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# Theoretical Model and Simulation on Heat and Moisture Transfer in Soil Around Underground Heat Exchanger

Li Xin-Guo[1] , Chen Yan[1] , Li Li-Mei[2]

1．Department of Thermal Engineering, School of Mechanical Engineering, Tianjin University, Tianjin 300072, PR China

2．Beijing Longyuan Cooling Technology Co.Ltd, Beijing 100176, PR China

E-mail: xgli26@163.com

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## ABSTRACT

Based on the heat and mass transfer theory in soil, an unsteady three-dimensional coupled heat and moisture transfer model for the U-vertical underground heat exchanger (UHE) in soil was set up in double cylinder coordinates. According to the model, analyses were presented about the influences of different soil properties, different operational modes, and different initial humidity on the temperature and moisture fields in soil around the UHE.

## 1. INTRODUCTION

The heat and moisture transfer in soil around the U-vertical underground heat exchanger (UHE) is what of most interest in the research on Ground-Coupled Heat Pump (GCHP) system. Present study methods on this tissue are classified into two types: theoretical analysis and numerical simulation. The former has distinct physical significance and logical reasoning and its results, as an approximate solution, can be used to check the accuracy of the latter when solving complex engineer problems. But it is difficult even impossible for theoretical analysis to provide exact analytical solutions in most of the practical coupled heat transfer problems, nor in the complicated equation or solving conditions (such as nonlinear problem, variable coefficient equation) as well. In contrast, numerical method manifests a good flexibility in such cases as coupled heat transfer, complex geometrical shape, etc. Based on the heat and moisture transfer theory in surface soil, this article presents an unsteady three-dimensional model to calculate heat and moisture transfer around underground heat exchanger. This model takes into account the interactive effects of the heat and moisture in soil and its validity was verified by experimental results.

## 2. PHYSICAL AND MATHEMATICAL MODELS ON HEAT AND MASS TRANSFER IN SOIL AROUND UHE

### 2.1 Physical model

Experimental research indicated that soil temperature was constant when the distance above 10m away from the centre of the UHE. According to this, a cylinder calculation domain was employed with the core of borehole as its centre and the radius and depth of 10m and 90m respectively, as shown in Fig.1. The ground temperature out of this field was invariable regardless of heating or cooling. Considering vertical soil delaminating, the double cylinder coordinates was set up in Fig.2.

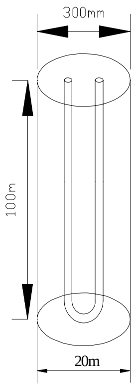



**Fig.1 Geometry structure for physical model of the UHE**

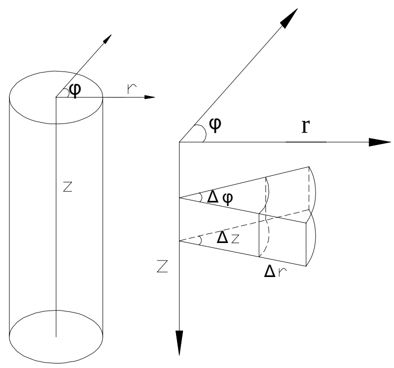



**Fig. 2 Control volume in cylinder coordinates**

### 2.2 Grid division

Under double cylinder coordinates, the vertical axes are coincident with the centerlines of the outlet and inlet water pipes underground, and a grid fills the calculation domain around them. The grid spacing is 1m and $\pi/10$ along z-direction and φ-direction respectively. Moreover, a fine grid with uniform interval of 0.01m is employed along r-direction in the borehole where the T-r variation is steep. Whereas, the soil temperature changes rather slowly out of the borehole, and various spacing is sufficient for a satisfied accuracy. So an adjacent interval ratio of 1.2 is adopted according to the reference documentation. In horizontal, the calculation domain is semi-circle considering its symmetry, as shown in Fig.3.

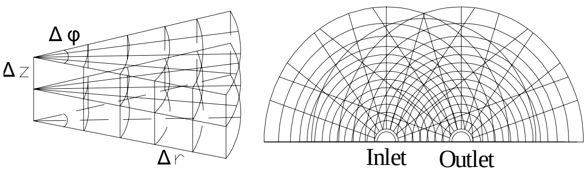
### 2.3 Mathematical model

Based on energy and mass conservation laws, the heat transfer and moisture movement equations were set up for the micro-element control volume shown in Fig.2.

