A NOVEL DESIGN METHOD FOR GROUND SOURCE HEAT PUMP

by

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This paper proposes a novel design method for ground source heat pump. The ground source heat pump operation is controllable by using several parameters, such as the total meters of buried pipe, the space between wells, the thermal properties of soil, thermal resistance of the well, the initial temperature of soil, and annual dynamic load. By studying the effect of well number and well space, we conclude that with the increase of the well number, the inlet and outlet water temperatures decrease in summer and increase in winter, which enhance the efficiency of ground source heat pump. The well space slightly affects the water temperatures, but it affects the soil temperature to some extent. Also the ground source heat pump operations matching with cooling tower are investigated to achieve the thermal balance. This method greatly facilitates ground source heat pump design.

Key words: *ground source heat pump, affected circle, well number, well space, cooling tower*

Introduction

Ground source heat pump (GSHP) has been investigated experimentally and numerically in the past few decades. However, there is still a big deficiency especially in the design of GSHP. Energy conservation was ignored for some engineering projects, *i. e*., heat output to the ground in summer is not equal to heat inlet from the ground in winter. The design of GSHP is based on the estimates of heat transfer per meter without any scientific guidance, thus causing the unreasonable design and heat imbalance [1, 2]. On the other hand, three-dimensional CFD technology is more suitable for study the GSHP in research project, but not convenient for the GSHP design and optimization in engineering applications [3, 4]. The reason may be the fact that the physical model, boundaries and soil properties for each engineering project are not the same, therefore the GSHP design using CFD method requires tremendous effect and time [5, 6].

In this paper, we put forward a novel design method for GSHP. The heat transfer model of well group is simplified and established. Through case analysis, we study the effect of well number and well space for GSHP. Also, the operations of GSHP matching with cooling tower are analyzed.

Heat transfer model and its simplification

Simplification of boundary conditions

Inspired by Einstein's idea of limited boundless universe, we suppose that the number of well is limited for each project, and the well group is boundless. Based on it, every well

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lies in the center of the well group. Therefore, the boundary conditions of each well have a uniform calculated formula, which greatly simplifies the modeling.

The models are simplified as follows:

- The soil properties around the buried pipe are independent of time, space, and temperature, and their values are constant.
- The heat transfer is in radial direction and not in axial direction.
- The thermal resistance of the well is constant.
- Each well is surrounded by wells.
- The region around the single well can be simplified as a cylinder.
- The affected area around the single well is adiabatic, fig. 1, *i. e*., the affected area is enclosed without heat exchange.

The simplified heat transfer model above ignores the heat conduction outside the boundary. So the design is relatively conservative, and the surplus can be regard as the design margin.

Equivalent circle

Based on the layout of the wells, the influencing scope of the central well can be rectangle or hexagon. As shown in fig. 1, the rectangle or hexagon can be converted to an affected circle. The diameter of the affected circle can be calculated by:

$$r_{\mathrm{e}} = \sqrt{\frac{WH}{\pi}} \tag{1}$$

where W and H are denoted in fig. 1.

