

Article

Study on Calculation Method of Heat Exchange Capacity and Thermal Properties of Buried Pipes in the Fractured Rock Mass-Taking a Project in Carbonate Rock Area as an Example

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Abstract: Fractures are developed in carbonate rock areas, and the fracture water flow significantly influences the heat exchange between buried pipes and the rock mass by inducing heat convection, providing the carbonate rock area a strong heat exchange capacity and preferable conditions for shallow geothermal development and utilization. In this paper, the calculation method of heat exchange capacity of buried pipes based on fracture distribution characteristics is proposed and deduced, featuring such advantages as quick speed and low cost. Taking an actual project in carbonate rock area as an example, the heat exchange capacity of buried pipes was obtained by the following two methods: in-situ thermal response test and calculation based on fracture distribution characteristics. In the thermal response test, the initial ground temperatures of the two test holes were 15.18 °C and 12.72 °C. By fitting the linear equation of time and average temperature with a linear thermal source model, the heat exchange capacities were 57.21 W/m and 58.22 W/m, the thermal conductivities were 3.56 W/(m·K) and 2.32 W/(m·K), the thermal diffusivities were $1.71 \times 10^{-6} \text{ m}^2/\text{s}$ and $1.12 \times 10^{-6} \text{ m}^2/\text{s}$, and the volume specific heat capacity was $2.08 \times 10^6 \text{ J (m}^3 \cdot \text{K)}$. The test results indicated that the thermal property parameters of rock and soil mass were higher than those of other areas, with obvious wide-range distribution characteristics. Through the statistical analysis of outcrop fracture characteristics, combined with the cube law to calculate the fracture water flow and convective heat transfer, an alternative method for the calculation and optimization of buried pipe heat transfer in fractured rock mass area is also proposed in this paper. According to the measured fracture distribution characteristics of the field outcrop, the heat exchange capacities of the two holes were 57.26 W/m and 58.56 W/m, which were basically consistent with the thermal response test values and verified the reliability of the calculation method of heat exchange capacity of buried pipes based on fracture distribution characteristics.

Keywords: carbonate rock; buried pipe; thermal property parameter; thermal response test; fracture distribution characteristics



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1. Introduction

In September 2020, China clearly proposed the goal of reaching peak carbon emission before 2030 and carbon neutrality before 2060, which attracted worldwide attention [1]. The promotion and utilization of new energy is an important means to achieve this strategic goal [2]. Ground source heat pump (GSHP) system is used to efficiently develop and utilize the clean and eco-friendly shallow geothermal energy, and it is one of the most promising heat pump air-conditioning technologies [3,4]. GSHP features long life, wide applications, stable use, low emissions [5], and it has been widely applied in building heating/cooling [6].

However, when the geological conditions are not fully explored, the ground source heat pump system will accumulate hot and cold, which will affect the operating efficiency of the system. The ground coupled heat pump, as one of main technical methods, exchanges energy with the surrounding rock and soil mass through a closed U-shaped pipe filled with circulating heat carrying fluid. Its heat exchange capacity and efficiency are directly related to the geological conditions and the thermal properties of rock and soil mass.

The thermal property parameters of rock and soil include thermal conductivity, thermal diffusivity and specific heat capacity [7]. These parameters reflect the thermal storage and thermal conductivity capacity of rock and soil, and they are the basic data for the study of occurrence of shallow geothermal energy resources, resource potential evaluation and heat pump system development [8]. Thermal conductivity is an important parameter in the design of ground source heat pump system of buried pipes [9], which has a great influence on the long-term operation of the system and the evaluation of heat storage/release capacity of rock and soil [10]. If 10% errors occur in thermal conductivity, it will result in a deviation of 4.5~5.8% in the length of the buried pipe [11], which is very important for the design and initial input of the length of underground heat exchanger [12]. In order to determine these parameters, in-situ thermal response test (TRT) is usually conducted in practice [13–17], which can truly simulate the actual operation of the ground source heat pump [18].