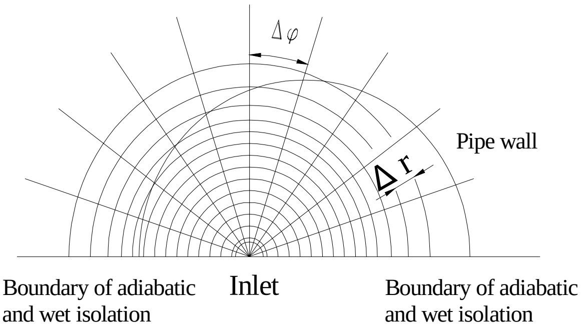
In r-direction, the area of face to the heat flow and moisture enter respectively in soil is $r\cdot\Delta\varphi\cdot\Delta z$ , and the corresponding water flow and heat flux are: $J_r$ and $q_r$;

The heat and moisture transferring into the unit volume in $\Delta\tau$ time interval are:

$q_r\cdot r\cdot\Delta\varphi\cdot\Delta z\cdot\Delta\tau$ and $J_r\cdot r\cdot\Delta\varphi\cdot\Delta z\cdot\Delta\tau$




**(a) Grid division in z-direction (b) Grid division in r and Φ direction**




**(c) Grid division in r and φ direction around inlet pipe**

**Fig.3. Three-dimensional mesh in soil surrounding UHE**

Area of the face from which the heat and moisture leave is $(r+\Delta r)\cdot\Delta\varphi\cdot\Delta z$ . Accordingly, the water flow and heat flux are: $J_r+\frac{\partial J_r}{\partial r}\cdot\Delta r$ and $q_r+\frac{\partial q_r}{\partial r}\cdot\Delta r$, and the heat and moisture leaving the unit volume are:

$$(q_r+\frac{\partial q_r}{\partial r}\cdot\Delta r)\cdot(r+\Delta r)\cdot\Delta\varphi\cdot\Delta z\cdot\Delta\tau$$

And

$$(J_r+\frac{\partial J_r}{\partial r}\cdot\Delta r)\cdot(r+\Delta r)\cdot\Delta\varphi\cdot\Delta z\cdot\Delta\tau$$

respectively.

So the transient three-dimensional equation for the moisture movement in soil surrounding UHE is:

$$\frac{\partial\theta}{\partial\tau}\cdot r\cdot\Delta r\cdot\Delta\varphi\cdot\Delta z\cdot\Delta\tau=$$
$$-((J_r+\frac{\partial J_r}{\partial r}\cdot r)+\frac{\partial J_\varphi}{\partial\varphi}+\frac{\partial J_z}{\partial z}\cdot r)\cdot\Delta r\cdot\Delta\varphi\cdot\Delta z\cdot\Delta\tau$$

and that for the heat transfer is

$$\frac{\partial h}{\partial\tau}\cdot r\cdot\Delta r\cdot\Delta\varphi\cdot\Delta z\cdot\Delta\tau=$$
$$-((q_r+\frac{\partial q_r}{\partial r}\cdot r)+\frac{\partial q_\varphi}{\partial\varphi}+\frac{\partial q_z}{\partial z}\cdot r)\cdot\Delta r\cdot\Delta\varphi\cdot\Delta z\cdot\Delta\tau$$

**2.4 Discretization equation**

With a representative micro-element volume (the grid point is P and its neighbors are W, E, F, B, N, S, shown in Fig.4.) taken from the grid divided as above, the discretization form of the mathematical model is derived by integrating these two equations over the control volume of $r\cdot\Delta r\cdot\Delta\varphi\cdot\Delta z$ and over the time interval from $\tau$ to $\tau+\Delta\tau$. Thus,

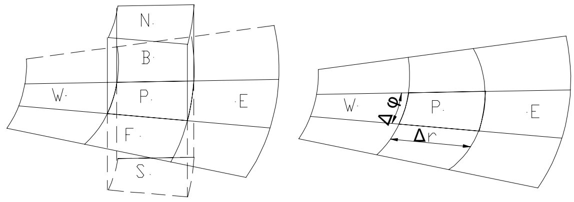



**Fig.4 Element volume for three dimension model**

1. The heat transfer discretization equation

$$a_{PT}\cdot T_P=a_{ET}\cdot T_E+a_{WT}\cdot T_W+a_{BT}\cdot T_B$$
$$+a_{FT}\cdot T_F+a_{NT}\cdot T_N+a_{ST}\cdot T_S+b_T$$

where,

$$a_{PT}=a_{ET}+a_{WT}+a_{BT}+a_{FT}+a_{NT}+a_{ST}+a_{PT}^0-S_{PT}\cdot\Delta V$$
$$+((\rho_w K_w\cdot c_w)_s-(\rho_w K_w\cdot c_w)_n)\cdot r_P\cdot\Delta r\cdot\Delta\varphi$$

