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Numerical Study on Heat Transfer Performance of Geothermal Pile-Foundation Heat Exchanger in GSHP System

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ABSTRACT

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NUMERICAL STUDY ON HEAT TRANSFER PERFORMANCE OF GEOTHERMAL PILE-FOUNDATION HEAT EXCHANGER IN GSHP SYSTEM

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Abstract

Targeting the heat transfer performance of geothermal pile-foundation heat exchanger in ground source heat pump system (GSHP), the physical model of pile-foundation heat exchanger with treble U-shaped form of pipes in surrounding soil were established. CFD software was used to simulate heat transfer processes based on the Finite Element Method for Nanjing area. In cooling mode, heat transfer performance inside and outside of concrete pile was analyzed. Heat transfer flux per meter of the pile-foundation heat exchanger (Q , $W \cdot m^{-1}$) gradually decreases and eventually stabilizes at around $60 W \cdot m^{-1}$ with system running for one month. The higher thermal conductivity of pile-foundation heat exchanger contributes to the higher heat transfer efficiency than soil. Simulation results are approximate to the actual results and can be used as theoretical basis for the design and application of pile-foundation heat exchanger in GSHP system.

Keywords: Ground source heat pump, Pile-foundation heat exchanger, Heat transfer performance, Temperature distribution, Numerical simulation

1. Introduction

With the development of society and the improvement of people's living standards, energy consumption has been growing apace. Nowadays, urban heating has been accounting for the largest proportion of the total building energy consumption in China [1]. For the purpose of saving energy and protecting environment, geothermal energy has attracted increasing interest around the world as one of renewable energies. One of the main technologies of using geothermal energy is ground source heat pump system (GSHP), which has been widely studied and applied since the early 20th century. Compared to traditional air conditioning system, GSHP system has a lot of significant advantages. By extracting heat into and injecting heat from soil, GSHP system can avoid the impact of weather changes on system performance and run stably, which helps to meet the requirements of sustainable development strategy. Without material exchanges with the atmosphere, the pollution of waste heat, vapor and noise can be reduced. Moreover, GSHP system

has a great advantage in investment and maintenance costs [2].

However, the disadvantages of GSHP system cannot be ignored neither. To invest a new system, a large area of land is needed, and drilling holes costs additional investment. Consequently, geothermal pile-foundation heat exchangers in GSHP system with pipes laid inside the foundation and fixed via concrete are applied, which contribute to declining outlays, saving ground area and reducing thermal interference between heat exchanger [3].

For pile-foundation heat exchangers, there are many forms to choose from, of which different forms of pile-foundation heat exchangers have been put into use. The most widely seen and used forms are as: single U-shaped, single W-shaped, double U-shaped and treble U-shaped. The structure of single U-shaped form is simple, but the heat transfer efficiency is reduced. Compared to single U-shaped form, single W-shaped one enhances the heat transfer efficiency, but the gas accumulated in pipes remains another problem. The structures of double U-shaped and treble

U-shaped are more complex, and the latter one has the higher heat transfer efficiency obviously [4].

Currently, analysis method, numerical method and experimental method are the three main methods to study the heat transfer performance of heat exchangers. In comparison, the numerical method are more widely applied resulting from the authenticity of results, cost-saving and time-saving [5].

The heat transfer between the pile-foundation heat exchanger and soil is a complex unsteady process involving a long time scale and a large spatial area. Consequently, the actual heat transfer process cannot be fully realized by simulation. In order to improve the simulation speed and to ensure the reliability of simulation as far as possible, some hypotheses should be put forward before creating the model and simulating: All simulations were carried within designed size, with homogeneous and isotropic properties over the entire space; the thermophysical properties of the subsurface soil are considered uniform and constant; the initial soil temperature is considered uniform; the fluid flow rate and temperature of the same cross section are the same; the impact of groundwater is ignored; the contact resistance between different parts is neglected [6]. Physical parameters of materials used in simulation calculation are shown in Table 1.

In this paper, the treble U-shaped form of geothermal pile-foundation heat exchangers in GSHP system was selected and studied via numerical method. The object with pile-foundation heat exchanger buried in soil was established and meshed via Gambit 2.4.6, the simulation was carried out in Fluent 6.3.26 and heat transfer process was analyzed with Tecplot 2010 and Origin 9.0 based on the Finite Element Method for Nanjing area. In cooling mode, temperature distribution inside the concrete pile with time was researched. Soil temperature distributions at selected points or on created lines and

planes at different position or during different periods were studied. The heat transfer flux per meter of the pile-foundation heat exchanger every second was analyzed.

