Influence of contact shape and distribution on fluid flow through a fracture

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ABSTRACT: Fluid flow through a rough fracture can be affected by several geometrical parameters such as aperture, roughness, and contact area. Of these, eddy flow can occur around contact areas and change streamline patterns. Fluid flow behavior through a 10 cm × 10 cm square fracture was numerically analyzed with different contact shapes and distributions. The basic shape of the contact area is assumed to be square with a 1 cm^2 area. The squares as contact areas through fractures were distorted with different ratios, rotations, and relocations. The total contact area and the physical aperture in all models were 25 cm^2 and 1 mm, respectively. The flow rates through the fractures were computed with 5 different water pressures. The Forchheimer equation was adopted to analyze results. The calculations highlight the importance of the parameter β in the Forchheimer equation, which reflects the impact of fracture surface geometry on fluid flow.

Keywords: fluid flow, contact area, hydraulic aperture, numerical modeling.

1 INTRODUCTION

Evaluation of fluid flow rate through a fracture is important due to its great influence on oil and gas production, safety of nuclear waste repositories, carbon dioxide sequestration, and water resource management. The flow rate and hydraulic aperture of a fracture are controlled by different variables such as geometrical properties of fractures, hydraulic gradients, and stress states. Geometrical properties of fractures, such as physical aperture, roughness, and contact areas, can change under different normal and shear stress regimes.

Many efforts have been made to understand the effect of geometrical properties of fractures such as physical aperture (Chen et al. 2021), roughness (Brown 1987), and contact areas (Walsh 1981), on flow rate and distribution in discontinuities. Among the others, contact areas can play a crucial role on fluid flow. Variations in size and shape of contact areas can affect fluid flow by blocking potential void spaces. For example, an increase in normal stress could increase contact areas, and consequently, it decreases flow rate and increase/decrease violation in flow pathways. Contact ratio is used to define contact areas through a fracture (Equation 1);

$$C = \frac{S_{contact}}{S_{total}} \times 100\% \quad (1)$$

where $S_{contact}$ is the contact area and S_{total} is the fracture surface area (Chen et al. 2017).

The influence of contact area, shape, and distribution on the permeability and the hydraulic aperture (e_h) of the fracture has been studied theoretically and numerically. Walsh (1981) mathematically demonstrated that when the contact areas are circular in planform, the fractional decrease in fracture permeability is given by Equation 2:

$$\frac{e_h^3}{e_m^3} = \frac{1 - C}{1 + C} \quad (2)$$

where C is the fractional contact area and e_m signifies physical aperture. Zimmerman et al. (1992) extended this analysis to the case of randomly oriented elliptical contact areas and found that the fractional decrease in fracture permeability is given by Equation 3:

$$\frac{e_h^3}{e_m^3} = \frac{1 - bC}{1 + bC} \quad (3)$$

where b = (1+a)/2a and a is the aspect ratio of the elliptical contact areas. The formula proposed by Zimmerman & Bodvarsson (1996) for predicting the hydraulic aperture based on the mean and standard deviation of the aperture distribution can be expressed as Equation 4:

$$\frac{e_h^3}{e_m^3} = \left[1 - 1.5\left(\frac{s}{e_m}\right)^2\right] \times (1 - 2C) \quad (4)$$

where $(s/e_m)^2$ represents the ratio of the standard deviation of the physical aperture distribution to the mean physical aperture, (1-2C) the contact correction term. Yeo (2001) modified the contact correction term to (1-2.4C) and proposed a formula according to numerical study Equation 5:

$$\frac{e_h^3}{e_m^3} = \left[1 - 1.5\left(\frac{s}{e_m}\right)^2\right] \times (1 - 2.4C) \quad (5)$$

Chen et al. (2017) presented a formula based on relative fractal dimension (D_Δ^*) and effective physical aperture which isolated void spaces could not have any effect on permeability (Equation 6):

$$\frac{e_h}{e_m} = (1 - 1.1C)^4 \times \left(1 + \frac{2}{D_\Delta^*}\right)^{3.5} \quad (6)$$

Wei et al. (2023) numerically studied the effect of different size and distribution of two circles as contact area on fracture permeability. The research showed the contact ratio is not an accurate parameter to investigate the effect of contact area on permeability. It leads to proposing a quadratic function between gradient pressure and N which is the flow channel between two contact areas and the flow channel between contact area and lateral wall. These studies have provided valuable insights into the underlying mechanisms that govern fluid flow through fractures and have allowed researchers to study the effect of different contact area shapes and distributions on fluid flow. So far, there is not a comprehensive study about the effect of different shapes and distributions of contact area on permeability which is the main objective of this research work.

