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Research paper

Experimental study of heat transfer by water flowing through smooth and rough rock fractures



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ABSTRACT

It is important to have an accurate understanding of heat transfer process of water flowing through fractures for geothermal energy extraction and utilization. We designed an experiment to study the convective heat transfer characteristics of distilled water pumped through manmade smooth and rough fractures in granite samples. The flow velocity, permeating pressure, confining pressure, inlet and outlet fluid temperature and rock outer-surface temperature were measured and recorded to calculate the heat transfer coefficient. The effects of volumetric flow rate, fracture surface roughness, and outer wall surface temperature on the convective heat transfer process were analyzed. The results indicate that fracture surface roughness has a great influence on the heat transfer characteristics of water flowing through rocks. Overall heat transfer intensity improved along with an increase in rock fracture surface roughness. Our results have implications for geothermal energy extraction and utilization.

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1. Introduction

Geothermal energy is both renewable and an attractive, strong candidate to meet the urgent demand for a clean, pollution-free energy source. The official figures released by China's Ministry of Land and Resources report an abundance of geothermal sources at China's disposal. Currently available Hot Dry Rock (HDR) resources distributed at depths of 3–10 km are equal to 260000 times the capacity of annual energy consumption of China in mainland China (Zhao and Wan, 2014). In January 2017, the National Development and Reform Commission, Ministry of Land and Resources, and National Energy Administration in China released a public document regarding the 13th Five-Year Plan for geothermal energy development. The outline includes an EGS demonstration project, to be built in the next 5 years (National Development and Reform Commission, 2017). An enhanced geothermal system (EGS) provides a path toward efficient and economical use of the enormous resources provided by geothermal energy for human consumption. As attention in policy circles turns to geothermal energy, the study of convective heat transfer

characteristics when fluids flow across rock fracture surface has become an important object of scientific study.

Study of the convective heat transfer characteristics of water in fractures is relevant to both conventional and engineered or enhanced geothermal systems. For sustainable geothermal energy development and utilization, it is important to have a sufficient understanding of the characteristics of water flowing through fractures. As a consequence, many scholars have recently studied the fluid flow and heat transfer process via experimental and numerical modeling approaches. Zhang et al. (2017) performed an experimental study of the laminar convection heat transfer of supercritical pressure CO₂ in an artificial smooth parallel-plate fracture as well as rough and tortuous fractures created using the Brazilian technique. They found that the heat transfer performance in a rough fracture was influenced by channeling and disturbance effect interactions caused by the tortuous flow path. He et al. (2016) adopted fractal dimension *D* and profile waviness *R_a* to characterize surface roughness, and investigated the effects of surface roughness on the heat transfer characteristics of water flow through a single granite fracture by combining experimental and numerical modeling approaches. They found that the local heat transfer coefficient distribution depended primarily on the fracture surface roughness, and secondarily on aperture and flow rate. Heinze et al. (2017) derived a dynamic heat transfer coefficient dependent on fracture aperture, flow velocity and

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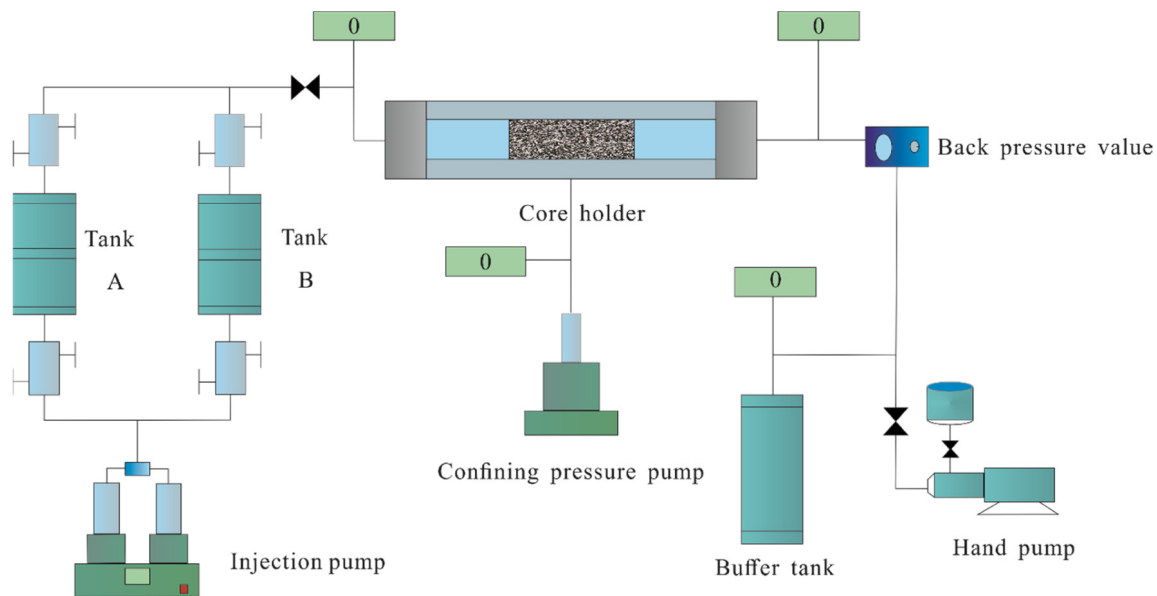


