Title: Investigation of Capillary Pressure Effects on Well Cleanup after Hydraulic Fracturing
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SPE

Investigation of Capillary Pressure Effects on Well Cleanup after Hydraulic Fracturing

Rong Lu, Colorado School of Mines

Abstract

Nowadays hydraulic fracturing is becoming a most popular practice for low permeability reservoirs. While in some cases fractured wells show superior productivity than non-fractured wells, in other cases the effective fracture length which is used to channel gas and oil from reservoir to wellbore, is much shorter than the propped fracture length, thus leading to a lower-than-expected production rate. A main reason is the unsatisfactory well cleanup following the fracturing treatment. In this work the research is focused on capillary pressure's role in post-fracturing well cleanup. Basically capillary pressure is inversely proportional to relative permeability to hydrocarbon fluids. Looking at LaPlace-Young equation, capillary pressure is determined by interfacial tension, contact angle and pore throat radius. Each of the three components is examined first in respect to its role in well cleanup, after which methods of reducing capillary pressure are investigated. Methods of lowering interfacial tension, alteration of contact angle and controlling of effective pore radius are come up with.

Introduction

Ineffective fracture cleanup has been regarded as one of the most important reasons accounting for fracturing treatment's underperformance. Cleanup is the practice of cleaning fracturing fluid out of the fracture and matrix immediately following the treatment. The effect of cleanup performance on well productivity has long been known, which is, better cleanup will yield us more satisfactory production results even in a very long term. During cleanup, as gel (frac fluid) continues to be produced from the underground, a corresponding porous volume will become available to channel reservoir fluids to the wellbore. Therefore, as more gel is produced, a corresponding increase in production should be observed.

In this work, the role of capillary pressure in controlling load water recovery is examined. Also influence of inefficient fracture cleanup due to capillary pressure effects are discussed to underscore the necessity of addressing this problem. Then methods of reducing capillary pressure are come up with, in respects of lowering interfacial tension, controlling pore radius and altering contact angle.

Capillary Pressure's Role in Post-Fracturing Well Cleanup

During a hydraulic fracturing treatment we need to pump several million gallons of water per well on average (Arthur and Coughlin, 2011), but in some cases only 5%-10% of the pumped water can be recovered (Cheng, 2010). A major reason is the drawdown pressure cannot exceed the capillary pressure of injected water trapped near the fracture face (Holditch, 1979). Capillary pressure is the pressure drop across a curved liquid interface between two immiscible phases in a small radius tube. During hydraulic fracturing treatment, the frac fluid pumped into the underground is assumed to be the wetting phase (which is not a bad assumption for most cases), then capillary pressure will serve as the driving force for fluid penetration into fracture and rock matrix. In other words, it is this force that we have to overcome during well cleanup following fracturing treatment. The significance of capillary pressure can be evaluated using the LaPlace-Young equation (LaPlace, 1839):

$$P_c = \frac{2\sigma\cos\theta}{r} \tag{1}$$

Where: σ is the interfacial tension,
θ is the contact angle between the liquid and solid surface, and
r is the mean or effective pore radius.

Capillary pressure plays a more important role in unconventional gas wells. Unconventional reservoirs are characterized by ultra-low permeability, which means effective pore throat radius is very small. As we can see from the LaPlace-Young equation, a small pore radius r means high capillary pressure. So when conducting cleanup in an unconventional gas well, there will exist high resistant force against frac fluid's flowing-back, not to consider the effects of interfacial tension and contact angle. If we run into a situation where the interfacial tension between frac fluid and reservoir gas is high and/or the contact angle is small which means strong water-wetting, then the capillary pressure effects are even more difficult to tackle.

Effects of Poor Cleanup on Well Productivity

Water Blockage

Water blockage is the result of water trapping after stimulation operations in low permeable portions of a reservoir. In this situation, the aqueous phase is trapped in the pore throats by capillary pressure. Then the production of hydrocarbon fluids cannot be commenced before the trapping water is mobilized. The case where oil/gas production cannot proceed because of trapped water is called water blockage.

Mechanical Damage

In this work, mechanical damage effects are mainly characterized by a reduction of absolute permeability caused by clay swelling, fine/broken gel migration, polymer solids deposition near the fracture face, etc (Ding et al., 2012). All these effects including clay swelling are triggered by the fracturing fluid-solid incompatibility or interactions; so as long as we do not clean frac fluids up, the absolute permeability will be impaired even into long-term production. Once the absolute permeability is decreased, not only hydrocarbon fluids will flow in a much slower rate, but also a much higher capillary pressure will come into presence due to effective pore radius reduction. This in turn will lead to much higher resistant force for hydrocarbon fluids as well as fracturing fluid itself to flow.