The province of Guizhou, located in southwest of China, abounds in shallow geothermal energy resources. The geological and geomorphological conditions, which are dominated by carbonate rocks, are special, and the fractures in the rock mass are well-developed. Heat convection brought by abundant fracture water flow can help strengthen the heat exchange effect of buried pipes. Generally, the occurrence conditions of shallow geothermal energy are ideal [19], but the degree of development and utilization is low. In the coming five years, the geothermal industry is expected to vigorously develop, and it has been urgent to break through the key problems in the development and utilization of shallow geothermal energy and obtain technical parameters. However, in-situ thermal response test usually has some problems such as high cost and time consuming. In the existing codes and standards, the effect of the fracture water flow is not considered in the calculation model of heat exchange capacity of buried pipes. For example, the standard DZ/T 0225-2009. Based on the fundamental theory of heat transfer, this paper proposes and derived the calculation method of heat exchange capacity of buried pipes based on fracture distribution characteristics. This method is simple, quick and low-cost. Taking a ground source heat pump project in a carbonate area of Guizhou as an example, the distribution characteristics of fractures were obtained by field outcrop measurement, and then the heat exchange capacity of buried pipes was calculated by using the above method. In addition, the thermal response parameters of the study area were measured through TRT, and the infinite linear source (ILS) model was used to fit the arithmetic average inlet and outlet temperatures of the fluid, and the heat exchange capacity and thermal conductivity were obtained to evaluate the heat exchange capability of the site. The results showed that the heat exchange calculated based on the fracture distribution characteristics was close to the calculated value of TRT, which proves that this method can be used as a quick and low-cost alternative for TRT. Meanwhile, the test and calculation results in this paper also provide a design basis for the development and utilization of shallow geothermal energy in similar projects.

2. Thermal Response Test Devices and Test Methods

2.1. Test Devices

The thermal response tester developed by Beijing Geothermal Research Institute mainly consists of heating device with adjustable power, water storage tank, circulating water pump, temperature and flow measuring devices, and data acquisition and automatic control system. The tester is connected with heat exchange test holes of 2 double-U buried pipes with the borehole depths of 160 m and 200 m to provide stable heat flow and obtain

the temperature changes and flow data of inlet and outlet water of underground heat exchanger. The two test holes are distributed in different areas, and the thermal interference between the holes can be neglected. The diagram (Figure 1) and parameters of the test system device are shown in Table 1.

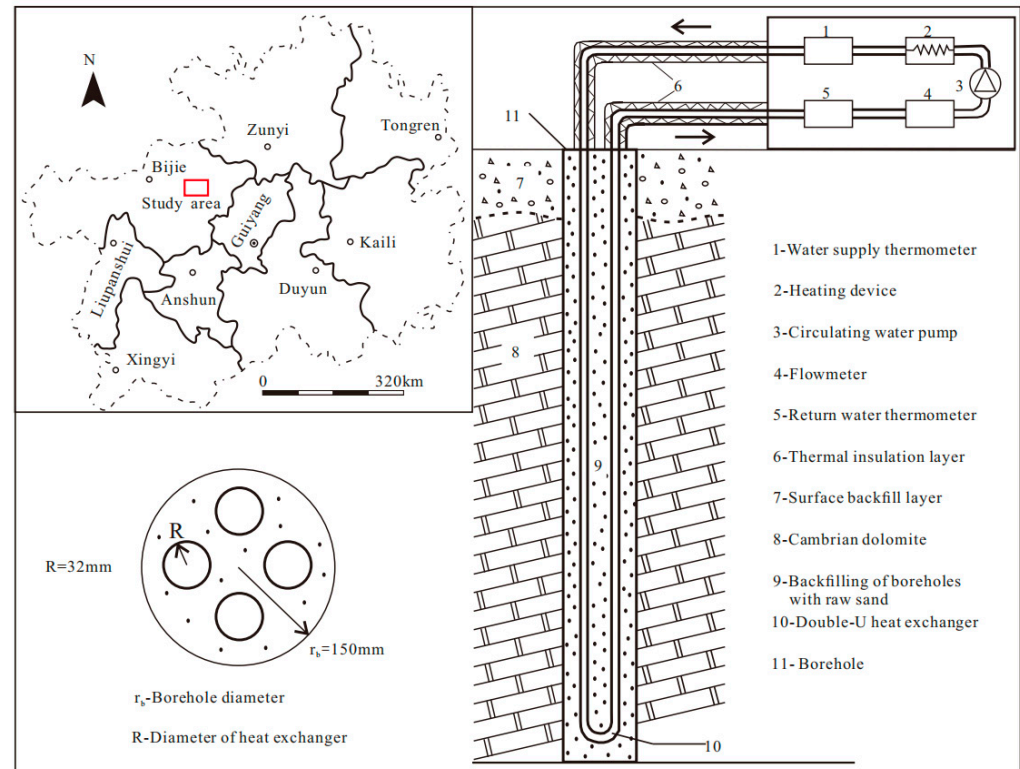


Figure 1. Working area location and test diagram.

