Research Article

Numerical Simulation on Heat Transfer Characteristics of Water Flowing through the Fracture of High-Temperature Rock

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Deep geothermal resources are becoming an increasingly important energy source worldwide. To achieve the optimal efficiency of this resource, the heat transfer characteristics between flowing water and rock need to be further studied. Using the stereotopometric scanning system 3D CaMega, the fracture geometry data of five cuboid granite rocks were obtained to determine the effects of fracture roughness on the heat transferability of rock. A 3-D model was built based upon the scanned geometry data to assess the effects of rock temperature, water velocity, and roughness, and aperture size of fracture surface on the heat transfer coefficient. The simulation tests show that water velocity has the most noticeable effect, followed by aperture size and rock roughness. On the other hand, the initial rock temperature has the least influence. A new heat transfer coefficient was proposed considering aperture size, water flow velocity, and rock fracture roughness. The calculated values of Reynolds, Prandtl, and Nusselt numbers obtained using this coefficient are in good agreement with the numerical simulation results. This study provides a reference for enhancing the heat transfer coefficient to benefit the exploitation of heat energy of hot dry rock.

1. Introduction

Clean energy can help solve the problems of air pollution and energy shortages as fossil fuels become exhausted in the coming generations. The deep geothermal energy of hot dry rock (HDR) has been utilized worldwide, including in China [1–3]. China is rich in coal resources and has a well-developed mining system [4–7]. At the same, China is also a vast country with abundant geothermal resources, mostly of the low-medium temperature type. China's geothermal resources potential is about 8% of the total global geothermal potential (Zhao et al. 2014). Thus, it is necessary to further develop this sustainable energy technology to meet the growing energy demand.

Fluid circulation and heat transmission are essential in conventional or enhanced geothermal systems (Figure 1). Hot water and steam can be extracted from fluids flowing through the fractures found in natural hydrothermal systems. However, dry reservoirs with low permeability require an enhanced geothermal system in which man-made fractures provide a heat exchange surface and pathways for fluids to flow. The existence of fractures is important for affecting the rock mass properties [8–10]. For both natural and man-made fractures, the characteristics of fluid flowing through fractures in the subsurface vary based upon water velocity, surface roughness, temperature, and porosity/permeability characteristics. Further research is needed to accurately model the geothermal

FIGURE 1: Diagram of a geothermal system.

system in these reservoirs to properly develop geothermal energy.

To explicitly represent the heat transfer of fluid through a fractured surface, a heat transfer coefficient (HTC) was proposed to predict hot water production from an enhanced geothermal reservoir. There has been much in-depth research on this parameter (Zhao et al. 2014; Ganguly et al. 2014; [11–14]; Teke et al. 2018; [15]). For example, Mohais et al. [16] proposed a simplified interpretation and mathematical analysis of flow and heat transfer through a single horizontal fracture in an enhanced geothermal system. Bai et al. [17] proposed an analytical method to develop a more effective equation for the HTC based on the temperature distribution in the fracture wall along the direction of the sample radius. Finally, Abbasi et al. [18] proposed an analytical method to describe the transient temperature distribution in a single fracture model to help investigate water injection into a fractured geothermal reservoir.

Understanding the heat transfer process between fluids and rocks is critical for efficiently exploiting geothermal systems. Many laboratory experiments have been conducted to determine the heat transfer properties of various rock types [19–21]. Huang et al. [22] performed convective heat transfer experiments to study the behavior of water flowing in a simulated rock specimen. Based on two rock specimens with different roughness coefficients, the influence of rock roughness on the seepage characteristics was determined. The secondary damage characteristics of HDR reservoirs were studied through experiments. Guo et al. [23] obtained the damage formulas of granite rock properties based on experimental results.

Although various parameters for specific rock types have been determined, the effects of the flow path and changes in rock temperature on the evolution of fluid temperature have not yet been studied in-depth. Luo et al. [24] used two groups of granite samples with a single fracture obtained from the Gonghe Basin, China, to determine the influence of the flow path. The results showed that the larger the fracture area ratio, the higher the hydraulic conductivity of the rock. Ma et al. [25] created rock samples with different rough surfaces by 3D printing to study heat transfer of water flowing through rough fractures. They found that the tortuosity of a fracture surface influences local fluctuations in temperature. In another study, distilled water was passed through artificial

smooth and rough fractures of rock samples to study the impact of fracture surface roughness on the heat transfer intensity [26]. The results showed that the roughness of the rock fracture surface improves the overall heat transfer intensity to a certain extent. While surface roughness has been studied, the effect of variations in aperture size on heat transfer in geothermal systems has not been extensively studied.

