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Zoning operation of multiple borehole ground heat exchangers to alleviate the ground thermal accumulation caused by unbalanced seasonal loads

Yu Mingzhi [a,*], Zhang Kai [a], Cao Xizhong [c], Hu Aijuan [a,b], Cui Ping [a,b], Fang Zhaohong [a]

[a] School of Thermal Engineering, Shandong Jianzhu University, Jinan 250101, China
[b] Key Laboratory of Renewable Energy Utilization Technology in Building, Ministry of Education, Jinan 250101, China
[c] Production Preparation Branch, Shandong Iron and Steel Group Co. Ltd., Rizhao 276800, China

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ABSTRACT

When the heat extraction and injection of a borehole ground heat exchanger (GHE) are not seasonally balanced, ground thermal accumulation will occur and will cause a decline in the ground source heat pump's operational efficiency, especially for large multiple borehole ground heat exchangers (LMBGHE). A zoning operation strategy, in which only the relatively central part of the GHE runs during the low load season, is adopted in this paper to alleviate the thermal accumulation. By analyzing the case in which the heat injected into the ground in the summer is greater than that extracted from the ground in the winter, it was found that, in comparison with the full operation mode, the highest and average field temperatures significantly decrease when only the central part of the GHE runs during the winter. Analysis shows that the thermal accumulation can be effectively alleviated by this GHE zoning operation. This study also indicates that the zoning operation method is more effective when the ground has a smaller thermal conductivity.

1. Introduction

Ground coupled heat pump (GCHP) is a typical renewable energy technology that utilizes the low rank thermal energy of the ground [1,2]. Some large GCHP systems are in need of a large number of buried pipes. Presently, the ground heat exchangers (GHEs) mostly operate at full capacity (i.e., they use all of the buried pipes in summer and winter). Nevertheless, the ground temperature at the GHE buried area, especially in the central part of the field, will continuously increase or decrease after the long-term running of GHEs in cases with unbalanced heating and cooling workloads. However, a continuous increase or decrease in ground temperature will induce a decline in the GCHP system performance, and some of the buried pipes may fail to work due to the extreme heat or cold accumulation. Therefore, especially for large multiple borehole ground heat exchangers (LMBGHE), reducing the thermal accumulation of GHEs has an important engineering significance [3–5].

Presently, the main effective methods for solving the problem of thermal accumulation include enlarging the space between the boreholes [6,7], operating intermittently [8,9] or adopting a hybrid ground-coupled heat pump system (HGCHP) [10,11]. In fact, enlarging the space between the boreholes increases the ground volume occupied by the GHE, and the ground temperature variation will be maintained relatively even due to the increase of the total heat capacity in the GHE field. Yu et al. [12] noted that increasing the space between the boreholes could slow down the thermal accumulation. Enlarging the borehole spacing is a simple and practicable method, but it requires more ground area and is restricted in places where there is a shortage of land. Gao et al. [13] indicated that intermittent operation provides the time for ground thermal recovery and that effective control of the intermittent process can optimize the capacity of the heat exchange units and better utilize the GHE. Yang et al. stated that the intermittent operation for the HGCHP system can lower the average soil temperature and the exiting fluid temperatures of both the GHE and the heat pump units. These methods will alleviate the soil heat accumulation and improve the operational efficiency of the heat pump units [14]. However, the operation mode of a HVAC system is determined according to the demands of the building and hardly guarantees a sufficient operation time needed for ground thermal recovery. The HGCHP systems are often used in cases with unbalanced thermal loads. A HGCHP system with a cooling tower is usually adopted

* Corresponding author.
E-mail address: yumingzhiwh@163.com (M. Yu).

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Nomenclature

a	the ground thermal diffusivity (m^2/s)
H	the borehole depth (m)
i	the serial number of the borehole
j	the time step
$q_{i,j}$	the heat flux per unit depth of the ith borehole at time j (W/m)
q_l	the heat release of a borehole per unit depth (W/m)
r	the distance from the center of a buried pipe (m)
ΔT_{FLS}	the surplus temperature of the site with the distance of r away from a borehole center (°C)
t	time (s)
z	the distance between the site and the ground surface (m)
λ_S	the ground thermal conductivity (W/m K)
$\theta(x, y, z)_{FLS}$	the surplus temperature of the site with the coordinate of (x,y,z) (°C)

when the thermal load in summer is greater than that in winter [15]. On the contrary, if the winter load is larger than the summer load, a supplemental heating loop, such as a solar energy collector, would be employed to take a partial load during the winter and also to inject heat into the ground during the summer so the heat can be used later during the winter [16–18]. Kjellsson et al. [19] have analyzed a GCHP combined with solar collectors, and they indicated that the energy deficit in the ground can be replenished by a feeding solar heat injection. Although thermal accumulation can be reduced effectively by a composite heat pump heating system, the energy efficiency of the augmented system is usually lower than that of an unaugmented GCHP. Moreover, the operation strategy and the adjustment of a composite system are much more complex than that of an unaugmented GCHP. Bayer et al. [20] offered two ways to diminish the thermal anomalies of GHEs: the workload optimization of individual boreholes and the removal of redundant boreholes for a given layout. In their strategy, the boreholes in the field center are first moved away.

