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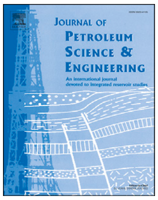

Microcrack-based geomechanical modeling of rock-gas interaction during supercritical CO_2 fracturing

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ABSTRACT

Relative to water-based fluids, non-aqueous fracturing fluids have the potential to increase production, reduce water requirements, and to minimize environmental impacts. Since the viscosity of supercritical CO_2 is one-tenth that of water, its density is close to that of water, and is capable of promoting sorptive rejection of methane, it is an attractive substitute for water in the extraction of shale gas and coalbed methane. The following defines a geomechanical model accommodating the interaction of fluid flow, adsorption-induced swelling stress, solid deformation and damage to quantify rock-gas interactions during supercritical CO_2 fracturing for shale gas production. The architecture of the shale is accommodated that includes both pore- and micro-crack-based porosity. According to the microcrack model representing shales with low porosity, both analytical and numerical results show that the effective stress coefficient is much smaller than unity. We analyze the potential advantages of fracturing using supercritical CO_2 including enhanced fracturing and fracture propagation, increased desorption of methane adsorbed in organic-rich portions of the shale and the potential for partial carbon sequestration. Rock-gas interactions include both the linear poroelastic response and the chemo-mechanical interaction due to sorption. Simulation results demonstrate that supercritical CO_2 fracturing indeed has a lower fracture initiation pressure and a significantly lower breakdown pressure, as observed in experiments, and that fractures with greater complexity than those developed with liquid CO_2 and water fracturing result. With increasing dynamic viscosity of the fracturing fluids, the predicted breakdown pressure also increases, consistent with experimental observations.

1. Introduction

Hydraulic fracturing is used for the production of hydrocarbons but also for the recovery of deep geothermal fluids. The development of massive hydraulic fracturing has substantially increased shale oil and gas production, generated an energy boom in the US and significantly lowered hydrocarbon costs (Middleton et al., 2015; Yuan et al., 2015a, 2017). However, its use in low permeability (tight) gas reservoirs has presented significant challenges (Pijaudier-Cabot, 2013; Ye et al., 2017; Yuan et al., 2015b). The permeabilities of such reservoirs are typically in the nanodarcy range ($10^{-21}\,m^2$) prohibiting efficient recovery (Javadpour, 2009; Sheng et al., 2015; Wu et al., 2015). Mechanisms of gas recovery by hydraulic fracturing (Middleton et al., 2015) are shown in Fig. 1. These highlights that various length scales involved in shale gas production cover thirteen orders of magnitude, ranging from nanometer size pores where methane is trapped to kilometer-scale hydraulic fractures that are conduits to the production well (Davies et al., 2012).

Currently, water is the only fracturing fluid widely used in commercial shale gas and shale oil production. This is principally due to its low cost, availability, and its suitability for fracturing. However, a representative shale gas well needs to inject from 2 to 4 million gallons of water into the deep reservoir (API, 2010; Scanlon et al., 2014). In the initial stages of gas recovery, about 15%–80% of flow-back water is recovered (GWPC, 2009; EPA, 2010). Meanwhile, flow-back water is contaminated with secondary components, which are added to the water to induce fracture generation (Jackson et al., 2013). This flow-back water must be disposed, usually through deep re-injection into geologic formations. Large-scale water re-injection has been related to triggered seismicity that induces low-level earthquakes (Vidic et al., 2013; Ellsworth, 2013; Elsworth et al., 2016). In this respect, using non-aqueous fluids is promising to solve large volumes of water re-injection. In addition, water from the conventional water-based fracturing fluids will be trapped in the

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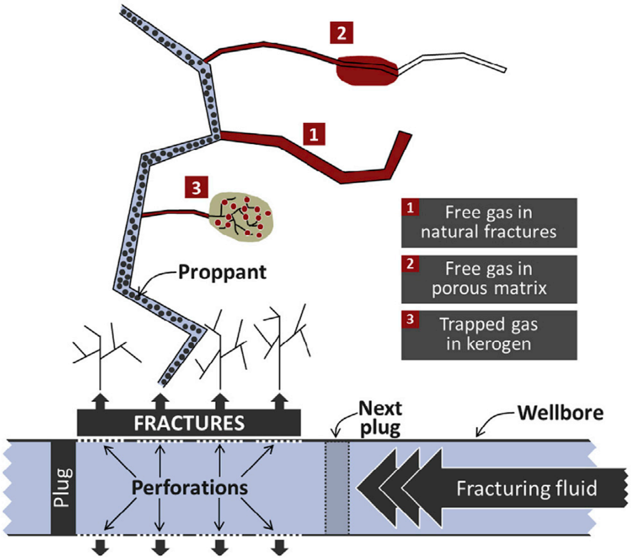

Fig. 1. Schematic of a fracturing system highlighting induced and natural fractures and three primary gas-in-place origins of methane. An alternative fracturing fluid such as CO_2 may more efficiently extract gas from (1) and (2) since CO_2 is miscible with hydrocarbons thereby preventing multi-phase flow blocking and from (3) since CO_2 can exchange with methane that is absorbed in the kerogen (Middleton et al., 2015).