The evaluation of the potential of geothermal energy and accurate prediction of hot water production remains a challenge because of its complexity. As the increasing confining pressure caused by geothermal energy production affects the fracture geometry to some extent, the influence of the aperture size of the fracture on the heat transfer characteristics needs to be studied. While it is known that aperture size affects temperature and production, the increase in aperture size is on the micron level under typical conditions. Therefore, it is difficult to measure the fluid temperature and inner surface temperature at various points along the flow direction in the laboratory or in-situ experiments.

Numerical simulation can easily determine the heat transfer process between water and hot dry rock under the typical complex environment of geothermal reservoirs [27–29]. Kolditz et al. (1998) used a fully 3-D finite-element model to study the heat transfer during forced water circulation through fractured crystalline rock. The applicability of this model was proven by a 900-day test at an HDR site in the United Kingdom. Bai et al. [30] built a numerical model to simulate the local heat transfer coefficient (LHTC) of fluid flowing through a single fracture under confining pressure, and the numerical results were verified by test data. To study the coupled thermal-mechanical-hydraulic process in fractured porous media, Lee et al. [31] proposed the TOUGH-UDEC numerical software to simulate heat transfer and multiphase fluid flow in fractured porous media. To study the effects of heat transfer between fluid and rock on economic hot water production from geothermal systems, Shaik et al. [32] proposed a numerical approach to simulate the heat transfer process by coupling fluid flow with heat transfer. Most of the previous studies on the heat transfer process are mainly based on 2-D analysis, and influencing factors such as rock temperature, roughness, and aperture size of the fracture surface, and water velocity are not comprehensively considered.

Herein, a 3-D numerical model was adopted to quantitatively investigate the characteristics of the heat transfer process between flowing water and rough granite fracture wall. Rock properties, including rock temperature, roughness, and aperture size of the fracture surface, and water velocity, were included in the model to create a comprehensive heat convection process of water in rock fractures.

2. Heat Transfer Coefficient

The heat transfer coefficient is an important parameter that describes the heat transfer characteristics of working fluid flowing through a fractured rock. The average heat transfer coefficient h can be obtained based on energy conservation because the heat absorbed by water in the entire fracture pathway equals the heat transfer by convection between the

water and the inner surface of the fracture [30]. It can be expressed as follows:

$$h = \frac{c_{p,w} \rho_w v s (T_2 - T_1)}{2L(T_i - T_1 + T_2/2)}, \quad (1)$$

where $c_{p,w}$ is the specific heat capacity of water at constant pressure, ρ_w is the density of water, v is the steady flow velocity of water, s is the aperture width, T_2 and T_1 are the water temperatures at outlet and inlet ends, respectively, T_i is the inner wall temperature of the rock fracture, and L is the length of the rock sample.

Equation (1) requires information on the temperature distribution on the inner wall of the fracture. Here, the formula of the inner wall temperature T_i presented by Carslaw and Jaeger (1973) is adopted:

$$T_i = T_c - \frac{\pi c_{p,w} \rho_w v ds (T_2 - T_1)}{42.32 K_r L}, \quad (2)$$

where K_r is the rock thermal conductivity, and d is the equivalent radius of fracture.

Substituting Eq. (2) into Eq. (1), the following equation is obtained:

$$h = \frac{c_{p,w} \rho_w v s (T_2 - T_1)}{2L(T_c - \pi c_{p,w} \rho_w v ds (T_2 - T_1) / 42.32 K_r L - T_1 + T_2/2)}. \quad (3)$$

Compared with previous calculation formulas ([33]; Zhao et al. 1992), this proposed equation does not consider a simplification of specimen section shape. Nevertheless, it can obtain the temperature on the fracture wall by solving the two-dimensional heat conduction equation on a semi-disk region.

The Reynolds number Re is calculated as follows:

$$Re = \frac{2q}{dv}, \quad (4)$$

where v is the fluid viscosity, and q is the flow rate.

