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Effect of Ceramic Proppant Surface Wettability on Oil Flow Efficiency in Hydraulic-Fractured Wells

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ABSTRACT: *Ceramic proppants are key products for enhancing oil and gas well productivity in low-permeability reservoirs. However, they are not all created equal in size, material, and surface properties. The effects of proppant size and materials on oil and gas well productivity have been well studied in the past, but the role of proppant surface property in the performance improvement of oil and gas wells has not been thoroughly investigated. Nine experiments were conducted in this study to investigate the effect of wettability of ceramic proppant on the oil flow efficiency from core samples to "fractures" filled with the proppant in this study. Result of this shows that oil-wet ceramic proppant promotes oil flow efficiency from sandstone core samples to proppant packs and thus should promote oil well productivity. The mechanism behind this phenomenon is believed to be the formation of oil flow channels across the fracture face due to the imbibition of oil in the core onto the oil-wet surface of the proppant, promoting oil flow from the core to the fracture. Oil-wet proppant is more effective in improving oil flow efficiency in low-water saturation cores than in high-water saturation cores. Using larger size of oil-wet proppant helps improve oil flow efficiency. This may be explained by the more significant effect of adhesion/affinity of oil to the narrow corners of the solid surface in large-size proppant packs.*

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I. INTRODUCTION

Ceramic proppants are key products for enhancing oil and gas well productivity in low-permeability reservoirs. However they are not all created equal in size, material, and surface properties (Saldungaray and Palisch, 2013). The effects of proppant size and materials on oil and gas well productivity have been well studied in the past (Economides and Nolte, 2000; Vincent, 2002;Liang et al., 2015). However the role of proppant surface property in the performance improvement of oil and gas wells has not been thoroughly investigated. The key surface property of ceramic proppant affecting fluid flow efficiency is the wetting behavior which is often quantified by a parameter called contact angle measured in the wetting phase. In a water-oil system a solid surface is called strongly water-wet if the contact is approach 0 and strongly oil-wet if the contact angle is approach 180 degrees. A contact angle of around 90 degrees implies an intermediate wetting condition. A solid surface made of both water-wet and oil-wet materials is called mixed-wet surface.

The effect of solid surface wettability on oil recovery efficiency form oil reservoir was first investigated in late 1969's and early 1970's. Donaldson et al. (1969) demonstrated that water breakthrough and oil recovery from waterflood depend on core sample wettability.Anderson (1986a, 1986b, 1986c, 1987a, 1987b)presented a series of literature survey that summarizes the effects of wettability on fluid flow in porous media. It was pointed out that wettability affects relative permeability by controlling the flow and spatial distribution of fluids in a porous medium. In uniformlywetted systems, the effective oil permeability ata given initial water saturation decreases as the wettability is variedfrom water-wet to oil-wet. In fractionally wetted sandpacks, where the size of the individualwater- and oil-wet surfaces are on the order of a single pore,relative permeabilities appear to be similar to those in uniformlywetted systems. Wang (1988) found that during waterflood, a strongly water-wet core ceases to produce oil as soon as water breaks through, while a mixed-wettability core continuously produces oil for many PV's, resulting in a very low residual oil saturation.Dubey et al. (1991) investigated wettability alteration due to asphaltene adsorption and desorption from mineral surfaces. Humphry et al. (2014) analyzed the impact of wettability on residual oil saturation and capillary desaturation.Abdallah et al. (2017) presents a thorough review onapplications of wettability concept in oil field.

In the area of hydraulic fracturing, Mora at el. (2010) studied the dependence of hydraulic fracture conductivity on the proppant wettability.Interestingly, his result shows opposite to the experimental work by Donaldson et al. (1969). Such discrepancy was explained by the significant difference in absolute permeabilities of reservoirrocks and proppantpacks. In porous media with very high permeability, such asproppant packs and the bead packs used in this investigation, wettability becomes a lessrelevant factor in determining the fate of fluid mobility when compared with permeability. Large amounts of fracturing fluids left in the hydraulic fractures may leak-off into the porous formation or block part of the proppant pack thus impairing hydrocarbon production. A typical frac-pack treatment fluid contains water-wetting surfactants to maximize flow-back fluids. RecentlyBestaoui-Spurr et al. (2017)and Bestaoui-Spurr (2018) investigated the effect of proppant wettability on the flowback recovery and flow in frac-packs. Laboratory studies were conducted to compare neutral wettability to native proppant surfaces. Results showed that the neutral wettability surfaces not only reduce water saturation in the fracture but also improve oil movement. When this proppant was applied in frac-pack completions it was observed that flow-back recovery was dramatically increased compared to offset wells that used similar proppant. Furthermore, well production data showed that oil flow that the productivity index is higher when the surface of the proppant is neutral.

