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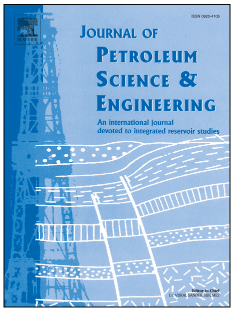

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Numerical Simulation of Hydraulic Fracture Propagation in Naturally Fractured Formations Using The Cohesive Zone Model

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Abstract. This paper presents an integrated methodology that utilizes the cohesive zone model (**CZM**) to simulate propagation of hydraulic fractures, and their interactions with pre-existing natural fractures. **CZM** has the advantage of capturing the non-elastic behavior of shales; usually induced by total organic carbon (TOC) as well as dissimilar mechanical properties of cemented natural fractures. At the intersection of an advancing hydraulic fracture and a stationary natural fracture, the hydraulic fracture may arrest, cross, or divert into a pre-existing natural fracture depending on the rock mechanical properties, magnitude and direction of rock principal stresses, and fracture intersection angle. The activation of natural fractures during hydraulic fracture treatments improves fracture complexity and expands reservoir drainage area, making stimulation treatments more effective. In this work, triaxiality effects are incorporated into the cohesive zone model. Utilizing triaxiality makes the traction separation law (**TSL**) tied to confining pressure and this ensures a more reliable transition from laboratory test environment to bottomhole conditions. We present a methodology to determine the cohesive properties or TSL characteristics of rock, after performing semicircular bending tests (**SCBT**). Finite element analysis (**FEA**) is then used to calibrate the cohesive properties of both rock and natural fractures. The calibrated parameters were utilized in a field-scale **FEA** to simulate the growth of complex fracture networks. The results show how fracture intersection angle and the nature of cemented materials inside the natural fractures might divert a hydraulic fracture initially propagating in a direction perpendicular to the minimum horizontal stress. The sensitivity analysis of primary parameters such as fluid viscosity, natural fracture distribution, fracture intersection angle, and differential stresses is implemented to provide a better insight into the performance of hydraulic fracturing jobs in naturally fractured reservoirs. Results indicate the importance of nonlinear fracture tip effects as in-situ stress differences increase.

Keywords: Hydraulic Fracturing, Cohesive Zone Model, Fracture Intersections, Natural Fractures, Complex Fracture Network, Traction Separation Law.

Introduction

The recent success in exploiting low permeability shale reservoirs in the United States has heavily relied on hydraulic fracturing to produce hydrocarbons economically. Although horizontal drilling significantly increases the contact area between the wellbore and the reservoir, the objective of hydraulic fracturing is to create more conductive flow paths in the reservoir. Geological studies have shown that a significant portion of hydrocarbon resources are situated in low permeability naturally fractured formations for instance Marcellus Shale (Pommer, 2013, Inks *et al,*. 2014), Barnett Shale (Patel *et al.*, 2014), Eagle Ford Shale (Fan *et al.*, 2011), and Woodford Shale. Outcrop studies (Seeburger and Zoback, 1982, Hennings *et al.*, 2000) as well as core sample studies (Gale *et al.*, 2007) have revealed details of the presence of natural fractures in unconventional formations, such as the Mesa Verde formation (Lorenz *et al.*, 1989), Haynesville (Parker *et al.*, 2009), Tuscaloosa Marine Shale (Lu *et al.*, 2011) and Barnett Shale formation (Jarvie *et al.*, 2007). If the hydraulic fracture gets linked to the natural fracture network, the stimulated rock volume may expand tremendously by opening pre-existing natural fractures. For instance, in the Barnett Shale, fractures are mostly sealed with calcite and quartz precipitated from underground water flowing in the underlying Ellenberger limestone aquifer (Gale *et al.*, 2007). While production analyses

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