Fuel 222 (2018) 83–97

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Laboratory study of proppant on shale fracture permeability and compressibility

Yuling Tan[a,b,c], Zhejun Pan[c,*], Jishan Liu[d], Xia-Ting Feng[a,e], Luke D. Connell[c]

[a] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] CSIRO Energy, Private Bag 10, Clayton South, VIC 3169, Australia
[d] School of Mechanical and Chemical Engineering, The University of Western Australia, 35 Stirling Highway, WA 6009, Australia
[e] Key Laboratory of Ministry of Education on Safe Mining of Deep Metal Mines, Northeastern University, Shenyang 110004, China

ARTICLE INFO

Keywords:
Shale gas
Microscopic X-ray computed tomography
Proppant
Permeability anisotropy
Compressibility

ABSTRACT

Hydraulic fracturing is key for shale gas production and fracture permeability or conductivity is one of the most important parameters for gas production rate. Investigating the proppant distribution and fracture permeability in the field is difficult, therefore, laboratory study is a good alternative. In this work, the effect of the layer number and type of proppant on fracture permeability and compressibility were investigated. A cubic shale sample from the Cambrian Niutitang Formation at Sangzhi, Hunan Province, China, was used in this work. Sands and glass beads of different number of layers were added into an artificial fracture and seven cases, including original sample, non-propped fracture, and four kinds of propped fractures were considered. Permeability at three gas pressure steps and five confining pressure steps were measured in each case at two flow directions. Microscopic X-ray computed tomography was used to detect the distributions of proppant, and the relationship with permeability and its anisotropy was studied. A permeability model combining the stress and Klinkenberg effects was used to match experimental data and a new fracture compressibility model was proposed to predict the change of fracture compressibility with the layer number of proppant. It was found that permeability and compressibility of proppant supported fracture are closely related to proppant packing pattern and layer number, as well as the permeability anisotropy. These results improve our understanding on permeability behaviour for the proppant supported fracture and can assist in the model of fracture permeability and simulation of shale gas production.

1. Introduction

Shale gas has become an important natural gas resource in recent years. Production of shale gas increased drastically in the past decade in the U.S. and reached 15.2 Tcf (0.43 Trillion m^3) in 2015, about 50% of total U.S. dry natural gas production [1,2] and triggered significant interest worldwide [3,4]. As shales have very low porosity and permeability, the success of shale gas development owe significantly to the multi-staged hydraulic fracturing technology in horizontal wells [5]. Fracture will dynamically extend in length and aperture to form complex fracture network under the process of multi-staged hydraulic fracturing [6,7]. Moreover, the economic development of shale gas requires not only the large-sale complex fracture system in the reservoir, but also the increased and sustained fracture conductivity [8]. The fracture conductivity, defined as the product of permeability and fracture aperture, is a key indicator to evaluate the effectiveness of fracturing [9]. During hydraulic fracturing, proppant particles are mixed with fracturing fluids and then injected into fracture system to prevent fracture closure, hold fractures open, and obtain high fracture conductivity [10]. Shale fracture conductivity plays a critical role in determining the long term production of shale wells, so studies on the impact of proppant on the fracture conductivity are highly desirable.

Laboratory measurements on propped-fracture conductivity are important for analysing reliable well performance and optimizing fracturing design [11]. The fracture conductivity is affected by rock strength [12], stress [13], the proppant material, size, added amount, distribution and embedment, etc. [10,14–16]. Experimental studies on conductivity for proppant supported fracture of rock cores have been performed [16–18], demonstrating that the permeability of propped sample was drastically improved from the original sample. The effect of proppant embedment on the fracture conductivity on rock cores propped with two types of proppants at different concentrations was

* Corresponding author.
E-mail address: Zhejun.Pan@csiro.au (Z. Pan).

https://doi.org/10.1016/j.fuel.2018.02.141
Received 22 August 2017; Received in revised form 19 February 2018; Accepted 21 February 2018
0016-2361/

Table 1
TOC content and mineralogical composition of the shale sample.

TOC	Quartz	Feldspar	Calcite	Dolomite	Pyrite	Clay minerals			
						Illite/Smectite	Illite	Chlorite	Chlorite/Smectite
2.4%	42.3%	11.6%	–	–	1.5%	29.9%	7.6%	4.7%	–

studied by Wen et al. [16]. Their results showed that the proppants were not obviously damaged until the closure pressure reached a certain value, and the conductivity was increased by several times when proppant concentration was double. Fredd et al. [17] experimentally studied hydraulic fracture conductivity of fractured sandstone cores, using Jordan sand and sintered bauxite proppants at different concentrations and various closure stresses. The results showed that conductivity could be proppant or asperity dominated depending on the proppant concentration, proppant strength, and formation properties, and the conductivity varied by several orders of magnitude when low strength proppants were used at low concentrations.