2. The moisture movement discretization equation

$$a_{P\theta}\theta_{wP}=a_{E\theta}\theta_{wE}+a_{W\theta}\theta_{wW}+a_{B\theta}\theta_{wB}$$
$$+a_{F\theta}\theta_{wF}+a_{N\theta}\theta_{wN}+a_{S\theta}\theta_{wS}+b_\theta$$

Where:

$$a_{P\theta}=a_{E\theta}+a_{W\theta}+a_{B\theta}+a_{F\theta}+a_{N\theta}+a_{S\theta}$$
$$+a_{P\theta}^0-S_{P\theta}\cdot\Delta V$$

**2.5 Boundary and initial conditions**

Based on the soil situation, boundary conditions are determined for a given calculation domain as follows:

1. in z-direction

| | On surface：Z=2m | In undisturbed soil：Z=92m |
|---|---|---|
| For moisture： | $\theta(r,\varphi,2,\tau)=\theta_\infty(r,\varphi,2)$ | $\theta(r,\varphi,92,\tau)=\theta_\infty(r,\varphi,92)$ |
| For heat： | $T(r,\varphi,2,\tau)=T_\infty(r,\varphi,2,\tau)$ | $q_z\big\|_{z=92}=const$ |

2. in r-direction

| | On the pipe wall：r =0.016m | Far from the pipe wall：r=10m |
|---|---|---|
| For moisture： | $\frac{\partial\theta}{\partial r}\Big\|_{r=0.016}=0$ | $\frac{\partial\theta}{\partial r}\Big\|_{r=10}=0$ |
| For heat： | $q_r\big\|_{r=0.016}=q_r(\tau)$ | $T\big\|_{r=10}=T_\infty$ |

3. in $\varphi$ -direction

| | At the start edge of the semi-cycle： $\varphi=0$ | At the end edge of the semi-cycle： $\varphi=\pi$ |
|---|---|---|
| For moisture： | $\left.\frac{\partial\theta}{\partial\varphi}\right\|_{\varphi=0}=0$ | $\left.\frac{\partial\theta}{\partial\varphi}\right\|_{\varphi=\pi}=0$ |
| For heat： | $\left.\frac{\partial T}{\partial\varphi}\right\|_{\varphi=0}=0$ | $\left.\frac{\partial T}{\partial\varphi}\right\|_{\varphi=\pi}=0$ |

4. Initial conditions

At the start time for calculation: $\tau=0$

Initial moisture distribution: $T(r,\varphi,z,0)=T_{\infty}(r,\varphi,z)$

Initial temperature field: $\theta(r,\varphi,z,0)=\theta_{\infty}(r,\varphi,z)$

### 2.6 Solution of the model

The solution model belongs to the unsteady three-dimensional heat and mass transfer model. Its solving process, like the Cotdma method for one-dimensional discretization equation, takes the alternating-direction implicit (ADI) method, that is, Cotdma method is employed for a given direction of the coordinates while explicit scheme is taken for other directions. Specifically, for unsteady equation of coupled heat and mass transfer ADI method solves the heat and moisture equations simultaneously using the implicit scheme in one direction (e.g. z-direction) and the explicit scheme in the other two (r and directions). Then the same was applied to the r and directions separately. So, this converts the three-dimensional tissue to one-dimensional implicit scheme including three series equations. Each of them can be solved by Cotdma method.

Moreover, the series equation on discrete grid points can be solved by computer program written in Visual Basic6.0. With Brain ADI scheme, the program obtains solutions for temperature and moisture fields around the inlet and outlet water pipes using iterating method. Finally, the effects of different initial moisture, different operation modes and different soil properties on the heat and mass transfer in soil can also be simulated.

## 3. THE EFFECTS OF DIFFERENT SOIL PROPERTIES ON THE TEMPERATURE AND MOISTURE DISTRIBUTION

In the simulation, the emitting heat rate to soil per unit depth was given as 40W/m. The effects of different soil properties on the temperature and moisture fields were shown in Fig.5. After a 30-day continuous emitting operation, the temperature of the sand layer in 20m underground increased from 14.82℃ to 18.98℃, and the temperature rise of the silt layer in 8m underground was 5.7 ℃. And the temperature rise in silt was sharper than that in sand. Moreover, for other soil layers (e.g. clay), the variation was somewhere between the above two. For the high thermal conductivity and low heat capacity in sand layer, heat transfer was easier than that in silt.

Different soil temperatures and layer properties had different influence on the moisture as shown in Fig.5. In initial running, the soil temperature increased sharply in the radial direction at the neighbor area of underground pipe, resulting in a steep moisture decrease in this direction. Meanwhile, different soil properties led to different drop ranges. On the other hand, the vertical temperature gradient exerted a gradual increasing influence on soil moisture in the remote area. That mean the lower the layer, the higher the moisture.

