International Journal of Heat and Mass Transfer xxx (xxxx) xxx

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/hmt

Study on heat transfer performance of geothermal pile-foundation heat exchanger with 3-U pipe configuration

Bo Xu[a], Hezhi Zhang[a], Zhenqian Chen[a,b,c,*]

[a] School of Energy and Environment, Southeast University, Nanjing, PR China
[b] Jiangsu Provincial Key Laboratory of Solar Energy Science and Technology, School of Energy and Environment, Southeast University, Nanjing, PR China
[c] Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, School of Energy and Environment, Southeast University, Nanjing, PR China

ARTICLE INFO

Article history:
Received 3 June 2019
Revised 28 October 2019
Accepted 7 November 2019
Available online xxx

Keywords:
Ground source heat pump
Pile-foundation heat exchanger
Heat exchanger group
Heat transfer performance
Numerical simulation
Experiment

ABSTRACT

Targeting the heat transfer performance of geothermal pile-foundation heat exchanger in ground source heat pump system (GSHP), the physical models of 3-U pile-foundation heat exchanger and heat exchanger group were established. CFD software was used to simulate heat transfer processes and heat transfer performance was analyzed both in cooling and heating mode. The simulation results indicated that the higher thermal conductivity of pile-foundation heat exchanger contributed to the higher heat transfer efficiency than soil. Heat transfer flux per meter of the pile-foundation heat exchanger gradually decreased with time went on. After operating for ten years, the average soil temperature increased by 2.96 K in non-equilibrium condition and decreased by 0.61 K in equilibrium condition. The equilibrium condition of cooling and heating load was beneficial to operation system's safety and efficiency. The experimental values of temperature differences were 2.2 K, 2.5 K and 3.5 K, and the heat transfer flux were stable at 58.1 $W \cdot m^{-1}$, 65.9 $W \cdot m^{-1}$ and 46.2 $W \cdot m^{-1}$ in three schemes separately. The maximum difference value was 8.4% for temperature difference between experiment and simulation. The simulation results corresponded well with experimental data, indicating the reliability of simulation. The study results were approximate to the actual situation and can be used as theoretical basis for design and application of pile-foundation heat exchanger in GSHP system.

1. Introduction

With the development of society and 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, as one of renewable energies, has attracted increasing interest around the world. 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. In contrast 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 operate stably by avoiding the impact of weather changes on system performance, meeting the requirements of sustainable development strategy. Without material exchanges with 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. 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 [3]. Consequently, geothermal pile-foundation heat exchangers in GSHP system with pipes laying inside the foundation and fixing via concrete are applied, contributing to declining outlays, saving ground area and reducing thermal interference between heat exchanger [4]. Compared with horizontal pile-foundation heat exchanger, vertical heat exchangers had better performance in heat transfer efficiency and land consumption [5]. Heat transfer performance around pile-foundation heat exchanger was investigated in detail based on numerical and experimental methods [6]. In practical engineering applications, stability and rigidity in pile-foundation heat exchangers were verified to be crucial to the ef-

* Corresponding author at: zhenqian chen, School of Energy and Environment, Southeast University, 2 Si Pai Lou, Nanjing, Jiangsu 210096 China.
E-mail address: zqchen@seu.edu.cn (Z. Chen).

https://doi.org/10.1016/j.ijheatmasstransfer.2019.119020
0017-9310/© 2019 Elsevier Ltd. All rights reserved.

Please cite this article as: B. Xu, H. Zhang and Z. Chen, Study on heat transfer performance of geothermal pile-foundation heat exchanger with 3-U pipe configuration, International Journal of Heat and Mass Transfer, https://doi.org/10.1016/j.ijheatmasstransfer.2019.119020

ficient operation of system [7]. 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 [8,9]. The structure of single U-shaped form is simple with the disadvantage of low heat transfer efficiency. Compared with single U-shaped form, although the single W-shaped one can enhance the heat transfer efficiency, 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 [10].

Nowadays, the research on heat transfer performance and heat transfer processes via theory, simulation and experiment and related technologies has been widely conducted [11–14]. In theoretical study, Kelvin was the first to put forward the theory of line heat source, which laid the theoretical foundation for the later research on ground source heat pump technology. Based on the Kelvin's line heat source model, Ingersoll and Plass made simplified assumptions for the underground soil. The buried pipe heat exchanger was approximately a line heat source with constant heat flow and infinite length, and a modified line heat source model was established, which was also the most classical line heat source model [15]. On the basis of previous studies, Kavanaugh considered the thermal short circuit between buried pipes, regarded the underground heat exchanger as an infinite cylinder and established an infinite cylinder heat source model closer to the actual heat transfer process [16]. In addition, a large number of achievements in heat transfer performance of pine-foundation heat exchangers with different configurations of pipes have been made [17–20]. Focusing on the effect of groundwater advection on heat transfer performance of heat exchangers, Go et al. [21] designed a novel hybrid algorithm and found that groundwater could enhance the heat transfer through attenuating thermal interference between piles. Meanwhile, mathematical models and analytical solutions are also developed and improved. In contrast, the numerical method was more widely applied on account of the authenticity of results, cost-saving and time-saving [22]. Numerical heat transfer model was mainly based on finite difference method, finite element method and other numerical analysis methods [23], including Yavuzturk model, Emerson model, Mitchell model and NWWA model. Hackel [24] concluded that applicability of composite ground source heat pump system was superior to single ground source heat pump system in larger summer cooling load case by simulation. Morino [3] used the finite difference method to conduct numerical simulation and experiment on the heat transfer characteristics of buried pipe in building pile foundation, and proposed the concept of buried pipe heat exchanger based on pile foundation for the first time. Pahud [25] conducted a numerical simulation analysis and research on the heat transfer process of u-type buried pipe with a Duct Ground Heat Storage model, and a pile-based buried pipe heat exchanger was designed and applied in Zurich airport building based on the simulation results of simulation software developed on the TRNSYS platform. Gao [26] used FLUENT software to study the effect of different run length and drilling arrangement factors on the performance of heat exchanger, and thermal effect of different arrangement of heat exchanger group on the soil in the process of system operation. Simulation analysis and experimental verification was an important way to effectively study the heat transfer performance of ground source heat pump.

Compared with single U type, series 2-U type, parallel 2-U type and spiral type, the parallel 3-U pipe configuration [27] had a larger heat transfer performance and higher efficiency. In addition, the pile-foundation heat exchanger group with the better pile-foundation configuration was needed to study. The parallel 3-U pipe was a better choice. Finally, the number and depth of building pile-foundation were limited and it can't be designed by themselves like ordinary drilling holes. Under this premise, parallel 3-U pipe configuration can greatly improve the heat transfer performance and make full use of existing building pile-foundation. In this paper, the treble U-shaped in parallel form of geothermal pile-foundation heat exchangers in GSHP system was selected and studied via numerical and experimental method. The objects of pile-foundation heat exchanger and heat exchanger group buried in soil were established and were simulated by Fluent based on the Finite Volume Method for Nanjing area in China, which was a typical representation of hot summer and cold winter area with sultry in summer, wet and cold in winter, small daily temperature range, large annual precipitation and less sunshine. Heat transfer processes of pile-foundation heat exchanger and heat exchanger group were studied in different conditions. Pile-foundation heat exchanger group was running for ten years in non-equilibrium and equilibrium condition to simulate more realistic long-term results. The non-equilibrium condition referred to the isolated operation of pile-foundation heat exchanger group of GSHP system, and the equilibrium condition referred to the joint operation of GSHP system and cooling tower system. Experimental tests were carried out as a contrast to simulation result.

2. Simulation models and methods

2.1. Simplification and assumption

The heat transfer between 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. The thermal physical properties of the subsurface soil and other materials at temperature from 278 K to 313 K are considered uniform and constant; the initial soil temperature is considered uniform; the fluid flow rate and temperature of water in the same cross section are the same; the impact of groundwater and the contact resistance between different parts of pile-foundation heat exchanger are neglected [28] to ensure the pure heat conduction process between buried pipe and pile foundation concrete, and between pile foundation concrete and soil. Physical parameters of materials [29] used in simulation calculation at 291 K are shown in Table 1.

2.2. Physical models and specifications

The physical models and configurations of pile-foundation heat exchanger and heat exchanger group were shown in Fig. 1. Treble U-shaped in parallel form of geothermal pile-foundation heat exchangers in GSHP system was selected and modeled. The physical model of pile-foundation heat exchanger was a vertical cylinder with the diameter of d_1 and depth of h_1. The concrete pile with diameter of d_2 and depth of h_2 combined with treble U-shaped buried pipes was laid inside soil. The buried pipes were high-density polyethylene (HDPE) with inner diameter of d_3, thickness of k and depth of h_3, fixed via concrete inside the pile. The distance between two pins of U-shaped pipe was l_1 and the center of U-shaped pipe was l_2 away from center of concrete pile. The relevant model parameters were listed in Table 2. 3×3 concrete piles were chosen to constitute the model of heat exchanger group, depicted in Fig. 1(b). The distance between piles was 10 m and the whole size of heat exchanger group was $30\,m \times 30\,m \times 30$ m. The model top of heat exchanger group was regarded near ground surface and set as adiabatic.

