

# Numerical Simulation of the Soil Unsteady Temperature Field around Vertically Buried Pipe

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**Abstract:** A transient heat transfer model of the soil temperature field around a vertical U-tube of ground source heat pump was established. The numerical simulation was obtained by using the implied finite difference method. By making the simulation of cooling and heating mode, the change rules of the soil temperature along the radial direction, the change rules of the exit water temperature of the buried pipe and the thermal influencing radius in the vertical multi-pipe were obtained.

**Keywords:** Ground-source heat pump(GSHP); Vertical U-Tube; Transient temperature field

## NOMENCLATURE

|             |                                                                            |
|-------------|----------------------------------------------------------------------------|
| $\lambda_g$ | Conduction coefficient of backfill material<br>[ W/(m <sup>2</sup> ·°C) ]  |
| $\rho_g$    | Density of backfill material [kg/m <sup>3</sup> ]                          |
| $c_g$       | Heat specific volume of backfill material<br>[ J/(kg·°C) ]                 |
| $\lambda_s$ | Conduction coefficient of soil [ W/(m <sup>2</sup> ·°C) ]                  |
| $\rho_s$    | Density of soil [kg/m <sup>3</sup> ]                                       |
| $c_s$       | Heat specific volume of soil [ J/(kg·°C) ]                                 |
| $r_{eq}$    | The equivalent tube's outer radius [m]                                     |
| $r_b$       | The broach's radius [m]                                                    |
| $T_r$       | The temperature of backfill material [°C]                                  |
| $T$         | The temperature of soil [°C]                                               |
| $\tau$      | Time [s]                                                                   |
| $r_b$       | The radius of the broach [m]                                               |
| $r_0$       | The radius of the ramose tube [m]                                          |
| $\beta_0$   | Geometry parameter ,which relates to layout manner of U-tube in the broach |
| $\beta_1$   | Geometry parameter ,which relates to layout manner of U-tube in the broach |
| $T_{eq}$    | The temperature of equivalent tube wall [°C]                               |
| $q$         | Dissipated heat of unit broach [W/m]                                       |
| $q_l$       | The dissipated heat of unit length of pipe [W/m]                           |
| $R_{pipe}$  | The thermal resistance of equivalent tube<br>[ (m <sup>2</sup> ·°C)/W ]    |
| $h_i$       | Heat exchange coefficient of ramose tube<br>[ W/(m <sup>2</sup> ·°C) ]     |
| $T_0$       | The exit water temperature of the buried pipe [°C]                         |

## 1. INTRODUCTION

It is the key and precondition of GSHP system optimization design and economic running that mastering and understanding soil temperature field distribution around the buried pipe .With start and stop, and running time variation of GSHP, soil temperature around the buried pipe shows unsteady characteristic. Numerical simulation on the unsteady temperature field around vertical U-tube heat exchangers, is useful to design logically depth, number and distance of heat exchangers. It can improve performance coefficient and economic capability, as well as reduce the initial investment of heat pump system. The physical and mathematical models of the unsteady temperature field around vertical U-tube heat exchangers are established in this paper .The temperature field around the buried pipe is simulated numerically with implied finite difference .The factors are analyzed ,which influence temperature field distribution and the heat transfer characteristic of vertical U-tube heat exchangers. These provide reference basis for designing GSHP with vertical U-tube heat exchangers .

## 2. HEAT TRANSFER MODEL

The structure of underground buried pipes is shown in Fig.1(a),(b). Heat transfer medium flows oppositely and form circular loop .

For early heat transfer model<sup>[1]</sup> about soil temperature field around the buried pipe ,the equivalent diameter of U-tube is  $\sqrt{2}D_0$  ,which only relates to the radius of ramose tubes. This model is rough because it can't take the location of two tubes into account. In this paper, the thought of backfill thermal resistance is used to predigest two tubes as a single tube, which synthesizes the influences of ramose tube radius and location in the broach. The physical and mathematical models are established, of the unsteady temperature field of backfill material and soil out of the broach, which the heat transfer along axis can be neglected.

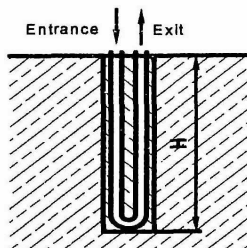


Fig.1(a): U-tube sketch map

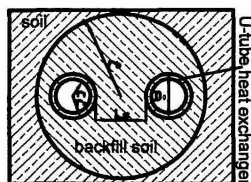


Fig.1(b): U-tube sketch map

## 2.1 Assumption

In order to predigest the evaluation, the heat transfer model<sup>[2-3]</sup> is supposed as follow:

- (1) the soil is even
- (2) entourage of the buried pipe is regarded as infinite space, original temperature of earth is consistent in the different depth, and the heat transfer on the interface ground and air is not considered
- (3) the thermodynamic parameters of soil and backfill material remain constant
- (4) the influence of heat and humidity transfer is not considered
- (5) the temperature and heat losses of the equivalent tube wall are consistent in different depth
- (6) the contacting resistance is neglected, between tube wall and backfill material, and between backfill material and broach wall