2. Literature Review

The research and application of ground source heat pump system have been carried out since 1912. Nowadays, the research on heat transfer performance and heat transfer processes via simulation, programming and experiment and related technologies has been relatively mature [7-10]. In 1994, steel pipes in pile foundation were applied to buildings for the first time, and then the concept of pile-foundation heat exchanger was proposed [11]. Compared with horizontal pile-foundation heat exchanger, vertical heat exchangers had better performance in heat transfer efficiency and land consumption [12]. Heat transfer performance of heat exchangers with different configurations including single U-shaped, single W-shaped, double U-shaped, treble U-shaped and spiral forms were studied and analyzed [13-14]. Heat transfer behavior around spiral form pile-foundation heat exchanger was studied detailedly based on numerical and experimental methods [15]. In practical engineering applications, stability and rigidity in pile-foundation heat exchangers were verified to be crucial to the efficient operation of system [16]. Focusing on the effect of groundwater advection on heat transfer performance of heat exchangers, Go et al. designed a novel hybrid algorithm and found that groundwater could enhance the heat transfer through attenuating thermal interference between piles [17].

Meanwhile, mathematical models and analytical solutions are also developed and improved. A large number of achievements in study of the heat transfer performance of pile-foundation heat exchangers with different configurations of pipes have been made [18-21].

Little research on the heat transfer inside of the pile-foundation heat exchanger has

been carried out. It is necessary to explore the characteristics relative to this aspect.

Table. 1. Physical parameters of materials

Materials	Density	Heat Capacity [J·kg ⁻¹ ·K ⁻¹]	Thermal Conductivity [W·m ⁻¹ ·k ⁻¹]
Water	1000	4200	0.6
HDPE	1100	1465	0.42
Concrete	2500	837	2.3
Soil	1847	1200	2.0

Table. 2. Model parameters

Parameter	h ₁ [m]	h ₂ [m]	h ₃ [m]	d ₁ [m]	d ₂ [m]	d ₃ [m]	l ₁ [m]	l ₂ [m]	k [m]
Value	30	28	27	20	0.60	0.02	0.20	0.10	0.003

This paper describes the related studies conducted to this end.

3. Research Methods

Physical model and specifications

The physical model and configuration of the created object with pipes, pile-foundation and soil are shown in the following Figure 1. Treble U-shaped form of geothermal pile-foundation heat exchangers in GSHP system was selected and modeled. The physical model is a vertical cylinder with the diameter of d₁ and depth of h₁. The concrete pile with treble U-shaped pipes was laid inside soil. It was modeled with diameter of d₂ and depth of h₂. Piles are high-density polyethylene (HDPE) with inner diameter of d₃, k thickness and depth of h₃, which were designed and fixed via concrete inside the pile. This construction was designed in Figure 1. The relevant model parameters are given in Table 2.

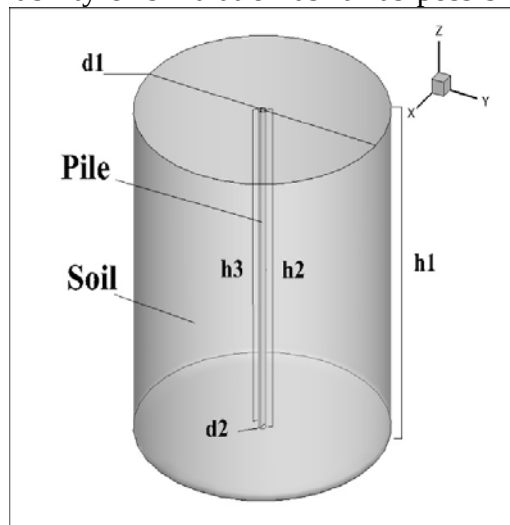
Solution and method

In this study, the object with pile-foundation heat exchanger buried in soil was established and meshed via Gambit 2.4.6, the simulation was carried out in

Fluent 6.3.26 and heat transfer process was analyzed with Tecplot 2010 and Origin 9.0 based on the Finite Element Method for Nanjing area.

