Paper ID: 2011927

A Numerical Study of the Effect of Surface Roughness on the Fluid Flow through Rock Joint

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1. Introduction

Fluid flow though rock fractures and matrix is important to understand for hydrocarbon production (Li et al., 2009), geothermal energy extraction (Kishida et al., 2013), waste disposal (Shen et al., 2011) and carbon dioxide geosequestration (Wang et al., 2013). Conventional method of numerical description uses Darcy's Law with parabolic velocity profile to describe the fracture flow. The fracture flow is compared to the linear fluid flow through parallel plate. But investigations by several authors (Qian et al., 2005; Javadi et al., 2010) indicate that the presence of surface roughness induces considerable amount of non-linearity in the flow. So the applicability of the Darcy's Law is questionable. The alternate approach of modelling the fluid flow is the Navier-Stokes (NS) equation (Wang et al., 2013). In this modelling, it is assumed that viscous flow is the dominant factor, so inertial terms can be ignored in the calculation.

A considerable amount of research work has been carried out on the evolution of non-linear flow in the fractures. Mathematically, in numerical and experimental simulation non-linearity has been manifested by the "Critical Reynolds Number". While Zimmerman et al (2004) reports a decrease of "Critical Reynolds Number" with increasing fracture roughness, Oron et al (1998) reported Reynolds Number 10 as the critical value. Experiments have been carried out in granite specimen (Hakami et al., 1996), analogue rock (Singh et al., 2014) under different inlet pressures, wall pressures and fracture apertures. The results show that Reynolds Number is strongly affected by the fracture aperture, inlet pressure. Presence of surface roughness also has a strong impact of the flow velocity distribution, particle transport time and shear rate evolution.

The present work examines the effect of surface roughness on the fluid flow parameters of 2D fractures. Finite element simulation has been performed for the flows under constant aperture and no-shear condition for a range of inlet pressures. The fracture roughness is represented by "Joint Roughness Coefficient" (JRC) and fluid flow is modelled using Navier-Stokes equation. The flow Reynolds Number has been calculated using a modified equation and the "Critical Reynolds Number" has been derived from the Forchheimer's law.

2. Background Theory

The Navier-Stokes equation for the incompressible Newtonian fluid with constant density and viscosity for rough fracture is expressed as –

$$\rho(\frac{\partial U}{\partial t}+U.\nabla U)=-\nabla p+\mu\nabla^2 U+F$$

Where, is the viscosity, is the viscosity of the flowing fluid, U is the velocity vector of the flow particle, F=body force vector. By omitting the inertial term NS is reduced to Linear Stokes equation and Volumetric flow (Q) is expressed as –

$$Q = -\frac{We^3}{12\mu}\nabla p$$

This is called the “Cubic law” ' (Witherspoon et al., 1980) where “W” is the fracture width and “e” is the “Hydraulic aperture” respectively. It shows that the flow rate is directly proportional to the cube of fracture aperture. To apply this equation in the fracture flow, the following empirical relation of Barton et al (1985) is used to establish a relation among the “Joint Roughness Coefficient (JRC)”, “Mechanical Aperture (W)” and “Hydraulic Aperture (e)” –

$$e = W^2 / JRC^{2.5}$$

Also, the Conventional Reynolds Number is customized to apply it to the rough fractures (Zimmerman et al., 2004) –

$$R = \frac{\rho Q}{\mu W}$$

Where, Q is the flow rate, W is the fracture width, ρ is the viscosity and μ is the viscosity of the flowing fluid.

3. Numerical Modelling

The single phase fluid flow through the 2D fractures with different JRC values were modelled using COMSOL Multiphysics finite element software. Artificial surface roughness were created on the sandstone blocks and the JRC values were measured using Barton’s comb. Based on this JRC values, fractures with 1 mm apertures were created for the simulation purpose. A triangular mesh with maximum element size 0.233 cm and minimum element size 0.00104 cm was implemented throughout the fracture path. A “no slip” boundary condition was implemented on the impermeable “top” and “bottom” walls. Details are shown in Figure 1 & 2.

