OPERATION MODE AND HEAT PERFORMANCE OF ENERGY DRILLED PILES

by

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Energy pile takes a full use of shallow geothermal, the heat exchanger is buried in the foundation extract the ground heat source for heating and cooling of the upper building. Firstly, the geothermal potential of the region is calculated. Then, the heat transfer efficiency of pile foundation under different operation conditions is tested by field test. Finally, the numerical simulation software is used to analyze and compare the field measured results with the numerical simulation results to simulate the heat transfer efficiency of the heat exchange pile under different operation modes. The results shows the heat transfer efficiency of the double U connected tubes is suitbable used in drilled pile, and the heat transfer capacity of the energy piles does not decrease significantly during a year operation mode and even long.

Key words: *shallow geothermal, drilled pile, heat exchange performace, operation mode, field test*

Introduction

Energy pile is an efficient way to use shallow geothermal, the heat exchanger is buried to the pile to extract the ground heat source for heating and cooling of the buildings. Energy piles can take advantage of the good heat storage capacity and heat conduction performance of concrete, and it also can save drilling costs and underground space. However, many scholars have studied the influence of the application of energy piles on building. Laloui *et al.* [1] carried out the in-situ thermal response test on different heat exchange pile with structure loads for 28 days. The test results showed that when the temperature and the structure load acted together, the soil properties around the pile had a great influence on the change of the strain value of the pile, and the considerable additional stress would be generated. Bourne-Webb *et al.* [2] through experiments obtained that the temperature stress of the pile changed greatly with temperature under cooling conditions. Although the heat exchange pile was subjected to the load of the overlying structure, the middle and lower parts of the pile might still be subjected to tensile stress. You *et al.* [3-5] carried out bearing capacity tests of energy piles, and discussed the testing method of thermalphysical properties, heat transfer performance and load bearing capacity of energy piles as well as the effect of ground-water. Gao *et al.* [6] have also conducted studies from laboratory tests to field testing. Laloui *et al.* [7] proposed a corresponding numerical model to simulate the temperature and stress distribution of the pile foundation and surrounding rock

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and soil under the working conditions of the heat pump of the heat exchange pile. Cooke [8] found that the stress superposition method can better reflect the load-settlement relationship and the load transfer law of pile group through the field test of pile group. Danno *et al.* [9] compared and analyzed the pile groups with different pile spacings under the same working condition, and found that the pile group effect weakened with the increase of pile spacing . Ren *et al.* [10] carried out field tests on the thermal response tests of energy piles under five different operating conditions. Fang *et al.* [11] studied the thermal response characteristics of energy piles through a short-term operation mode. Wang [12] built a non-uniform temperature field through indoor model tests, and studied the influence of the non-uniform temperature field on the internal force of the pile and the soil around the pile during the temperature balance process. Dehghan *et al.* [13, 14] established a numerical model of heat transfer of pile group by using COMSOL finite element software, studied the influence of pile spacing on heat transfer performance.

This study aimed to evaluate the heat transfer efficiency of pile foundations under different operating modes through field tests and simulations. The test pile is located in a serviced apartment. First of all, test pile formation and pipes burying were carried out, and then in-situ tests on energy pile and borehole heat exchangers were performed to seek suitable shallow geothermal energy utilization forms and heat exchange pile lay-out forms. Then, numerical simulation software was used to carry out the 3-D non-linear finite element analysis of the heat exchange pile, the field measurement results were compared with the numerical simulation results, and the heat exchange efficiency of the long-term operation mode of the heat exchange pile was simulated. This article aimed to provide the basis of design and calculation for the lay-out and design of heat exchange pile foundations.

Testing procedure

The heat exchange piles are drill-pouring piles, the depth of the pile foundation is 20 m, the pile diameter is 800 mm, and the concrete strength is C30. The heat exchange pipes are HDPE pipes with a diameter of 25 mm. Three piles are selected as heat exchange testing piles. In order to compare and analyze the difference of heat exchange capacity between pile foundation and bore hole exchanger, another 100 m deep borehole buried pipes were laid. Test skeleton can be seen in tab. 1.

