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A visualization study of proppant transport in foam fracturing fluids

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ABSTRACT

The placement of proppants in hydraulically fractured wells determines the conductivity of fractures and the productivity of shale wells. In slickwater farcturing, proppants are often not transported deep into fractures. In this paper, proppant transport in foam-based fracturing fluid is visualized in a laboratory-scale fracture slot. Effect of parameters like foam quality, proppant loading, and injection rate are systematically investigated. Experiments show that dry foams (80% quality) can carry proppants between the lamellas with little vertical settling. A complex flow pattern develops at the bottom of the slots in dry foams due to protrusion of foam fingers into proppant laden foam flow. Proppants are not carried very well in wet foams (70% quality) and form a proppant bed near the injection well. This is due to drainage of liquid and low effective viscosity of the foam as it moves through the fracture.

1. Introduction

The commercial exploitation of unconventional shale has led to a dramatic increase in the production of oil and gas in the US. Slickwater (water mixed with a small amount of friction reducer) fracturing is commonly used because it produces a thin, long primary fracture intersecting secondary fractures. However, common proppants such as sand settle down very quickly in slickwater (Tong and Mohanty, 2016) and leave a large portion of fracture surfaces and network unpropped or sealed after stimulation (Kern et al., 1959; Mohanty et al., 2017; Warpinski et al., 2009; Yu et al., 2014), which could potentially leads to the under-performance of fracturing. There are two common methods to transport the proppants deep into the fractures. The first method is to use polymer-based viscous fracturing fluids. They carry the proppants well, but can plug the tiny pores in low permeability shales and damage the productivity of the fractures (Barati and Liang, 2014; Ribeiro and Sharma, 2012; Yang and Balhoff, 2017). Zhou et al. (2015) included guar-based polymeric particles in the fracturing fluid, and these particles could take the space between the proppants and prevent proppants from settling. After cleaning, no gel or filter cake damage was found, and the fracture could regain 91% of its conductivity. The second method is to use ultra-light weight proppants (ULWP) (Gaurav et al., 2012). ULWPs usually have a specific gravity of 1.08–2.0 (which lies between the specific gravity of water and sand). Based on Stoke's Law, ULPWs have significantly smaller settling velocity compared to that of sand. However, ULWPs typically offer a lower conductivity compared to conventional proppants (Rickards et al., 2006) and may suffer severe flowback issues.

Another alternative approach is to use foam fluids. Foams possess high apparent viscosity (Kong et al., 2016; McAndrew et al., 2017; Xu et al., 2017) which is good for suspending proppants. In addition, foams reduce water use, fracturing fluid leak-off, clay swelling and lead to faster fracture clean-up due to gas expansion (Gu and Mohanty, 2014). Foam fluid has been widely investigated by previous researchers (Reidenbach et al., 1986; Harris and Reidenbach, 1987; Harris, 1989, 1995). Temperature, pressure, gas types and additives determined the bubble property and foam stability. Foam stability at high temperature depended more on surfactant type and concentration (Harris and Reidenbach, 1987). Generally, a Herschel-Bulkley model or a power-law model was used to describe the rheological behavior of foams (Reidenbach et al., 1986), and the rheology was hardly affected by the type of gas (Harris, 1995).

Transparent Hele-Shaw slots have been widely used to visualize and investigate proppant transport in the literature (Liu and Sharma, 2005; Malhotra et al., 2014; Zhou et al., 2015). Liu and Sharma, 2005 systematically studied proppant settling within a rough-walled Hele-Shaw slot. Effect of fracture width, fluid rheology, proppant diameter and concentration were incorporated into an empirical settling velocity of concentrated proppant slurry. Malhotra et al. (2014) made use of viscous fingering phenomenon (Doorwar and Mohanty, 2011) and developed an alternate-slug pumping of polymeric fluid and just water to enhance proppant transport. Proppant could be nicely held in fingers generated by adverse viscosity fronts. Proppant transport in foams has not been visualized in Hele-Shaw slots.

In this work, proppant transport in foam has been investigated

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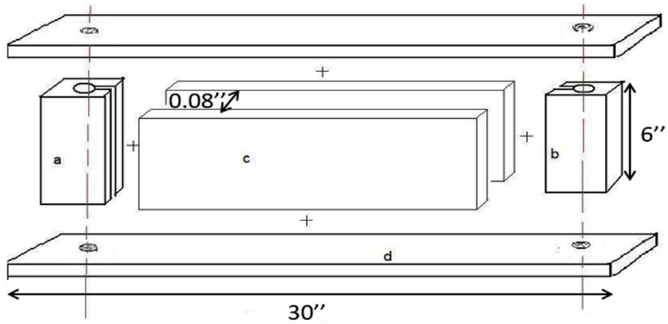

Fig. 1. Dimensions of the slot (hele-shaw slot) used in the study.

systematically at the room conditions. At the field conditions, the density of the gas can change considerably and would affect the liquid drainage; but that is outside the scope of this study. We conducted dynamic proppant settling experiments in foam within a transparent Hele-Shaw slot, and proppant trajectory was tracked. The effects of foam quality, proppant loading and injection rate on proppant velocity were analyzed with trajectories.