In order to investigate the effect of contact area shape and distribution on permeability of flow paths in fractures, a numerical study based on a parallel platform of fractures was conducted in COMSOL software. In addition, the effect of these properties on fluid flow through the fracture was investigated. Contact areas with the rectangular form with different dimensions, and square form with different rotations and distribution were considered as the geometrical basis of numerical hydraulic modeling and flow rates and patterns at different hydraulic gradients were calculated and visualized. The Forchheimer equation was used to analysis the numerical data.

2 METHODOLOGY

Three-dimensional fluid flow simulation in fractures was modeled using the finite element analysis tool, COMSOL software, with dimensions of 10 cm × 10 cm (Figure 1). The contact areas were modeled with rectangular shapes having different width-to-length ratios (X/Y) of 0.4, 0.5, 0.66, 1, 1.5, and 2. The total area of the contact areas was kept constant for all simulations at 25 cm^2, and the individual area of each shape was equal, at 1 cm^2. The number of contact shapes in the X and Y directions was equal, with 5 in each direction. To investigate the influence of contact area distribution, for the case with a square aspect ratio (1), the contacts were rotated at angles of 1, 5, 10, 15, 20, 25, 30, and 45 degrees. In addition, for columns 2 and 4 along the Y direction, the contacts were relocated by 0.5, 2.5, 5, and 10 mm. Figure 1 illustrates some patterns used to simulate. The physical aperture and contact ratios are 1 mm and 25% for all models, respectively.

The Navier-Stokes equation was used to simulate fluid flow through the fractures. The equation was solved using the COMSOL-Multiphysics code based on the finite element method. A non-slip boundary condition was applied to the walls of the fractures (Figure 2). Five different water pressures (1, 2, 3, 4, and 5 kPa) were applied to the inlets of the fracture models while the outlet pressure was zero Pa.

The flow rate data were analyzed using the Forchheimer equation (Zhou et al. 2016), which describes the relationship between fluid flow rate and pressure gradient. The Forchheimer equation is given by Equation 7:

$$-\nabla \mathrm{P} = \mathrm{AQ} + BQ^2 \tag{7}$$

where $-\nabla P$(Pa/m) $=\Delta P/L$ represents the pressure drop (ΔP) across the fracture length (L). The terms AQ and BQ^2 represent the linear and nonlinear flow rates respectively. $A= 12\mu/we_h^3$ and $B=\beta\rho/w^2e_h^2$ are the Forchheimer coefficients. Q (m^3/s) denotes the flow rate, μ (10^{-3} Pa.s) is the viscosity of the fluid, w (m) is the width of the fracture perpendicular to the flow direction, e_h signifies hydraulic aperture, β denotes the non-Darcy coefficient correlating with the geometrical characteristics of fractures and ρ (1000 kg/m^3) is the fluid density.

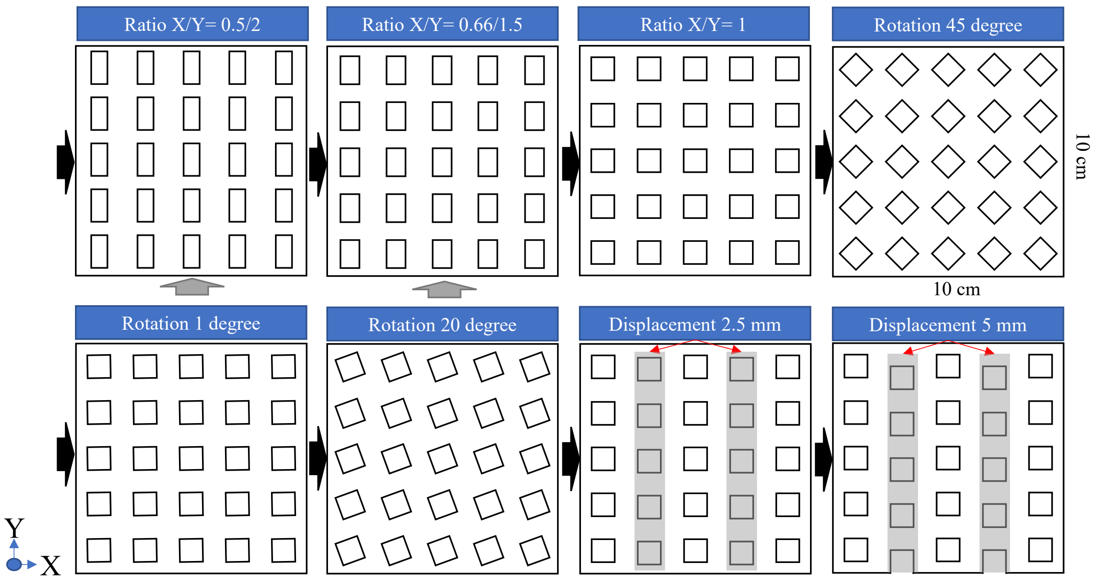

Figure 1. 10 cm × 10 cm fractures with different patterns of contact areas with variable shapes and distributions.