The effect of proppant wettability on fractured well performance has only been studied in limited conditions including one proppant size range, and one fluid type, and low water-saturation condition. The objective of this study was to determine the effects of proppant size range and type of fracturing fluid on the oil flow efficiency in low and high water-saturation conditions.

II. EXPERIMENTS

Test Apparatus. Experimental investigations were carried out using a 2-foot long core holder assembly shown in **Figure 1**. A section of a 2-inch diameter core sample with a fracture is shown in the left side of the image. A rubber sleeve for sealing core samples is seen at the top of the image. A cut off drawing of the core holder with surrounding connections is presented in **Figure 2**. As shown in **Figure 3**, inside the core holder is a core sample with a slot cut and filled with proppants, simulating a propped fracture.

Test Procedure. The experimental procedure is outlined as follows:

1. Measure the dimension and dry weight of a sand stone core sample.
2. Remove the air in the core sample by vacuum in a water chamber.
3. Measure the wet weight of the core sample and determine its porosity.
4. Transfer the wet core sample into the core holder, seal the core with confining pressure, inject water through the core, and determine core permeability.
5. Inject oil into the core till desired residual water saturation is reached.
6. Remove the core sample from the core holderand cut a slot in the axial orientation of the core to simulate a hydraulic fracture.
7. Fill the slot with proppant, transfer the core sample into the core holder, and seal the core with confining pressure.
8. Inject water and oil with deignedwater cut through the coreand record water and oil flow rates at the outlet.
9. Stop fluid injection when the effluent water cut reaches the water cut at the inlet.
10. Analyze the effluent water cut data to determine oil flow efficiency.

