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Numerical Simulation Analysis of Continuous Heat Storage Using Different Number of Inclined Ground Heat Exchangers

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Inclined ground heat exchangers are rarely used in engineering at present. We build a model for numerical simulation of continuous heat storage using inclined ground heat exchangers within a cylindrical area with diameter of 14m and height of 20m. Continuous heat storage using different number of inclined ground heat exchangers and different diameter of water-collecting tube is simulated. It is found that the heat exchange effect is the best using 8 inclined ground heat exchangers with diameter of water-collecting tube being 2m. Under these parameters, less heat is accumulated and the occupation area of boreholes is reduced.

1. Introduction

Ground heat exchanger is a key component of heat exchange in ground source heat pump. The heat exchange effect directly determines the efficiency, service life and cost of ground source heat pump. By the way of burying, the ground heat exchanger may be vertical or horizontal. Inclined ground heat exchangers are rarely seen in engineering. In this study, we build the model for numerical simulation of inclined ground heat exchanger. Continuous heat storage is simulated within a cylindrical soil area measuring 14m in diameter and 20m in height using different number of heat exchangers and different diameter of water-collecting tube. It has been indicated by simulation with FLUENT software that the optimal inclination angle of the heat exchanger is 75° relative to the ground surface. Thus the numerical model is built with the inclination angle of 75°.

2. Numerical model

2.1 Assumptions

The following assumptions are made: (1) the soil is uniform and has constant physical property parameters during heat exchange; (2) the thermal contact resistance is neglected; (3) the influence of thermal transport and moisture transport caused by the flowing of groundwater is neglected; (4) heat exchange between the ground surface and the environment is neglected.

2.2 Mathematical model

For the cylindrical-shaped ground heat exchanger, the heat conduction equation expressed in the cylindrical coordinate system is:

$$\frac{\partial^2 T}{\partial r^2}+\frac{\partial^2 T}{r\partial r^2}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

The conservation-of-momentum equation is:

$$\rho_0\left(\frac{\partial u}{\partial \tau}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=F_x-\frac{\partial \rho}{\partial x}+\eta\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

Temperature distribution in the soil around the heat exchanger is expressed as follow:

$$T_\infty-T_0=\frac{q}{\lambda_s L}G(z,p) \tag{3}$$

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Where

T_∞ is the temperature at border radius (°C);

T_0 is the temperature of outer wall of ground heat exchanger (°C);

q is the quantity of heat exchange of the heat exchanger (W);

λ_s is the coefficient of thermal conductivity of soil, $W/(mk)$;

$G(z,p)$ is the theoretical function of G ;

$$G(z,p)=\frac{1}{\pi^2}\int_0^\infty \frac{e^{-\beta^2 z}-1}{J_1^{\,2}(\beta)+Y_{12}(\beta)}[J_0(P\beta)Y_1(P\beta)-J_1((P\beta)Y_0(P\beta))]\frac{1}{\beta^2}\,d\beta$$

$$z=\frac{a_s t}{r^2},\; p=\frac{r}{r_0}$$

2.3 Geometric model and mesh division

For both the inclined and vertical ground heat exchangers, the model is constructed within a cylindrical soil area measuring 14m in diameter and 20m in height, as shown in Figure 1.

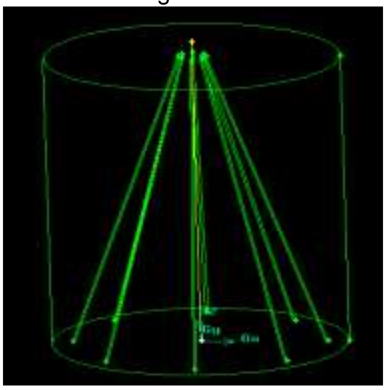

Figure 1: Heat storage model for inclined ground heat exchanger

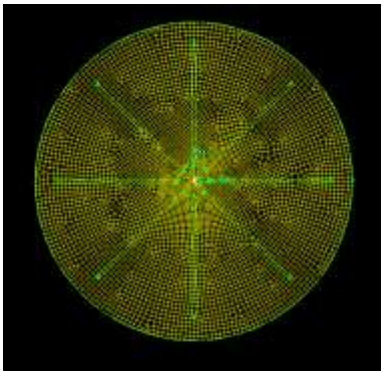

Figure 2: Mesh division of inclined ground heat exchanger at the ground surface

Mesh division is closely related to the discretization of equation and the convergence and accuracy of the model. The temperature gradient is considerable near the heat exchanger and the diameter of the water-collecting tube is very small relative to the entire calculation area. Therefore, the meshes are denser near the heat exchange tube. Hexahedral mesh generation is performed for the tube using Cooper's method, and tetrahedral mesh generation is performed for the soil area using TGrid software. Figure 2 shows the mesh division of ground heat exchanger at the ground surface.

2.4 Physical property parameters and boundary conditions

Ground heat exchanger is composed of U-shaped heat exchange tube, backfill, circulating water and soil. The burial depth of the heat exchange tube is 20m, the diameter of the borehole is 120mm, and the heat exchange tube is the HDPE pipe with outer radius of 32m. The physical property parameters of the materials are shown in Table 1.

