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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) systems 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 boreholes 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; Influence 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

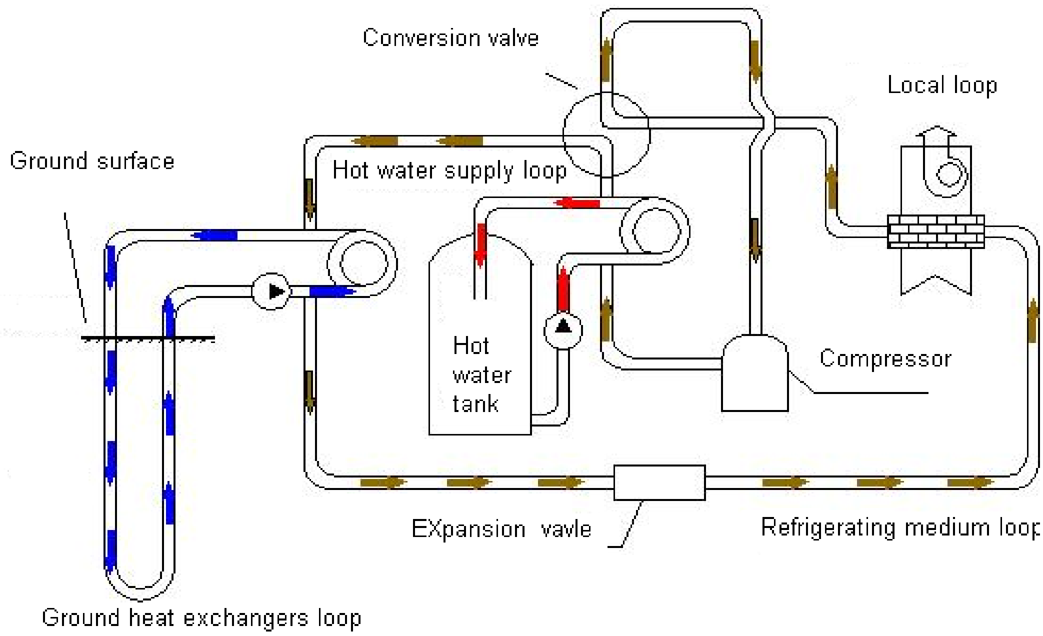
i infinite line heat source
f finite line heat source
l line heat source
b borehole
in inlet
out outlet
0 initial time
1, 2, 3, 4 the order number of branch pipe

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 this technology avails itself 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, 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. There is a belief that 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, the performance is easily affected by ambient atmosphere and large land area need to be occupied for distributing heat exchange tubes[1]. Thus, 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 level of between 1m and 2m. It should be admitted that the deeper the GHE, the lower the degree of being influenced by outdoor air temperature. The borehole is firstly drilled and then heat exchange tubes that are often fabricated by high density polyethylene (HDPE) are installed during the period of producing GHE [2]. HDPE has notable advantages in terms of corrosion resisting, good coefficient of heat transmission and other characteristics. The borehole is filled with backing materials possessing favourable thermal conductivity, thus the gap between U-tube and borehole wall can be made up, which means the groundwater seepage and underground pollution are prevented in such a way. The schematic diagram of the whole system with vertical borehole GHE is described in Fig.1.



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Two types of buryi

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the longitudinal and transverse section diagrams are both shown in Fig.2.

