Numerical investigation of energy tunnel lining ground heat exchangers in a mountain environment

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Abstract. The energy tunnel lining ground heat exchangers (GHEs) is a new technology to extract geothermal energy. At present, the researches on the feasibility of energy tunnel lining GHEs design are rare. In order to evaluate the feasibility of energy tunnel lining GHEs design in a mountain environment, a 3D numerical model was developed to simulate the transient heat transfer of energy tunnel lining GHEs. In this model, the inlet temperature varied with time based on the building refrigeration load, the numerical results were verified with the field monitoring data. According to the relationship between outlet temperature and the energy efficiency ratio (EER) of heat pump, the numerical results of outlet temperature were used to calculate the EER. Then, the energy efficiency of energy tunnel lining GHEs was evaluated. The results show that the design of the energy tunnel lining GHEs with a pipe pitch of 0.6 m and a pipe length of 329.4 m is feasible. Under continuous operation mode, the energy efficiency ratio reaches 4.44 and the refrigeration power reaches 175 kW in summer.

1. Introduction
With the application of ground source heat pump technology, energy geostuctures have been gradually used in the field of geothermal energy development [1-7]. Energy tunnel lining ground heat exchangers (GHEs) are the new technology for extracting geothermal energy to heat and cool adjacent buildings. This technology offers the advantages of a large heat exchange area and high heat exchange efficiency, which has attracted the interest of many researchers. Brandl [8] first proposed the energy tunnel technology in Austria and conducted a field test in a cut and cover tunnel to provide heating for a school. The calculation results showed that this energy project could provide heating power of 150 kW and energy of 214 MWh in one heating period. Adam and Markiewicz [9] arranged energy geotextiles (composed of GHEs) between the tunnel primary and secondary linings in the experimental section of the Lainzer tunnel, leading to a good operation of the energy tunnel. Lee et al. [10, 11] conducted field thermal response tests to evaluate the thermal efficiency of energy textiles arranged in an abandoned tunnel and developed numerical models to simulate the operation of GHEs encased in an energy textile under different conditions. Zhang et al. [12] introduced mountain tunnel...
lining GHEs in China and conducted field thermal response tests in the Linchang Tunnel (Inner Mongolia). Based on the field test data, a theoretical analysis of the mountain tunnel lining GHEs was developed to investigate the heat transfer mechanism of the tunnel lining GHEs system. This provided theoretical support for the study of cold-region energy tunnels [13]. Constant inlet temperatures are often used to study the thermal performance of energy tunnel lining GHEs. For the energy tunnel projects, the inlet temperature of the absorber pipe varies with time based on the energy tunnel GHE refrigeration load, the energy efficiency ratio (EER) needs to be designed quantitatively, which is the reason driving the research.

In this paper, a 3D heat transfer model was devoted to studying the thermal performance of energy tunnel lining GHEs based on the climate of Shenzhen. The fluid temperature, energy efficiency ratio (EER) of the hump and the ground temperature distribution were be analyzed. Finally, the feasibility of the mountain energy tunnel design was proven.

2. Heat transfer model of mountain tunnel lining GHEs

2.1. Mathematical formulation

Heat transfer between heat exchanger pipes and the surrounding rock (Fig. 1) depends on the ground properties, the ground conditions, ventilation conditions and so on [1]. To simplify the model, the following assumptions are made: (1) both surrounding rocks and tunnel linings are assumed to be homogenous and their thermal properties are assumed to be constant; (2) the underground water flow is not considered because the underground water flow is helpful to improve the energy efficiency of energy tunnel lining GHEs [2] and it is safe to design without considering groundwater; (3) the contact boundary between the lining and surrounding rock is assumed to be continuous [3, 4]; (4) the pipe wall is considerably thin, and the heat transfer through the pipe wall is assumed to follow a quasi-steady behavior [1].