Continuous heat storage in summer is simulated. The heat exchange process of real ground source heat pump is very complex, and we make some simplifications. The heat exchange is considered a closed system. The soil boundary is set as constant wall temperature; the inlet of the U-shaped tube is set as velocity inlet, with flow rate of 1m/s and water temperature of 45℃; the fully developed outlet is set as outflow; the tube wall the borehole wall are set as wall; the boundary conditions are set as coupled heat exchange; the initial soil temperature is 12℃.

Table 1: Physical property parameters of the materials

Material	Density (kg/m3)	Specific heat (J/kg-k)	Coefficient of thermal conductivity (w/m-k)
Cement sand	1925	1499	2.8
Water	998.2	4182	0.6
HDPE pipe	1860	840	0.4

3. Numerical simulation of inclined ground heat exchanger

3.1 Comparison of heat exchange using different number of heat exchangers

Within a cylindrical soil area measuring 14m in diameter and 20m in height, 4, 6, 8 and 10 inclined ground heat exchangers are installed, respectively. The heat storage is simulated numerically using fluent software.

Simulation is carried out for different number of heat exchangers and different diameter of water-collecting tube. The distribution of temperature field and the changes of heat exchange are obtained after 3 years of continuous heat storage.

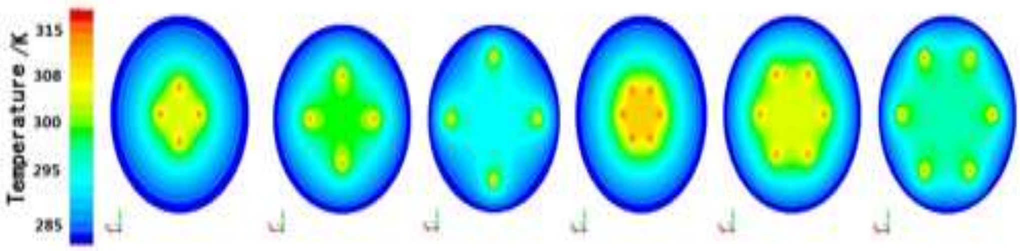

Figure 3: Nephograms of soil temperature field with burial depth of 5m, 10m and 15m using 4 and 6 heat exchangers

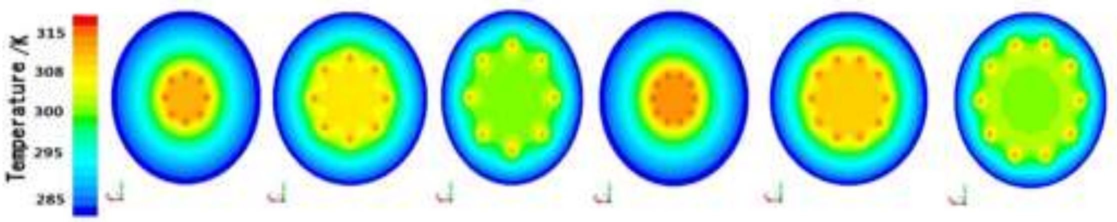

Figure 4: Nephograms of soil temperature field with burial depth of 5m, 10m and 15m using 8 and 10 heat exchangers

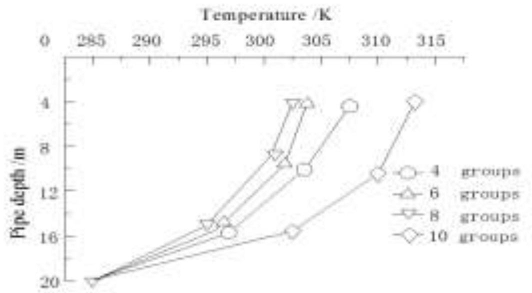

Figure 5: Temperature curve after 3 years of continuous heat storage

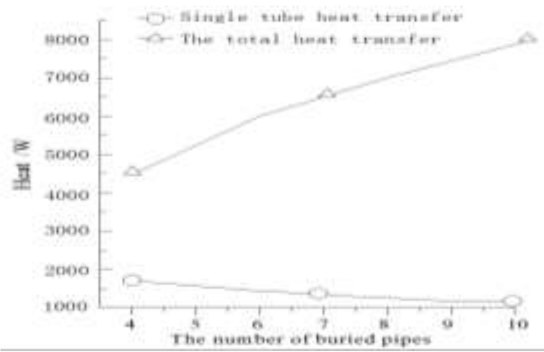

Figure 6: Quantity of heat exchange using different number of inclined ground heat exchangers

Figure 3 and Figure 4 are the nephograms of soil temperature field for burial depth of 5m, 10m and 15m using 4, 6, 8 and 10 heat exchangers, respectively. The quantity of heat exchange increases with greater number of heat exchangers for the same burial depth. When 4 heat exchangers are installed, the total heat exchange is small and the heat utilization rate is low. However, the heat is accumulated seriously in the region between 5m and 10m underground using 10 heat exchangers. The overall heat exchange effect is impaired. Figure 5 shows the variation of temperature with burial depth in soil after continuous heat storage for 3 years using different number of ground heat exchangers. It can be seen that as the number of heat exchangers increases from 4 to 8, the rise of temperature at the same burial depth slows down. But as the number of heat exchangers increases from 8 to 10, the temperature rises rapidly at the same burial depth, indicating severe heat accumulation and poor heat exchange effect. Figure 6 shows the heat exchange after 3 years of continuous heat storage using different number of heat exchangers. It is easy to see that although the total heat exchange increases using more heat exchangers, the heat exchange of a single heat exchanger decreases, indicating the reduction in heat exchange efficiency. Thus, for a cylindrical soil area measuring 14m in diameter and 20m in height, 8 ground heat exchangers are the most appropriate to harvest more energy without severe heat accumulation.