Recently, the propped fracture conductivity measurements on shale samples have been performed. For instance, Hou et al. [10] performed measurements on a steel plate, a shale and a sandstone, using three types of proppants to investigate brine conductivity of fracture propped with heterogeneous and uniform proppant placements. Their results indicated that heterogeneous proppant placement led to higher fracture conductivity than a uniform proppant distribution at low closure pressures, and the fracture conductivity was directly proportional to the proppant concentration. Zhang et al. [11] conducted shale conductivity experiments on natural and induced, non-propped and propped fractures. Their results indicated that the larger proppant size and higher concentration led to higher fracture conductivity at elevated closure stress, and proppant partial monolayer failed to maintain the fracture conductivity at elevated closure stresses. Through a series of tests on fractured shale propped with Ottawa sand and ceramic proppants, Kassis and Sondergeld [19] found that a sparse one layer of proppant was equally or more effective than a fairway distribution of proppant in enhancing fracture permeability for both types of proppant, and permeability using sand tended to be higher. However, no studies considered directional fracture permeability or conductivity and the impact of proppant on fracture compressibility.

In order to investigate the directional shale permeability and compressibility of propped fracture, Tan et al. [14] conducted measurements on a shale sample in four different cases. Their results also suggested that adding proppants could significantly increase the absolute permeability but would not signficantly change the fracture compressibility. However, the effect of the layer number and material of proppant on fracture conductivity and fracture compressibility were not studied. Furthermore, they found that proppants could change the direction and ratio of permeability anisotropy, although the directional permeability or conductivity for proppant supported fracture of shale still require further experimental study, especially with better description of proppant distribution in the fracture.

Modelling work on non-propped fracture has been conducted in the past [12,20]. Recently, a few theoretical models have been proposed to estimate the conductivity of propped fracture. Hou et al. [10] developed analytical models to predict the fracture conductivity with a heterogeneous proppant placement. Bortolan Neto et al. [21] developed a simple mathematical model to evaluate the effects of proppant compressibility and in-situ stresses on the hydraulic fracture conductivity. Zhang et al. [22] presented a new correlation to calculate shale fracture conductivity considering proppant properties which could predict the crushed proppant size distribution at increasing closure stress. Khanna et al. [23] proposed a simplified approach to determine the conductivity of narrow fracture propped with a sparse monolayer of proppants, which could provide rough estimates of the optimum proppant concentration. However, these above models did not consider the impact of layer number of proppant on fracture conductivity. Thus, there is a further need to study permeability or conductivity, and compressibility change with respect to effective stress for fracture supported with proppant, as this information is important in understanding and predicting the gas production behaviour from shale reservoirs.

This work studied the effect of different proppant material, size, amount, and distribution on shale fracture permeability and compressibility. Seven different experimental cases were studied on a cubic shale sample from Cambrian Niutitang Formation at Sangzhi, Hunan Province, China. Permeabilities at two different directions along the fracture were measured at three gas pressure steps and five confining pressure steps using methane. After permeability measurement of each proppant supported fracture case, the distribution of proppant was scanned using microscopic X-ray computed tomography (X-ray μ-CT), aiming to investigate the impact of proppant on the change of permeability and its anisotropy in different cases. At last, fracture compressibility in relation to proppant was studied.

2. Experimental

In this study, a shale block was collected from the outcrop of Cambrian Niutitang Formation at Sangzhi, Hunan Province, China. The total organic content (TOC) and mineral composition are shown in Table 1. A cubic sample with a length of 20 mm of each side was cut from the shale block using a wire saw for permeability study. The detailed description of cubic sample cutting can be found in our previous paper [24]. After permeability measurements on the original shale cubic sample, the cubic sample was cut into two pieces along its bedding plane using the wire saw. The cutting simulated a fracture to study the permeability behaviour with proppant.

Glass beads and sands were added to support fracture in two separate configurations: one layer and multiple layers in the fracture. Glass beads are uniform sphere with 0.539 mm in diameter. Sand particles have irregular size and shape, and the range of the length of long axis for sand grains in our experiments is about from 0.43 mm to 1.07 mm. Small amount of water was mixed with the glass beads or sands, making it paste-like and easy to be added between the two pieces of shale. The sample with proppant was wrapped with filter paper and then held in a 3D printed membrane. A standard rubber sleeve was used to hold the cubic sample and the 3D printed membrane before installed in a tri-axial cell. The details about cubic sample installation can be found in Pan et al. [25]. The sample was then put on vacuum for two days to fully remove the water mixed with the proppant before performing permeability measurements.

For the purpose of comparing the impact of proppant on permeability, seven different cases were considered. Before adding proppant in each case, the sample was heated in a vacuumed oven for more than 2 days to dry. The experimental cases are listed as follows:

1. Case 1: original sample.
2. Case 2: the fracture without proppant.
3. Case 3: the fracture propped with one layer of glass beads.
4. Case 4: the fracture propped with multiple layers of glass beads.
5. Case 5: the fracture propped with one layer of sands.
6. Case 6: the fracture propped with multiple layers of sands.