Fig. 1. Experimental system.

thermal parameters based on an experimental setup with simple geometry and a steady state scenario. Huang et al. (2016) conducted experiments to investigate the single-phase convective heat transfer and pressure drop of water flowing through a single fracture in a cylindrical granite rock. Abdallah et al. (1995) used a simple model representing two blocks separated by a horizontal fracture, and found that convection is sensitive to the hydraulic aperture of the fracture, the circulation velocity and the viscosity of the fluid. Shaik et al. (2011) developed a numerical procedure by coupling fluid flow with heat transfer. de La Bernardie et al. (2018) provided a new framework for interpreting joint solute and thermal tracer tests in fractured media, and showed the impact of fracture geometry on heat recovery in geothermal systems. Cherubini et al. (2017) carried out heat transfer tests in order to analyze heat transfer dynamics in a network of fractures. Lu and Xiang (2012) conducted experiments on saturated water flow and heat transfer for a meter-scale model of regularly fractured granite and found that the temperature distribution was influenced by water flow in the fractures. Luo et al. (2017) investigated the hydraulic and heat transfer properties of two sets of artificially fractured granite samples. Natarajan and Kumar (2010) studied the behavior of thermal fronts along the fracture in a coupled fracture-matrix system with sinusoidal fracture geometry and found the sinusoidal fracture geometry enhanced the heat transfer into the rock-matrix. Neuville et al. (2010) examined the influence of fracture roughness on hydraulic permeability and heat flux through the fracture by numerically studying heat exchange during laminar flow in an open fracture. Zhao (1999) conducted an experimental study on the hydrothermal properties of rock fractures by heating the rock and forcing the water circulation through the rock fractures.

Thus far, most study of the convection heat transfer of fluid flowing through rock fractures is based on smooth and horizontal fractures. However, the fractures in geothermal reservoirs are rough. Limited experimental research has been conducted on real rock fractures. The effect of fracture surface roughness on fluid flow and heat transfer in fractured rock has yet to be thoroughly investigated.

In this paper, an experimental approach was used to study the convection heat transfer characteristics of distilled water in a single rock fracture. The effects of flow rate, fracture surface roughness and outer wall surface temperature on the convective heat

transfer process were measured, analyzed and discussed. Our results help provide a better understanding of the heat transfer process of water flowing through rock fractures.

2. Experiment

2.1. Experimental apparatus

The experimental system used to simulate and measure water flow and heat transfer in rock fractures is presented in Fig. 1. The system comprises five main subsystems: the permeating pressure subsystem, the temperature control subsystem, the confining pressure subsystem, the specimen holder subsystem and the data acquisition subsystem. The permeating pressure was supplied by an ISCO pump. The maximum pressure of the pump was 68.95 MPa and the flow rates ranged from 0.00001 to 45 ml/min. The maximum confining pressure provided by an electric-controlled plunger pump was 40 MPa. The temperature control subsystem could heat to 200 °C. The flow velocity, permeating pressure, confining pressure, inlet and outlet fluid temperature and the rock outer surface temperature were measured and recorded by the data acquisition subsystem.

