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Feasibility of ground source heat pump using spiral coil energy piles with seepage for hotels in cold regions

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Abstract

Ground source heat pump (GSHP) using energy piles is a clean and efficient air conditioning technology. However, this system may suffer annual soil thermal imbalance when it is applied in buildings in cold regions, causing cold or heat accumulation in soil and having effect on the system's long-term operation. To simulate the system performance and investigate system feasibility in Chinese cold regions, a system simulation model is established considering important influential factors of energy piles group. The system is applied in a hotel of four typical cities (Harbin, Changchun, Shenyang and Beijing). The dynamic building load is simulated which shows that the hotels in four cities are heating-dominated with load ratios of 6.78 in Harbin, 6.51 in Changchun, 2.94 in Shenyang and 1.20 in Beijing. Results show that GSHP system using spiral coil energy piles is efficient and only consumes 51%~62% power of conventional Boiler + AC system. When GSHP is applied in hotels in cities with similar climates to Harbin and Changchun, the soil thermal imbalance with serious cold accumulation will cause the heating performance decline as well as the heating deficiency. When GSHP is applied in hotels in cities with similar climates to Shenyang, the soil thermal imbalance with cold accumulation will cause the heating performance decline but the system's heating capacity is acceptable. When GSHP is applied in hotels in cities with similar climates to Beijing, the soil thermal imbalance with slight heat accumulation will increase the heating performance. This work contributes to the performance prediction and application guidance of GSHP systems using spiral coil energy piles in cold regions.

Keywords: ground source heat pump, energy pile, soil thermal imbalance, different climates, cold regions

Nomenclature

B	dimensionless pitch of spiral coil
c	specific heat, J/(kg·°C)
Fo	dimensionless time
H	pile depth, m
L	length of spiral coil pipe, m
m	flow rate, kg/s
P	power consumption of ground source heat pump unit, kW
Q	heating or cooling capacity of ground source heat pump unit, kW
q	specific heat flux rate of an energy pile, W/m
R	heat resistance, (°C·m)/W
t	temperature, °C
S	dimensionless groundwater velocity
X, Y, Z	dimensionless coordination

Greek letters

Θ	dimensionless excess temperature
τ	operating time, s

θ	excess temperature, °C
λ	thermal conductivity, W/(m·ºC)
η	equipment efficiency

Abbreviations

AC	split air conditioner
COP	coefficient of performance
DeST	building load simulation software, Designer's Simulation Toolkit
GSHP	ground source heat pump

Subscript

c	cooling strategy
ci	inlet of condenser
co	outlet of condenser
ei	inlet of evaporator
f	fluid inside the pipe
h	heating strategy
in	inlet of spiral coil

ni	energy piles' serial number
s	soil
wp	water pump

1 Introduction

Ground source heat pump (GSHP) is a clean and efficient air conditioning technology [1, 2]. The system uses ground heat exchanger to extract heat from soil and to inject heat into soil for space heating and cooling of buildings [3, 4]. In GSHP system, ground heat exchanger is an important component and has many different styles [5-8], of which spiral coil energy piles can save the drilling cost and have good performance in heat transfer, drawing more attention from the academic and industrial fields [9-11].

The system performance of GSHP is affected seriously by the different climates [12, 13]. In China, more than 42% GSHP systems are applied in cold regions[14]. Most buildings in cold regions are heating dominated. So, the large soil heat extraction may cause the cold accumulation in soil and heating deficiency of the building. The problems arising from soil thermal imbalance in GSHP system using boreholes have been studied currently. You et al. [14] summarized the problems of soil thermal imbalance of GSHP in cold regions and listed three different solutions from the aspects of ground heat exchanger, operation strategy and system composition. Qian and Wang [15] alleviated the thermal imbalance of soil by increasing the borehole space and depth. Ni et al. [16] investigated the energy efficiency and economic performance of the hybrid GSHP system assisted by the boiler. A number of researchers studied the solar energy [17-19] and air source devices [20-21] assisted hybrid GSHP system using boreholes. Liu et al. [22] analyzed the applicability and performance of GSHP using boreholes as the ground heat exchanger in heating-dominated areas.

However, the previous research is targeting on the GSHP with boreholes, while there is no research on the GSHP using energy piles in different sub climates. Cities in cold regions still have differences in climate like ambient air temperature, which may cause the different GSHP performances and soil thermal conditions. To conduct the analyses, the accurate simulation model of thermal transfer of energy piles group with seepage should be adopted to design the GSHP system and predict the system performance in different sub climates. The three dimensional numerical model is usually used for a single energy pile [23] and can not consider the influence of pile thermal interactions. Since the grid number of the energy piles group is so large, the numerical model of pile groups is usually two dimensional[24], ignoring the influence of pile depth. The analytical model of energy piles group was developed and the soil thermal imbalance of a project was analyzed for optimum design in our previous study [13, 25]. This proposed three dimensional energy piles group model can consider the influential factors, like seepage, geometry of heat exchange pipe and the thermal influences among different piles, which can simulate the heat transfer around energy piles accurately. This model is adopted to simulate the energy efficiency of GSHP system in a Beijing residential building. However, the feasibility and applicability of GSHP using spiral coil energy piles in different sub climates has not been investigated and the system performance has not been compared to that of the common heating and cooling system.

In this paper, the system model of GSHP using spiral coil energy piles is set up based on the proposed energy pile group model. A hotel is selected as the objective and applied in four typical cities of cold regions in China for simulation. The dynamic hourly building loads in different cities are simulated by a transient software. The long-term soil thermal condition, the energy efficiency and the heating effect of the buildings in different cities are investigated. This work contributes to the performance prediction and application guidance of GSHP system using spiral coil energy pile in sub climates.

2 Ground source heat pump system using spiral coil energy piles with seepage

The studied GSHP system in this paper is mainly composed of a building, spiral coil energy piles, a heat pump and a water pump in principle. The pile foundations with spiral coil buried inside are considered as the soil heat exchanger, which is a significant component to determine the system performance.

In winter, the cooled fluid flowing from the heat pump's evaporator goes into the energy piles to complete the thermal extraction from the surrounding soil and then flows back to the evaporator, composing a circulation in the soil side. It causes the temperature decrease and cold accumulation in the soil. Meanwhile, the heat from the evaporator is released to the water flowing past the condenser by the refrigeration cycle inside the heat pump. Then, the heated water is pumped to the building for indoor heating. After the heat is released in the building, the cooled water flows back to the heat pump's condenser for absorbing heat, composing a circulation in the user side.

In summer, the heated fluid flowing from the heat pump's condenser goes into the energy piles to inject heat into the surrounding soil and then is pumped back to the condenser, composing a circulation in the soil side. It causes the temperature increase and heat accumulation in the soil. At the same time, the heat from the evaporator is released to the condenser by the refrigeration cycle inside the heat pump. Then, the chilled water from the evaporator is pumped to the building for indoor cooling. After the heat in the building is absorbed by the supplied water, the heated water flows back to the heat pump's evaporator for releasing heat, composing a circulation in the user side.

For the practical GSHP system, the groundwater seepage can increase the heat exchange around energy piles effectively. Compared to U pipe, the adopted spiral pipe is much longer in an energy pile, bringing about a stronger heat transfer. And the thermal interaction among different energy piles makes the underground heat exchange in energy piles group different from that around a single pile. All these three factors (i. e. groundwater seepage, spiral pipe and thermal interaction in energy piles group) are important and should be considered in the system simulation.

