NUMERICAL SIMULATION OF TEMPERATURE FIELD AROUND BURIED PIPES OF GROUND SOURCE HEAT PUMPS BASED ON MATHEMATICAL MODELS

by

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The author established a physical and mathematical model for the heat exchange of a ground source heat pump buried heat exchanger under the co-operation of heat and seepage, including the soil and fluid inside the pipe surrounding the heat exchanger. Using ANSYS finite element APDL language for programming, based on the line heat source model, simulate the temperature field around the vertical double U-tube underground heat exchanger, the effects of soil thermophysical properties, temperature outside the pipe, soil type and backfill material on soil temperature field were obtained through simulation analysis. The experimental results indicate that, the changes in soil temperature are also significant with different backfill materials. Therefore, it is necessary to conduct serious research and optimization on backfill materials, develop new types of backfill materials, improve backfill construction techniques, and conduct in-depth research by combining theoretical analysis with practical engineering to ultimately find efficient and economical backfill materials. The change in equivalent pipe diameter has little effect on soil temperature, and the linear heat source model is used for calculation without causing significant errors. It has been proven that the soil itself has strong resilience and has reference value for the design of buried heat exchangers in practical engineering.

Key words: *ground source heat pump, underground buried heat exchanger, heat transfer model, ANSYS*

Introduction

Energy and environmental issues are two major social issues facing contemporary humanity. Energy is the driving force for promoting economic development and the material foundation for human social development. However, with the rapid growth of the world economy and population, energy consumption has sharply increased. It is estimated that by 2020, the global energy demand will be 15 billionns, and the global consumption of coal, oil, and natural gas will reach 38, 53, and 3.5 billionns, respectively. The cumulative effect of overexploitation and consumption of energy has produced environmental pollution problems that restrict economic development and affect human survival. Climate change caused by GHG emissions has posed a serious challenge to global ecology and human social development [1]. At the UN Conference on Environment and Development in, sustainable development was included in Agenda 21, and it has become a common direction for the development of countries in the 21st century and a consensus for the development of human society. The key to sustainable development

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lies in sustainability, with the core being environmental and resource protection, as well as the development and utilization of energy.

From the perspective of energy development strategy, humans must seek a sustainable energy path and find a development model that organically integrates energy and the environment [2]. The key is to establish a sustainable energy system and efficient and clean utilization technologies, try to solve the problem of energy utilization and environmental co-ordination and compatibility, and actively strive to change our energy utilization methods, for example:

– Improving existing energy utilization technologies, making rational use of energy, including improving energy utilization efficiency, reducing pollution emissions, distinguishing energy by quality, and utilizing it in a cascade manner.
– Develop and utilize new energy, such as solar energy, wind energy, marine energy, geothermal energy, nuclear energy, *etc*. [3].

The shallow surface is like a huge solar collector, collecting more than twice the energy that humans use every year. This almost infinite and geographically unrestricted low energy source is a clean and renewable energy that humans can utilize, and surface energy is not affected by climate like solar energy, nor is it limited by resources and geological structures like deep geothermal energy.

During winter heating, the heat from the surface is *extracted* to supply indoor heating, while storing cold energy underground for summer use. During summer cooling, the indoor heat is extracted and released to the surface to store heat underground for winter use. The ground source heat pump system only takes heat and does not take water. There are no problems of groundwater level decline and land subsidence, no problems of corrosion and digging of reinjection wells, no thermal pollution of air heat and cooling exhaust, and no pollution of smoke, dust and water drainage. It is a real green energy. Therefore, conducting research on ground source heat pumps has high theoretical significance, practical value, and social and environmental benefits.