2.2. Sample preparation

Rock blocks were collected from exposed outcrops in Gonghe Basin. The Gonghe Basin in northeast Qinghai is a target geothermal exploitation demonstration area in China (Xu et al., 2018). In order to study the effect of rock surface roughness on its convective heat transfer characteristics, smooth fractures and rough fractures were prepared using granite, a common rock type in most EGS reservoirs. The core, with a radius of 50 mm and length of 100 mm, was cut symmetrically into two parts along the cylinder axis to produce two flat parallel surfaces. A rough fracture was created by splitting the sample using the Brazilian technique (Carneiro, 1943) a geotechnical laboratory test for indirect measurement of the tensile strength of rocks. The manmade smooth and rough fractures in the granite samples are shown in Fig. 2. The physical properties of the samples were tested and are shown in Table 1. The rock sample's porosity was measured using a gas permeation tester. The specific heat capacity of the rock sample was tested by a Specific Heat Capacity Tester (XY-BRR). Heat conductivity was measured by Thermal Conductivity Sensor.

Table 1
Basic physical properties of the specimen.

Parameters	Values
Diameter/(m)	50
Length/(m)	100
Density/(g/m ³)	2.58
Porosity/(%)	3.97
Specific heat capacity /kJ/(kg k)	0.748
Heat conductivity/W/(m K)	2.682

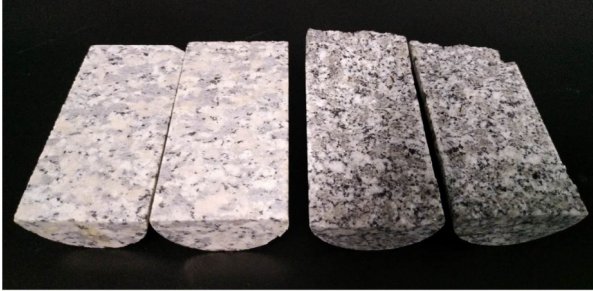


Fig. 2. Manmade smooth and rough fractures of granite samples.

2.3. Experimental procedure

Four temperature cases and four flow rates were designed for the experiment. All the tests were conducted according to the same experimental procedure including the following steps. First, the rock was placed in the specimen holder. Then, confining pressure was exerted to 1 MPa. Then, the electric heater was installed and began heating until the outer surface temperature of the rock reached the temperature milestones of 60, 70, 80, and 90 °C. Water was injected via the ISCO pump at set flow rates of 5, 10, 15, 20 ml/min. The inlet and outlet fluid temperature and the rock outer surface temperature were then recorded, after reaching steady state at each flow rate.

3. Data reduction

Formula (1) was used to calculate the heat quantity transferred to the water from the rock. The form of the equation is:

$$Q = c_p \times \rho \times q_v \times (T_{out} - T_{in}) \quad (1)$$

where Q is the overall heat quantity extracted from the hot rock; c_p is the specific heat capacity at constant pressure of water (J/(kgK)); ρ is the density of water (kg/m³); q_v is the volumetric flow rate (m³/s); T_{out} , T_{in} are the outlet and inlet temperature of the water.

The heat transfer coefficient is a significant parameter in the description of the heat transfer process's characteristics. It can also be used to predict the production of hot water from an enhanced geothermal reservoir. A number of other studies have provided several formulas to calculate the heat transfer coefficient (Zhao, 2014; Bai et al., 2017). Bai et al. (2017) assume that the temperature along the radius of a given specimen is a linear function, and obtained formula (2). experimental conditions, we used formula (2) to obtain the heat transfer coefficient. The form of the equation is:

$$h = \frac{c_p \times \rho \times q_v \times (T_{out} - T_{in})}{dL(T_c - (T_{in} + T_{out})/2)} \quad (2)$$

where h is the heat transfer coefficient (W/(m²K)); d is the diameter of the rock (m); L is the length of the specimen (m); T_c is the temperature at the outer wall surface of rock (K).