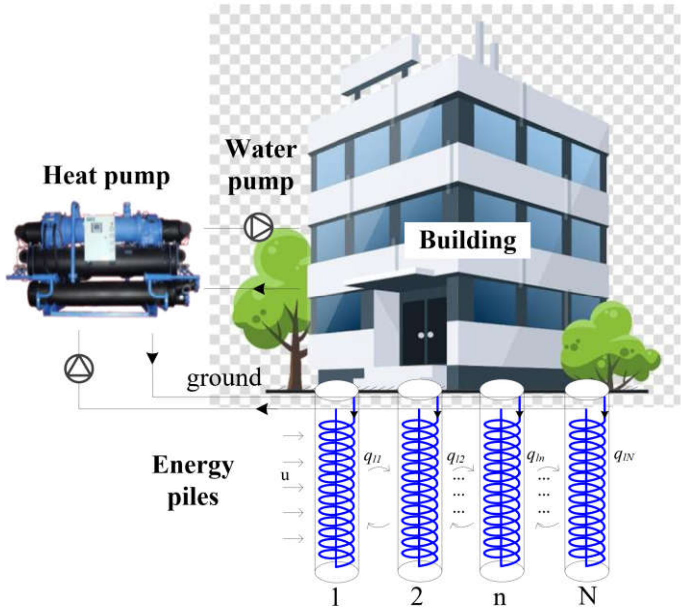


Figure 1 Schematic of GSHP using spiral coil energy piles with seepage

3 Methodology

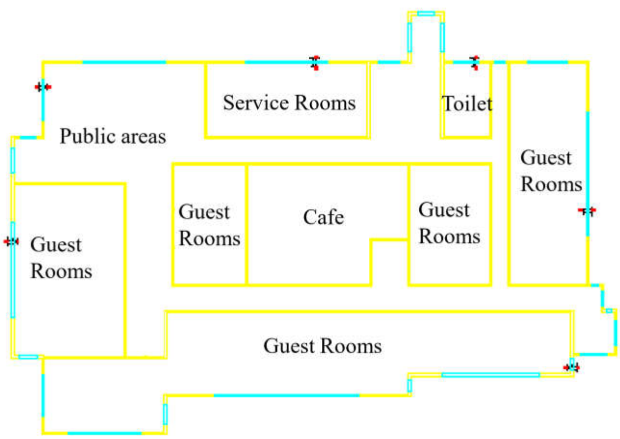
Based on the system principle, the system model is composed of the building load model, the energy piles model, the heat pump model and the water pump model. The model details of each component in the system are explained in this section. Besides, two evaluation indexes are defined to analyze the system efficiency and heating effect.

The cold region in this manuscript is a broad-sense definition, including the narrow-sense severe cold region A, severely cold region B, and cold regions classified in the China national standard "Design standard for energy efficiency of public buildings (GB50189-2015)[27]. Four big and provincial capital cities in cold region of China are selected, which are Harbin, Changchun, Shenyang, and Beijing. They are further classified into three categories: (1) severely cold region A (Harbin), (2) severely cold region B (Changchun, Shenyang), and (3) cold region (Beijing). Therefore, they can cover the main climate characteristics of Northern China and practical to investigate the feasibility and applicability of GSHP using spiral coil energy piles in different cold regions. After the results of these typical cities are obtained, other cities with similar or close climate characteristics can be regarded to have similar feasibility and applicability. However, if a more specific long-term simulation is required for a targeted city other than the four typical ones, the model and method in this paper can be used to conduct similar analyses.

3.1 Building model

To investigate the effect of different sub climates on the system performance of GSHP using energy piles under the condition with seepage, a hotel is selected as the objective building. The building layout and floor plan of simulated hotel are illustrated in Figure 2. The total air conditioning areas is 8700m^2, of which 3500m^2 is controlled by GSHP system. The hotel has 5 floors (Figure 2a), including the guest rooms, cafes, service rooms, public areas, and toilets (Figure 2b).

(a) Building layout



(b) Floor plan of standard layer in DeST

Figure 2 Layout and floor plan of simulated hotel

The floor plan of standard layer drawn in DeST for the simulation of building load is shown in Figure 2b. DeST [28], which is the abbreviation of Designer's Simulation Toolkit, is a dynamic building simulation software proposed by Tsinghua University. Based on the “Design standard for energy efficiency of public buildings (GB50189-2015)” [27] and “Code for thermal design of civil building (GB50176-2016)” [29], the thermal properties of building envelope and the indoor properties are designed as Table 1 and inputted to the simulation software of building load. After that, the heating and cooling load of each room and the whole building can be calculated by DeST.

Table 1 Designed thermal properties of building envelop and the indoor properties of building

Items	Values
Conditioned areas by GSHP	3500 m^2
Roof, Outer wall, Floor	Heat transfer coefficient ($W/(m^2 \cdot K)$): 0.595, 0.958, 0.792
Windows	Area Ratio of window to wall (North: 0.25, East or West: 0.3, South: 0.35)
	Heat transfer coefficient ($W/(m^2 \cdot K)$): 2.7
	Shading Coefficient: 0.25
Indoor air temperature	Winter: 20~22°C; Summer: 24~26°C
Indoor air relative humidity	Winter: 35%~40%; Summer: 55%~65%
Ventilation	Fresh air volume: 30 $m^3/(h \cdot Person)$
	Air change rate: 0.3 time per person
Operation time of GSHP system	24h

3.2 Energy pile model and validation

The model of energy pile group with seepage is described in Equation 1[13]. In Equation 1, the transient heat fluxes of each energy pile can be simulated by the matrix if the inlet temperature of each energy pile is input. It accurately considers the practical geometry of spiral coil energy piles and the underground water flow because the heat source of analytical dimensionless soil temperature (Θ) is a moving spiral coil with the velocity of seepage. Besides, the thermal interaction among energy piles group can be considered by the simultaneous calculation of the coupled heat fluxes of energy piles.

$$Q_l = A^{-1} \times B \tag{1}$$

$$Q_l = \left[q_{l,1}(j\Delta\tau) \quad q_{l,2}(j\Delta\tau) \quad \dots \quad q_{l,n}(j\Delta\tau) \quad \dots \quad q_{l,N}(j\Delta\tau) \right]^T \tag{1a}$$

$$A = \begin{bmatrix} \frac{R_p \times H}{L_{pipe}} + \frac{H}{2c_f m_f} + \frac{\Theta_{1,1}(\Delta\tau)}{\lambda_s} & \frac{\Theta_{2,1}(\Delta\tau)}{\lambda_s} & \dots & \frac{\Theta_{n,1}(\Delta\tau)}{\lambda_s} & \dots & \frac{\Theta_{N,1}(\Delta\tau)}{\lambda_s} \\ \frac{\Theta_{1,2}(\Delta\tau)}{\lambda_s} & \frac{R_p \times H}{L_{pipe}} + \frac{H}{2c_f m_f} + \frac{\Theta_{2,2}(\Delta\tau)}{\lambda_s} & \dots & \frac{\Theta_{n,2}(\Delta\tau)}{\lambda_s} & \dots & \frac{\Theta_{N,2}(\Delta\tau)}{\lambda_s} \\ \dots & \dots & & \dots & & \dots \\ \frac{\Theta_{1,n}(\Delta\tau)}{\lambda_s} & \frac{\Theta_{2,n}(\Delta\tau)}{\lambda_s} & \dots & \frac{R_p \times H}{L_{pipe}} + \frac{H}{2c_f m_f} + \frac{\Theta_{n,n}(\Delta\tau)}{\lambda_s} & \dots & \frac{\Theta_{N,n}(\Delta\tau)}{\lambda_s} \\ \dots & \dots & & \dots & & \dots \\ \frac{\Theta_{1,N}(\Delta\tau)}{\lambda_s} & \frac{\Theta_{2,N}(\Delta\tau)}{\lambda_s} & \dots & \frac{\Theta_{n,N}(\Delta\tau)}{\lambda_s} & \dots & \frac{R_p \times H}{L_{pipe}} + \frac{H}{2c_f m_f} + \frac{\Theta_{N,N}(\Delta\tau)}{\lambda_s} \end{bmatrix} \tag{1b}$$

