Advances in Geo-Energy Research

Vol. 5, No. 4, p. 376-385, 2021

Original article

Improved test method for convection heat transfer characteristics of carbonate fractures after acidizing etching

Hongyang Zhan[1,2], Wenbao Dong[2,3], Sili Chen[1], Dawei Hu[2,3]*, Hui Zhou[2,3], Jing Luo[4]

[1]*College of Architecture and Civil Engineering, Shenyang University of Technology, Shenyang 110870, P. R. China*

[2]*State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, P. R. China*

[3]*State Key Laboratory of Geomechanics and Geotechnical Engineering, University of Chinese Academy of Sciences, Beijing 100049, P. R. China*

[4]*Sinopec Star Hubei New Energy Development Co., Ltd., Wuhan 430010, P. R. China*

Keywords:
Heat extraction
carbonate reservoir
acidizing etching
convection heat transfer
fracture roughness

Cited as:
Zhan, H., Dong, W., Chen, S., Hu, D., Zhou, H., Luo, J. Improved test method for convection heat transfer characteristics of carbonate fractures after acidizing etching. Advances in Geo-Energy Research, 2021, 5(4): 376-385, doi: 10.46690/ager.2021.04.04

Abstract:
Understanding of convection heat transfer characteristics of fractures is of great significance to improve the heat extraction efficiency of carbonate reservoir. Previous studies on convection heat transfer of fluid flowing through rock fractures are on either granite or sandstone. Limited experimental research has been performed on carbonate fractures after acidizing etching. In this work, an improved test method is developed to analyze the convection heat transfer characteristics of carbonate fractures after acidizing etching under real-time high temperature and high confining pressure. In this method, the traditional test method of convection heat transfer coefficient is improved by monitoring the temperature of inner fracture surface and flowing water. Two thermocouples are especially arranged inside the sample to monitor the temperature of inner fracture surface along the flow direction, and two other thermocouples for the inlet and outlet water temperatures. The results show that the temperature differences between the fracture surface and the flowing water are significantly dependent on confining pressure, fracture roughness and flow rate, and the maximum temperature difference could be reached 2.2 °C, which leads to a significant difference in the convection heat transfer coefficient between the traditional and improved test methods. A larger number of pores, caves, and micro-fractures caused by acid etching are observed on the fracture surface by scanning electron microscopy. The special fracture morphology of carbonate is totally different from those of granite and sandstone in previous studies, and can increase the convection channel and increase the contact area with flowing fluid and results in the inapplicability of the hypothesis to carbonate fractures after acidizing etching. The present work could improve the knowledge of convection heat transfer characteristics of carbonate fractures.

1. Introduction

Deep geothermal energy is clean and renewable, and can contribute huge thermal and electrical energy. Due to these advantages, deep geothermal energy is of great importance for the development of energy industry. Large-scale karst heat reservoirs developed in widely distributed carbonate reservoirs in North China have excellent quality of geothermal resources, can be used for large-scale development and utilization of balanced extraction and irrigation (Wang et al., 2020a, 2020b). Acid fracturing is an essential means of stimulation and reconstruction of carbonate geothermal reservoirs (Zhao et al., 1992; Cao et al., 2016; Luo et al., 2018). During the acid fracturing, the fractures in the rock undergo a non-uniform dissolution reaction. Consequently, the fractures after acid etching maintain a specific opening under the action of formation closure stress and form artificial transport path to improve the convection conditions and increase the extraction rate of geothermal energy (Anyim et al., 2020).

The convection heat transfer characteristics of geothermal reservoir rocks are the key factors determining the thermal

Yandy Scientific Press

*Corresponding author.
E-mail address: zhanliu202106@163.com (H. Zhan); dongwenbao20@mails.ucas.ac.cn (W. Dong); chen1458@163.com (S. Chen); dwhu@whrsm.ac.cn (W. Hu); hzhou@whrsm.ac.cn (H. Zhou); luojing@sinopec.com (J. Luo).

Received September 10, 2021; revised September 28, 2021; accepted September 29, 2021; available online October 2, 2021.

energy production capacity of geothermal reservoirs (Shaik et al., 2011; Song et al., 2018; Aliyu et al., 2021). We can reasonably predict thermal productivity of geothermal reservoirs by accurately recognizing the convection heat transfer characteristics of rocks (Zhao et al., 1994, 1999). Moreover, previous numerical investigation of the heat production process of geothermal reservoirs indicated that temperature, stress and flow rate have significant influence on the convection heat transfer characteristics and thus the heat extraction (Yao et al., 2018). Therefore, it is highly important to knowledge the fluid flow and heat transfer of the carbonate fractures after acid etching under in situ temperature and stress of geothermal reservoirs (Yu et al., 2021).

Convection heat transfer coefficient is usually used to quantitatively describe the convection heat transfer process of fluid through the fracture surface under high temperature (Jiang et al., 2017; Luo et al., 2019). Different methods have been proposed to determine the convection heat transfer coefficient on different types of rock fracture by theoretical or laboratory approaches (Ma et al., 2018; Jiang et al., 2020). By calculating the average heat transfer coefficient between two disk walls, Ogino et al. (1999) creatively proposed that the forced convection between water and the crack surface plays an essential role in the convection heat transfer process. Zhao et al. (2014) derived two analytical solutions to simulate the convection heat transfer experiment of rough granite fractures, and both models showed that the water temperature along the fracture surface increased nonlinearly. Zhu et al. (2016) established a single-fracture cylinder physical model, and derived an analytical solution of the convection heat transfer coefficient of the fractured channel. Bai et al. (2016) established a two-dimensional numerical model of water flow heat transfer to calculate the temperature and pressure distribution along with granite fractures, and proposed the local heat transfer coefficient that can describe the local convection heat transfer characteristics of the fractures. He et al. (2016) and Bai et al. (2017) combined experiments and numerical simulation methods to monitor the temperature changes of inlet and outlet water temperature, and proposed an analytical method for calculating convection heat transfer coefficient under the hypothesis that the average value of inlet and outlet water temperature is identical to that of inner fracture surface. Li et al. (2017) used six temperature sensors to monitor the temperature changes on the external surface of rock samples, and the convection heat transfer coefficient was determined based on the distributions of external surface temperatures. Heinze et al. (2017) considered dynamic changes and local heterogeneity, and derived a dynamic heat transfer coefficient that depends on the fracture aperture, flow rate, and thermal parameters.

