Fuel 236 (2019) 179–189

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Effect of coal maturity on CO_2-based hydraulic fracturing process in coal seam gas reservoirs

K.H.S.M. Sampath[a], M.S.A. Perera[a,*], D. Elsworth[b], P.G. Ranjith[c], S.K. Matthai[a], T. Rathnaweera[c], G. Zhang[c]

[a] Department of Infrastructure Engineering, Engineering Block B, Grattan Street, Parkville, The University of Melbourne, Victoria 3010, Australia
[b] Energy and Mineral Engineering, G3 Center and EMS Energy Institute, Pennsylvania State University, University Park, PA 16801, USA
[c] Department of Civil Engineering, Monash University, Clayton Campus, Victoria 3800, Australia

ARTICLE INFO

Keywords:
Coal seam
Hydraulic fracturing
Break-down pressure
Liquid CO_2

ABSTRACT

Hydraulic fracturing of deep coal seams is challenging due to both the complex processes involved in fracturing and the typically poorly defined characteristics such as natural cleat system, mineral-maceral distribution and strength parameters of the subsurface. This study evaluates the effectiveness of fracturing using liquid CO_2 as the propellant through observations of break-down pressures and the form of the induced fracture network in various ranked coals. Coal ranks are defined through a rigorous proximate analysis to determine the moisture, volatile matter, ash and fixed carbon contents of each coal type fractured. Fracturing experiments were conducted on 38 mm × 76 mm core samples, under fixed stress, temperature conditions (i.e. σ_3 = 6 MPa, σ_1 = 8 MPa and T = 25 °C). Break-down pressures are observed to increase with increasing coal maturity. Increasing rank or maturity identifies that the coal has been subjected to progressively higher pressures and temperatures, has gained proportionately higher strength and thus exhibits a higher break-down pressure. No direct relationship is observed between volatile matter content and either strength or break-down pressure. The colocation of acoustic emission (AE) hypocenters and mineral grain boundaries delineated by micro-CT imaging indicate preferred pathways for the propagation of fractures induced by liquid CO_2. Stiffness contrasts between mineral phases result in stress concentrations and localized weakness at grain-grain boundaries. The complex mineral distribution in coal accentuates such heterogeneity of weakness and may be the key feature promoting the evolution of a well distributed rather than localized fracture network. For low rank coal, hydraulic fracturing is least effective, as the fracturing process does not create a significant fracture network to enhance the permeability. This may result, since low rank coals are intrinsically weak due to their low carbon content and high moisture content allowing extensive fracturing to develop at only very low break-down pressures – minimizing damage. These observations emphasize the sensitivity of break-down pressures and the resulting complexity of fracturing to pressurization rates and coal rank – inferring important controls on these parameters for the safe and effective use, when fracturing with CO_2 as the propellant.

1. Introduction

The need for sustainable energy resources is rapidly expanding due to the rapid growth of population and the spectre of climate change. Exploration of alternative energy resources has become essential to fulfill an ever-increasing energy demand. One potential source of energy is extraction of unconventional gases, such as basin-centered gas, tight gas, coal seam gas (CSG) and shale gas [1]. The extraction of natural gas from low permeability unconventional reservoirs requires methods to improve access to the reservoir. 'Hydraulic fracturing' is one such technique which has made gas extraction both feasible and commercially viable [2].

Hydraulic fracturing is defined as the injection of a pressurized fluid into a rock formation through a wellbore, to create a network of fractures as a pathway for the gas to move towards the wellbore [3]. Hydraulic fracturing is a well-accepted technique in gas extraction, particularly in low permeability reservoirs such as for coal and shale. For low-permeability unconventional reservoirs, horizontal wells with multi-staged hydraulic fractures are necessary to deliver an economic production [4]. The first experiment on hydraulic fracturing for well

* Corresponding author at: Department of Infrastructure Engineering, Room: B 209, Engineering Block B, Building 175, Grattan Street, Parkville, The University of Melbourne, Victoria 3010, Australia.
E-mail address: samintha.perera@unimelb.edu.au (M.S.A. Perera).

https://doi.org/10.1016/j.fuel.2018.08.150
Received 7 January 2018; Received in revised form 13 June 2018; Accepted 30 August 2018

stimulation was completed in 1947 and the technique was first introduced to the petroleum industry by the Stanolid Oil and Gas Company in 1949 [2]. Since then, hydraulic fracturing has become a routine and widespread technique and it is estimated that up to 80% of all natural gas wells in the next 10 years will be hydraulically fractured [1].

Hydraulic fracturing in coal seams is mainly associated with conventional water based techniques, which use water as the base fluid along with additives and proppants. Although, "conventional" fracturing with "slick-water" is generally simple and cost effective [5], it is sometimes no longer acceptable due to environmental impacts from constituent chemicals, water scarcity, and from poor fracture containment or performance [2,3]. The excessive usage of water may cause several social and environmental issues, including agricultural and residential issues due to depletion of the local groundwater table, high cost to dispose of and treat the contaminated flow-back water and localized low-level earthquakes due to uncontrolled fracture performance [6]. These significant issues associated with water-based hydraulic fracturing in coal seams have led to the exploration of the use of alternative non-aqueous fracturing fluids.

