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The influence of ground heat exchangers operation modes on the ground thermal accumulation

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Abstract

When the heat extraction and injection of a ground heat exchanger (GHE) is not seasonally balanced, ground thermal accumulation will occur in the GHE region and cause a decline of the GSHP's operation efficiency after long-time running. However, GHE zoning running is one of the methods proposed to alleviate the thermal accumulation. In this paper, a case of the GHE thermal load in summer is greater than that in winter is studied. The ground temperature distribution, borehole wall temperature and ground enthalpy increase after 20 years operation is calculated. By analysis, the most effective GHE zoning running modes under different load ratios is recommended.

Keywords: imbalance load, thermal accumulation, zoning operation, load ratio

Nomenclature

a	ground thermal diffusivity, m^2/s
H	borehole depth, m
H'	ground enthalpy, J
i	the sequence number of boreholes
j	the sequence number of time steps
M	mass of soil, kg/m^3
m	the total number of boreholes
n	the total number of time steps
q_l	heat released of a borehole per unit depth, W/m
r	distance from the borehole center, m
r_b	borehole radius, m
r_i	distance from calculated point to the center of *i*th borehole, m
T	temperature, ℃
T_0	initial temperature, ℃
t	time step, s
V	volume of soil, m^3

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ΔT	surplus temperature of soil, ℃
λ_s	ground thermal conductivity, W/(m·K)
$\rho_s c_s$	soil volumetric specific heat, J/(m^3·K)
τ	time, s

1. Introduction

As a sustainable energy utilization technology, Ground source heat pump (GSHP) plays an important role in building air conditioning and is used widely [1]. For a large-scale GSHP system which usually has many buried pipes, if its GHE thermal load in summer and winter is unbalanced, the ground temperature will greatly deviate from its initial temperature after long term operation and induce the ground thermal accumulation [2-3]. However, ground thermal accumulation in the relative central GHE region is particularly serious. As a result, the efficiency of the ground source heat pump system is decreasing and even leads operation failure of some buried pipes.

There are several methods to alleviate the effect of ground thermal accumulation such as increasing borehole spacing[4-6], GSHP intermittent operation[7-9], adopting hybrid ground-coupled heat pump (HGCHP) system[10,11]and GHE zoning operation[12-14]. Lazzari, et al[4] has studied on the GHE long-term operation characteristics under different borehole spacing and found that the larger the spacing of boreholes is, the better the soil temperature recovers. Yu [5] and Liu [6]indicated that the larger the buried pipes spacing is, the weaker the thermal interference between them induces, and thus the higher operation efficiency the GHE maintains. Increasing buried pipe spacing increases the volume of the ground occupied by GHE, which enlarges the total heat capacity of the GHE region, so the ground thermal accumulation decreases. However, this method usually increases the occupied ground surface and is not suitable for those locations which are lack of land. The method of intermittent operation is to operate GSHP intermittently, so that the ground temperature can be recovered in the shutdown stage, thus slowing the ground temperature variation. Gao [7] and Shang [8] pointed that the ground temperature recovery is fast at the initial stage of intermittent operation. Therefore, properly adjust the interval can recover the ground temperature, which is conducive to the utilization of geothermal energy. Yang Jing, et. al., shows that intermittent operation can reduce the ground thermal accumulation and therefore improve the GSHP system operation efficiency [9]. In fact, the operation of a GSHP system is usually based on buildings air conditioning load demand rather than on ground temperature recovery need[10,11]. Adopting HGCHP system is also an effective method to reduce the ground thermal accumulation. For instance, GSHP with cooling tower system is utilized for cooling load dominating buildings, and adopting cooling towers as the supplemental cold source. The solar energy assisted GSHP systems can be applied for heating load dominating buildings, in which a solar energy collecting loop usually undertakes a part of heating load. A disadvantage of a HGCHP system is that its operation optimization and adjustment is very complex due to the complex system composition. GHE Zoning operation is a method proposed to alleviate ground thermal accumulation in recent years. In this method, by running a part of boreholes in the less load season, a balance of heat and cold load can be achieved and significantly reduces the ground thermal accumulation[12-14]. However, the research on zoning operation is quite less and some problems such as zoning strategies and zoning operation modes optimization need to be discussed thoroughly. In view of this, the paper studies the influence of GHE operation modes on the ground thermal accumulation.