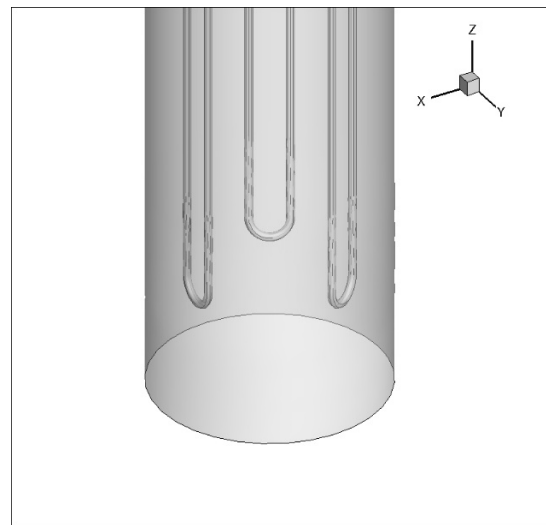
While simulation for heat transfer performance of pile-foundation heat exchanger was carried out, inlet velocity of water was set to be 0.6m/s. Inlet temperature was specified about 308K. The Reynold Number of flow in pipes was more than 7000, which meant water flow was turbulent. Consequently, standard k-ε was opted for simulation as well as energy equation. Turbulence intensity was calculated about 5% based on $0.16 \cdot Re^{-1/8}$ equation. For Nanjing area, the initial temperature of soil and piles was set to be 292K, and the temperature of outer surfaces of the model was treated as constant according to the Dirichlet Problem [22]. SIMPLE algorithm was selected to evaluate the pressure-velocity coupling in the flowing section. Relevant initial and boundary conditions were considered according to above description. Various mesh elements and types were applied in different parts of each configuration. Generally, the more the mesh number is, the more approximate to the actual results the simulation would be, but the slower the simulation process is. For the purpose of improving the

simulation speed and ensuring the reliability of simulation as far as possible,

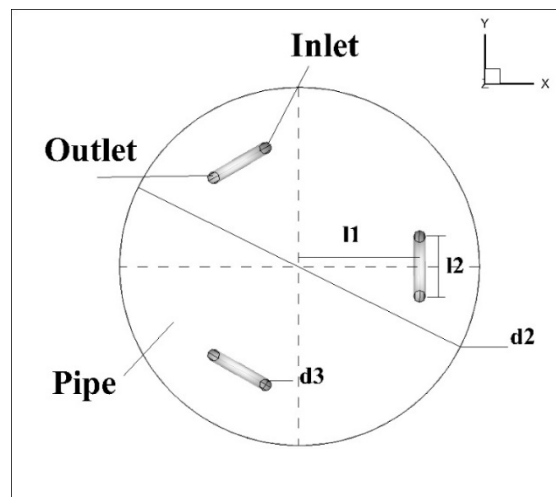


a

the model was meshed with dense grids in



b



c

Figure.1 Physical model and structure of pipes: (a) view of the whole model; (b) bottom of the model; (c) arrangement of pipes

complex structure inside and sparse grids in the other zone. Finally, mesh number for the created object with pipes, pile and soil is 866568. Structures of meshes on the model are depicted in Figure 2.

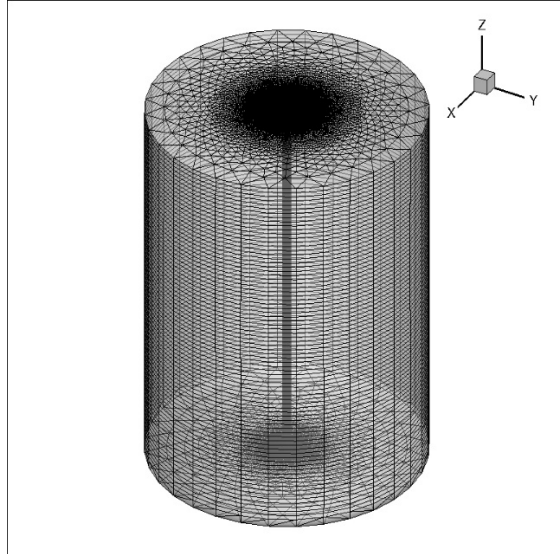
4. Analysis & Results

In order to observe and analyze simulation results, planes M1 ($Z=-15\text{m}$), M2 ($X=0.2\text{m}$), points P1 ($X=0.4\text{m}$, $Y=0\text{m}$, $Z=-15\text{m}$), P2 ($X=1.0\text{m}$, $Y=0\text{m}$, $Z=-15\text{m}$) and P3 ($X=1.6\text{m}$, $Y=0\text{m}$, $Z=-15\text{m}$) in the model were created.

