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Development of new testing procedures to measure propped fracture conductivity considering water damage in clay-rich shale reservoirs: An example of the Barnett Shale

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ABSTRACT

Multi-stage hydraulic fracturing is the key to the success of many shale gas and shale oil reservoirs. The main objective of hydraulic fracturing in shale is to create fracture networks with sufficient fracture conductivity. Due to the variation in shale mineralogical and mechanical properties, fracture conductivity damage mechanisms in shale formations are complex. Standard fracture conductivity measurement procedures developed for fractures with high proppant concentration had to be modified to measure the conductivity in fractures with low proppant concentration. Water-based fracturing fluids can interact with the clay minerals in shale and eventually impact shale fracture conductivity. All these challenges require more experimental studies to improve our understanding of realistic fracture conductivity in shale formations.

The aims of this work were to design an experimental framework to measure fracture conductivity created by low concentration proppants and to investigate the mechanisms of conductivity damage by water. We first presented the laboratory procedures and experimental design that can accurately measure fracture conductivity of shale fractures at low concentrations of proppants. Then we measured the undamaged shale fracture conductivity by dry nitrogen. Water with similar flowback water compositions was injected to simulate the damage process followed by secondary gas flow to measure the recovered fracture conductivity after the water damage.

This study shows that the developed laboratory procedures can be utilized to reproducibly measure shale fracture conductivity by both gas and liquid. The conductivity measurement of propped fractures by small size proppants at low concentrations requires strict control on gas flow bypassing the fracture both parallel and perpendicular to the fracture length direction. Shale fracture surface softening is identified as the dominant cause for the significant conductivity reduction after water flow.

1. Introduction

Laboratory measurement is a direct, controllable, and repeatable approach to study fracture conductivity. Generally, there are two types of laboratory procedures for the measurement, namely, the standard ISO conductivity test and the modified ISO conductivity test. The ISO 13503-5:2006(E) was developed to establish standard procedures and experimental conditions to evaluate conductivity of proppants under laboratory conditions. All test apparatus and conditions under ISO 13503-5:2006(E) are specified to guarantee the proppant evaluation results are comparable. In a word, the standard ISO procedures and apparatus are designed for the purpose of proppant material studies and the measured conductivity is the baseline value without considering more realistic conditions.

The modified ISO test, or non-ISO standard test, on the other hand, has been made by various research parties for different applications. The commonest application is to use a modified API conductivity cell to accommodate 3 times thicker samples to account for fluid leakoff through the sample during the experiment. Instead of flowing 2% KCl through the fracture as specified by ISO standards, the modified tests can flow dry gas, wet gas, fresh water, brine of various concentrations and multi-phase flow for different reasons, such as protecting the shale sample by flowing dry nitrogen (Zhang et al., 2013; Zhang et al., 2015), keeping the

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Nomenclature

D_H	Hydraulic diameter, m
h_f	Width of the shale sample, m
R_e	Reynolds number, dimensionless
v	Fluid velocity in the fracture, m/s
w_f	Fracture width, m
ρ	Fluid density, kg/m^3
μ	Fluid viscosity, Pa·s
φ	Porosity, fraction

gel hydrated by wet gas (Awoleke et al., 2012), studying the water sensitivity (Conway et al., 2011), and investigating the effect of multiphase flow and non-Darcy flow (Barree et al. 2009). Both cylindrical core plugs and samples of API dimensions (7 in. long, 1.5 in. wide with curved ends) are used in the non-ISO tests (Ramurthy et al., 2011). Moreover, proppants are placed on smooth saw-cut Berea sandstone samples in ISO tests while any type of rock with either saw-cut smooth faces or rough faces can be used in the non-ISO tests.