$$B = \begin{bmatrix} t_{in}(j\Delta\tau) - t_0 + \sum_{ni=1}^{N} \left\{ q_{l,ni}((j-1)\Delta\tau) \times \Theta_{ni,1}(\Delta\tau) - \sum_{i=2}^{j-1} \left[q_{l,ni}(i\Delta\tau) - q_{l,ni}((i-1)\Delta\tau) \right] \times \Theta_{ni,1}((j-i+1)\Delta\tau) - q_{l,ni}(\Delta\tau) \times \Theta_{ni,1}(j\Delta\tau) \right\} \Big/ \lambda_s \\ t_{in}(j\Delta\tau) - t_0 + \sum_{ni=1}^{N} \left\{ q_{l,ni}((j-1)\Delta\tau) \times \Theta_{ni,2}(\Delta\tau) - \sum_{i=2}^{j-1} \left[q_{l,ni}(i\Delta\tau) - q_{l,ni}((i-1)\Delta\tau) \right] \times \Theta_{ni,2}((j-i+1)\Delta\tau) - q_{l,ni}(\Delta\tau) \times \Theta_{ni,2}(j\Delta\tau) \right\} \Big/ \lambda_s \\ \dots \\ t_{in}(j\Delta\tau) - t_0 + \sum_{ni=1}^{N} \left\{ q_{l,ni}((j-1)\Delta\tau) \times \Theta_{ni,n}(\Delta\tau) - \sum_{i=2}^{j-1} \left[q_{l,ni}(i\Delta\tau) - q_{l,ni}((i-1)\Delta\tau) \right] \times \Theta_{ni,n}((j-i+1)\Delta\tau) - q_{l,ni}(\Delta\tau) \times \Theta_{ni,n}(j\Delta\tau) \right\} \Big/ \lambda_s \\ \dots \\ t_{in}(j\Delta\tau) - t_0 + \sum_{ni=1}^{N} \left\{ q_{l,ni}((j-1)\Delta\tau) \times \Theta_{ni,N}(\Delta\tau) - \sum_{i=2}^{j-1} \left[q_{l,ni}(i\Delta\tau) - q_{l,ni}((i-1)\Delta\tau) \right] \times \Theta_{ni,N}((j-i+1)\Delta\tau) - q_{l,ni}(\Delta\tau) \times \Theta_{ni,N}(j\Delta\tau) \right\} \Big/ \lambda_s \end{bmatrix} \tag{1c}$$

$$\begin{aligned} \Theta = \frac{B}{16\pi^{5/2}} \int_0^{Fo} \frac{1}{(Fo - Fo')^{3/2}} \int_{2\pi H_1/B}^{2\pi H_2/B} \exp\left[-\frac{\left[X - \cos\varphi' - S(Fo - Fo') \right]^2 + (Y - \sin\varphi')^2}{4(Fo - Fo')} \right] \times \\ \left\{ \exp\left[-\frac{(Z - B\varphi'/2\pi)^2}{4(Fo - Fo')} \right] - \exp\left[-\frac{(Z + B\varphi'/2\pi)^2}{4(Fo - Fo')} \right] \right\} d\varphi' dFo' \end{aligned} \tag{1d}$$

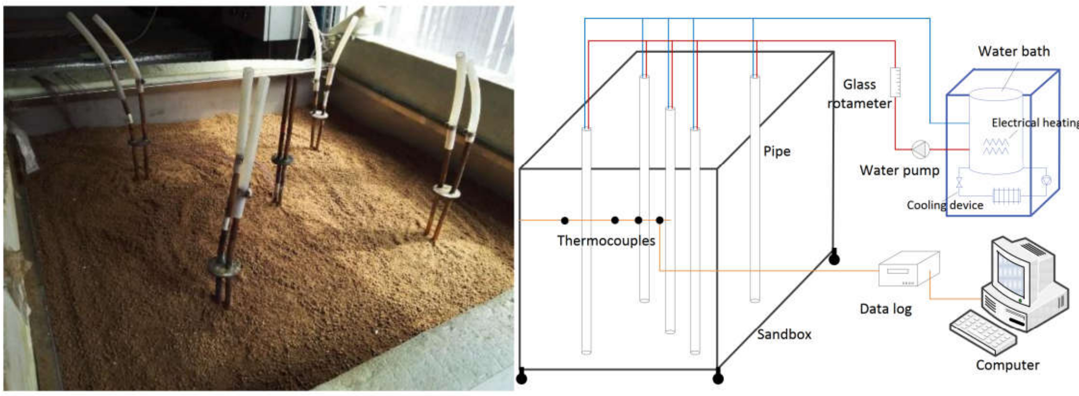
where, q is specific heat flux rate of an energy pile, W/m; R_p is heat resistance of pipe, (m·K)/W; H is depth of each energy pile, m; L is length of spiral coil pipe, m; c is specific heat capacity, J/(kg·ºC); λ is the heat conductivity coefficient, W/(m·ºC); t is the temperature, ºC; τ is the time, s; m is the mass flow rate, kg/s; Θ is the dimensionless temperature of a single energy pile with seepage [25]; Q_l is a heat flux matrix of different energy piles; Fo, B, and S are respectively the dimensionless time, coil pitch, and velocity of groundwater flow; X, Y, Z are the dimensionless coordination of soil points; H_1 and H_2 are dimensionless depths of the energy pile top and bottom.

After the heat fluxes of energy piles are calculated, the three dimensional soil temperature distribution can be calculated as Equation 2 [13, 26], and the outlet fluid temperature of energy piles can also be easily calculated.

$$\theta_s\left(j\Delta\tau\right)=\frac{1}{\lambda_s}\sum_{ni=1}^{N}\sum_{i=1}^{j}\left[q_{l,ni}\left(i\Delta\tau\right)-q_{l,ni}\left(\left(i-1\right)\Delta\tau\right)\right]\times\Theta_{ni,s}\left(\left(j-i+1\right)\Delta\tau\right) \qquad (2)$$

where subscript s is the soil point.

Since the field test of energy pile projects has many uncontrolled interference factors, the parameters setting of simulation is hard to keep the same with the test. Consequently, the testing results of practical projects are not very reasonable to validate the model. In addition, the principle of proposed energy pile group model is adaptable to ground heat exchangers group in different sizes. Therefore, to validate the energy pile group model accurately, the sandbox experiment is set up in the laboratory. The sandbox has a size of 1m×1m×1m, and is filled with sand. The walls of the sandbox are adiabatic by covering the insulating material. Five heat exchanging pipes are buried inside and the water flows inside the pipes from the water bath with a constant temperature. Four thermocouples are buried in the sand in the middle depth of the sandbox. The photo and schematic diagram of the sandbox experiment are illustrated in Figure 2. When the excess temperature of the pipe inlet (i. e. the temperature difference between the pipe inlet and the initial soil) is 10 ºC, the soil temperatures of 4 positions tested by the experiment and simulated by the analytical energy piles model (Equation 1) are shown in Figure 3. Results show that the temperatures of these two different methods match well. The analytical energy piles group model has good accuracy.



(a) Photos of experiment (b) Schematic diagram

Figure 2 Sandbox experiment

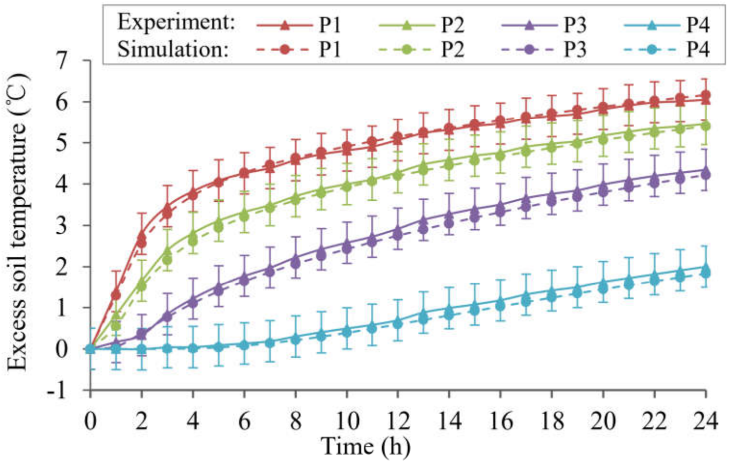


Figure 3 The simulated excess soil temperature validation by experiment results[13]

3.3 The system model

Apart from the building model and the energy piles model, the system model also includes the heat pump model and the water pump model, which are described as the follows.