## 2.2 Conduction differential equation

For the backfill material between tube wall and broach wall, it can be described as:

$$\frac{\partial T_r}{\partial \tau} = \frac{\lambda_g}{\rho_g c_g} \left( \frac{\partial^2 T_r}{\partial r^2} + \frac{1}{r} \frac{\partial T_r}{\partial r} \right) \quad (r_{eq} \leq r \leq r_b) \quad (1)$$

For the soil out of broach, it can be followed by:

$$\frac{\partial T}{\partial \tau} = \frac{\lambda_s}{\rho_s c_s} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (\sqrt{x^2 + y^2} \geq r_b) \quad (2)$$

## 2.3 Initial condition

The original earth is viewed as isothermal. The original temperature of soil is opted as the year average of earth.

## 2.4 Boundary condition

Take the second boundary condition as that of equivalent tube wall. When the heat pump runs, it can be followed by:

$$-\lambda_g \frac{\partial T_r}{\partial r} \Big|_{r=r_{eq}} = \frac{q}{2\pi r_{eq}} \quad (3)$$

When the heat pump stops, it can be described as follows:

$$-\lambda_g \frac{\partial T_r}{\partial r} \Big|_{r=r_{eq}} = 0 \quad (4)$$

Remote boundary of soil out of the broach is supposed to be adiabatic, which means

$$-\lambda_s \frac{\partial T}{\partial x} \Big|_{x=\infty} = 0 \quad (5)$$

$$-\lambda_s \frac{\partial T}{\partial y} \Big|_{y=\infty} = 0 \quad (6)$$

## 2.5 Equivalent radius

The reference equivalent tube is shown in Fig.2.

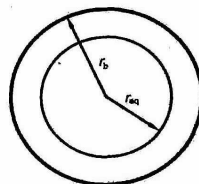


Fig.2: Equivalent tube sketch map

The backfill thermal resistance can be calculated as follows:

$$R_g = \frac{1}{S_b \lambda_b} \quad (7)$$

$$R_g = \frac{1}{2\pi \lambda_g} \ln \left( \frac{r_b}{r_{eq}} \right) \quad (8)$$

Shape factor<sup>[4]</sup> is confirmed with:

$$S_b = \beta_0 \left( \frac{r_b}{r_0} \right)^{\beta_1} \quad (9)$$

The equivalent tube outer radius

$$r_{eq} = \frac{r_b}{e^{2\pi \lambda_s R_s}} \quad (10)$$

## 2.6 Involved temperature

The average temperature<sup>[5-7]</sup> of liquid in the underground buried pipe is

$$T_a = T_{eq} + q_l R_{pipe} \quad (11)$$

$$R_{pipe} = \frac{\ln(r_{eq}/(r_{eq} - (r_0 - r_i)))}{2\pi\lambda_p} + \frac{1}{2\pi r_i h_i} \quad (12)$$

The exit water temperature of the buried pipe is

$$T_0 = T_a - q/(2mc_{pw}) \quad (13)$$

### 3. RESULT ANALYSIS

In this paper, the unsteady temperature field around vertical U-tube heat exchangers is solved with implied finite difference. According to principle of implied difference and mathematical model of unsteady temperature field, a numerical computation result with FORTRAN is given on the unsteady temperature field of soil around buried pipes.

The temperature field distribution around the buried pipe is simulated when GSHP runs continually in the heating and cooling mode. The result is shown as Fig. 3-8.

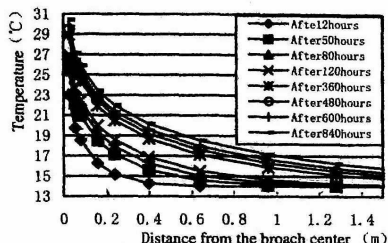


Fig.3: Temperature field around the tube in cooling mode

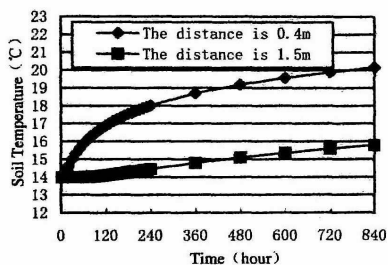


Fig.4: Soil temperature in cooling mode

Fig.3 and Fig. 4 display the variation of soil temperature in the cooling mode when the heat loss is 70W/m and heat bump runs continually for 840h. Fig.5 reveals the variation of the exit water temperature when the cooling mode lasts for 240h. Fig.3 and Fig.4 indicate that the closer distance between buried pipes is, the more promptly soil temperature rises with the same running time. With running time increasing, the increasing degree of soil temperature will drop around buried pipes. In the initial stage of the heat bump running, soil temperature rises promptly until running time reaches to 70h, the increasing degree of soil temperature

starts to decrease at 0.4m away from the broach center. While the distance of 1.5m, the temperature remains nearly constant until 70h, soil temperature rises promptly because soil is affected by heat disturbing; after running 480h, the increasing degree of soil temperature will fall. It also shows that the larger heat loss of a single broach is, the higher exit water temperature is. For example, when heat loss of a single broach is 50W/m, the exit water temperature is 23.48 °C, whereas when heat loss of a single broach is 70W/m, the exit water temperature of the buried pipe becomes 27.27 °C when the running time is 60h.