Table 1. The parameters of thermal response test.

Parameter	Unit	Value		Parameter	Unit	Value
		Hole ZK1	Hole ZK2			
Diameter of PE pipe	m	0.032	0.032	Pipe and specification	-	HDPE100
Inner diameter of PE pipe	m	0.026	0.026	Time interval for data point	minutes	3
Distance between double-U pipes	m	0.064	0.064	Inner diameter of borehole	m	0.15
Duration of power supply	h	48	48	Input power	W	9
Depth of borehole	m	200	160	System flow	m ³ /h	1.5
Rock integrity		Local fracture development	Local fracture development	Circulating fluid	-	Water
Water table		89 m	96 m	Backfill material	-	Raw sand
Stratum lithology	-	Dolomite of Cambrian Loushanguan Formation		-	-	-

2.2. Test Methods

The thermal response test is carried out according to the following steps, and the test results are shown in Table 2.

1. After the PE pipe is filled with circulating fluid, lower it to the required borehole depth, and backfill it for times to ensure that the backfilling is dense;
2. The reactive circulation of the test system lasts for at least 12 h, and the initial ground temperature is obtained after the temperature of the circulating fluid and the surrounding rock and soil mass reaches a constant and stable level;

3. Start the tester, convey the stable heat flow to the testing well for at least 48 h, and record the data of inlet/outlet temperature, circulating fluid flow and heating power of underground heat exchanger every 3 min after the test is started;
4. After the test time meets the requirements, export and save the data after checking the data records, and turn off the tester to finish the test.

Table 2. Test result of initial ground temperature.

Borehole No.	Test Time/h	Basically Stable Time/h	System Flow/m ³ /h	Initial Ground Temperature/°C
Hole ZK1	14	13	1.5	15.18
Hole ZK2	14	12	1.5	12.72

2.3. Linear Source Heat Transfer Model

Generally, the heat transfer model which is commonly used in the TRT is a simplified steady-state heat transfer model with constant heat flux. The test data in this paper adopt the linear source model [20,21]. Ingersoll et al. [22] assumed that the rock and soil mass around the buried heat exchangers was a semi-infinite heat transfer medium, the underground heat exchanger (U-pipe) was regarded as an infinitely long line heat source, and the initial temperature of the surrounding rock and soil mass was constant without considering radial heat transfer. The infinite long linear source model is adopted for logarithmic curve fitting analysis, and the analytical equation is as follows:

$$T_f - T_0 = \frac{q}{4\pi\lambda_g} \left[\ln\left(\frac{4at}{r_b^2}\right) - \gamma \right] + qR_b \quad (1)$$

where T_f is the average temperature of supply and return water (°C); T_0 the initial average temperature (°C); q the linear meter heat exchange capacity (W/m); λ_g the thermal conductivity of rock and soil mass W/(m·°C); a the thermal diffusivity of rock and soil mass (m²/s); t the time (s); r_b the radius of borehole (m); γ Euler's constant ($\gamma = 0.5772$); R_b the thermal resistance of borehole (m·K/W).

The heat exchange capacity of heat exchanger in the buried hole represents the heat that can be exchanged per unit depth of heat exchanger:

$$q = \frac{Q}{L} \quad (2)$$

where Q is the heat exchanged by the heat exchange holes (W); L the depth of the heat exchanger (m).

According to the thermal and mass flow equation:

$$Q = cm\Delta t = C_f Q_v \Delta t \quad (3)$$

where c is the specific heat capacity of circulating fluid, J/(kg·°C); m the mass of circulating fluid (kg); Δt the temperature of absorption or release (°C); C_f the volume specific heat capacity of the fluid, J/(m³·K); Q_v the volume flow of fluid (m³/s).

