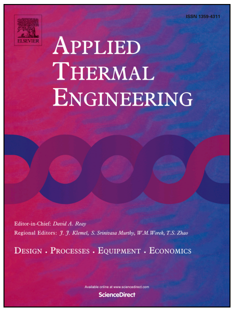

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Investigation on Influential Factors of Engineering Design of Geothermal Heat Exchangers

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Abstract

The research on heat transfer models of geothermal ground heat exchangers (GHEs) of ground-coupled heat pump (GCHP) system has recently advanced greatly. However, although it is important to optimize the design size of GHEs for reducing the total length of GHEs, the optimization of GHEs by means of models is a little. This paper describes the interior simulation models of borehole in which single U-tube and double U-tubes are each buried. The analytical solutions concerning the borehole's exterior heat transfer are given. All the factors that exert influences on the design size of GHEs are described based on the results of the heat transfer models. These significant parameters consist of the centre to centre distance of the U-tube, thermal conductivity of the backfill material, distance of adjacent boreholes, types of circulating liquid or underground medium, arrangement of boreholes, and the minimum temperature of the circulating liquid which enters the heat pump. Using the simulation models and computer programming, the influence degrees of the above factors are discussed in terms of the adoption of different values or types. Therefore, the initial cost and the economic performance of the system are respectively dropped and improved. The investigation on optimization of GHEs is favourable for the further development of GCHP technology.

Keywords Borehole; Ground Heat Exchangers; Ground-coupled heat pump; Heat Transfer; U-tube; Influential factors.

Nomenclature

k_s	thermal conductivity of underground medium (W m^{-1} K^{-1})
k_b	thermal conductivity of backfilling material (W m^{-1} K^{-1})
k_p	thermal conductivity of high-density polyethylene (W m^{-1})
R	thermal resistance outside tube
a	thermal diffusivity (m^2 s^{-1})
c_p	specific heat (J kg^{-1} K^{-1})
M	flow mass (kg / s)
D	distance of two branch pipes of one group U-tube
T	temperature (K)
Fo	Fourier number
r_{pi}	inner radius of U-tube (m)
r_o	outer radius of U-tube (m)
r_b	radius of borehole
h_c	coefficient of convective heat transfer
h	depth of borehole
H	dimensionless depth of borehole
q	heating rate per meter line heat source (W m^{-1})
R_p	heat resistance from liquid to the outer wall of pipe
x ,y, z	rectangular coordinate (m)
X,Y,Z	dimensionless rectangular coordinate

Superscript

$'$	integration parameter

Subscripts

i	infinite line heat source
f	finite line heat source
l	line heat source
b	borehole
in	inlet
out	outlet
0	initial time
1, 2, 3, 4	the order number of branch pipe

Greek symbols

τ	time (s)
θ	excess temperature (K)
Θ	dimensionless excess temperature

1. Introduction

With the increasing requirements of energy saving and environmental protection, the groud-coupled heat pump (GCHP) has gained more and more attentions because it takes advantage of underground medium as a cooling source in summer and a heat source in winter. Accordingly, the indoor heat of buildings can be discharged into subsurface soil in cooling state, and then underground energy is abstracted to heat the space of buildings while the heating condition is conducted. To make use of underground source for cooling and heating is reasonable as the underground temperaure fluctuates a little all the year round [1], therefore the performance of the GCHP system is provided with high quality. The system usually consists of three parts inculding ground heat exchangers (GHEs), heat pump unit and indoor air-conditioners. The GHE is the vital element revealing significant differences with other kinds of heat pump systems. Currently, there are mainly two types of GHEs containing horizontal ditches and vertical boreholes. Easy construction and installation are actualized while horizontal GHE is put into use, however, not only the heat transfer performance of GHE is easily affected by ambient atmosphere but also the large land area for distributing heat exchange tubes is needed [2]. Admittedly, the vertical borehole GHE is widely employed because it is more suitable for our national situations, that is, a large population with relatively little land. In addition, the borehole's depth is usually from 50m to 150m and therefore it is obviously longer than that of horizontal GHE with the depth between 1m and 2m; the deeper the GHE, the lesser the degree of being influenced by outdoor air temperature [3]. Heat exchange tubes often fabricated by high density polyethylene (HDPE) are installed after drilling the borehole [4]. HDPE has notable advantages in terms of corrosion resisting, good coefficient of heat transmission and other characteristics. The borehole is filled with backing materials holding favourable thermal conductivity, which means the gap between U-tube and borehole wall is made up to prevent the groundwater seepage or underground pollution. The schematic diagram of the whole system with vertical borehole GHE is described in Fig.1.

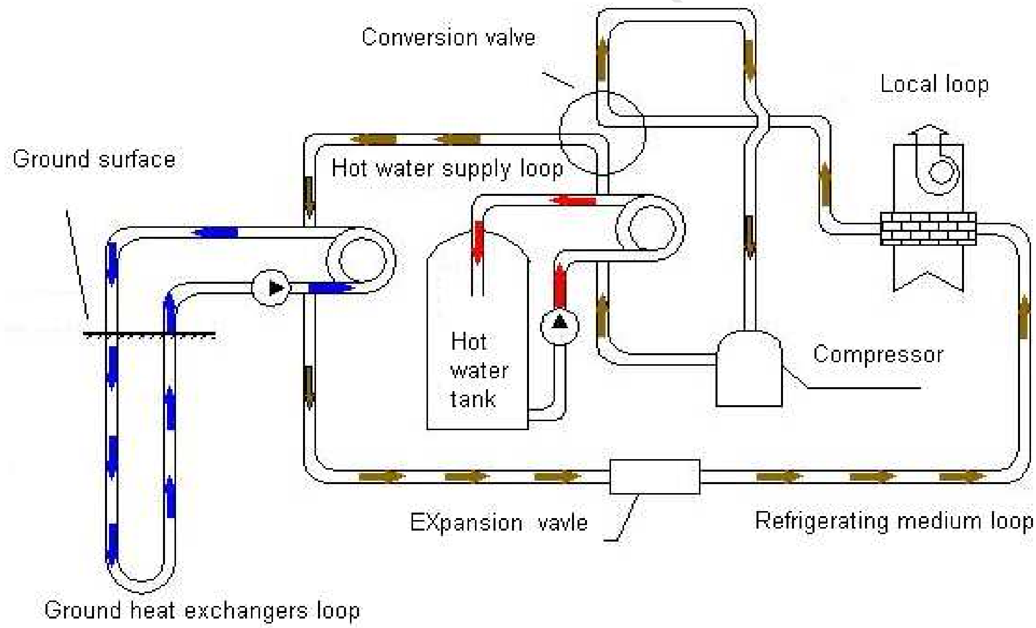

Fig.1 Schematic diagram of ground-coupled heat pump system

Two types of burying tubes are generally utilized for the vertical GHEs; one mode is to set single U-tube usually adopted in the United States [5], and the longitudinal and transverse section diagrams are both shown in Fig.2.