In cooling mode, heat transfer simulation with system running for one month was carried out.

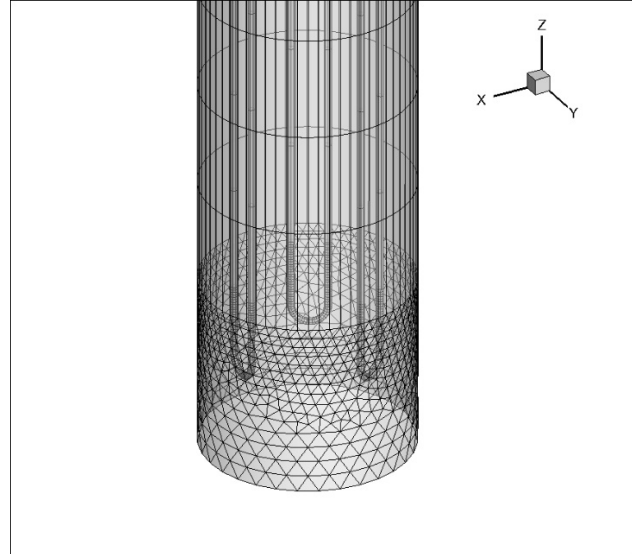
Temperature distributions of concrete pile in the early stages with system running are depicted in the following Figure 3, which reveal the high heat transfer efficiency of pile-foundation heat exchanger due to its higher thermal conductivity than soil. It is apparent that, heat exchange is limited to the area near the pipes in the first hour.

With system running, the thermal area gradually increases, and the temperature of

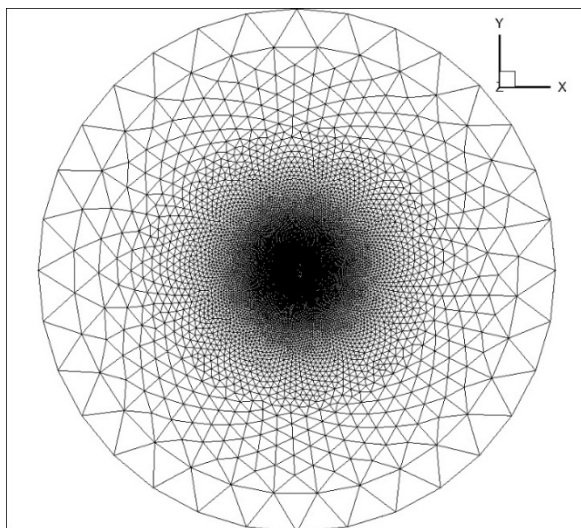


a

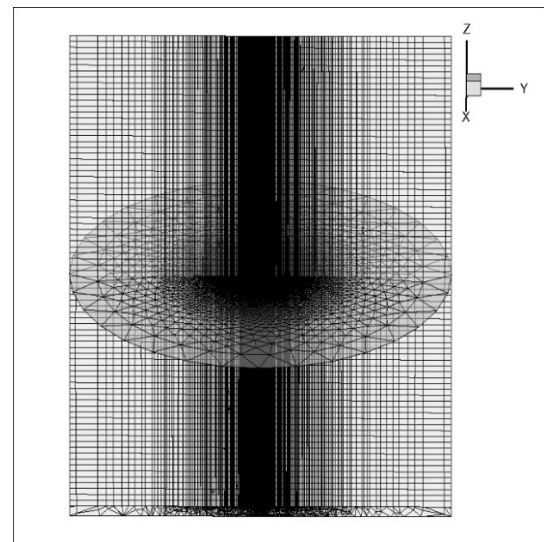
water in outlet pipes is rising. After 4 hours, the central area of concrete pile



b



c



d

Figure.2 Structures of meshes on the model: (a) meshed on the whole model; (b) meshed on bottom of the model; (c) top view of meshed; (d) meshed on selected faces

begins to be affected by the thermal effect, which will result in the enhancement of thermal interference between different pipes. After 7 hours, concrete pile is completely affected, and heat is injected into soil through the pile-foundation heat exchanger in all directions. After the system running for 12 hours, the heat exchanger has been in a state with the

average temperature of 297K, resulting in the high heat exchange efficiency between the pile-foundation heat exchanger and soil. It can also be concluded that, the upward trend of increasing of thermal area gradually slows with time on account of temperature gradients in concrete pile and soil.