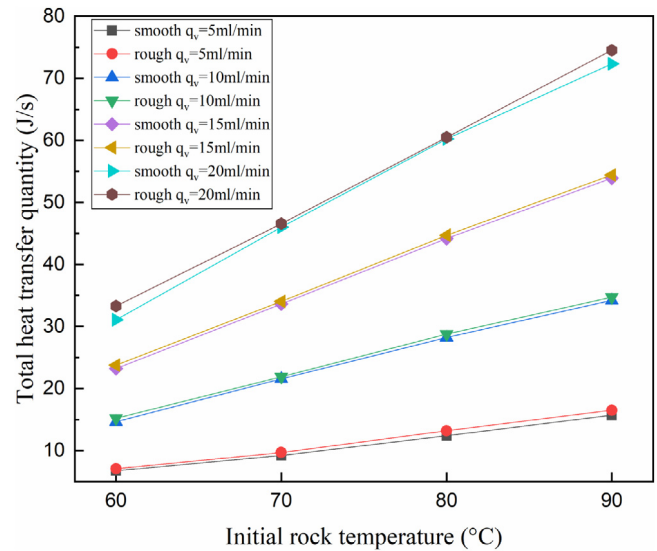


Fig. 3. Heat transfer quantities for various initial rock temperature under four volumetric flow rates with smooth and rough fracture.

4. Results and discussion

4.1. Effect of initial rock temperature

The overall heat extraction process from hot rock by water flowing through a fracture was investigated at laboratory scale. The experimental data for water temperature at the fracture inlet and outlet were used to calculate the overall heat quantity for initial rock temperature of 60 °C, 70 °C, 80 °C and 90 °C.

The overall heat quantities extracted from hot rock by water flowing through smooth parallel-plate fracture and rough fracture calculated by Eq. (1) are shown in Fig. 3. As shown in Fig. 3, the overall heat quantity increased linearly as the initial rock temperature increased under a constant volumetric flow rate with water flowing through the smooth parallel-plate fracture and the rough fracture. The cold water was heated to a higher temperature by the hot rock when flowing through the fractures.

The obvious discrepancy in overall heat quantity extracted from smooth and rough fractures under the same initial outer-wall rock temperature and volumetric flow rate indicates that fracture surface roughness significantly influences the heat transfer characteristics of water flowing through rock. Compared with the smooth fracture, the overall heat quantity extracted from the rough fracture was higher. The geometric characteristics of the fracture's surface was one of the most important factors in the heat transfer process. The rough fracture's heat transfer area was larger than that of smooth fracture. Therefore, the overall heat quantity extracted from the rough fracture was higher.

4.2. Effect of volumetric flow rate

Volumetric flow rate significantly impacts heat extraction efficiency. We tested four different outer wall surface temperatures of 60 °C, 70 °C, 80 °C and 90 °C, each under four different volumetric flow rates. The results illustrate the effect of volumetric flow rate on the heat transfer characteristics. Fig. 4 shows the total heat transfer quantity extracted from hot rock by water. As shown in Fig. 4, water with the highest volumetric flow rate extracted more heat. The total heat transfer quantity and the volumetric flow rate present a positive correlation under a constant temperature. Water flowed with the same regularity through the rough fracture and the smooth fracture.

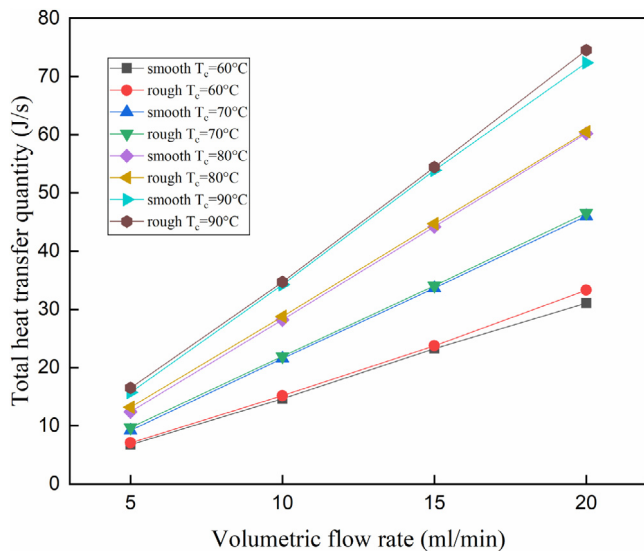


Fig. 4. Heat transfer quantities for various volumetric flow rate under four initial rock temperatures with smooth and rough fracture.