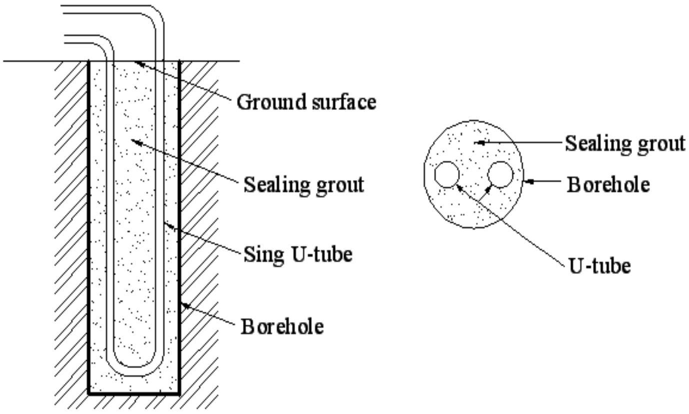

Fig.2 The vertical profile and horizontal section of single U-tube GHE

Another type being entitled "double U-tubes" is to arrange two U-tubes into borehole [5]. The corresponding diagram is shown in Fig.3 displaying the circumstances of longitudinal and transverse sections.

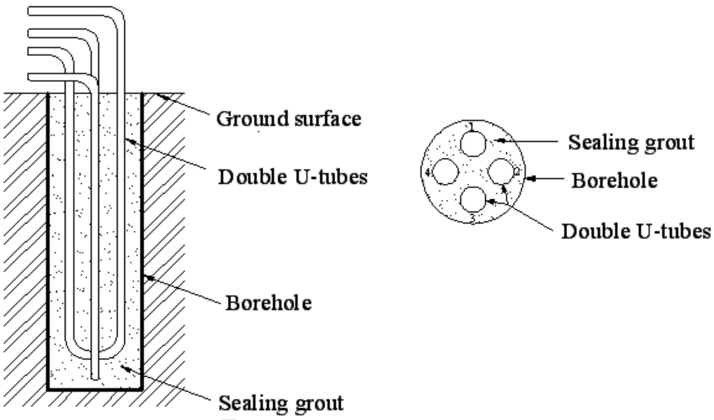

Fig.3 The vertical profile and horizontal section of double U-tube GHE

Undoubtedly, borehole GHE with double U-tubes can increase the interior heat transfer area and thus the interior thermal resistance and the total length of borehole are respectively reduced and decreased. However, the expense of tubes and the energy consumption of the system are both increased. Although the research on mathematical models simulating interior and exterior heat transfer of borehole has made great progress, the optimization on GHEs based on models is a little. The parameters or factor involved in heat transfer models can be investigated to conduct the optimization of GHE [6], this is a significant work as the optimization can improve cost performance and promote the further development of GSHP technology.

2. Mathematical models of heat transfer

2.1 The equations describing interior heat transfer

For one thing, single U-tube is composed of two branch pipes and the circulating liquid flows through them in sequence to abstract or release heat [7]. If the conduction along z-axis is ignored and the heat flux densities of pipes are respectively q_1 and q_2, the temperature filed under discussion is the superposition of the total contribution of two branch pipes according to the principle of linear superposition. T_1 and T_2 are respectively the average liquid temperatures of two tubes and T_b is the mean temperature of tubes. In addition, R_{11} and R_{22} are regarded as the thermal resistances between every tube and the corresponding interior circulating liquid, R_{12} is the thermal resistance of two tubes. Therefore, the relevant equation is obtained in Eq.(1) [8]:

$$\begin{cases} T_1 - T_b = R_{11}q_1 + R_{12}q_2 \\ T_2 - T_b = R_{21}q_1 + R_{22}q_2 \end{cases} \tag{1}$$

When it comes to the actual engineering projects, the structure of U-tube is supposed to be symmetrical and thus it is viable that $R_{11}= R_{22}$, the appropriate formulas of thermal resistance are acquired and they are shown in Eq.(2).

$$\begin{cases} \sigma = (k_b - k_s)/(k_b + k_s) \\ R_{11} = \dfrac{1}{2\pi k_b}(\ln\dfrac{r_b}{r_0} + \sigma \cdot \ln\dfrac{{r_b}^2}{{r_b}^2 - D^2}) + R_p \\ R_{12} = \dfrac{1}{2\pi k_b}(\ln\dfrac{r_b}{2D} + \sigma \cdot \ln\dfrac{{r_b}^2}{{r_b}^2 + D^2}) \\ R_p = \dfrac{1}{2\pi k_p}\ln\dfrac{r_0}{r_{pi}} + \dfrac{1}{2\pi r_{pi} h} \end{cases} \tag{2}$$

where D is the spacing between two branch pipes, R_p means heat resistance from circulating liquid to the outer wall of pipe. As well as this, r_pi and r_0 respectively denote the inner and outer radii of U-tube, and that r_b is the radius of borehole. The thermal conductivity of surrounding soil, backfill materials and HDPE are respectively k_s, k_b and k_p; in addition, h_c indicates the coefficient of convective heat transfer.