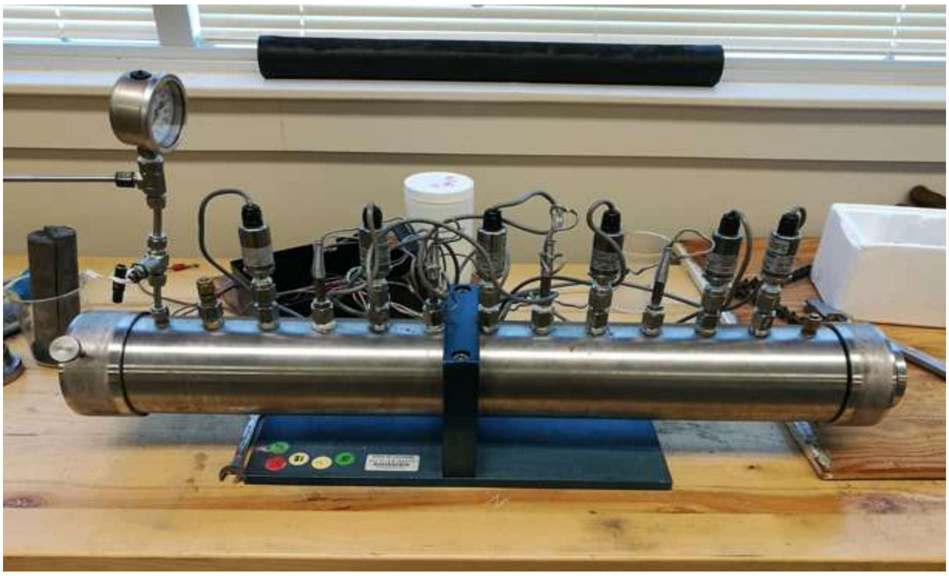

Figure 1: **Image of a 2-foot long core holder**

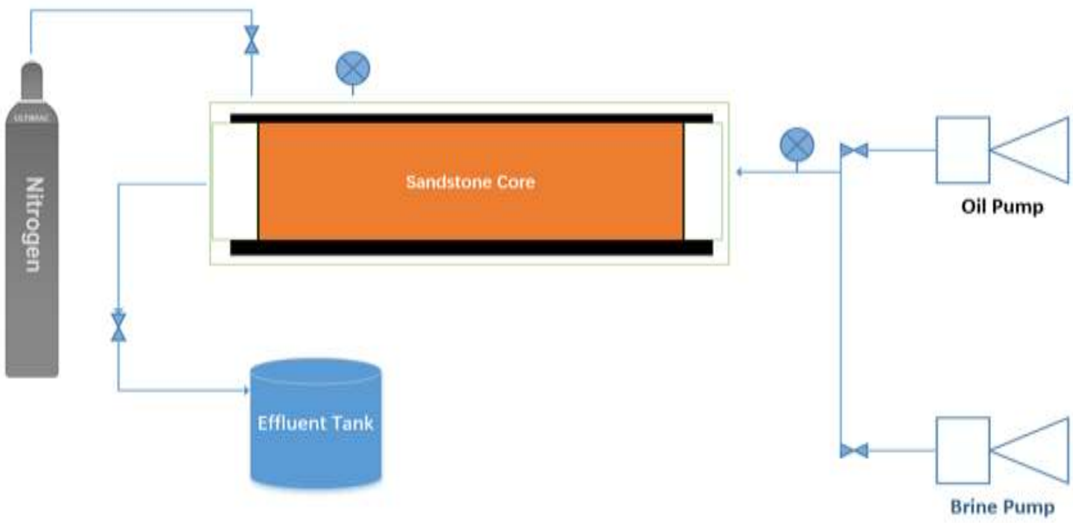

Figure 2: A schematic drawing the of core holder with surrounding connections

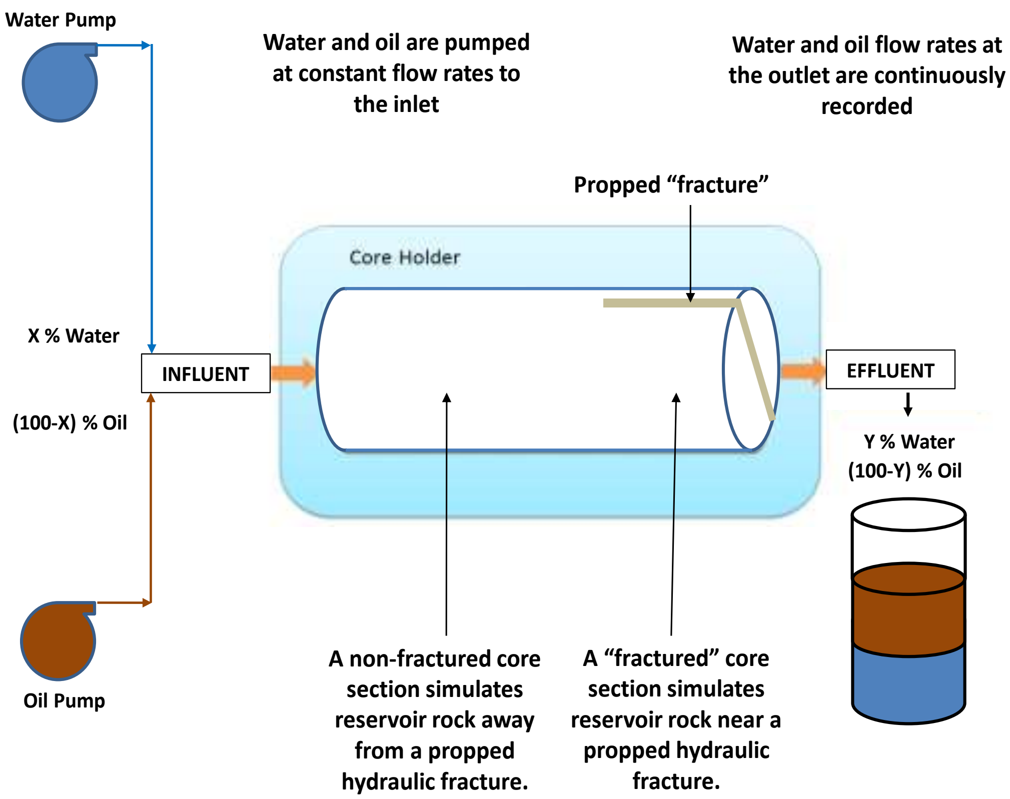

Figure 3: A flow diagram to show water-oil 2-phase injection

Test Materials. The materials used in the experiments include:
1. Parker Berea sandstone cores
2. CC20/40 "water-wet", 20/40 "oil-wet", and SL12/18 "oil-wet" proppants
3. 48~50^{o} API gravity crude oil
4. Tap water.

where the CC and SL are used for denoting the manufacturers of proppants to avoid the issue of commercial promotions in this paper.