Further the effect of the surface roughness on the fluid flow and the transport time was calculated using the “Transmission Probability”, which is defined as the square of the ratio of number of incoming particles to the number of transmitted particles. A density driven flow of 3000 particles of diameter 1e-6 were simulated under advection transport mechanism and “Stoke’s Law” was used as the drag force. The “breakthrough curves” were generated to compare the particle transport times at different inlet pressures.

JRC 3

JRC 7

JRC 17

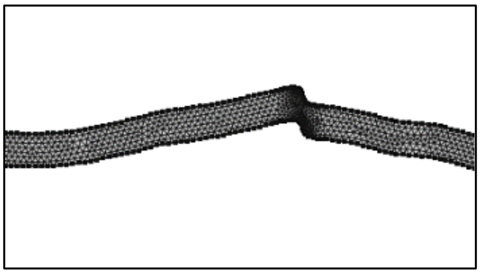
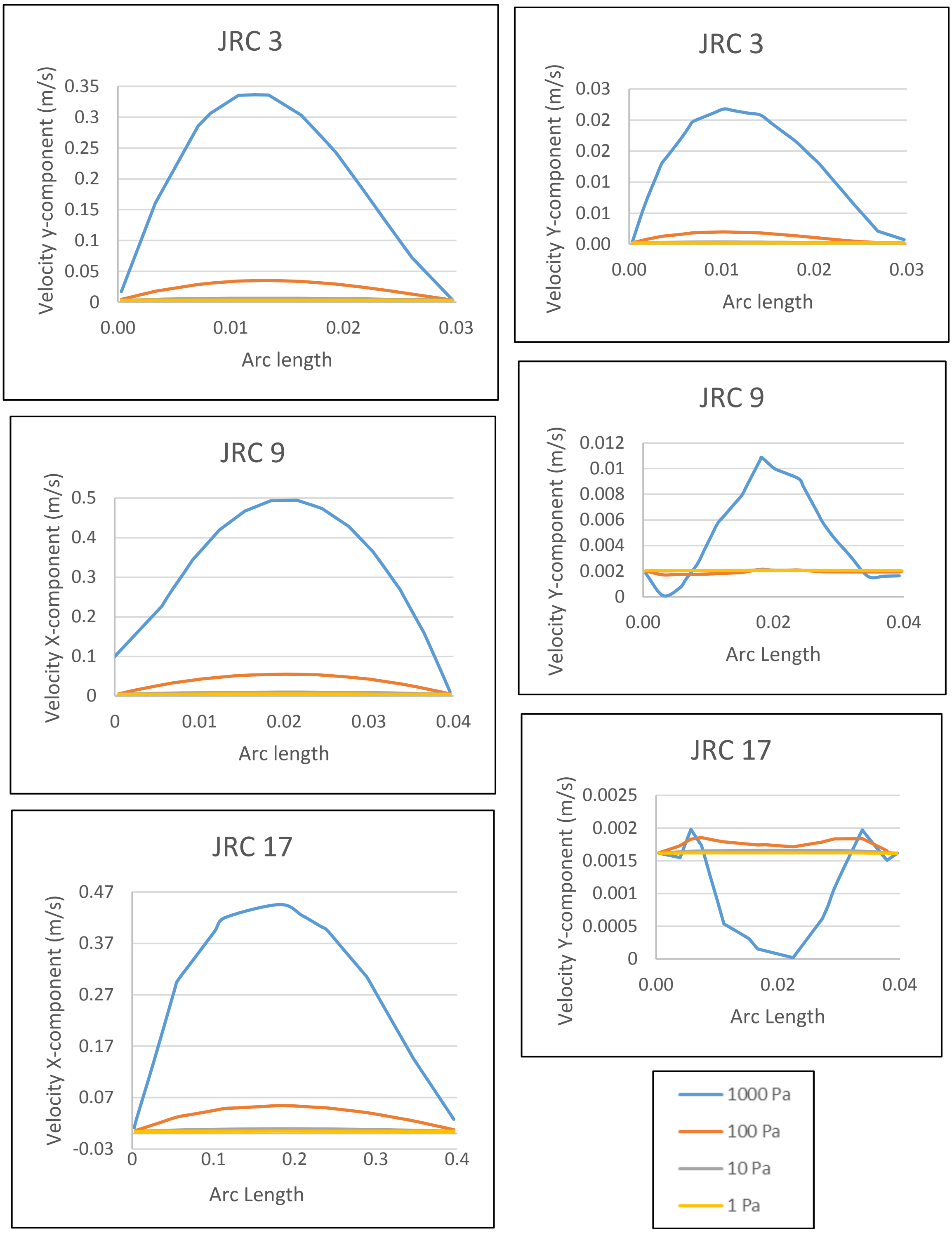


