NUMERICAL SIMULATION AND THERMAL ANALYSIS OF ECOLOGICAL ENERGY-SAVING GROUND SOURCE HEAT PUMP DESIGN

by

Linxin YANG *

Business School, Hunan Agricultural University, Hunan Changsha, China

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By constructing the heat transfer model of the buried tube heat exchanger, using the mathematical method and numerical calculation software, the temperature of the buried tube heat exchanger is calculated numerical, so as to better understand the temperature effect of the buried tube heat exchanger on the surrounding soil. This paper establishes a mathematical model of a vertically buried heat transfer system based on the principle of thermal equilibrium and the thermal conductivity differential equation. Conduct research on the temperature field around single pipes in different soil (geological conditions), temperature field under different drilling backfill materials, and the temperature around buried pipe-lines in both short-term and long-term operation of the system. The experimental results show that the simulation results of the system's short time (10 days) and long time (90 days) performance show that the cooling and temperature cycles in different areas directly affect the heat radius of the buried pipe and the heat accumulation near the buried pipe. The thermal action radius of the short-term operation system is about 1.8 m, and the long-term operation reaches 4.5 m.

Key words: *ecological energy-saving, ground source heat pump design, numerical simulation, thermal analysis*

Introduction

At present, energy and environmental issues have become major social issues faced by countries around the world. With the development of the economy and the acceleration of modernization construction, in order to adapt to the rapid growth of urban population and continue to improve people's living standards, before 2020, the total area of newly built urban buildings in China will continue to be around 1 billion m per annual. With the expansion of existing buildings, the proportion of energy consumption has been increasing [1]. According to relevant data, the world average energy consumption is about 37%, while China accounts for 40% of the global energy consumption. The main sources of household energy consumption are heating, air conditioning, and indoor water temperature. According to incomplete data, energy consumption of HVAC in residential buildings in China has exceeded 55% of monthly energy consumption. Therefore, how to achieve the goals of energy conservation and environmental protection for air conditioning has become a hot issue concerned by people at present. Conventional air conditioner design is often only to improve the efficiency of equipment for the purpose of doing so can only reduce the energy consumption of HVAC system to a certain extent. Therefore, to find out the main factors affecting energy consumption, can only be analyzed

* Author's e-mail: LinxinYang8@163.com

from the whole [2]. In the existing air conditioning system, the efficiency of air conditioning, the energy consumption of pipe-line transportation, cold and hot two ways have a great impact. The first two methods have made more research progress, but their cooling and heat source is still mainly air cooling or cooling tower water cooling, which is more sensitive to the external environment, and compared with the ground source heat pump, its energy consumption is larger, so it can better solve the problem of high energy consumption. In 2005, ground source heat pump technology was listed as one of the ten new technologies in the construction industry by the Ministry of Construction [3]. Soil source heat pump technology is a kind of technology that uses soil as heat source and air as power to regulate the air of buildings. The condenser and evaporator in the conventional air conditioning system are directly buried underground to carry out heat exchange with the surface, or the intermediate medium is used as the heat carrier to circulate through the surface to carry out heat exchange with the surface. From the perspective of thermodynamics, the application of soil as cold and heat source in air conditioning system has broad application prospects. In recent years, with the continuous rise of surface temperature, the efficiency and energy consumption of surface pumps are higher than that of conventional HVAC. The research status of ground source heat pump system is introduced, and its core technology is discussed. The change of temperature field near the buried pipe-line will greatly affect the long-term operation of the heat exchange equipment. Therefore, combined with the local weather and climate, the heat transfer characteristics and environmental characteristics of underground pipe-lines and underground heat pumps are studied, which is of great significance for improving the heat transfer performance of underground heat pumps, reasonable operation, and promoting the popularization and use of underground heat pumps [4].

Numerical simulation of soil temperature field around vertical buried heat exchanger

Considering that experimental research on the temperature field around buried pipes requires arranging temperature measuring wells at a certain distance around the pipes, which can only be used for ground temperature testing and cannot be used as working holes to arrange buried pipe heat exchangers, this greatly increases the cost of drilling and is also restricted in practical engineering. By constructing the heat transfer model of the buried tube heat exchanger and using mathematical method and numerical calculation software, the temperature of the soil around the buried tube heat exchanger is numerically calculated, so as to better understand the temperature effect of the buried tube heat exchanger on the surrounding soil. Based on the principle of heat balance and heat conduction equation, a thermal calculation method suitable for underground heat exchange system is presented. Study the temperature field around a single pipe in different soil (geological conditions), temperature field under different drilling backfill materials, and temperature field around buried pipes under short-term and long-term operating conditions of the system [5].