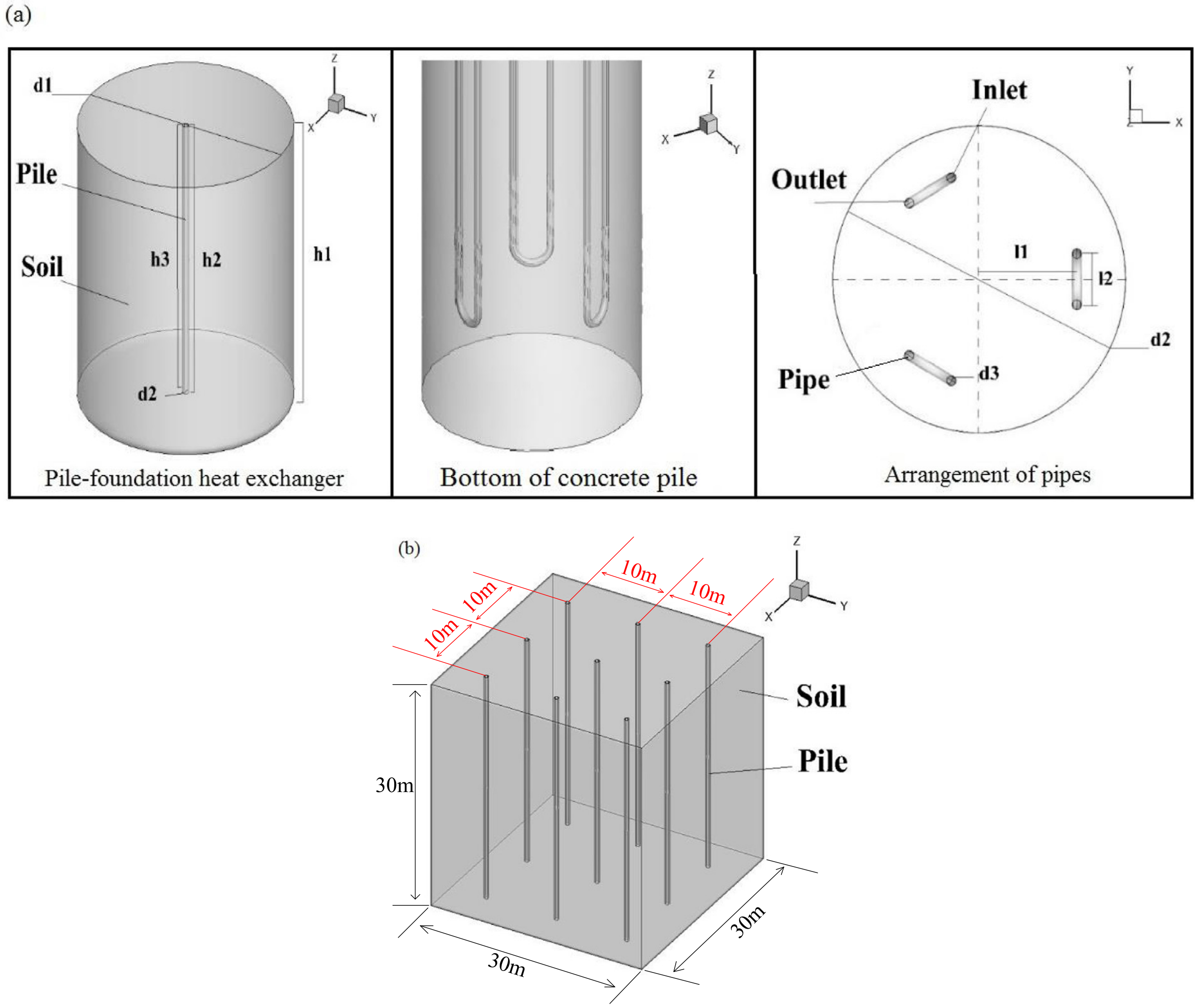

Fig. 1. Physical models and specifications (a. Pile-foundation heat exchanger; b. Pile-foundation heat exchanger group).

Table 1
Physical parameters of materials.

Materials	Density	Heat Capacity/ $J \cdot kg^{-1} \cdot K^{-1}$	Thermal Conductivity / $W \cdot m^{-1} \cdot K^{-1}$
Water	1000	4200	0.6
HDPE	1100	1465	0.42
Concrete	2500	837	1.628
Soil	1847	1200	1.3

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

2.3. Solution and method

The objects of pile-foundation heat exchanger and heat exchanger group buried in soil were established and were simulated by Fluent for Nanjing area in China.

When simulation for heat transfer performance of pile-foundation heat exchanger was carried out, inlet velocity of water was set to be 0.6 $m \cdot s^{-1}$ both in cooling and heating conditions. In addition, the inlet water temperature was specified about 308 K in cooling condition and 278 K in heating condition. The Reynold number of flow in pipes was more than 7000, indicating the turbulent water flow. Standard k-ε was opted for simulation as well as energy equation. Turbulence intensity was calculated about 5% based on $0.16 \times Re^{-1/8}$ equation. For Nanjing area, the initial temperature of soil and piles was set to be 291 K both in cooling and heating conditions, and the temperature of outer surfaces was treated as constant according to the Dirichlet Problem [30]. SIMPLE algorithm was selected to evaluate the pressure-velocity coupling in the flowing Section. 3D double precision solver and separate and implicit solution were chosen to improve the accuracy. The inlet boundary of pipe was “Velocity inlet” and outlet boundary was “Outflow”. The bottom and side of cylindrical model was

Table 3
Main parameters in three schemes.

Scheme	Inlet Temperature / K	Inlet Velocity / m·s^{-1}	Depth of pipe / m	Diameter of pipe / m
1	308	0.60	27	0.6
2	313	0.60	27	0.6
3	308	0.30	27	0.6

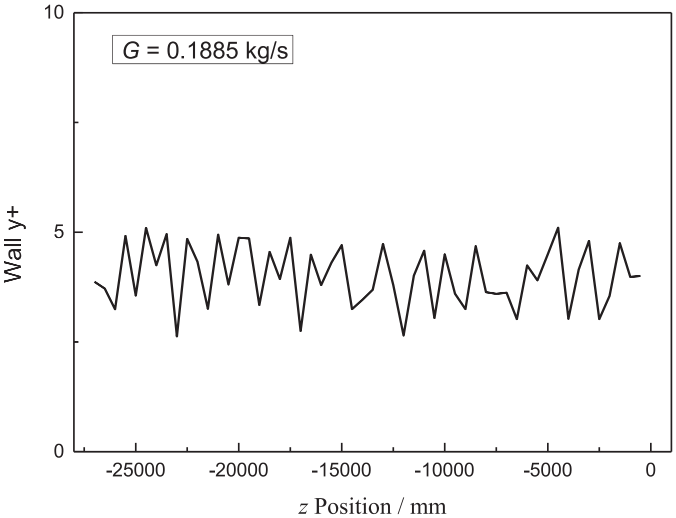

Fig. 2. Axial variation of heated wall $y+$.

thermostatic wall, and the top was thermal isolation. The interface between circulating water and buried pipe, buried pipe and pile-foundation, and pile-foundation and soil was defined as “Coupled” boundary condition. The time step is 10 s for short time simulation like several hours, 120 s for medium time simulation like several days to 1 month and 1800s for long time simulation like 1 year to 10 years.

For pile-foundation heat exchanger group, the method settings were the same as that of single pile-foundation heat exchanger. The bottom and side of cube model was thermostatic wall, and the top was thermal isolation. In addition, four User Defined Function (UDF) programs were programmed as source items according to calculating data of dynamic building load.