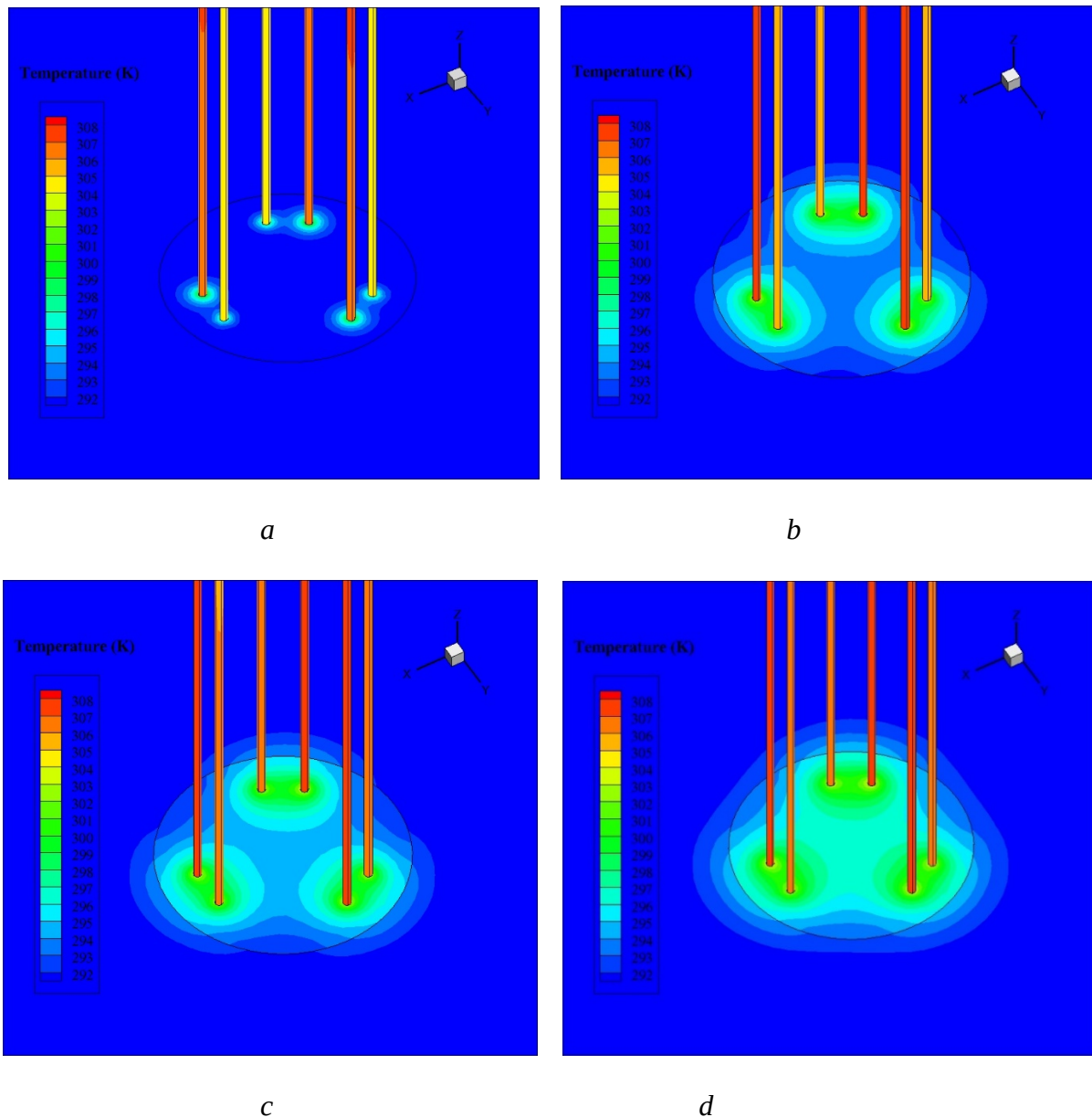


Figure.3. Temperature distributions of concrete pile on M1 with system running: (a) after 1 hour; (b) after 4 hour; (c) after 7 hour; (d) after 12 hour

Figure 4 shows the final temperature distributions of the pile-foundation heat exchanger after the system running for one month in cooling mode. The temperature distributions on line L in created model and in concrete pile with system running are depicted in the following Figure 5 and Figure 6. The position of concrete pile is between -0.3m and 0.3m. It can be concluded from the two figures that, the temperature in concrete pile is obviously higher than that in soil. Moreover, the

closer positions and pile surface are, the higher temperature is within thermal area in soil. Homoplastically, the closer positions and pipe surfaces are, the higher temperature is in pile area. In addition, the temperature in concrete pile and soil increases with system running, but the upward trend is reduced. After 10 days consecutively running, the temperature in the pile tends to be stable while the temperature in soil that away from pile

surface in thermal area remains slowly increasing.