Equation (3) is substituted into Equation (2) to obtain:

$$q = C_f Q_v (T_{in} - T_{out}) / L \quad (4)$$

where T_{in} is the supply water temperature (°C); T_{out} the return water temperature.

$$a = \lambda_g / C_g \quad (5)$$

where C_g is the volume specific heat capacity of rock and soil mass, J/(m³·K)

When $\frac{at}{r_b^2} \geq 5$ and the error is less than 10% [23,24], Equation (1) can be expressed as:

$$T_f = \frac{q}{4\pi\lambda_g} \ln t + \frac{q}{4\pi\lambda_g} \left[\ln\left(\frac{4a}{r_b^2}\right) - \gamma \right] + qR_b + T_0 \quad (6)$$

Suppose the constant:

$$k = q / (4\pi\lambda_g) \quad (7)$$

$$b = \frac{q}{4\pi\lambda_g} \left[\ln\left(\frac{4a}{r_b^2}\right) - \gamma \right] + qR_b + T_0 \quad (8)$$

When q is constant, the linear Equation (6) can be obtained:

$$T_f = k \ln t + b \quad (9)$$

The average temperature of the supply water and return water of the buried pipe in the TRT of constant heat flow is fitted into the logarithmic curve of Equation (7) to obtain the slope k and the intercept b , and then the thermal conductivity λ_g of rock and soil mass can be calculated.

3. TRT Results and Analysis

3.1. Measurement of Initial Ground Temperature

The initial ground temperature is an important parameter and factor in the optimal design and operation evaluation of GSHP system [25]. Based on the reactive circulation method, the thermal response tester was used in the test. Instead of turning on the heating device, only the circulating pump was used to maintain the loop circulation of underground heat exchanger. After a certain period of time, when the temperature of the supply/return water inlets of the underground heat exchanger gradually became equal or maintained a small temperature difference (normally 0.1~0.2 °C), the average temperature of the supply/return water inlet could be regarded as the initial ground temperature.

The study area is located in the middle of Bijie City, Guizhou Province with an altitude about 1500 m, which belongs to the warm humid monsoon climate zone with an average annual temperature of 11.8 °C and a geothermal gradient of 3.5 °C/100 m. The site test results show (Table 2) that although the hole depth ZK1 was only 40 m deeper than that of ZK2, the initial ground temperature increased by 2.46 °C from 12.72 °C to 15.18 °C. The higher the regional geothermal gradient, the higher the stratum temperature. Below the water table of 89 m, the dolomite with strong water-bearing and permeability maintained the temperature of the stratum well, indicating preferable geothermal resource potential in the area.

3.2. Measurement of Temperature of Supply and Return Water

In the test, the heating power of the electric heating device was constantly maintained at 9 kW. The electric heating device was turned on to continuously heat the water in the storage tank. The test time was 48 h, the flow of the circulating water pump was maintained at 1.5 m³/h, and the data were recorded every 3 min.

The changes of supply/return water temperature and average temperature of ZK1 and ZK2 with time are shown in Figure 2. About 6 h before the test, the inlet and outlet temperatures of the system changed sharply, and the curve showed a steep growth trend. After the 7th hour, the change tended to be stable and gentle until it reached a stable state. At last, the temperature difference between supply water and return water of ZK1 was maintained at about 5 °C, while ZK2 was maintained at about 4.6.

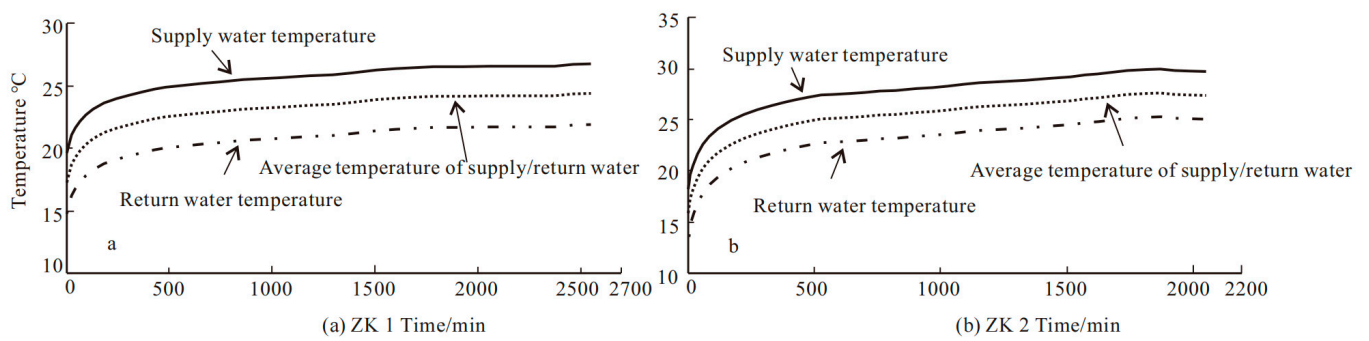


Figure 2. Supply/return water and its average temperature change curves of the testing well ZK1 (a) and ZK2 (b).