The heat pump model uses the typical performance curves of practical products in the market, as shown in Equation 3. The heating and cooling capacity and electricity consumption of heat pump unit are the functions of water temperatures of evaporator and condenser.

$$Q_h = 5.91T_{ei} - 1.24T_{co} + 162.99 \qquad R^2 = 0.9943 \tag{3a}$$

$$P_h = 0.46T_{ei} + 0.64T_{co} + 5.78 \qquad R^2 = 0.9815 \tag{3b}$$

$$Q_c = -1.64T_{ci} + 201.21 \qquad R^2 = 0.9956 \tag{3c}$$

$$P_c = 0.65T_{ci} + 22.40 \qquad R^2 = 0.9973 \tag{3d}$$

$$COP = \frac{Q}{P} \tag{3e}$$

where Q is the cooling or heating capacity of ground source heat pump unit, kW; P is the electricity consumption of ground source heat pump unit, kW; COP is the cooling or heating efficiency of ground source heat pump unit; T is fluid temperature, ºC; subscript ei, ci, and co are inlet of evaporator, inlet of condenser, and outlet of condenser, respectively; h and c mean heating and cooling strategy, respectively.

The water pump model is shown in Equation 4. The power consumption of water pump can be calculated by the flow rate, water head and pump efficiency.

$$P_{wp} = \frac{G_{wp} \times H_{wp}}{\eta_{wp}} \tag{4}$$

where G_{wp} is flow rate of water pump, m^3/s; H_{wp} is water head of water pump, kPa; η_{wp} is efficiency of water pump, 0.6.

By coding in the MATLAB based on the component models, the system model is established and summarized in Table 2. To guarantee the indoor air temperature and the outlet fluid temperature of energy piles, 25 energy piles with the depth of 50 m are adopted in the project and arranged in a 5 × 5 matrix. The density, thermal conductivity, and specific heat of soil are 1690 kg/m^3, 1.74 W/(m·K), and 1800 J/(kg·K) respectively. The velocity of groundwater flow in soil is 3×10^{-7} m/s. The rated heat capacity of heat pump unit is 352kW in Harbin, 307kW in Changchun, 256kW in Shenyang and 170kW in Beijing.

Table 2 Models of main components in the system

Component models	Specific methods
Building model	Hourly building load simulation using DeST software
Energy piles model	Analytical energy piles group model considering various practical factors (Eq. 1& 2)
Heat pump model	Typical performance curves of practical products in the market (Eq. 3)
Water pump model	Eq. 4 based on flow rate, water head and water pump efficiency

3.3 Evaluation indexes

The gas boiler and split air conditioner system (Boiler + AC) is a common heating and cooling system in cold region of China. This system is selected as the contrast to analyze the energy consumption of ground source heat pump using energy piles. In the Boiler + AC system, the split air conditioner is used in summer for cooling. The average seasonal COP of air conditioner is 3.5 in summer according to the common products in the Chinese market. Since the energy source of boiler is gas, the energy consumption of boiler should be transformed to the equivalent power consumption [30] before the comparison. The equivalent power consumption of boiler is defined as Equation 5.

$$\sum P_{boiler} = \frac{\sum Load_h \times \eta_{power}}{\eta_{boiler}} \tag{5}$$

where, ΣP_{boiler} is the equivalent power consumption of gas boiler each month, MWh; $\Sigma Load_{\text{h}}$ is the monthly heating load, MWh; η_{power} is the efficiency of gas boiler to produce power, 0.5; η_{boiler} is the efficiency of gas boiler to produce hot water, 0.9[30].

For the heating-dominated system, due to the cold accumulation in soil annually, the soil temperature decreases year by year and the heating capacity produced by the GSHP system declines yearly. The monthly heating deficiency of GSHP is defined as the difference between the supplying heat produced by the GSHP system and the heating load demanded by the building. The amount of heating deficiency can be calculated by Equation 6.

$$\sum Q_{def} = \sum Q_{sup} - \sum Load_h \tag{6}$$

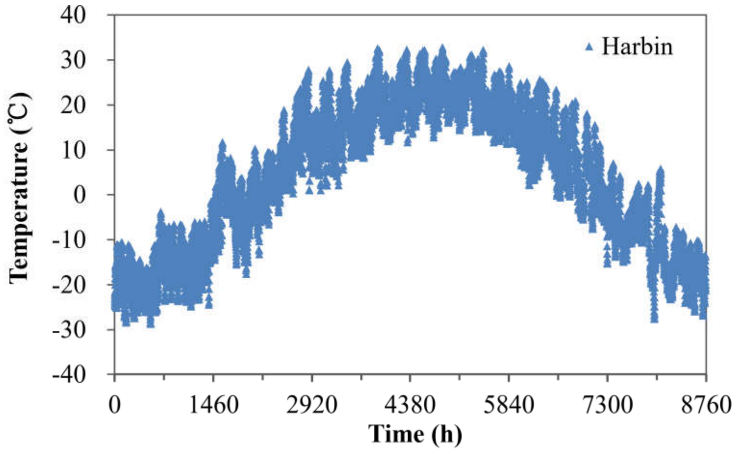
where, ΣQ_{def} is the monthly heating deficiency of the building, MWh; ΣQ_{sup} is the monthly supplying heat for the building produced by the heat pump, MWh; $\Sigma Load_{\text{h}}$ is the monthly heating load of the building to keep the indoor air temperature at the design range, MWh.

4 Results and analyses

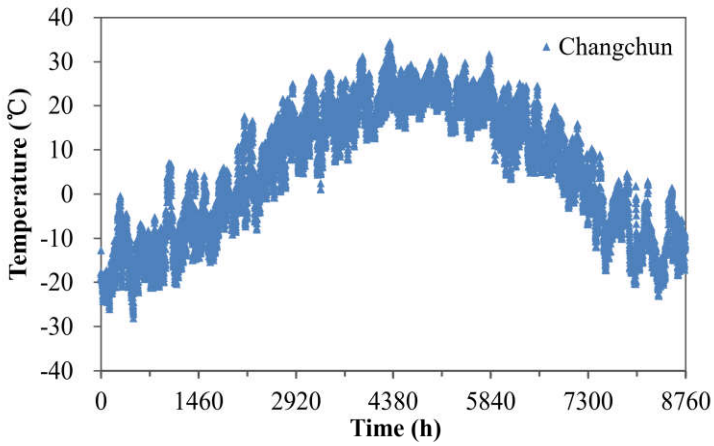
Based on the proposed system model, the system performance is simulated and the influence of different sub climates is investigated. First, the basic analysis of the typical sub climates and the building loads in four cities are calculated. Besides, the soil thermal exchange and the outlet fluid temperature from the energy piles are studied to reflect the heat exchange between the soil and system in ten years. Apart from that, the system energy efficiency in a long term is demonstrated by studying the heating COPs of heat pumps and comparing the electricity consumption of the GSHP system to the conventional boiler and split air conditioner (Boiler + AC) system. Finally, the unsatisfied heating demand caused by the soil thermal imbalance is investigated.

4.1 Climate and building load

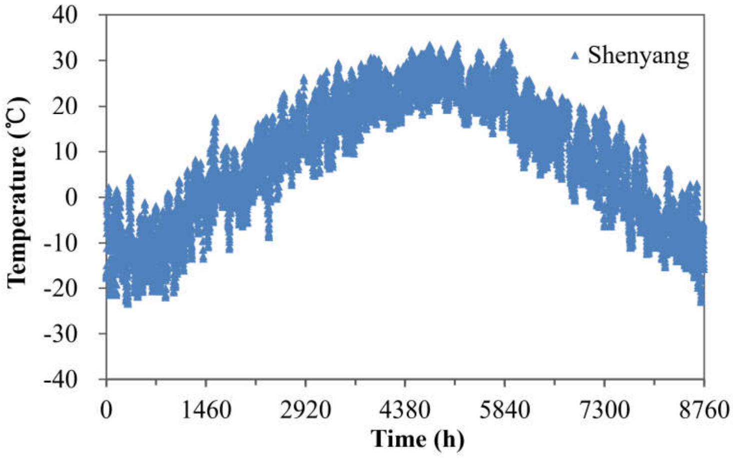
The hourly average air temperatures in four cities [31] are shown in Figure 4. The minimum air temperature is -28.7 ºC in Harbin, -28.1 ºC in Changchun, -23.4 ºC in Shenyang and -14.2 ºC in Beijing. And the maximum air temperature is 32.8 ºC in Harbin, 34.4 ºC in Changchun, 34.1 ºC in Shenyang and 37.2 ºC in Beijing. As for the monthly average air temperature, the maximum and minimum values are respectively 22.9 ºC and -18.8 ºC in Harbin, 22.9 ºC and -15.4 ºC in Changchun, 25.7 ºC and -11.5 ºC in Shenyang, 26.5 ºC and -3.8 ºC in Beijing. It is obvious that Harbin has the coldest winter among all four cities and the summers in all four cities are not hot.