![Fig. 1. The heat transfer model of tunnel lining GHEs.](image)

Based on the above assumptions, the transient conduction heat transfer equation of surrounding rock and the energy tunnel lining is presented below:

\[
\rho_i C_{p,i} \frac{\partial T_i}{\partial t} = \nabla \cdot (k_i \nabla T_i) \quad (i = 1, 2, 3)
\]

\[
\text{MERGEFORMAT (1)}
\]

where \(T_i\) is the temperature (K), \(\rho_i\) is the mass density (kg/m\(^3\)), \(C_{p,i}\) is the specific heat capacity (J/(kg K)), \(t\) is the time (s), \(k_i\) is the thermal conductivity (W/m K), \(i = 1, 2, 3\), 1 secondary lining; 2 primary lining; 3 surrounding rock.
The transient convective heat transfer equation of circulating fluid inside the absorber pipe and the pipe wall is presented below:

The momentum equation

\[ \rho \frac{\partial \mathbf{u}}{\partial t} = -\nabla p + \frac{1}{2} \rho \frac{D}{d} \mathbf{u} \cdot \mathbf{u} \]  
\* MERGEFORMAT (2)

The continuity equation

\[ \frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{u}) = 0 \]  
\* MERGEFORMAT (3)

The energy conservation equation

\[ \rho L C_p \frac{\partial T}{\partial t} + \rho L C_p \mathbf{u} \cdot \nabla T = \nabla \cdot \left( A k \nabla T \right) + \frac{1}{2} \rho \frac{D}{d} \mathbf{u} \cdot \mathbf{u} + q_{\text{wall}} \]  
\* MERGEFORMAT (4)  
\* MERGEFORMAT (5)

\[ q_{\text{wall}} = h_i (T_i - T_w) \]  
\* MERGEFORMAT (6)

\[ h_i = \frac{2\pi}{d_{\text{p, in}} h_{\text{in}}} + \frac{1}{k_p} \ln \left( \frac{d_{\text{p, out}}}{d_{\text{p, in}}} \right) \]  
\* MERGEFORMAT (7)

where \( \rho \) is the mass density of the fluid (kg/m\(^3\)), \( C_{p,i} \) is the specific heat capacity of fluid (J/(kg K)), \( \mathbf{u} \) is the flow rate of fluid (m/s), \( p \) is the fluid pressure (Pa), \( f_D \) is the Darcy friction factor, \( d \) is the hydraulic diameter (m), \( d_{p, \text{out}} \) and \( d_{p, \text{in}} \) are the outer and inner diameters of absorber pipe (m), \( A \) is the inner cross section of pipe (m\(^2\)), \( h_i \) is the equivalent convective heat transfer coefficient (W/m\(^2\)K), \( h_w \) is the convective heat transfer coefficient of internal film of pipe (W/m\(^2\)K), \( T_i \) is the temperature of the fluid (K), \( q_{\text{wall}} \) is the external heat exchange rate through the pipe wall (W/m).

2.2. Initial and boundary conditions

To solve the above system of equations, appropriate initial and boundary conditions must be provided. The initial condition represents the thermal state of the surrounding rock is assumed to be constant because the tunnel is in the constant temperature layer and the effect of the initial temperature field is negligible for long-term calculation [18]. In the constant temperature layer, the thermal boundaries of the model are set as the adiabatic condition and the size of geometry is adequate for the operations (no temperature change at the boundary).

The initial temperature condition is as follows:

\[ T_i(x, y, z, t)|_{t=0} = T_{\text{in}}(x, y, z) \]  
\* MERGEFORMAT (8)

The adiabatic boundary conditions are as follows:

\[ \frac{\partial T_i(x, y, z, t)}{\partial r} \bigg|_{r=\pm R} = 0 \]  
\* MERGEFORMAT (9)

\[ \frac{\partial T_i(x, y, z, t)}{\partial r} \bigg|_{r=\pm R} = 0 \]  
\* MERGEFORMAT (10)

\[ \frac{\partial T_i(x, y, z, t)}{\partial z} \bigg|_{z=\pm L} = 0 \]  
\* MERGEFORMAT (11)
The convective heat transfer boundary condition between the tunnel surface and the air is as follows:

\[ k_i \nabla T_i = h(T_i - T_{\text{air}}) \]  

