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Displacement of water by gas in propped fractures: Combined effects of gravity, surface tension, and wettability

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ABSTRACT

Inefficient recovery of fracturing water used in multi-stage hydraulic fracturing operations is a growing industrial concern. Non-recovered water can be trapped in the tight rock matrix and/or in the complex fracture network. This paper reports results of various drainage experiments conducted to identify the factors controlling water displacement in proppant-filled hydraulic fractures. Experiments were conducted to investigate the displacement of water and isopropanol–water solution by gas (Nitrogen). The displacement direction relative to gravity is changed to investigate the gravity effect on the displacement pattern and ultimate fluid recovery. The visual images of displacement patterns were obtained by taking high-resolution pictures of the porous medium model during displacement experiments. Results plotted in the form of normalized water recovery versus dimensionless time show three distinctly different clusters of data corresponding to vertical upward, vertical downward and horizontal displacements directions. The lowest water recovery was observed during the upward vertical displacements, which could be explained by the formation of gas fingers observed in the images. Reducing the surface tension and using treated hydrophobic proppants considerably improved the sweep efficiency and in turn the normalized water recovery. The effect of changing the wettability by using hydrophobic sand was more pronounced, and could be explained by the formation of thicker fingers in the upward displacement. The results of this study suggest that a significant portion of fracture fluid could be retained in vertical hydraulic fractures below the horizontal well due to the formation of gas fingers and poor sweep efficiency, which in turn are the results of adverse Mobility ratio and gravity segregation.

Introduction

Hydraulic fracturing is a very common technique to enhance hydrocarbon recovery from shale and tight reservoirs. Fracturing operation involves pumping millions of barrels of fracturing fluid (Cipolla et al., 2010), generally water based, at pressures above the reservoir fracture pressure. A very low percentage of fracturing fluid is recovered back during the flowback operations (<25%) (Pagels et al., 2012). The non-recovered fracturing fluid staying in the fractures or leaking into the rock matrix might cause loss in fracture conductivity (Tannich, 1975; Parekh et al., 2004; Fahimpour et al., 2012) and fracture face damage (Yu and Guo, 2010; Fletcher et al., 1992).

The two basic parameters that may govern the fracture drainage during the flowback are capillary pressure (Paktinat et al., 2006) and mobility ratio (Cooke, 1975). Cyclic stresses due to shut-ins and high production rates can result in crushing of proppants and thus in increasing of capillary pressure (Cheng, 2012; Ouabdesselam and Hudson, 1991). Increased capillary pressure results in low microscopic displacement efficiency and in turn poor fracturing fluid recovery. Similarly, use of high viscosity fluids results in adverse mobility ratio (Cooke, 1975) leading to formation of fingers. Fingering causes early breakthrough of non-wetting fluid. This in turn reduces the areal sweep efficiency resulting in inefficient fracture drainage. Previous studies have shown that increasing viscosity of displaced fluid and capillary forces of the system negatively impacts fluid recovery in porous media (Tidwell and Parker, 1996; Benham et al., 1963).

In addition to mobility ratio, the direction of displacement relative to gravity direction can influence the sweep efficiency. As shown in Figure 1, in horizontal wells fractures are generated above and below the well. For fractures above the well, drainage is in the gravity direction and for fractures below the well, the drainage is against gravity direction. Lab experiments conducted on gas/water drainage in the gravity direction (Parmar et al., 2012; Lovell et al., 2005; Shahidzadeh-bonn et al., 2004) and against gravity direction (Glass et al., 2010; Ji et al., 2007) show that drainage against gravity is very unstable and results in fingering.

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Nomenclature

μ_1, μ_2	viscosity of fluid 1 and 2 respectively
k_1, k_2	absolute permeability of fluid 1 and 2 in porous media respectively
ρ_1, ρ_2	density of fluid 1 and 2 respectively
g	gravitational constant
α	Angle of the model from the vertical (0^o for displacement of fluid 1 by fluid 2 vertically against gravity)
σ^*	effective surface tension
σ	bulk surface tension
λ_c	critical wavelength of perturbation
V_c	critical displacement velocity
V	displacement velocity
d_p	proppant diameter
L	length of experimental cell
W	width of experimental cell
h	thickness of experimental cell
μ_g	injection gas viscosity
μ_L	frac-fluid viscosity
ΔP	drawdown
$\Delta\rho$	density difference between frac-fluid and gas injected
Θ	contact angle
H	thickness of finger
μ	viscosity of driven fluid
U	velocity of finger

In general, displacement stability in porous media is controlled by the interplay of the following forces (Parmar et al., 2012; Lovell et al., 2005).