4.3. Effect of fracture surface roughness

The heat transfer coefficient is a significant parameter when evaluating the heat extraction potential between water and surrounding hot dry rock. The heat transfer coefficient calculated by Eq. (2) is shown in Fig. 5. As shown in Fig. 5, the heat transfer coefficient has a positive linear relation to volumetric flow rate under a given initial rock temperature. And on the other hand, the heat transfer coefficient increases with the increase of experimental initial rock temperature under a given volumetric flow rate. Fig. 5 indicates that the heat transfer coefficients were different between smooth and rough fractures, even under the same outer wall initial rock temperature and volumetric flow rate. This indicates that the fracture surface roughness influenced the heat transfer characteristics of water flowing through rocks. Comparing the results from the smooth fracture and the rough fracture, the heat transfer intensity of the rough fracture increased. For instance, when the initial rock temperature was 80 °C and the volumetric flow rates were 5, 10, 15, 20 ml/min, the enlargement of the heat transfer coefficient was 9.4%, 3.0%, 1.8%, 0.7%, respectively. A rough fracture surface facilitated greater heat removal as fluid flowed across the fracture's surface. In addition, compared with Figs. 3 and 4, the difference in the total heat transfer quantity between rough and smooth fractures and the difference in heat transfer coefficients show the same trend.

5. Conclusions

In order to study the heat transfer characteristics of water flowing through smooth and rough fractures, we presented an experimental study about the heat transfer process of water flowing through rock fractures. The effects of volumetric flow rate, initial rock temperature and the fracture roughness on the heat transfer characteristics of water flowing through fractures were measured, analyzed and discussed. Based on the above discussion, the following conclusions were drawn:

(1) There is a positive linear relationship between the overall heat quantity and the increase in initial rock temperature when under a constant volumetric flow rate. Hot, dry rock with a hotter temperature yields heat transfer quantities extracted by water flowing through the rock.

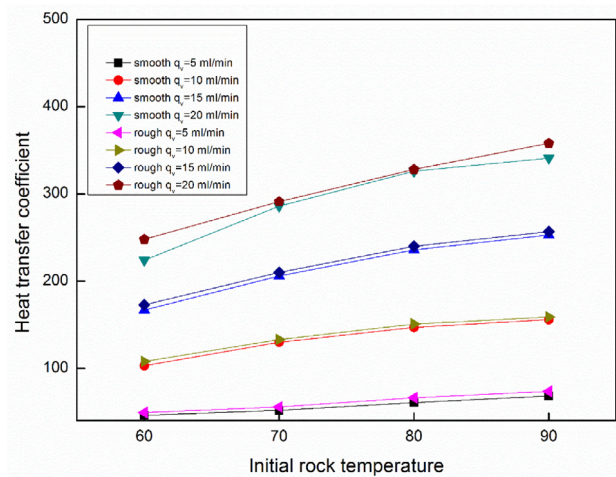


Fig. 5. Heat transfer coefficient comparison of smooth and rough fracture.

(2) Under a given temperature level, the total heat transfer quantity and the volumetric flow rate were positively correlated. Larger volumetric flow rates extracted more heat.

(3) The fracture surface roughness significantly influences the heat transfer characteristics of water flowing through rocks. Rock fracture surface roughness improves the overall heat transfer intensity.

The experimental results show that the roughness of a fracture has a great influence on the heat transfer characteristics. Due to the impact that fracture surface roughness has on heat transfer, applying parameters obtained from studies with smooth fractures to the evaluation of real-world enhanced geothermal systems will cause inaccuracies. Further study of the influence of differing degrees of fracture roughness on heat transfer characteristics should be undertaken.