China has a large population and relatively scarce energy resources. China's energy consumption per 10000 US$ of gross domestic product is very high, four to six times that of the country. Among the seven major energy consuming countries in the world, namely the USA, China, Russia, Japan, Germany, Canada, and India, only China's coal accounts for more than 72.8% of the energy consumption [4]. The pollution of acid rain, greenhouse effect, and ozone layer damage have become the main environmental factors which restrict the harmonious and steady economic development in China. Among the sources of consumption, the amount of energy consumed by the construction industry is considerable. According to statistics, China accounts for 19-20% of energy consumption, while the average is 19.8%. The energy consumption of HVAC is about 85% of the total energy consumption, and it is 6-7 times higher than that of ordinary houses. At present, heating, air conditioning, and hot water supply, which account for a high proportion of building energy consumption, mainly rely on the consumption of conventional energy to meet demand. This not only poses serious environmental problems, but also causes significant irreversible losses. Since entering the 21st century, China's construction industry has been continuously developing, and the requirements for building energy efficiency have become increasingly high. Reducing the air pollution caused by winter heating in China, reducing the energy consumption of heating and air conditioning systems, and saving energy have been the goals pursued by building energy-saving and HVAC workers. Especially in recent years, large and medium-sized cities urgently need to reduce coal consumption and vigorously promote the use of clean energy, including renewable energy, in order to improve the atmospheric environment. Ground source heat pumps are not only energy-saving technologies, but also the utilization of clean energy and new energy.

Therefore, the application and development of ground source heat pumps are in line with the development of *green buildings*, and the combination of the two is in line with the background of *energy, environment, and sustainable development* with green as the theme. In recent years, China's ground source heat pump has maintained a good development momentum, and more and more users are familiar with it and have developed a sense of interest in it. As a ground source heat pump that only takes heat without water, there are no concerns in this regard. Although there may be more initial investment, the operating cost is lower, and it is a promising new refrigeration and air conditioning technology. Ground source heat pump technology has a development history of decades in Europe and North America, and the technology is quite mature. A complete set of standards and specifications have been formulated for the design and installation of ground source heat pump units and geothermal heat exchangers. This technology has become a widely adopted heating and air conditioning method, growing at a rate of 10% per year. It can be expected that this technology will become the most effective technology for building environmental heating and air conditioning in the 21st century, allowing for joint work in different regions, environmental protection, and resource reuse. However, the research of soil heat sources in China varies from place to place in winter. The Soil type, rock soil moisture content, original ground temperature, and oral data in different places are unique, and there is a lack of accumulated basic data. To promote this *green air conditioning technology*, a lot of research is needed. This project will focus on soil basic data and improve theoretical calculation models, providing reliable reference for design. This project will focus on the key components of ground source heat pumps - underground heat exchangers and their surrounding soil.

Literature review

In recent years, due to the growing problems of energy and pollution, the global voice of energy conservation and environmental protection has been increasing. In the air conditioning industry, ground source heat pumps are gaining popularity due to their energy-saving utility features. The ground pump will use the earth as a source of low temperature cooling (heating) and store the earth's energy reserves in full. It not only consumes less electricity but also reduces heat pollution. It is an energy efficient and environmentally friendly green air conditioner [5]. A ground source heat pump (GSHP) uses the ground as a heat source and sink, and can use buried heat to create cold air and hot water by exchanging heat and cold. The temperature of the surface of the ground is constant, and it has less sweat and higher temperature in summer and winter. In winter, GSHP raise low global temperatures to heat buildings and store cooling energy for summer use. In summer, heat pumps are used to transfer heat from the ground to cool the house, and in winter, they are used to store heat. Hot summers and cold winters are areas with roughly similar cold and hot air. With the same system, the role of underground energy supply can be fully realized. In addition, cooling and heating devices can be used to help treat areas with different cooling and heating conditions [6]. The northern part can use solar energy, while the southern part can use cooling towers to compensate for the heat balance problem that occurs when the load is not equal in winter and summer. Li *et al*. [7] used TRNSYS to analyze the heating efficiency of GSHP and SGSHP in process and parallel systems of heated buildings and compared them for 20 years by varying the borehole length and solar collector area. Sang *et al*. [8] discuss the process of differences between actual ground source heating performance and design expectations in cold regions. Bayomy *et al*. [9] proposed mixture model including modified model and vertical mixing system analysis.

The author established a physical and mathematical model of an underground heat exchanger for a vertical buried pipe GSHP system, and used ANSYS program to conduct parametric, ANSYS parameter design language (APDL), to numerically simulate the soil temperature field. Through simulation analysis, the effects of soil thermal properties, temperature outside the pipe, soil type and backfill on the soil temperature field were obtained.