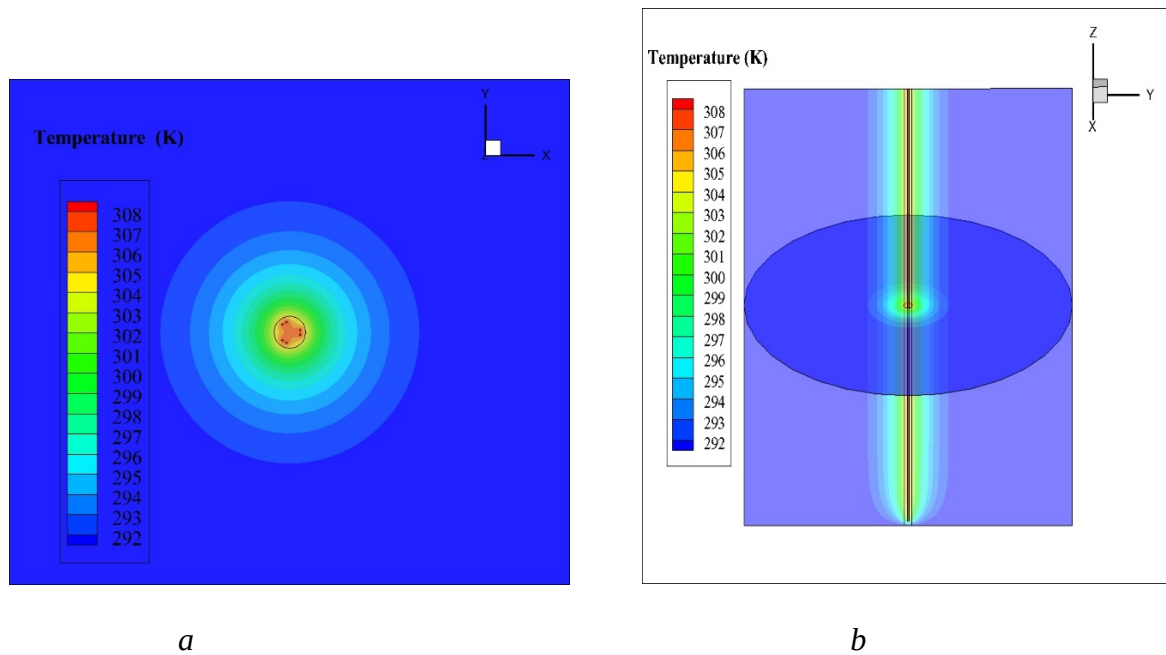


Figure.4. Temperature distributions after system running for one month: (a) on M1; (b) on M1 and M2

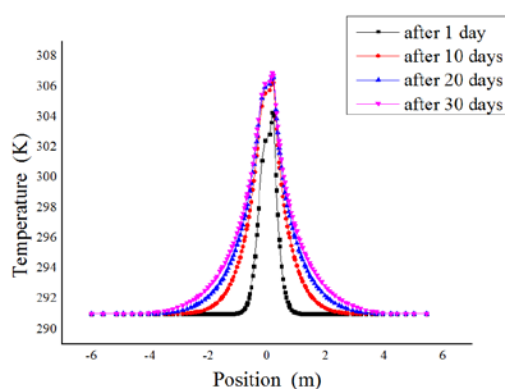


Figure.5. Temperature distributions on line L in created model

Figure 7 below depicts soil temperature distributions at created points P_1 , P_2 , and P_3 with system running. It can be concluded from the figure that, soil temperature at different points within thermal effect area gradually increases with time, but the upward trend is slowing down. The final soil temperature at different points tends to be stable. Nevertheless, the closer points and pile

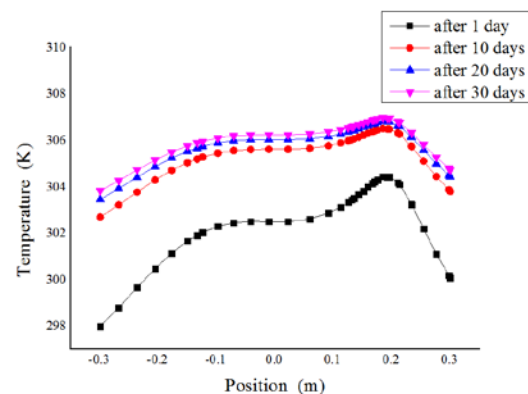


Figure.6. Temperature distributions on line L in concrete pile

surfaces are, the earlier soil temperature rises and the higher the final stable temperature is on account of soil temperature gradients.

