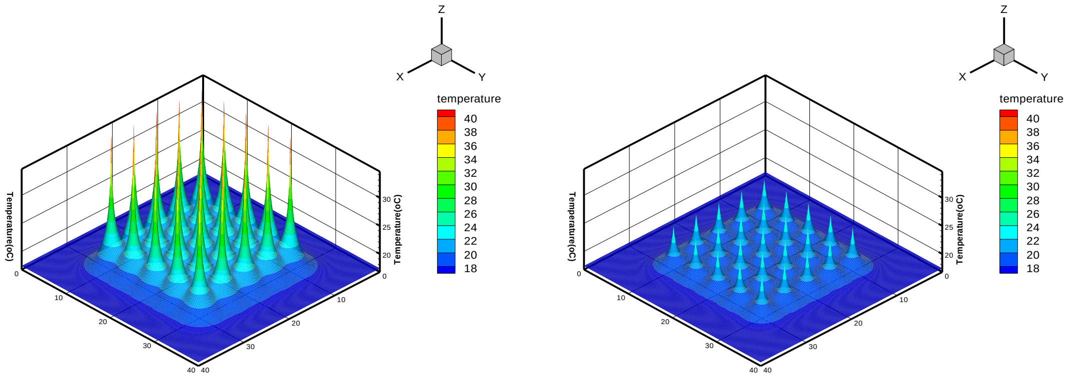
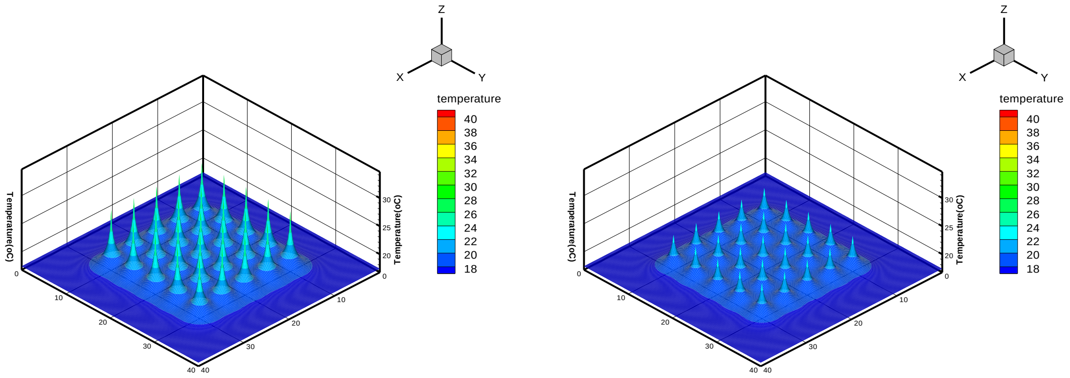


Figure 6. The temporal variation of the soil temperature for four different daily running scenarios in the summer.



(A) Scenario 1 (24hr, 0hr)

(B) Scenario 6 (10hr, 14hr)



(C) Scenario 7 (12hr, 12hr)

(D) Scenario 5 (8hr, 16hr)

Figure 7. The soil temperature distribution for four scenarios at the end of three-month running period.

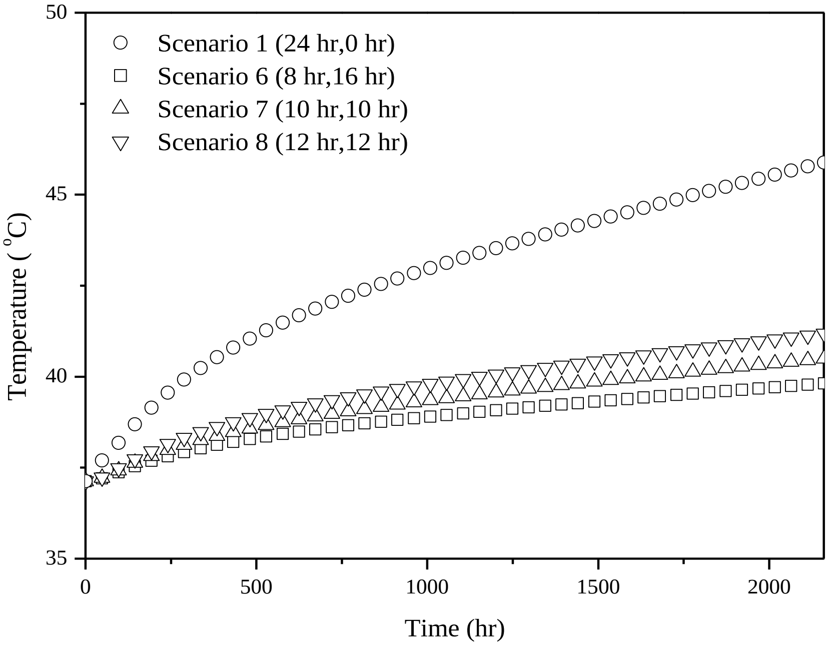


Figure 8. The temporal variation of the water temperature at the outlet of the GHE for four scenarios.