In this paper, we present a zoning operation method to reduce the thermal accumulation of GHEs with unbalanced seasonal workloads. To alleviate the thermal accumulation formed after the larger workload season, only a portion of the boreholes in the zone where the thermal accumulation is most serious were employed during the lower workload season. This method is easy to apply and is particularly suitable to allow an existing system to diminish its ground thermal abnormalities without extensive system modifications.

2. Zoning operation strategy

Even after several years, the heat accumulated in the central GHE field induced by unbalanced seasonal thermal loads can hardly be effectively transferred to a field outside of the GHE area. Therefore, the thermal accumulation problem of the relatively central field is the most serious. For the case in which the heat injection in the summer is greater than heat extraction in the winter, it is obvious that the thermal abnormalities would be gradually aggravated over time if all of the buried pipes in the GHE are utilized during the winter and the summer. For this case, the zoning operation mode can be used, in which the whole GHE operates during the summer and only the relatively central part of the GHE operates during the winter. By reducing the number of running boreholes used during the winter, the workload imbalance of the relatively central part of the GHE, between the summer and the winter, will drop significantly. Therefore, the heat accumulation would be pronouncedly reduced. Though the boreholes in the fringe area of the GHE only release heat into the ground during the summer, the heat accumulation in this area can be tolerated as the heat can be transferred to an outside field without buried pipes during the whole GHE life cycle. For cases in which the heat injection during the summer is smaller than heat extraction during the winter, the whole GHE will operate during the winter and the relatively central part of the GHE will operate during the summer.

3. Analysis and discussion

3.1. Mathematic model

Assuming that the ground is a semi-infinite media with a uniform initial temperature and constant thermal properties and that the GHE is regarded as a group of finite line heat sources, the finite line heat source model can be used to describe the heat transfer between the GHE and the ground. Then, the soil temperature increase around a borehole can be obtained by [21,22]:

$$\Delta T_{FLS} = \frac{q_l}{4\pi\lambda_S}\int_0^H \left[\frac{erfc\left(\sqrt{r^2+(z-h)^2}/2\sqrt{at}\right)}{\sqrt{r^2+(z-h)^2}} - \frac{erfc\left(\sqrt{r^2+(z+h)^2}/2\sqrt{at}\right)}{\sqrt{r^2+(z+h)^2}}\right] dh \quad (1)$$

where q_l is the heat release of a borehole per unit depth, W/m; λ_s is the ground thermal conductivity, W/m K; a is the ground thermal diffusivity, m^2/s; r is the distance from the center of the buried pipe, m; z is the axial coordinate of the pipe, m; and H is the borehole depth, m. The temperature change of any point in the GHE area is the superposition of the temperature rises induced by each borehole according to the superposition principle [23,24]. For cases with inconstant loads, the temperature can be obtained by considering the varying load as the integration of a series of step loads [25,26],

$$\theta(x,y,z)_{FLS} = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{q_{i,j}-q_{i,j-1}}{4\pi\lambda_S} \times \int_0^H \left[\frac{erfc\left(\left(\sqrt{r_i^2+(z-h)^2}\right)/\left(2\sqrt{a(t_m-t_{j-1})}\right)\right)}{\sqrt{r_i^2+(z-h)^2}} - \frac{erfc\left(\left(\sqrt{r_i^2+(z+h)^2}\right)/\left(2\sqrt{a(t_m-t_{j-1})}\right)\right)}{\sqrt{r_i^2+(z+h)^2}}\right] dh \quad (2)$$

where t is time, s, and

$$r_i = \sqrt{(x-x_i)^2+(y-y_i)^2} \quad (3)$$

Here, (x_i, y_i) is the coordinate of the ith borehole.

3.2. Case studies

Two GHEs have been analyzed in this paper, as shown in Fig. 1a and b. One GHE has 64 boreholes with an 8 × 8 layout and the other has 84 boreholes with a 7 × 12 layout. The borehole heat injection during the summer is 45 W/m, and the heat extraction during the winter is 30 W/m. The systems' operation duration in the summer and the winter are 3 months each. Therefore, the