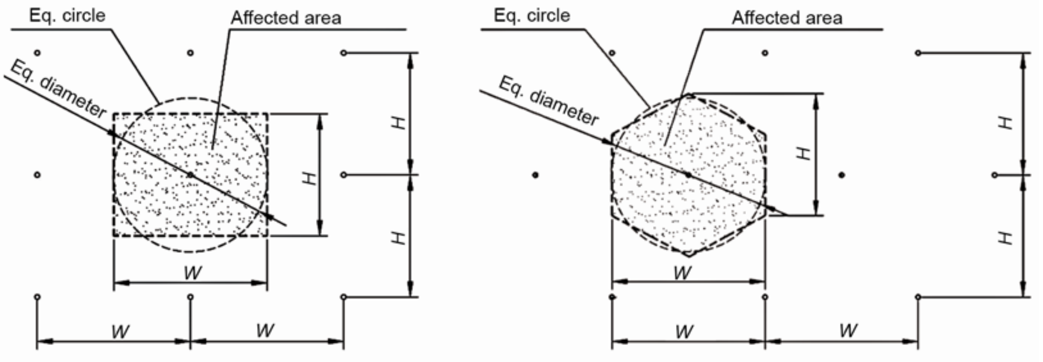

Figure 1. Equivalent circle

Heat transfer model

The heat transfer model of GSHP for single well included four equations: eqs. (2)-(5). For the group of wells, the boundary of the affected circle is adiabatic. Thus, the boundary can be written as:

$$\frac{\partial T}{\partial \tau} = a_{\mathrm{s}}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right), \quad r_{\mathrm{b}} < r < +\infty \tag{2}$$

$$-2\pi r_{\mathrm{b}} \lambda_{\mathrm{s}} \left(\frac{\partial T}{\partial r}\right)_{r=r_{\mathrm{b}}} = q_\tau, \quad \tau > 0 \tag{3}$$

$$(T - T_\infty)_{\tau=0} = 0, \quad r > r_{\mathrm{b}} \tag{4}$$

$$R_{\mathrm{b}} = \frac{T_{\mathrm{f}} - T_{\mathrm{b}}}{q_\tau} \tag{5}$$

$$\left(\frac{\partial T}{\partial r}\right)_{\mathrm{r}=r_e} = 0, \quad \tau > 0 \tag{6}$$

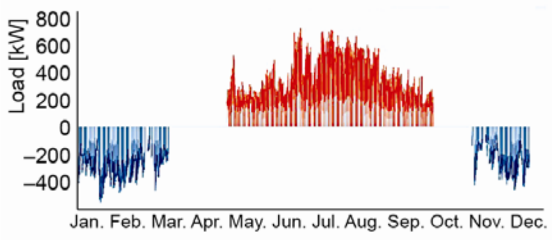

Figure 2. The annual dynamic load

Case analysis

Figure 2 presents the annual dynamic load of a project. It can be seen that the time for supplying cooling is from May 1 to October 15, while the time for supplying heat from November 15 to March 15.

The peak cooling load in summer is 719 kW, and the peak heat load in winter is 557 kW.

According to the thermal response test, the known parameters are as follows: soil initial temperature is 21 °C; soil composite thermal conductivity is 3.0 W/mK°C; soil composite thermal capacity is 2100 kJ/m^{3}K; the well thermal resistance is 0.1 mK/W.

Effect of well number on GSHP

The designed GSHP is: the well depth is 80 m, the diameter of well is 0.11 m, the space between wells is 4.5 m, the well number is 180, 210, and 240, relatively, the average energy efficiency ratio (*EER*) of GSHP is defined as 5.0 in summer, and the average coefficient of performance (*COP*) is 4.0 in winter.

According to the heat transfer model mentioned, we calculate the water and soil temperatures at 180 wells. The results are shown in fig. 3 and fig. 4. The maximal inlet water temperature in summer is 38.7 °C, and the minimal inlet water temperature is 13.7 °C in winter. Through one year operation, the soil temperature increases by 4.4 °C, from 21.0 °C to 25.4 °C.

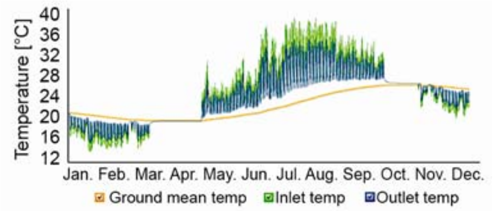

Figure 3. Inlet/outlet water temperature at 180 wells

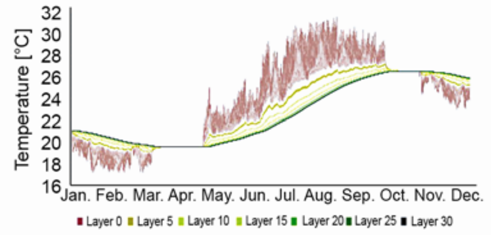

Figure 4. Soil temperature at 180 wells

The results at 210 wells are shown in figs. 5 and 6. The maximal inlet temperature in summer is 36.1 °C, and the minimal inlet temperature is 14.7 °C in winter. Through one year operation, the soil temperature increases by 3.8 °C, from 21.0 °C to 24.8 °C.

