Heat transfer efficiency of energy tunnel influenced by inlet temperature, flow rate and pipe spacing

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Abstract. Energy geostructures can be used in urban Heating Ventilating and Air Conditioning (HVAC) system to save energy and reduce emissions. Energy tunnel can extract shallow geothermal energy economically and efficiently without pollution. Based on the utility tunnel in Nanjing, China, heat transfer pipes are buried in the utility tunnel on the non-constant temperature zone to be an energy tunnel. Field test and numerical simulation on the heat exchange efficiency of energy tunnel are carried out. The inlet/outlet temperature and thermal induced stresses are measured and discussed. The results show that the unit heat area transfer efficiency of the energy tunnel is about 63W/m², the heat transfer efficiency is positively correlated with the inlet temperature and flow rate, and negatively correlated with the pipe spacing.

1. Introduction

With the rapid development of China's economy, the city's building energy consumption is gradually increasing, and its proportion in total social energy consumption rise to 21.1%[1]. As a renewable source, shallow geothermal energy can be used to alleviate energy consumption problem of urban Heating Ventilating and Air Conditioning (HVAC) system and achieve purpose of energy conservation and emission reduction, which has been concerned by engineers and technicians[2]. Energy geostructures have the double role of extracted shallow geothermal energy and supports underground structures by burying heat transfer pipes into the underground structure[3]. Energy tunnel is a new type of energy geostructures by burying heat transfer pipes in tunnel structure, it plays an important role in the development and utilization of shallow geothermal energy in the future[4].

The arrangement of heat transfer pipes is directly related to the construction technology of tunnel. Based on the Lainzer Tunnel in Vienna, the Stuttgart-Fasanenh of Tunnel in Germany and the LinChang tunnel in Inner Mongolia, which are constructed by New Austrian Tunnelling Method (NATM or mining method), the feasibility and economy of energy tunnel were studied[5], the heat transfer performance under different operation modes were discussed, and an approximate calculation method for estimating air temperature in tunnel was point out[6], the effects of inlet temperature, flow rate and pipe spacing on the heat transfer capacity of tunnel and the effects of heat transfer on the temperature field of tunnel surrounding rock and lining were studied, respectively[7]. Relying on the energy tunnels constructed by Tunnel Boring Machine (TBM), such as the Warsaw metro tunnel in
Poland, the Jenbach tunnel in Austria, the Turin metro line 1 tunnel in Italy and the Qinghuayuan tunnel in Beijing-Zhangjiakou railway, the construction technology of burying heat transfer pipes in shield segments were introduced[8], combined with numerical simulation analysis to evaluate the heat transfer potential of the Warsaw metro tunnel and the influence of geological conditions on heat transfer performance[9]. Field test and numerical model data of the energy tunnel of the Turin metro line 1 were applied to different ground and environmental conditions, and some parametric design charts were given[10]. Combined with the numerical simulation method, the heat transfer pipes buried in inverted arch tunnel, the effects of buried pipes spacing, inlet temperature and thermal conductivity of surrounding rock on the tunnel heat transfer efficiency were designed and discussed[11].

However, previous research are mainly focused on the NATM (or mining method) tunnel or TBM tunnel, and there are little studies focused on the utility tunnel constructed by cut and cover method, which is common in urban underground. There are some differences between the cross-section form and boundary conditions of cut and cover tunnel and NATM tunnel or TBM tunnel, especially it is located in the non-constant temperature zone within the range of 0~10m, which is quite different from the buried depth of the traditional energy tunnel. Hence, based on the utility tunnel located in Nanjing, China, field test and numerical simulation on the heat transfer performance of energy tunnel are carried out, which provides reference for the preliminary design of energy tunnel based on urban utility tunnel.

2. Overview of field test

2.1. Background of project

Based on the utility tunnel located in Nanjing, China, the main body of utility tunnel is 1.07km long, the cross-section is 3.8m×3.0m rectangular, and the reinforced concrete wall thickness is 0.35m using C35 concrete. In the west branch tunnel, a tunnel section of 3.0m long with buried heat transfer pipes is taken as the test section, and the buried depth of the top plate is about 4.0m (Figure 1).