3.3. Heat Exchange Capacity and Thermal Conductivity

According to the above analysis, the duration for the heat exchange between the circulating fluid in the buried pipe and the rock and soil mass to reach a relatively stable level was about 6 h before the test, and the basic condition of $at/r_b^2 \geq 5$ needed to be met. The data from the test for 7~48 h hours were used for analysis.

According to Equation (4), the heat exchange capacities of the rocks ZK1 and ZK2 were 57.21 W/m and 58.22 W/m. The average temperature of the supply and return water was fitted into a logarithmic relationship with time. The logarithmic function of ZK1 had a relatively high fitting degree ($R^2 = 0.988$), and the constant k was 1.2771 (Figure 3a). The logarithmic function of ZK2 also had an ideal fitting degree ($R^2 = 0.935$), and the constant k was 2.0005 (Figure 3b). The thermal conductivities of rock and soil mass of ZK1 and ZK2 could be calculated from the above Equation (7), which were 3.56 W/(m·K) and 2.32 W/(m·K).

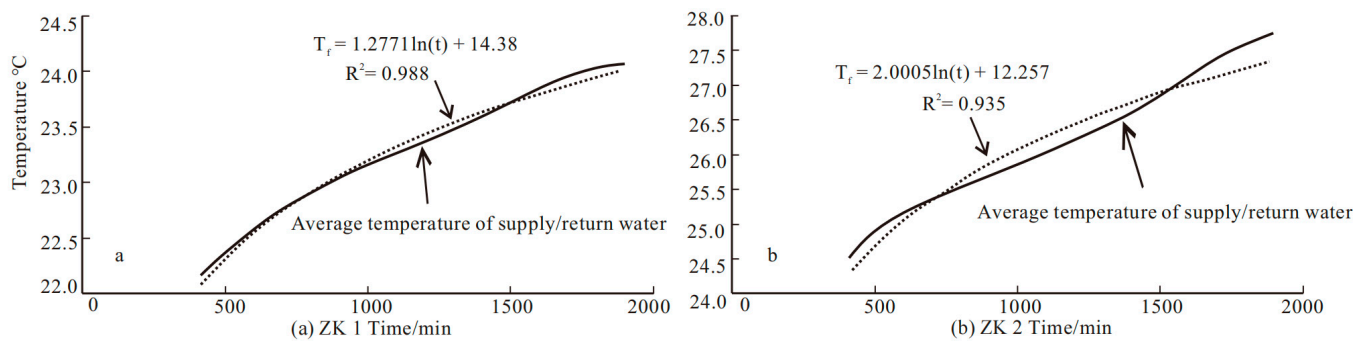


Figure 3. Fluid temperature and time logarithm ZK1 (a) and ZK2 (b).

3.4. Thermal Diffusivity and Specific Heat Capacity

According to the research results of [26], the average specific heat capacity of dry samples of Cambrian dolomite in Guizhou was 0.535 kJ/(kg °C), and that of saturated samples was 0.459 kJ/(kg °C). It can be seen from Table 1 that the hole depths of ZK1 and ZK2 were 200 m and 160 m, and the measured water table were 89 m and 96 m. The average value of 0.497 kJ/(kg·°C) of dry and saturated samples was assumed. That is, 2.08×10^6 J/(m³·K) can be taken as the specific heat capacity of rock and soil mass in this thermal response test. According to Equation (5), the thermal diffusivities of rock and soil mass in ZK1 and ZK2 were 1.71×10^{-6} m²/s and 1.12×10^{-6} m²/s.