These previous test methods could enlarge the knowledge for the determination of convection heat transfer coefficient of rock fracture. However, accurate determination of the heat transfer coefficient of a rock fracture needs to find the temperature distributions in flowing fluid and inner fracture surface, respectively (Zhao et al., 2014), which is still an challenge for either theoretical approach due to the complex morphology of rock fractures or laboratory approach due to difficulties in experimental measurements, especially for carbonate fractures after acid etching under in situ temperature and stress of geothermal reservoirs. For this purpose, an improved test method is developed to respectively measure the temperature of inner fracture surface, inlet and outlet of water in this work. The carbonate fractures after acid etching are applied to perform convection heat transfer tests under high temperature and stress conditions. The convection heat transfer coefficient of carbonate fractures are determined after obtain the temperature distributions in flowing fluid and inner fracture surface. The effect of confining stress, roughness and flow rate on the convection heat transfer coefficient are analyzed.

2. Experimental procedures

2.1 Test method

Fig. 1 presents a conceptual model of convection heat transfer process in a single rock fracture. To simplify the research and reduce the amounts of calculation, some basic assumptions are proposed. First, the convection heat transfer process only considers heat conduction and heat convection and ignores the influence of heat radiation. Second, the permeability of rock fracture is far greater than that of the rock matrix, the permeability of the rock matrix is thus ignored, and the water flow only flows within the range of the fracture; the heat transfer process of water flow only occurs in the fracture channel. Finally, the heat loss during the flow process is ignored.

Based on the above basic assumptions, according to the Newton's cooling equation (Ezekoye, 1962) and the steady heat conduction equation (Bai et al., 2017).

$$Q = 4hLR\left[\frac{1}{2}(T_c + T_{i0}) - T_{w0}\right] \tag{1}$$

where Q is the total heat flow of the convection heat transfer process (J), h is the convection heat transfer coefficient (W/(m^2·K)), L and R are the length and the radius of the rock sample (m), respectively. T_c is the temperature of the external surface temperature, which is identical to the oil temperature (°C). T_{i0} and T_{w0} are the average of temperature of the inner fracture surface and the average of the water temperature along the longitudinal axis of the fracture (°C).

As mentioned above, the temperature distributions of inner fracture surface and flowing water are usually difficult to obtain. For sake of simplicity, the hypothesis, that fracture

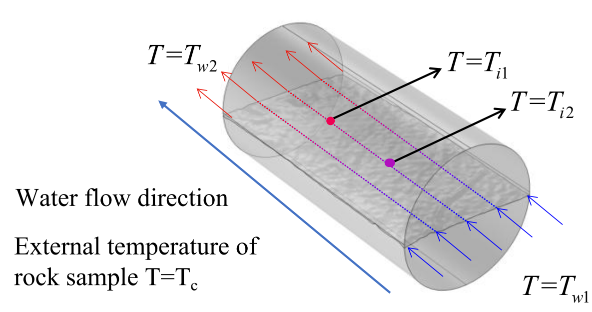
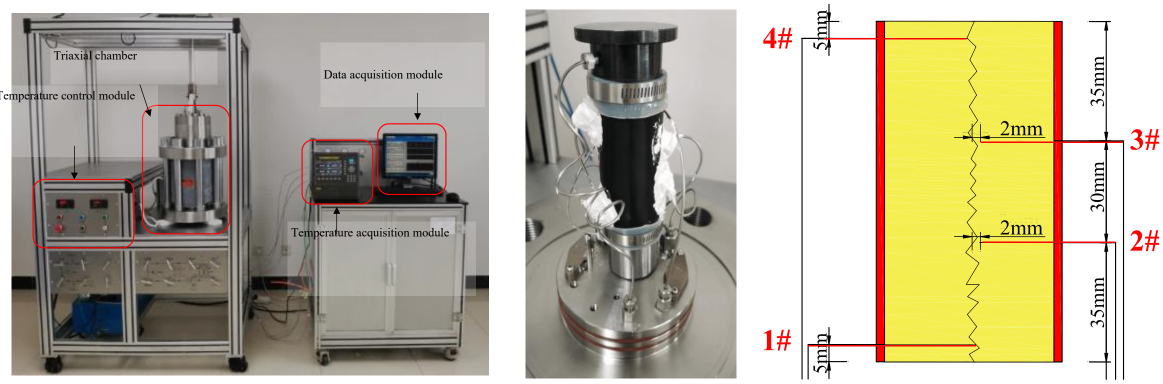


Fig. 1. Conceptual model of single fracture seepage heat transfer.



(a) Test system (b) Sample (c) Layout of thermocouples

Fig. 2. Schematic of convection heat transfer test.

surface temperature is identical to the average value of the inlet and outlet water temperatures, is usually adopted in the traditional test method of convection heat transfer coefficient. To improve the knowledge of convection heat transfer of carbonate fracture, an improved test method is developed to respectively measure the temperature of inner fracture surface and flowing water through 4 thermocouples, which are placed at different positions along the flow direction (see Fig. 2). The thermocouples #1 and #4 are placed at the inlet and outlet of the fluid channel to monitoring the water temperature, while the thermocouples #2 and #3 are placed near the center point of height and at a distance of 2 mm from the inner fracture surface, and the temperature of the thermocouples of #2 and #3 is thus considered to be identical to that of the inner fracture surface. Consequently, the average of temperature of the inner fracture surface and the average of the water temperature along the longitudinal axis of the fracture are determined by the following relations:

$$T_{i0} = \frac{1}{2}(T_{i2} + T_{i3}) \tag{2}$$

$$T_{w0} = \frac{1}{2}(T_{w1} + T_{w4}) \tag{3}$$

where T_{i2} and T_{i3} are the temperatures of the thermocouples #2 and #3, respectively. T_{w1} and T_{w4} are the temperatures of the thermocouples #1 and #4.