For another, being different from the case of single U-tube, the double U-tubes are normally connected in a parallel manner and there are totally four branch pipes, which means there are two inlets and two outlets for circulating liquid flowing through tubes. The depth of borehole is far larger than its outer diameter and the average temperature of circulating liquid changes a little, accordingly the axial conduction induced by circulating liquid and backfill material can be ignored. The convection between fluid and tube is the heat exchange mode along z-axis and the fluid keeps turbulent during the heat exchange period. The temperature T_b of borehole wall is nearly stable along z-axis and therefore it is regarded as the constant parameter. q_1, q_2 , q_3 and q_4 are respectively the heat flux of every branch tube, meanwhile T_1 ,T_2, T_3 and T_4 respectively indicate the mean temperature of liquid inside every branch tube. And that, R_{ij} (i=j) is the thermal resistance from liquid to tube and R_{ij} (i≠j) shows the thermal resistance between every two branch tubes. The energy equations are listed in Eq.(3) [9]:

$$\begin{cases} T_1 - T_b = R_{11}q_1 + R_{12}q_2 + R_{13}q_3 + R_{14}q_4 \\ T_2 - T_b = R_{21}q_1 + R_{22}q_2 + R_{23}q_3 + R_{24}q_4 \\ T_3 - T_b = R_{31}q_1 + R_{32}q_2 + R_{33}q_3 + R_{34}q_4 \\ T_4 - T_b = R_{41}q_1 + R_{42}q_2 + R_{43}q_3 + R_{44}q_4 \end{cases} \tag{3}$$

Two groups of U-tube constitute the double U-tubes and every group consists of two branch pipes; two U-tubes are assumed symmetrically distributed and they are set in parallel; D is the distance of two branch pipes of every U-tube. The relationships of thermal resistances can be summarized as $R_{11}= R_{22} = R_{33}= R_{44}$, $R_{mn}= R_{nm}$ $(m,n = 1,2,3,4)$ and $R_{12}= R_{14.}$ The corresponding equations of every thermal resistance are obtained in Eq.(4).

$$\begin{cases} \sigma = (k_b - k_s)/(k_b + k_s) \\ R_{11} = \dfrac{1}{2\pi k_b}(\ln\dfrac{r_b}{r_0} - \sigma \cdot \ln\dfrac{{r_b}^2 - D^2}{{r_b}^2}) + R_p \\ R_{12} = \dfrac{1}{2\pi k_b}(\ln\dfrac{r_b}{\sqrt{2}D} - \dfrac{\sigma}{2} \cdot \ln\dfrac{{r_b}^4 + D^4}{{r_b}^4}) \\ R_{13} = \dfrac{1}{2\pi k_b}(\ln\dfrac{r_b}{2D} - \sigma \cdot \ln\dfrac{{r_b}^2 + D^2}{{r_b}^2}) \\ R_p = \dfrac{1}{2\pi k_p}\ln\dfrac{r_0}{r_{pi}} + \dfrac{1}{2\pi r_{pi} h} \end{cases} \tag{4}$$

where the relevant parameter signs appeared in Eq.(4) (such as k_s , k_b) have the same meaning with those stated in Eq.(2).

2.2 The temperature response of any point outside borehole

The underground space is also regarded as the semi-infinite medium. The borehole diameter and length are respectively from 100mm to 200mm and between 50m and 150m in the engineering projects, accordingly the radial scale is shorter compared with the surrounding medium scale and the length is several orders of magnitude larger than diameter. As for the exterior heat transfer of borehole, the diameter is often ignored and thus the GHE is considered as a line heat source emitting heat continuously. One assumption is that the heat transfer along depth is neglected, it means only thermal transmission at radial direction is taken into account. Therefore, the one-dimensional conduction of GHE forwards with the time, which can be found in a large number of GCHP monographs or specifications. The temperature response is induced by instantaneous point heat source existing in the infinite space while heat transfer develops from borehole GHE to underground medium. A method entitled Green function [10] was proposed to obtain the temperature response of any point except heat source in the infinite space, the corresponding expression of Green function is shown in Eq.(5).

$$G(x,y,z,\tau;x',y',z',\tau') = \frac{1}{8\left[\sqrt{\pi a(\tau-\tau')}\right]^3}\exp\left[-\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4a(\tau-\tau')}\right] \tag{5}$$

The Kelivin's infinite line heat source model is also employed in a great amount of studies; this model ignores the impact of ground boundary and thus the temperature response cannot be stable at last. To analyze the thermal exchange from GHEs to the surrounding medium, the first step is to ignore the heat transfer along the z-axis, then the conductions along x and y directions are both taken into account. The expression of the Kelvin's model [11] is displayed in Eq.(6) presenting the temperature response.

$$\theta_{l,i} = \frac{q_l}{4\pi a\rho c}\int_{(-x^2-y^2)/4a\tau}^{-\infty}\frac{\exp(m)}{m}dm \tag{6}$$

The Kelvin's model provides a favourable basis for investigating the finite model, because any borehole GHE has the finite length ranging from 50m to 150m. Three directions, that is, *x*, *y* and *z* directions should all be considered to embody the actual circumstance of borehole GHE. The method named "virtual heat source method" is introduced to obtain the analytical solution of the finite model. To be more specific, there must be a point heat sink if there is a point heat source in the infinite space, which means sink and source are symmetrical on the ground boundary. The borehole GHE is regarded as a line heat source emitting heat with the intensity of q_l, thus the line heat sink releases the same heat intensity with that of line heat source. The line heat source and the line heat sink have the same length and they are symmetrical on the ground boundary [12, 13]. The temperature response at any point except heat source in the underground medium is the total contribution of line heat source and line heat sink; the corresponding formula of temperature response induced by the finite line heat source is shown in Eq.(7).

$$\begin{aligned}\theta_{l,f} &= \frac{q_l}{\rho c}\int_0^{\tau} d\tau'\left[\int_0^{h} G\,dz' - \int_{-h}^{0} G\,dz'\right] \\ &= \frac{q_l}{4\pi k}\int_0^{h}\left\{\frac{\mathrm{erfc}\left[\frac{\sqrt{x^2+y^2+(z-z')^2}}{2\sqrt{a\tau}}\right]}{\sqrt{x^2+y^2+(z-z')^2}} - \frac{\mathrm{erfc}\left[\frac{\sqrt{x^2+y^2+(z+z')^2}}{2\sqrt{a\tau}}\right]}{\sqrt{x^2+y^2+(z+z')^2}}\right\}dz'\end{aligned} \tag{7}$$

where h is the depth or length of borehole GHE and k is the thermal conductivity of underground medium. The next procedure is to introduce non-dimensional parameters for simplifying the expressions. The radius of broehole is $r_0 = \sqrt{x_0{}^2 + y_0{}^2}$ and the dimensionless parameters are listed as: $\Theta = k\theta/q_l$, $X = x / r_0$, $Y = y / r_0$, $Z = z / r_0$, $Z' = z' / r_0$, $H = h / r_0$, $Fo = a\tau / r_0^2$.