* MERGEFORMAT (12)

In order to reduce required computational resources, the convective heat transfer coefficient can be simplified as a function of wind speed based on the turbulence model (CHTC) [5-7]. The CHTC correlation is expressed as follows:

\[ h = aU_r^b + c \]  

* MERGEFORMAT (13)

The coefficients a, b and c can be determined by fitting the measured data of wind speed and the CHTC. The coefficients a, b and c of Equation are 4.2, 1 and 6.2, respectively [4].

where \( T_{\text{in}} \) is the initial temperature (K), \( T_{\text{air}} \) is the air temperature (K), \( h \) is the convection heat transfer coefficient (W/m² K), \( \rho_a \) is the mass density of air (kg/m³), \( u_a \) is the flow rate of air (m/s), \( d_a \) is the characteristic length of the tunnel (m), \( \mu \) is the dynamic viscosity of air (Pa s).

3. Finite element model

A commercial finite element software, Comsol Multiphysics, was used to solve all mathematical formulations of models. A 3D heat transfer numerical model was developed to simulate the thermal behaviors of tunnel lining GHEs with the Heat Transfer in Solids model and Non-isothermal Pipe Flow model.

3.1. The function of time-dependent inlet temperature

During the continuous operation of tunnel lining GHEs, the inlet temperature of the absorber pipe varies with time based on the energy tunnel GHE refrigeration load. To simulate the operation state of tunnel lining GHEs, a time-dependent temperature is prescribed at the inlet. The inlet temperature is defined as a function of the outlet temperature and energy tunnel GHE refrigeration load.

The function can be expressed as:

\[ T_{\text{in}}(t) = T_{\text{out}}(t) + \frac{Q(t)}{\rho_a u_a A C_p L} \]  

* MERGEFORMAT (14)

where \( T_{\text{in}}(t) \) is the inlet temperature of absorber pipe (K), \( T_{\text{out}}(t) \) is the outlet temperature of absorber pipe (K), \( Q(t) \) is the tunnel GHEs refrigeration load (W).

The energy efficiency ratio (EER) can be used to evaluate heat pump work performance. Hence, the EER is an important indicator for designing the tunnel lining GHEs. The heat pump model can be simplified as a function of (EER) and outlet temperature [8, 9] that is offered by the manufacturer [10, 11]. The EER equation in this paper is as follows:

\[ \text{EER}(t)=11.02-0.2170T_{\text{out}}(t)+0.0009T_{\text{out}}(t)^2 \]  

* MERGEFORMAT (15)

3.2. Model validation

In our previous study, the thermal response field tests were carried out in Linchang Tunnel (Inner Mongolia). There are two lines in the tunnel, the length of left line is 2515 m, and the length of the right line is 2525 m. The inner diameter of the tunnel is 5.7 m, and the thicknesses of secondary and primary linings are 35 cm and 17 cm, respectively. The total length of heat exchanger pipes is 70 m, the longitudinal length is 8 m, and the distance is 50 cm. The surrounding rock is slightly weathered sand rock [12]. The varying inlet temperature can be used to validate the model, the parameters of the validation model are shown in Table 1.
### Table 1 Numerical simulation parameters.