Table 1. Test skeleton

Layer	Depth [m]	Pipe connection	Sensors	Tests
Bore Hole 1	100	Parallel double-U	–	TRT
Bore Hole 2	100	Parallel double-U	–	TPT
Energy Pile 1	20	Series double-U	Strain, temperature	TRT
Energy Pile 2	20	Parallel double-U	Strain, temperature	TPT
Energy Pile 3	20	Triple-U in Series	–	TPT

Thermal balance calculation

The shallow geothermal deposit in this area is calculated:

$$Q_r = \sum_{i=1}^{n} C_1 A D_1 \Delta t \tag{1}$$

and

$$C = \rho_r C_r (1-\Phi) + \rho_w C_w \Phi \tag{2}$$

where Q_r is the geothermal potential, A – the area of calculation area, D – the thermal storage thickness, Δt – the temperature difference between thermal storage temperature and annual average temperature, C – the average specific heat capacity of heat storage rock and water, ρ_r – the density of heat storage rock, C_r – the specific heat of heat storage rock, ρ_w – the density of geothermal water, C_w – the specific heat of water, and Φ – the porosity of heat storage rock.

Heat performance of drilled energy piles

Heat transfer efficiency of borehole pipe exchanger

The initial average ground temperature is measured by gauges about 17.1 °C. The thermal response test (TRT) of Bore Hole 1 heat exchanger takes 48 hours, and the difference between the inlet and outlet temperature is 2.5 °C. The flow rate is 0.8 m^3 per hourh, the calculated single-U heating power is 2.3 kW. The total heating power of the borehole buried pipe is 4.6 kW. From the relationship curve of average temperature with time, shown in fig. 1, according to the line heat source model [15], it can be obtained that k = 2.0446, m = 22.225. The comprehensive thermal conductivity of the borehole is 1.792 W/m°C, and the thermal resistance is 0.081 mk/W.

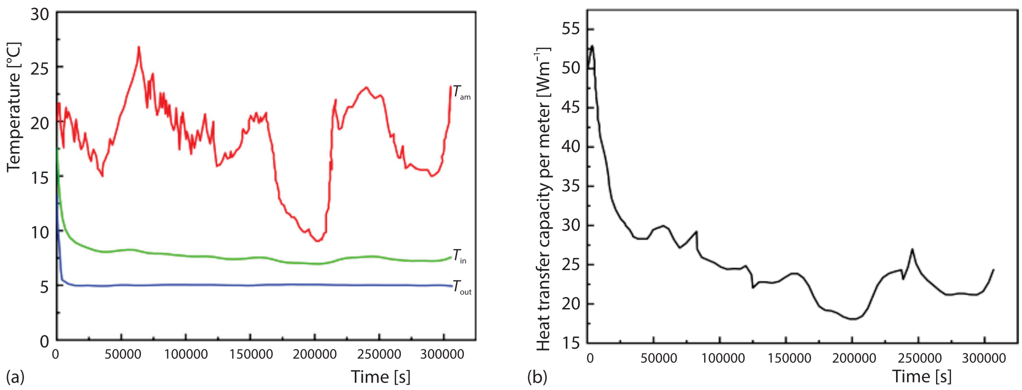

Figure 1. Pipe 1; (a) variation of T_{am}, T_{in}, and T_{out} with time and (b) variation of heat transfer capacity with time

The thermal performance test (TPT) of Borehole 2, given cooling condition. It is cooled for 72 hours, and the inlet water temperature keeps constant at 5 °C. As shown in fig. 2, the heat transfer rates per meter are achieved, and the results can be seen in tab. 2. The average heat exchange rate of double-U parallel borehole heat exchange pipes is 26 W/m. The temperature difference between the inlet and outlet water is stable at 2.4-2.5 °C, and the total heat transfer is 2600 W.

Table 2. Heat transfer rates per meter results

Test time [hour]	q_1 [Wm^{-1}]	q_2 [Wm^{-1}]	q_{total} [Wm^{-1}]
24	26.13	24.27	50.4
48	20.53	21.47	42
72	21.47	20.53	42