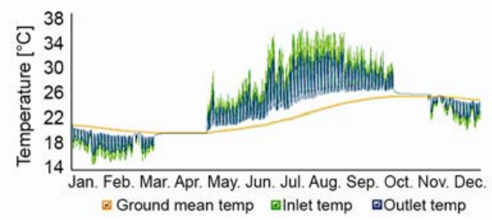

Figure 5. Inlet/outlet water temperature at 210 wells

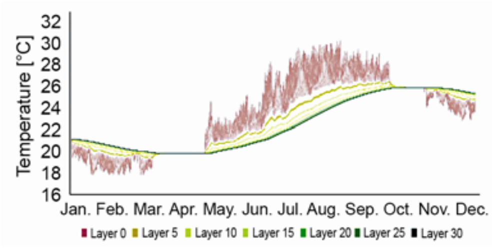

Figure 6. Soil temperature at 210 wells

We can conclude that with the increase of the well number, the inlet and outlet water temperatures decrease in summer and increase in winter, which enhances the efficiency of GSHP.

Effect of well space on GSHP

The well space is always 3-6 m. When the space is below 3 m, the thermal capacity of the affected cylinder decreases, and heat transfer between wells affects each other, especially at the end of the season. For instance, in late summer, the averaging soil temperature grows up, which may lead to the abnormal operation of the CSHP. Likewise, when the well space is great than 6 m, the floor area increases and the investment grows.

Figures 7 and 8 present the simulated results at 6m, respectively. It can be seen that compared with fig. 5 and fig. 6, the well space slightly affects the water temperatures, but it affects the soil temperature to some extent. We adopt 4.5 m as the well space in this project.

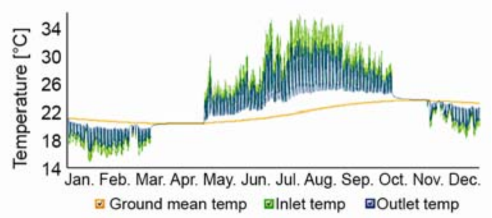

Figure 7. Inlet/outlet water temperature at 6 m

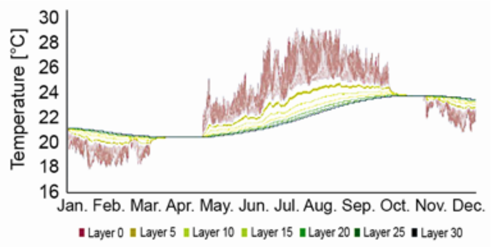

Figure 8. Soil temperature at 6 m

GSHP matching with cooling tower

In the application of GSHP, the heat load in summer is about 4 times than that in winter. Thus, it is difficult to reach the thermal balance only by using GSHP. Auxiliary cooling tower matching GSHP is a better option. This may not only achieve the thermal balance, making the system continuously in operation, but also induce the well number, decreasing the project investment. By analysis, we determine the combined scheme that the well number is 131 and the well space is 4.5 m; the heat dissipation capacity of cooling tower is 372 kW.

Priority operation of GSHP

We suppose that the buried pipe has 50 W cooling capacity per meter. So GSHP has a total of 524 kW cooling power. In summer, GSHP runs first. When the heat load is great than 524k W, the cooling tower starts. The simulated results are shown in figs. 9 and 10. The maximal inlet temperature is 39.9 °C, and the minimal inlet temperature is 11 °C. The soil temperature varies from 21.0 °C to 26.2 °C. The soil temperature increases by 5.2 °C annually.

