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Research paper

Three-dimensional finite-volume modelling and laboratory validation of non-Darcy flow in rough rock fractures

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ABSTRACT

This study presents a systematic investigation into non-Darcy fluid flow through rough-walled rock fractures to elucidate the complex interplay between fracture geometry, surface roughness, and hydraulic conditions. The research integrates high-resolution 3D finite-volume numerical simulations, solving the full Navier-Stokes equations, with rigorous experimental validation. Laboratory tests were performed on 3D-printed fracture models with precisely controlled roughness (Joint Roughness Coefficient, JRC), confirming the numerical model's accuracy with flow rate deviations under 3%. The validated model was then used for a comprehensive parametric analysis. Key findings reveal that surface roughness is a dominant parameter, reducing fracture permeability by up to 60% and inducing complex flow channelization. Crucially, non-Darcy flow behavior emerges at Reynolds numbers as low as 0.86, challenging conventional Darcy-based assumptions. The analysis further quantifies departures from the cubic law, demonstrating that flow rate scales non-linearly with fracture width and length and that the strong dependence on aperture is substantially attenuated by roughness. A significant scale effect was also identified, where the influence of localized surface morphology on bulk flow diminishes as fracture size increases, becoming negligible for fractures larger than 90 mm. While inlet flow direction minimally affected the total flow rate, it significantly altered local channelization. These insights underscore the necessity of incorporating realistic surface topography and employing nonlinear models to accurately predict fluid transport in fractured media, holding significant implications for applications in geothermal energy, hydrocarbon recovery, and contaminant hydrology.

1. Introduction

Evaluation of fluid flow behavior through rock fractures is very important in various geological, engineering, and environmental projects [1–6]. Understanding the mechanics of flow within these fractures is essential for accurately modeling hydraulic conductivity [7], predicting fluid transport in reservoirs [8], and assessing the migration of contaminants in the subsurface environment [9]. Fractures serve as primary pathways for fluid movement in otherwise low-permeability rock masses, and their complex geometries significantly influence flow behavior. Fracture surfaces are inherently rough and irregular, deviating substantially from the idealized smooth and parallel-walled assumptions often employed in classical flow models [10,11]. This roughness leads to complex flow patterns, including channeling and preferential pathways, which cannot be accurately described by conventional models. Conventional flow models, such as the cubic law, assume smooth fracture walls and laminar flow dominated by viscous forces [12]. While the cubic law provides a foundational understanding, it fails to account for the effects of surface roughness, aperture variability, and the consequent nonlinearities in flow behavior [13–15]. The governing equations for fluid flow in fractures are derived from the Navier-Stokes equation, which describe the motion of Newtonian fluids while considering the conservation of mass and momentum [16]. However, adopting these equations to real fractures is challenging due to the intricate geometries involved. Numerical methods, such as the Finite Volume Method (FVM) [17–22] and Lattice Boltzmann (LB) [23–27], have been employed to tackle these complexities, enabling more accurate simulations of flow through rough-walled fractures.

Surface roughness not only alters the velocity profile within the fracture but also increases energy losses due to friction, leading to deviations from Darcy's law even at low Reynolds numbers [28–33]. Zimmerman and Bodvarsson (1996) showed that the hydraulic aperture

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