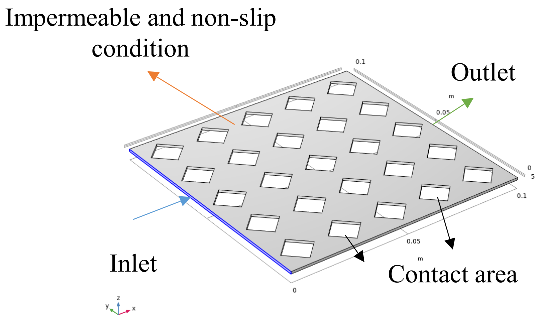

Figure 2. Boundary conditions for fluid flow simulation through a 10 cm × 10 cm fracture.

3 RESULT AND DISCUSSION

The Forchheimer equation is used to do regression analysis of the numerical results in order to obtain the Forchheimer coefficients (A and B). The hydraulic apertures and parameter β were computed according to Equation 7 and tabulated in Table 1. The simulation results were produced using COMSOL software, which provides a graphical representation of the fluid flow through the fractures. The effect of water pressure on fluid flow was also studied by comparing the results for different inlet pressures (Figure 3). The hydraulic aperture values fluctuated, and the trends are different (Figure 3b,e,h). However, it seems that there is a negative correlation between the calculated parameter β and uneven patterns (Figure 3c,f,i). Obviously, parameter β is an important parameter that have different values for different patterns in numerical models and has a great influence on fluid flow behavior. More distributed and uneven patterns result in high values of β.

Table 1. Ftting parameters of the Forchheimer equations: Forchheimer coefficients, hydraulic aperture, and parameter β.

Shape			A [10^8 kg. $s^{-1}.m^{-5}$]	B [10^{12} kg.m^{-8}]	e_h [μm]	β
Rectangular	Ratio	0.4	2.64	0.75	769	4.45
		0.5	2.95	1.09	741	5.99
		0.66	2.99	1.73	737	9.38
		1	3.91	2.14	675	9.73
		1.5	3.26	7.45	717	38.29
		2	2.53	1.89	780	114.91
Square	Rotation [°]	1	3.34	3.28	711	16.58
		5	3.33	4.03	712	20.41
		10	3.39	5.29	707	26.43
		15	3.45	6.76	703	33.44
		20	3.58	8.47	695	40.84
		25	3.66	10.33	690	49.15
		30	3.76	11.97	683	55.87
		45	4.06	13.79	666	61.16
	displacement [mm]	0.5	3.23	3.84	719	19.83
		2.5	3.02	6.48	735	35.03
		5	1.96	11.56	848	83.25
		10	2.02	20.23	841	143.15