Implementing heat transfer analysis using MATLAB ABPDE tool

The MATLAB (MA TrixLABoratory) is a matrix laboratory, which is an engineering calculation software for numerical calculation, graphic interaction system and control system simulation launched by MathWork Company of the USA. It is widely used in automatic control, heat conduction, fluid mechanics, engineering statistics and other fields. The MATLAB PDE-Tool is a finite element solutionol software for partial differential equations in MATLAB. It has a visually friendly interface and powerful data processing functions, making the modelling, solving, and post-processing of finite element problems easy and intuitive [6].

The finite element method uses partial interpolation discretize the differential equations solved continuously in the region into Linear algebra equations. Before using PDETool of MATLAB for finite element calculation, some preprocessing work is required, such as discretization of the geometric shape or shape of the solved model, that is, using relatively simple shapes and shapes to approximate and replace actual shapes and shapes, this can transform complex curve and surface problems into relatively simple straight line or plane problems. When solving the soil temperature field in practice, PDETooI can be directly opened and the established mathematical model equation can be solved using a graphical user interface.

Firstly, select a soil temperature field heat transfer model around a vertically buried pipe, and establish a physical model to describe the corresponding heat transfer problem. By using the draw mode, geometric settings are made for the soil temperature field area that requires a solution. For the convenience of establishing physical models, AxesLimnits and AxesEqual can be selected from the options menu to determine the co-ordinate range and proportion, and grid and gridspacing can be selected to draw the grid and specify the grid spacing. Here, the grid settings are based on the experimental platform site conditions and simulated operating conditions. Set boundary conditions and select boundaries. Open the specify boundary condition under the boundary menu option, enter boundary conditions. For steady-state boundaries with constant temperature, choose the dirichlet condition, and for boundaries with heat exchange with the outside world, choose the Neumann condition. Set the equation type to parabolic for the heat transfer problem around the buried pipe and input the heat conduction problem. Determine parameters such as soil heat capacity, density, and heat source density. Meshing first, the initial mesh is generated for the solution area of the temperature field, so that the number of nodes and triangular elements can be determined, the node number can be displayed, and the nodes, boundary matrix and triangular matrix can be output, respectively. If you want to obtain a more accurate solution, you can encrypt the grid. To solve a PDE, first set the initial values and errors for the equation that needs to be solved. Set the time vector for solving the heat transfer model, and the relevant time interval depends on the dynamic state of the problem. Then set the initial value of the heat transfer model, which is related to the original soil temperature at the experimental site and the wall temperature of the buried pipe under operating conditions. The output of numerical solutions includes the nodes and unit numbers of the mesh division, as well as the numerical solutions on the nodes, which can be easily output in numerical form for the next step of data analysis. The default variable in MATLAB is u, so simply type u in the password window to display the numerical solution by node number. The visualization of numerical solutions in PDE includes the visualization function of numerical solutions, which allows for the selection of colored, 3-D, and dynamic numerical solution visualization results according to research needs. For the temperature field, dynamic temperature changes can intuitively reflect the heat transfer process around underground pipes.

Heat transfer model and numerical solution of temperature field around vertical U-shaped buried pipes

Furthermore, a soil heat exchange model based on the heat conduction theory. Because the temperature of the soil layer near the vertical *U*-shaped buried pipes is a very complicated problem, and it depends on the type of soil layer, thermal parameters, water content, pump temperature time, cooling and heating, *etc.*, in order to make it easy to solve, a model has been established to predict that the mode of heat transfer between soil and buried pipe is of pure thermal conductivity. Due to the fact that the underground soil in A region is mainly composed of rocks (sandstone) with low water content, the thermal migration caused by water migration in the soil is ignored. Buried pipes have good contact with soil, ignoring contact thermal resistance. The soil is layered along the deep direction, and the thermal conductivity of each layer is constant: replacing the two *U*-shaped pipes with the equal water pipes, and the equivalent radii *A* and *r* are electrons of one *U*-shaped pipe. It can be considered that the heat transfer between the wall of pipe is equal and the soil is identical everywhere .

Since air temperature has a great influence on both vertical and horizontal aspects, these two influencing factors are mainly considered in the solution process. All kinds of physical models are modeled by MATLAB software, and the finite element method built in PDETool is used for numerical simulation. The calculation is shown in fig. 1.