2. Heat transfer model of GHE

To simplify the analysis, we assume that[15]:

- Heat transfer between the GHE and the ground is a two-dimensional heat conduction along the radial and vertical direction
- The ground is regarded as a semi-infinite uniform medium and its thermal physical parameters maintain constant.
- The influence of moisture migration in the ground is ignored.
- The thermal contact resistance in boreholes is ignored.
- The influence of the ground surface temperature fluctuation is ignored.
- The initial ground temperature distribution is uniform and the infinite far field temperature always maintains constant.
- A buried pipe is regarded as a finite long line heat source.

Based on the above assumptions, a single buried pipe heat transfer with the ground can be described as:

$$\frac{\partial T}{\partial \tau}=\frac{\lambda}{\rho_s c_s}\left(\frac{\partial^2 T}{\partial^2 r}+\frac{1}{r}\cdot\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial^2 z}\right),\quad \left(r_b \le r<\infty,\tau>0,z\ge 0\right) \tag{1}$$

The initial condition:

$$T=T_0,\quad \left(\tau=0,\ z\ge 0,r\ge r_b\right) \tag{2}$$

The boundary conditions:

$$\begin{cases} \frac{q_l(\tau)}{2\pi r_b} = -\lambda \frac{\partial T}{\partial r}\Big|_{r=r_b} , & (\tau>0) \\ T=T_0 , & (r\to\infty, \tau>0) \\ T=T_0 , & (z=0, \tau>0) \\ T=T_0 , & (z\to\infty, \tau>0) \end{cases} \tag{3}$$

Based on Equation (1) ~ (3), the soil temperature around a buried pipe is obtained as [16,17]:

$$\Delta T = \frac{q_L}{4\pi\lambda_S}\int_0^H [\frac{erfc(\sqrt{r^2+(z-h)^2}/2\sqrt{at})}{\sqrt{r^2+(z-h)^2}} - \frac{erfc(\sqrt{r^2+(z+h)^2}/2\sqrt{at})}{\sqrt{r^2+(z+h)^2}}]dh \tag{4}$$

Where, ΔT is the surplus temperature of soil, $\Delta T= T-T_0$, ℃; q_l is the heat released of a borehole per unit depth, W/m; λs is the ground thermal conductivity, W/m·K; a is the ground thermal diffusivity, m^2/s; r is the distance from the borehole center, m; z is the axial coordinate, m; and H is the borehole depth, m.

A GHE is usually composed of multi-boreholes, based on the superposition principle and separate the load as the sum of a series of step loads, thereby the temperature variation of the soil at point(x, y, z) can be expressed by Equation (5)[18]:

$$\Delta T(x,y,z) = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{q_{i,j}-q_{i,j-1}}{4\pi\lambda_S}\int_0^H [\frac{erfc(\frac{\sqrt{r_i^2+(z-h)^2}}{2\sqrt{a(t_m-t_{j-1})}})}{\sqrt{r_i^2+(z-h)^2}} - \frac{erfc(\frac{\sqrt{r_i^2+(z+h)^2}}{2\sqrt{a(t_m-t_{j-1})}})}{\sqrt{r_i^2+(z+h)^2}}]dh \tag{5}$$

Where, i is the sequence number of boreholes and the total number is n; j is the sequence number of time steps and the total time steps is m; and $r_i = \sqrt{(x-x_i)^2+(y-y_i)^2}$, (x_i, y_i) is the coordinate of the ith borehole.