Therefore, by combining Eqs. (1)-(3), the convection heat transfer coefficient of the rock fracture is calculated by the following relation:

$$h = \frac{c_w \rho_w q_w (T_{w2} - T_{w1})}{2LR\left[\frac{1}{2}(T_{i1} + T_{i2}) + T_c - (T_{w1} + T_{w2})\right]} \tag{4}$$

where c_w, ρ_w, q_w are the specific heat capacity (J/(kg·K)), density of water (kg/m^3), and the volume flow (m^3/s) of water, respectively.

2.2 Rock fracture preparation and characterization

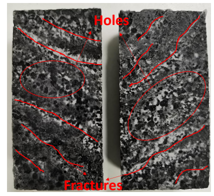
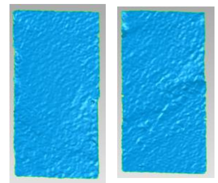
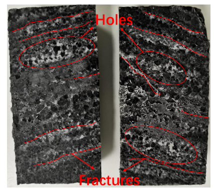
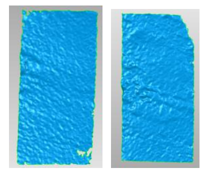
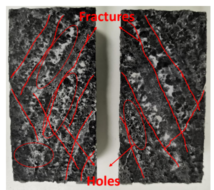
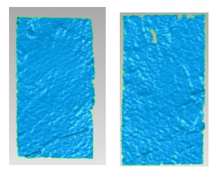
The studied rocks are collected from Xianxian, Hebei Province of China and belong to Wumishan Formation of Jixian System. The X-ray diffraction tests show the dolomite is the dominant mineral (100%-) with a small quantity of calcite. The core processing standard refers to the International Society for Rock Mechanics and Rock Engineering (Bieniawski et al., 1979). According to the experimental requirements, the cylindrical specimens are with a diameter of 50 mm and a height of 100 mm. The processed specimens have a smooth surface and good integrity, ensuring that the parallelism of the upper and lower end faces is within 0.02 mm, and meet the specification requirements. The wire cutting machine is used to make a straight fracture surface (Yilmazkaya, 2011). Because the fracture surface is relatively flat, the dissolution is not evident under low-concentration acid dissolution. When the high-concentration acid is used for soaking and erosion, crisscross dissolution streaks can be seen, convenient for quantitative calculation of roughness (Singh et al., 2018). Therefore, the hydrochloric acid solutions with mass fractions of 15%, 20%, and 25% are prepared for the static dissolution reaction tests on fracture surfaces of carbonate rocks to facilitate comparative analysis.

The fracture surfaces after acid etching are also characterized by three-dimensional (3D) roughness index reference to study the variations in roughness of the fracture surfaces. The point cloud file with the suffix Polygon File Format format is obtained by the 3D scanning device and Geomagic Studio software for further point cloud data post-processing (Zhou et al., 2018). By using a program for the three-dimensional roughness index (Song et al., 2017), the roughness of the fracture surface after acidizing etching are 5.825, 6.993, and 7.736 for the hydrochloric acid solutions with mass fractions of 15%, 20%, and 25%, respectively.

It can be seen from Table 1 that when the corrosion test is performed in a lower concentration solution, the crisscrossing corrosion streaks can be seen on the surface of the sample. With the increase of solution concentration, small dissolution holes and fractures are distributed on the surface. The above test results show that acidification and corrosion can form a better asperity structure on the fracture surface, increasing the fracture surface's roughness.

To study the influence of fracture surface roughness on the process of convection heat transfer, scanning electron

Table 1. Characterization of fracture surfaces after acidizing etching.

Hydrochloric acid concentration	Surface photo	Reconstruction image	Roughness (JRC)
15%			5.825
20%			6.993
25%			7.736

microscopy analysis are performed on the rough fractures of carbonate rocks dissolved by different acid concentrations. The changes in microstructure of fracture surface due to acid etching are thus investigated by a Quanta250 scanning electron microscope with magnifications of 200×, 800×, and 2000×, and the scanning results are shown in Figs. 3 and 4. Comparing and analyzing two electron microscopy scans results, the intact sample is relatively dense. However, a large number of dissolved pores, caves, and micro-fractures are observed after acid etching. Similar phenomenon has been also observed in other carbonate rocks (Wu et al., 2019; Li et al., 2020; Tan et al., 2020). These pores, caves, and micro-fractures caused by acid etching can increase the convection channel and increase the contact area with the heat transfer working medium, thereby increasing the heat production of geothermal reservoir (Ma et al., 2019). The special fracture morphology of carbonate is totally different from those of granite and sandstone in previous studies (Zhao et al., 1999; He et al., 2016; Bai et al., 2017, Ma et al., 2018; Jiang et al., 2020), and can increase the convection channel and increase the contact area with flowing fluid and results in the inapplicability of the hypothesis to carbonate fractures after acidizing etching.

2.3 Test procedure

The real-time high temperature triaxial test system is applied in this work (see Fig. 2). The temperature control module includes an electromagnetic heating jacket with a proportional-integral-derivative temperature controller, and the maximum heating temperature could reach 200 °C. Two closed-loop servo pumps are used to apply confining pressure and inject water on the samples, respectively. The data acquisition module includes thermal couples, confining pressure transducers, water pressure transducers at the inlet and outlet. All of these modules are connected to the host computer to realize real-time monitoring and control of the data.

Table 2. Test variables.