The Prandtl number Pr is calculated as follows:

$$Pr = \frac{v}{a}, \quad (5)$$

where a is the thermal diffusivity. $a = \lambda / \rho c$. λ is the fluid thermal conductivity coefficient; ρ is water density, and c is fluid specific heat.

The Nusselt number Nu is calculated as follows:

$$Nu = \frac{hl}{\lambda}, \quad (6)$$

where l is the characteristic length.

However, the characteristics of rough-walled fracture are not included in most of the established relationships of Nu , Re , and Pr .

FIGURE 2: Scanned rock samples, each with different roughness values.

3. Numerical Modeling and Simulation

It is difficult to directly obtain the temperature inside the fracture surface using microscale sensors. Moreover, the installment of such sensors would affect the natural flow of water through the fracture. Numerical simulation is an effective method to explore the heat transfer process at the microscale. According to the previous research of Bai et al. [30], numerical modeling is an alternative method to obtain the necessary heat transfer characteristics values. Many scholars have studied heat transfer processes primarily based on 2-D analysis, whereas the influencing factors such as rock temperature, roughness, and aperture size of fracture surface along with water velocity have not been comprehensively considered. Based on the previous detailed research [30], COMSOL software was used in this work to study the heat transfer process between the water and fracture surface.

In COMSOL, the single-phase water flow in the fracture follows the Navier-Stokes equations ([34–38]), which can be written:

$$\begin{aligned} \nabla \mathbf{u} &= 0, \\ \rho_w \frac{\partial \mathbf{u}}{\partial t} + \rho_w \mathbf{u} \nabla \mathbf{u} &= -\nabla p + \nabla \left(\mu \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right) \\ &\quad - \frac{2}{3} \mu ((\nabla \mathbf{u}) I), \end{aligned} \quad (7)$$

$$\rho_w c_{p,w} \left(\frac{\partial T_w}{\partial t} + (\mathbf{u} \nabla) T_w \right) = -\nabla \mathbf{q}_w,$$

where ρ_w is the density, $\mathbf{u}$ is the velocity vector, p is the pressure, $c_{p,w}$ is the specific heat capacity, T_w is the absolute temperature, and $\mathbf{q}_w$ is the heat flux vector in water. The heat conduction equation in the rock can be given by:

$$\rho_s c_{p,s} \frac{\partial T_s}{\partial t} = -\nabla \mathbf{q}_s, \quad (8)$$

where $\mathbf{q}_s$ is the heat flux in rock specimen. The boundary condition of the outlet is the standard atmospheric pressure corresponding to the experiment.

FIGURE 3: 3D discretization of the fracture surfaces in the five samples.

The fracture geometries of five cuboid granite rocks (Figure 2) were obtained through the stereotopometric scanning system 3D CaMega with high measurement speed and precision [34]. The resolution of a sampling point obtained by the scanning system was $\pm 25 \mu\text{m}$, which is defined as the error of 3D space along the x , y , and z directions. Roughness measurements were performed on the 64 mm $\times$ 64 mm lower and upper halves of the five fracture replicas. 3D discretization of the fracture surface is shown in Figure 3.

The fracture geometries were then imported into Comsol software. The initial inlet temperature of water was set at 293.15 K. The fractal dimension of the fracture surface (D) for each sample, rock temperature, water velocity, and aperture size of the fracture surface (s) for each simulation are listed in Table 1. The fractal dimension was calculated according to the variogram function of 2D profiles. More detailed information can be seen in Xiong et al. [34].

The heat transfer process between water and fracture surface was calculated based on the finite element method through precision meshing on these models after setting each simulation parameter of the model in COMSOL. The calculation results of water pressure and rock temperature are plotted in Figure 4, and the calculation results of different heat transfer processes are shown in Table 2.

4. Simulation Results Analysis

4.1. Effects of Fracture Aperture Size on the Heat Transfer Characteristics. The distribution of the temperature field is an important indicator of the efficiency of the heat transfer process. The temperature field of water flowing within granite with different aperture sizes (0.5 mm, 0.7 mm, and 0.9 mm) was taken as an example, and the effects of fracture aperture size on heat transfer were studied. The flow velocity

TABLE 1: Fracture parameters influencing the heat transfer coefficient.

