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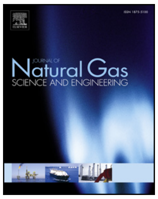

Proppant-packed fractures in shale gas reservoirs: An in-situ investigation of deformation, wettability, and multiphase flow effects

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ABSTRACT

The results of a systematic, micro-scale experimental investigation on two-phase gas/brine flow through proppant-packed fractured shale samples under increasing effective stresses of up to 5000 psi are presented in this paper. We use a miniature core-flooding apparatus integrated with a high-resolution X-ray micro-CT scanner to perform the flow experiments. Geomechanical deformation and its impact on displacement mechanisms governing fluid transport within the packed fractures are studied at the pore scale under certain flow and stress conditions. These conditions were carefully designed to represent reservoir depletion and transport of water through such media. Since proppant grains are placed to maintain the long-term conductivity of the induced fractures, they significantly influence the geomechanical and multi-phase flow behavior of these conduits during reservoir depletion. We particularly examined the effectiveness of modified resin-coated sand (compared to a basic white sand) in maintaining the hydraulic conductivity of induced fractures. Significant bullet-like embedment and proppant crushing under severe stress conditions were found to be the shortcomings of these proppants, respectively. We then developed a methodical framework to design improved proppants with a similar mechanical strength to the host shale rock to withstand these drawbacks.

Sphericity, roundness, and size of the proppant grains also impacted the critical properties of the constructed pore space such as pore size distribution and pore-throat aspect ratio. Such parameters control pore-scale gas-to-brine and brine-to-gas displacements within the hydraulic fractures. We specifically studied the non-wetting phase trapping and its subsequent impact on reduction of available pore space for other fluids to flow. It was found that trapped gas globules are very likely to deform within the medium and redistribute/reconnect under a higher effective stress. For the first time, wettability alteration of the proppant pack from water-wet to oil-wet was observed in a gas/brine fluid system. Wettability alteration occurred non-uniformly and was thought to be due to deposition of the shale organic matter released after significant proppant embedment. Such wetting characteristics aggravate multi-phase trapping within the fractures, which in turn leads to dramatic reductions in effective gas permeability. This study is concluded with a set of recommendations that can be used to effectively maintain the productivity of propped fractures for extended period of time.

1. Introduction

Natural gas production from unconventional reservoirs, e.g., tight sand and shale plays, is the only growing component of the U.S. energy supply and has increased twelve-fold over the last decade (Annual energy outlook, 2012). Sustainable economic development of these resources depends on innovative advances particularly in horizontal drilling, multi-stage hydraulic fracturing, and other well stimulation technologies (Sayed et al., 2015). During hydraulic fracturing operations, a fracturing fluid (mostly slickwater mixed with certain chemicals) is injected into the formation at exceedingly high pressures to break down the rock and induce fractures (Economides and Martin, 2007). Due to low permeability of the rock matrix, induced fractures are considered to be the principal conduits for production from a commercial prospective by facilitating hydrocarbon flow from the rock matrix to the wellbore (Abbas et al., 2007). Various types of proppants are added to the fracturing fluid and placed within induced fractures to prevent them from closing after the well is allowed to flow back (Rahm, 2011). The proppants are of extreme importance as they help fractures to maintain long-term conductivity. Proppant grains experience different levels of breaking, crushing, and embedment as the reservoir pore pressure reduces due to depletion. Such geomechanical

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deformations ultimately lead to fracture closure and production loss in shale reservoirs (Mueller et al., 2015). Furthermore, since most often reservoir brine (or fracturing fluid) is produced along with gas, the aforementioned geomechanical deformations may impact two-phase flow properties of induced fractures contributing to a higher reduction in effective gas permeability. Thus, investigating geomechanical deformation and subsequent transport properties of propped fractures under increasing closure stress has great importance in understanding the mechanisms responsible for rapid production loss as reported for many shale gas reservoirs. This might contribute to proppant designs that could help provide higher fracture conductivity for hydrocarbon phase (e.g., gas) and/or slow down fracture closure during reservoir depletion. Furthermore, improved insight into pore-scale displacement mechanisms governing flow of gas and brine through packed fractures has potential applications in reducing uncertainties when recovery from a shale gas reservoir is predicted using reservoir simulation tools.