As for the infinite model, that is, Kelvin's model, Eq.(6) can be transformed into Eq.(8) if dimensionless parameters are employed.

$$\Theta_{l,i} = \frac{1}{4\pi}\int_{(-X^2-Y^2)/4Fo}^{-\infty} \frac{\exp(m)}{m}dm \tag{8}$$

With reference to the finite model, the expression is obtained after changing the Eq.(7) while the non-dimensional parameters are utilized.

$$\Theta_{l,f} = \frac{1}{4\pi}\int_0^{H}\left\{\frac{\mathrm{erfc}\left[\frac{\sqrt{X^2+Y^2+(Z-Z')^2}}{2\sqrt{Fo}}\right]}{\sqrt{X^2+Y^2+(Z-Z')^2}} - \frac{\mathrm{erfc}\left[\frac{\sqrt{X^2+Y^2+(Z+Z')^2}}{2\sqrt{Fo}}\right]}{\sqrt{X^2+Y^2+(Z+Z')^2}}\right\}dZ' \tag{9}$$

It is obvious that the equations are relatively concise in case the non-dimensional methods are applied; we can analyze the temperature response trends of both the infinite and the finite models, the corresponding curves obtained by means of detailed calculation and programming are shown in Fig.4.

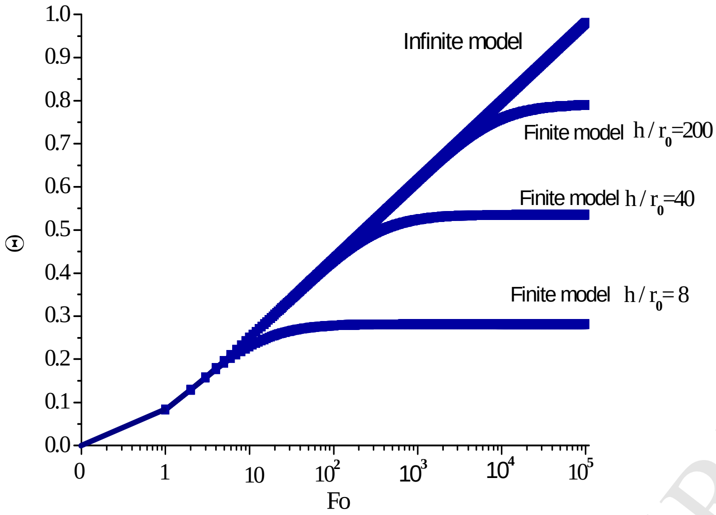

Fig.4 The temperature response trends of line heat source models

The temperature response of the infinite model increases all the time, which means there is no upper limitation of the response that is finally infinitely-great. However, the finite model must arrive at the stable state at last, and the ratios of depth to radius demermine the last response value being with the corresponding time. According to the curves in Fig.4, the larger the ratio, the longer the time needed for achieving steady state while the larger temperature response appears. From another perspective, the temperature response strengthens gradually with the increase of the ratios of depth to radius in case the time is constant. It is generally accepted that the response value of the infinite model is larger than that of the finite model if the time is constant. The analysis on mathematical models lays foundation for the optimal design of actual engineering project, the following work is to optimize the design of engineering projects based on interior and exterior heat transfer models of borehole. As a general rule, a number of borehole GHEs constitute the underground heat exchange elements, the temperature response in underground space is the contribution of all borehole GHEs. Eq.(10) shows the superposition of all finite line heat sources [14, 15].

$$\Theta = \sum_{j=1}^{n} \Theta_j \tag{10}$$

3. The information of one engineering project

An engineering project is provided as the reference object for analysis and optimization; every parameter that exerts impact on the design size of borehole GHEs are well-considered.

The total floor area of this building is nearly 20000m^2 and approximately 12000 m^2 employs air-conditioning for cooling in summer and heating in winter, the height is 41m comprising nine floors. The local geology is suitable for drilling borehole and thus the GCHP system is employed. When the cooling is conducted in summer, the load that borehole GHEs assume not only includes cooling load of buildings but also covers the power of heat pump unit, deducing that the heat discharged into underground is cooling load×(1+1/ performance coefficient of cooling). In contrast, the heating load of building is composed of the heat abstracted from underground medium and the power of heat pump unit. The heat comes from underground is heating load × (1-1/ performance coefficient of heating). The distribution of cooling and heating load affects the design size of borehole GHEs [16]. The heat absorption and discharge show a periodical change with the months; if the cumulative discharged heat is more than the corresponding absorptive heat annually, the redundant heat is stored in underground space and the mean temperature of underground medium rises, and vice versa. The building' and GHEs' loads are summarized in Table 1 while the COP values of heat pump unit are certain for the cooling and heating periods.

Table 1
The load of building and borehole GHEs

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Building load (10^3 kWh)	*274*	*198*	*108*	*0*	*0*	*-79*	*-210*	*-166*	*-36*	*0*	*97*	*257*
GHEs load (10^3 kWh)	*-206*	*-148*	*-81*	*0*	*0*	*94*	*252*	*199*	*43*	*0*	*-73*	*-192*
Cumulative GHEs load (10^3 kWh)	*-206*	*-354*	*-435*	*-435*	*-435*	*-341*	*-89*	*110*	*153*	*153*	*80*	*-112*

Table 1 shows the building's and GHEs' loads of every month, and the cumulative load of GHEs with the month is recorded. The unbalance rate between absorption and discharged loads is nearly 16%, accordingly the rate is unfavourable for the running of the whole system in winter because the temperature difference between GHEs and the surrounding reduces due to the dropped underground temperature; fortunately the adverse effect is not obvious as the rate is not obvious. The corresponding loads are described in Fig.5.