Mathematical models

Physical model

The *U*-shaped vertical heat exchange buried pipe is a common way of GSHP, which can be divided into single *U*-tube and double *U*-tube. For the single *U* buried pipe method, there are usually two plastic pipes arranged in the pipe well, one in and one out, forming a closed loop, as shown in figs. 1(a) and 1(b). Double *U* buried pipes are two in and two out, as shown in fig. 1(c). The heat transfer process between *U*-shaped pipes and soil includes the following parts: convective heat transfer of water inside *U*-shaped pipes, convective heat transfer between water and pipe wall, when the heat pump system starts to operate, the temperature of pipe wall, backfill and soil changes in turn, and shows different temperature distribution characteristics in different operating seasons and years [10]. Therefore, the heat transfer process between buried *U*-shaped pipes and soil is a non-stationary heat transfer process. For the convenience of research, the following simplified assumptions can be made:

- Throughout the entire heat transfer process, the physical composition and thermophysical parameters of the soil remain unchanged, and the calculated physical parameters of the soil are averaged.
- Because the groundwater is small, the effect of water transfer on heat transfer is not considered, and the heat transfer process between the buried pipe and the soil is a pure convective heat transfer process.
- It is believed that the initial temperature of the soil is uniform and only changes with depth.

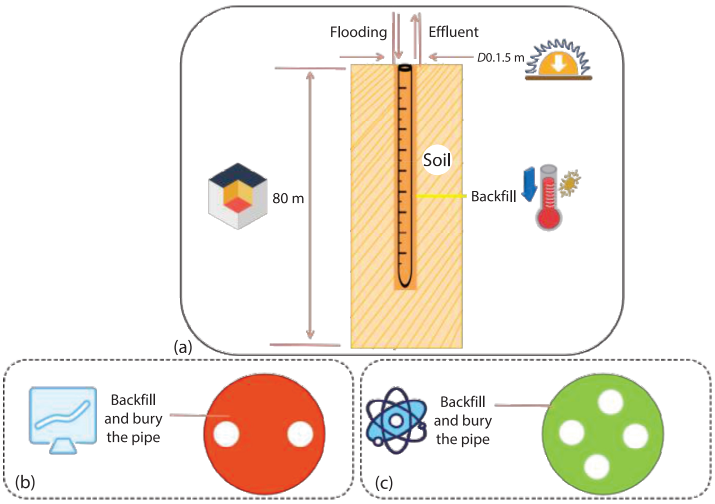

Figure 1. Single *U*-tubes and double *U*-tubes;
(a) schematic diagram of vertical buried pipe,
(b) cross-section diagram of single u buried pipe, and
(c) cross-section diagram of double u buried pipe

The wellbore wall and bottom can be set as equal heat flow boundaries, and an isothermal boundary can be set at a depth of 10 m below the wellbore bottom. The surface temperature varies with the local meteorological conditions throughout the four seasons. In order to ensure the normal heat exchange effect and long-term use of underground buried pipes, a reasonable number of buried pipes, burial depth, and horizontal spacing between pipe wells should be designed. In most cases, the cooling capacity required for summer air conditioning and the heat required for winter heating are unequal. Therefore, the heat emitted by air conditioning to the soil in summer is not equal to the heat extracted during winter heating. The long-term operation results will inevitably lead to the soil temperature field deviating from the initial temperature field, resulting in a continuous decrease in the amount of cooling (or heat) that can be obtained, thereby putting the heat pump in an uneconomical operating state [11]. In order to achieve the long-term utilization of soil heat sources (cold sources), it is necessary to achieve a basic balance between the total amount of heat taken and released by the soil every year. Therefore, the purpose of numerical simulation is to provide basic data on the allocation of operating time in winter and summer, as well as the horizontal spacing between tube wells, under different buried tube modes, in order to provide reference for the design of vertical buried tube heat exchangers [12].