Temperature (°C)	Confining pressure (MPa)	Flow rate (ml/min)
70	0, 5	3, 6, 9
90	10, 15	12, 15, 18

The temperature, confining pressure, and flow rate used in the present work are chosen according to the in situ stress and temperature and the recharge rate of the studied geothermal reservoir (Zhang et al., 2018). The detailed test variables are shown in Table 2. It is noted that three tests are performed for each test condition, and the average value of the three tests are used for the further analyses in the present work.

Distilled water is selected as the heat transfer working medium for the test. Inspired by the previous tests on granite and artificial rock fracture (Huang et al., 2016; Bai et al., 2017; Huang et al., 2018), the tests are carried out as follows:

1) Sample installing
The rock samples are first placed in a rubber jacket with appropriate length, four thermocouples are inserted into four prefabricated holes, and the temperature data recorder is connected with the temperature measuring line to record the temperature data of the four temperature measuring points. The thermocouples and the rock sample's external surface are sealed with sealant resistance to high temperature and high pressure.
2) Heating and loading of confining pressure
The whole triaxial chamber is heated after the installation

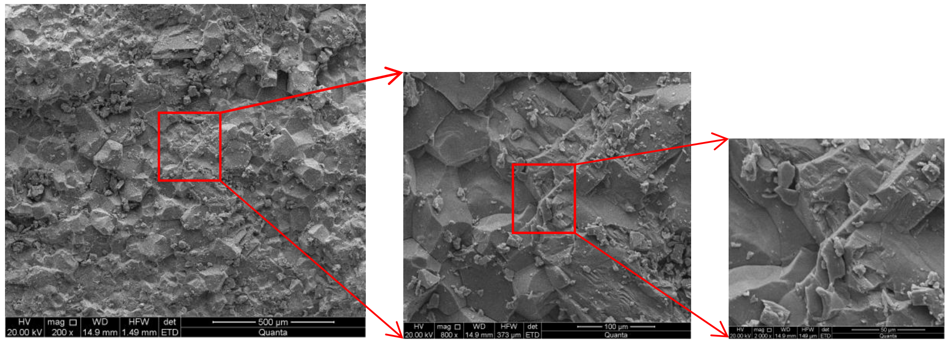


Fig. 3. SEM images of carbonate rock before acidizing etching (200× (left), 800× (middle), 2000× (right)).

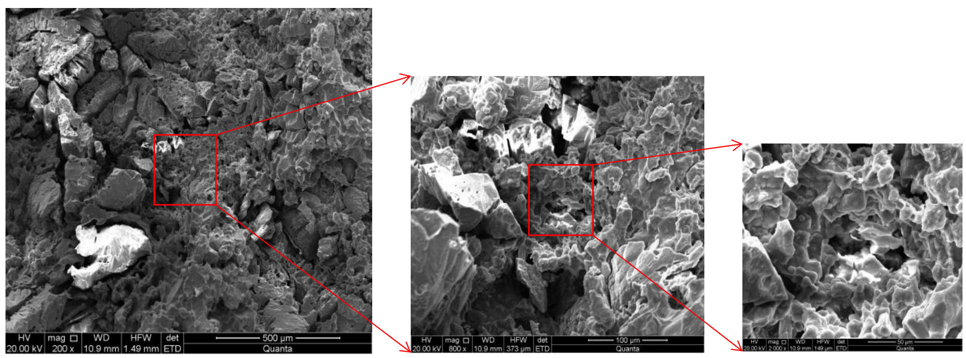


Fig. 4. SEM images of carbonate rock after acidizing etching (200× (left), 800× (middle), 2000× (right)).

of the electric heating coil. After the temperature of rock sample reaches the desired temperature, a thermal equilibrium state is assumed to be achieved once the temperature change does not exceed 1 °C within 20 minutes. After the thermal equilibrium state, confining pressure is applied on the samples and kept constant during the tests.

3) Water injection
A flow rate of 3 ml/min is first injected to the rock fracture, the water temperature at inlet and outlet, and the inner fracture temperature are continuously monitored. When the thermal equilibrium state is recovered, the temperatures at different measuring points are recorded and the flow rate is increased for the next test.

3. Temperature variations in flowing water and inner fracture surface

As mentioned above, three repetitive tests were carried out for each test condition in this study. Because of the consistency of test results and space limitations, only the samples (JRC = 6.993) after acid etching of 20% hydrochloric acid solutions and with external surface temperature of 90 °C is taken as an example, the temperature variations at each point during the convection heat transfer process are shown in Fig. 5. It is clear that the temperature distributions at the four measuring points show a continuous increasing trend along the flow direction, while the temperature differences between the points of #2 and #3 are relatively small comparing with those between the points of #1 and #4. As mentioned above, the temperatures at the two points (#2 and #3) are identical to the inner fracture surface, while the temperatures at the two points (#1 and #4) are the temperature of the flowing water at inlet and outlet. In other words, the temperature distributions in flowing fluid and inner fracture surface are not the same, and thus need to be measured and analyzed respectively (Zhao et al., 2018).

Fig. 5 shows that the flow rate and confining pressure have significant effect on the temperature field during convection heat transfer process. Under each confining pressure, the temperature differences between the inlet and outlet increase with increasing of flow rate. That means a faster fluid flow along the fracture could take more heat away in the form of convection heat transfer. Moreover, the temperature differences between different flow rates at the outlet become smaller with increasing of confining pressure. Similar phenomenon has been also observed in previous laboratory tests of convection heat transfer characteristics of granite fracture (Huang et al., 2019) and analytical solutions of heat convection process in rock fractures (Zhao et al., 2014).