The heat accumulation effect of ground can be presented by its enthalpy increase. The more heat accumulated in the ground, the larger its enthalpy is, vice versa. The ground enthalpy can be calculated by the following equation:

$$H' = \rho_s c_s \int TdV \tag{6}$$

Where, $\rho_s c_s$ is the soil volumetric specific heat, J/(m^3·K); T is the soil temperature, ℃; V is the volume of soil, m^3.

3. GHE operation modes

The case of the summer GHE load is larger than the winter load, i.e. the heat injection to the ground in summer is greater than heat extraction in winter, is analyzed in this paper. As well known, after a long period of operation, heat accumulation in the central GHE region is more serious than the peripheral region. According to the different heat accumulation degree between the central and peripheral GHE region, the GHE zoning operation is to put only boreholes in the central GHE region into use during the less load seasons and let all buried pipes work in the larger load seasons. The aim of GHE zoning operation is to balance the summer and winter loads of the central GHE regions, and thereby reduce the ground heat accumulation.

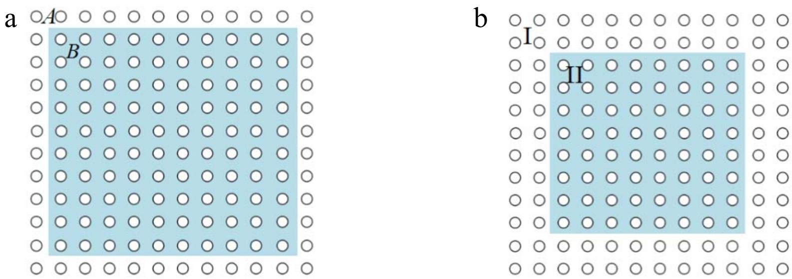

Fig.1 Illustration of GHE zoning

Table.1 Operation modes

Operation mode		Summer			Winter		
		Jun	Jul	Aug	Dec	Jan	Feb
No zoning	Mode 1	A+B	A+B	A+B	A+B	A+B	A+B
Zoning	Mode 2	A+B	A+B	A+B	B	B	B
	Mode 3	I+ II	I+ II	I+ II	II	II	II

Figure 1 shows A GHE consist of 12×12 multi-borehole, and is divided into two regions, i.e., the central region (shadow) and outer region (no shadow). Table 1 gives three available operating modes. Mode 1 is let all boreholes work in summer and winter. The other two are zoning operation modes. For both Mode 2 and 3, all boreholes are put in use in summer. In winter, the most outside row of boreholes (region A) stop running for Mode 2 while the most outside two rows of boreholes (region I) stop operating for Mode 3.

Table.2 Main parameters of boreholes and soil

Soil initial Temperature t_0/[℃]	Soilthermal conductivity λ/[W/m·K]	Soilvolumetric specific heat capacity ρc/[J/m^3·K]	Borehole spacing d/[m]	Borehole depth H/[m]
15	2.0	5×10^6	5	100

4. Results and discussion

For the case discussed, the GHE start running from the first June, and inject heat into ground in June, July and August, and extract heat from soil in December, January and February. The main parameters are shown in table 2. Considering the outlet water temperature of heat pump units condenser cannot rise unlimited in actual, it assumes those borehole invalid when their wall temperature reaches 40 ℃. Here we introduce a parameter of load ratio, which is the ratio of the heat injected into the ground in summer to that extracted in winter.

According to the calculation, when the load ratio is less than 1.5:1, the average ground temperature of the whole GHE region does not exceed 30 ℃, and the highest temperature of any borehole wall is less than 36 ℃ in Mode 1. In such condition, the ground heat accumulation is not very serious, thus we recommend that there is no need to adopt GHE zoning operation when the load ratio is less than 1.5:1. Given this, the paper chose to analyze under the condition of load ratio not less than 1.5:1.

Figure 2 is the ground temperature distribution after 20 years operation when the load ratio is 1.5:1, the heat flux per depth of running boreholes of each month are shown in table 3.