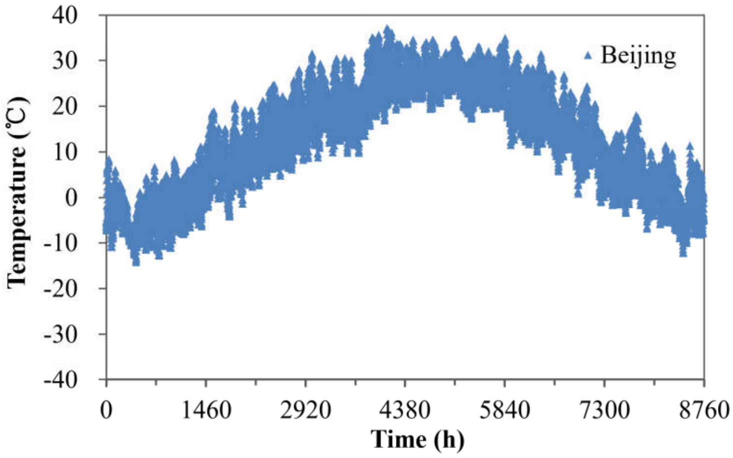
(a) Harbin



(b) Changchun



(c) Shenyang

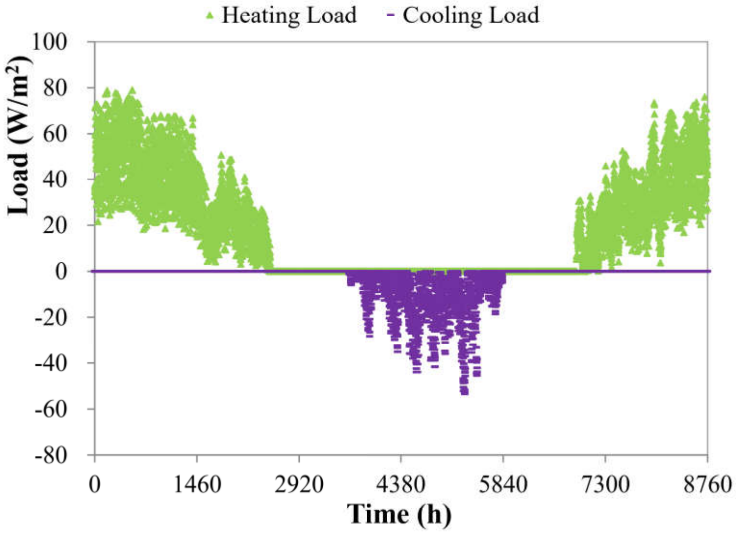


(d) Beijing

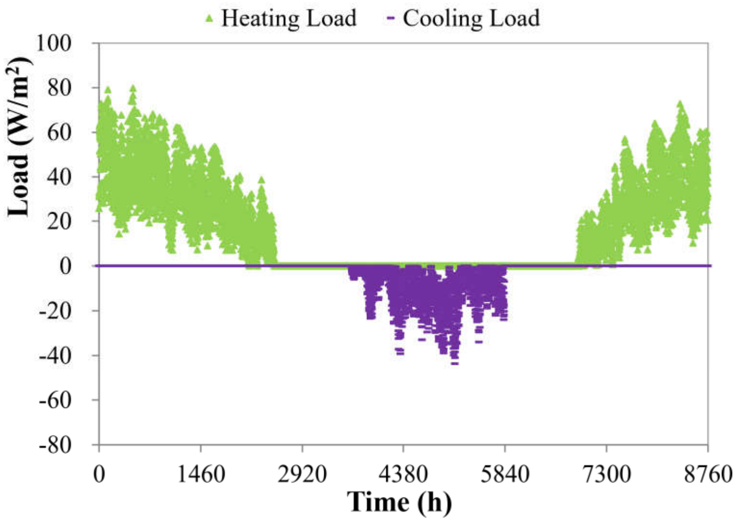
Figure 4 The hourly average air temperature in different cities

The hourly building loads in four cities are simulated by DeST as shown in Figure 5. The maximum monthly heating loads are -120.91 MWh in Harbin, -111.91 MWh in Changchun, -98.63 MWh in Shenyang, and -68.94 MWh in Beijing. The maximum monthly cooling loads are 33.47 MWh in Harbin, 33.71 MWh in Changchun, 59.23 MWh in Shenyang and 78.19MWh in Beijing. The annual accumulated heating and cooling loads are -483.97 MWh and 71.43 MWh in Harbin, -450.19 MWh and 69.10 MWh in Changchun, -340.48 MWh and 115.62 MWh in Shenyang, -203.15 MWh and 169.14 MWh in Beijing respectively. To describe the difference between heating and cooling loads, $R_{h/c}$ is defined as the ratio of annual accumulated heating load to cooling load. $R_{h/c}$ are respectively 6.78 in Harbin, 6.51 in

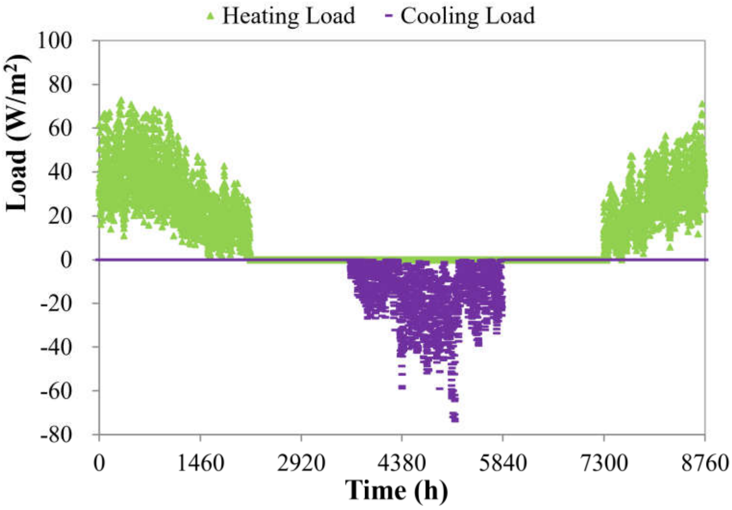
Changchun, 2.94 in Shenyang and 1.20 in Beijing. It demonstrates that the buildings in these four cities are heating dominant. Harbin has the largest heating load and the smallest cooling load compared to other cities. Beijing has the smallest heating load and the largest cooling load.