Figure 1 – Fracture geometries with different JRC va

4. Results & Discussion

4.1 Velocity component distribution

The velocity components parallel (x-component) and perpendicular (y-component) to the fracture length were evaluated to see the effect of fracture roughness at 1 Pa, 10 Pa, 100 Pa and 1000 Pa. The results in Figure 3 show that the roughness has minimal effect on the x-components but it effects the y-component tremendously. The effect is more prominent for the fractures with high JRC values.



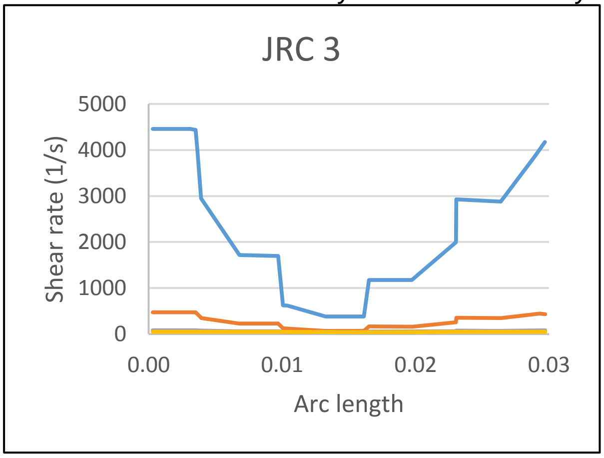
4.2 S

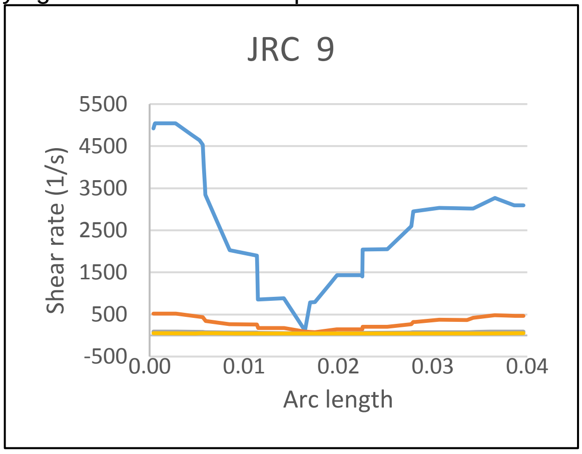
Figure 3 - X- and Y- velocity components across the fracture aperture