Decrease of Gas Relative Permeability

In gas well production, the increase of water saturation will have a direct effect on the mobility of the gas phase; and particularly in unconventional gas formations gas relative permeability will decline strongly when water saturation increases (Ding et al., 2012). For example, it has been reported (Ford et al., 1988) that by injecting water into high-clay-content core samples, the normal relative gas permeability at 40% water saturation is ~0.82 while it will drop rapidly to ~0.35 when water saturation increases to 60% (Fig. 1). And this impairment of gas relative permeability will influence production performance in a long time unless really good cleanup practice can be conducted to get rid of the load water in the invaded zone.

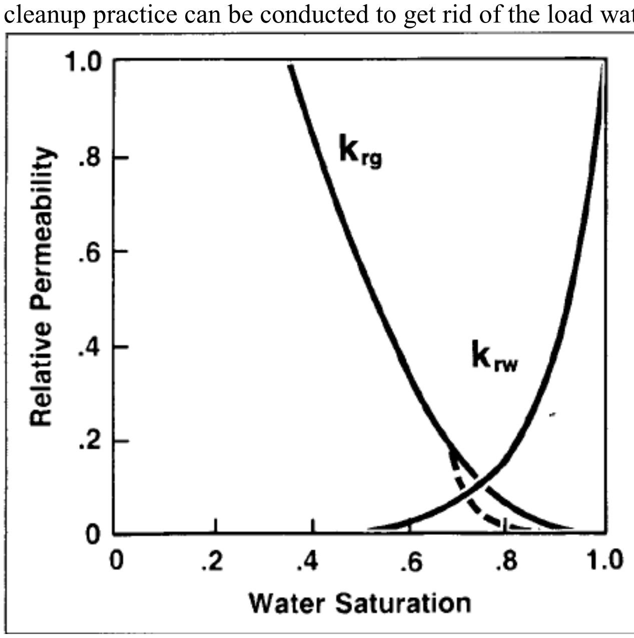

Fig. 1 – Relative permeability to gas as a function of water saturation (from Ford et al., 1988).

Methods of Reducing Capillary Pressure

As discussed above, the post-fracturing cleanup is restricted by high capillary pressure – so we will focus our efforts finding ways to approach low (the best case would be zero) capillary pressure to promote efficient well cleanup. And methods for gas and oil wells will be discussed separately.

Gas Well Cleanup

<u>Interfacial Tension Lowering</u>

In order to decrease the capillary pressure, we can lower the interfacial tension between gas and water. This value can be decreased by 2-3 folds to 20-30 dynes/cm using conventional surfactant. Although the absolute value of this changing seems to be significant, it still might not be sufficient to allow the return of aqueous frac fluid from unconventional gas reservoirs (Penny et al., 1983).

Control of Effective Pore Radius

As frac fluid is pumped down into the fracture and imbibing into the rock matrix, the effective pore radius will decrease due to the effects of fine migration, clay swelling, etc. This reduction of pore radius will result in an increase of capillary pressure. Control of pore radius can be achieved by using dehydrating solvents such as methanol and isopropanol adding into the treatment fluid. Basically, the mechanism is that dehydrants will disrupt the water layer that contributes to channel (pore throat) constrictions. However, there is one disadvantage related to this method: the dehydrating effect offered by dehydrants is temporary – after some time, the water layer can reconstruct itself.

Contact Angle Alteration

Another variable we can use to change the capillary pressure is contact angle. Contact angle is the mathematical description of wettability, and it is the most important factor in reducing capillary pressure and enhancing cleanup. One obvious reason is that in LaPlace-Young equation, contact angle's effect is acting through a cosine function, which means that we can render the whole capillary pressure term to zero (contact angle equals 90 degrees). Other reasons would be limited effect of interfacial tension lowering, and dehydrating solvents' effect to be temporary, as discussed above.

To negate capillary pressure, we should achieve a contact angle of 90 degree. In this case, the surface which is in contact with water and gas is called non-wet, that is, neither wetted by water nor gas. In the field, polymer additives (e.g. flexible polymer) are typically used to alter the contact angle. This approach is attractive in that not only capillary pressure can be lowered, but the buildup of water layer around the pore can be deterred as well, which means there will be no more blockage of hydrocarbon flow channels (Penny et al., 1983).

Oil Well Cleanup

The oil well cleanup scenario involves a liquid-liquid-solid interaction, instead of the gas-liquid-solid situation in gas well cleanup. This makes oil well cleanup require special considerations and there are more factors to be accounted for.