Mathematical description of unstable temperature field in soil around single well and double U-shaped pipes

In the model, the well-buried pipe depth is 80 m, the pipe diameter is 32 mm, the back thickness is 43 mm, and the area difference is 5 m. Real hot soil around standpipes is complex and involves important factors such as soil type, humidity, heat pump operating time, cooling and heating. In order to simplify the problem solving, after the analysis, the small problems with less impact were ignored and the following assumptions were made when creating the model:

- The thermodynamic and physical properties parameters of soil and backfill materials are constants.
- The velocity of the fluid on the same cross-section inside the buried pipe is the same.
- The thermophysical parameters of soil, backfill, buried pipes, and fluids in the pipes do not change with the progress of heat transfer.
- Neglecting the impact of heat and moisture migration.
- Neglecting the contact thermal resistance between buried pipes and backfill layers, as well as between backfill layers and rock and soil.
- The entire system can be seen as a cylindrical body symmetrical about the axis of the buried pipe.
- Compared with the heat flux in the horizontal direction, the heat transfer in the vertical direction can be ignored.
- The earth has a strong heat storage capacity, and the temperature remains basically unchanged in places where the soil is deep enough [13].

In actual calculations, only the situation within the area shown in fig. 2 is considered. In the figure, Y represents the axis of symmetry, and the centerline of the equivalent circular tube is taken as the axis of symmetry 1-2-3-4-5 edges are the surface, side 10-11-12-13-14 is

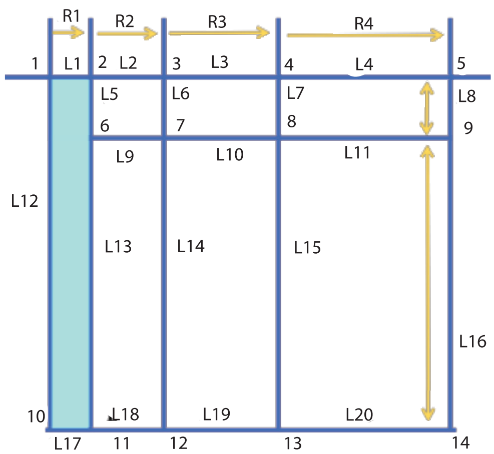

Figure 2. Schematic diagram of a single well model

the soil boundary at a depth of 80 m, side 5-9-14 represents the distance from the pipe wall 5. The remote boundary of 075 m. The H1 is 5 m, H2 is 75 m, R1 is 0.032 m, R2 is 0.043 m, R3 is 2 m, and R4 is 3 m.

Heat transfer differential equation. Based on the aforementioned assumptions and the selected calculation area, the mathematical description of the unstable temperature field of the soil around the underground pipe-line:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{R}\frac{\partial}{\partial R}\left(\lambda R \frac{\partial T}{\partial R}\right) + \frac{\partial}{\partial Y}\left(\lambda \frac{\partial T}{\partial Y}\right) \tag{1}$$

where T [°C] is the transient temperature of the soil, t [second] – the duration of the process, and Y [m] – the axis of symmetry, *i. e.* the centerline of the tube.

Initial condition. According to the analysis and calculation of soil temperature distribution, the soil temperature at 15 m below the surface basically remains unchanged, and the soil temperature within 0-15 m is affected by the surface temperature [14]. For simplicity of calculation, the initial soil temperature in this section is the same as the soil temperature below 20 m. The average annual temperature of soil below 15 m in the Chengdu area is basically 13.5 °C. Therefore, the initial calculated temperature of the soil is taken as 13.5 °C.

Boundary conditions:

– Take the first type of boundary condition with 1-2-3-4-5 edges. Because the vertical buried pipe is located under the lawn and has a high amount of sunlight radiation, its impact cannot be ignored. Therefore, the temperature of the soil surface is the calculated temperature.
– The 5-9-14 edge adiabatic boundary conditions:

$$-\lambda \frac{\partial T}{\partial R}_{|R=5.075} = 0 \tag{2}$$

– The 10-11-12-13-14 edge adiabatic boundary conditions:

$$-\lambda \frac{\partial T}{\partial R}_{|H=-80} = 0 \tag{3}$$

– The first type of boundary condition (given pipe wall temperature) is taken from sides 2-6-11:

$$t\big|s = t_w \tag{4}$$

Analysis of calculation results

For analysis, the calculation results of Points 7-9 along the X-direction and Points 3, 7, and 12 along the Y-direction are provided [15].The temperature change of key Point 3 is greater than the other two points at the same depth, because Point 3 is on the ground surface and is significantly affected by climate, which changes significantly with temperature changes. But the other two points are basically unaffected by temperature, only slightly decreasing with the increase of heat pump operation time.