4. Analyses of test results

4.1 Comparisons of two test methods

As mentioned above, the fracture surface temperature is assumed to be identical to the average value of the inlet and outlet water temperatures in the traditional test method of convection heat transfer coefficient. The improved test method in the present work could separately measure the fracture surface temperatures and water temperatures. The average

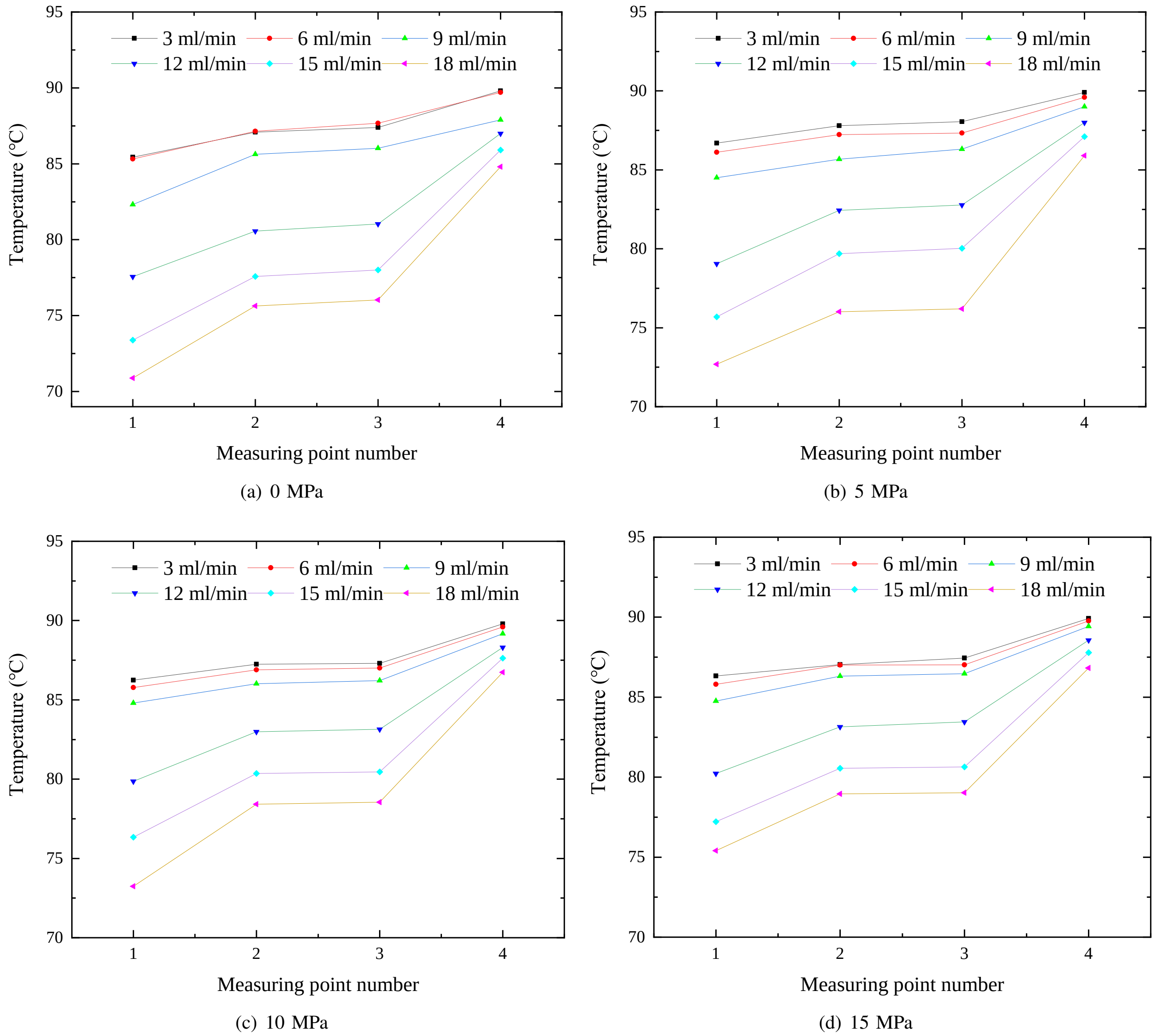


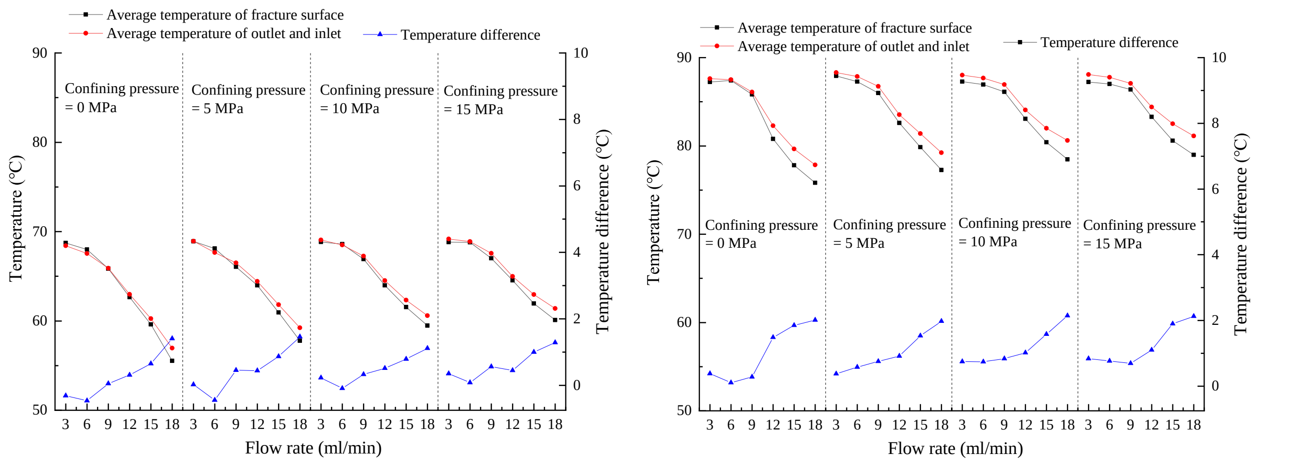
Fig. 5. Temperature variations at different measuring points with external surface temperature of 90 °C.

values of fracture surface temperature, the average values of the inlet and outlet water temperatures and the differences between the two average values are plotted in Fig. 6.

