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On the heat transfer coefficient between rock fracture walls and flowing fluid

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ABSTRACT

Two analytical solutions are derived to model the heated flow-through experiments for granite fractures in the literature. The first model, which assumes an identical/continuous temperature between the bulk fluid and fracture surfaces, represents an upper bound solution of water temperature in rock fractures. The second model including the empirical parameter of heat transfer coefficient is used to calculate the average heat transfer coefficient based on the available experimental data. The obtained heat transfer coefficients are smaller than that from the thermal boundary layer theory for flat plates, but larger than the previous estimates. A power function is fitted to describe the relation between heat transfer coefficient and flow velocity. Both models show that water temperature increases non-linearly along fracture plane.

1. Introduction

Prediction of hot water production from an enhanced geothermal reservoir and evaluation of its potential for geothermal energy, are a complex problem, and hence remain a major challenge for the geothermal industry [1,2]. An understanding of convective heat transfer between rock fracture surfaces and circulating fluid plays a key role in estimating heat recovery in fractured rocks. Even though heat convected away from a solid surface by an ambient fluid involves complex mechanisms of heat conduction and fluid dynamics within (velocity or thermal) boundary layers between the solid and the fluid, Newton's law of cooling was widely used to lump together all the complexities [3],

$$\frac{Q}{A} = h(T_s - T_f) \tag{1}$$

where Q is the heat flow into the fluid; A is the contacting area between the fluid and the rock surface; h is the heat transfer coefficient; T_s and T_f are the temperatures at fracture surface and in the fluid (measured at points far from the fracture surface). Note that heat transfer coefficient is an empirical parameter considering influences of the composition of the fluid, the geometry of the solid surface, and the hydrodynamics of the fluid motion past the surface, rather than a material property.

In particular, heat transfer coefficient is a critical parameter in the numerical modeling that explicitly represents fractures, e.g. discrete fracture network model [4], because it determines the heat exchange between circulating fluid and host rocks. However, no available empirical/exact solution (heat transfer coefficient as a function of fluid velocity and thermal properties of rock and fluid) is available at present [1]. A theoretical approach to determine the heat transfer coefficient of a rock fracture needs to find the temperature distributions in flowing fluid and rock matrix, respectively, which is usually impractical due to the complex geometry and boundary conditions of rock fractures. Similar difficulties also exist in experimental measurements, so only limited experimental data pertaining to thermal convection in rock fractures has been reported. Zhao [5,6] conducted a series of heated flow-through experiments to study the thermal convection behavior in rock fractures with different apertures, under various flow velocities. Based on the same experiments, significantly different ranges of heat transfer coefficient were determined: 200–1400 W m^{-2} K^{-1} [5,7] and 5–200 W m^{-2} K^{-1} [8], and the reason is that different theoretical models were used in those studies. Due to the poor understanding of the relationship between heat transfer coefficient and fluid velocity, fracture geometry and thermal properties of rock and fluid, a constant value of 900 W m^{-2} K^{-1} was abruptly used in Shaik et al. [1]. Therefore, It is doubtful for the practitioners to decide what values of heat transfer coefficient should be used in their respective applications. In view of that, this important issue is revisited in the present study.

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In addition, an identical temperature between the fluid and fracture surfaces was assumed in the literature [9–13] so as to derive analytical solutions for temperature distribution in single fracture or parallel fractures model, but their validity has not been well demonstrated. This assumption is also investigated in this study.

Overall, the aim of this study is to advance our understanding of heat convection process in rock fractures, in terms of (1) testing the validity of the assumption of an identical temperature between the fluid and fracture surfaces; and (2) providing some insights of determining heat transfer coefficients and notes of applying the heat transfer coefficients in geothermal modeling.

2. Methods

The experimental results obtained by Zhao [5] serve as a basis of model calibration in this study, so a brief review of the experimental procedure is given below. More details about the experiments can be found in Zhao [5,6] and Zhao and Tso [8]. The artificial extension fractures were prepared by splitting cylindrical core samples with a length of 102 mm and a diameter of 51 mm, and a total of 78 granite fracture samples were tested. During the flow-through experiments (Fig. 1), the temperature of the rock sample's outer surface was maintained constant (T_0), while the water was injected at one end (at a low temperature, T_{in}) and collected from the other end (heated to a high temperature, T_{out}). After reaching a steady state, the water temperatures at inlet and outlet ends were measured, but the temperature profile of water along the fracture plane was not recorded in their experiments. The temperature distribution in the rock matrix was not known either.

In order to model the above heated flow-through experiments [5], two analytical models with different assumptions at fracture surfaces are derived. In 'Model I' (Section 2.1), it is assumed that an identical temperature between the fluid and fracture surfaces. In 'Model II' (Section 2.2), the heat transfer coefficient is assumed as constant along the fracture plane, which can be understood as the average heat transfer coefficient. The heat flow from the fracture walls to the fluid is calculated according to Eq. (1).