| Material          | Properties                        | Unit         | Value  |
|-------------------|-----------------------------------|--------------|--------|
| **Surrounding rock** | Thermal conductivity ($k_3$)     | W/m K        | 3.22   |
|                   | Specific heat capacity ($C_{p,3}$) | J/kg K       | 2530   |
|                   | Density ($\rho_3$)                 | kg/m³        | 1670   |
| **Tunnel lining**  | Thermal conductivity ($k_{1,2}$)  | W/m K        | 1.85   |
|                   | Specific heat capacity ($C_{p,1,2}$) | J/kg K   | 970    |
|                   | Density ($\rho_{1,2}$)             | kg/m³        | 2400   |
|                   | Inner diameter ($d_{i,n}$)         | m            | 5.7    |
|                   | Thickness of primary lining ($\delta_1$) | m        | 0.17   |
|                   | Thickness of secondary lining ($\delta_2$) | m    | 0.35   |
| **Absorber pipes**| Thermal conductivity ($k_p$)       | W/m K        | 0.32   |
|                   | Inner diameter ($d_{p,in}$)        | mm           | 23     |
|                   | Outer diameter ($d_{p,out}$)       | mm           | 32     |
|                   | Flow rate of carrier liquid ($u_L$) | m/s        | 0.6    |
|                   | Pipe spacing ($J$)                 | m            | 0.5    |
|                   | Pipe length ($L$)                  | m            | 70     |
| **Carrier liquid**| Thermal conductivity ($k_L$)       | W/m K        | 0.56   |
|                   | Specific heat capacity ($C_{p,L}$) | J/kg K       | 4200   |
|                   | Density ($\rho_L$)                 | kg/m³        | 1000   |

**Fig. 2** showed the experimental outlet temperature and the numerical outlet temperature of liquid inside the absorber pipe. There was a reasonable agreement between the experimental results and the numerical results of the outlet temperature. Hence, it is believed that the numerical model can correctly simulate transient state phases of heat transfer during continuous operation.

![Fig. 2. The numerical and experimental results.](image)
3.3. The case design: the mountain energy tunnel GHEs

A mountain tunnel is designed to apply the energy tunnel technology for the tunnel management center refrigeration. According to the meteorological condition of Shenzhen, this region has a subtropical monsoon climate with a high temperature in summer and a moderated temperature in winter. The initial ground temperature in Shenzhen was measured as 20 ^°C and the average annual wind speed was measured as 2 m/s. The surrounding rock was mudstone, The thermal conductivities of surrounding rock and concrete lining were obtained by the thermal response tests, the specific heat capacities of surrounding rock and concrete lining were measured by the differential scanning calorimeter, and the densities of surrounding rock and concrete lining were measured by the density meter, which was present in Table 2. The other parameters from our previous study [4] are shown in Table 2.

Table 2 Main parameters of the mountain tunnel.

| Material          | Properties                              | Unit     | Value |
|-------------------|-----------------------------------------|----------|-------|
| Surrounding rock  | Thermal conductivity ($k_i$)            | W/m K    | 2.80  |
|                   | Specific heat capacity ($C_{p,i}$)      | J/kg K   | 900   |
|                   | Density ($\rho_i$)                      | kg/m³    | 2600  |
|                   | Initial temperature ($T_{ini}$)         | ℃        | 20    |
| Tunnel lining     | Thermal conductivity ($k_i, k_2$)       | W/m K    | 1.85  |
|                   | Specific heat capacity ($C_{p,i}, C_{p,2}$) | J/kg K   | 970   |
|                   | Density ($\rho_i, \rho_2$)              | kg/m³    | 2400  |
|                   | Inner diameter ($d_{i,in}$)              | m        | 7.85  |
|                   | Thickness of primary lining ($\delta_i$) | m        | 0.45  |
|                   | Thickness of secondary lining ($\delta_2$) | m      | 0.60  |
| Absorber pipes    | Thermal conductivity ($k_p$)            | W/m K    | 0.32  |
|                   | Inner diameter ($d_{p,in}$)              | mm       | 23    |
|                   | Outer diameter ($d_{p,oue}$)             | mm       | 32    |
|                   | Flow rate of carrier liquid ($u_c$)      | m/s      | 0.6   |
| Carrier liquid    | Thermal conductivity ($k_l$)            | W/m K    | 0.56  |
|                   | Specific heat capacity ($C_{p,1}$)      | J/kg K   | 4200  |
|                   | Density ($\rho_l$)                      | kg/m³    | 1000  |