The proppant samples were checked for their wetting property upon receiving from their providers. **Figure 4** shows two images of the CC20/40 “water-wet” proppant after droplets of water and oil were placed to their surfaces. Both water and oil were absorbed by the proppant immediately, indicating neutral-wetting surfaces of the proppant. **Figure 5** presents two images of the CC20/40 “oil-wet” proppant after droplets of water and oil were placed to their surfaces. Water was not absorbed by the proppant immediately and oil was absorbed by the proppantimmediately, indicating oil-wetting surfaces of the proppant. **Figure 6** demonstrates two images of the SL12/18“oil-wet” proppant after droplets of water and oil were placed to their surfaces. Water was not absorbed by the proppant immediately and oil was absorbed by the proppantimmediately, indicating oil-wetting surfaces of the proppant.

(a) Water was absorbed by the proppant immediately, indicating water-wetting surface of the proppant.

(b) Some oil was absorbed by the proppant, indicating certain degree of oil-wetting behavior of the proppant surface.

Figure 4: **Wettability check of the CC 20/40 “water-wet” proppant**

(a) Water was not absorbed by the proppant immediately, indicating non-water-wetting surface of the proppant.

(b) Oil was absorbed by the proppant immediately, indicating oil-wetting surface of the proppant.

Figure 5: **Wettability check of the CC 20/40 “oil-wet” proppant**

(a) Water was not absorbed by the proppant immediately, indicating non-water-wetting surface of the proppant.

(b) Oil was absorbed by the proppant immediately, indicating oil-wetting surface of the proppant.

Figure 6: **Wettability check of the SL12/18"oil-wet" proppant**

Experimental Design. Nine experiments were designed to investigate oil flow efficiency in ceramic proppants of different sizes and wettability under low and high-water saturation "reservoirs" conditions. They are:

1. CC 20/40 "oil-wet" proppantwith 40% water-cut two-phase injection
2. CC 20/40 "water-wet" proppant with 40% water-cut two-phase injection
3. CC 20/40 "oil-wet" proppantwith 70% water-cut two-phase injection
4. CC 20/40 "water-wet" proppant with 70% water-cut two-phase injection
5. CC 20/40 "oil-wet" proppantwith oil injection followed by 40% water-cut two-phase injection
6. CC 20/40 "water-wet" proppant with oil injectionfollowed by 40% water-cut two-phase injection
7. SL 12/18 "oil-wet" proppant with oil injection followed by 40% water-cut two-phase injection
8. CC 20/40 "oil-wet" proppantwith oil injection followed by 70% water-cut two-phase injection
9. CC 20/40 "water-wet" proppantwith oil injectionfollowed by 70% water-cut two-phase injection

III. RESULT

Experiment 1: 20/40 "Oil-Wet"Proppant with 40% Water-Cut Two-Phase Injection

This experiment was designed to investigate the oil flow efficiency in oil-wet proppant packs in low-water saturation oil reservoirs. A 22-inch long 2-inch diameter Parker Berea sand stone core was first testedto obtain porosity of 22.4% and water permeability of 14.92 md. The core was then taken out from the core holder. A slot of 6-inch long and 0.15-inch wide was cut and filled with 25 grams of CC 20/40 "oil-wet" proppant. The core was then transferred back to the core holder and sealed with confining pressure. Water and oil were injected into the core sample at 4 ml/min of water and 6 ml/min of oil, i.e., the water cut in the influentis 40%.The received water and oil in the effluent were continuously recorded as the injection time went on. The water cut in the effluent is plotted in **Figure 7.**It indicates that the water-cut in the effluent dropped quickly, fluctuated, and approached to the influent water cut of 40%.