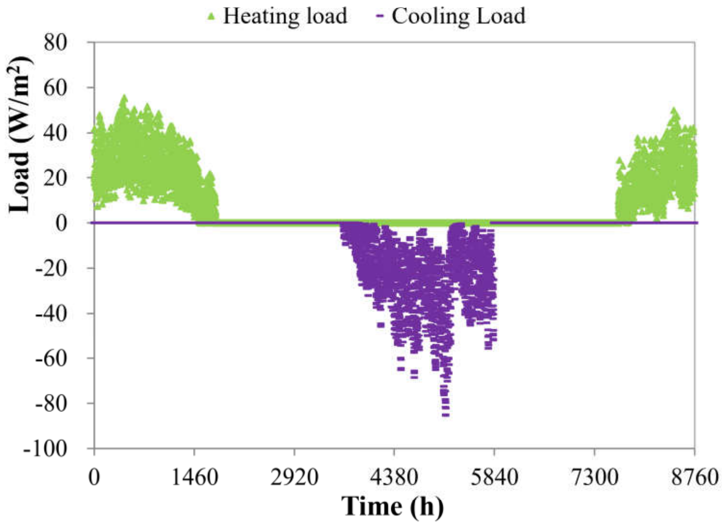
(a) Harbin



(b) Changchun



(c) Shenyang

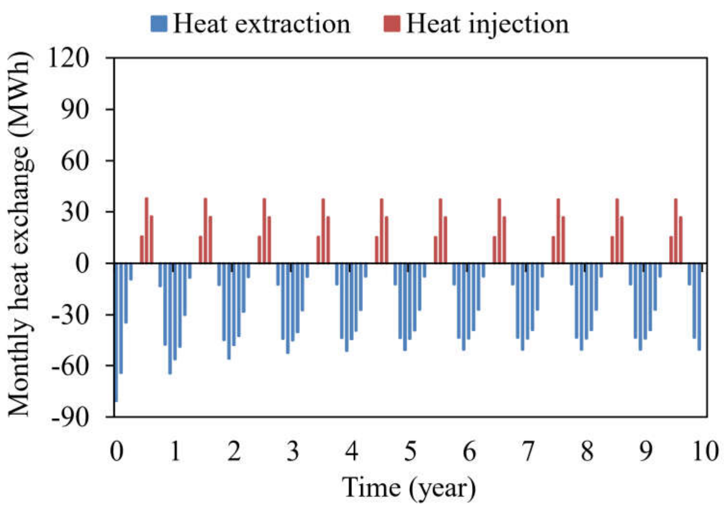


(d) Beijing

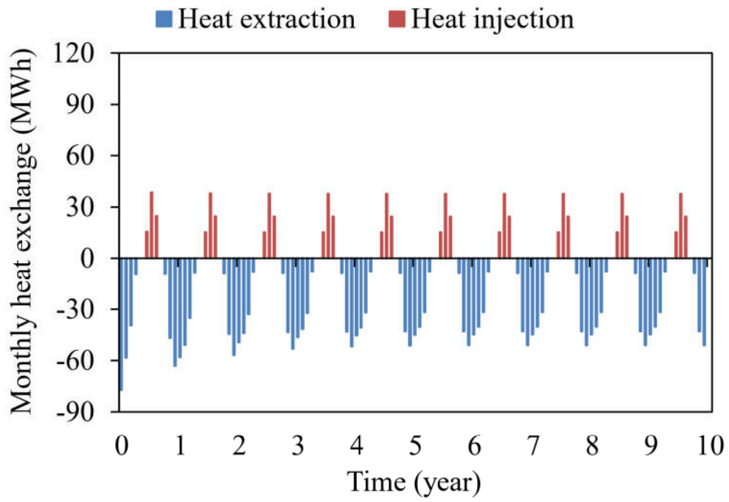
Figure 5 The hourly building load of a hotel in different cities

4.2 Dynamic soil heat exchange

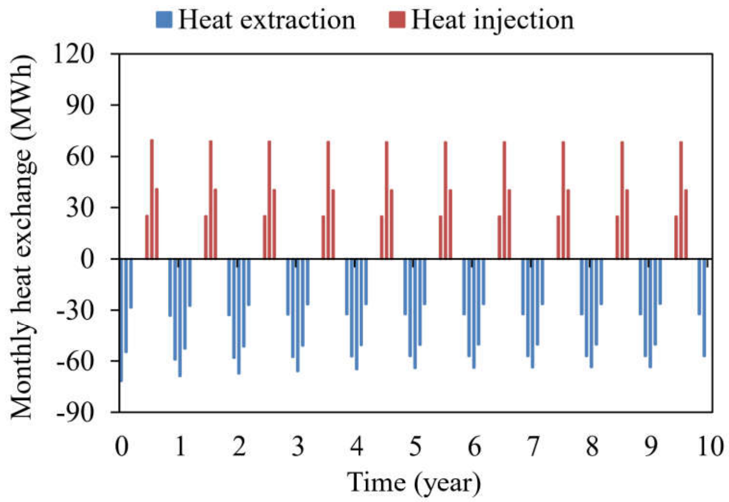
The monthly soil heat extraction and injection in ten years of four cities are shown in Figure 6. In the first year, the accumulated heat extraction from the soil is -314.06 MWh and heat injection into the soil is 80.73 MWh in Harbin (Figure 6a). It has a serious soil thermal imbalance and the cold is accumulated in the soil. Since the soil temperature decreases yearly, the soil heat extraction driven by the heat pump decreases and meanwhile it causes the heating deficiency which will be analyzed in section 4.4. The variation of soil thermal imbalance becomes gentle year by year. The accumulated heat extraction is -223.70 MWh and heat injection is 79.28 MWh in the 10th year. As shown in Figure 6b, the trend of yearly heat extraction and injection in Changchun is similar to that in Harbin. The accumulated heat extraction is -303.74 MWh and heat injection in Changchun is 78.55 MWh in the first year. In the 10th year, they become -226.97 MWh and 76.97 MWh. Figure 6c shows that the decrease in yearly heat extraction in Shenyang is not that serious due to the relatively high soil temperature and the smaller difference between heating and cooling load. The accumulated heat extraction and heat injection are -247.15 MWh and 135.12 MWh in Shenyang in the first year, and -229.47 MWh and 132.99 MWh in the 10th year. During heating period, the heat supplied by the heat pump to the building is equal to the soil heat extraction plus the power consumption of heat pump. During cooling period, the heat absorbed by the heat pump from the building is equal to the soil heat injection minus the power consumption of heat pump. Thus, even though the accumulated heating load is a little bit larger than cooling load in Beijing, the soil heat extraction is smaller than the soil heat injection. For this hotel in Beijing, GSHP system has the heat accumulation in soil. The accumulated heat extraction and heat injection are -156.54 MWh and 205.63 MWh in Beijing in the first year, and -159.28 MWh and 206.03 MWh in the 10th year. The ratios of annual accumulated soil heat extraction to the soil heat injection ($R_{Qh/Qc}$) in the first year are respectively 3.89 in Harbin, 3.87 in Changchun, 1.83 in Shenyang and 0.76 in Beijing.



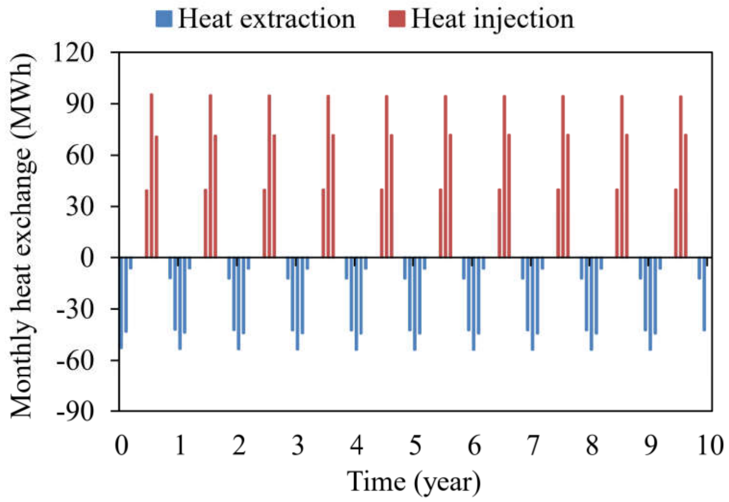
(a) Harbin



(b) Changchun



(c) Shenyang



(d) Beijing

Figure 6 The monthly accumulated heat extraction and injection in different cities

The 10 years' outlet fluid temperature of energy piles in different cities is shown in Figure 7. Due to the low initial soil temperature and the large soil heat extraction, Harbin has the lowest outlet fluid temperature of energy piles. It is low to -3.6°C in the first year and its decreasing rate becomes gentle yearly. Finally, the minimum outlet fluid temperature of energy piles diminishes to -7.7 °C in the tenth year. The variations of outlet fluid temperature in Changchun and Shenyang have the similar tendency to that in Harbin. The minimum fluid temperature is -1.9 °C and -6.8 °C in the first and tenth year in Changchun. The minimum fluid temperature is 2.9 °C and -1.6 °C in the first and tenth year in Shenyang. Due to the heat accumulation in soil, Beijing has an increase in outlet temperature with minimum value changing from 8.7 °C in the first year to 11.9 °C in the tenth year.