Various mesh elements and types were applied in different parts of each configuration. Generally, the simulation would be more approximate to the actual results with larger mesh numbers. But it will slower the simulation process and take more time. For the purpose of improving simulation speed and ensuring simulation reliability as far as possible, the model was meshed with dense grids in complex structure inside and sparse grids in the other zone. For pile-foundation heat exchanger, the meshes of pipe, concrete pile and soil in the x and y direction adopted Tgrid type with size of 4 mm, 40 mm and 80 mm separately. The meshes of pipe and concrete pile in the z direction were divided into the upper and lower areas, with the dividing line 2 m away from the lower area. The upper region adopted cooper grid with a size of 300 mm both for pipe and concrete pile. The lower region adopted cooper grid of 10 mm for pipe and Tgrid type of 40 mm for concrete pile. The meshes of soil adopted cooper grid of 300 mm in whole z direction. For heat exchanger group, all meshes adopted cooper grid of 300 mm in whole x, y and z direction. Grid independence was first checked before carrying out extensive case studies by doubling the number of elements with changes of less than 0.5% and halving the number of elements with changes of more than 2% in the outlet water temperature of final state. As the present case corresponds to turbulent flow, it was also important to evaluate non-dimensional distance, $y+$, from the wall based on the selected cell size. It was defined as $y^+ = \frac{yu_t}{v}$, where y, u_t and v were absolute distance from the wall, friction velocity and kinetic viscosity of mixture respectively. Non-dimensional distance represented a standard measure of mesh refinement for heat and mass transfer phenomena of interest. This parameter fluctuated along the channel due to property variation and local phase change. As described in Fig. 2, the selected cell size yields $y+ < 5$ along the heated wall for the entire channel length, which was small enough to capture relevant physical phenomena in the viscous sublayer. Finally, mesh numbers of pile-foundation heat exchanger and heat exchanger group were 1,796,568 and 981,500 respectively. Structures of meshes on the models were depicted in Fig. 3.

3. Results and discussion

3.1. Experiment

3.1.1. Experimental platform

Schematic diagram of experimental system was depicted in Fig. 4. It included temperature monitoring system, temperature control system, water transport system and pile-foundation heat exchanger. Temperature monitoring system composed of temperature acquisition module and temperature probe. Water bath was used to control the inlet water temperature. Pump, valve, flowmeter, pipe and water tank constituted the water transport system. Experimental platform of single-U pipe was set up in Jiulonghu Campus of Southeast University, as was shown in Fig. 5. Thermostatic water tank was applied to keep the inlet temperature constant. The experimental study was carried out in three designed schemes based on constant temperature method. The relevant parameters were depicted in Table 3. The difference between scheme 1 and scheme 2 was inlet temperature, and the difference between scheme 1 and scheme 3 was inlet velocity.

3.1.2. Experimental result

In three designed schemes, the temperature difference between inlet and outlet was depicted in Fig. 6(A) and heat transfer flux per meter of pile-foundation heat exchanger (q) was shown in Fig. 6(B). The increasing of inlet temperature could enhance the temperature difference between inlet and outlet temperature and the heat transfer flux per meter of the pile-foundation heat exchanger. In addition, the decrease of inlet velocity could also increase the temperature difference while the heat transfer flux decreased. It was because the inlet velocity decreased more than the increase of temperature difference. Experimental data of final state can be observed in Table 4. The values of temperature differences were 2.2 K, 2.5 K and 3.5 K, and the heat transfer flux were stable at 58.1 W·m^{-1}, 65.9 W·m^{-1} and 46.2 W·m^{-1} in three schemes, respectively.

Table 4
Experimental data of final state.

Scheme	Outlet Temperature / K	Temperature difference / K	q / W·m^{-1}
1	305.8	2.2	58.1
2	310.5	2.5	65.9
3	304.5	3.5	46.2

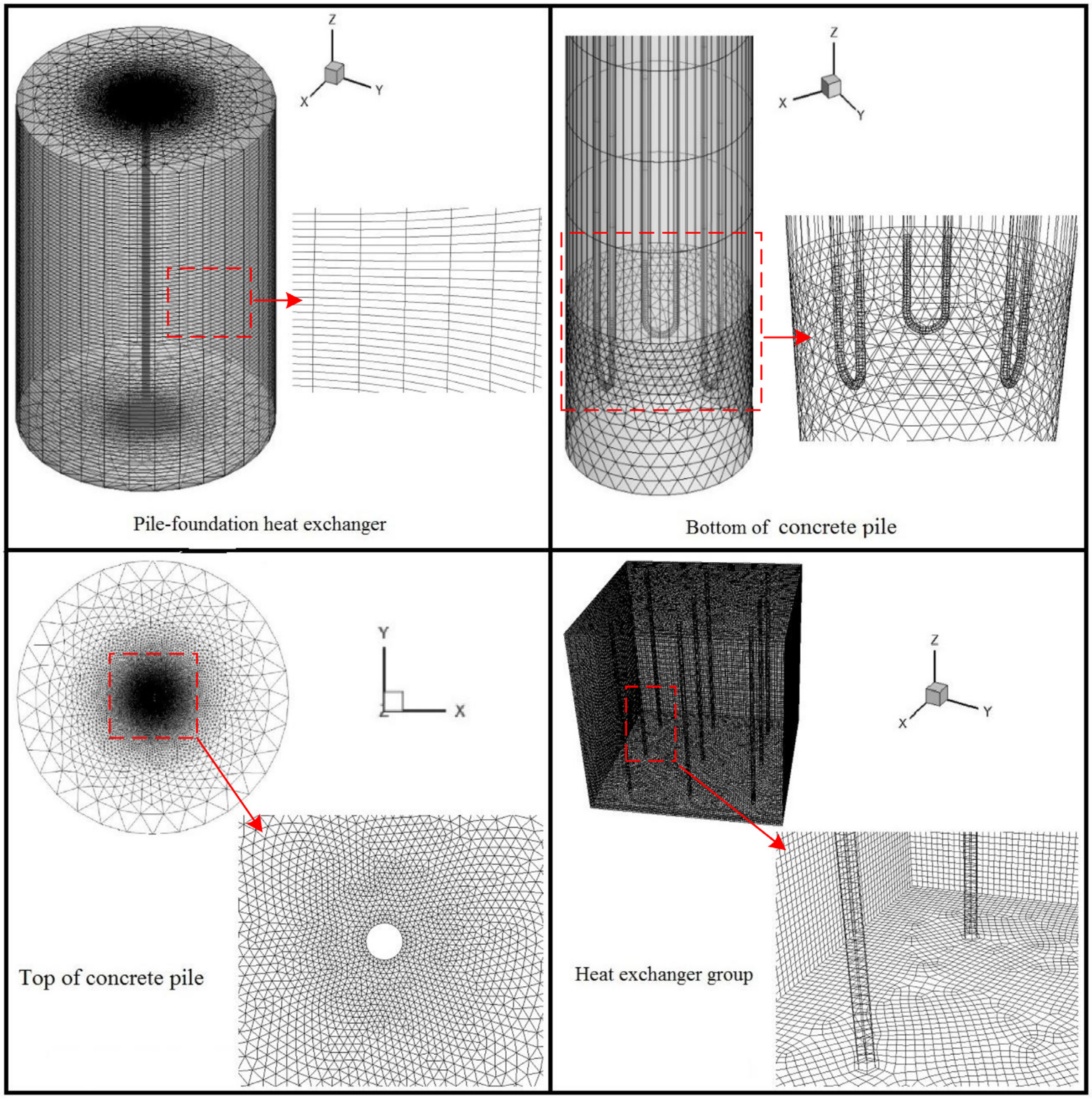

Fig. 3. Structures of meshes on the model.

Table 5
Direct measurement relative error.

Item	Maximum measurement error of equipment	Minimum measurement value	Maximum relative error
Inlet water temperature	0.15 K	20.1 K	0.75%
Outlet water temperature	0.15 K	18.1 K	0.83%
Temperature difference between inlet and outlet water	0.15 K	1.95 K	7.69%
Flow flux	0.003 m^3/h	0.349 m^3/h	0.86%

3.1.3. Experimental error analysis

The error analysis is inevitable due to the influence of various factors for experiment. The results are meaningful only when the error of measured value is within an acceptable range, indicating the accuracy of experiment.

Measurement maximum relative error of inlet water temperature, outlet water temperature, temperature difference between inlet and outlet water, and flow flux were described in Table 5. The maximum direct measurement relative error was 7.69%.

Indirect measurement error of heat release per unit length of meter was calculated as followed: The calculation formula of heat transfer between pile foundation heat exchanger and soil was shown in the following equation:

$$q = \frac{c_p \cdot m \cdot (T_{in} - T_{out})}{L} \quad (1)$$

Where c_p was constant-pressure specific heat of circulating water (W/m), m was mass flow of circulating water (kg/s), T_{in} was inlet water temperature (K), T_{out} was outlet water temperature (K), and L was depth of pile foundation (m).