The design refrigeration load of the building is 140 kW. Every group of absorber pipe is assumed to bear a building refrigeration load of 4 kW, the minimum EER of heat pump is assumed to be 4. According to the Equation, the maximum tunnel GHEs refrigeration load is 5 kW and the tunnel GHEs need 35 groups of absorber pipe.

\[
\begin{align*}
Q(t) &= Q_{hp}(t) + Q_b(t) \\
Q_{hp}(t) &= \frac{Q_b(t)}{EER} \quad \text{/* MERGEFORMAT (16)}
\end{align*}
\]

where $Q_{hp}(t)$ is the energy consumption of the heat pump (W), $Q_b(t)$ is the building load, $Q_b(t)$ is the tunnel GHEs refrigeration load (W).

Fig. 3 presents the numerical model of the energy tunnel lining GHEs. The domain size of the model is 100 m × 60 m × 11 m to prevent any edge effects on the numerical results. The pipe length and pitch are 329.4 and 0.6 m, respectively.
As shown in Fig. 4 (a), the inlet temperature and outlet temperature of different absorber pipe layout models are presented. For the type-1 absorber pipe layout, the inlet temperature and outlet temperature reach the maximum value of 40.34 and 35.56 °C, respectively. There are some local minimum temperatures on the 14th, 25th, 35th, 42th, 64th, 80th and 88th day during the 90-day operation. For the air temperature, diurnal variation of air temperature is taken into account, the maximum temperature difference is about 10 °C during the 90 days, and there are some local minimum temperatures in the 13th, 24th, 34th, 41th, 63th, 79th and 87th day. The local minimum temperatures of fluid inside the absorber pipe are delayed by one day approximately and the diurnal temperature variation range of fluid inside the absorber pipe decreases significantly compared to the one of air. According to Equation (16), the variation of EER with time is plotted in Fig. 4 (b). Contrary to outlet temperature, the EER of type-1 and type-2 absorber pipe layout decreases gradually during the 90-day operation, reaching the minimum value of 4.44.
**Fig. 5.** Ground temperature distribution after 90 d.

**Fig. 6.** Ground temperature disturbance of different days.

**Fig. 5** depicts the ground temperature distribution on the 90th day. The figure shows the difference between the temperature field in the upper section and the lower section of the tunnel. This temperature distribution is due to absorber pipe placed on the upper section of the tunnel lining. The lower section of the tunnel would be used by road and cabling. Therefore absorber pipes do not be placed in the bottom part under the road. As shown in **Fig. 5**, the surrounding rock and tunnel lining temperatures of line AB on the 10, 30, 60 and 90 d are plotted in **Fig. 6**. The tunnel lining temperature of 0-0.6 m increases with the distance due to heating by the absorber pipes. The highest temperature occurs at 0.6 m which is the location of the absorber pipes, then the temperature decreases with the distance. The distance of ground temperature disturbance increase with time while there some different variations of the tunnel lining temperature at 0 m. Because the tunnel lining temperature of 0 m is susceptible to air temperature due to it is closed to the inner wall of the tunnel, which varies with air temperature. Moreover, the growth rates of the temperature with time decreased due to the increasing temperature difference of the lining and air, which can induce more heat exchange.

**4. Conclusions**

The paper investigated the fluid temperature, energy efficiency ratio (EER) of the hump and the ground temperature distribution of mountain tunnel lining GHEs by the 3D numerical models. And based on the EER of the heat pump, a design of a mountain tunnel lining GHEs was proposed.
(1) The diurnal temperature range of the fluid inside the tube is much smaller than that of the air temperature, and has a hysteresis.

(2) It is feasible that time-dependent inlet temperature depended on the GHEs load is used in the numerical model to design the mountain tunnel lining GHEs.

(3) The design of the energy tunnel lining GHEs with a pipe pitch of 0.6 m and a pipe length of 329.4 m can produce 175 kW of refrigeration power under continuous operation mode in summer with a rational energy efficiency ratio (more than 4).

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