Acknowledgments

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References

- Abdallah, G., Thoraval, A., Sfeir, A., Pigué, J.P., 1995. Thermal convection of fluid in fractures media. *Int. J. Mech. Min. Sci. Geomech.* 32 (5), 481–490.
- Bai, Bing, He, Yuanyuan, Li, Xiaochun, Li, Jun, Huang, Xiaoxue, Zhu, Jialing, 2017. Experimental and analytical study of the overall heat transfer coefficient of water flowing through a single fracture in a granite core. *Appl. Thermal Eng.* 116, 79–90.
- Carneiro, F., A new method to determine the tensile strength of concrete, in: *Proc. 5th Meet. Brazilian Assoc. Tech. Rules*, 1943, pp. 126–129.
- Cherubini, C., Pastore, N., Giasi, C.I., Allegretti, N.M., 2017. Laboratory experimental investigation of heat transport in fractured media. *Nonlinear Process. Geophys.* 24 (1), 23–42.
- He, Yuanyuan, Bai, Bing, Hu, Shaobin, Li, Xiaochun, 2016. Effects of surface roughness on the heat transfer characteristics of water flow through a single granite fracture. *Comput. Geotech.* 80, 312–321.
- Heinze, Thomas, Hamidi, Sahar, Galvan, Boris, 2017. A dynamic heat transfer coefficient between fractured rock and flowing fluid. *Geothermics* 65, 10–16.
- Huang, Xiaoxue, Zhu, Jialing, Li, Jun, Bai, Bing, Zhang, Guowei, 2016. Fluid friction and heat transfer through a single rough fracture in granitic rock under confining pressure. *Int. Commun. Heat Mass Transfer* 75, 78–85.
- de La Bernardie, J., Bour, O., Le Borgne, T., Guihéneuf, N., Chatton, E., Labasque, T., et al., 2018. Thermal attenuation and lag time in fractured rock: Theory and field measurements from joint heat and solute tracer tests. *Water Resour. Res.* 54, 10053–10075.

- Lu, W., Xiang, Y., 2012. Experiments and sensitivity analyses for heat transfer in a meter-scale regularity fracture granite model with water flow. *Appl. Phys. Eng.* 13, 958–968.
- Luo, J., Zhu, Y., Guo, Q., Tan, L., Zhuang, Y., Liu, M., Zhang, C., Xiang, J., 2017. Experimental investigation of the hydraulic and heat-transfer properties of artificially fractured granite. *Sci. Rep.* 7, 39882.
- Natarajan, N., Kumar, G.S., 2010. Thermal transport in a coupled sinusoidal fracture-matrix system. *Int. J. Eng. Sci. Technol.* 2, 2645–2650.
- National Development and Reform Commission Report, Thirteenth Five Year Plan of the geothermal energy development in China, 2017 Information on, http://www.sdpc.gov.cn/zcfb/zcfbghwb/201702/t20170204_837204.html.
- Neuville, A., Toussaint, R., Schmittbuhl, J., 2010. Fracture roughness and thermal exchange: a case study at Soultz-sous-Forêts. *C. R. Geosci.* 342, 616–625.
- Shaik, Abdul Ravoof, Rahman, Sheik S., Tran, Nam H., Tran, Thanh, 2011. Numerical simulation of fluid-rock coupling heat transfer in naturally fractured geothermal system. *Appl. Thermal Eng.* 31, 1600–1606.
- Xu, Tianfu, Yuan, Yilong, Jia, Xiaofeng, Lei, Yude, Li, Shengtao, Feng, Bo, Hou, Zhaoyun, Jiang, Zhenjiao, 2018. Prospects of power generation from an enhanced geothermal system by water circulation through two horizontal wells: A case study in the Gonghe Basin, Qinghai Province, China. *Energy* 148, 196–207.
- Zhang, Le, Jiang, Peixue, Wang, Zhenchuan, Xu, Ruina, 2017. Convective heat transfer of supercritical CO₂ in a rock fracture for enhanced geothermal systems. *Appl. Thermal Eng.* 115, 923–936.
- Zhao, J., 1999. Experimental study of flow-rock heat transfer in rock fractures. *Chin. J. Rock Mech. Eng.* 18, 119–123.
- Zhao, Zhihong, 2014. On the heat transfer coefficient between rock fracture walls and flowing fluid. *Comput. Geotech.* 59, 105–111.
- Zhao, Xin-gang, Wan, Guan, 2014. Current situation and prospect of China's geothermal resources. *Renew. Sustain. Energy Rev.* 32, 651–661.