Fractal dimension D	Rock temperature t (K)	Velocity of water v (m/s)	Aperture width of fracture surface s (mm)
1.2 (I rock)	323.15	0.0025	0.3
1.4 (II rock)	343.15	0.0050	0.5
1.6 (III rock)	363.15	0.0075	0.7
1.8 (IV rock)	/	/	/
2.0 (V rock)	/	/	/

FIGURE 4: Calculation results of water pressure and rock temperature (Temperature: K).

of water and rock temperature were set as 0.005 m/s and 343.15 K, and the 1.4 roughness fracture surface (F_2 sample) was chosen as the flow surface. The calculation results are shown in Figure 5. Similar temperature trends are observed for the results of the other samples with water flowing through the fracture.

Overall, the aperture size has a significant influence on the heat transfer process (Table 2). As the fracture aperture size increases, the heat transfer coefficient [39–47] increases. When water flows along the fracture surface of a rock, it absorbs the surrounding heat energy of the rock. The temperature of the water gradually increases during the flow process, and the temperature of the surrounding rock decreases slowly along the flow direction. The most significant decrease in temperature occurs at the water inlet. As seen from Figure 5, with the increase in aperture size, the water heating rate decreases and the lower temperature area at the inlet further expands. This is mainly because the increase in aperture size leads to a rise in water flow to maintain a constant flow rate. The total volume of water flowing inside the fracture surface to absorb heat energy increases. Thus, the heat energy stored in the surrounding rock decreases. Overall, the heat transfer coefficient increases.

4.2. Effects of Flow Velocity on the Heat Transfer Characteristics. Using the same rock and aperture size conditions as above, the temperature field of water flowing

through granite at different velocities (0.005 m/s, 0.01 m/s, and 0.015 m/s) was taken as an example, and the effects of flow velocity on the heat transfer characteristics were studied. The fracture aperture size and rock temperature were set to 0.5 mm and 343.15 K, and the 1.4 roughness fracture surface (F_2) was chosen as the flow surface. The calculation results are shown in Figure 6. The results of the other surfaces with varying water velocities exhibit similar trends.

The water velocity has a more significant influence on the heat transfer process than the fracture aperture size (Table 2). With the increase in flow velocity, the heat transfer coefficient markedly increases, although the inner wall temperature and outlet temperature of rock fracture also decrease to some extent. Increase in flow velocity results in an increase in the total volume of water flowing inside the rock to absorb the heat energy. Thus, the heat energy stored in the rock transfers to the water (Figure 6). Finally, the water reaches equilibrium with the rock closer to the outlet with increasing velocity.

4.3. Effects of Rock Temperature on the Heat Transfer Characteristics. At constant water velocity and aperture size of the fracture surface, the effects of rock temperature on the heat transfer characteristics were studied, taking the example of the temperature field of water flowing through granite at different temperatures (323.15 K, 343.15 K, and 363.15 K). The fracture aperture size and flow velocity of

TABLE 2: Calculation results of different heat transfer processes.