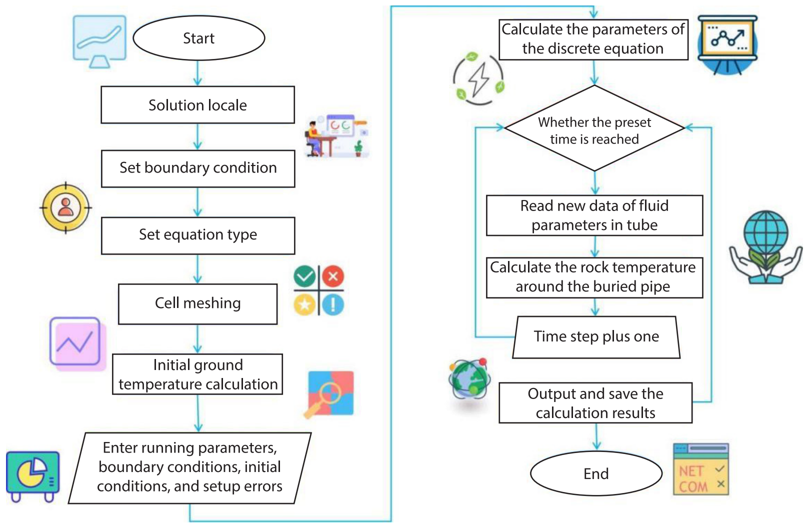

Figure 1. Numerical simulation program block diagram of temperature field around a u-shaped buried pipe

Results and analysis

This section analyzes the numerical simulation results of the temperature field distribution of the soil around the underground heat exchanger. The numerical simulation under different geological conditions uses soil physical parameters and climatic Conditions from A and B regions, while other simulations use parameters from A region. The thermal action radius is defined as less than 0.1 °C per m. The operating parameters used in the simulation solution are: simulate under the condition of heat flux density of 650 W/m^2.

Impact of geological conditions in different regions on soil temperature field

The thermophysical properties of soil have a significant impact on the performance of soil source heat pump systems. The thermal conductivity, specific heat, density, moisture content, and other parameters of soil may vary in different geological conditions in different regions, therefore, the author discussed the heat transfer in the soil around underground heat exchangers under different geological conditions in A and B regions.

The diameter of underground buried pipes is taken as 25 mm. Table 1 lists the soil thermophysical parameters in two different regions, due to the fact that the underground soil in both simulated regions belongs to rocks with low water content, the migration of underground-water is not considered. This simulation condition is calculated starting from the ground temperature conditions in July. The initial soil temperature in Chongqing is set at 22 °C at a depth of 3 m and 19.852 °C at a depth of 20 m. Take 21 °C at a depth of 14013 m and 16 °C at a depth of 20 m in Qingdao.

Table 1. Soil physical parameters table

Numerical simulation area	Chongqing	Qingdao	
Depth [m]	0-50	0-2	2-53
Soil category	Sandstone	Backfill	Granite
Thermal conductivity [Wm^{-1}°C^{-1}]	2.035	0.936	3.49
Specific heat [kJkg^{-1}°C^{-1}]	0.92	1. 17	0.92
Density [kgm^{-3}]	2400	1600	2400

Figures 2 and 3, respectively show the curves of soil temperature changes with operating time (continuous operation) at different radial distances around buried pipe heat exchangers at a depth of 20 m underground in Chongqing and Qingdao areas, calculated from the time the operating system is started, the data is processed every 10 hours, and from the graph, we can see that the overall trend of temperature field changes is consistent under two different geological conditions, that is, the closer the buried pipe is, the more significant the soil temperature change is, and the further away the buried pipe is, the smaller the temperature change is. After 300 hours of system operation, the soil temperature only increased by about 0.1 °C at a distance of 3 m radially from the buried pipe. But each region has its own unique temperature variation characteristics, due to the different thermal conductivity of the soil, therefore, it is obvious that the radial length is the same as the length buried in the pipe. Taking Chongqing as an example, the surface temperature difference is 0.1 m, and the surface temperature difference is 7.95 °C, while Qingdao is only 5.19 °C. The results show that the temperature rise around the buried pipe decreases with the increase of soil heat conductivity.