Heat transfer flux per meter of the pile-foundation heat exchanger (Q , $W \cdot m^{-1}$) is depicted in Figure 8. It is apparent that the maximum value of heat transfer rate is about $118 W \cdot m^{-1}$ at the first day. However, it is decreasing with system running and

eventually stabilizes at around $60 \text{ W}\cdot\text{m}^{-1}$. In detail, the attenuation rate gradually

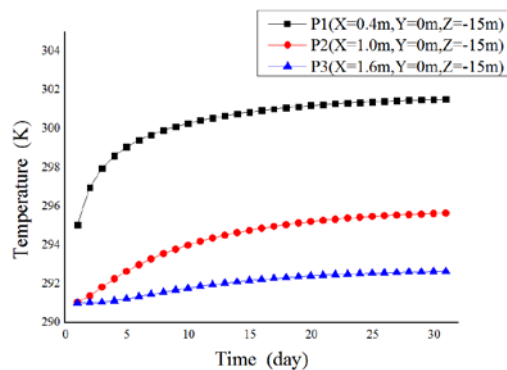


Figure 7. Soil temperature distributions at selected points.

it decreases to about $1.53 \text{ W}\cdot\text{m}^{-1}\cdot\text{day}^{-1}$. And after 20 days, the attenuation rate can be bypassed.

In practical applications, the GSHP system will not be running without interruption. In most instances, the system will be operated under shut-down condition at night time. The temperature of soil and concrete pile will be recovering, which will be conducive to enhancing heat transfer efficiency in the next operation [23].

5. Discussion & Conclusion

In this paper, the treble U-shaped form of geothermal pile-foundation heat exchanger in GSHP system was selected and studied via numerical method. Simulation and analysis were carried by CFD software based on the Finite Element Method for Nanjing area. In cooling mode, heat transfer performance of the pile-foundation heat exchanger and temperature distributions in soil and concrete pile were studied. The results of the study are summarized as follows:

- Regarding the illustrations in Figure 3, Figure 5 and Figure 6, the higher thermal conductivity of pile-foundation heat exchanger contributes to the higher heat transfer efficiency than soil. The temperature in concrete pile is obviously higher than that in soil. After 10 days consecutively

goes down. In the first 5 days, it is around $6.95 \text{ W}\cdot\text{m}^{-1}\cdot\text{day}^{-1}$. In the next 15 days,

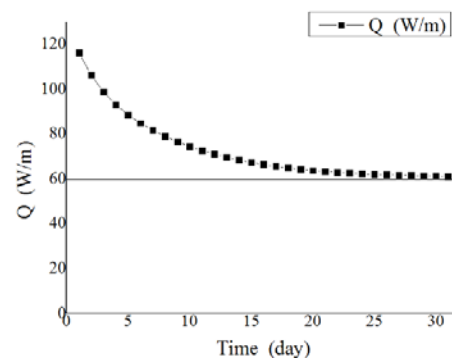


Figure 8. Heat transfer flux per meter of the pile-foundation heat exchanger.

running, the temperature in the pile tends to be stable while the temperature in soil that away from pile surface in thermal area remains slowly increasing.

- On the basis of results in Figure 7, it can be concluded that soil temperature at different positions within thermal effect area gradually increases with time. The final soil temperature at different points tends to be stable. Nevertheless, the closer points and pile surfaces are, the earlier soil temperature rises and the higher the final stable temperature is on account of soil temperature gradients.
- Figure 8 reveals that heat transfer flux per meter of the pile–foundation heat exchanger gradually decreases, but the attenuation rate gradually goes down with system running. Eventually, heat transfer flux stabilizes at around $60 \text{ W}\cdot\text{m}^{-1}$ after system running for 20 days.

The study results in this paper are approximate to the actual results, and can be used as theoretical basis for the design and application of pile-foundation heat exchanger in GSHP system.

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