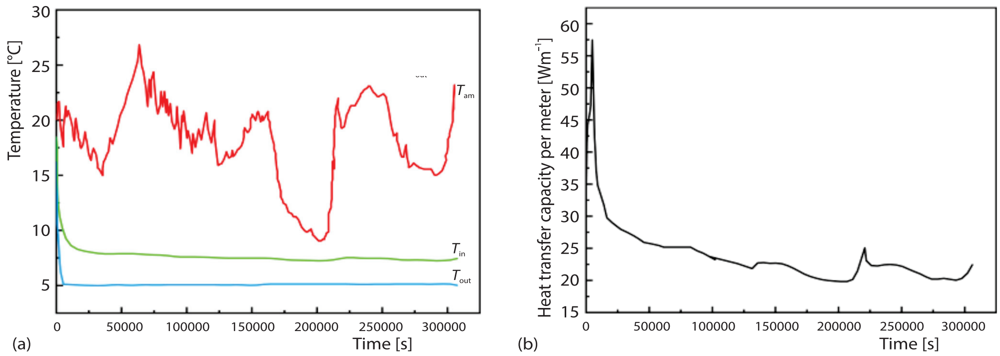

Figure 2. Pipe 2; (a) variation of T_{am}, T_{in}, and T_{out} with time and (b) variation of heat transfer capacity with time

Heat transfer efficiency of drilled energy pile

The TRT of drilled Pile 1 was performed. The inlet and outlet temperature difference keeps at 2.5 ºC, and the heating power is 2.33 kW. The test lasted for seven days. According to the column heat source model [16], the comprehensive thermal conductivity is 3.5 W/m°C, and the thermal resistance is 0.36 m°C/W.

The TPT of Pile 2 with double-U parallel connection was performed. The inlet water temperature keeps constant at 5 ºC, and the cooling test lasted for 28 hours. Figure 3 shows that the heat exchange rate is 88 W/m, and the total heat exchange rate is 1760 W.

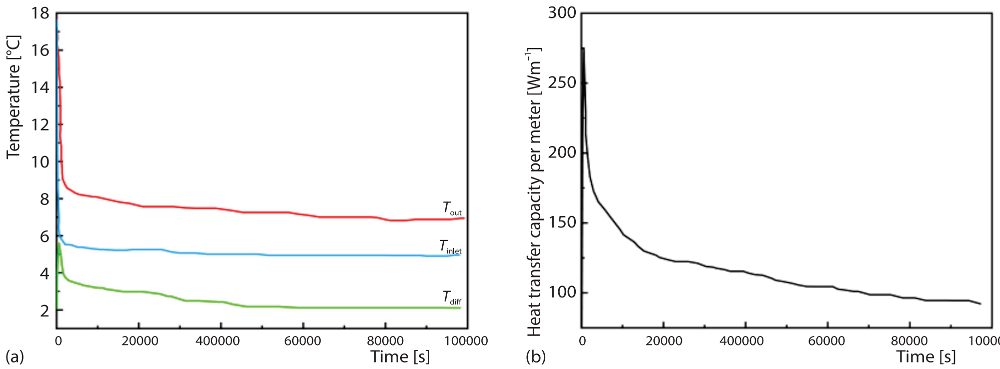

Figure 3. Pile 2; (a) T_{in} and T_{out} of TPT test and (b) variation of heat transfer capacity of TPT test

The TPT of Pile 3 with triple-U series connection was carried out. The inlet water temperature is 5 °C, and the test lasted seven days. Finally, the cooling power per meter is stable at 60 W/m, the total heat transfer rate is 1200 W, and the temperature difference between inlet and return water is stable at 1.3-1.4 °C.

The TPT of Piles 1 and 2 with parallel connection was conducted. The inlet water temperature is 5 °C. The test time lasted for six days. Finally, the cooling rate per meter of Pile 1 is stable at 80 W/m and that of Pile 2 is at 75 W/m. The total heat transfer rate of Pile 1 is 1600 W and that of Pile 2 is 1500 W. By comparing and analyzing the test results, we can see that the long-term heat transfer efficiency of the series heat exchanger is better than that of the double-U parallel heat exchanger. Because the heat transfer path of the fluid in the series pipe is longer and the time for heat transfer is more abundant.

As for the double-U and triple-U series heat exchanger, the heat transfer rate of double-U in Pile 1 is 1600 W, and that of triple-U in Pile 3 is 1200 W. Although there are many heat exchange tubes in triple-U and the distance between heat exchange tubes is small, the temperature radiation range of single tube in heat exchange process affects other heat exchange tubes. Therefore, for the drilled pile with a diameter of 800 mm, the optimal arrangement of heat exchanger is double-U series connection.