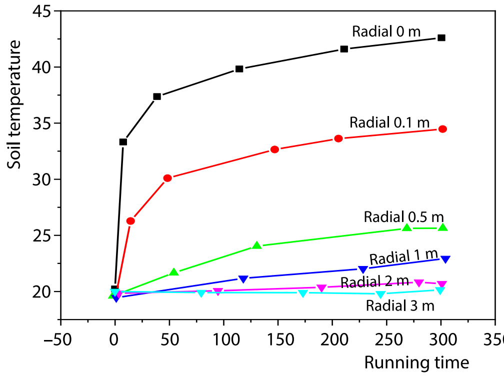

Figure 2. Distribution of soil temperature at 20 m depth from buried pipe in Chongqing with different radial lengths

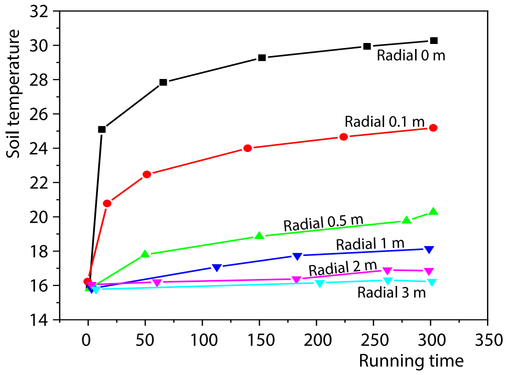

Figure 3. Distribution of soil temperature at 20 m depth from buried pipe in Qingdao with different radial lengths

Impact of backfill materials on soil temperature field during drilling

The basic parameters describing the physical properties of backfill materials include thermal conductivity, density, specific heat capacity, water content, saturation, *etc.* In addition the geological conditions where groundwater has a significant impact on the performance of the heat exchanger, among them, thermal conductivity is the most crucial factor and also the main factor determining the effectiveness of the system. Therefore, this article analyzes the effects of two different backfill materials, fine river sand (thermal conductivity 2.6 W/m°C) and cement mortar (thermal conductivity 0.93 W/m°C), on the heat transfer performance of buried pipes. The soil temperature field around a buried pipe 20 m underground after 300 hours of system operation with two different backfill materials. From the graph, it can be seen that, the thermal radius of both backfill materials is above 3 m, and the thermal radius of fine river sand backfill material is about 0.2 m larger than that of cement mortar backfill. This indicates that backfill materials with good thermal conductivity are beneficial for buried heat exchangers to dissipate heat into the soil. The temperature value of the soil on the buried pipe wall is significantly higher when using cement mortar backfill material than when using fine river sand backfill material. The highest soil temperature of the former is about 50.9 °C, while the highest temperature of the latter is only 42.3 °C. The results show that the thermal conductivity of the two backfills is different due to their different thermal conductivity. Using salt water as backfill medium can effectively reduce the temperature of the soil layer around the buried pipe, increase the temperature difference between the soil layer and the soil layer, and improve the heat transfer effect between the buried pipe and the soil layer. The results show that although the volume of the backfill is smaller than that of the soil, the backfill near the pipe has a great influence on the heat transfer between the pipe and the soil. Figures 4 and 5, respectively, show the curves of soil temperature changes with operating time (continuous operation) at different radial distances around a buried pipe heat exchanger at a depth of 20 m under two different backfill materials. The data is processed every 10 hours. As shown in the figure, in different backfill materials, the soil temperature in the backfill area (within the distance of 0.055 m of buried pipe) changes considerably. When backfilling with fine sand water, the temperature difference between pipe buried wall and hole wall is 4.77 °C [7]. When backfilling with cement mortar, the highest temperature near the buried pipe wall reached 52.02 °C, with a temperature difference of 13.34 °C compared to the drilled wall. The results show that the high thermal conductivity filling can effectively reduce the temperature increase of the soil around the buried tube, which is beneficial to the long time insulation of the buried tube in the soil. However, using cement mortar with low thermal conductivity as backfill, will produce thermal crack near the buried

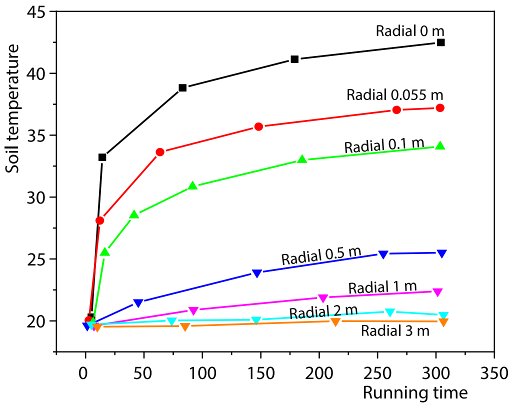

Figure 4. Distribution of soil temperature at different radial lengths from buried pipe with fine river sand backfilling material