Actually heat transfer occurs as a consequence of temperature difference between the fluid in the fracture voids and the surrounding rocks, and some variation of fluid temperature exists from the stream boundary ($z = \pm b$) to the stream centerline ($z = 0$). For simplicity, a bulk temperature is defined to represent the uniform temperature cross the fracture aperture, and this assumption is reasonable for a thin fracture and therefore used in both models. In addition, other assumptions employed in these two models include two-dimensional geometry of smooth parallel plates, impermeable rock matrix, fully-developed fluid flow state and uniform velocity cross the fracture section, and constant (i.e. temperature-independent) properties of water and rocks.

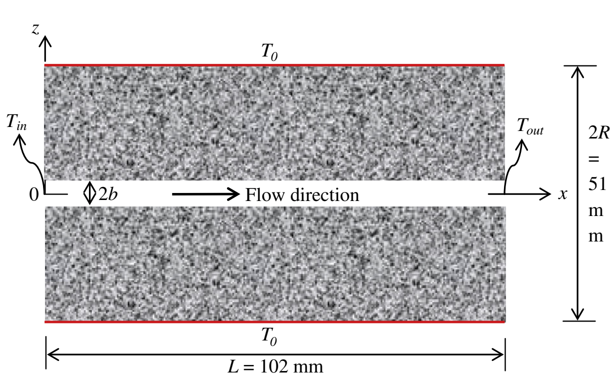

Fig. 1. A conceptual diagram of heated flow-through experiment in a rock fracture [4]. Note that fracture roughness was neglected in this study, and b represents a half of fracture aperture.

2.1. Model of continuous temperature at fracture surfaces

By assuming that the temperature at rock fracture surface is the same as that of the bulk fluid, the steady heat transport in the fracture, including advection, conduction and convection from the fracture walls, can be expressed as,

$$v\frac{\partial T_f(x)}{\partial x} - \frac{K_w}{\rho_w c_w}\frac{\partial^2 T_f(x)}{\partial x^2} - \frac{K_r}{\rho_w c_w b}\frac{\partial T_r(x,z)}{\partial z}\bigg|_{z=\pm b} = 0 \quad (2)$$

where ρ_w is the water density; c_w is the specific heat of water; K_w is the water thermal conductivity (the term of $D = \frac{K_w}{\rho_w c_w}$ is called the water thermal diffusivity); K_r is the rock thermal conductivity; v is the steady flow velocity; b is the half aperture of the fracture; T_f is the bulk temperature of water; T_r is the temperature of reservoir rock matrix. The steady heat conduction in the rock is governed by,

$$\frac{\partial^2 T_r(x,z)}{\partial z^2} = 0 \quad (3)$$

which assumes that the heat conduction is one dimensional, perpendicular to the fracture plane.

The boundary conditions associated with the heated flow-through experiments are [8],

$$T_f(0) = T_{in} \quad (4a)$$

$$T_f(\infty) = T_0 \quad (4b)$$

$$T_r(x,R) = T_0 \quad (5)$$

where R is the radius of fracture sample (Fig. 1). The identical temperature between the fluid and fracture surfaces is expressed as,

$$T_r(x,b) = T_f(x) \quad (6)$$

The solutions to Eqs. (2) and (3) subjected to boundary conditions Eqs. (4)-(6) are,

$$T_f(x) = T_0 + (T_{in} - T_0)\exp\left[\frac{x}{2}\left(\frac{v\rho_w c_w}{K_w} - \sqrt{\left(\frac{v\rho_w c_w}{K_w}\right)^2 + \frac{4K_r}{bRK_w}}\right)\right] \quad (7)$$

$$T_r(x,z) = \frac{(T_0 - T_f(x))}{R}z + T_f(x) \quad (8)$$

If thermal diffusion in the fluid is not considered, Eq. (7) becomes,

$$T_f(x) = T_0 + (T_{in} - T_0)\exp\left(-x\frac{K_r}{v\rho_w c_w bR}\right) \quad (9)$$

Eqs. (7) and (9) were used to estimate the temperatures (T_{out}) at the outlet ends of all 78 fractures. It was shown that both equations gave the almost same outlet temperatures and overlapped temperature profiles (Fig. 2). This verifies that thermal diffusion in the fluid could be negligible under the experimental conditions, so Eq. (9) is used in the later analysis and only the outlet temperatures predicted by Eq. (9) are presented in Table 1.

2.2. Model of constant heat transfer coefficient along fracture plane

If a constant heat transfer coefficient was assumed along the fracture plane, based on Eq. (1), the governing equation for steady heat transport in the fracture becomes,