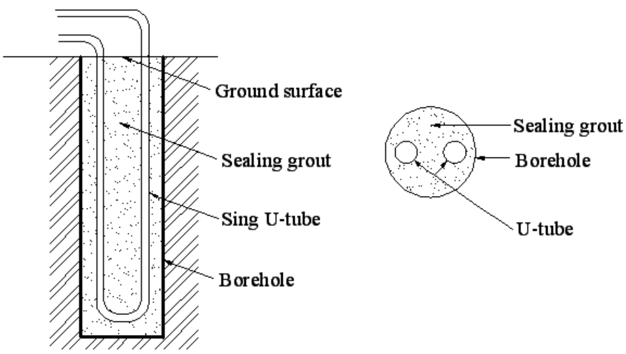


Fig.2 The vertical profile and horizontal section of single U-tube GHE

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

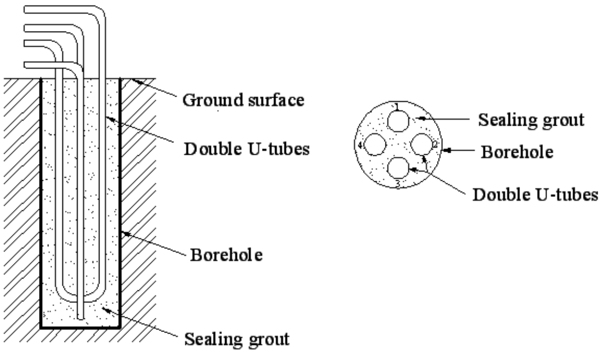


Fig.3 The vertical profile and horizontal section of double U-tube GHE

Undoubtedly, borehole GHE with double U-tubes can increase the interior heat transfer area and thus the thermal resistance inside borehole is reduced, accordingly the total length of GHEs decreases. However, the expense of tubes and the energy consumption of the system are both added. The optimization on GHEs based on heat transfer models is a little although the study of models has made great progress in recent years, it follows that the optimization is worth investigating [4]. To weigh the advantages and the disadvantages for every GCHP engineering project is significant for making the appropriate plan.

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. 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 temperature 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) [4]:

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

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 by means of analyses and they are shown in Eq.(2).

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

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, two inlets and two outlets for circulating liquid flowing through tubes. Since the depth of borehole is far larger than its outer diameter; and the average temperature of circulating liquid changes a little so that axial conduction induced by circulating liquid and backfill material can be ignored. The convection occurred 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 along z-axis is nearly equal and therefore T_{b} is regarded as the constant parameter at every time along z-axis. 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) [5]:

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

(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 thereby they are set in parallel. D is the distance of two branch pipes of every U-tube. The relationships among 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 always looked upon as the semi-infinite medium. For engineering projects, the borehole diameter is also from 100mm to 200mm and therefore radial scale is shorter compared with the surrounding medium scale and borehole length that is generally between 50m and 150m, which means the length is several orders of magnitude larger than borehole diameter. With regard to the heat transfer of outside borehole, the diamter is often ignored and the borehole GHE is considered as a line heat source emitting heat continuously. One assumption is that the heat transfer along depth direction seems to be overlooked, and only thermal transmission at radial direction is taken into account. The investigation on the heat transfer of GHE belongs to one-dimensional problem. It is universally acknowledged that the one-dimensional conduction model is widely applied in some GCHP monographs or relevant specifications. In the process of heat transfer between borehole GHE and the underground medium, to study the temperature response induced by instantaneous point heat source existing in the infinite space is significant whereby the underground temperature distribution can be understood. A method entitled Green function [6] 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 widely adopted in a great amount of researches; this model ignores the ground boundary impact and thus the temperature response does not seem to 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 depth direction i.e. z-axis, the conductions along x and y directions are both taken into account. The expression of the Kelvin's model [7] 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 exploration on the Kelvin's model provides a favourable basis for investigating the finite model, because any borehole GHE has the finite length usually 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, if there is a point heat source in the infinite space, there must be a point heat sink, which means they are symmetrical on the ground boundary. Because borehole GHE is regarded as a line heat source emitting heat with the intensity of q_l, 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 [8, 9]. 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).

$$\theta_{l,f} = \frac{q_l}{\rho c}\int_0^{\tau} d\tau' \left[\int_{\mathbf{0}}^{h} G dz' - \int_{-h}^{0} G dz'\right]$$

$$= \frac{q_l}{4\pi k}\int_0^{h}\left\{\frac{erfc\left[\frac{\sqrt{x^2+y^2+\left(z-z'\right)^2}}{2\sqrt{a\tau}}\right]}{\sqrt{x^2+y^2+\left(z-z'\right)^2}} - \frac{erfc\left[\frac{\sqrt{x^2+y^2+\left(z+z'\right)^2}}{2\sqrt{a\tau}}\right]}{\sqrt{x^2+y^2+\left(z+z'\right)^2}}\right\}dz' \tag{7}$$

where h is the depth or length of borehole GHE and k is the thermal conductivity of underground medium. The next procedure is to regard these equations as the main research objects, and then non-dimensional parameters can be introduced to simplify 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.