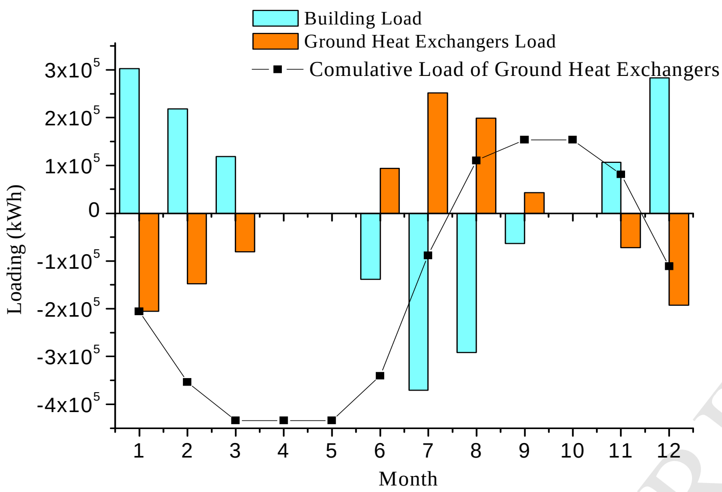

Fig.5 The relevant loads all the year round

4. The analysis on every parameter influencing the design size of GHEs

For one thing, Eqs.(1) and (2) respectively show the energy equations and the corresponding thermal resistances inside borehole if single U-tube is employed. The inlet and outlet temperatures of circulating liquid are respectively $T_{\rm in}$ and $T_{\rm out}$ while $R_{11}= R_{22}$ and $R_{12}= R_{21}$. In addition, the temperature response of any borehole is inevitably exerted influences by other borehole GHEs and the correasponding expression is obtained in Eq.(11).

$$T_b - T_0 = \theta_{\rm total} = \sum_{i=1}^{n} \frac{q_l}{4\pi k} \int_0^h \left\{ \frac{erfc\left[\frac{\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z')^2}}{2\sqrt{a\tau}}\right]}{\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z')^2}} - \frac{erfc\left[\frac{\sqrt{(x-x_i)^2+(y-y_i)^2+(z+z')^2}}{2\sqrt{a\tau}}\right]}{\sqrt{(x-x_i)^2+(y-y_i)^2+(z+z')^2}} \right\} dz' \quad (11)$$

where $x_{\rm i}$ and $y_{\rm i}$ mean the coordinates of any borehole GHE at the horizontal plane, and x, y and z are the coordinates of any borehole wall. Therefore, the aggregate equations for any borehole GHE are achieved in Eq.(12):

$$\begin{cases} T_1 - T_b = R_{11}q_1 + R_{12}q_2 \\ T_2 - T_b = R_{21}q_1 + R_{22}q_2 \\ T_1 - T_2 = (T_{\rm in} - T_{\rm out})/2 \\ q_1 + q_2 = q_l = C_{\rm p}M\,(T_{\rm in} - T_{\rm out})/h \\ T_b - T_0 = \theta_{\rm total} \end{cases} \quad (12)$$

The heat transfer rate $q_{\rm l}$ of every borehole GHE can be obtained according to Eqs (2) and (12), then the average value of q_l is achieved when the calculations of all borehole GHEs are finished. Thereby, the total length of borehole GHEs can be got according to the average q_l.

For another, two U-tubes are connected in parallel in case double U-tubes are put to use, $R_{11}= R_{22} = R_{33}= R_{44}$, $R_{mn}= R_{nm}$ $(m,n = 1,2,3,4)$ and $R_{12}= R_{14}$. What is more, $T_1 = T_2$, $T_3 = T_4$, $q_1 = q_2$ and $q_3 = q_4$, then the Eq.(12) should be integrated to take the arrangement manner of borehole GHEs into account. Accordingly, the aggregate equations are listed in Eq.(13).

$$\begin{cases} T_1 - T_b = R_{11}q_1 + R_{12}q_2 + R_{13}q_3 + R_{14}q_4 \\ T_2 - T_b = R_{21}q_1 + R_{22}q_2 + R_{23}q_3 + R_{24}q_4 \\ T_3 - T_b = R_{31}q_1 + R_{32}q_2 + R_{33}q_3 + R_{34}q_4 \\ T_4 - T_b = R_{41}q_1 + R_{42}q_2 + R_{43}q_3 + R_{44}q_4 \\ T_1 - T_3 = T_2 - T_4 = (T_{\text{in}} - T_{\text{out}})/2 \\ q_1 + q_3 = q_2 + q_4 = C_{\text{p}}M(T_{\text{in}} - T_{\text{out}})/h \\ T_b - T_0 = \theta_{\text{total}} \\ q_1 + q_2 + q_3 + q_4 = q_l \end{cases} \tag{13}$$

Thus, the average heat transfer rate is obtained if every borehole's q_l is calculated, then the total length of borehole GHEs can be understood supposing that the building's air-conditioning load is known.

According to Eqs.(2), (4), (12) and (13), the total length of borehole GHEs can be calculated while every impact factor changes. The following contents carry out the investigations on the influence that every factor exerts on the borehole GHEs' design length.

4.1 The centre to centre distance of U-tube

25mm and 32mm are also employed as the outer diameter of U-tube and the corresponding inner diameters are respectively 20mm and 26mm. As stated above, single U-tube and double U-tubes are usually set into borehole to form GHEs for engineering projects, and Fig.6 shows the cross sections of these two types of heat exchange tubes inside borehole.

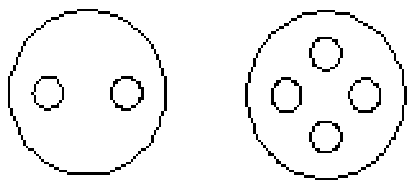

Fig.6 The cross sections of single U-tube and double U-tubes

The circulating liquid enters U-tube from one end and outflows at another one for single U-tube, and there exits two inlets and two outlets for circulating liquid while double U-tubes are in working state. It should be emphasized that the centre to centre distance of U-tube exerts impact on the design size of borehole GHEs, because the thermal interference between two branch pipes is determined by this distance [17]. We hope that the distance should be large enough to reduce the thermal interference; however, this will increase the difficulty in construction and installation. The heat transfer performance is improved assuming that the separation distances is increased, therefore the design size of borehole GHEs is reduced. r_t and r_b respectively denote the radii of tube and borehole, here the radius means outer radius for tube. Four cases, that is, A, B, C and D are adopted for representing different distances of single U-tube and the corresponding explanations are as follows.

A: distance is equal to the diameter of tube i.e. $2\,r_{t.}$

B: distance is equal to the value which the diameter of tube plus 0.3 times the borehole clearance i.e. $2\,r_{t.}+0.3\,(2\,r_b-4r_t)$.

C: distance is equal to the radius of borehole i.e. $r_{b.}$

D: distance is equal to the value which the diameter of borehole minus the diameter of tube i.e. $2r_b-2\,r_{t.}$

In addition, three cases including A, B and C are selected to describe the distance while double U-tubes are considered.