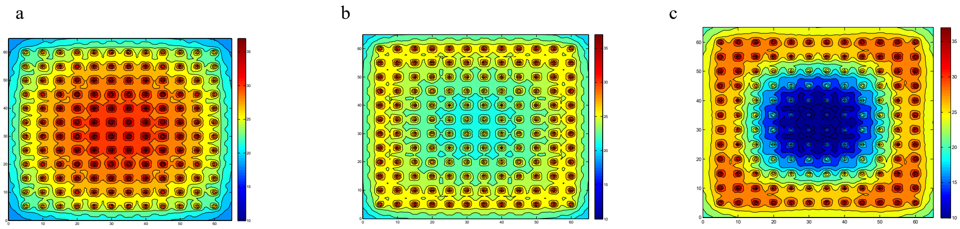

Fig.2 Ground temperature distribution after 20 years operation (load ratio is 1.5:1) (a)mode1 (b)mode2 (c)mode3

Table.3 Heat flux running boreholes (load ratio is 1.5:1) (W/m)

Operation mode		Summer				Winter			
		Jun	Jul	Aug	mean	Dec	Jan	Feb	mean
No zoning	Mode 1	30	60	36	42	-20	-40	-24	-28
Zoning	Mode 2	30	60	36	42	-28.8	-57.6	-34.6	-40.3
	Mode 3	30	60	36	42	-45	-90	-54	-63

Figure 3-5 respectively present the average ground temperature, average borehole wall temperature, and the maximum and minimum borehole wall temperature. Figure 6 shows the ground enthalpy increase and Table 4 presents the amount of invalid boreholes which wall temperature reaches 40℃.

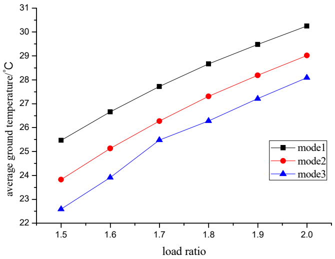

Fig.3 Average ground temperature after 20 years

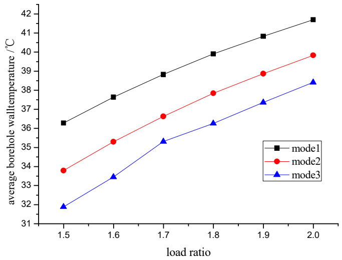

Fig.4 Average borehole wall temperature after 20 years

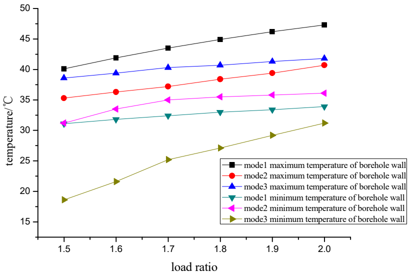

Fig.5 Maximum and minimum borehole wall temperature after 20 years

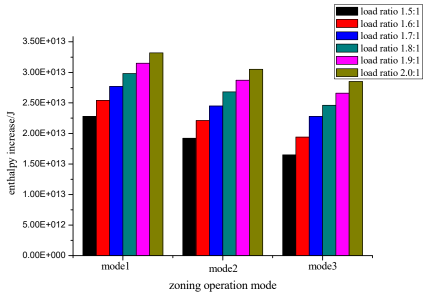

Fig.6 Ground enthalpy increase after 20 summers

Table4. The amount of invalid boreholes after 20 years

Operation mode	Load ratio					
	1.5:1	1.6:1	1.7:1	1.8:1	1.9:1	2.0:1
Mode 1	4	32	60	76	88	92
Mode 2	0	0	0	0	0	88
Mode 3	0	0	4	12	44	72

From Figure 2-6 and Table 3 and 4, we can see that the larger the load ratio is, i.e., the more obvious load imbalance in summer and winter is, the more serious the heat accumulates in the central GHE region is, and the more invalid boreholes appears.