Interfacial Tension Lowering

Surfactants are still the candidate to lower interfacial tension. However, for oil well, special attention should be paid that surfactants may promote emulsification, in which situation one liquid is dispersed in the other and they are immiscible. According to Jamin effect, a stable dispersed system of water in oil or oil in water will lead to reduction of relative permeability. A corresponding solution is that non-emulsification surfactants can be chosen as options.

Control of Effective Pore Radius

There is not much difference between oil and gas well cleanup in respect of pore radius controlling. Similarly, we still resort to an alcohol additive to achieve radius controlling.

Contact Angle Alteration

The overriding factor for oil well cleanup is also contact angle. We have to differentiate waterflood and cleanup situations to choose the optimum contact angle, which is explained as follows.

We first have a look at the relationships for relative permeability vs. water saturation and contact angle (Fig. 2).

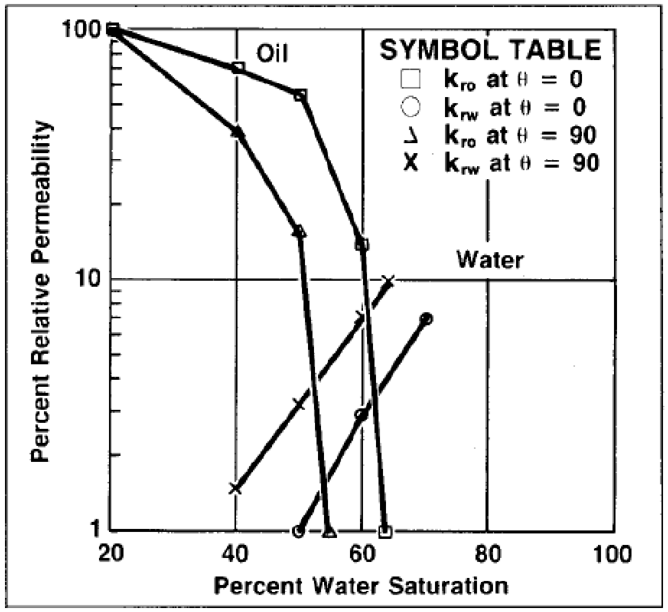

Fig. 2 – Relative permeability vs. water saturation for various contact angles (from Owens and Archer, 1971).

As we can see from Fig. 2, when θ equals zero which means the formation is strongly water-wetting, the relative permeability to oil far exceeds the relative permeability to water. This situation is considered favorable in waterflooding. However, in post-fracturing well cleanup, the oil will tend to break through quickly leaving behind a large percentage of fracturing fluid and high water saturation (Penny et al., 1983). This situation can be illustrated by Fig. 3. In this case, cleanup efficiency is especially poor and relative permeability to oil is low, thus leading to unsatisfactory production results. Things get even worse if we use cross-linked gel as fracturing fluid, since polymer in frac fluid will take up much porous space and majority of channels. Production rate will continue to be low until water saturation is diminished with time.

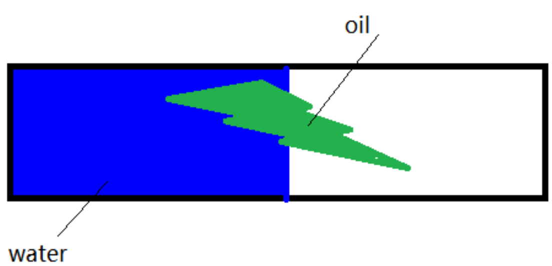

Fig. 3 – Illustration of oil breaking through when θ = 0° in post-fracturing well cleanup

Another case would be θ equals 90 degrees, which means the formation is neither wetted by oil nor water. As we can see from Fig. 2, the relative permeability to water can be higher than oil in the invaded zone; or for a certain range of water saturation, the relative permeability to oil is similar as that to water. Therefore, the oil will not break through rapidly but rather displace the non-wetting fracturing fluid phase in a piston-like manner (Lefebvre du Prey, 1973). This scenario can be illustrated by Fig. 4. This recovery mechanism results in the rapid return of a large percentage of fracturing fluid. In the meantime, it leaves water saturation low and thus the relative permeability to oil is higher. Cleanup efficiency in this case will be much higher which leads to improved production results.