Of the various non-water based fracturing fluids, CO_2 has been identified as an effective option. Alpern et al. [7] showed that CO_2 based hydraulic fracturing has the ability to create more controlled and interconnected fracture networks, which significantly enhances the ultimate gas productivity. CO_2 as a fracturing fluid eliminates formation damage and the residual fracturing fluid [8]. Furthermore, studies have been extended on evaluating the possibility of combining CO_2 sequestration with CO_2-based gas recovery from tight gas reservoirs [9]. More importantly, it will significantly reduce the potential social and environmental issues caused by conventional fracturing fluids. For all of these reasons, it is necessary to understand the behavior of CO_2 in the rock mass, once it is injected through the wellbore. The flow behavior, fluid-rock mass interactions and storage mechanisms are some of the crucial factors which should be considered when evaluating a hydraulic fracturing project.

Coal seams are formed from partially decomposed vegetation that has undergone a process called 'coalification' over millions of years. Unlike other potential gas reservoirs, coal seam hydraulic fracturing is quite challenging due to a number of factors including: 1) mechanical complexity, 2) complex geometry of induced fractures, 3) high sensitivity of coal to the fracturing fluid and; 4) stress sensitive permeability of coal seams [10]. Coal can be categorized according to its various characteristics and the CO_2 flow behavior in each coal type is different. Coal mass strength, coal-CO_2 interactions and fracture mechanisms may vary according to the coal type and its composition. Accordingly, the hydraulic fracturing break-down pressure, fracture initiation and propagation, and induced fracture characteristics also vary. This implies that the characteristics of the targeted coal reservoir should be investigated and identified, and that hydraulic fracturing projects should be specifically designed and implemented, targeting the particular characteristics of the coal formation.

This study experimentally investigates the variations of CO_2-based hydraulic fracture characteristics in coals of various compositions. A high-pressure tri-axial loading apparatus has been developed to conduct the fracturing experiments on coal samples by simulating in situ reservoir conditions. Four coal types in the range of sub-bituminous to bituminous (according to ASTM classification [11]) have been selected for the study and all specimens were fractured under the same conditions with CO_2 as the fracturing fluid. A proximate analysis classifies the coal types by determining the moisture, ash, volatile and fixed carbon content in each specimen. The fracturing results are discussed relative to these categories. The break-down pressure, acoustic emission (AE) event locations and counts, and micro-CT analysis are used to evaluate and compare mechanisms of fracture initiation and propagation in each coal type.

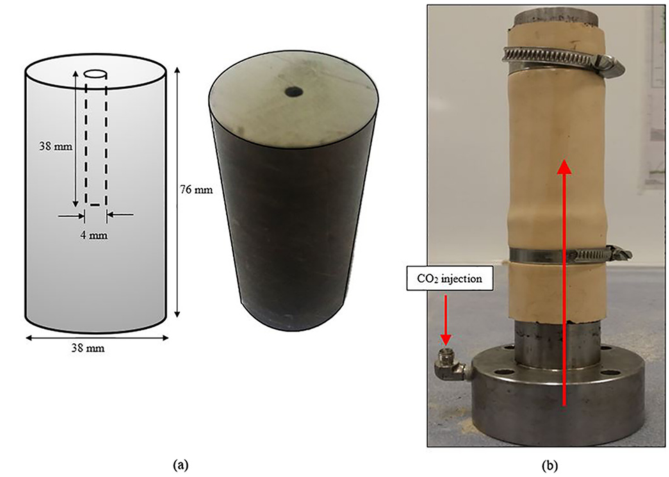

Fig. 1. a) prepared sample for fracture experiment; b) sample placement on the modified pedestal for CO_2 injection into the sample.

2. Experimental procedure

2.1. Sample preparation

The coal samples from each coal type were cored and cut with a diameter of 38 mm and a length of 76 mm using diamond coring and cutting machines available in the Deep Earth Energy Research Laboratory (DEERL) of Monash University. Both ends of the cored samples were ground to achieve smooth, flat, parallel surfaces using a face grinder to ensure a uniform stress distribution. The fracturing fluid was injected at a constant flow rate through a 4 mm diameter hole drilled halfway through at the middle of the sample (see Fig. 1(a)). The prepared sample was placed on a specially designed pedestal and the bottom was sealed off to prevent any CO_2 leaking during the fracture fluid injection. A nitrile membrane with 37.5 mm internal diameter and 3 mm wall thickness was used to cover the sample to prevent any damage from the confining oil (see Fig. 1(b)).

2.2. Modified rock tri-axial setup for CO_2 hydraulic fracturing

The high pressure tri-axial apparatus developed in the DEERL of Monash University is ideal for rock hydraulic fracturing using CO_2. The apparatus consists of four major parts: 1) pressure cell, 2) loading frame, 3) fluid pumping system and, 4) data acquisition system (see Fig. 2). The setup can deliver injection pressures up to 50 MPa, confining pressure up to 70 MPa, axial load up to 100 kN and temperature

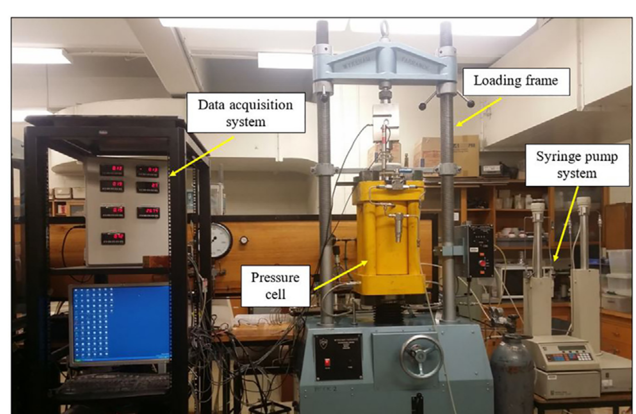

Fig. 2. Modified rock tri-axial setup used for CO_2-based hydraulic fracturing, indicating the four major components.