Operation mode of heat exchange pile numerical analysis

The RSAS modelling theory

The 3-D model of underground soil and groundwater distribution is established based on the geological survey data. According to Darcy's law and the conservation of energy, the percolation equations read:

$$\mu \frac{\partial H}{\partial t} = \text{div}(k\text{grad}H) + W \tag{3}$$

and

$$V = -k\text{grad}H \tag{4}$$

where H is the groundwater head, k – the permeability coefficient, μ – elastic water release coefficient, and W – pumping volume per unit volume.

Redbud 3-D simulation and analysis system (RSAS) for geothermal is a new generation of 3-D linear elastic and elastoplastic finite element calculation and analysis system. It can accurately simulate the heat exchange efficiency of double-U shaped heat exchange piles in different operating modes, and can also analyze and check the heat exchange efficiency of heat exchanger projects.

Heat transfer efficiency of drilled piles under annual intermittent operation mode

Through the field experiments, it is found that the double-U series connection is the most advantageous lay-out model. In order to verify its long-term operation effect, numerical model is established to verify its heat transfer efficiency and the numerical simulation results were compared with the measured values, shown in fig. 4. Under cooling condition, the inlet water temperature is controlled to 5 °C, and the operation time is 10 hours. It takes 16 hours to recover to room temperature and then the heating process is carried out. The inlet temperature is controlled to 60 °C, and the flow rate is 0.6 m^3 per hour. The field test results show that the

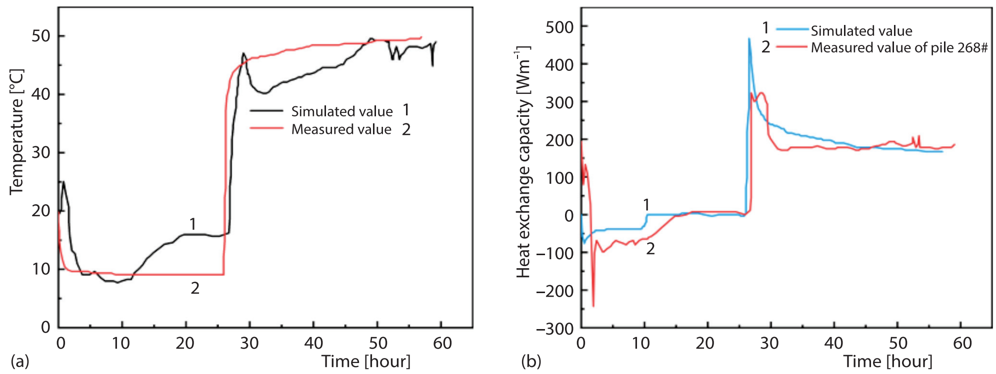

Figure 4. Cooling condition; (a) temperature curve of T_{out} with time and (b) heat transfer per meter

heat absorption rate in the cooling stage is 48.75 W/m, and the heat release rate in the heating stage is 193 W/m. The numerical simulation results are basically consistent with the test results. The heat absorption capacity is 43.7 W/m in the cooling stage and the heat transfer capacity is 203 W/m in the heating stage.

Figure 5 shows that under heating condition the inlet water temperature of energy pile is controlled at 60 °C for 30 hours, the flow rate is 0.8 m^3 per hour, and it takes 16 hours to recover to the room temperature, and then the cooling process is carried out. The inlet water temperature keeps at 5 °C and the flow rate is 0.6 m^3 per hour. The field test results show that the heat absorption rate in the cooling stage is 99.2 W/m, and the heat release rate in the heating stage is 125.6 W/m. The numerical simulation results are basically consistent with the test results.

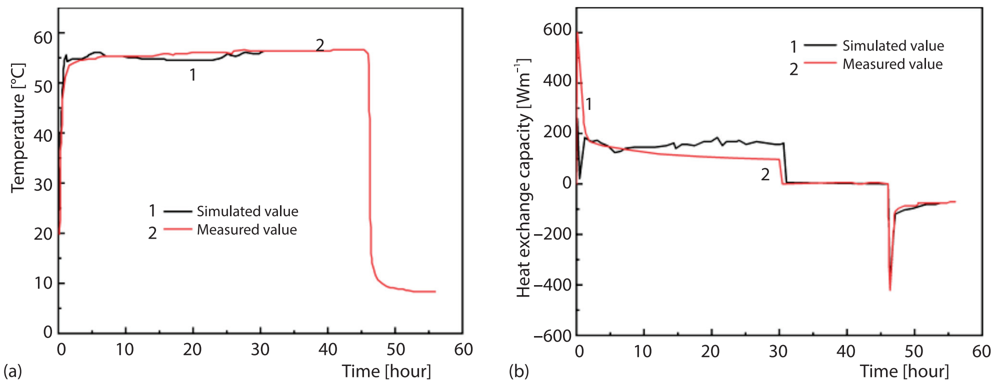

Figure 5. Heating condition; (a) temperature curve of T_{out} with time and (b) heat transfer capacity per meter