![Figure 1. The cross-section of energy tunnel](image)

2.2. Energy tunnel and the layout of sensors

Combined with the construction steps of cut and cover method, the heat transfer pipes are bound in reinforcing cages of bottom plate, side plate and top plate of the tunnel, respectively. The heat exchange pipes are HDPE pipe with outer diameter of 20mm, inner diameter of 16mm and the heat transfer pipe spacing is 0.3m. The heat transfer pipe in the different plates is connected to a closed loop. The arrangement of the heat transfer pipe is shown in Figure 2.
2.3. Soil properties parameters in-situ

The construction method of the energy tunnel is cut and cover method, hence, original soil is below the bottom plate, and the backfill soil is near the side plate and above the top plate, the backfill time is less than 5 years during the test. The soil in-situ can be divided into three layers: layer ① is miscellaneous fill, layers ③1 and ③3 are both silty clay. The thickness and mechanical properties of each soil layers are shown in Table 1.

| Layer number | Depth (m) | % | κ (kN/m³) | e | Consolidated quick shear | c (kPa) | φ(°) |
|--------------|-----------|---|-----------|---|-------------------------|--------|------|
| ①           | 0-7       | 27.5 | 18.0     | 0.840 | 15 | 10 |
| ③1          | 7-8       | 24.6 | 19.8     | 0.721 | 62.8 | 18.6 |
| ③3          | 8-10      | 23.7 | 19.9     | 0.687 | 59.1 | 18.4 |

Note: w is the water content, γ is the unit weight of soil, e is the porosity ratio.

3. Introduction of numerical simulation

3.1. Numerical model

A three-dimensional model is established, and the heat transfer between the energy tunnel and the surrounding environment is simulated by using non-isothermal pipe flow and solid heat transfer module. On the basis of the tunnel in the actual test section, the simulated energy tunnel has been simplified to reduce the calculation amount, the simulated tunnel is 10m long, with cross-section is 3.8m×3.0m and wall thickness is 0.35m, the heat transfer pipe is buried in the middle, 15cm away from the tunnel surface, and the pipe spacing is 0.3m, total length of the energy tunnel of the buried
The pipe section is 3m, the inlet and outlet are located at the bottom plate and the top plate, respectively. Because the surrounding soils are silty clay and the related physical parameters are similar, so it can be modeled as a whole, the calculation area is a cube with a length × width × height of 30m×10m×20m. The heat transfer pipe is modeled as a three-dimensional curve by using non-isothermal pipe flow module. Soil and tunnel structure use free quadrilateral element, and the heat transfer pipe uses edge element, and the mesh around the heat transfer pipe is refined to improve the calculation accuracy (Figure 3).

![Figure 3. Numerical model diagram of the energy tunnel](image)

The heat transfer fluid is water, and the heat transfer pipe is HDPE pipe, the temperature of the tunnel and surrounding soil will change during the heat transfer process, because the temperature change is small, the thermal conductivity of soil and concrete will not change significantly[12]. Therefore, the numerical model assumes that the thermal conductivity of concrete and surrounding soil is constant. According to the thermal conductivity diagram of different types of soil given in "Technical standard for utilization of geothermal energy through piles" (JGJ/T 438-2018)[13], the thermal conductivity of soil is taken as 1.6 W/(m·K) in the numerical model. During the field test, the thermal conductivity of the tunnel concrete and the heat transfer pipe is not measured, and they are selected within reasonable range in Table 2, the thermophysical parameters of water are temperature-related variables, which are directly imported from the model library.

![Table 2. Properties of materials in numerical model](image)

| Material          | Thermal conductivity $\lambda$ W/(m·K) | Specific heat $C_p$ J/(kg·K) | Density $\rho$ g/cm$^3$ |
|-------------------|--------------------------------------|-----------------------------|-------------------------|
| Silty clay        | 1.6                                   | 2500                        | 1.8                     |
| Concrete          | 2.5                                   | 880                         | 2.3                     |
| PE pipe           | 0.4                                   | 900                         | 1.38                    |

3.2. Boundary conditions and initial conditions

The heat transfer in energy tunnel will be affected by ground temperature and air temperature inside the tunnel, and the ground temperature will also be influenced by environmental temperature. The environmental temperature change is shown in Figure 4, and upper surface of the soil is set as the thermal convection boundary, due to the symmetry of the model, and in order to reduce the influence of thermal convection caused by different initial temperatures of the soil, the surrounding soil is set as an adiabatic boundary, and the lower surface is set as a constant temperature boundary, whose temperature is the same as that of adjacent ground temperature.
The temperature distribution of soil is not uniform in space, the temperature change in horizontal direction is relatively small but relatively large in the vertical direction. In this paper, the numerical model assumes the same initial temperature in horizontal direction of the soil, and the initial temperature in vertical direction is set as linear distribution along depth according to field measurement (Figure 5). Inner surface of the tunnel is a thermal convection boundary, according to the field measurement, the air temperature inside tunnel is set at 12℃. Initial temperature of the tunnel structure is consistent with ground temperature at the same depth.

3.3. Research condition design
The numerical simulated temperature load is consistent with the field test, which is basically stable at 20.1℃ after a period of temperature rise. The velocity of circulating water is set at 0.6m³/h, and running time of the numerical simulation is 240h, which is the same as the field test. In order to improve calculation efficiency, each time sub-step length is 5h in the first 80h and 10h in the last 160h, and the model solver is a time-dependent transient solver. Temperature recovery process is not considered.