4. Calculation of Heat Exchange Power of Buried Pipes Based on Fracture Characteristics

4.1. Heat Conduction-Heat Convection Coupling Model

The heat exchange power Q (W) in Equation (3) of 2.3 was obtained according to the heat exchange flow of circulating fluid. When considering the effect of fracture water on the

heat exchange power of the buried pipe, it can be further described as the heat conduction Q_r (W) with the rock mass, the heat convection Q_w (W) with the fracture water flowing through the heat exchange holes, and heat conduction with the air in fractures Q_a ,

$$Q = Q_r + Q_w + Q_a \quad (10)$$

where Q_r is the heat exchange capacity (W) by conduction with the surrounding rock; Q_w is the heat exchange capacity (W) by convection with the fracture water flowing through the heat exchange holes.

Where the heat exchange capacity Q_r (W) of the rock mass around the heat exchange holes can be expressed as Equation (11):

$$Q_r = \frac{2\pi L_r (T_f - T_0)}{\frac{1}{\lambda_r} \ln \frac{R_0}{r}} \quad (11)$$

where, L_r is the contact length of the rock mass in the heat exchange hole (m); λ_r is the thermal conductivity of the rock mass around the heat exchange holes, W/(m·K); r is the equivalent radius of pipe bundle, the radius of the double-U pipe is $2r_b$, and the wall thickness is 0.055 m; R_0 is the temperature balance radius around the heat exchange holes, which is 2.5 m.

The heat exchange capacity Q_w (W) of the fracture water flowing through the heat exchange holes can be expressed as Equation (12):

$$Q_w = \frac{h \Delta t_f \pi d e_{sum}}{\sin \theta} \quad (12)$$

where h is the convective heat transfer coefficient between fracture water and heat exchange hole, W/(m²·K); Δt_f is the temperature difference between heat exchange hole and fracture water, taking the arithmetic average temperature difference (K); d is the diameter of the heat exchange hole, taking r_b , m; e_{sum} is the sum of the gap widths e of all water-filled fractures within the depth range of heat exchange hole (m); θ is the intersection angle between fracture water flow and heat exchange hole (°).

$$Q_a = \frac{2\pi (L - L_r - \frac{e_{sum}}{\sin \theta}) (T_f - T_0)}{\frac{1}{\lambda_a} \ln \frac{R_0}{r}} \quad (13)$$

where, λ_a is the thermal conductivity of the air around the heat exchange holes, W/(m·K).

4.2. Measured Fracture Characteristics and Heat Exchange Power of Heat Exchange Holes

Site survey and measurement of fractures in the stratum outcrop of the project site were conducted (Figure 4). Statistics on the distribution characteristics of fractures was made, including the distribution of fracture density and gap width, as shown in Table 3. The heat exchange power of the heat exchange hole was calculated according to Equations (10)–(13) in Section 4.1, and it was compared with the value obtained by TRT in Section 3.3.

The motion viscosity coefficient of the fracture water was 1.003×10^{-6} (m²/s), the flow rate of the fracture water was 0.0007(m/s); the thermal conductivity λ_r of the rock mass around ZK1 was 3.9 W/(m·K); the thermal conductivity λ_r of the rock mass around ZK2 was 2.55 W/(m·K); the thermal conductivity λ_a of air was 0.025 W/(m·K); other parameters were calculated according to Equations (10)–(13).

When the intersection angle θ between fracture water flow and heat exchange hole was 90°, the heat exchange power of ZK1 and ZK2 were 57.26 W/m and 58.56 W/m. In addition when the intersection angle θ was 30°, the heat exchange power of ZK1 and ZK2 were 58.43 W/m and 59.92 W/m. According to the basic heat transfer equation and

the measured fracture characteristics, and they were basically consistent with the value obtained by TRT in Section 3.3. To some extent, it proved that the method of calculating heat exchange power of the heat exchange hole according to the statistical data of fracture characteristics was scientific.



Figure 4. The photos for outcrop fractures.

Table 3. Calculation of water flow in typical fracture gap widths of Groups I and II.

Hole ZK1 Distribution of Fractures						
Aperture, mm	0.5	1	1.5	2	3	4
Frequency, %	90	4	3	2.5	0.3	0.2
Quantity, piece	1499	67	50	42	5	3
Trace length, m	3	3	3	3	3	3
Hole ZK2 Distribution of fractures						
Aperture, mm	0.5	1	1.5	3	6	12
Frequency, %	75	10	7	5	2	1
Quantity, piece	720	96	67	48	19	10
Trace length, m	3	3	3	3	3	3

5. Characteristics of Thermal Property Parameters in Carbonate Rock Area

After comparing the analysis results of this experiment with the previous results [14,15,26,27] (Table 4), it is found that thermal conductivity, thermal diffusivity and volume specific heat are in consistency with the parameters listed in the code, and they are consistent with the research data of major urban agglomerations in Guizhou Province. This proves the reliability of this experiment.

