



# Permeability evolution of propped artificial fractures in coal on injection of CO<sub>2</sub>



Hemant Kumar<sup>a,\*</sup>, Derek Elsworth<sup>a</sup>, Jishan Liu<sup>b</sup>, Denis Pone<sup>c</sup>, Jonathan P. Mathews<sup>a</sup>

<sup>a</sup> John and Willie Leone Department of Energy and Mineral Engineering, EMS Energy Institute, and G3 Center, Pennsylvania State University, University Park, PA 16802, USA

<sup>b</sup> School of Mechanical Engineering, University of Western Australia, WA 6009, Australia

<sup>c</sup> ConocoPhillips, Bartlesville, OK, USA

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## ABSTRACT

Proppants are often utilized during hydraulic fracturing to aid the retention of the fracture aperture. However, for coal the permeability enhancement may be mitigated due to proppant embedment within the natural/artificial fractures of coalbed methane reservoirs. This process may become increasingly complex if CO<sub>2</sub> is injected in the reservoir for enhanced recovery. The reduction in effective fracture aperture occurs under the influence of overburden stress either when CO<sub>2</sub>-induced coal softening causes proppant penetration into the coal fracture surface or coal swelling encroaches into the propped fracture. Here permeability transformations at simulated in situ conditions were evaluated through a suite of laboratory experiments conducted on split-cores of high-rank coals. A single smooth-surface saw-cut fracture was created and the permeability evolution measured for both non-sorbing (He) and sorbing (CO<sub>2</sub>) gases at constant applied confining stress of 10 MPa. Permeability was also measured for the idealized case of a uniform monolayer of #70–140 mesh quartz sand proppant sand introduced within the saw-cut fracture for coal. The increase in He permeability was as high as ~10 fold over the unpropped fracture for a monolayer of proppant sandwiched within the coal. A similar increase in permeability with the addition of proppant was observed in the case of sorptive gas (CO<sub>2</sub>) for coal. For He there was an exponential increase in permeability with increasing gas pressure ( $p=1\text{--}6$  MPa) for coal without proppant, as expected, as the effective stress on the core was reduced. However, with CO<sub>2</sub> the permeability decreased in the 1–4 MPa pressure range due to either coal swelling or softening or their combination but increased above 4 MPa due to reduced effective stress.

Optical profilometry pre- and post-exposure was used to quantify any surface deformation due to proppant embedment. Comparison of the fracture surface before and after showed only infrequent new isolated pits, similar to the size of the proppant grains. The slight increase in surface roughness following exposure to CO<sub>2</sub> was presumed due to irreversible rearrangement of the coal structure due to CO<sub>2</sub> uptake then loss. A mechanistic model explains the evolution of permeability in a propped artificial fracture due to interaction with a sorbing gas (CO<sub>2</sub>). Permeability evolves with a characteristic “U-shaped” trend with increasing gas pressure at constant confining stress – permeability reduces to a minimum at approximately double the Langmuir pressure flanked by elevated permeabilities at either low sorptive states (low  $p$ ) or at low effective stress (high  $p$ ). An excellent fit is recovered between model and experimental observations.

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## 1. Introduction

Hydraulic fracturing is extensively used for tight shale and sand reservoirs to enhance the permeability. Also, low permeability coalbed reservoirs are often considered good candidates for hydraulic fracturing for economical production of coalbed methane

(Davidson et al., 1995; Holditch et al., 1988). There are many studies which have explored various processes e.g. permeability evolution, proppant crushing, proppant embedment, proppant diagenesis, movement of fines in fractures in the context of hard rocks. Prior experimental (Piggott and Elsworth, 1993; Walsh, 1981) and analytical evaluations (Bai and Elsworth, 1994; Elsworth and Yasuhara, 2010; Yasuhara and Elsworth, 2008; Yasuhara et al., 2006) of fractured rocks indicate that permeability is strongly influenced by the variation in mechanical, chemical, thermal, and hydraulic processes.

\* Corresponding author. Current address: Chevron-ETC, Houston, Texas-77002, USA.

Proppant embedment and fracture closure have received additional attention for hard rock as optimization of proppant effectiveness is necessary to prevent fracture closure. Mechanisms of fracture conductivity impairment have been explored including the roles of fines migration (Pope et al., 2009), proppant diagenesis (LaFollette and Carman, 2010; Lee et al., 2010), proppant crushing (Terracina et al., 2010), and reduction in fracture aperture due to the embedment of proppant grains into the surface of the hydraulic fracture (Freeman et al., 2009; Lacy et al., 1997). Proppant embedment studies on 20/40 and 40/60 mesh Ottawa sand and sintered bauxite indicate that the embedment is primarily modulated by closure stress, proppant size and fluid viscosity (Lacy et al., 1997). The reduction in fracture conductivity at higher effective stresses occurs due to generation of proppant-fines in hard rocks (such as granite). The reduction in conductivity may be up to 60% in rock (Lacy et al., 1997) and perhaps higher for coal. With higher temperatures, extended duration of stress loading, and pressurized fluid saturation levels may accelerate the fines generation or proppant embedment (Freeman et al., 2009). An increase in temperature decreases the fracture conductivity due to the thermal expansion of asperities under mechanical constraints (Stoddard et al., 2011). The time dependent tensile strength, proppant hardness, and fatigue failure of proppant under reservoir conditions are known to affect proppant efficacy (LaFollette and Carman, 2010; Freeman et al., 2009). The fracture treatment may also be impacted by proppant-diagenesis, which evolves as a result of mineral dissolution, transport and re-precipitation in the particle interstices. Thus various mechanisms may be responsible for porosity and permeability loss in proppant packs within hard rocks (Lee et al., 2010) if the proppant layer is sufficiently thick so that the surface asperities do not play a significant role (Stoddard et al., 2011).