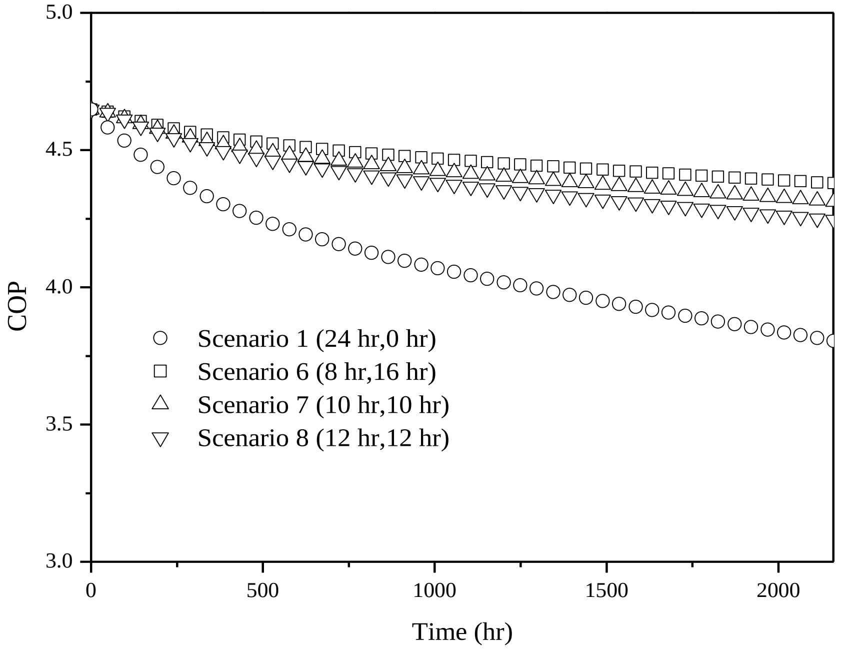


Figure 9. The temporal variation of the heat pump COP over the three-month period for four different daily running scenarios.

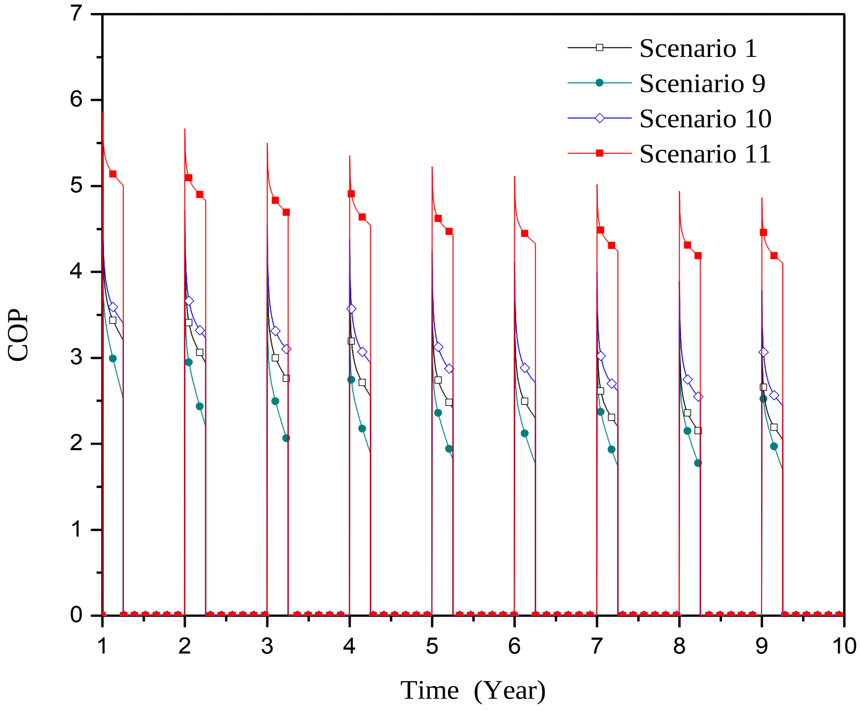


Figure 10. The temporal variation of COP for different space and borehole numbers over the period of 10 years. .