A: distance is equal to the value which the diameter of tube plus 0.3 times borehole clearance i.e. $2\,r_{t.}+0.3\,(2\,r_b-4\,r_t)$.

B: distance is equal to the radius of borehole i.e. $r_{b.}$

C: distance is equal to the value which the diameter of tube plus 0.8 times borehole clearance i.e. $2\,r_{t.}+0.8\,(2\,r_b-4r_t)$.

In case other parameters are constant, the distance adjustment for single U-tube or double U-tubes can lead to the change of the design size of borehole GHEs, the detailed information is given in Fig.7. The curves prove that the size of GHEs can be saved if centre to centre distance of U-tube increases.

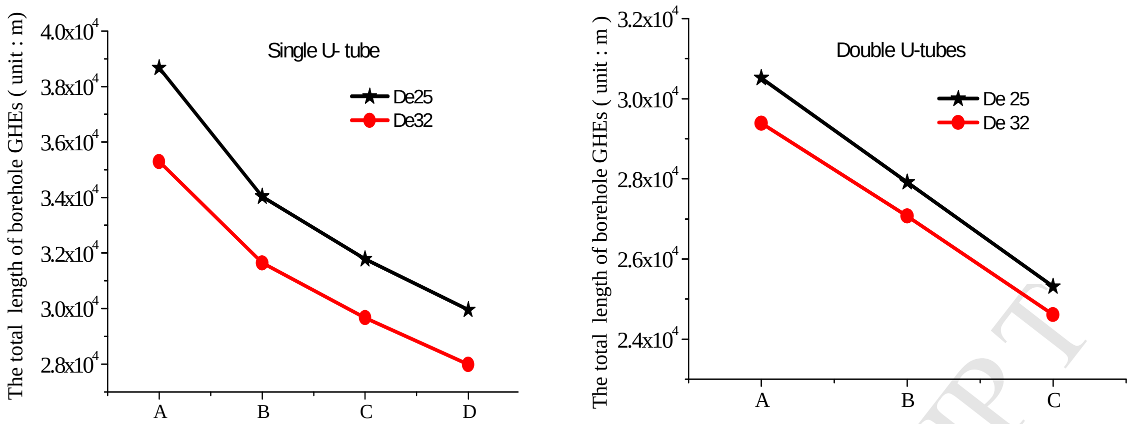

Fig.7 The influence that centre to centre distance of U-tube exerts on the size of GHEs

4.2 The thermal conductivity of backfill material

The backfill material usually consists of sand, cement and bentonite; these materials are mixed according to different mass ratios and the thermal conductivity differs with the variation of mass ratios of components. The backfill material is filled in the gap between U-tube and borehole wall and it assumes the role of heat carrier from U-tube to borehole wall. The material has non-ignorable influence on the design size of GHEs because it influences the interior heat transfer performance of borehole [18-20]. The heat exchange effect between U-tube and borehole wall is improved availably if the material has excellent capability of conduction, bringing the benefits of reducing the design size of GHEs. Fig.8 shows the reduction trend of GHEs size with the improvement of thermal conductivity while other parameters are defined unchangeable. Some studies covering a large number of experiments of backfill material stem from 1990s last century; nowadays heat conductivity of high-performance backfill material can reach about 2.1 W/ m·K.

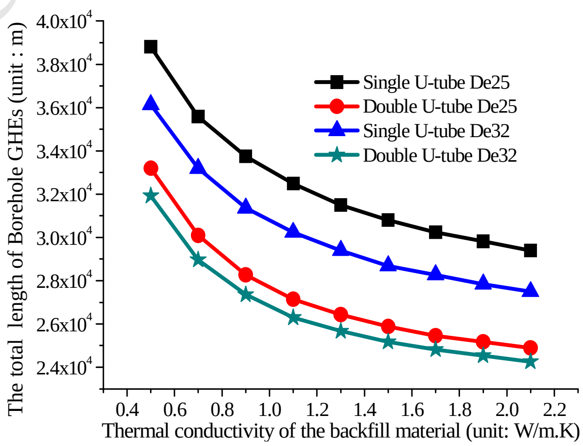

Fig.8 The influence which thermal conductivity of backfill material exerts on the size of GHEs

4.3 The distance between adjacent boreholes

In the event of constant values of other parameters, distance between adjacent boreholes is only the parameter of impacting the design size of GHEs [21]. The distance is a significant factor because the thermal interference of boreholes changes with it; the interference influences underground thermal exchange and then the GHEs size can be adjusted as long as both cooling and heating loads are guaranteed. Although small distance means that the land area needed for distributing GHEs is diminished, heat disturbance between every two adjacent boreholes becomes more serious and the total length of GHEs is added; this inevitably leads to higher initial cost of the whole system. The thermal interference is alleviated on condition that the distance is large enough, but the land area must be increased. It goes without saying that the distance should be determined according to the actual in-site circumstance, that is, whether to set it large or small should consider the on-the-spot condition comprehensively; the distance should have the large value if only the condition permits. The analysis on the distance influence is conducted while different types of U-tube come to service. Fig.9 explains that the size drops with the increase of the distance between adjacent boreholes.

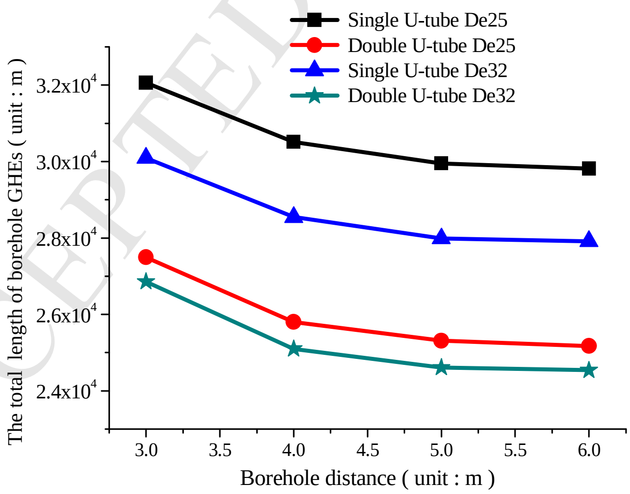

Fig.9 The influence which distance between adjacent boreholes exerts on the size of GHEs

