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Heat transfer by water flowing through rough fractures and distribution of local heat transfer coefficient along the flow direction

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ABSTRACT

Heat transfer coefficient is a significant parameter that can describe the characteristics of the heat transfer process of fluid through fracture surface and can be used to predict hot water production from an enhanced geothermal reservoir and conventional geothermal systems. This study adopted numerical and experimental approaches that produce specimen with different rough surfaces through a 3D printing technique to improve the understanding of the heat transfer characteristics of water flowing through rough fractures and the distribution of local heat transfer coefficient along the flow direction. Results indicate that the local heat transfer coefficient increases to the maximum at the inlet and then decreases to a relatively constant value further along the flow direction. In addition, fracture surface tortuosity influences the local fluctuations.

1. Introduction

Geothermal energy, as a pollution-free and renewable energy resource that can be used to handle environmental problems caused by extensive use of fossil fuels, can potentially meet the gradually increasing energy requirements. In 2015, 82 countries have been identified as geothermal resources [1], and the official figures released by the Ministry of Land and Resources in China show that the total hot dry rock resources distributed at 3–10 km depth are equivalent to 8.6×10^{14} t of the standard coal; this figure is 260,000 times the capacity of the annual energy consumption of China [2]. Hot water and steam can be extracted from fluids and fractures found in natural hydrothermal systems. Dry and low permeability reservoirs require an enhanced geothermal system, in which man-made fractures that provide heat exchange surface and pathways for fluid to flow are required to extract and completely use the geothermal energy. Thus, fluid circulation and heat transmission are essential in conventional and enhanced geothermal systems. The evaluation of the potential of geothermal energy and accurate prediction of hot water production remains a huge challenge because of its complexity. Therefore, a sufficient understanding of the characteristics of fluid flow through fractures has an important role in developing sustainable geothermal energy.

Heat transfer coefficient is a significant parameter that can describe the characteristics of the heat transfer process of fluid through the fracture surface and can be used to predict hot water production from an enhanced geothermal reservoir. Many studies have examined this parameter. Zhao et al. [3] proposed a formula for calculating the heat transfer coefficient under the assumption that the sample surroundings have reached a uniform constant temperature, and an invariable average temperature is used to replace the fracture surface temperature. Zhang et al. [4] presented the analytical solution of heat transfer coefficient, in which the inner surface temperature can be calculated by assuming that the flux and wall temperature are uniform. Zhao [5] developed two analytical solutions for heated flow through granite fractures. Bai [6] introduced a new assumption that the temperature along the sample radius is a linear function and proposed a formula according to this assumption. Most of the formulas proposed previously are represent the average characteristics of fluid flow through the fracture surface. Few studies deal with dynamic non-averaged values and mention the local heat transfer coefficient. Heinze et al. [7] derived a new approach to calculate the heat transfer coefficient between rock and flowing fluid in a fractured system in which they consider dynamic changes and local heterogeneity. Dirker et al. [8] studied the local heat transfer coefficients at the inlet of an annular flow passage and found that the local heat transfer coefficient is significantly higher at the inlet and decreases while the boundary layers developed.

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Nomenclature

A	heat convection exchange area (m^2)
A_f	contact area per unit fluid volume (m^2)
A_s	contact area per unit volume of solid (m^2)
a	thermal diffusivity (m^2/s)
C_f	specific heat of fluid [J/(kg K)]
c_p	isobaric heat capacity (J/ kg K)
C_s	specific heat of rock [J/(kg K)]
$c_{p,w}$	specific heat capacity at constant pressure of water [J/(kg K)]
d	specimen diameter (m)
h	fluid /rock heat transfer coefficient [W/(m^2 K)]
h'	local heat transfer coefficient [W/(m^2 K)]
h_{total}	total heat transfer coefficient [W/(m^2 K)]
k_f^T	fluid thermal conductivity [W/(m K)]
k^T	rock thermal conductivity [W/(m K)]
L	specimen length (m)
l	characteristic length (m)
N_u	Nusselt number
P	the pressure of the fluid (P$_a$)
P_r	Prandtl number
Q	heat removed by fluid through the fracture (J/s)
q_f^T	specific heat flux in the fluid (W/m^2)
q^f	specific fluid discharge (m^3/s)
q^T	specific heat flux in the rock (W/m^2)
q_v	volumetric flow rate (m^3/s)
R_e	Reynolds number
t_1	inlet temperature of the element (K)
t_2	outlet temperature of the element (K)
T_c	temperature at the outer wall surface of the specimen (K)
T_f	fluid temperature (K)
T_{in}	inlet temperature of the water (K)
T_{out}	outlet temperature of the water (K)
T_r	arithmetic mean temperature of fracture inner surface (K)
T_w	arithmetic mean of t_1 and t_2 (K)
x_1	one of the x-coordinates of the element ends
x_2	one of the x-coordinates of the element ends
ρ_f	fluid density (kg/m^3)
ρ_s	solid density (kg/m^3)
ρ_w	density of water (kg/m^3)
μ	fluid viscosity (m^2/s)
υ	water viscosity (m^2/s)
λ	thermal conductivity [W/(m K)]