3.2 Comparison of heat exchange using water-collecting tube with different diameter

We compare the heat exchange effect between 4 different diameters of water-collecting tube, so as to find the optimal diameter of the water-collecting tube.

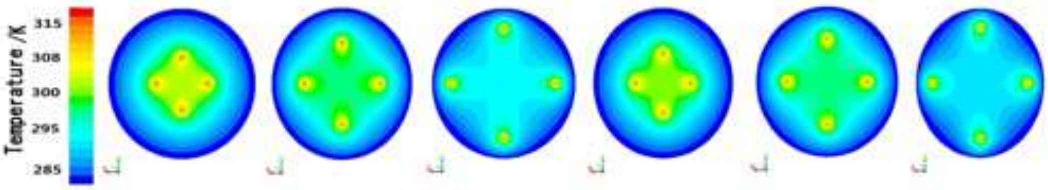

Figure 7: Nephograms of temperature field at different burial depth and 4 different diameter of water-collecting tube

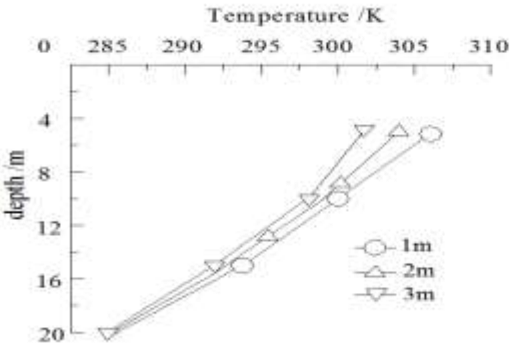

Figure 8: Variation of temperature with depth for different diameter of water-collecting tube after 3 years of continuous heat storage

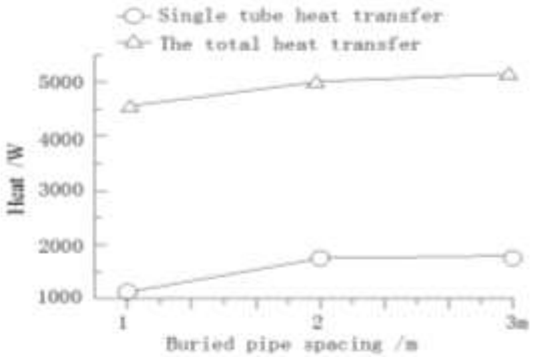

Figure 9: Heat exchange for different diameter of water-collecting tube Spacing between inclined heat exchangers

Figure 7 shows the nephograms of temperature field at the burial depth of 5m, 10m and 15m when the diameter of water-collecting tube is 2m and 3m, respectively. Figure 8 shows the variation of temperature as the diameter of water-collecting tube increases from 1m to 3m after continuous heat storage for 3 years. It can be seen that the soil temperature decreases for the same burial depth as the diameter of water-collecting tube increases and the soil temperature is similar at the burial depth of 20m. Figure 9 shows the variation of heat exchange after continuous heat storage for 3 years as the diameter of water-collecting tube increases from 1m to 3m. It can be seen that both the heat exchange of a single heat exchanger and total heat exchange increase as the diameter of water-collecting tube increases from 1m to 3m. The total heat exchange increases by 600w as the diameter of water-collecting tube increases from 1mto 2m; however, the total heat exchange increases by 100w as the diameter of water-collecting tube increases from 2m to 3m. Thus, for the cylindrical shaped soil area measuring 14m in diameter and 20m in height, the heat exchange effect is the best when the diameter of water-collecting tube is 2m at the ground surface.

4. Conclusion

Numerical simulation is performed for ground-coupled heat exchange under unsteady state in U-shaped ground heat exchanger using fluent software. The heat exchange effect using inclined ground heat exchangers in different number and with different diameter of water-collecting tube is compared with that of vertical ground heat exchanger. The following conclusions are obtained:

(1) Compared with vertical ground heat exchanger, inclined ground heat exchanger is associated with severe heat accumulation near the ground surface. However, the heat accumulation is not severe away from the ground surface. Thus inclined ground heat exchanger has superiority to vertical ground heat exchanger as it can solve the problem of heat accumulation.

(2) For the cylindrical soil area measuring 14m in diameter and 20m in height, more energy can be harvested without causing too severe heat accumulation using 8 inclined ground heat exchangers.

(3) The optimal diameter of water-collecting tube is 2m near the ground surface for the cylindrical soil area measuring 14m in diameter and 20m in height.

Acknowledgments

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