Under the condition of no zoning operation (Mode 1), every borehole takes larger load in summer than that in winter (take load ratio is 1.5:1 for example, 42W/m in summer and 28W/m in winter), namely heat injected into the ground for every borehole in summer is larger than that extracted in winter. At the end of the 20th summer, the temperature of the central region is apparently higher than that of the outside region. With the increase of load ratio, the heat accumulation becomes more serious. The average ground temperature, average borehole wall temperature, ground enthalpy increase and the amount of invalid boreholes are all appear an increasing trend with the load ratio increases. When the load ratio increases from 1.5:1 to 2.0:1, the values of the above increase respectively from 25.5 ℃, 36.3 ℃ and 2.28×10^{13} J to 30.2 ℃, 41.7 ℃ and 3.32×10^{13} J and 92, and the relative increase are 19%, 15%, 45.6% and 2200% respectively.

Both Mode 2 and 3 make the loads of the running boreholes in the central GHE region in summer and winter to be relatively balanced by reducing the amount of operating boreholes in winter. Take the load ratio of 1.5:1 for example, the running borehole summer load is 42W/m, and that in winter is -40.1W/m for Mode 2 and -63W/m for Mode 3.

For Mode 2 of load ratio 1.5:1, the average ground temperature, average borehole wall temperature, ground enthalpy increase are 23.8 ℃, 33.8 ℃ and 1.92×10^{13} J respectively, and they are 6.4%, 6.9% and 15.8% less than those of Mode 1. When the load ratio reaches 2.0:1, the average ground temperature, average borehole wall temperature, ground enthalpy increase and the amount of invalid boreholes are 29.0℃, 39.8℃, 3.05×10^{13}J and 88 separately, and they are 22%, 18%, 58.8% and 88 larger than those of load ratio 1.5:1, while 4.1%, 4.5%, 8.1% and 4.3% less than those of Mode1.

For Mode3 of load ratio 1.5:1, the average ground temperature, average borehole wall temperature, ground enthalpy increase are 22.6℃, 31.9℃ and 1.65×10^{13}J respectively, decreasing 11.3%, 12.1% and 27.5% than no zoning operation. And there is no invalid borehole. When the load ratio reaches 2.0:1, the average ground temperature, average borehole wall temperature, ground enthalpy increase and the amount of invalid boreholes are 28.1℃, 38.4℃, 2.85×10^{13}J and 72 separately, and they are 24%, 20%, 72.4% and 72 larger than those of load ratio 1.5:1, while 2.8%, 3.1%, 14.1% and 21.7% less than Mode 1.

From Table 4, it can be found when the load ratio reaches 2.0:1, there is a large number of invalid boreholes appear for all above zoning operation modes. It can be considered that if the load ratio is larger than 2.0:1, the GHE zoning operation method is no more significantly effective to alleviate the ground heat accumulation, so other methods should be considered to solve the problem. With the increasing of load ratio, ground temperature and enthalpy increase has always been in a low level under Mode 3, but it is not obvious under Mode 2. Compared with Mode 3, ground temperature distribution of Mode 2 is more even, and the amount of invalid borehole is apparently less. Therefore, under the condition of this paper, Mode 2 is the most effective method to solve the problem of ground heat accumulation that induced by unbalanced seasonal GHE load.

This conclusion is also suitable for the cases of winter load is greater than summer load. For these cases, the load ratio refers to the ratio of load that GHE extracted from the ground in winter to that injected into soil in summer.

5. Conclusions

By a case of GHE summer load is greater than winter load, this paper calculates the average ground temperature, average of borehole wall temperature, and ground enthalpy increase after 20 years operation for three GHE operation modes. By analysis, it obtains the following conclusions:

- When the load ratio is less than 1.5:1, GHE zoning operation is not recommended for no zoning operation method can also ensure the GHE normal operation.
- When the load ratio is between 1.5:1 ~2.0:1, appropriate zoning operation mode can effectively alleviate the GHE thermal accumulation. Under the condition of this paper, Mode 2 is the most effective zoning operation mode.
- When the load ratio is beyond 2.0:1, zoning operation is unfavorable and other methods should be taken in order to solve the problem of imbalance GHE load.

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