Over the last decade, several experimental investigations have been conducted to study proppant embedment and subsequent reduction in hydraulic conductivity of packed fractures under increasing effective stresses of up to 10,000 psi (Penny et al., 2012; Alramahi and Sundberg, 2012; Rivers et al., 2012; Zhang et al., 2014; Ghanizadeh et al., 2016). Alramahi and Sundberg reported that shale samples with high clay content may experience up to six (6) orders of magnitude reduction in fracture conductivity due to embedment (Alramahi and Sundberg, 2012). Visualization techniques such as acoustic waves, optical profilometry, microscopic observations, and X-ray tomography imaging have been recently employed to study proppant embedment and integrity, and fracture closure under varying effective stress conditions (Ghanizadeh et al., 2016; Kassis and Sondergeld, 2010; Terracina et al., 2010; Arshadi et al., 2017; Akrad et al., 2011; Chen et al., 2014; Ingraham et al., 2015; Sanematsu et al., 2015). Higher embedment and micro-fracture induction were observed in propped fractured shale samples with the fracture being perpendicular to the bedding (Chen et al., 2014). Kassis and Sondergeld (2010) reported that ceramic proppant did not crush under high stress conditions and only embedded into the shale matrix, whereas Ottawa sand crushed under high stress conditions and induced micro fractures in the shale sample. Micro-scale observations of shale/proppant interactions under different confining pressures (Arshadi et al., 2017) show that, fracture closure due to proppant embedment and/or disintegration, i.e., breaking and crushing, is highly impacted by the shale rock mechanical properties and mineralogy, and proppant strength. Recent advances in proppant manufacturing technologies have resulted in low-weight/high-strength proppants for use in fracturing treatments (Liang et al., 2015). Shale mineralogy, however, has been seldom considered in such proppant designs. For example, high clay content reduces the Young's modulus of shale leading to significant bullet-like embedments (Alramahi and Sundberg, 2012). Some of the key questions in these situations are: is it still beneficial to use modified high-strength proppants in relatively ductile shale formations? and what is the optimum strength of proppants that can prevent them from both embedment and crushing?

Furthermore, previous studies mostly quantified the reduction in single-phase permeability due to increases in effective stress and seldom investigated the pore-scale displacement mechanisms that govern multi-phase flow through hydraulic fractures under relevant flow and stress conditions. This is particularly important as tremendous reductions in relative gas permeability (up to ten-fold) have been observed in proppant-packed fractures due to multi-phase flow effects (Penny et al., 2012). In a previous study, we probed the effect of deformation on two-phase oil/brine flow through three separate fractured shale samples housing different packings of proppant (multi-layer, uniform mono-layer, and non-uniform mono-layer). The proppant distributions were designed to represent proppant packing at various distances/heights of hydraulic fractures in a typical shale reservoir (Arshadi et al., 2017). It was concluded in this study that the productivity of induced fractures, especially at areas with lower concentrations of proppants, is adversely impacted by interplay of geomechanical and multi-phase flow physics at micron level. This is primarily due to a higher degree of proppant pack deformation, e.g., changes in porosity, pore size distribution, and pore-throat aspect ratio, which negatively impacts the transport of hydrocarbon in the presence of brine. Furthermore, these effects could be more profound at further distances because of low velocity of producing fluids and, hence, critically important role of pore-level, capillary-driven displacements in determining the macroscopic transport properties of induced fractures at these regions (Arshadi et al., 2018; Kazmouz et al., 2016). Reservoir-scale studies (Sharma and Agrawal, 2013) show that low reservoir drawdown, low matrix permeability or low initial production rate aggravate multi-phase flow factors, e.g., wetting characteristics, non-wetting phase trapping, and liquid loading, even in areas close to productions wells.

In this study, we investigate the effects of closure stress (up to 5000 psi) and proppant strength on the flow of gas and brine through proppant-packed fractured reservoir shale samples. We use a miniature core-flooding apparatus integrated with a high-resolution X-ray micro-CT scanner to perform identical tests in two miniature shale samples packed with different types of proppant, i.e., basic white sand and modified resin-coated variety of the same sand. This was particularly designed to determine the optimum strength of modified proppants that could potentially slow down the fracture closure caused by proppant crushing and/or embedment. In addition, we explore multi-phase flow factors that contribute to the effective gas permeability reduction and production loss in the above-mentioned samples. For instance, changes in critical properties of the proppant packs (such as porosity, pore size distribution, and pore-throat aspect ratio) due to deformation and their subsequent effect on transport properties of hydraulic fractures are quantified in this study. We visualize trapped gas globules within the proppant packs during various imbibition and deformation cycles and inspect their impact on the flow of other fluid phase, i.e., brine. Moreover, we probe the wetting characteristics of both proppant packs in the course of the experiments to see if they experience wettability alteration under elevated stress conditions as observed in our previous experiments (Arshadi et al., 2017). To the best of our knowledge, this is the first micro-scale study that combines the physics of geomechanics and multi-phase flow disciplines to seek production enhancement from hydraulic fractures in shale gas reservoirs.

This paper is structured as follows. First, we provide information on the materials and conditions of the experiments. Next, we include a detailed description of the experimental setup and procedures used to perform the flow tests. This is followed by the image acquisition and analysis techniques deployed in this work. We then present the results and discuss the main findings. This paper is concluded with a set of final remarks.

2. Experiments

We performed two-phase gas/brine flow experiments through two individual fractured shale samples packed with different types of proppants. Both samples were subjected to 500, 2500, and 5000 psi confining pressures during the flow tests. Certain gas-displacing-brine (drainage) and brine-displacing-gas (imbibition) flow experiments were carried out under each stress condition to represent fluid transport through the propped fractures at various stages of production. Flow experiments were performed through vertically-oriented samples where fluids (methane and brine) were injected into the samples from top to suppress gas segregation. Unsteady-state technique was used to conduct the tests. This means that only one fluid phase was injected into the core at a time during each flow process.

2.1. Materials

The reservoir shale samples were obtained from a shale prospective in the Middle East. Water-wet proppant grains (white and modified