From fig. 3, it can be seen that the periodic changes in soil temperature have a greater impact than the changes in soil temperature caused by water flow in the U-shape, indicating that the soil temperature field has a strong self-healing function [16].

From fig. 4, different soil type have significant changes in soil temperature. Therefore, when designing ground source heat pumps, it is necessary to strengthen on-site investigation, select suitable locations for drilling, and bury underground heat exchangers.

Below, take key Point 7 as an example to illustrate the impact of different parameter changes on soil temperature:

– The influence of temperature changes on the outer wall of the pipe is shown in fig. 3.
– The impact of changes in soil type is shown in fig. 4.
– The impact of different backfill materials is shown in fig. 5.
– The impact of pipe diameter changes is shown in fig. 6.

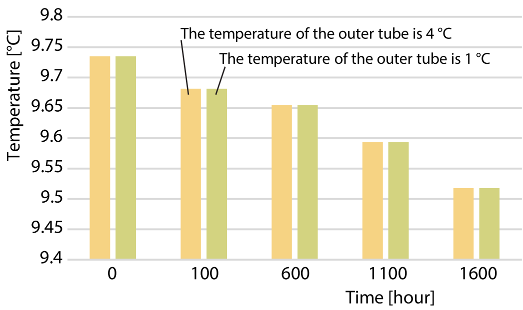

Figure 3. Soil temperature change at 7 points when the temperature of the outer wall of the pipe changes

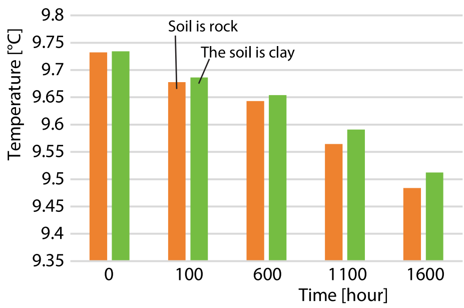

Figure 4. Change of soil temperature at 7 points when soil type changes

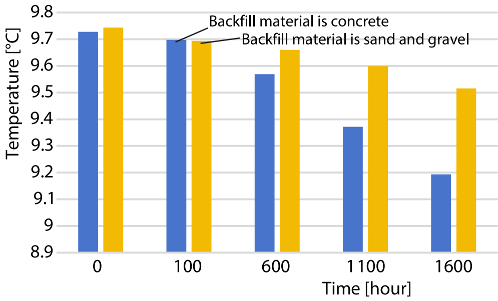

Figure 5. Soil temperature changes at 7 points during backfill changes

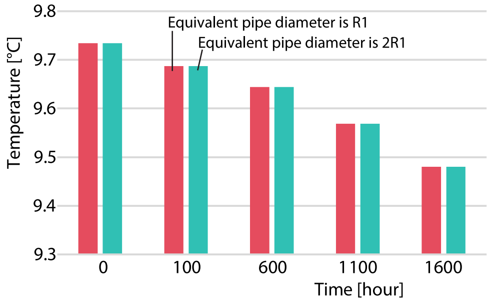

Figure 6. Soil temperature changes at 7 points when pipe diameter changes

From fig. 5, it can be seen that different backfill materials also have significant changes in soil temperature. Therefore, it is necessary to conduct serious research and optimization on backfill materials, develop new types of backfill materials, improve backfill construction techniques, and conduct in-depth research by combining theoretical analysis with practical engineering to ultimately find efficient and economical backfill materials [17-20].

From fig. 6, it can be seen that the change in equivalent pipe diameter has little effect on soil temperature, and the linear heat source model is used for calculation without causing significant errors. Therefore, in practical engineering, a linear heat source model can be used to provide a basis for future design calculations.

Conclusion

In the model, the well-buried pipe depth is 80 m, the pipe diameter is 32 mm, the back thickness is 43 mm, and the area difference is 5 m. Real hot soil around standpipes is complex and involves important factors such as soil type, humidity, heat pump operating time, cooling and heating. In order to simplify the problem solving, after the analysis, the small problems with less impact were ignored and the following assumptions were made when creating the model.

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