Heat transfer efficiency of drilled piles under long-term operation mode

In the annual intermittent operation, the heating stage is from May to September and stops in October, and then cooling stage starts from November to March of the following year and stops in April. Five-year intermittent operation was simulated under long term intermittent operation, and the heat transfer performance of long-term operation mode for energy pile was simulated. Figure 6 shows the distribution of temperature field inside and around the pile during heating and cooling stage.

According to the field test results, shown in fig. 7, within 365 days of the whole operation period, the average heat release of 35 °C water inlet is 10 W/m, and that of 5 °C water inlet is 12.5 W/m. Figure 7 show the operation mode of long term intermittent operation is five years continuous operation. By comparing the operating period of one year and the five-year operating period of heat transfer efficiency data, the simulation results can reflect that the heat transfer capacity of the energy piles does not decrease significantly with long term operation.

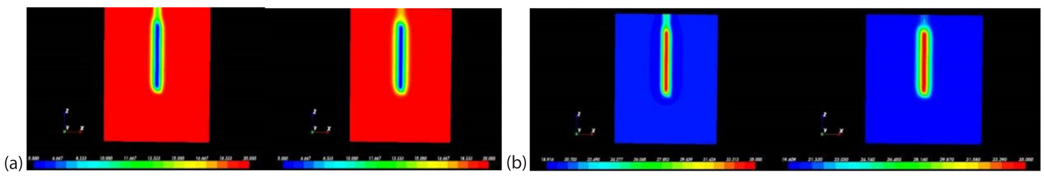

Figure 6. Contour of vertical cross-section; (a) at 5 °C and the end of cooling and (b) at 35 °C and the end of heating

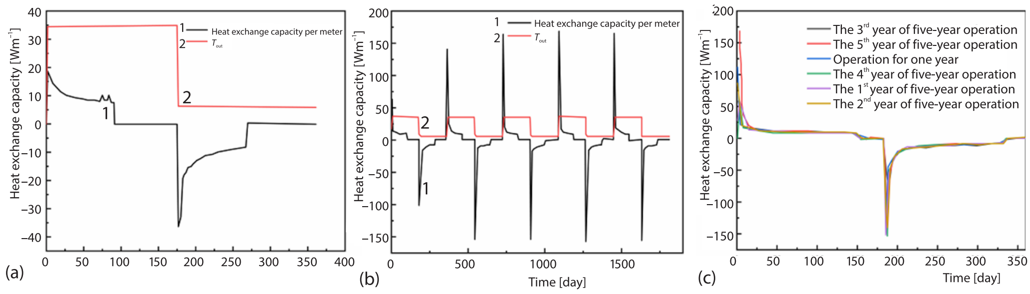

Figure 7. Heat exchange per meter and T_{out} under (a) the annual intermittent operation, (b) the five-years intermittent operation, and (c) comparison of heat transfer capacity between one year and five year operation

Conclusion

The drilled pile is a shallow geothermal energy utilization form. The in-situ test is performed to achieved the heat transfer efficiency of energy piles, and numerical simulation are carried out to investigate the influence of the operation mode on heat exchange capacity. The heat transfer efficiency of the drilled pile is better than that of the borehole heat exchanger. The heat performance of the double-U tubes in series connection is better than that of the parallel connection styles. The field tests show that heat transfer capacity of triple-U exchanger pipe in series is lower than that of the double-U form, the reason is mainly duo to the temperature overlap effect of a pipe on others heat exchangers. so the optimal heat exchanger arrangement of energy piles with 800 mm diameter is double-U in series. Based on the RSAS finite element method analysis of energy pile, the results indicate that the heat transfer capacity of the energy piles does not decrease significantly during a year operation mode and even long.