4.4 The type of circulating liquid inside U-tube

The circulating liquid flows between U-tube and heat pump unit to release heat in summer and extract heat in winter. When the GCHP system is in heating mode in winter, the temperature of circulating liquid may below 0℃ under some running conditions, on this occasion the coagulation may occur if pure water is chosen as the circulating liquid. Accordingly, a certain amount of antifreeze is added to form antifreeze liquid [22]. Once the antifreeze is used, the minimum temperature of circulating liquid can drop when it enters heat pump unit and the temperature difference between underground medium and circulating liquid increases, therefore the heat transfer quantity is strengthened and then the total length of borehole GHEs is saved. In addition to pure water (PW), sodium chloride solution (SCS), calcium chloride solution (CCS) and ethylene glycol solution (EGS) are either selected as the circulating liquid because the latter three types play the role of antifreeze. SCS and CCS have the advantages of safety, non-toxicity and good thermal conductivity, but they are corrosive to metals while the air exists. EGS has the low corrosion and favourable thermal conductivity, but its viscosity increases in the low temperature condition and this add the flow resistance and debase the heat exchange efficiency.

Four types of circulating liquid, that is, PW, SCS, CCS and EGS are applied in the engineering project introduced in section 3, the differences of impacts that different type exerts on the length of GHEs are compared by means of detailed calculation and simulation. Fig.10 shows that the effects of CCS, SCS and EGS are better than that of PW, and the optimal choices for circulating liquid are CCS and EGS.

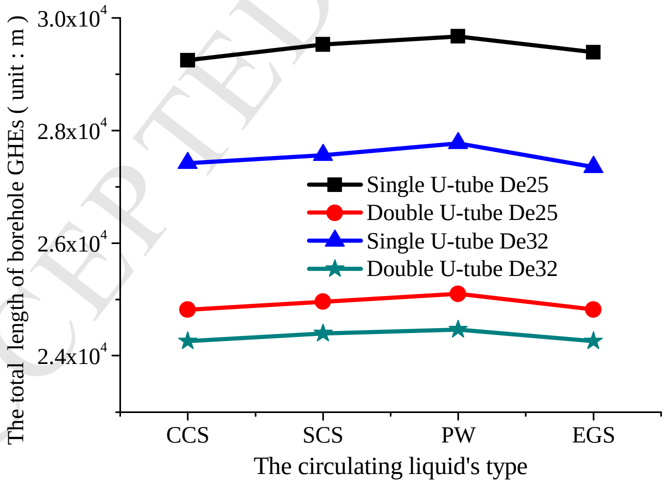

Fig.10 The impact of circulating liquid’s type on the size of GHEs

4.5 The type of underground medium

The running process of the GCHP system is a period of heat release and heat absorption, and these two modes appears alternately meanwhile underground medium is regarded as the source. The heat is firstly transferred between circulating liquid and U-tube afterwards be transmitted from liquid to borehole wall through the stuffed backfill material, at last be delivered to the surrounding underground medium. The type of underground medium directly determines the heat transfer performance of borehole GHEs [23], because every type of medium has the corresponding thermophysical property such as specific heat capacity, conductivity factor and density [24].

Four types including granite, sandstone, concrete and dry soil are assumed as the underground mediums of the project. The borehole's lengths are obtained when every type of underground medium is employed and the corresponding information is provided in Fig.11, different U-tubes are all taken into account for every medium. The differences induced by medium types are obvious and thus the acquaintance on local underground medium of any project is vital, this is favourable to avoid the superabundant length of GHEs and then the economic investment of the system is dropped.

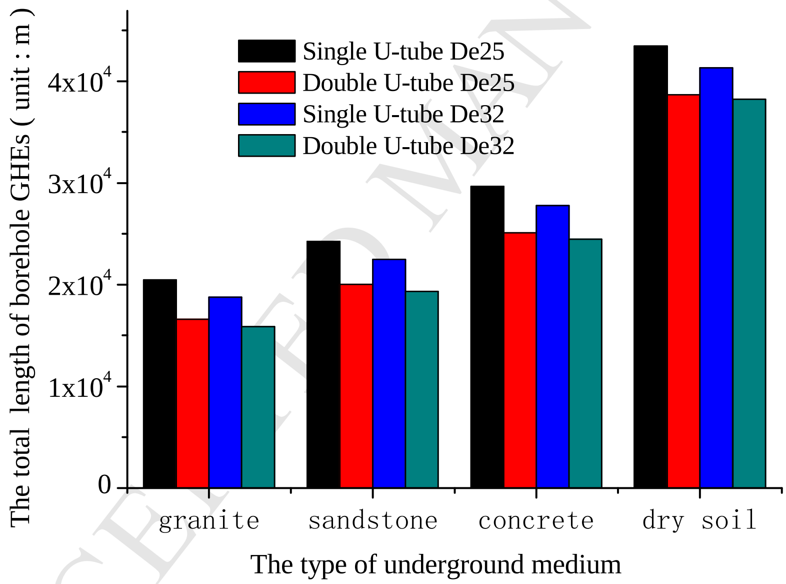

Fig.11 The influence which the type of underground medium exerts on the size of GHEs

4.6 The arrangement of boreholes

Every borehole GHE is regarded as a line heat source and the heat interferences of them appear in the running process, the arrangement manner is a remarkable factor because it explains whether the borehole GHEs is properly distributed reasonably to utilize land area, and the heat interferences are influenced by it. Four manners comprising matrix type, double "L" type, rectangle type and "U" type are introduced, and the distributing modes of arrangements are shown in Fig.12.