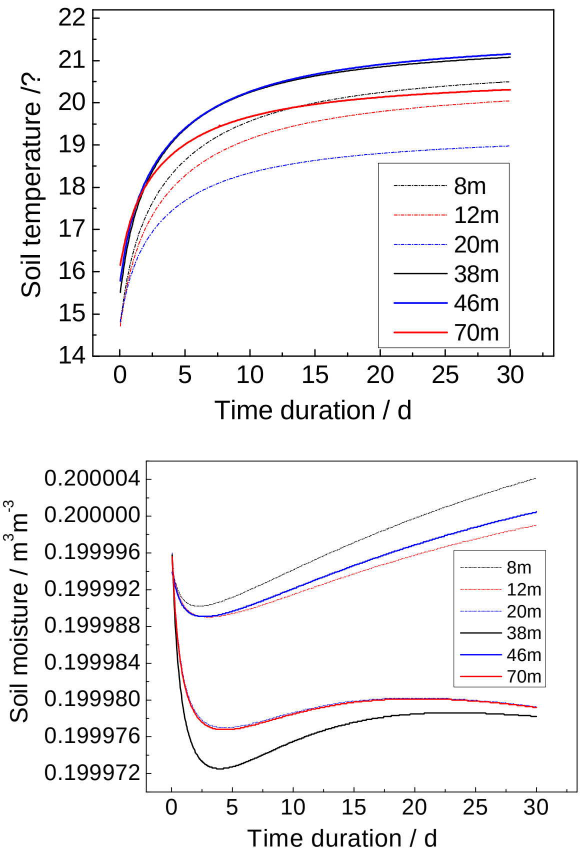



**Fig.5 Temperature and moisture variation in different layers**

## 4. THE EFFECTS OF DIFFERENT OPERATION MODES ON THE TEMPERATURE AND MOISTURE DISTRIBUTION IN SOIL

To study the effects of different operation modes, the emitting heat rate to soil per unit depth was given as 40W/m in both continuous and intermittent modes. The running time was 30 days for the two modes and 10 hours per day for the latter. The simulation results showed in Fig.6.

Under intermittent mode, the temperature of the well was 17.88℃ and 16.55℃ for sand and clay respectively after a 30-day running, while that of the continuous mode were 20.31℃ and 18.98℃. It was obvious that continuous running causes a sharper temperature rise than that in intermittent mode. Therefore, intermittent mode was more favorable for the system stability in a long-term perspective.

## 5. CONCLUSION

(1). Soil properties have significant effects on the temperature and moisture distribution. The higher the heat conductivity, the faster the temperature and moisture transfer. Moreover, high thermal diffusivity will lead to a greater temperature change and a relatively poor heat storage capacity in soil. For the heat exchange of UHE it is better to have high soil conductivity, however, better heat storage capacity is more favorable for a seasonal underground heat storage system.

(2). The temperature and moisture in soil changed slower in the intermittent mode than that in continuous mode. So the intermittent mode should be adopted for long-term stable operation.

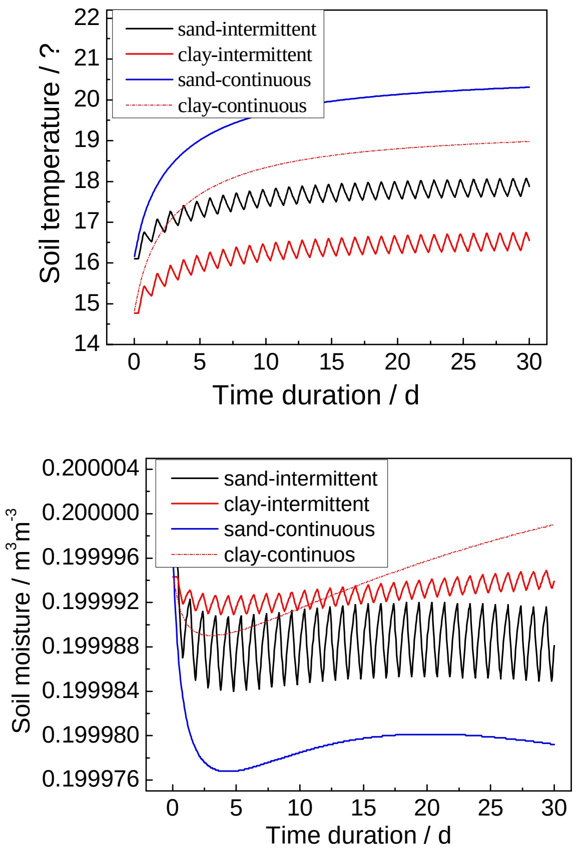



**Fig. 6 Temperature and moisture variation in different layers in continuous and intermittent operation mode**

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