Roughness	Aperture (m)	Water velocity (m/s)	Rock temperature (K)	Ti (K)	Outlet temperature (K)	Heat transfer coefficient
1.2	5e-4	0.0025	323.15	319.5125	323.043	107.4001
			343.15	337.0955	342.985	107.4214
			363.15	354.6715	362.915	107.416
		0.005	323.15	316.0465	322.241	285.7587
			343.15	331.3185	341.65	285.8437
			363.15	346.5825	361.041	285.7897
		0.0075	323.15	313.0875	320.591	543.1123
			343.15	326.3865	338.903	543.4135
			363.15	339.6895	357.223	543.6105
		0.0025	323.15	318.027	322.831	169.814
			343.15	334.6085	342.612	169.7923
			363.15	351.202	362.415	169.8297
	7e-4	0.005	323.15	313.5595	320.84	484.4274
			343.15	327.1735	339.318	484.6754
			363.15	340.7835	357.798	484.955
		0.0075	323.15	310.255	318.017	916.9923
			343.15	321.666	334.614	917.6287
			363.15	333.0795	351.218	918.0965
		0.0025	323.15	316.542	322.367	245.5782
			343.15	332.144	341.86	245.6567
			363.15	347.7375	361.334	245.6099
		0.005	323.15	311.4425	318.989	710.0856
			343.15	323.64	336.229	710.6735
			363.15	335.8445	353.481	711.0104
	9e-4	0.0075	323.15	308.11	315.376	1279.624
			343.15	318.09	330.212	1280.801
			363.15	328.063	345.021	1279.712
1.4	5e-4	0.0025	323.15	319.5595	323.043	106.9598
			343.15	337.1745	342.984	106.9772
			363.15	354.782	362.913	106.9723
		0.005	323.15	316.1265	322.261	283.5782
			343.15	331.4415	341.662	283.531
			363.15	346.7535	361.057	283.4858
		0.0075	323.15	313.181	320.618	536.74
			343.15	326.543	338.949	537.0395
			363.15	339.9085	357.288	537.2532
		0.0025	323.15	317.987	322.827	170.4365
			343.15	334.5415	342.605	170.4152
			363.15	351.1095	362.406	170.4481
	7e-4	0.005	323.15	313.5105	320.834	487.7402
			343.15	327.0915	339.29	487.4112
			363.15	340.676	357.764	487.5822
		0.0075	323.15	310.212	318.001	923.32
			343.15	321.594	334.586	923.8931
			363.15	332.979	351.18	924.4104
	9e-4	0.0025	323.15	316.5125	322.363	246.3158
			343.15	332.094	341.853	246.4041
			363.15	347.6675	361.325	246.3648

TABLE 2: Continued.

Roughness	Aperture (m)	Water velocity (m/s)	Rock temperature (K)	Ti (K)	Outlet temperature (K)	Heat transfer coefficient
1.6	5e-4	0.005	323.15	311.4085	318.979	713.6627
			343.15	323.5885	336.216	714.0491
			363.15	335.773	353.463	714.3618
		0.0075	323.15	308.0825	315.371	1287.704
			343.15	318.0445	330.202	1288.598
			363.15	327.999	345.008	1287.639
	7e-4	0.0025	323.15	319.734	323.049	105.4043
			343.15	337.454	342.977	105.3962
			363.15	355.0385	362.755	105.401
		0.005	323.15	316.1165	322.141	280.7423
			343.15	331.4165	341.452	280.7037
			363.15	346.5535	360.559	280.7069
		0.0075	323.15	312.981	320.29	533.38
			343.15	326.343	338.579	533.4634
			363.15	339.7085	356.888	533.9026
		0.0025	323.15	317.787	322.457	168.5644
			343.15	334.3415	342.195	168.9517
			363.15	350.9095	361.93	169.0013
	9e-4	0.005	323.15	313.3105	320.524	485.6311
			343.15	326.8915	338.97	485.8183
			363.15	340.476	357.425	485.9981
		0.0075	323.15	310.062	317.771	921.7325
			343.15	321.394	334.266	921.5292
			363.15	332.779	350.838	921.4334
		0.0025	323.15	316.3125	322.04	244.6681
			343.15	331.894	341.483	244.7837
			363.15	347.4675	360.93	244.9673
		0.005	323.15	311.2085	318.669	711.0851
			343.15	323.3885	335.886	711.3734
			363.15	335.573	353.11	711.522
1.8	5e-4	0.0075	323.15	307.8825	315.062	1285.096
			343.15	317.8445	329.88	1285.271
			363.15	327.999	344.99	1285.894
		0.0025	323.15	319.334	322.009	100.6993
			343.15	337.054	341.55	100.7489
			363.15	354.6385	360.855	100.4835
	7e-4	0.005	323.15	315.7165	321.49	276.8732
			343.15	331.5165	341.32	276.6828
			363.15	346.1535	359.659	276.2579
		0.0075	323.15	312.981	320.29	533.38
			343.15	326.343	338.579	533.4634
			363.15	339.7085	356.888	533.9026
	9e-4	0.0025	323.15	317.387	321.7	164.5648
			343.15	333.9415	341.24	164.8952
			363.15	350.5095	360.79	164.9999
		0.005	323.15	312.9105	319.9	481.101
			343.15	326.4915	338.3	481.6045
			363.15	340.076	356.7	481.7055

TABLE 2: Continued.