Many researchers have explored the fluid flow and heat transfer process by experimental and numerical modeling approaches [9–18]. Shaik et al. [9] developed a numerical procedure to investigate the role of heat transfer between the rock matrix and circulating fluid on geothermal system and found that the heat transfer between rock and fluid has a profound effect on the economic potential of a geothermal reservoir. Cheng et al. [10] demonstrate that the heat conduction in the unbounded domain can be handled using the Green's function approach and find a much more efficient numerical solution. Mohais et al. [11] present an analysis of fluid flow and heat transfer through a single horizontal channel with permeable walls which are at different temperatures. Lu et al. [12] analyze the effect of the assumption that instantaneous local thermodynamic equilibrium exists between the water, the fills in the fractures, and the surfaces of the neighboring rock matrix blocks through semi-analytical calculation of heat transfer in a single fracture impermeable rock. Bower et al. [13] used coupled thermo-hydro-mechanical codes with the ability to model fractured materials for predicting groundwater flow behavior in fractured aquifers containing thermal sources. Abdallah et al. [14] shows the importance of thermal convection caused by fluid circulation through the fractures in rock masses. This paper found that convection is sensitive to the hydraulic aperture of the fracture, the circulation velocity and the viscosity of the fluid by developing the UDEC code. Zhao [15] presented a description of experiments using a geothermal rock mechanics testing system capable of testing medium-sized cylindrical rock sample and found that the heat convection rate is a function of flow velocity in the fracture. Ogino et al. [16] conducted an experimental analysis of heat transfer using forced convection for water flow through circular fractures. Lu et al. [17] conducted experiments of saturated water flow and heat transfer for a meter-scale model of regularly fractured granite. Ogino et al. [18] conducted the experimental and numerical study of heat transfer from hot dry rock to flowing water in the circular fracture and found that the forced convection between flowing water and the surface has an important role in the heat transfer mechanism only in the early stage of heat extraction.

In the literature, many researchers study heat transfer process mainly based on one single smooth and horizontal fracture in order to analyze problems conveniently [19,20]. However, the natural and man-made fractures in enhanced geothermal systems are typically irregular and coarse. Therefore, several studies explored the heat transfer processes based on the rough fracture surface. Luo et al. [21] determined the two distributions of joint roughness coefficient, considered two empirical models, and found that fracture surface roughness affects the fluid flow and heat transfer processes in fracture networks to various extents depending on mechanical–hydraulic apertures. Huang [22] conducted experiments with a cylindrical granite rock to investigate the convective heat transfer and found that the heat transfer is weakened significantly due to the large relative roughness. Thus, the effect of fracture surface morphology on fluid flow and heat transfer must be studied to thoroughly understand the characteristics of fluid flow through the fractures.

Only a few studies on the local heat transfer coefficient and the effects of fracture surface tortuosity on heat transfer characteristics have been conducted. This study aims to investigate the distribution of the local heat transfer coefficient of water flowing through three samples with different fracture surface tortuosities through experimental and numerical studies. The effects of fracture surface tortuosity on the distribution characteristics of local heat transfer coefficient are discussed.

2. Experiment

2.1. Experimental apparatus

The test was conducted based on the hot dry rock laboratory simulation system, which was developed by our research group independently. The experimental system is presented in Fig. 1. This system mainly consists of permeating pressure, temperature control, confining pressure, specimen holder, and data acquisition subsystem. The permeating pressure was supplied by an ISCO pump, which comprises Pumps A and B. The volume of a single pump