- *Gravity force:* Depends on the density difference and the drainage direction with respect to the gravity direction.
- *Viscous force:* Depends on the displacement velocity and the mobility ratio.
- *Capillary force:* Depends on the interfacial tension between the fluids and wettability of the porous medium.

Various experimental (mostly using Hele shaw models) and numerical studies have been conducted to understand the interplay of these forces and their effect on instability (McLean and Saffman, 1981; Saffman and Taylor, 1958; Homsy, 1987; Bensimon et al., 1986; Chuoke et al., 1959). Onset of this instability was described by Chouke's theory (Chuoke et al., 1959). For displacement of fluid 1 by fluid 2, the system is unstable for all displacement velocities (V) greater than the critical displacement velocity (V_c).

$$V_c = \frac{(\rho_1 - \rho_2) g \cos\alpha}{\left(\frac{\mu_2}{k_2} - \frac{\mu_1}{k_1}\right)} \tag{1}$$

The perturbation, caused due to unbalanced forces, contains a wavelength which is greater than the critical wavelength (λ_c) given by following equation

$$\lambda_c = 2\pi \sqrt{\frac{\sigma^*}{\left(\frac{\mu_2}{k_2} - \frac{\mu_1}{k_1}\right)(V - V_c)}} \tag{2}$$

This means that $V > V_c$ is the necessary condition for instability and $\lambda > \lambda_c$ is the necessary and sufficient condition.

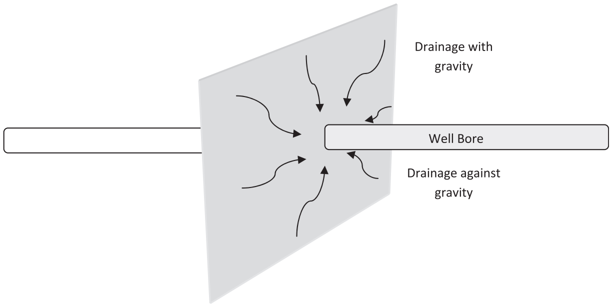

Figure 1. Conceptual model showing water drainage in a horizontal well. Water drains with gravity in fractures above the well and against gravity in fractures below the well.

Here, σ^* is proportional to σ (Chuoke et al., 1959).

The above equation was experimentally (Chuoke et al., 1959) verified by displacing oil with a water–glycerine solution in a parallel plate model. In these experiments, density and viscosity of the oil and glycerine–water solution were constant with $\rho_2 = 0.877$ gm/cm^3 and $\mu_2 = 1.39$ poise for oil, and $\rho_1 = 1.21$ gm/cm^3 and $\mu_2 = 0.522$ poise for glycerine–water solution. The system was tilted at an angle of $44°25'$. The critical velocity for this system was then calculated to be 0.23 cm/s using Eq. (1). Furthermore, it was found that with an increase in flow rate, the number of fingers increased. Also, when oil viscosity was reduced, smaller fingers were formed. We performed a sensitivity analysis for better understanding of the concept of critical velocity, using the data provided above. We plot the results in graphs presented in Appendix A.1. This analysis indicates that increasing the density of water (displacing phase) or decreasing the viscosity of oil (displaced phase) increases the stability of the displacement.

From Eq. (1), it can be deduced that the displacement direction relative to gravity direction plays a vital role in deciding the stability of the system. For vertical displacement of fluid 1 by fluid 2 against gravity ($\alpha = 0°$), an increase in the density of the displaced fluid (fluid 1) decreases the critical velocity. This in turn increases instability of the system.

Studies conducted in the past mainly focus on viscous and capillary forces to understand the drainage and instability in porous media (Tidwell and Parker, 1996; Benham et al., 1963). Very limited research has been conducted on instability during drainage against gravity direction in porous media (Shariatpanahi, 2005). Most of the studies carried out using Hele-shaw models and by packing sand between glass plates do not take the gravity into consideration. Some drainage experiments that have been conducted against gravity direction (Glass et al., 2010; Ji et al., 2007) are not aimed at studying the factors such as drawdown, surface tension and wettability.

Recently, a simulation study (Agrawal and Sharma, 2013) showed that there is inefficient water drainage in fractures below a horizontal well due to gravity effects. Furthermore, in a field study (Taylor, 2011) it was observed that wells placed at the bottom of the formation had better fracture cleanup due to gravity drainage as compared to wells placed at the top of the formation. These studies indicate the dominant role of gravity in fracture drainage, which needs to be investigated experimentally.

This paper reports the results of comparative drainage experiments that investigate the effect of gravity, drawdown (pressure difference between injection and production ends), surface tension and wettability on fluid recovery in propped fractures. A series of experiments were conducted in a propped fracture model, produced by packing glass beads between two glass plates.