The sensitivity of shale to water has been studied in the areas of drilling engineering and formation damage. Common authigenic clay minerals present in petroleum reservoirs are kaolinite, chlorite, illite, smectite and mixed-layer clays (Civan, 2007). Clay particles are very small. The maximum dimension of a typical clay particle is less than 5 μm (Hughes, 1951). Formation damage caused by clay swelling, dispersion and migration in sandstone reservoirs were identified during water flooding early in the 1960s (Jones, 1964). Clay related porosity and permeability impairment usually happens in two ways: clay swelling and fines migration. Smectite is the most swellable clay mineral. According to Ezzat (1990), smectite is 100% expandable and it causes tremendous loss of micro-porosity and permeability. However, smectite is not as common as the other clay minerals in most of the reservoirs currently being developed (Conway et al., 2011). Mixed layer clay minerals are also believed to have some swelling ability due to the illite-smectite and chlorite-smectite layers. Clay swelling mechanisms, modeling, porosity and permeability reduction were reviewed by Civan (2007).

The other mechanism of formation damage due to water–clay interaction is fines migration. In sandstone, when the fluid velocity exceeds a critical value, fines would be released from the pores (Gruesbeck and Collins, 1982). Sharma et al. (1985) derived a model to estimate the rates of fine release and deposition in a single pore. Reservoir permeability is severely impaired due to the release, migration and entrapment of fines at the pore throats. Sharma and Yortsos (1986) also investigated fines entrapment using a statistical approach and general population balance equations. Experimentally, fines migration is observed by a standard water shock experiment where the flow through a sandstone core is suddenly switched from brine to fresh water. It was reported that in the water shock experiment, permeability can be reduced by two orders of magnitude (Khilar and Fogler 1983).

Conductivity damage due to clay–water interaction has been studied during pre-fracturing formation evaluation in shale. The test is called unpropped fracture conductivity test (UFCT). It is done to determine fluid sensitivity to shale rocks and the residual fracture conductivity after different fluid damages. It was reported that the clay–water interaction can reduce shale rock strength, and the variation of shale rock mechanical properties depends on rock mineralogy, fluid compositions and test conditions (Akrad et al., 2011; LaFollette and Carman, 2013; Lin and Lai 2013).

There is a need to develop a laboratory framework to accurately measure shale fracture conductivities at low proppant concentration. Shale fracture conductivity damage by water needs to be proved with sound laboratory evidence. Therefore, this work aims at developing new laboratory procedures for shale fracture conductivity measurement and examining the conductivity damage mechanism.

2. Development of laboratory setup and procedures

2.1. Laboratory setup

The setup was developed for conductivity measurement by both gas and water. The entire apparatus consists of five separate units: (1) gas injection unit; (2) liquid injection unit; (3) conductivity cell assembly; (4) closure stress application unit; and (5) pressure/rate data acquisition unit. Fig. 1 shows the schematic of the apparatus. The photograph of the setup is shown in Fig. 2.

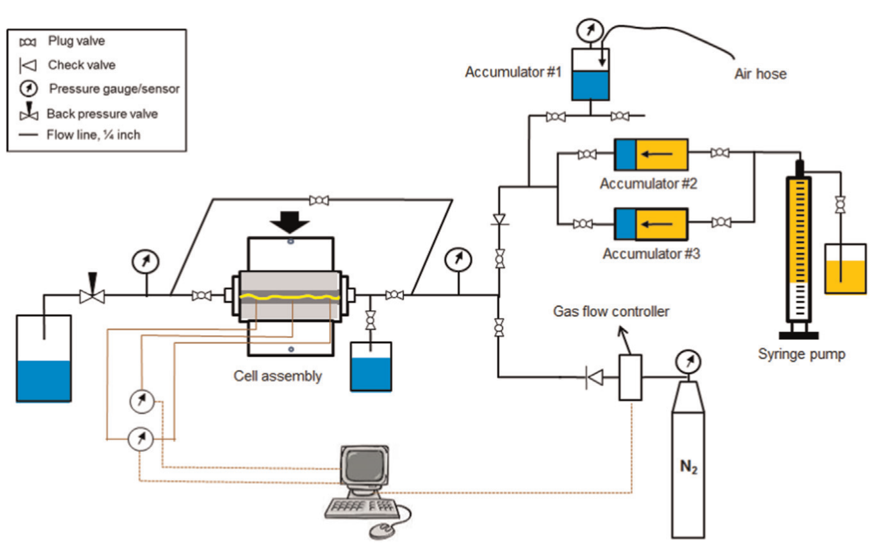

Fig. 1. Schematic of the setup to evaluate the conductivity damage by water.