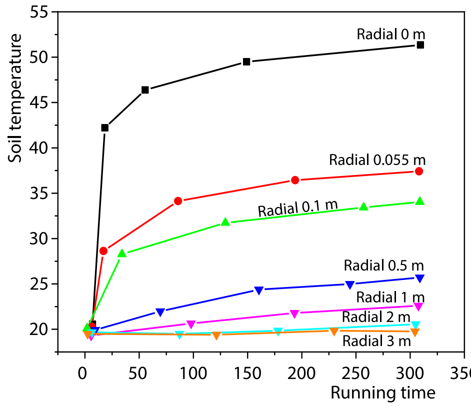

Figure 5. Distribution of soil temperature at different radial length from buried pipe when backfilling with cement mortar

pipe. Long operation will lead to the height of the soil layer around the buried heat pipe, which will affect the heat transfer capacity of the buried heat pipe to the soil, and thus affect the overall performance of the overall heat pump.

Temperature field distribution of heat pump systems during short-term and long-term operation

At some low temperatures, the longer the duration of the ground in the heat source is, the worse the environment is. The heat generated by long-term operation will produce close to the pipe-line, which will affect the thermal level of the soil and thus affect the performance of the heat pump [8]. Therefore, this part has conducted experiments on short-term (10 days) and long-term (90 days) performance of heat pumps in refrigerants, in order to further explore the effects of changes in soil temperature on different operating time of heat transfer performance of buried pipes.

Figures 6 and 7 shows how the temperature of the soil layer buried in the 0.5 m diameter pipe changes over time in the short and long time of the system. As shown in the figure, after a long period of operation, the soil temperature at 0.5 m showed a significant change, with a range of nearly 8 °C [9, 10]. For temperature fields at different depths, due to differences in the original soil temperature, the deeper the buried pipe, regardless of the length of operation, the lower the temperature at a radial distance of 0.5 m at the deeper the buried pipe, this is conducive to the heat exchange between the buried pipe and the soil, so the drilling depth should be appropriately increased within the allowable range of economic conditions.

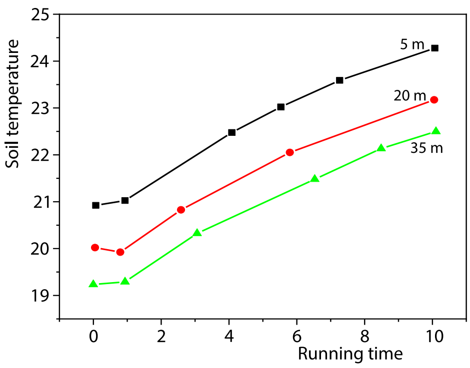

Figure 6. Soil temperature changes at a radial radius of 0.5 m during short-term operation

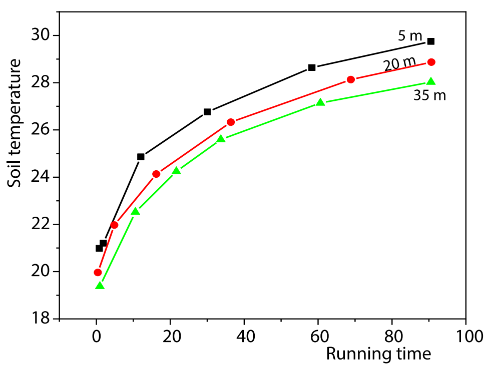

Figure 7. Soil temperature changes at a radial radius of 0.5 m during long-term operation

Conclusion

On this basis, the PDETool is used to simulate the soil around the buried pipe, and the temperature distribution of the soil around the buried pipe under different working conditions is calculated. On this basis, a heat transfer model of buried pipe based on soil heat conduction theory is proposed. The heat conduction characteristics of soil are analyzed, and the heat conduction characteristics of soil are analyzed. Therefore, it is necessary to pay attention the measurement of soil thermal conductivity, and to select backfill materials before the design parameters are determined. Through the simulation of short-term (10 days) and long-term (90 days) operation characteristics of the system, it is found that in different areas, the heat radius of the buried pipe-line and the heat flow around the pipe-line will be affected differently.

In a short period of time, the working radius of the system is about 1.8 m, and in a long period of time, the working radius is about 4.5 m. On this basis, a more perfect mathematical model of interfacial heat transfer between buried pipe and soil is established, and on this basis, the influence of soil water exchange on heat transfer characteristics is considered comprehensively to further improve the calculation accuracy. The author assumes that the soil thermophysical parameters at different depths are consistent during the simulation process, but in reality, the soil thermophysical properties at different depths may be different. Therefore, it is necessary to consider soil stratification research.

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