Under the studied confining pressure and external fracture temperature, the average values of the inlet and outlet water temperature are generally higher than the average temperature of the fracture surface, and the differences between the two average values become greater when the flow rate is higher. The maximum difference could be reached 2.2 °C under flow rate of 18 ml/min, external fracture temperature of 90 °C and confining pressure of 15 MPa.

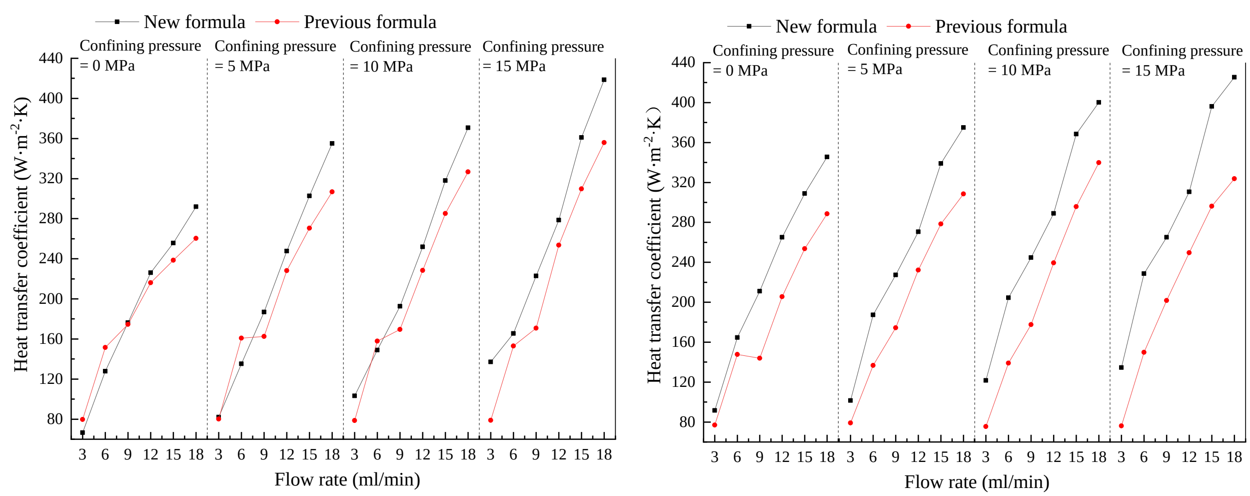
The results of convection heat transfer coefficient determined by the traditional and improved test method are shown in Fig. 7. Under the studied confining pressures of 0, 5, 10, and 15 MPa, the convection heat transfer coefficient determined by both methods become higher with increasing flow rate. However, some differences of convection heat transfer coefficient are also observed between the two methods, especially with higher external fracture temperature, flow rate and confining pressure. The convection heat transfer coefficient determined by the improved test method is about 1.31 times the one by the traditional test method with flow rate of 18 ml/min, external fracture temperature of 90 °C and confining pressure of 15 MPa.

The lower the flow rate of the fluid flowing through the fracture surface, the closer the fracture surface's average temperature is to the inlet and outlet water temperature. The average inlet and outlet water temperature can be substituted for the average temperature of the fracture surface. However, under the condition of high temperature and high flow rate, the intensity of fluid thermal convection in the rock sample fracture passage is enhanced, which reduces the heat transfer time with the fracture surface. The fluid takes away less heat and reduces the heat recovery rate, when the transfer model is dominated by convection with high flow rate. Therefore, the hypothesis that fracture surface temperature is identical to the



(a) 70 °C (b) 90 °C

Fig. 6. Average values of fracture surface temperature, the average values of the inlet and outlet water temperatures and the differences between the two average values.



(a) 70 °C (b) 90 °C

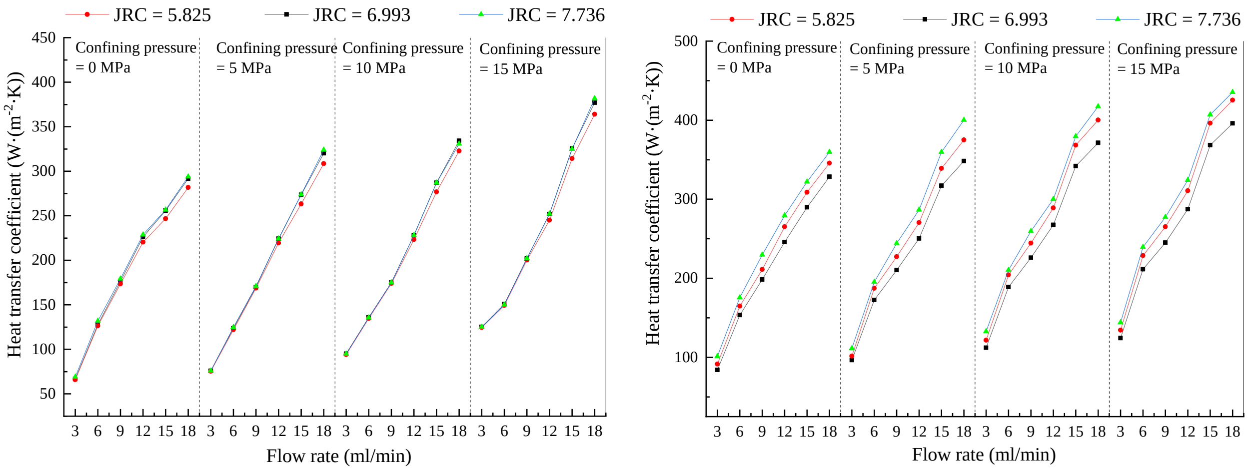
Fig. 7. Convective heat transfer coefficients measured by conventional and improved methods.

average value of the inlet and outlet water temperatures may not be adopted under high under the condition of high temperature and high flow rate. It is of great value to measure the actual temperature distribution of the inner fracture surface to improve the accuracy of convection heat transfer coefficient.