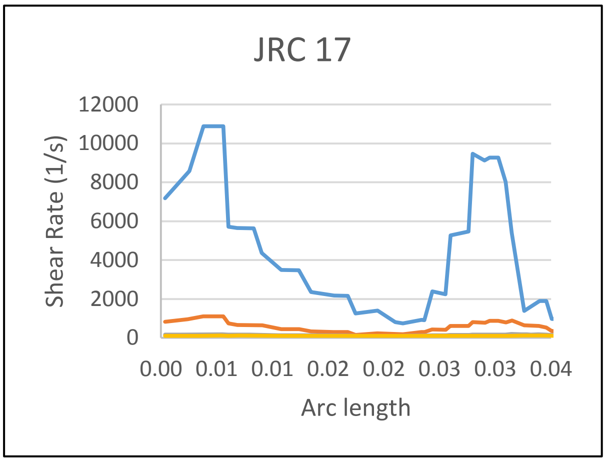
Shear rate distribution at different inlet pressures provide important insight on the flow behavior. The shear rate distribution of a flow through parallel plates is symmetric with respect to the fracture axis and is concave in nature. So, any deviation from the ideal geometry would provide information regarding the turbulence and effect of surface roughness on key flow parameters. The present study provides information on two aspects of fracture flow –

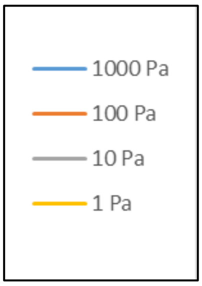
a) For a single fracture, with increasing inlet pressure, the shear rate distributions become strongly asymmetric and highly varies across the fracture opening. Increasing inlet pressure causes more turbulence and chaos in flow.

b) For a constant inlet pressure, with increasing JRC value, the shear rate distribution becomes more asymmetric. The widely varying shear distribution represents internal friction among different fluid layers.



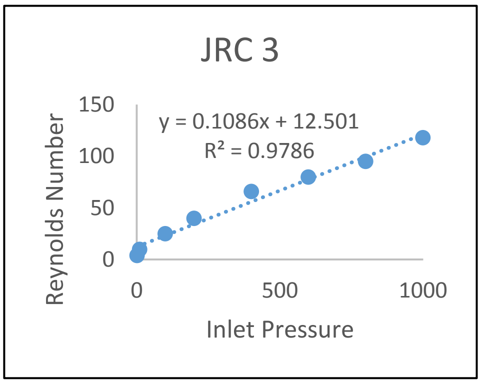






4.3 Reynolds Number evolution

Reynolds number was for all the fractures were evaluated at 1 Pa, 10 Pa, 100 Pa, 20 Pa, 400 Pa, 600 Pa, 800 Pa and 1000 Pa. For all the fractures a linearly increasing Reynolds number were recorded. The result of best-fit linear regression analysis and the R2 values are shown on the figure. The Figure 5 show a linear increase of the Reynolds Number with increasing inlet pressure.



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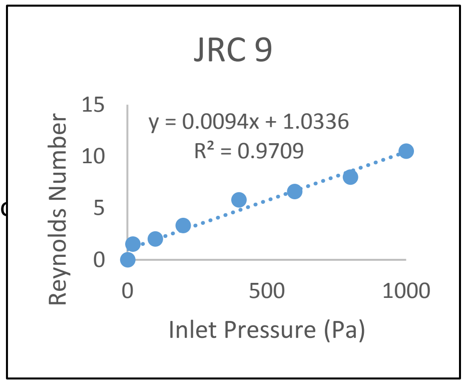

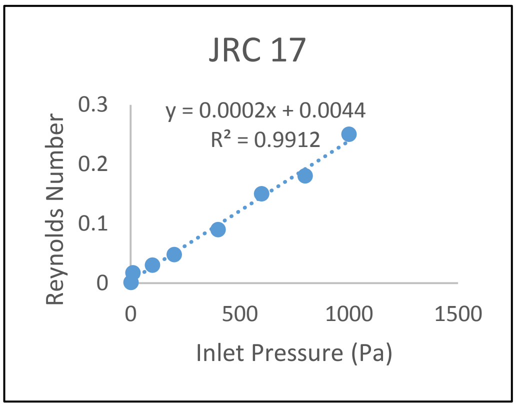

Figure 5 – Reynolds Number evolution with Inlet pressure

4.4 Particle transport

The effect of inlet pressure on the particle transport mechanism were investigated at 1 Pa, 10 Pa, 100 Pa and 1000 Pa inlet pressures and the results are shown in Figure 6. The “Particle Transmissivity” is expressed as the breakthrough curves. It is observed that for a constant inlet pressure, with increasing JRC, the required time for particle transport increases proportionately.