Error analysis was conducted based on the error transfer method of Kline [32], and the standard deviation of heat release

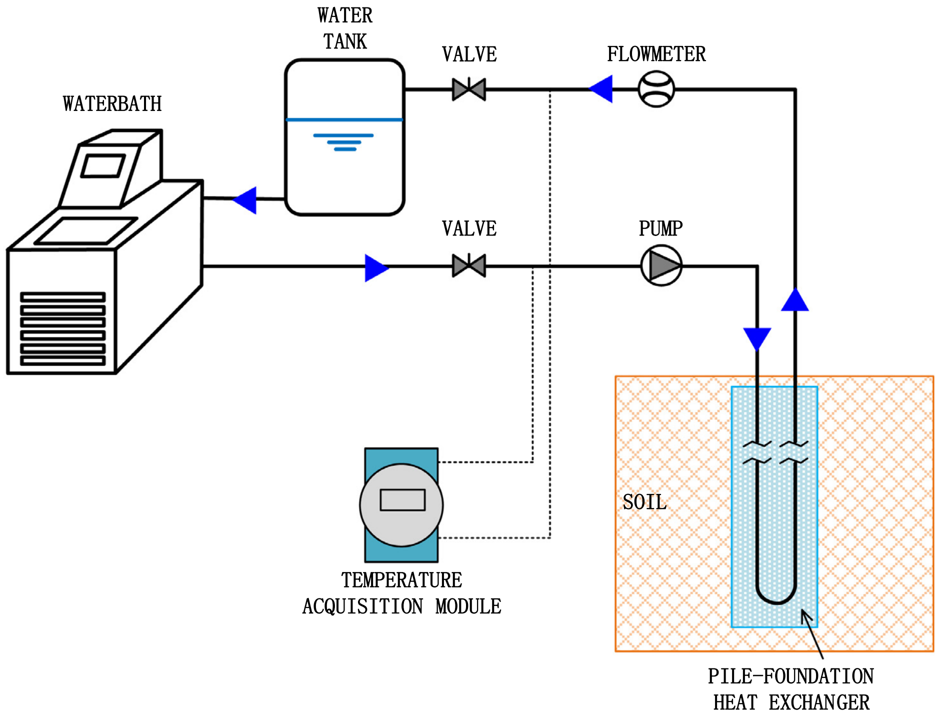

Fig. 4. Schematic diagram of experimental system.

Fig. 5. Experimental platform.

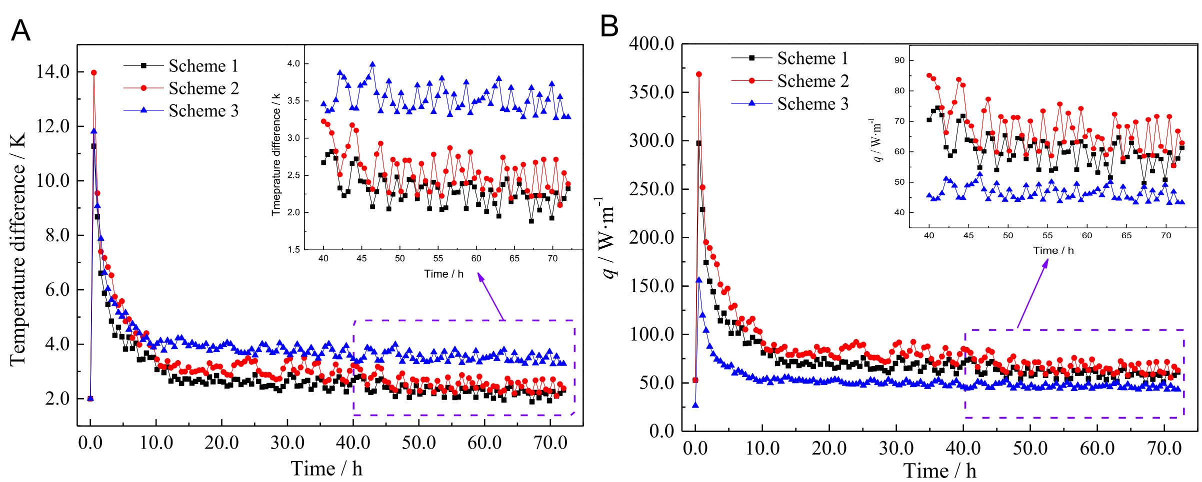

Fig. 6. Parameters with different schemes (A. temperature difference; B. q).

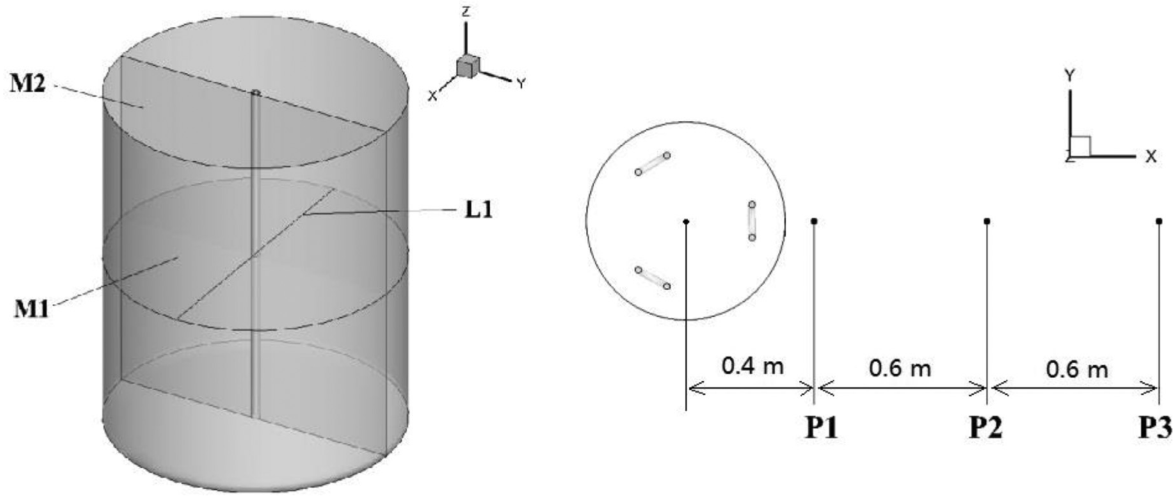

Fig. 7. Positions of M1, M2, L1, P1, P2 and P3 .

per unit length of meter was as followed:

$$\sigma_q = \sqrt{\left(\frac{\partial q}{\partial m}\right)^2 \sigma_m^2 + \left(\frac{\partial q}{\partial \Delta T}\right)^2 \sigma_{\Delta T}^2} \quad (2)$$

The experimental data were taken in Eq. (2) to obtain the maximum relative error of the measured heat release per unit length of meter, which was 7.73% within the acceptable range.

Based on the above experimental error analysis results, it can be concluded that the errors of all measured values were small, indicating a high credibility of experimental results.

3.2. Simulation

3.2.1. Pile-foundation heat exchanger

In order to observe and analyze simulation results, planes M_1 (Z=−15 m), M_2 (X=0.2 m), line L_1 (Y=0.0 m, Z=−15.0 m), points P_1 (X=0.4 m, Y=0.0 m, Z=−15.0 m), P_2 (X=1.0 m, Y=0.0 m, Z=−15.0 m) and P_3 (X=1.6 m, Y=0.0 m, Z=−15.0 m) were created and described in Fig. 7.

3.2.1.1. Temperature distributions of planes M_1 and M_2. Heat transfer simulations with system operating for one month in cooling and heating modes were carried out and shown in Fig. 8. With the operation of system, heat transfer was gradually carried out from the circulating water, buried pipe, pile foundation concrete and then to the soil. The heat effect radius of heat exchanger on the soil kept expanding, while its increasing rate gradually decreased. With pile foundation as the center, the temperature of surrounding soil increased gradually in cooling mode and decreased gradually in heating mode. In the *x-y* plane, the soil temperature rose more quickly in cooling mode and decreased more rapidly in heating mode with closer to the pile foundation wall surface, by the effect of temperature gradient in the radial direction within the range of thermal action.

3.2.1.2. Temperature distributions of L_1. The temperature distributions on line L_1 in created model with system running were depicted in Fig. 9. The position of concrete pile is between −0.3 m and 0.3 m, marked as the yellow area in the figure. It can be concluded that temperature in concrete pile was obviously higher than that in soil in cooling mode. Moreover, soil temperature decreased with the increase of distance between soil and pile surface. With time went on, the temperature both in concrete pile and soil increased. However, the upward trend of temperature was reduced and it tended to be stable after 10 days. Thermal effect was opposite in heating mode to that in cooling mode, while the change trend was similar to each other. However, the maximum temperature change is higher in cooling mode than that of heating mode because the cooling load in summer was higher than heating load in winter.

3.2.1.3. Soil temperature distributions of P_1, P_2, and P_3. Soil temperature distributions at created points P_1, P_2, and P_3 with system running were depicted in Fig. 10. With time went on, soil temperature at different points within thermal effect area increased gradually in cooling mode, while the upward trend was slowing down. The final soil temperature at different points tended to be stable. However, when the point was closer to pile surfaces, the soil temperature rose earlier and the final stable temperature was higher on account of soil temperature gradients. In addition, the change trend was opposite in heating mode.