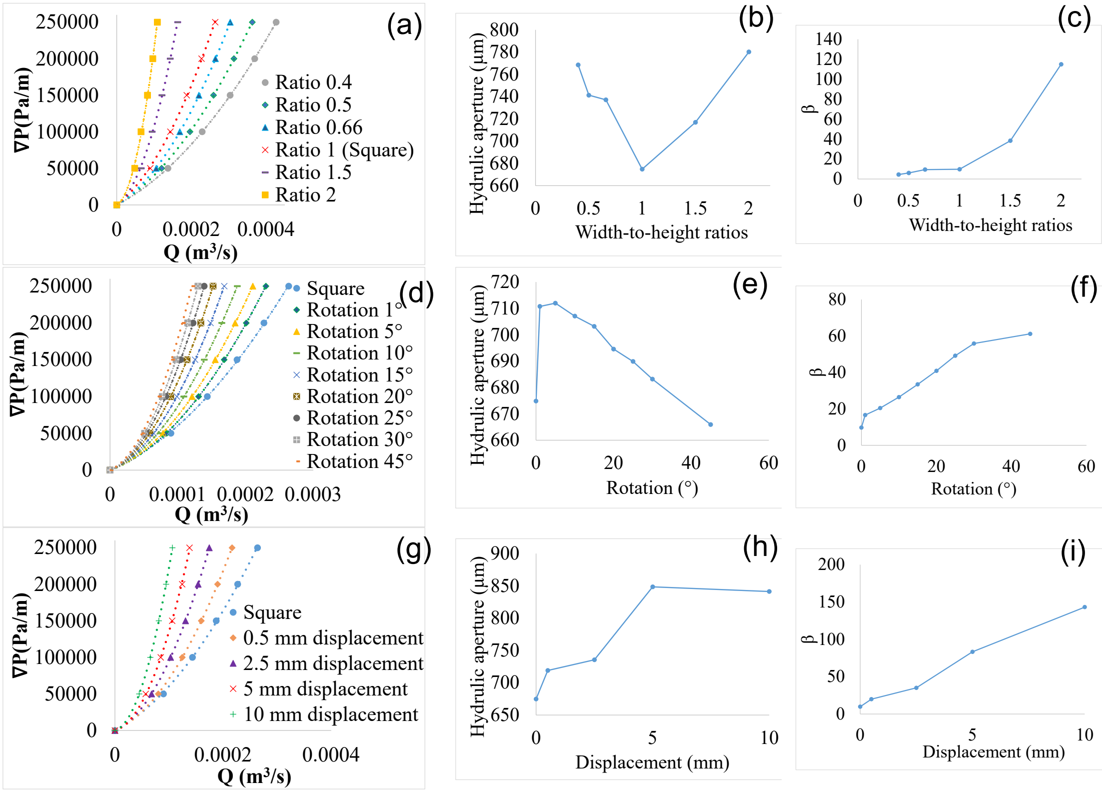

Figure 3. Numerical data analyzed with polynomial regression analysis of measured pressure gradient as a function of flow rate using the Forchheimer equation for the fracture with 10 cm × 10 cm domain and different contact area's shapes and distributions.

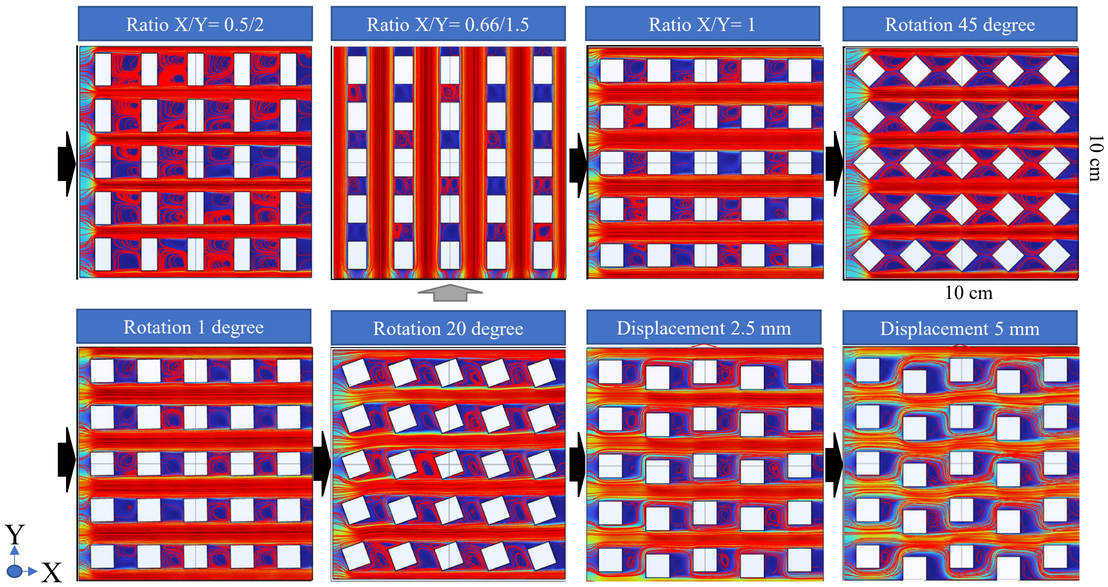

Figure 4. Simulations of streamlines through the fractures with different shapes and distributions of contact areas.

Figure 4 shows fluid flow simulations of the fracture with eight patterns illustrated in Figure 1. By changing the contact shape areas and distributions, more eddy flows were observed around the contacts, for instance, the comparison between the square and the 2.5 mm displacement pattern with a water pressure of 10 kPa. The calculated hydraulic apertures according to Equations 2, 4, and 5 were 843, 926, and 804 µm, respectively. Each equation gives the same value of the hydraulic aperture for all shapes and distributions. Although contact areas in all models were kept constant, the calculated hydraulic apertures were changed by different shapes, rotations, and displacements of the contact locations. Based on the data obtained, it appears that the equations presented in the introduction may not be entirely reliable for estimating hydraulic aperture. This is because the hydraulic apertures varied in each numerical model, indicating that the equations may not be accounting for all of the relevant factors that affect hydraulic aperture.

4 CONCLUSION

This research involved conducting 90 numerical simulations using COMSOL software on a 10 cm × 10 cm fracture. The simulations used different contact area shapes and distributions, and five different water pressures ranging from 5 kPa to 25 kPa with a 5 kPa interval. The results showed that the calculated flow rate in a fracture based on the evaluated hydraulic apertures can lead to a significant degree of uncertainty. For instance, the numerical hydraulic apertures for the rectangular contact areas with ratios of 0.4 and 2 were 768 µm and 780 µm, respectively. However, in the case of water pressure of 25 kPa, the flow rate of ratio 0.4 was four times greater than that of ratio 2. These findings highlight the importance of the parameter β in the Forchheimer equation, which can reflect the impact of fracture surface geometry on fluid flow to a significant extent.

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