4.2 Variations in convection heat transfer coefficient

The convection heat transfer coefficient with different roughness under external temperatures, different flow rates and confining pressures are determined by the improved test method, and the results are plotted in Fig. 8.

To obtain the best heat transfer efficiency, it is essential to select the appropriate volume flow rate of the geothermal reservoir system. Through the characteristic number equation, the Nu value range was calculated, and it was verified that the flow rate at the laboratory scale met the laminar flow state of the fluid (Li et al., 2017). When the experimental flow rate is 6 ml/min, the conversion corresponds to the flow rate of 4.02×10^{-4} m/s in the actual project, consistent with the geological flow rate data-target carbonate reservoir. In the experiment, six different flow rates are tested, namely 3, 6, 9, 12, 15, and 18 ml/min, respectively, to illustrate the influence of flow rate on convection heat transfer. It can be seen from Fig. 8 that under any given confining pressure, the convection heat transfer coefficient has a positive correlation with the flow rate. Taking the test results of 70 °C, acid corrosion concentration of 20% (JRC = 6.993), and confining pressure of 15 MPa as an example. When the flow rate increases from 3 ml/min to 18 ml/min, the convection heat transfer coefficient increases from 107.05 to 418.56 W·m^{-2}·K, which proves once again that the carbonate rock is a medium with excellent heat transfer efficiency. The large increase in the flow rate will increase the total heat transfer and increase the heat transfer intensity per unit flow. Moreover, it is clearly that the convection heat transfer coefficient is positively correlated with fracture roughness under each temperature, flow rate and



(a) T = 70 °C (b) T = 90 °C

Fig. 8. The evolution of convection heat transfer coefficient with flow rate and fracture roughness at two external fracture temperatures.

confining pressure.

5. Conclusion

An improved test method was developed to measure the temperature of inner fracture surface, inlet and outlet of water, respectively in this work. Two thermocouples were especially arranged on the inner fracture surface to monitor the temperature evolution process of inner fracture surface along the flow direction, and two other thermocouples for the inlet and outlet water temperatures. The traditional test method based on the hypothesis that fracture surface temperature is identical to the average value of the inlet and outlet water temperatures was improved. The temperature field of the inner fracture along the flow direction and the convection heat transfer coefficient of carbonate fractures after acid etching were determined under in situ temperature and stress of geothermal reservoirs. The results show that the temperature differences between the fracture surface and the average value of the inlet and outlet water temperatures are significantly dependent on confining pressure, fracture roughness and flow rate, and the maximum temperature difference could be reached 2 °C, which leads to a significant difference in the convection heat transfer coefficient between the traditional and improved test method. Confining stress, fracture roughness and flow rate have significant effect on the convection heat transfer coefficient. The convection heat transfer coefficient increases linearly with increasing confining pressure, flow rate and fracture roughness. The SEM results of the fracture surface indicated that a large number of dissolved pores, caves, and fractures were generated after acid etching, which can increase the convection channel and increase the contact area with the heat transfer working medium, thereby increasing the heat production of geothermal reservoir. The present work could improve our knowledge of convection heat transfer process for carbonate geothermal reservoir. Some other temperature conditions, i.e., above 100 °C will be performed in the further work.

Acknowledgement

This work was supported by the National Key Research and Development Program of China (Nos. 2018YFC0809600 and 2018YFC0809601), the National Natural Science Foundation of China (No. 51779252), and the Geological Survey Project of China Geological Survey (No. DD20190128).

Conflict of interest

The authors have declared that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work.

References

Aliyu, M., Archer, R. Numerical simulation of multifracture HDR geothermal reserveoirs. Renewable Energy, 2021, 164(2): 541-555.

Anyim, K., Gan, Q. Fault zone exploitation in geothermal reservoirs: Production optimization, permeability evolution and induced seismicity. Advances in Geo-Energy Research, 2020, 4(1): 1-12.

Bai, B., He, Y., Hu, S., et al. An analytical method for determining the convection heat transfer coefficient between flowing fluid and rock fracture walls. Rock Mechanics and Rock Engineering, 2017, 50(7): 1787-1799.

Bai, B., He, Y., Li, X., et al. Local heat transfer characteristics of water flowing through a single fracture within a cylindrical granite specimen. Environmental Earth Sciences, 2016, 75(22): 1460.

Bai, B., He, Y., Li, X., et al. Experimental and analytical study of the overall heat transfer coefficient of water flowing through a single fracture in a granite core. Applied Thermal Engineering, 2017, 116: 79-90.

Bieniawski, Z. T., Bernede, M. J. Suggested methods for determining the uniaxial compressive strength and deformability of rock materials: Part 1. Suggested method for determining deformability of rock materials in uniaxial compression. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 1979, 16(2): 138-140.

Cao, W., Huang, W., Jiang, F. A novel thermal-hydraulic-mechanical model for the enhanced geothermal system heat extraction. International Journal of Heat and Mass Transfer, 2016, 100: 661-671.

Ezekoye, O. A. Conduction of heat in solids. Physics Today, 1962, 15(11): 74-76.

He, Y., Bai, B., Hu, S., et al. Effects of surface roughness on the heat transfer characteristics of water flow through a single granite fracture. Computers and Geotechnics, 2016, 80: 312-321.

Heinze, T., Hamidi, S., Galvan, B. A dynamic heat transfer coefficient between fractured rock and flowing fluid. Geothermics, 2017, 65(1): 10-16.

Huang, X., Zhu, J., Li, J., et al. Fluid friction and heat transfer through a single rough fracture in granitic rock under confining pressure. International Communications in Heat and Mass Transfer, 2016, 75(7): 78-85.

Huang, Y., Zhang, Y., Yu, Z., et al. Experimental investigation of seepage and heat transfer in rough fractures for enhanced geothermal systems. Renewable Energy, 2018, 135(3): 846-855.