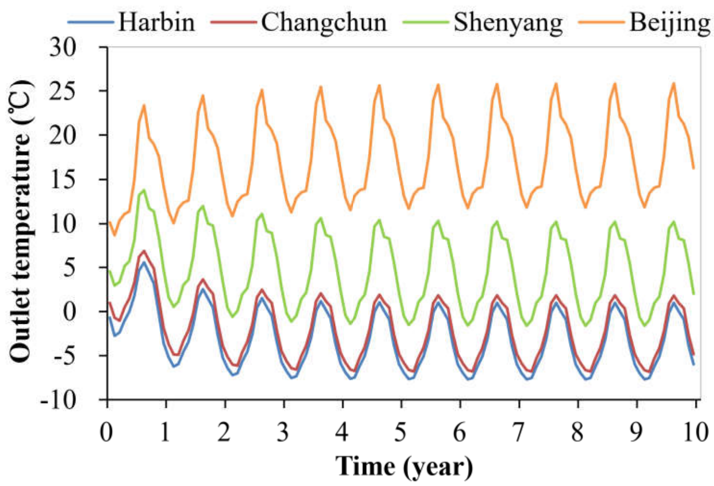


Figure 7 The outlet fluid temperature of energy piles in different cities

4.3 Long term system efficiency

To evaluate the system efficiency in a long term, the heating COP of heat pump is investigated and the system's power consumption is compared to the conventional boiler and split air conditioner (Boiler + AC) system.

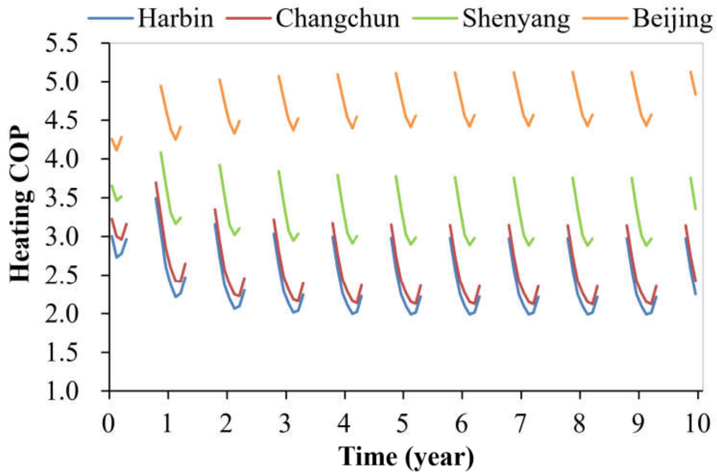
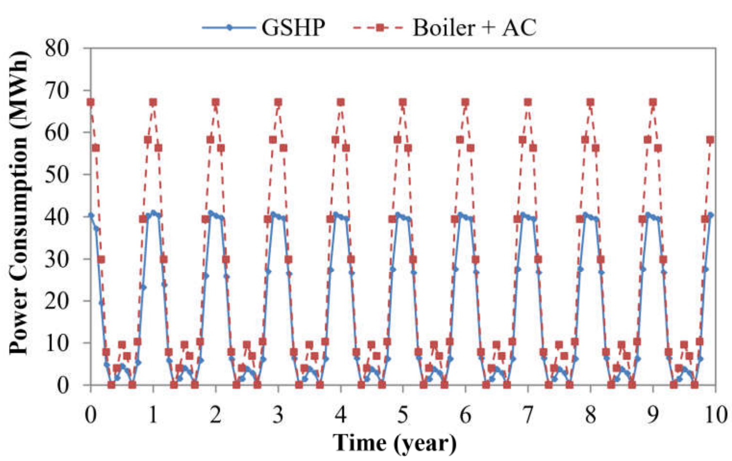
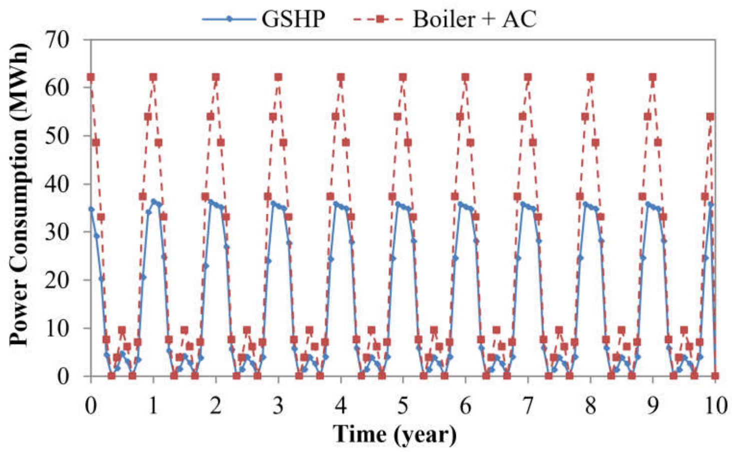


Figure 8 The monthly heating COP of heat pump in different cities

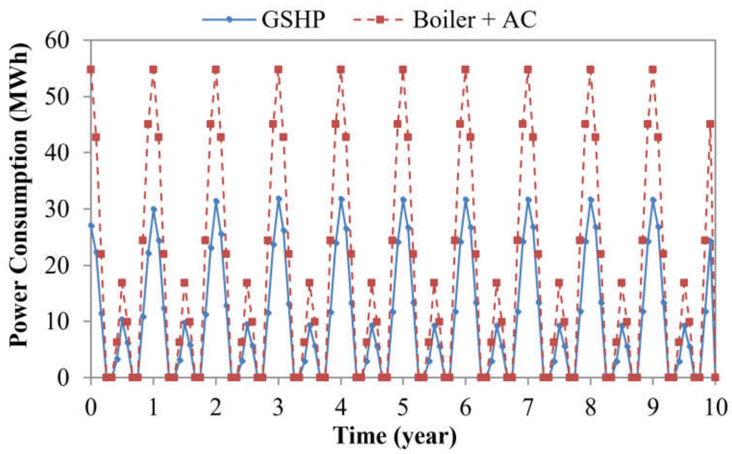
The monthly heating COP of heat pump in different cities is shown in Figure 8. Due to the dominant heating load and the cold accumulation in soil, the heating COP in Harbin, Changchun and Shenyang decreases yearly. The seasonal average heating COP decreases from 2.95 to 2.30 in Harbin, from 3.17 to 2.46 in Changchun, from 3.68 to 3.20 in Shenyang and increases from 4.45 to 4.71 in Beijing. The seasonal heating COP decreases by 22% in Harbin, 22% in Changchun and 13% in Shenyang and increases by 6% in Beijing during 10 years. The minimum COP in Harbin decreases from 2.61 in the first year to 1.99 in the tenth year. The minimum COP in Changchun decreases from 2.85 in the first year to 2.13 in the tenth year. The minimum COP in Shenyang decreases from 3.46 in the first year to 2.88 in the tenth year. The heating COP in Beijing increases with minimum value changing from 4.11 in the first year to 4.43 in the tenth year.