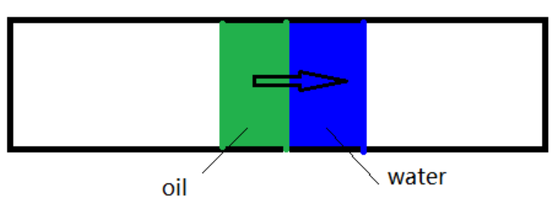

Fig. 4 – Illustration of oil displacing load water in a piston-like manner when θ = 90° in post-fracturing well cleanup

Future Work

Additives for Altering the Surface Activity

It was not until two years ago since microemulsion (ME) system was introduced to cleanup practice in petroleum industry. Compared to conventional surfactants (CS) such as aliphatic ethoxylate (AE) and cationics (CAT), ME is "a thermodynamically stable combination of surfactant, solvent/oil/cosolvent and water" (Paktinat et al., 2006) and offers much better cleanup performance. The effectiveness comparison of situations with no surfactant, CS and ME system has been reported (Paktinat et al., 2006) and can be seen from Fig. 5.

As cleanup characteristics are formation-dependent and well-dependent, future work is focused on optimizing the compositions of ME system for a certain producing field.

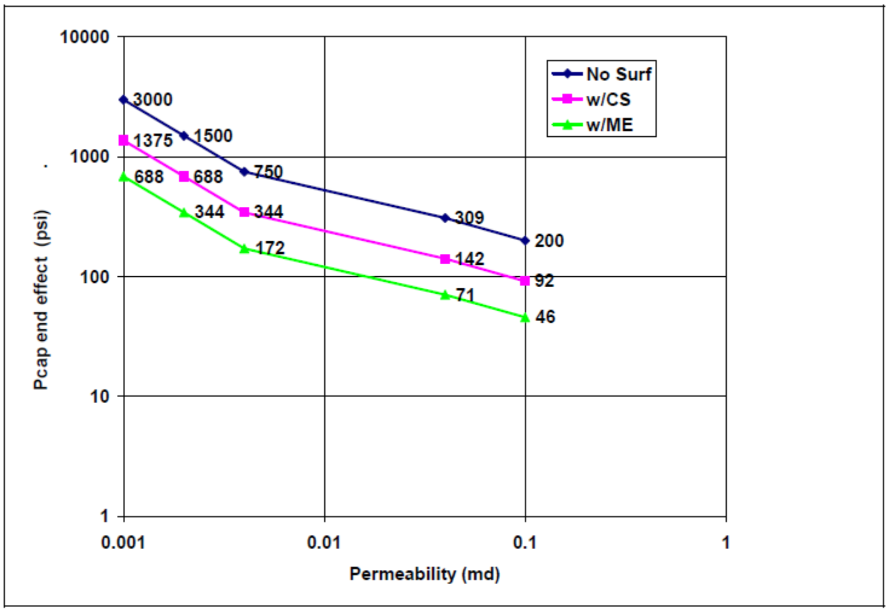

Fig. 5 – Capillary end effect vs. permeability with no surfactant, conventional surfactant (CS) and microemulsion (ME) (from Paktinat et al., 2006)

Dynamic Contact Angle Measurement

Before investigating the necessity of measuring dynamic contact angle, an examination of the concept of static and dynamic contact angle is in order.

Generally, dynamic contact angle can be further categorized into advancing and receding contact angles, which differ substantially from static contact angles. While the advancing contact angle describes the dynamic contact angle of a fluid (wetting phase) invading a surface, known as imbibition, the receding contact angle describes the dynamic contact angle of a fluid (wetting phase) that is displaced from the surface, which is most appropriate for well cleanup scenario. There can be a large hysteresis between the two dynamic contact angles with the static contact angle (Pagels et al., 2012).

As cleanup is no doubt a dynamic process which involves fluid-solid interactions, the dynamic contact angle measurements should be better and more convincible than static goniometer measurements which are presently used in the industry. To design the treatment fluids which contain optimum types and amounts of the additives for a given producing field, reliable dynamic contact angle information is a prerequisite. Adopting a modified Washer method (Pagels et al., 2012) is an option and future work should be aimed at finding out a cost-effective method of measuring dynamic contact angle.

Conclusions

It has been found that capillary pressure acts as resistant force during post-fracturing well cleanup. Zero capillary pressure can be achieved by altering water/solid contact angle to 90^o (a non-wetting state). And for oil well cleanup, a 90^o contact angle allows oil to displace fracturing fluid in a piston-like manner, which helps rapid cleanup. The reservoir and field-specific ME system is to be researched and dynamic contact angle is more appropriate than static contact angle when investigating cleanup process. Once we have reliable dynamic contact angle information, it is possible that treatment fluids can be designed that contain optimum types and amounts of additives for a given rock/reservoir.

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