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

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 relevant curves obtained by means of detailed calculation and programming are shown in Fig.4.

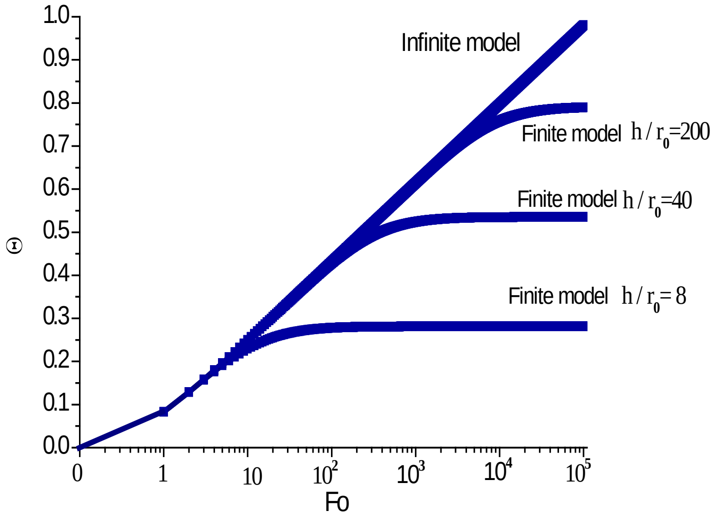


Fig.4 The temperature response trends of line heat source models

The temperature response of the infinite model increases all the time and there is no upper limitation of the response degree, thus the final response is infinitely-great. However, the finite model must arrive at the stable state finally, 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 to be steady while the larger the stable 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 while the time is constant. The analysis on mathematical models can lay foundation for the optimal design of actual engineering project. Now that the heat transfer models of inside and outside borehole have been established, the following work is to optimize the design of engineering projects based on the theoretical research. As a rule, underground heat exchange component consists of a number of borehole GHEs for engineering project, and it is clear that the temperature response at any underground point except borehole GHEs is the contribution of all borehole GHEs. Eq.(10) shows the superposition of all finite line heat sources [10, 11].

$$\Theta = \sum_{j=1}^{n} \Theta_j \qquad (10)$$

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 favourable to drill borehole and thus it is suitable to employ GCHP system. 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, hence the heat discharged into underground is cooling load×(1+1/ performance coefficient of cooling). In contrast, both the heat abstracted from underground medium and power of heat pump unit constitute the heating load of building at the stage of heating in winter. The heat derived from underground with the help of GHEs is heating load × (1-1/ performance coefficient of heating). The distribution of cooling and heating load affects the design size of borehole GHEs [12]. The GCHP is a system with the characteristics of energy storage, and the heat absorption and heat discharge process shows a periodical change with the seasons. If the cumulative discharged heat is more than the cumulative absorption heat yearly, the redundant heat is stored in underground space and the annual 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 no matter in the cooling or in the heating season.

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 annually, and the cumulative load of GHEs with the month is recorded. The unbalance rate between absorption and discharged loads is nearly 16%. This 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. The corresponding loads are described in Fig.5.

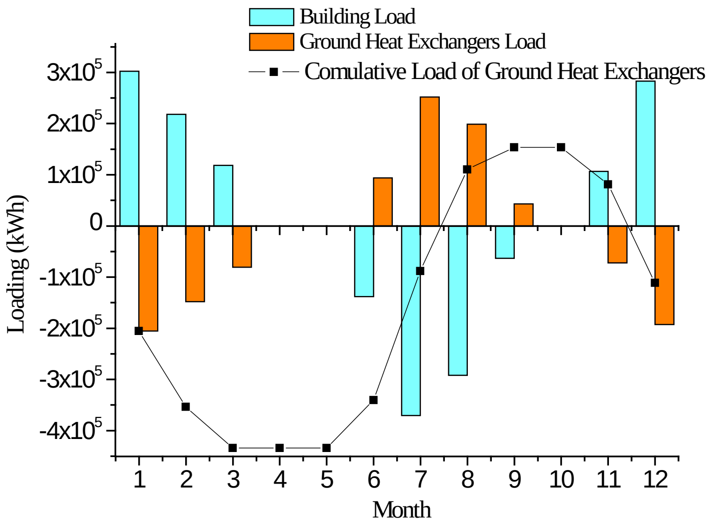


Fig.5 The relevant loads all the year round

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 while single U-tube is employed. The inlet and outlet temperatures of circulating liquid are respectively T_{in} and T_{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, the expression can be obtained and shown in Eq.(11).