Roughness	Aperture (m)	Water velocity (m/s)	Rock temperature (K)	Ti (K)	Outlet temperature (K)	Heat transfer coefficient
2.0	9e-4	0.0075	323.15	309.162	316.442	919.013
			343.15	320.994	333.66	919.552
			363.15	332.379	350.23	919.9104
		0.0025	323.15	317.9125	323.82	240.1812
			343.15	331.494	340.65	240.293
			363.15	347.0675	360.01	240.9346
		0.005	323.15	310.8085	318.078	708.5908
			343.15	322.9885	335.275	708.7534
			363.15	335.173	352.48	708.8886
		0.0075	323.15	307.4795	314.167	1218.251
			343.15	317.4195	328.75	1218.772
			363.15	327.5555	343.62	1218.943
	5e-4	0.0025	323.15	318.734	320.53	94.41801
			343.15	336.654	339.75	94.60147
			363.15	354.2385	358.655	94.81679
		0.005	323.15	315.3165	320.82	272.4365
			343.15	331.1165	340.57	272.8525
			363.15	345.7535	358.859	272.9349
		0.0075	323.15	312.581	319.68	529.4248
			343.15	325.843	337.79	529.5298
			363.15	339.3085	356.18	529.6305
		0.0025	323.15	316.787	320.7	160.4109
			343.15	333.3415	340.01	160.5339
			363.15	349.9095	359.4	160.9596
2.0	7e-4	0.005	323.15	312.3105	318.99	475.5328
			343.15	325.8915	337.31	475.6835
			363.15	334.576	349.03	475.8615
		0.0075	323.15	308.562	315.53	913.1465
			343.15	320.394	332.715	913.4476
			363.15	331.279	348.53	913.8874
		0.0025	323.15	317.3125	322.8	234.4315
			343.15	330.894	339.48	234.6153
			363.15	346.4675	358.61	234.7439
		0.005	323.15	309.6085	316.322	702.2043
			343.15	322.3885	334.32	702.4912
			363.15	334.573	351.48	702.626
2.0	9e-4	0.0075	323.15	306.8795	313.26	1212.152
			343.15	316.8195	327.82	1212.229
			363.15	326.9555	342.67	1212.526

water were set as 0.5 mm and 0.005 m/s, and the 1.4 roughness fracture surface (F_2) was chosen as the flow surface. The calculation results are shown in Figure 7. The other samples have similar trends for temperature.

Initial rock temperature has a limited influence on the heat transfer process (Table 2). With the increase in surrounding rock temperature, the water temperature at outlet increases, but the heat transfer coefficient remains

essentially constant with only a small increase. The increase in the initial temperature of the rock results in a relatively constant rock temperature (Figure 7). The position where water has a similar temperature as the rock has no obvious deviation and is still near the inlet. Thus, the heat transfer characteristics between flowing water and the rock fracture are not significantly affected by the initial rock temperature.

FIGURE 5: Temperature field of water flowing through F₂ granite sample with various aperture sizes (Temperature: K).

4.4. Effects of Fracture Roughness on the Heat Transfer Characteristics. Using constant water velocity, the aperture size of the fracture surface, and initial rock temperature, the effects of fracture roughness on the heat transfer characteristics were studied, taking the temperature field of water flowing through granite rock with different roughness values of fracture surface (1.2, 1.4, 1.6, 1.8, and 2.0 roughness fracture surface) as an example. The rock temperature, fracture aperture size, and flow velocity of water were set to 343.15 K, 0.5 mm, and 0.005 m/s, respectively. The calculation results are shown in Figure 8. The other water velocities, aperture sizes, and initial rock temperatures have similar trends.

Fracture roughness has a slight influence on the heat transfer process (Table 2). The increase in fracture roughness results in increased contact area. However, some bumps and recesses in the fracture surface hinder effective heat transfer between flowing water and rock fracture. Overall, the heat

transfer coefficient decreases with the increase in the roughness coefficient. An increase in fracture roughness under the same flow velocity, rock temperature, and fracture aperture size results in gradually decreasing heat transfer abilities between flowing water and rock (Figure 8). A greater flow distance is needed to increase and maintain the water temperature at the rock temperature. Thus, the position where water has a similar temperature as the surrounding rock slowly moves towards the outlet. Overall, the decreasing temperature area of the rock becomes relatively large.