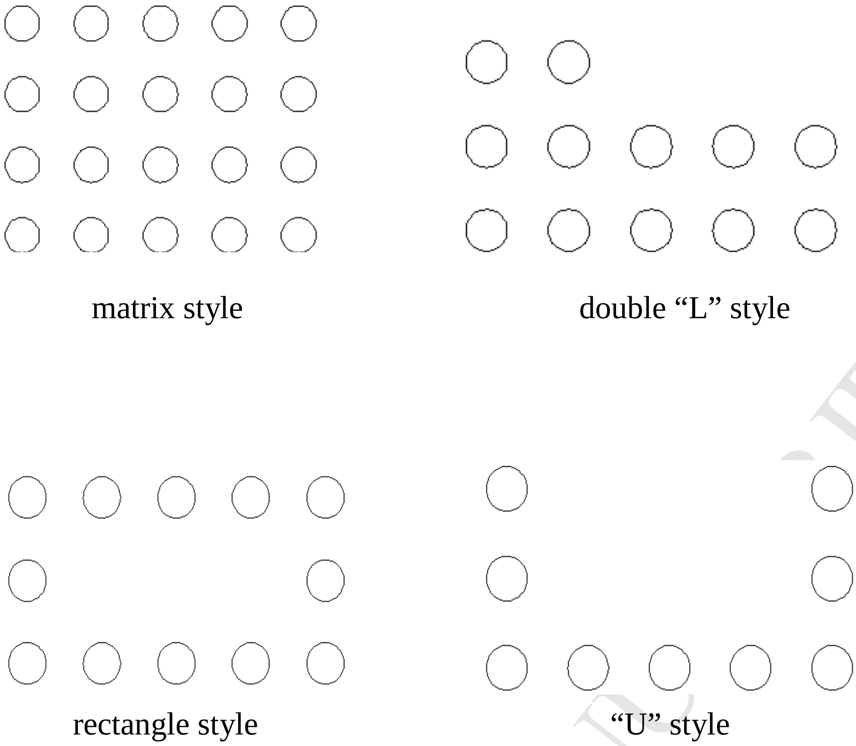

Fig.12 The arrangement of borehole GHEs

Fig.13 provides the corresponding lengths of borehole GHEs at the time of considering every arrangement; the disparity caused by different manners with four types of U-tube is minor if other parameters are constant. Although the design size of borehole GHEs under the condition of different arrangement manners are approximately same, the rectangle type should be the first choice in view of saving land area.

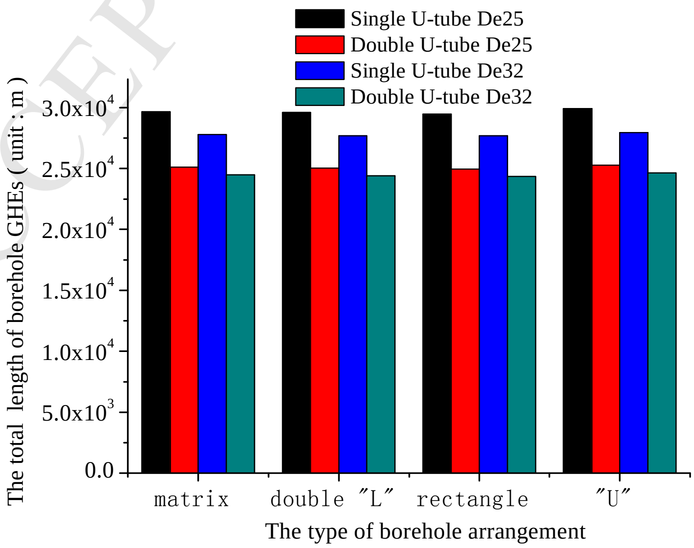

Fig.13 The influence which arrangement manner of borehole exerts on the size of GHEs

4.7 The minimum temperature of circulating liquid that enters heat pump unit

For this project, the heating load is higher than cooling load, which means the heat abstracted from underground in winter outweigh the heat discharged into underground in summer, therefore the total length of borehole GHEs should be designed according to the heating load. If the temperature of liquid is low enough when heat is extracted from underground, the temperature difference between underground medium and liquid becomes larger, thus the more heat is transferred from underground medium to GHEs, and the heat exchange performance is improved for saving the size of GHEs. One parameter tilted as "the minimum temperature entering heat pump unit" is proposed for circulating liquid to explain the variation trend of GHEs size [26, 27]. Fig.15 shows that the total length of borehole GHEs increases with the rise of the minimum temperature.

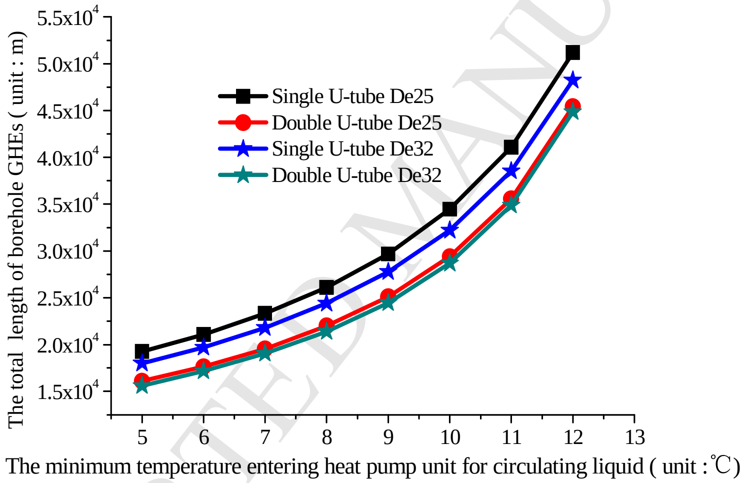

Fig.14 The influence which the minimum temperature exerts on the size of GHEs

5. Conclusions

The study on interior and exterior heat transfer models of borehole GHE is significant because models are the important bases of analyzing and optimizing GCHP system. The detailed energy equations or expressions describing the heat transfer inside and outside borehole are provided. The heat exchange process of GHE is complex because U-tube, circulating liquid, backfill material, underground medium and so on are all mentioned, and heat is delivered by different carriers. Some factors are involved in simulation models and they exert influence on the design size of borehole GHEs, the investigation on these influential factors is favourable to achieve the optimization of the GCHP system. Combined with an engineering project that employs GCHP technology as air-conditioning system, the heat transfer models are made full use of to explore the influence of every factor; this can provide theoretical guideline for the design and construction of actual GCHP projects. It can be found that different values or types selected for these parameters can induce different design size of GHEs. The initial cost spent on drilling borehole and installing U-tubes are dropped and then the cost performance of the whole system is improved. The paper not only elaborates theoretical knowledge but also covers actual application, which is significant to promote the further development of GCHP technology.

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Highlights

1. Describe the type of heat exchange tube and corresponding characteristics.
2. Present the interior and exterior heat transfer models of borehole.
3. Demonstrate an engineering project which employs ground source heat pump system.
4. Analyze every parameter that influences the design size of ground heat exchangers.
5. Illustrate the significance of optimizing ground heat exchangers.