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

where x_i and y_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):

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

Eq.(2) has given the expressions of relevant thermal resistances, the heat transfer rate q_l of every borehole GHE can be acquired according to Eq.(12), the average value of q_l is obtained when the calculations for all boreholes are finished. Thereby, the total length of borehole GHEs can be got according to the average q_l.

For another, when it comes to double U-tubes, because two U-tubes are connected in parallel, $R_{11} = R_{22} = R_{33} = R_{44}$, $R_{mn} = R_{nm}$ $(m,n = 1,2,3,4)$ 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 factor 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, the total length of borehole GHEs can be acquired 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 conduct the investigations on the influence that every factor exerts on the borehole GHEs' 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. For one thing, one group of U-tube is installed when single case is used. For another, two groups of U-tubes set in parallel are adopted in the event of double case. Fig.6 shows the cross sections of U-tubes including single and double cases.

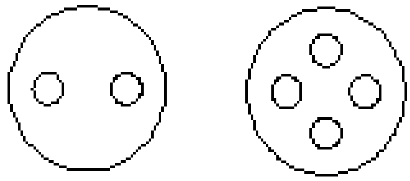


Fig.6 The cross sections of single U-tube and double U-tubes

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 affected by this distance [13]. We hope that the distance should be large enough from the perspective of reducing thermal interference; however, this will increase the difficulty in construction and installation. The heat transfer performance is improved assuming that the spacing 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 spacing of single U-tube and the corresponding explanations are as follows.

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

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

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

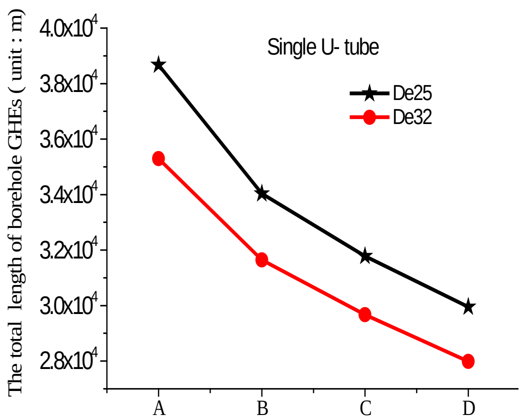
In addition, three cases including A, B and C are selected to describe the spacing of every group of U-tube while double U-tubes are considered.

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

C: spacing 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 spacing 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.



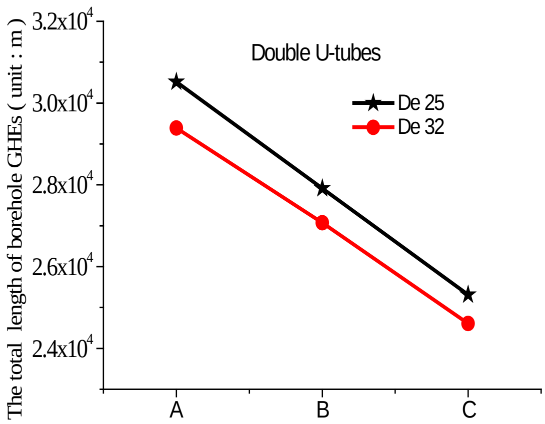


Fig.7 The influence that centre to centre distance of U-tube exerts on the size of GHEs

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 those components. The backfill material is stuffed in the gap between U-tube and borehole wall and it assumes the role of heat carrier from U-tube to borehole wall. The heat transfer quality of material has non-ignorable influence on the design size of GHEs because the heat transfer performance of inside borehole to a certain degree relies on it [14-16]. 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 corresponding size of GHEs. Fig.8 shows the reduction trend of GHEs size with the improvement of thermal conductivity while other parameters are defined unchangeable. It is beneficial to employ backfill material with high thermal conductivity in virtue of its contribution to saving the size of borehole GHEs. Some research works 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.