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Nomenclature

A – the area of calculation, [m^2]
C – average specific heat capacity, [kJkg^{-1}]
C_r – the specific heat, [kJkg^{-1}°C^{-1}]
C_w – specific heat of water, [kJkg^{-1}°C^{-1}]
D – thermal storage thickness, [m]
H – groundwater head, [m]
k – permeability coefficient, [m per day]
q – average heat exchange rate, [Wm^{-1}]
Δt – temperature difference between thermal storage temperature and annual average temperature, [°C]
W – pumping volume per unit volume, [m^3]

Greek symbols

μ – elastic water release coefficient, [–]
ρ_r – density of heat storage rock, [kgm^{-3}]
ρ_w – density of geothermal water, [kgm^{-3}]
Φ – porosity of heat storage rock, [%]

Acronyms

TPT – thermal permance test
TRT – response permance test

References

[1] Laloui, L., *et al*., Experimental and Numerical Investigations of the Behavior of a Heat Exchanger Pile, *International Journal for Numerical and Analytical Methods in Geomechanics*, *30* (2006), 8, pp. 763-781
[2] Bourne-Webb, P. J., *et al*. Energy Pile Test at Lambeth College, London: Geotechnical and Thermodynamic Aspects of Pile Response to Heat Cycles, *Geotechnique*, *59* (2009), 3, pp. 237-248
[3] You, S., *et al*., Experimental Study on Structural Response of CFG Energy Piles, *Applied Thermal Engineering*, *96* (2016), 35, pp. 640-651

[4] You, S., *et al.*, Heat Transfer Performance and Structure Response of Energy Piles, *Thermal Science*, *23* (2019), 3, pp. 235-235
[5] You, S., *et al*., Effects of Groundwater Flow on the Heat Transfer Performance of Energy Piles: Experimental and Numerical Analysis, *Energy and Buildings*, *155* (2017), 6, pp. 249-259
[6] Gao, M. Z., *et al*., Mechanical Behavior of Coal under Different Mining Rates: A Case Study from Laboratory Experiments to Field Testing, *International Journal of Mining Science and Technology*, On-line first, https://doi.org/10.1016/j.ijmst.2021.06.007, 2021
[7] Laloui, L., *et al*., Numerical Modelling of Some Features of Heat Exchanger Pile, Foundation Analysis and Design, *Innovative Methods-Proceedings of Sessions of GeoShanghai*, *12* (2006), May, pp. 189-194
[8] Cooke, R. W., Jacked Piles in London Clay, Interaction and Group Behavior under Working Conditions, *Geotechnique*, *30* (1980), 2, pp. 97-136
[9] Danno, K., *et al*., Pile Group Effect on End Bearing Capacity and Settlement of Pile Foundation, *Japanese Geotechnical Journal*, *3* (2008), 1, pp. 73-83
[10] Ren, L. W., *et al*., Field Tests on Thermal Response Characteristics of Micro-steel-pipe Pile under Multiple Temperature Cycles, *Renewable Energy*, *147* (2020), 2, pp. 1098-1106
[11] Fang, J. C., *et al*., Thermomechanical Behavior of Energy Piles and Interactions within Energy Pile-Raft Foundations, *Journal of Geotechnicao and Geoenvironmental Engineering*, *146* (2020), 9, ID04020079.
[12] Wang, Y. A., Model Test Research on Internal Force Response of Single Pile in Non-uniform Temperature Field, *Journal of Disaster Prevention and Mitigation Engineering*, (2017), 4, pp. 61-66
[13] Denghan, B., *et al*., Parametric Investigation of Helical Ground Heat Exchangers for Heat Pump Applications, Energy and Buildings, *127* (2016), Sept., pp. 999-1007
[14] Denghan, B., Experimental and Computational Investigation of the Spiral Ground Heat Exchangers for Ground Source Heat Pump Applications, *Applied Thermal Engineering*, *121* (2017), 1, pp. 908-921
[15] Carslaw, H. S., *et al*., *Conduction of Heat in Solids,* Claremore Press, Claremore, UK, 1986
[16] Fang, Z. H., Mathematical Model of the Axial Temperature of the Medium in the U-tube Geothermal Heat Exchanger, *Journal of Shandong Institute of Architecture and Engineering*, (2002), 1, pp. 7-11

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