3.2.1.4. Heat transfer flux. Heat transfer flux per meter of the pile-foundation heat exchanger (q) was depicted in Fig. 11. It was apparent that the maximum heat transfer rate appeared at the first day and the values were about 270 W·m^{-1} and 230 W·m^{-1} separately in cooling and heating mode. It was because the temperature difference between pile-foundation heat exchanger and soil was largest at the first day. What's more, the soil temperature would increase and the temperature difference would decrease with the time went on, resulting in the decrease of heat transfer flux, as well as the attenuation rate. The heat transfer flux tended to be stable after 30 h and finally it dropped to 107 W·m^{-1} and 87 W·m^{-1} for cooling and heating mode.

3.2.2. Pile-foundation heat exchanger group

3.2.2.1. Building load. An office building located in Nanjing was introduced and the all-year dynamic building load was calculated with DeST, including the cooling period from June to September, the heating period from December to March and two recovery periods, shown in Fig. 12. The design load was calculated according to the maximum cooling and heating load which were not guaranteed for 5 days in a year. Based on this requirement, the design cooling load (Q_c) was 530 kW and heating load (Q_h) was 400 kW. Related parameters of a brand of ground source heat pump unit were obtained as followed: *EER*=5.52 and *COP*=4.63. Finally, the largest heat taken (Q_t) and heat gain (Q_g) of pile-foundation heat exchanger group could be calculated by following equations [31]:

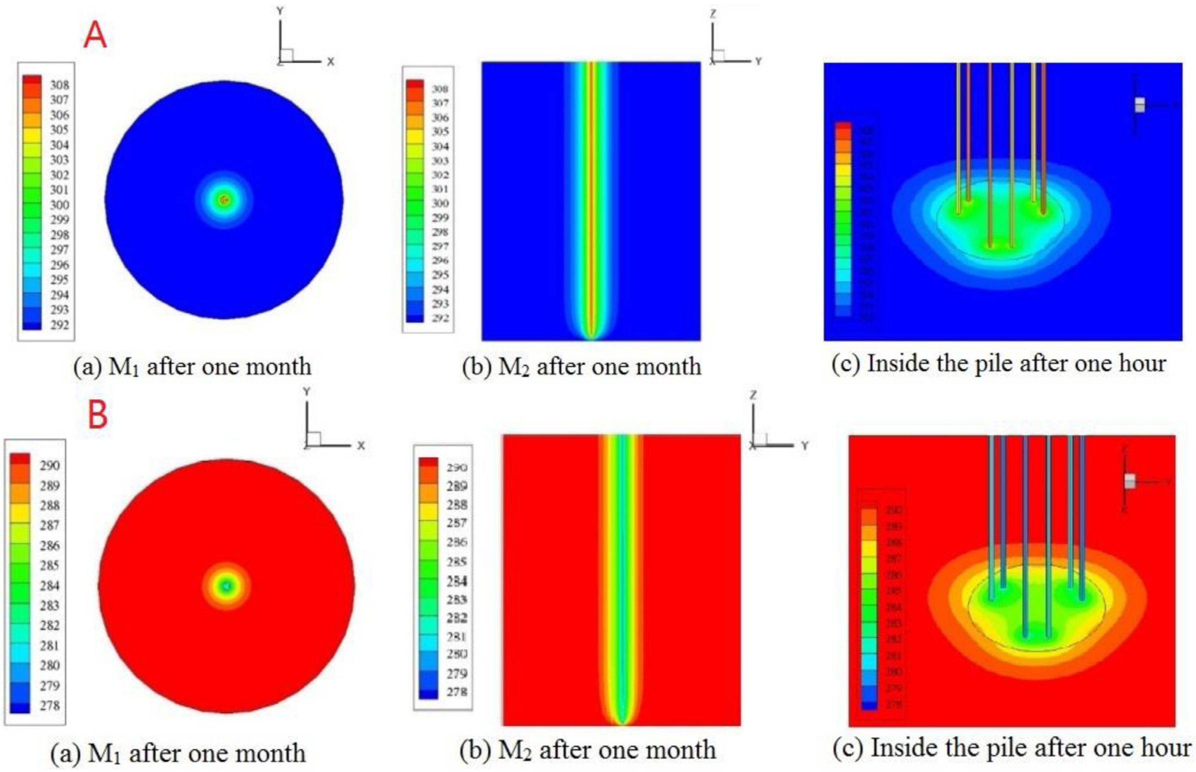

Fig. 8. Temperature distributions (A. cooling mode; B. heating mode).

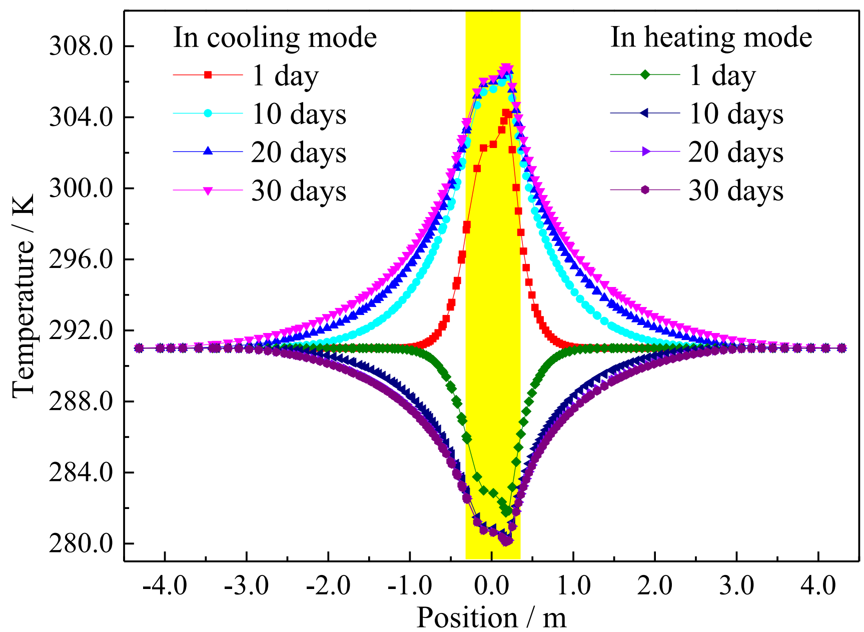

Fig. 9. Temperature distributions on line L_1 in created model.

$$Q_t = Q_c \times \left(1 + \frac{1}{EER}\right) \tag{3}$$

$$Q_g = Q_h \times \left(1 - \frac{1}{COP}\right) \tag{4}$$

After calculation, the largest heat taken was 626 kW in cooling mode and largest heat gain was 313.6 kW. Based on the above research of single pile-foundation heat exchanger, more than 250 pile-foundation heat exchangers were needed to meet the requirements of office building load. For the whole project, the number of pile-foundation heat exchangers was very large and the heat transfer process had a long time span and a large space span. Considering the orderly arrangement of pile-foundation groups, 3×3 pile-foundations were selected as the research object to study and analyze the heat transfer process of pile-foundation heat exchanger group.

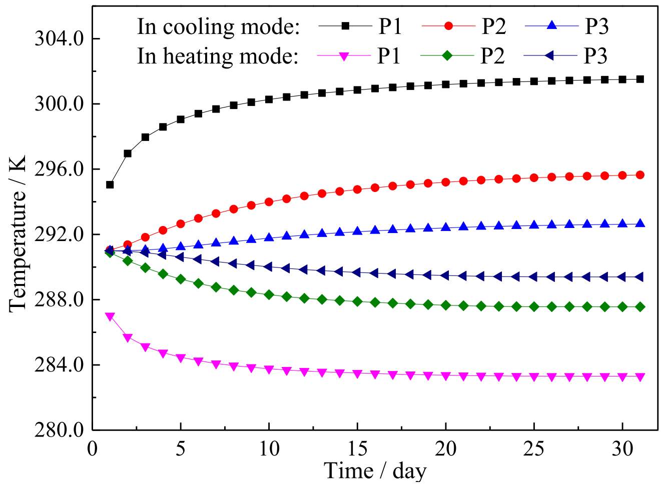

Fig. 10. Soil temperature distributions.

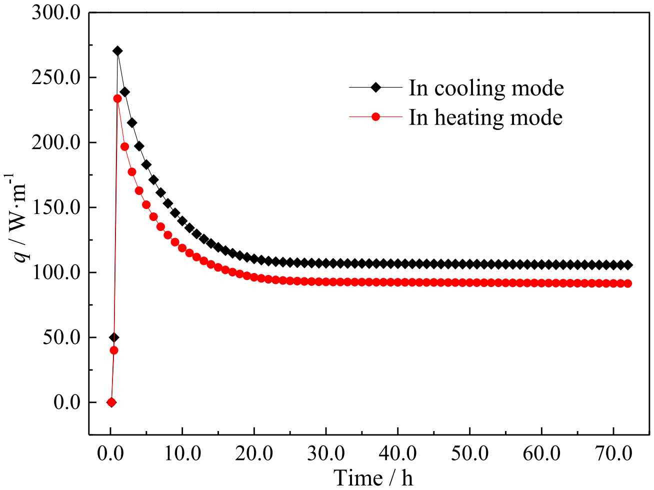

Fig. 11. Heat transfer flux per meter of the pile-foundation heat exchanger.