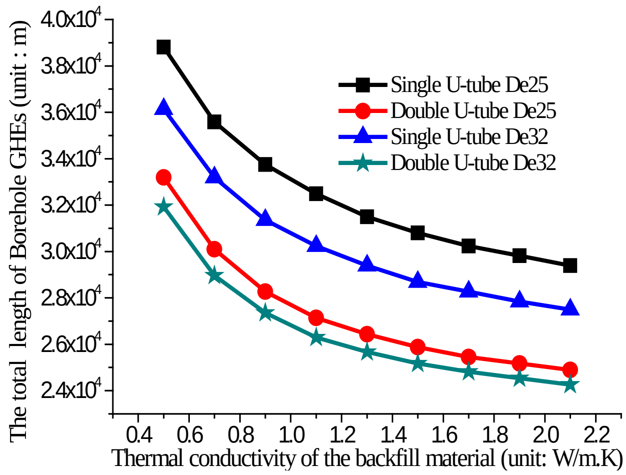


Fig.8 The influence which thermal conductivity of backfill material exerts on the size of GHEs

4.3 The distance between adjacent boreholes

In the event of constant values of other parameters, distance between adjacent boreholes is only the parameter that exerts impact on the design size of GHEs [17]. 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. On the one hand, the small distance means that the land area needed for distributing GHEs is diminished. However, 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. On the other hand, 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 respectively come to service. Fig.9 explains that the size drops with the increase of the distance between adjacent boreholes.

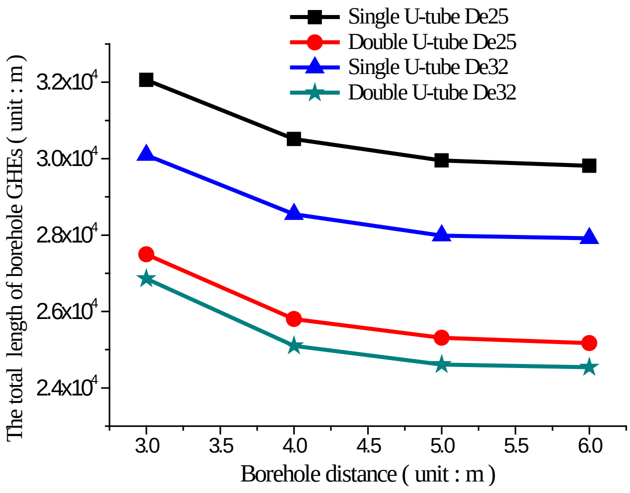


Fig.9 The influence which distance between adjacent boreholes exerts on the size of GHEs

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 should be added to form antifreeze liquid [18]. 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, however, 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 the detailed comparisons. It is evident that effects of CCS, SCS and EGS are better than that of PW, and the optimal choices for circulating liquid are CCS and EGS.

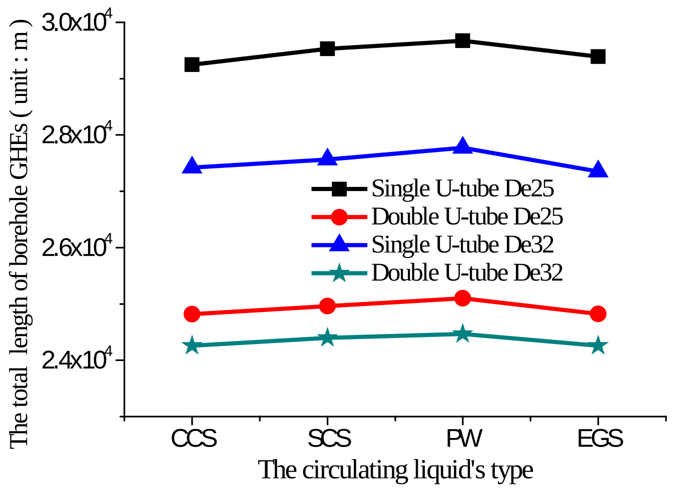


Fig.10 The impact of circulating liquid's type on the size of GHEs

4.5 The type of underground medium

The running process of the GCHP system is a period of heat release or heat absorption, and these two modes appears alternately while 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 heat transmission occurs between surrounding underground medium and borehole wall. Therefore, the type of underground medium can directly determine the heat transfer performance of borehole GHEs [19], because every type of medium has the corresponding thermophysical property such as specific heat capacity, conductivity factor and density [19].