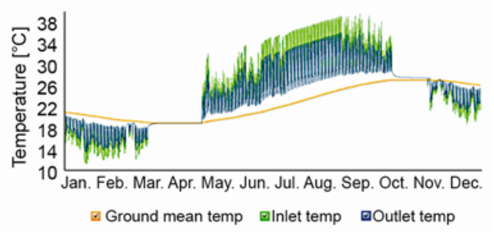

Figure 9. Inlet/outlet water temperature with GSHP priority

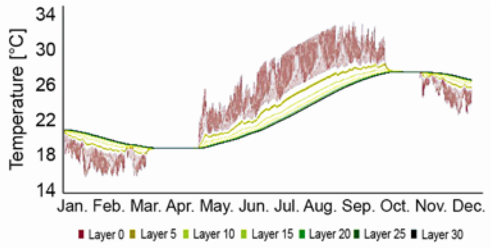

Figure 10. Soil temperature with GSHP priority

Priority operation of cooling tower

Priority operation of cooling tower is that the cooling tower (CT) runs first, when the heat load is great than 372 kW, GSHP starts. The simulated results are shown in figs. 11 and 12. The maximal inlet temperature is 31.8 °C, and the minimal inlet temperature is 11 °C. The soil temperature varies from 21.0 °C to 20.3 °C. The soil temperature decreases by 0.7 °C annually.

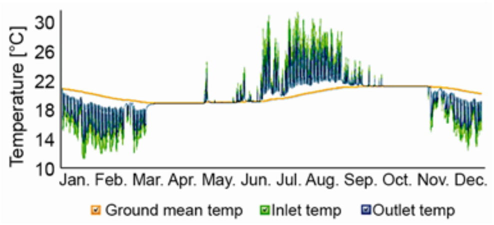

Figure 11. Inlet/outlet water temperature with CT priority

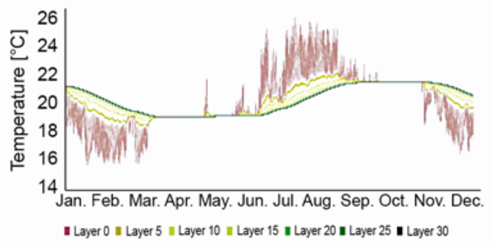

Figure 12. Soil temperature with CT priority

Priority operation of GSHP makes the soil temperature rise, while priority operation of cooling tower leads to the soil temperature lower. Therefore, it is possible to adjust the GSHP and cooling tower operations to balance the thermal energy in a year.

Conclusions

A novel design method for GSHP has been presented in this paper. It is based on the simplified heat transfer model only by using several parameters, including total liner meters of ground heat exchanger, the spaces between wells, soil thermal parameters such as composite heat conductivity and composite thermal capacity, the well thermal resistance and the soil initial temperature. Compared with 3-D CFD study, this method greatly improves the design efficiency. The well number and well space can affect the performance of GSHP to some extent. To reach the thermal balance, GSHP matching with cooling tower is a better choice.

Nomenclature

a_s – thermal diffusivity in eq. (2), [$\mathrm{m^2s^{-1}}$]
c_p – specific heat, [$\mathrm{Jkg^{-1}K^{-1}}$]
H – height in eq. (1), [m]
i – time
j – space
m – mass flow rate, [$\mathrm{kgs^{-1}}$]
q – heat flux, [$\mathrm{Wm^{-2}}$]
R – borehole thermal resistance, [$\mathrm{W^{-1}K}$]
r – radius, [m]
T – temperature, [°C]
W – width in eq. (1), [m]

Greek symbols

λ – thermal conductivity, [$\mathrm{Wm^{-1}K^{-1}}$]

ρ – density, [kgm^{-3}]
τ – time

Subscripts

s – soil
b – borehole
f – fluid
e – equivalent circle
τ – time

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