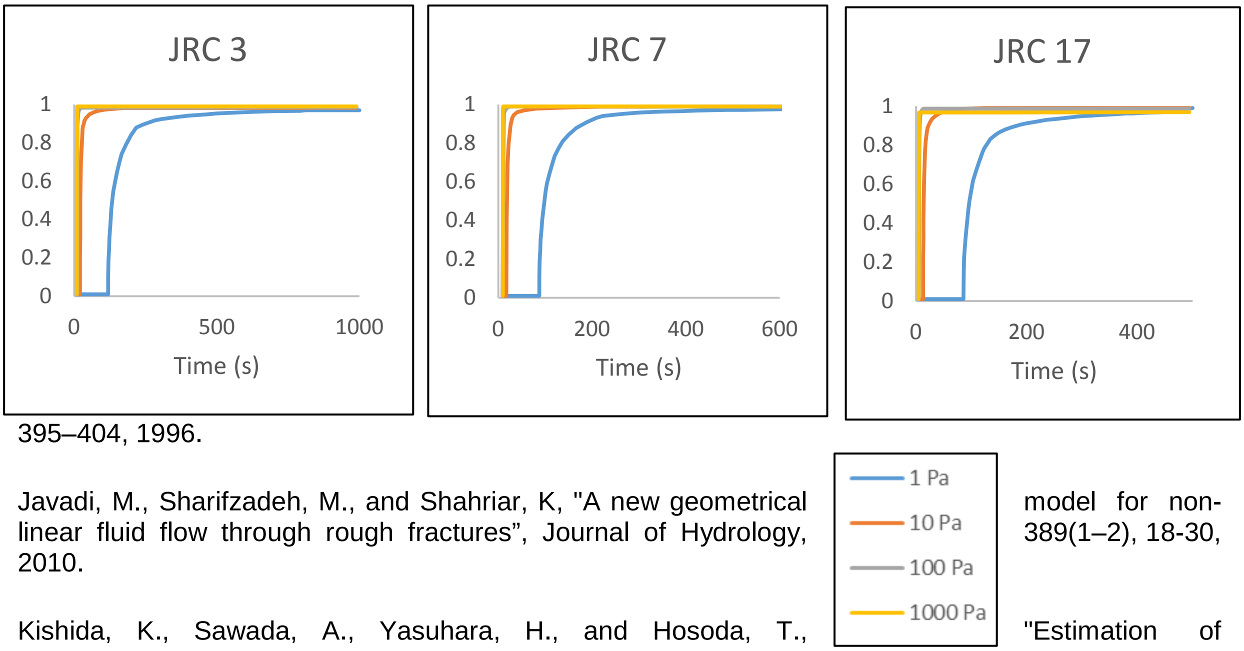

Figure 6 – Transmission probability of different fractures at different inlet pressure

5. Conclusion

The flow – and particle – simulation of the fracture flow contributes the following knowledge in the present study -

a) A predictive relationship between the inlet pressure and Reynolds number for different JRC values have been established.
b) From the shear rate and flow velocity distribution, it is interpreted that fracture surface roughness alter the flow behavior in the fracture through “wall effect”. Asymmetric shear rate distribution, strongly irregular y-velocity component distribution indicate the existence of turbulence in the flow. And turbulence would increase with fracture roughness.
c) Increasing particle transport time with the increasing JRC indicates that particles get trapped in the saddles of the undulations and at local bends. Also, presence of undulation increases the total path length and contribute to the large travel time.

This study can be extended further to incorporate the nonlinear flow through the Forchheimer’s law.

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