Four types including granite, sandstone, concrete and dry soil are respectively assumed as the underground mediums of the project. Total length of borehole GHEs while every type of underground medium is employed are obtained in Fig.11, and different U-tubes are all taken into account for every type of underground medium. So clear it is that the size difference induced by type of underground medium is obvious; this also indicates that the acquaintance on local underground medium for any project is vital because the reasonable basis for project design is provided, and superabundant size of GHEs can be avoided so that the economic investment of the system is lowered.

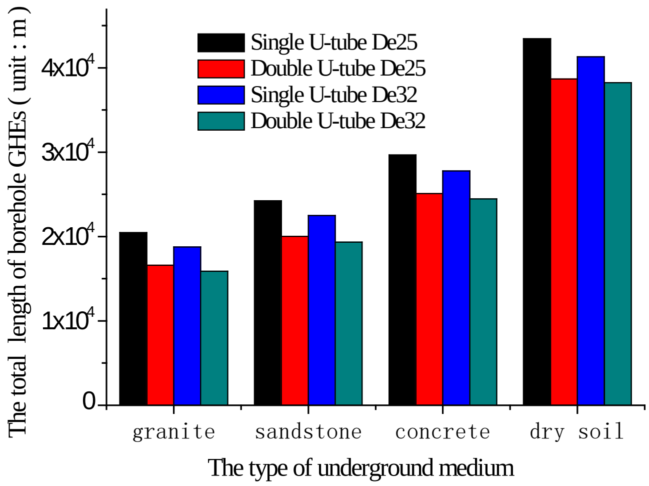


Fig.11 The influence which the type of underground medium exerts on the size of GHEs

4.6 The arrangement of boreholes

Every borehole GHE is regarded as a line heat source and the heat interference of them occurs in the running state, the arrangement manner is a factor that should be emphasized during the period of drilling boreholes [20]. The arrangement manner can explain whether the borehole GHEs is properly distributed reasonably to utilize land area, or whether the design size is saved. Four manners such as matrix type, double “L” type, rectangle type and “U” type are introduced for this project; the distributing modes of those arrangments are shown in Fig.12.

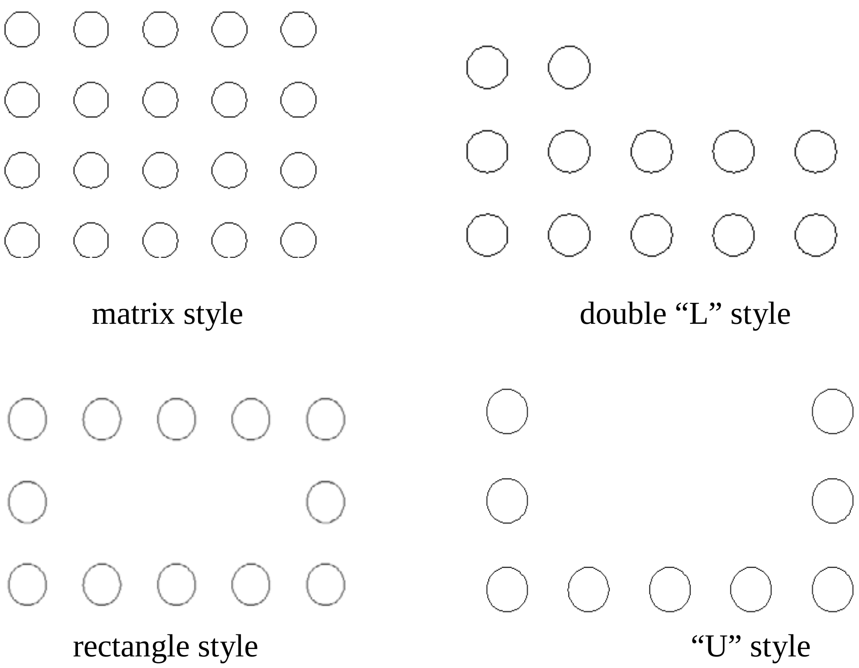


Fig.12 The arrangement of borehole GHEs

Total lengths of borehole GHEs are shown in Fig.13 while every arrangement is considered; it can be found that the disparity induced by different arrangement manners for every type U-tube is minor while other parameters are invariable. Although the design size of borehole GHEs under the condition of different manners are approximately same, for the sake of properly employing local land area of the project, the rectangle type should be the first choice in view of saving land area.