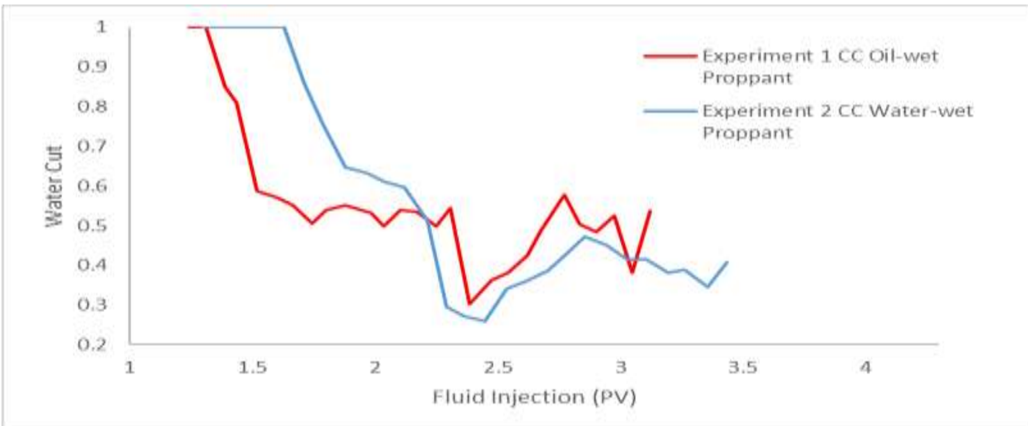

Figure 7:Comparison of 20/40 "oil-wet" proppant and 20/40 "water-wet" proppant with 40% water cuttwo-phase injection

Experiment 2: 20/40 "Water-Wet"Proppant with 40% Water-Cut Two-Phase Injection

This experiment was designed to investigate the oil flow efficiency in oil-wet proppant packs in low-water saturation oil reservoirs. A 22-inch long 2-inch diameter Parker Berea sand stone core was first tested for porosity and permeability with water. The porosity and water permeability were found to be of 22.6% and13.16 md, respectively. The water-saturated core was cut a slot of 6-inch long and 0.10-inch wide and the slot was then filled with 22 grams of CC 20/40 "water-wet" proppant. The core was then transferred to the core holder and sealed with confining pressure. Water and oil were injected into the core sample at 4 ml/min of water and 6 ml/min of oil, i.e., the water cut in the influent is 40%. The received water and oil in the effluent were continuously recorded as the injection time went on. The water cut data in the effluent is also plotted in **Figure 7**. The effluent water-cut dropped from the initial value of 100% and gradually approached the influent water cut of 40%. A comparison of the two curves in Figure 7 indicates that the effluent water-cut from the "oil-wet" proppantin Experimental 1 dropped faster than that from the "water-wet" proppant in Experiment 2, before they reached the influent water cut. This implies that the "oil-wet" proppant promoted oil flow and hindered water flow in low water-sturation conditions.

Experiment 3: 20/40 "Oil-Wet"Proppant with 70% Water-Cut Two-Phase Injection

This experiment was designed to investigate the oil flow efficiency in oil-wet proppant packs in high-water saturation oil reservoirs. A 22-inch long 2-inch diameter Parker Berea sand stone core was first tested to obtain porosity of 14.1% and water permeability of 12.99 md. A slot of 6-inch long and 0.15-inch wide was cut and filled with 21 grams of CC 20/40 "oil-wet" proppant. The core was then transferred into the core holder and sealed with confining pressure. Water and oil were injected into the core sample at 7 ml/min of water and 3 ml/min of oil, i.e., the water cut in the influent is 70%. The received water and oil in the effluent were continuously monitored as the injection time went on. The effluent water cut data is plotted in **Figure 8.** It indicates that the water-cut in the effluent dropped quickly, fluctuated, and approached to the influent water cut of 70%.