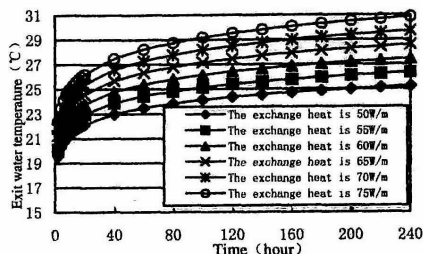


Fig.5: Exit water temperature in cooling mode

Fig.5 suggests that the exit water temperature rises more quickly in the initial stage, with the running time prolonging, the increasing degree of exit water temperature decreases until stabilization.

Fig.6 and Fig.7 show the variation of soil temperature in the heating mode when the absorbed heat is 20W/m. Fig. 8 show the variation of the exit water temperature when the heating mode lasts for 240h. Fig. 6 and Fig.7 indicate that the closer distance between buried pipes is, the more promptly soil temperature declines with the same running time. With running time increasing, the decreasing degree of soil temperature will drop. In the initial stage of the heat bump running, soil temperature declines promptly until running time reaches to 110h, the decreasing degree of soil temperature starts to decrease at 0.4m away from the broach center. While the distance of 1.5m, the temperature remains nearly constant until 110h, soil temperature declines smoothly because soil is affected by heat disturbing.

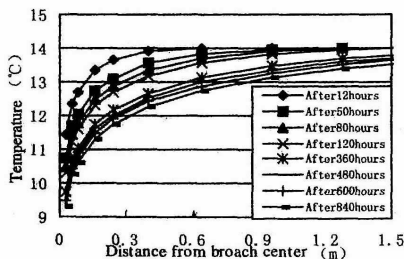


Fig.6: Temperature field around the tube in heating mode

Fig.8 suggests that the exit water temperature declines quickly in the initial stage, with the running time prolonging, the decreasing degree of the exit water temperature decreases. The less the absorbed heat of a unit broach is, the higher the exit water temperature is for the same running time. For example, when the running time is 80h and absorbed heat of a unit broach is 40W/m, the exit water temperature is 6.18°C; while when absorbed heat of a unit broach is 20W/m, the exit water temperature becomes 10.09°C.

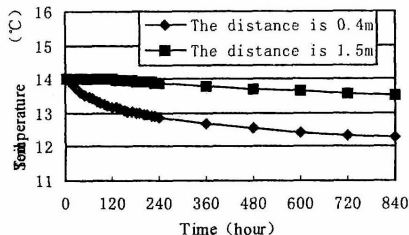


Fig.7: Soil temperature in heating mode

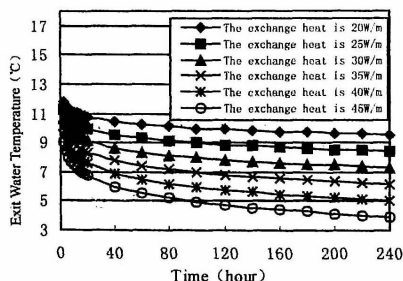


Fig.8: Exit water temperature in heating mode

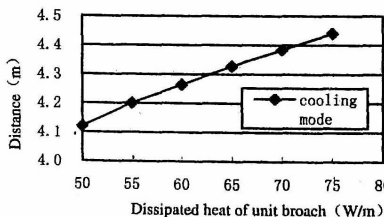


Fig.9: Thermal influencing radius in cooling mode

The thermal disturbing radius of buried pipes is also simulated in this paper for the same depth and different absorbed heat which is reflected as Fig. 9. When GSHP continually runs for 840h in the cooling mode (buried depth of 47.5m , outer radius of 32mm , wall thickness of 3mm for aluminium-plastic compound pipes), the thermal disturbing radius of buried pipes will gradually go up with the increasing of

transferred heat. When the heat loss of unit broach is 50W/m, the thermal disturbing radius of buried pipes is 4.12m, while heat loss increases to 70W/m , the thermal disturbing radius increases to 4.38m correspondingly.

#### 4. CONCLUSION

- (1)The thermal disturbing radius of buried pipes is given on a certain condition, which provide referenced basis for designing pipe group of the vertical U- tube heat exchangers.
- (2)The thermal disturbing radius of buried pipes will gradually increase with the enhancing exchanged heat of buried pipes.
- (3)The equivalent tube model is put forward on the basis of equivalent backfill thermal resistance, which the influences of ramose tube radius and the location of two tubes in the broach are taken into account.
- (4)The exit water temperature of buried pipes rises promptly in the initial stage of the heat bump running, while it changes gently with the running time until stabilization.
- (5)For the same running time, the larger heat loss of a unit broach is, the higher the exit water temperature of the buried pipe is in the cooling mode; while the larger the absorbed heat of a unit broach is, the lower the exit water temperature is in the heating mode.

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