5. Discussion

To better represent the geothermal system based upon the above results, a new heat transfer coefficient is proposed. Water velocity has the most significant influence on the heat transfer coefficient, followed by fracture aperture size, and

FIGURE 6: Temperature field of water flowing through granite sample F_2 with various velocities (Temperature: K).

rock fracture roughness; whereas initial rock temperature has the least influence. Therefore, the initial rock temperature can be ignored in the newly proposed heat transfer coefficient. The new heat transfer coefficient model considers aperture size, flow velocity of water, and rock fracture roughness and can be expressed as:

$$h = 6e9v^{1.4} \exp(-0.16D)s^{1.2}. \quad (9)$$

From Eq. (9), the heat transfer coefficient can be estimated approximately by water velocity, rock fracture roughness, and aperture size. With the increase in the rock aperture size and water velocity, and decrease in the rock fracture roughness, the heat transfer coefficient increases. Therefore, to enhance the heat transfer coefficient of fluid through the rock fracture surface, the water velocity and rock aperture size should be increased

appropriately, and the rock fracture surface should be as smooth as possible.

Additionally, the Reynolds, Prandtl, and Nusselt numbers were calculated by Eqs. (4)–(6), respectively. Figure 9 illustrates the positively correlated relationship between the Nusselt number and the Reynolds/Prandtl number ratio. The Reynolds number is within the range of 7.4–20.5 in the above experiments. Based on the characteristics of the curves plotted in Figure 9, a semiempirical relationship between the Nusselt number and Reynolds number/Prandtl number ratio is proposed below in the form of Eq. (10):

$$Nu = 0.94Pr^{1/3} Re^{1.23} \quad (10)$$

Figure 9 also presents the best-fitted curves of the numerical data for all the above cases. The results show that Eq. (10) fits well with the experimental data with a high correlation coefficient ($R^2 = 0.95$).

FIGURE 7: Temperature field of water flowing through a fracture in granite with various starting temperatures (Temperature: K).

Equations (9) and (10) were proposed based on a number of numerical simulations. However, the reliability of numerical simulation results is not acceptable. Hence, a series of heat transfer experiments should be conducted to verify the proposed Eqs. (9) and (10). In addition, the heat transfer coefficient model should be considered for future application in large scale engineering simulation.

6. Conclusion

Using a 3-D numerical model, the effects of rock temperature, roughness, and aperture size of fracture surface, and water velocity on the heat transfer characteristics of rock were studied in detail. The following are the main conclusions of this work:

- (1) The fracture geometry of five cuboid granite rocks was obtained using 3D CaMega stereotopometric scanning system, and 3-D models were built using

Comsol software by importing the geometry data. Based on previous research, a reasonable 3-D model was built to investigate the effects of rock temperature, roughness, and aperture size of fracture surface, and water velocity on the heat transfer characteristics between flowing water and a rock fracture. The simulation results were highly consistent with previous experimental results, which verifies the precision and practicality of the model

- (2) The test results showed that water velocity has the most significant influence on the heat transfer coefficient, followed by fracture aperture size and rock fracture roughness. The initial rock temperature has the least influence. The simulation results provide a foundation for the exploitation of heat energy of hot dry rock for renewable energy resources
- (3) A new heat transfer coefficient model was proposed considering aperture size, flow velocity of water,

FIGURE 8: Temperature field of water flowing through granite with various roughness values of fracture surface (Temperature: K).

and rock fracture roughness. The initial rock temperature was not taken into account because it has a negligible effect on the temperature of the water as

it passes through the fracture. The heat transfer coefficient can be estimated approximately by the water velocity, rock fracture roughness, and aperture

FIGURE 9: The relationship between Re and $Nu/Pr^{1/3}$.

size in this new coefficient model. The heat transfer coefficient of water flowing through a fracture in the hot dry rock can be enhanced by increasing the water velocity and aperture size and by decreasing the roughness of the fracture surface. Additionally, a relationship between Nusselt number and Reynolds number/Prandtl number ratio was also proposed based upon the relationships determined through the simulation results

Data Availability

The data are available and explained in this article, readers can access the data supporting the conclusions of this study.

Conflicts of Interest

The authors have no conflicts of interest to declare.

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