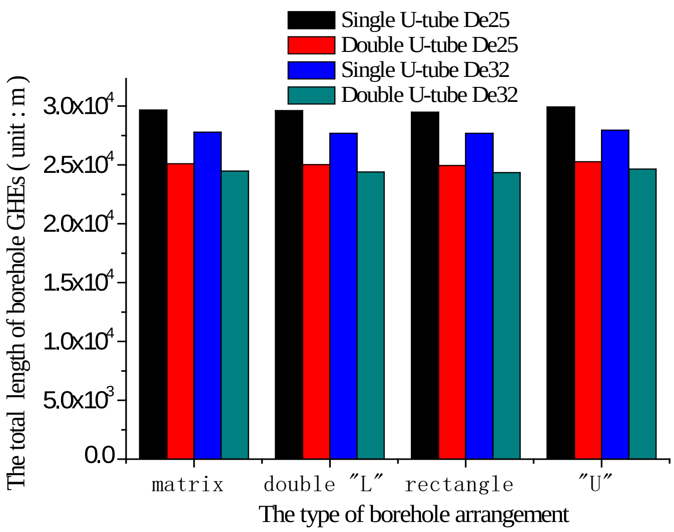


Fig.13 The influence which arrangement manner of borehole exerts on the size of GHEs

4.7 The minimum temperature of circulating liquid when it 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 on the basis of 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, which means more heat is transferred from underground medium to GHEs; the heat exchange performance is improved so that the size of GHEs can be saved. One parameter tilted as “minimum temperature entering heat pump unit” is proposed for circulating liquid to explain the variation trend of GHEs size [20]. Fig.15 shows that the total length of borehole GHEs increases with the rise of the minimum temperature.

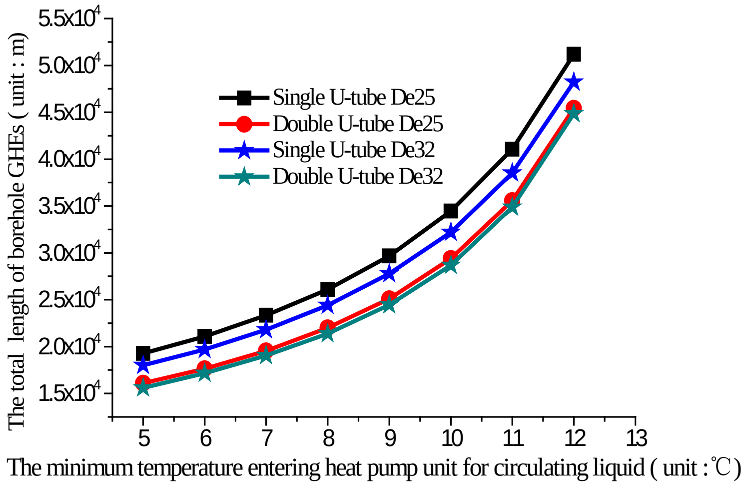


Fig.14 The influence which the minimum temperature exerts on the size of GHEs

5. Conclusions

The investigation on borehole GHEs is significant because the heat transfer performance of GHEs reports the superiority degree of GCHP system. The heat transfer models inside borehole and outside borehole are described in detail; every parameter that has influence on determining the design size of borehole GHEs should be discussed in order to provide reasonable suggestions on optimizing the total length of GHEs. The heat exchange process is complex because U-tube, circulating liquid, backfill material, underground medium and so on are all involved. The analysis of the paper can provide theoretical guideline for the design and construction of actual GCHP projects. Combined with an engineering project that employs GCHP technology as air-conditioning system, the relevant models are made full use of and every parameter influencing the performance of borehole GHEs is explored. It can be found that different values or cases selected for these parameters can induce different design size of GHEs; this is favourable to optimize the total length of GHEs. By means of optimization, the initial cost spent on drilling borehole and installing U-tubes are dropped. The paper not only elaborates theoretical knowledge but also covers actual application. There is no doubt that the research of this paper is significant to promote the further development of GCHP technology.

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