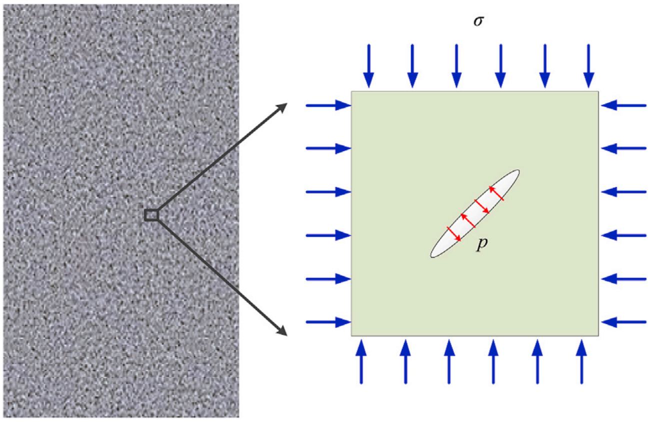

Fig. 2. Illustration of the single crack microelement.

near-wellbore region during the fracturing processes, which may impede gas to flow to the wells. This adverse effect is observed in many reservoirs (Al-Anazi et al., 2002; Mahadevan et al., 2007; Parekh and Sharma, 2004). For these reasons, reducing the use of water in hydraulic fracturing is a high priority for industry, policy makers, and concerned environmental groups. This possible reduction has stimulated investigation into the use of non-aqueous fracturing fluids, including hydrocarbons and supercritical CO_2 (Wang et al., 2012, 2015).

The fracture path and breakdown pressure vary with the composition and state of the fracturing fluid (Ishida et al., 2012; Alpern et al., 2012; Gan et al., 2015). Therefore, determining the mechanics of these interactions is important. The penetration of the fracturing fluid within the network of existing cracks depends directly on its viscosity and interfacial characteristics. By reducing the resistance indexed through these parameters, fluids will penetrate more easily in the existing cracks and apply pressure to reactivate them. Thus, the issue is to determine the “right” fluid. There are many candidate fluids, including propane, nitrogen and carbon dioxide.

Supercritical CO_2 is one such potential fluid. CO_2 is of potential interest as a class of energized fluid or foam, particularly as the drawbacks of conventional fracturing fluids become more obvious (Gupta and Bobier, 1998; Gupta, 2011). Supercritical CO_2 offers several significant advantages over water, as well as some potential drawbacks. Key potential advantages for CO_2 contain increased methane (CH_4) and hydrocarbon production, reduced pressurization requirements, enhanced fracturing properties, effective gas displacement from fractures, enhanced desorption of CH_4 from organics and the reduction or

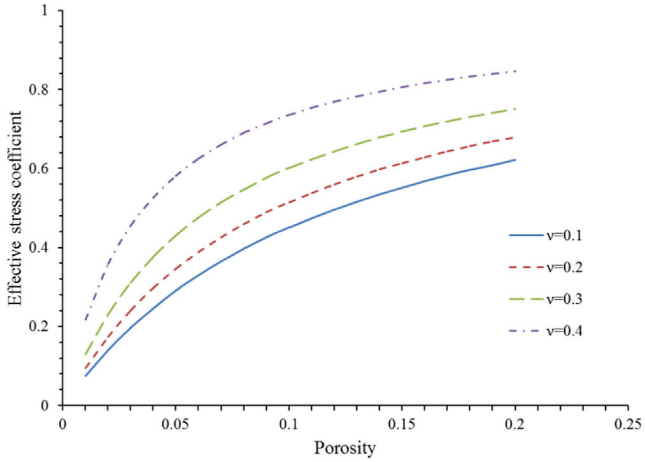

Fig. 4. Changes in effective stress coefficient with porosity and Poisson ratio.

Table 1

The impact of β and ν on effective stress coefficient at $\phi = 0.01$.

	$\beta = 1/10$	$\beta = 1/15$	$\beta = 1/20$	$\beta = 1/25$
$\nu = 0.1$	0.0762	0.1101	0.1416	0.171
$\nu = 0.2$	0.0964	0.1379	0.1758	0.2105
$\nu = 0.3$	0.1317	0.1853	0.2327	0.2749
$\nu = 0.4$	0.2188	0.2958	0.359	0.4118

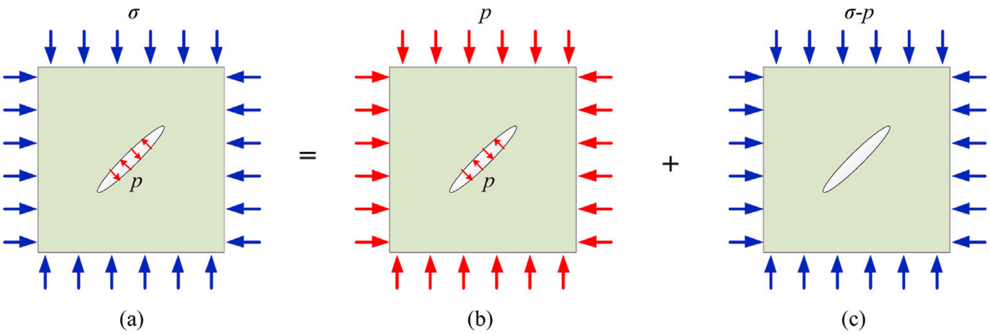

Fig. 3. Illustration of superposition principle.