2. Methodology

2.1. Materials

A C14-16 alpha-olefin sulfonate (AOS) anionic surfactant (39% active) was used in this study. This surfactant is an effective foaming agent and has been reported in foam fracturing (Gu and Mohanty, 2015) and EOR studies (Singh and Mohanty, 2017). A partially (30%) hydrolyzed polyacrylamide polymer with a molecular weight of 8 million Dalton was added into the solution as a viscosifier. Sodium chloride was used as received. 20-40 mesh size black ceramic proppant (specific gravity: 3.36) was selected in this study for better visualization (Kadhim et al., 2017). The foam fluid was prepared with 0.5 wt% surfactant in 1.0 wt% NaCl brine with 100 ppm polymer. Foam rheology was quantified with a power-law model based on pipe rheometry measurements. Measurement details could be found elsewhere in the literature (Enzendorfer et al., 1995).

2.2. Fracture slot

A transparent Hele-Shaw slot was used to mimic hydraulic fractures, and it is 30″, 6″ and 0.08″ in length, height, and width, respectively. This slot was designed to visualize the process of proppant transport in foam. Fig. 1 shows the schematic figure of the slot design. The inlet is on the left, and the outlet is on the right. The inlet and outlet holes were 0.5″ in diameter which run along the height of the slot (components a and b in Fig. 1). Note that this diameter (0.5″) is very large as compared to the width of the slot (0.08"); therefore, the holes also act as a fluid distributor which minimizes the entrance effects. Both top and bottom plates were attached to the slot (unlike the figure). Foam-proppant slurry was mixed in a blender at a fixed rpm to form a homogeneous mixture of proppant-laden foam. This mixture was injected in the slot using a peristaltic pump running at a constant flow rate, as shown in Fig. 2. The movement of proppant was recorded with cameras, and the trajectory of proppant was tracked in a video analysis software. The bubble texture of the foam in the Hele-Shaw cell was characterized using a Nikon optical microscope equipped with a high-resolution camera. The image processing was done using the open-source Fiji software. The pressure drop across the cell was measured using a Rosemount differential pressure transducer.

2.3. Experimental conditions

Black-colored, 20/40 ceramic proppant was used for better visualization (compared to sand). Effects of proppant loading and shear rate were investigated. The concentration of proppant varied from 2.5 vol% to 10.0 vol% (around 0.6–2.4 ppg sand loading), which is within the range of typical field applications. Due to the limitation of the pump, the maximum injection velocity and corresponding shear rate were 0.0467 m/s and 140 s^{-1}, respectively. The nominal shear rate (γ) in a rectangular channel is defined as

$$\gamma = \frac{6q}{w^2 h} \quad (1)$$

where q is the volumetric flow rate in the channel, w is the width (the shorter dimension of the channel), and h is the height. This shear rate is not an actual local shear rate because the formation of proppant bed can significantly affect the flow of the fluid.

The experimental matrix is listed in Table 1. 80% quality foam was studied comprehensively, and several experiments were conducted with the 70% quality foam for comparison. Foam quality is defined as the volume percentage of gas in the foam. Experiments were performed at common shear rates observed in the field applications (Ouyang et al., 2012). Proppant loading is the volume% of proppant in the slurry. Equivalent Sand Loading (ESL) is the lbs of sand proppant per gallon of slurry if sand is used as the proppant at the same volume %. It is calculated by multiplying sand density (lb/gallon) and proppant volume concentration. ESL is another way to express proppant loading.

3. Results and discussion

3.1. Static foam test

Static foam tests (SFT) are one of the most common bulk foam stability experiments which are extensively used in the literature for screening foaming formulations (Andrianov et al., 2012; Singh and Mohanty, 2016; Vikingstad et al., 2005). In this study, SFT were conducted to investigate the effect of polymer and foam quality on the bulk foam stability. Static foam tests were conducted for 70% and 80% foam

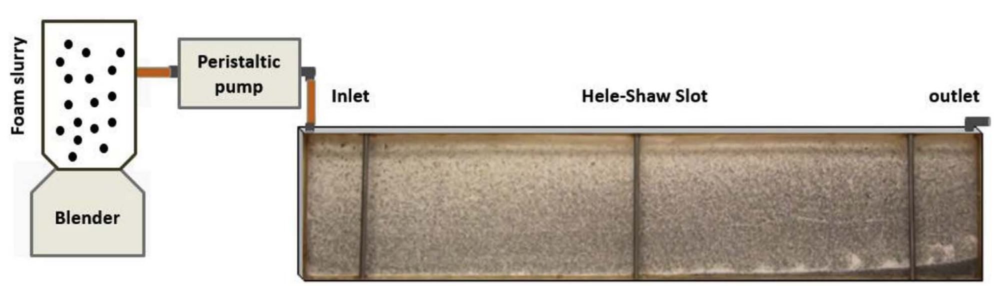

Fig. 2. Experiment setup.