3.2.2.2. Soil temperatures distribution of specific points and line. In order to observe and analyze simulation results, line L_2 ($Y=0.0$ m, $Z=-15.0$ m), points P_4 ($X=1.0$ m, $Y=0.0$ m, $Z=-15.0$ m), P_5 ($X=2.0$ m, $Y=0.0$ m, $Z=-15.0$ m), P_6 ($X=3.0$ m, $Y=0.0$ m, $Z=-15.0$ m) and P_7 ($X=5.0$ m, $Y=5.0$ m, $Z=-15.0$ m) in the model were created and depicted in Fig. 13.

In non-equilibrium and equilibrium conditions, soil temperatures distribution at selected points with the beginning of cooling period and on line L_2 after different periods were depicted in Fig. 14. As was well known, the thermal effect on soil varied according to building load, time and relative position to pile surfaces.

In non-equilibrium condition of Fig. 14(A), for the soil temperature of P_4, P_5 and P_6 during the cooling period in summer, the soil temperature rose rapidly within the range of thermal action and it rose much faster with the closer to pile wall surface. In the recovery period in autumn, the soil temperature rapidly decreased and gradually tended to be stable. The soil temperature declined faster and the final stable temperature value was higher with closer to the pile foundation wall surface. In the winter heating period, the soil temperature decreased gradually and the soil temperature also decreased faster with closer to the pile wall surface. In the spring recovery period, the soil temperature gradually tended to be stable. Due to the summer cooling load was much higher than winter heat load when pile-foundation GSHP system ran separately, the increase soil temperature of monitoring points in the summer was significantly greater than the decrease value in the winter. In addition, with the increase of distance between points and pile wall, the hysteresis of soil temperature change was more obvious and soil thermal response time gradually increased, which caused the change trend of soil temperature at P_7. In Fig. 14(C), due to the existence of temperature gradient in the radial direction of pile foundation, soil temperature decreased rapidly after cooling period in summer and increased quickly after the winter heating period with the greater distance from pile foundation wall surface. The cooling load in summer was much higher than that in winter, leading to the more obvious heat effect of heat exchanger group on the soil in summer. Soil temperature recovery in autumn and spring had a significant effect on soil temperature recovery, which was conducive to improving the heat transfer performance of pile heat exchangers in the following winter heating period and summer cooling period.

The soil temperature was obviously higher than the initial soil temperature after operating for one cycle in non-equilibrium condition. In addition, the adverse results will be gradually amplified with the long-term operation of the system. The combined operation of cooling tower system and pile-foundation GSHP system was introduced in this paper to reduce the adverse effect caused by the imbalance of cold and heat load. In Fig. 14(B) and Fig. 14(D), vari-

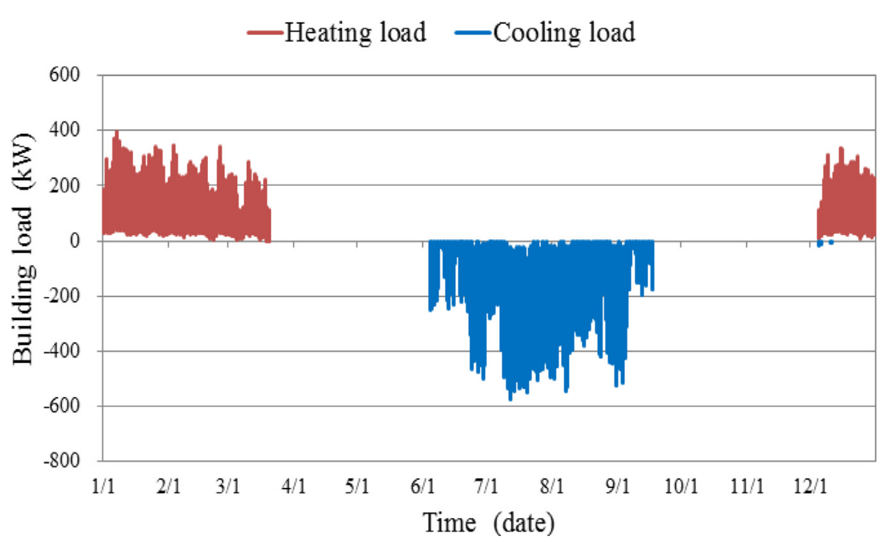

Fig. 12. All-year dynamic building load.

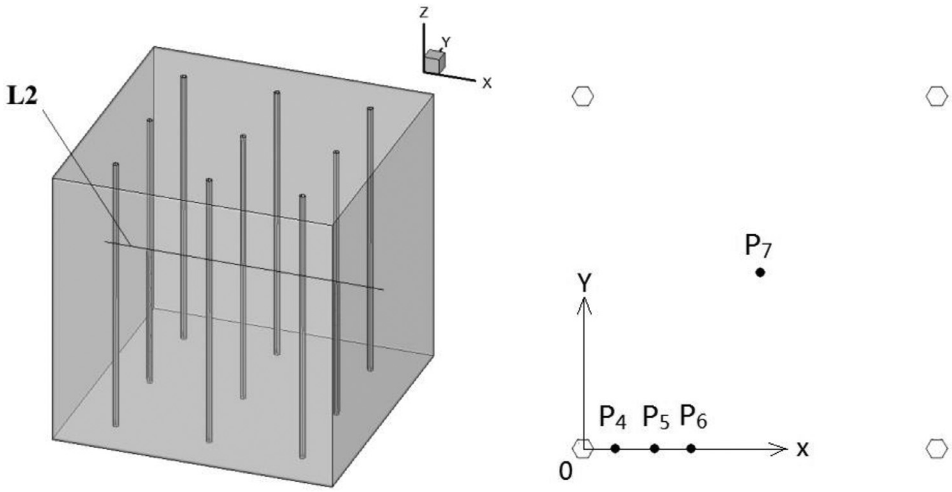

Fig. 13. Positions of L_2, P_4, P_5, P_6 and P_7.

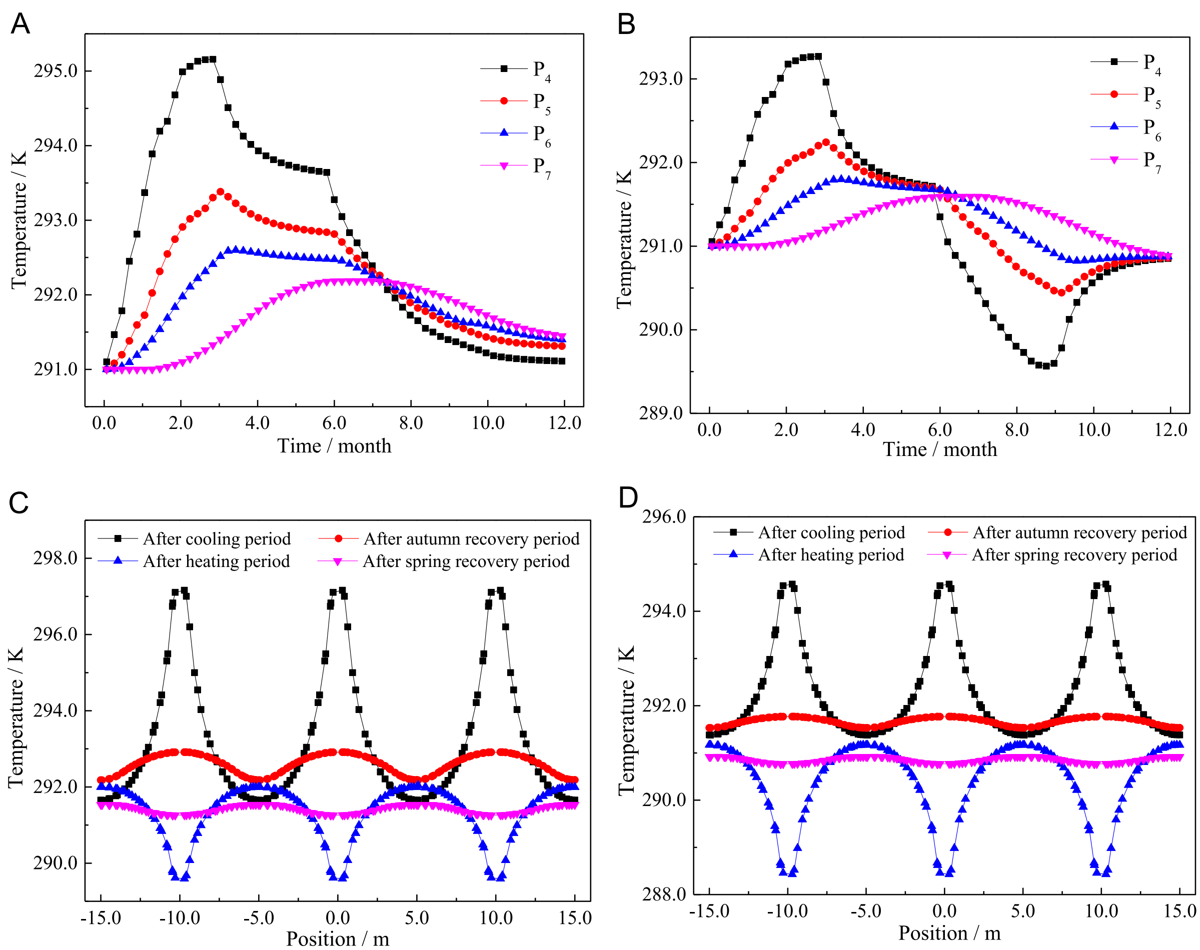

Fig. 14. Soil Temperature distributions (A. non-equilibrium condition of P_4, P_5, P_6 and P_7; B. equilibrium condition of P_4, P_5, P_6 and P_7; C. non-equilibrium condition of L_2; D. equilibrium condition of L_2).