3.4. Verification of numerical model
Under the condition of the same inlet temperature, the results obtained through the numerical simulation and the field test are shown in Figure 6, the simulated results of outlet temperature are basically consistent with the field test, both rise with the increase of inlet temperature, after 240h, the simulated and measured are 16.3℃ and 16.4℃, respectively, and the error between them is only 0.6%.

4. Results and analysis
4.1. Heat transfer efficiency versus inlet water temperature
The heat transfer efficiency of energy tunnel can be calculated by the following equation:

\[ q = m_w c_w (T_{in} - T_{out}) / A \]  

where \( q \) is the unit area heat transfer efficiency, W/m²; \( m_w \) is the mass flow of circulating fluid, kg/s; \( c_w \) is the specific heat of circulating fluid, J/(kg·K); \( T_{in} \) and \( T_{out} \) are the inlet/outlet circulating fluid temperature, respectively, K; \( A \) is the heat transfer area of energy tunnel, m².

The inlet temperature is simulated under different pipe spacing and flow velocity, and the relationship between inlet temperature and heat transfer efficiency is shown in Figure 7. The heat transfer efficiency linearly increased with the rise of inlet temperature, which indicates that
temperature difference between the inlet temperature and the original ground temperature are larger, more heat is transfer between the heat transfer pipe and the soil. These results are basically consistent with the research results obtained by Zhang Guozhu[14].

![Figure 6](image1.png) ![Figure 7](image2.png)

**Figure 6.** Inlet/outlet temperature versus time  **Figure 7.** Heat transfer efficiency versus inlet temperature

4.2. **Heat transfer efficiency versus flow rate**

The flow rate is simulated under different inlet water and pipe spacing, and the relationship between flow rate and heat transfer efficiency is shown in Figure 8. The heat transfer efficiency increases with the rise of flow rate, while the increment gradually becomes smaller, the reason may be that when the flow rate is small, the heat transfer fluid can exchange heat with the pipe wall more fully, but the mass flow rate is small at the same time. Therefore, the heat transfer amount is small according to the equation (1). With the rise of flow rate, the mass flow rate becomes larger, so the heat transfer amount gradually increases. However, when the flow rate increases further, the heat exchange between the heat transfer fluid and the pipe wall is insufficient. The temperature difference tends to smaller, so the heat transfer efficiency tends to be flat. The above rule is consistent with the research results obtained by Barla[15] and Di Donna[16]. Considering the practical application, 0.4m/s is the best flow rate, because heat transfer efficiency is relatively high and flow rate is small, which is beneficial to reduce the energy consumption of the pump.

4.3. **Heat transfer efficiency versus pipe spacing**

The pipe spacing is simulated under different inlet water temperature and flow rate, and the relationship between pipe spacing and heat transfer efficiency is shown in Figure 9. The heat transfer efficiency decreases with the increase of the pipe spacing, and the relationship between them is basically linear, the reason is that when heat transfer area is fixed, the pipe spacing is larger, the total length of heat transfer pipe is shorter, so heat transfer amount with surroundings is smaller, which is consistent with the research results of Cousin[17]. However, smaller spacing means longer pipes, so considering economic benefits and referring to the optimal design of flow rate, the efficiency is higher when the pipe spacing is about 0.4m.

Figures 7 and 9 are show that the heat transfer efficiency is basically linearly related to inlet temperature and pipe spacing. Therefore, when designers use the results in Figure 8 to calculate the heat transfer efficiency of energy tunnel, if the design parameters are between those given in the figure, the linear interpolation method can be used to determine the unit area heat transfer efficiency of the energy tunnel.
5. Conclusion

In this paper, based on the utility tunnel located in Nanjing, China, field test on the heat transfer of energy tunnel is carried out, and the influence of different parameters on heat transfer efficiency are studied through numerical simulation. The results provided a reference for preliminary design of the energy tunnel. Some main conclusions can be obtained based on this field test conditions:

(1) The unit area heat transfer efficiency is about 63W/m². Heat transfer efficiency is basically linearly with inlet temperature and pipe spacing, it increases with the rise of inlet temperature, and decrease with pipe spacing. The relationship between flow rate and heat transfer efficiency is nonlinear, and heat transfer efficiency gradually stabilizes with the increase of flow rate.

(2) Considering economic benefits, the optimal flow rate and pipe spacing are 4.0m/s and 0.4m, respectively. Meanwhile, heat transfer efficiency of energy tunnel under different design parameters can be determined through the design drawings provided in this paper, which provides a reference for preliminary design.

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