Although the behavior of propped artificial fractures in hard rocks has been well explored, the response of proppant packs in soft sorbing media (coal) is poorly understood due to the complex range of behaviors. Coal matrix swells and develops strains on exposure to CO<sub>2</sub> which may result in reduction of fracture-apertures therefore lowering the permeability (Karacan, 2003, 2007; Kumar et al., 2014). Also, it is known that coal can soften upon exposure to “good” solvents becoming ductile or plastic and easily deformable (Brenner, 1984, 1985). Presumably, both coal-CO<sub>2</sub> swelling and coal softening may result in effective aperture reduction either due to coal encroaching in the proppant void spaces (via coal swelling), or due to the proppant penetrating the coal (via coal softening). The response of coals is more complex as they are typically: (1) softer than the proppant grain, (2) exhibit swelling on exposure to CO<sub>2</sub>, (3) weaken upon interaction with CO<sub>2</sub> developing dynamic strains (Perera and Ranjith, 2012; Viete and Ranjith, 2006), and (4) perhaps soften. These processes are expected to result in permeability transformations.

Here the permeability evolution of an artificial saw-cut “fracture” in bituminous and anthracite cores both with and without proppant was explored for both inert helium (He) and sorbing carbon dioxide (CO<sub>2</sub>) as permeating gases. Permeability evolution was determined using the pulse-transient technique at constant applied confining stress (10 MPa) for non-propped and propped fractures at different (saturated) gas pressures. The evolution of surface morphology was evaluated using optical profilometry to aid in establishing the role, if any, of coal softening on permeability evolution. We also used these observations to constrain mechanistic models of permeability evolution of propped fractures in sorbing media.

## 2. Experimental methods

Cylindrical cores of bituminous and anthracite rank coals were

longitudinally-split to produce a single diametral artificial fracture. Fluid (gas) injection experiments were performed on the fracture in these cores in both non-propped and propped mode with samples stressed to in situ conditions but under ambient laboratory temperature (20 °C). The gases He and CO<sub>2</sub> were used as permeants to investigate the role of swelling/softening and effective stress on the dynamic evolution of permeability.

### 2.1. Samples

Two coals were used in the experiments: bituminous coal from the Uinta Basin, Colorado and anthracite from Pennsylvania. The coal block samples were cored horizontally (parallel to bedding) to produce the core plugs. The calorific value of sampled bituminous and anthracite coals were 12,000 and 14,286 BTU/lb (ASTM International D388, 2005) on a dry basis, respectively. The fixed carbon, volatile material and ash yield on a dry basis are 57%, 38%, 5% for bituminous and 86%, 7%, 4% for anthracite coals (ASTM International D7582, 2010). The moisture content of the coals are 5% and 2% respectively (ASTM International D3302/D3302M-10, 2010).

Six cylindrical cores of 2.5 cm diameter and 5 cm length were obtained and their ends cut to obtain flat surfaces (Fig. 1). Cores were cut in to two halves (horizontally lengthwise) using a thin diamond coated blade to produce smooth opposing surfaces forming an idealized fracture. The cut-surfaces of the coal were polished to remove the minor saw indents. Fine sand paper (#400) to very fine cotton cloth with alumina powders from 0.3 μm to 0.05 μm were used to polish the coal surface (ASTM International D5671, 2011). Surface roughness was quantified by optical profilometry (Kumar et al., 2009; Rousseau et al., 2010). The split-cores were re-mated either without or with a uniform monolayer of 70–140 mesh proppant sand. The cores were then wrapped in aluminum foil (to prevent diffusive loss of CO<sub>2</sub>) (Kumar et al., 2011) and sheathed in a latex jacket before being enclosed in a pressurized core holder for the permeability experiments.

### 2.2. Apparatus

An apparatus in simple tri-axial configuration was used for the injection of gases under predefined effective stress paths and capable of concurrent measurement of permeability (Fig. 2). All experiments were completed under a constant applied total stress with same axial and confining stresses. The apparatus comprised a tri-axial cell to confine the sample at prescribed stresses, an axial strain gauge to monitor the shrinkage or swelling in the axial direction, ISCO syringe pumps to apply stresses and to measure volume strains (axial and confining), pressure transducers to monitor the upstream and downstream reservoir pressures and a data acquisition system. Additional details of the equipment are described elsewhere (Kumar et al., 2012). A transient pulse test method (described in Section 2.4) was used to determine the saturated sample permeability. Permeability was evaluated from the rate of pressure decay/gain in the upstream/downstream reservoirs (Brace et al., 1968) assuming no additional sorption occurs in the saturated sample by insignificantly small pressure pulse during the experiments.

Both pre- and post-experiment an optical profilometer (Zygo NewView™ 7300) was used to quantify the surface indentation caused by stressing of the sample and the presence of sorptive gas pressure. In the interferometer a light beam is split into two paths. One path of light impinges on the specimen surface and is reflected. The other is reflected from a reference mirror. Reflections from these surfaces are recombined and projected onto an array detector to determine path differences by interference. This enables surface topography to be resolved to fractions of the

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