ation of soil temperature with different periods was similar to it in non-equilibrium condition. However, the increase of soil temperature in summer at each monitoring point was basically consistent with the decrease of temperature in winter, because the cold load in summer was roughly equal to the heat load in winter in equilibrium condition. What's more, the final soil temperature after spring recovery period was nearly equal to the initial soil temperature of the cycle, indicating that pile-foundation GSHP system could gain the heat from the soil sustainably.

3.2.2.3. Average soil temperature distribution. The distribution of average soil temperature with system running in non-equilibrium and equilibrium conditions was depicted in Fig. 15. In non-equilibrium condition, heat injection into soil in cooling mode was obviously higher than heat extraction from soil in heating

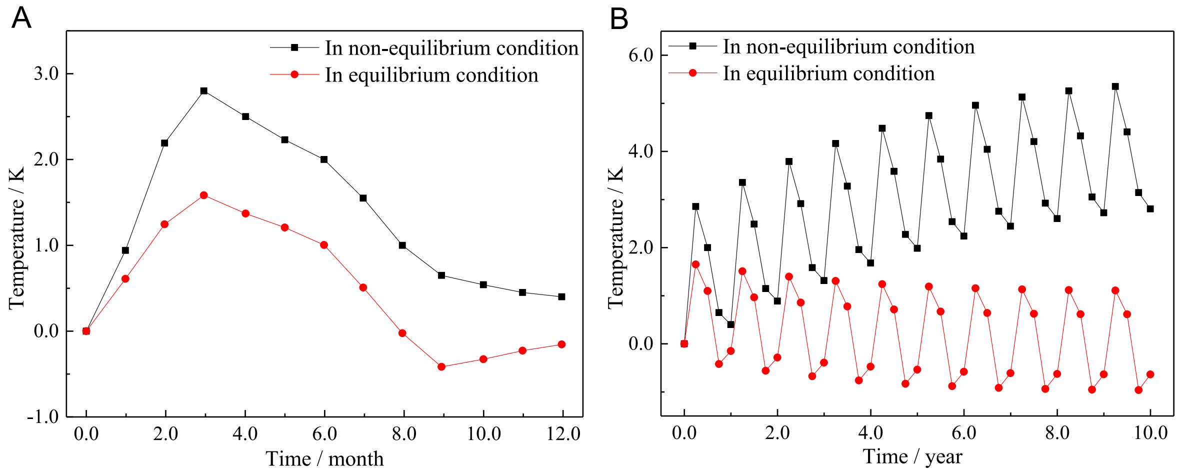

Fig. 15. The distributions of average soil temperature (A. one year; B. ten years).

Table 6
Change of soil temperature after heating and cooling modes within 10 years.

Time / year	1	2	3	4	5	6	7	8	9	0
Non-equilibrium (K)										
After cooling mode	2.86	3.36	3.79	4.16	4.48	4.75	4.96	5.13	5.26	5.35
After heating mode	0.65	1.15	1.59	1.96	2.28	2.54	2.76	2.93	3.05	3.15
Equilibrium (K)										
After cooling mode	1.65	1.51	1.40	1.31	1.24	1.19	1.16	1.13	1.12	1.11
After heating mode	−0.42	−0.56	−0.67	−0.76	−0.83	−0.88	−0.92	−0.94	−0.95	−0.96

Table 7
The average difference of relevant parameters between experiment and simulation.

Scheme	Outlet Temperature		Temperature difference		q	
	Average Value / K	Percentage /%	Average Value / K	Percentage /%	Average Value / W·m^{-1}	Percentage /%
1	0.18	0.55	−0.17	7.73	−2.91	5
2	0.26	0.69	−0.21	8.4	−4.96	7.53
3	0.13	0.41	−0.27	7.71	−1.45	3.14

mode. The value of average soil temperature increased by 0.42 K inevitably after system running for one year and it rose to 2.96 K after ten cycles. Furthermore, it would increase ceaselessly with system running. Contrastively, the average soil temperature was reduced by 0.16 K after running for one year in equilibrium condition and the value decreased to 0.61 K after ten cycles. With system running, the average soil temperature tended to be stable at the end of the following cycles. The change of soil temperature after heating and cooling modes within 10 years was described in Table 6. In non-equilibrium condition, soil temperature continued increasing with time went on both after cooling and heating mode. However, the result was opposite in equilibrium condition. What's more, the decrease degree in equilibrium condition was smaller than increase degree in non-equilibrium condition. Therefore, the equilibrium condition of cooling and heating load was beneficial to the system running safely and efficiently.

3.3. Compare of experiment and simulation result

The 3-U pipe configuration was applied in simulation, while it was single-U pipe for experiment. According to previous research results [27], the heat release per meter of the buried pipe heat exchanger with parallel 3-U pile foundation was about 87% higher than that of the single U type under the same initial parameters. Therefore, the simulated values are converted based on this. The temperature difference and heat flux difference between experimental data and simulation results was described in Fig. 16. As can be seen from the figure, the parameter differences became stable after 20 h and the following discussion was based on stable states of parameter differences. In addition, the temperature differences of outlet water and inlet water with different schemes were in the range of 0.53 K and 0.57 K respectively. The heat flux difference was between −6.78 W·m^{-1} and 2.31 W·m^{-1}. Due to the inevitable small amount of heat loss in experiment, it was finally reflected in the increase of temperature difference of inlet and outlet water. Therefore, the simulated heat flux was slightly lower than experimental value and the average difference was negative. The average values of parameter differences between experimental data and simulation results were described in Table 7. The maximum difference values of outlet temperature, temperature difference and q between experiment and simulation were all happened in scheme 2. The corresponded difference value was 0.26 K and 0.69% for outlet temperature, −0.21 K and 8.4% for temperature difference, and −4.96 W·m^{-1} and 7.53% for q. The simulation results corresponded well with experimental data, indicating the reliability of simulation. The difference between experiment and simulation was caused by the direct and indirect errors of experiment.

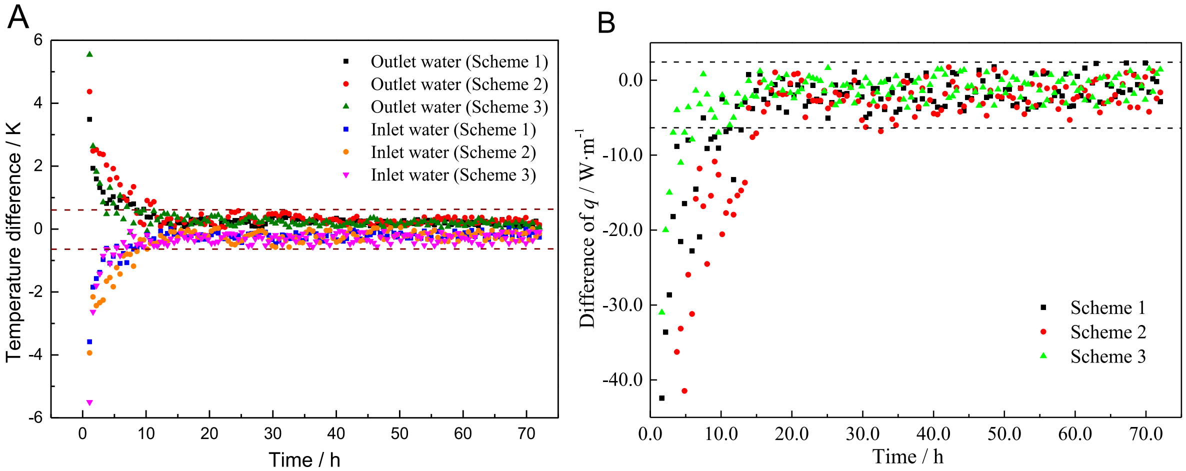

Fig. 16. Difference of parameters between simulation and experiment (A. temperature; B. *q*).