Jiang, P., Zhang, L., Xu, R. Experimental study of convection heat transfer of carbon dioxide at supercritical pressures in a horizontal rock fracture and its application to enhanced geothermal systems. Applied Thermal Engineering, 2017, 117: 39-49.

Jiang, Y., Yao, H., Cui, Y., et al. Evaluative analysis of equations of heat transfer coefficient of rock fracture. International Journal of Thermophysics, 2020, 41: 104.

Li, Q., You, X., Jiang, Z., et al. The origins of carbonate minerals of a source-controlled lacustrine carbonate succession in the Shulu sag, Bohai Bay Basin: Implications for porosity development and paleoenvironment. Marine and Petroleum Geology, 2020, 122: 104673.

Li, Z., Feng, X., Zhang, Y., et al. Experimental research on the convection heat transfer characteristics of distilled water in manmade smooth and rough rock fractures. Energy, 2017, 133(15): 206-218.

Luo, J., Zhu, Y., Guo, Q., et al. Chemical stimulation on the hydraulic properties of artificially fractured granite for enhanced geothermal system. Energy, 2018, 142(1): 754-764.

Luo, Y., Xu, W., Lei, Y., et al. Experimental study of heat transfer by water flowing through smooth and rough rock fractures. Energy Reports, 2019, 5: 1025-1029.

Ma, Y., Zhang, Y., Hu, Z., et al. Experimental study of the heat transfer by water in rough fractures and the effect of fracture surface roughness on the heat transfer characteristics. Geothermics, 2019, 81(9): 235-242.

Ma, Y., Zhang, Y., Yu, Z., et al. Heat transfer by water flowing through rough fractures and distribution of local heat transfer coefficient along the flow direction. International Journal of Heat and Mass Transfer, 2018, 119: 139-147.

Ogino, F., Yamamura, M., Fukuda, T. Heat transfer from hot dry rock to water flowing through a circular fracture. Geothermics, 1999, 28(1): 21-44.

Shaik, A. R., Rahman, S. S., Tran, N. H., et al. Numerical simulation of fluid-rock coupling heat transfer in naturally fractured geothermal system. Applied Thermal Engineering, 2011, 31(10): 1600-1606.

Singh, K., Anabaraonye, B. U., Blunt, M. J., et al. Partial dissolution of carbonate rock grains during reactive CO_2-saturated brine injection under reservoir conditions. Advances in Water Resources, 2018, 122: 27-36.

Song, L., Jiang, Q., Li, Y., et al. Stability of statistical parameters of discontinuities morphology and anisotropy based on different sampling intervals. Rock and Soil Mechanics, 2017, 38(4): 1121-1132. (in Chinese)

Sun, H., Belhaj, H., Tao, G., et al. Rock properties evaluation for carbonate reservoir characterization with multi-scale digital rock images. Journal of Petroleum Science and Engineering, 2019, 175: 654-664.

Tan, Q., You, L., Kang, L., et al. Changes in pore structures and porosity-permeability evolution of saline-lacustrine carbonate reservoir triggered by fresh water-rock reaction. Journal of Hydrology, 2020, 580: 124375.

Wang, G., Wang, W., Zhang, W., et al. The status quo and prospect of geothermal resources exploration and development in Beijing-Tianjin-Hebei region in China. China Geology, 2020, 3(1): 173-181.

Wang, Y., Li, C., Zhao, J., et al. The above-ground strategies to approach the goal of geothermal power generation in china: State of art and future researches. Renewable and Sustainable Energy Reviews, 2021, 138: 11057.

Wu, J., Fan, T., Gomez-Rivas, E., et al. Impact of pore structure and fractal characteristics on the sealing capacity of Ordovician carbonate cap rock in the Tarim Basin, China. Marine and Petroleum Geology, 2019, 102: 557-579.

Yao, J., Zhang, X., Sun, Z., et al. Numerical simulation of the heat extraction in 3D-EGS with thermal-hydraulic-mechanical coupling method based on discrete fractures model. Geothermics, 2018, 74: 19-34.

Yilmazkaya, Y. O. The effect of the rock anisotropy on the efficiency of diamond wire cutting machines. International Journal of Rock Mechanics and Mining Sciences, 2011, 48(4): 626-636.

Yu, G., Liu, C., Zhang, L., et al. Parameter sensitivity and economic analyses of an interchange-fracture enhanced geothermal system. Advances in Geo-Energy Research, 2021, 5(2): 166-180.

Zhang, L., Jiang, P., Wang, Z., et al. Convection heat transfer of supercritical CO_2 in a rock fracture for enhanced geothermal systems. Applied Thermal Engineering, 2017, 115(25): 923-936.

Zhang, X., Hu, Q. Development of geothermal resources in china: A review. Journal of Earth Science, 2018, 29(2): 452-467.

Zhao, J. Experimental study of flow-rock heat transfer in rock fractures. Chinese Journal of Rock Mechanics and Engineering, 1999, 18(2): 119-123. (in Chinese)

Zhao, J., Brown, E. T. Hydro-thermo-mechanical properties of joints in the Carnmenellis granite. Quarterly Journal of Engineering Geology and Hydrogeology, 1992, 25(4): 279-290.

Zhao, J., Tso, C. Heat transfer by water flow in rock fractures and the application to hot dry rock geothermal systems. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 1994, 30(6): 633-641.

Zhao, Z. On the heat transfer coefficient between rock fracture walls and flowing fluid. Computers and Geotechnics, 2014, 59: 105-111.

Zhou, H., Cheng, G., Zhu, Y., et al. A new method to originally reproduce rock structural plane by integrating 3D scanning and 3D carving techniques and mechanical characteristics of reproduced structural planes. Rock and Soil Mechanics, 2018, 39(2): 417-425. (in Chinese)

Zhu, J., Zhang, G., Li, J. Analytical solution and sensitivity analysis of fluid-solid heat transfer coefficient in fracture channel. Acta Energiae Solaris Sinica, 2016, 37(8): 2019-2025. (in Chinese)