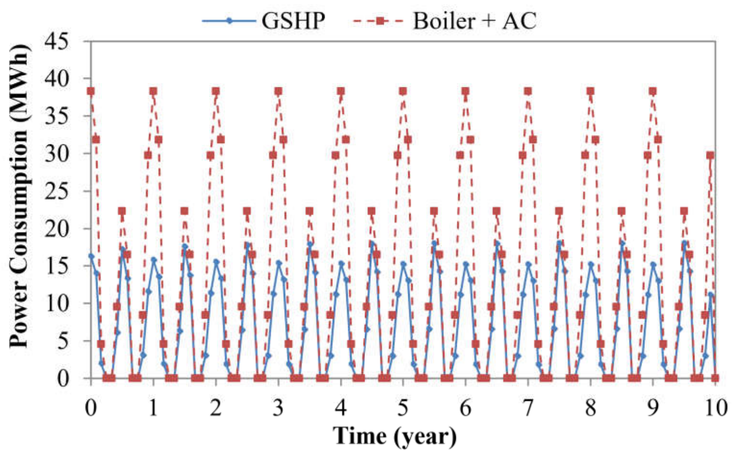
(a) Harbin



(b) Changchun



(c) Shenyang



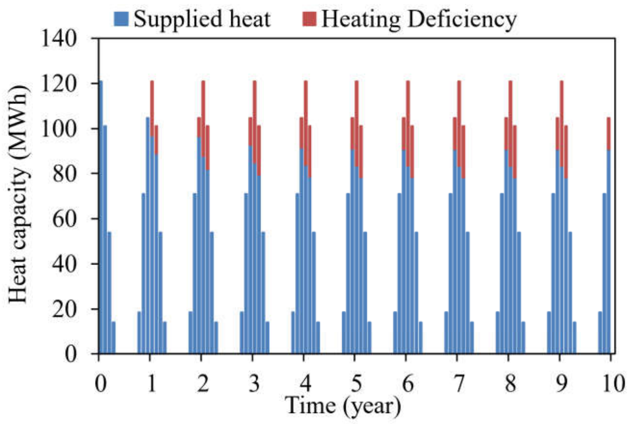
(d) Beijing

Figure 9 Power consumption of GSHP compared to the conventional system

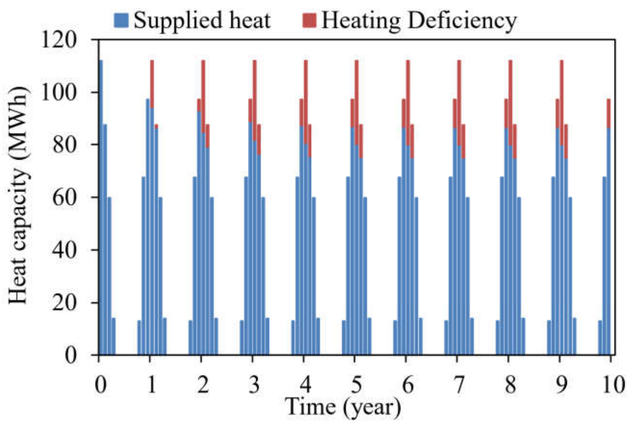
The power consumption of GSHP compared to the conventional system is shown in Figure 9. In the cold regions of China, Boiler + AC system is a common heating and cooling technology. For the selected building in all four cities, the GSHP is much more efficient than the Boiler + AC system both in summer and in winter. For Harbin, the accumulated power consumption of GSHP is respectively 169.91 MWh and 9.30MWh in winter and summer in the first year, while the accumulated power consumption of Boiler + AC is respectively 268.87 MWh and 20.41 MWh. For Changchun, the accumulated power consumption of GSHP is respectively 146.46 MWh and 9.44 MWh in winter and summer in the first year, while the accumulated power consumption of Boiler + AC is respectively 250.11 MWh and 19.74 MWh. For Shenyang, the accumulated power consumption of GSHP is respectively 93.33 MWh and 19.50 MWh in winter and summer in the first year, while the accumulated power consumption of Boiler + AC is respectively 189.16 MWh and 33.03 MWh. For Beijing, the accumulated power consumption of GSHP is respectively 46.61 MWh and 36.49 MWh in winter and summer in the first year, while the accumulated power consumption of Boiler + AC is respectively 112.86 MWh and 48.33 MWh. The power consumption of GSHP only accounts for 51%~62% of Boiler + AC system in four different cities.

4.4 Long term heating effect

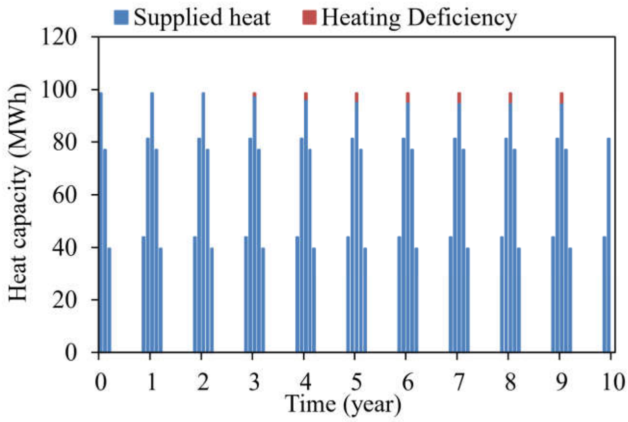
The heating deficiency means that supplied heat from the heat pump is less than the heat demanded by the building. Due to the heat accumulation in soil, Beijing has no heating deficiency in ten years. The monthly heating deficiencies of Harbin, Changchun and Shenyang are shown in Figure 10. All the cities have no heating deficiency in the first year. However, as the heat extraction from the soil decreases yearly, the heating deficiency increases yearly in these three cities. In Harbin, the maximum monthly heating deficiency of the building is 23.9 MWh and 37.4 MWh in the 2nd and 10th year respectively, and the annually accumulated heating deficiency the building is 43.9 MWh and 74.0 MWh in the 2nd and 10th year respectively. In Changchun, the maximum monthly heating deficiency the building is 17.6 MWh and 32.0 MWh in the 2nd and 10th year respectively. In Shenyang, the maximum monthly heating deficiency the building is 0 and 3.5 MWh in the 2nd and 10th year respectively. In the 10th year, the accumulated heating deficiency in the building accounts for 15%, 12% and 1% of the demanding heat of the building in Harbin, Changchun and Shenyang.



(a) Harbin



(b) Changchun



(c) Shenyang

Figure 10 The monthly heating deficiency in different cities

5 Conclusions

Soil thermal imbalances caused by the difference between heating and cooling load have different effects on the system performance of GSHP system in cold regions. To simulate the GSHP system performance, a system simulation model is developed, including the building model, the model of energy piles group with seepage, the heat pump model, and the water pump model. The effect of different sub climates on the system performance is investigated in this paper. Major conclusions are as follows.

Harbin, Changchun, Shenyang and Beijing have cold winter and not hot summer. Harbin is the coldest city with a minimum monthly average air temperature of -18.8 ºC. The annual accumulated heating and cooling loads are -483.97 MWh and 71.43 MWh in Harbin, -450.19 MWh and 69.10 MWh in Changchun, -340.48 MWh and 115.62 MWh in Shenyang, -203.15 MWh and 169.14 MWh in Beijing respectively. Therefore, the hotels in these cities are heating dominant with load ratios of 6.78 in Harbin, 6.51 in Changchun, 2.94 in Shenyang and 1.20 in Beijing.

Caused by the far larger heating load than cooling load, the soil heat extraction is obviously larger than heat injection with the heat ratio of 3.89 in Harbin, 3.87 in Changchun, 1.83 in Shenyang. The heat extraction decreases yearly because the soil temperature reduces. In Harbin, Changchun, and Shenyang, the annually accumulated soil heat extraction decreases from -314.06 MWh, -303.74 MWh and -247.15 MWh in the first year to -223.70 MWh, -226.97 MWh and -229.47 MWh in the tenth year; the minimum outlet fluid temperature of energy piles drops to -7.7 °C, -6.8 °C and -1.6 °C respectively. However, in Beijing the accumulated soil heat extraction is smaller than heat injection, which are respectively -156.54 MWh and 205.63 MWh in the first year, leading to minimum outlet fluid temperature increases from 8.7 °C in the first year to 11.9 °C in the tenth year

The GSHP system using spiral coil energy piles is efficient compared to the conventional systems. The power consumption of GSHP only accounts for 51%~62% of Boiler + AC system in four cities. However, the soil thermal imbalance brings the long term heating COP decrease and heating deficiency of GSHP. For Harbin, Changchun, and Shenyang, the seasonal heating COP decreases by 22% in Harbin, 22% in Changchun and 13% in Shenyang during 10 years; the accumulated heating deficiency in the10^{th} year accounts for 15%, 12% and 1% of the demanding heat of the building in Harbin, Changchun and Shenyang. In Beijing, the heating COP of GSHP does not drop yearly and all the heating demands can be satisfied.

As a summary, when GSHP is applied in hotels in cities with similar climates to Harbin and Changchun, the soil thermal imbalance with serious cold accumulation will cause the heating performance decline as well as the heating deficiency. Thus, the hybrid GSHP system by integrating with other technologies should be adopted to keep the long term operation effective. When GSHP is applied in hotels in cities with similar climates to Shenyang, the soil thermal imbalance with cold accumulation will cause the heating performance decline but the system's heating capacity is acceptable. When GSHP is applied in hotels in cities with similar climates to Beijing, the soil thermal imbalance with heat accumulation will increase the heating performance. It is reminding that the GSHP discussed in this manuscript is only used for space heating and space cooling in hotels, and the domestic hot water which is a large heating demand in hotel is provided by other technologies.

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