4. Conclusions

In this paper, the treble U-shaped form of geothermal pile-foundation heat exchanger in GSHP system was selected and studied via numerical simulation. Simulation and analysis were carried out by CFD software based on the Finite Volume Method for Nanjing area in China. Heat transfer processes of the pile-foundation heat exchanger and heat exchanger group were studied in different conditions. Experimental study was carried out as a contrast to simulation results. Several conclusions were summarized as follows:

- The higher thermal conductivity of pile-foundation heat exchanger contributed to higher heat transfer efficiency than soil. In cooling mode, the temperature in concrete pile was obviously higher than that in soil. After 10 days consecutively running, the temperature in the pile tended to be stable while the temperature in soil that away from pile surface in thermal area remained slowly increasing, which was opposite in heating mode.
- With time went on, soil temperature at different points within thermal effect area increased gradually in cooling mode. Nevertheless, when the point was closer to pile surfaces, the soil temperature rose earlier and the final stable temperature was higher on account of soil temperature gradients. In addition, the change trend was opposite in heating mode. Heat transfer flux per meter of the pile-foundation heat exchanger gradually decreased in cooling and heating mode with system running and the attenuation rate gradually went down.
- After ten year's running, average soil temperature increased by 2.96 K in non-equilibrium condition and decreased by 0.61 K in equilibrium condition. The equilibrium condition of cooling and heating load was beneficial to system running safely and efficiently.
- The experimental values of temperature differences were 2.2 K, 2.5 K and 3.5 K, and the heat transfer flux were stable at 58.1 $W{\cdot}m^{-1}$, 65.9 $W{\cdot}m^{-1}$ and 46.2 $W{\cdot}m^{-1}$ in three schemes separately. The maximum difference value was 8.4% for temperature difference between experiment and simulation. The simulation results corresponded well with experimental data, indicating the reliability of simulation.

The study results in this paper were approximate to actual results. It provided the research results about thermal response of concrete in pile-foundation during heat transfer process of pile-foundation heat exchanger and the soil thermal response of pile-foundation heat exchanger group under long-term operation condition. In addition, 308 K of inlet temperature of buried pipe and 0.60 m/s of flow rate in the pipe was appropriate to be set under cooling condition in summer. The equilibrium condition of cooling and heating load was beneficial to system running safely and efficiently. Therefore, it can be used as theoretical basis for design and application of pile-foundation heat exchanger in GSHP system.

Declaration of Competing Interest

I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

Acknowledgments

This study is financially supported by National Natural Science Foundation of China (no. 51578146).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijheatmasstransfer.2019.119020.

References

[1] A. Eisentraut, A. Brown, Heating Without Global warming: Market Development and Policy Consideration For Renewable Heat, Organization for Economic Cooperation and Development, 2014.
[2] L. Ting, Q. Tianwei, Analysis on performance and application of ground source heat pump system, Sci. Technol. Inform. (30) (2012) 147–148.
[3] K. Morino, T. Oka, Study on heat exchanged in soil by circulating water in a steel pile, Energy Build. (21) (1994) 65–88.
[4] M. Moel, P.M. Bach, A. Bouazza, R.M. Singh, Technological advances and applications of geothermal energy pile foundations and their feasibility in australia, Renew. Sustain. Energy Rev. (14) (2010) 2683–2696.
[5] Brussels, Ground Source Heat pump: A guide Book, European Geothermal Energy Council, 2008.
[6] P. Hyunku, L. Seung-Rae, Y. Seok, S. Hosung, L. Dae-Soo, Case study of heat transfer behavior of helical ground heat exchanger, Energy Build. (53) (2012) 137–144.
[7] B. Benamar, S. Rachid, B. Hamidou, O. Hakan, Analysis of thermal and dynamic comportment of a geothermal vertical U-tube heat exchanger, Energy Build. (58) (2013) 37–43.
[8] B. Hehrad, P. Soheil, A. Abbasali, 3-D simulation of heat transfer rate in geothermal pile-foundation heat exchangers with spiral pipe configuration, Appl. Therm. Eng. (87) (2015) 655–668.

[9] Florides, G., Christodoulides, P., Pouloupatis, P. (2013), Single and double U-tube ground heat exchangers in multiple-layer substrates, applied energy (102) : pp. 364–376.
[10] L. Xin, Heat Transfer Research and Engineering Application of Energy Piles, Shandong Jianzhu University, 2016.
[11] H. Philipp, K. Olaf, G. Uwe-jens, B. Anke, S. Haibing, A numerical study on the sustainability and efficiency of borehole heat exchanger coupled ground source heat pump systems, Appl. Therm. Eng. (100) (2016) 421–433.
[12] B. Hassan, A. Madjid, H. Mohammad, A numerical model for transient simulation of borehole heat exchangers, Renew. Energy (104) (2017) 224–237.
[13] M. Faozal, A. Bouazza, R. Singh, Heat transfer enhancement of geothermal energy piles, Renew. Sustain. Energy Rev. (57) (2016) 16–18.
[14] T. Silbasakthivel, K. Murugesan, K. Surya, H. Pingfang, P. Kobiga, Experimental study of thermal performance of a ground source heatpump system installed in a Himalayan city of India for composite climatic conditions, Energy Build. (133) (2016) 193–206.
[15] L. Ingersoll, O. Zobel, A. Ingersoll, Heat Conduction with Engineering, Geological, and Other Applications, Wisconsin University, 1954.
[16] S. Kavanaugh, Simulation and experimental verification of vertical ground-coupled heat pump systems, Int. J. Energy Res. 21 (8) (1985) 707–722.
[17] Z. Guoqing, Z. Yang, Z. Dinghai, Analytical solutions for two pile foundation heat exchangers in a double-layered ground, Energy (112) (2016) 655–668.
[18] H. Carslaw, J. Jaeger, Conduction of Heat in Solids, Oxford University Press, 1986.
[19] L. Lamarche, B. Beauchamp, A new contribution to the finite line-source model for geothermal boreholes, Energy Build. (39) (2007) 188–198.
[20] L. Min, L. Alvin, New temperature response functions (G functions) for pile and borehole ground heat exchangers based on composite-medium line-source theory, Energy (38) (2012) 255–263.
[21] G. Gyu-Hyung, L. Seung-Rae, K. Han-Byul, Y. Seok, K. Min-Jun, A novel hybrid design algorithm for spiral coil energy piles that considers groundwater advection, Appl. Therm. Eng. (78) (2015) 196–208.
[22] G. Yanling, Z. Xiaoli, W. Guanjun, D. Jun, Z. Hao, 3D dynamic numerical programming and calculation of vertical buried tube heat exchanger performance of ground-source heat pumps under coupled heat transfer inside and outside of tube, Energy Build. (139) (2017) 186–196.
[23] V. Mei, C. Emerson, New approach for analysis of ground-coil design for applied heat pump systems, Ashrae Trans. 91 (2) (1985).
[24] S. Hackel, G. Nellis, S. Klein, Optimization of cooling-dominated hybrid ground-coupled heat pump systems, Ashrae Trans. (115) (2009) 565–580.
[25] D. Pahud, A. Fromentin, J. Hadorn, The Duct Ground Heat Storage Model (DST) For TRNSYS Used For the Simulation of Heat Exchanger piles. DGC-LASEN, Lausanne, 1996.
[26] G. Yuan, Research On Temperature Field of Ground Source Heat Pump System Under Variant Working conditions, Master thesis, North China Electric Power University, 2010.
[27] L. Kuishan, Z. Xu, G. Jun, L. Jun, Research of heat transfer performance of pile–foundation ground-coupled heat pump and soil temperature rise, Chin. Assoc. Refrig. Conf. (2007) 54–59.
[28] Z. Chunfeng, L. Peng, L. Zhiyong, Numerical investigation of heat transfer performance of energy pile in GSHP, Power Gener. Air Cond. (150, 34) (2013) 40–44.
[29] L. Ting, in: Numerical simulation of heat transfer performance of a pile foundation ground source heat pump, Xi'an Polytechnic University, 2013, pp. 17–18.
[30] M. Zuiliang, L. Yue, Design and application of ground source heat pump system, Machinery, Industry Press, 2014.
[31] H. Jing, in: Numerical simulation and research on unsteady state ground temperature field of multiple well of ground source heat pump, North China Electric Power University, 2011, p. 59. Master thesis.
[32] S.J. Kline, The purposes of uncertainty analysis, J. Fluids Eng. (107) (1985) 153–160.

Please cite this article as: B. Xu, H. Zhang and Z. Chen, Study on heat transfer performance of geothermal pile-foundation heat exchanger with 3-U pipe configuration, International Journal of Heat and Mass Transfer, https://doi.org/10.1016/j.ijheatmasstransfer.2019.119020