Table 4. A comparison of thermal response test parameters.

Comparison Items		Research Results			
Literature comparison	This paper	Literature [27]	Literature [14]	Literature [15]	Literature [26]
Study region	Baili Dujuan, Guizhou	—	Plain area of Beijing	Major cities in North China Plain	Major urban agglomerations in Guizhou
Thermal conductivity, W/(m·K)	2.32~3.56	2.40~3.80	1.47~1.70	1.50~2.16	3.26~6.09
Thermal diffusivity 10^{-6} , m ² /s	1.12~1.71	0.97~1.51	0.45~0.84	—	2.00~3.00
Volume specific heat capacity 10^6 , J/(m ³ ·K)	2.08	—	2.32~3.08	—	1.16~2.74
Stratum lithology	Loushanguan Group Dolostone		Quaternary sandy soil and clay	Quaternary gravel, aggregate, clay, fine sand layer	Loushanguan Group Dolostone

Compared with North China which is dominated by the Quaternary strata, the thermal conductivity of rock and soil mass in the study area is generally maintained at a high level, which can reach 2 times or above [28]. The comprehensive thermal conductivity of rock and soil in most cities is 11.89~2.55 W/(m·K), and the characteristics of stratum structure and hydrogeological conditions are the main factors that affect the comprehensive thermal conductivity of rock and soil mass [29]. The average thermal conductivity of rock and soil mass in carbonate area is large, and it has a strong underground heat exchange capability, providing preferred condition for shallow geothermal development [30], showing strong heat exchange capability and providing favorable conditions for the increase of the heat exchange capacity of single hole.

Compared with other areas with the same lithologic conditions, thermal conductivity, thermal diffusivity and volume specific heat capacity in carbonate rock area have obvious wide-area distribution characteristics (Table 4). They are not merely affected by moisture content, density, mineral compositions and other factors of rock and soil mass. The fluctuation of groundwater levels [5], seepage rate [30], karst development degree [19], local air temperature and its geothermal gradient are all unstable sensitive factors. It is worth noting that the thermal property parameters of carbonate rock area still reflect the abundance and diversity of geothermal resources in this area, and provide an expected guarantee for the development and utilization of geothermal resources.

6. Conclusions

- (1) The data obtained from the in-situ thermal response test are matched with the existing research results and consistent with the thermal property parameters of the actual geological and hydrological conditions. The calculation method based on the linear source model and derivation is reliable.
- (2) The experimental results showed that the initial ground temperatures of holes ZK1 and holes ZK2 were 15.18 °C and 12.72 °C, the thermal conductivities were 3.56 W/(m·K) and 2.32 W/(m·K), the thermal diffusivities were $1.71 \times 10^{-6} \text{ m}^2/\text{s}$ and $1.12 \times 10^{-6} \text{ m}^2/\text{s}$, and the volume specific heat capacity was $2.08 \times 10^6 \text{ J (m}^3\cdot\text{K)}$. The hole depths of ZK1 and ZK2 were 200 m and 160 m, and the measured water table were 89 m and 96 m, respectively.
- (3) In this paper, the calculation method of heat exchange of buried pipes based on the distribution characteristics of rock mass fractures is proposed and deduced, featuring such advantages as simplicity, time saving and low cost. The heat exchange power of holes ZK1 and holes ZK2 were 57.26 W/m and 58.56 W/m, and the calculated results were basically consistent with the thermal response test results.
- (4) Due to the special stratigraphic structure and hydrogeological conditions, the thermal property parameters of rock mass in carbonate area were often higher than those in other areas. Influenced by the physical properties of rock and soil mass and restricted by geological and hydrogeological conditions, the thermal property parameters had obvious wide-range distribution characteristics.
- (5) The shallow geothermal resources in carbonate rock area are rich, with strong heat exchange capability, which provides favorable conditions for the development and utilization of shallow geothermal energy. This is an important energy utilization means to achieve the goals of energy conservation and environmental protection, ecological civilization construction, and “carbon emission peaking and carbon neutrality”.

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