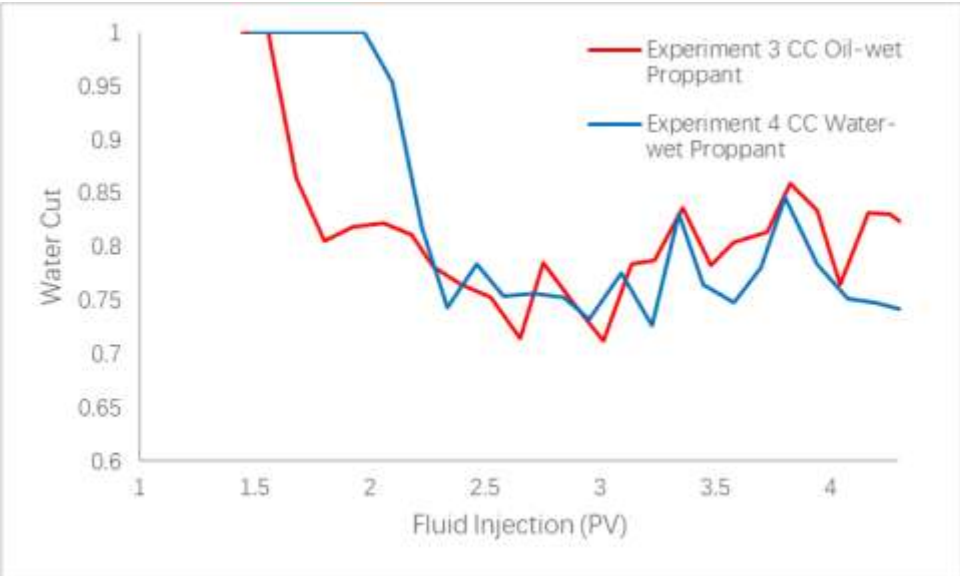

Figure 8:Comparison of 20/40 "oil-wet" proppant and 20/40 water-wet proppant with 70% water cuttwo-phase injection

Experiment 4: 20/40 Water-Wet Proppant with 70% Water-Cut Two-Phase Injection

This experiment was designed to investigate the oil flow efficiency in water-wet proppant packs in high-water saturation oil reservoirs. A 22-inch long 2-inch diameter Parker Berea sand stone core was first tested for porosity and permeability. The result is of 15.1% porosity and 13.40 md water permeability. A slot of 6-inch long and 0.10-inch wide was cut and filled with 19 grams of CC 20/40 "water-wet" proppant. The core was then transferred into the core holder and sealed with confining pressure. Water and oil were injected into the core sample at 7 ml/min of water and 3 ml/min of oil, i.e., the water cut in the influent is 70%. The received water and oil in the effluent were continuously monitored and recorded as the injection time went on. The effluent water cut data is also plotted in **Figure 8.**The effluent water-cut dropped from the initial value of 100% and gradually approached the influent water cut of 70%. A comparison of the two curves in Figure 8 indicates that the effluent water-cut from the "oil-wet" proppantin Experimental 3 dropped faster than that from the "water-wet" proppant in Experiment 4, before they reached the influent water cut. This implies that the "oil-wet" proppant promoted oil flow and hindered water flow in high water-cut conditions.

Experiment 5: 20/40 "Oil-Wet"Proppant withOil InjectionFollowed by40% Water-Cut Two-Phase Injection

This experiment was designed to investigate the oil flow efficiency in oil-wet proppant packs in virgin oil reservoirs at early time of water flooding. A 22-inch long 2-inch diameter Parker Berea sand stone core was first tested to obtain porosity of 13.1% and water permeability of 14.73md. A slot of 6-inch long and 0.15-inch wide was cut and filled with 21 grams of CC 20/40 "oil-wet" proppant. The core was then transferred to the core holder and sealed with confining pressure. Oil was first injected into the core sample at 10 ml/min to achieve an initial water saturation of 0.3284. Water and oil were then injected into the core sample at 4 ml/min of water and 6 ml/min of oil, i.e., the water cut in the influent is 40%. The received water and oil in the effluent were continuously recorded as the injection time went on. The water cut in the effluent is plotted in **Figure 9.** It indicates that the water-cut in the effluent severely fluctuated. The reason is not known.

Experiment 6: 20/40 "Water-Wet"Proppant withOil InjectionFollowed by40% Water-Cut Two-Phase Injection

This experiment was designed to investigate the oil flow efficiency in water-wet proppant packs in virgin oil reservoirs at early time of water flooding. A 22-inch long 2-inch diameter Parker Berea sand stone core was first tested for porosity and permeability with water. The porosity and water permeability were found to be of 16.3% and14.67 md, respectively. The water-saturated core was cut a slot of 6-inch long and 0.10-inch wide and the slot was then filled with 26 grams of CC 20/40 "water-wet" proppant. The core was then transferred to the core holder and sealed with confining pressure. Oil was first injected into the core sample at 10 ml/min to achieve an initial water saturation of 0.3223. Water and oil were injected into the core sample at 4 ml/min of water and 6 ml/min of oil, i.e., the water cut in the influent is 40%. The received water and oil in the effluent were continuously recorded as the injection time went on. The water cut data in the effluent is also plotted in **Figure 9**, which shows that the water-cut in the effluent slightly fluctuated around the influent water cut of 40%. A comparison of the two curves in Figure 9 indicates that the level of effluent water cut for the oil-wet proppant seems lower in average than that for the water-wet proppant before they approach to the same influent water-cut 40%, meaning that the oil-wet proppant helps improve oil flow efficiency.

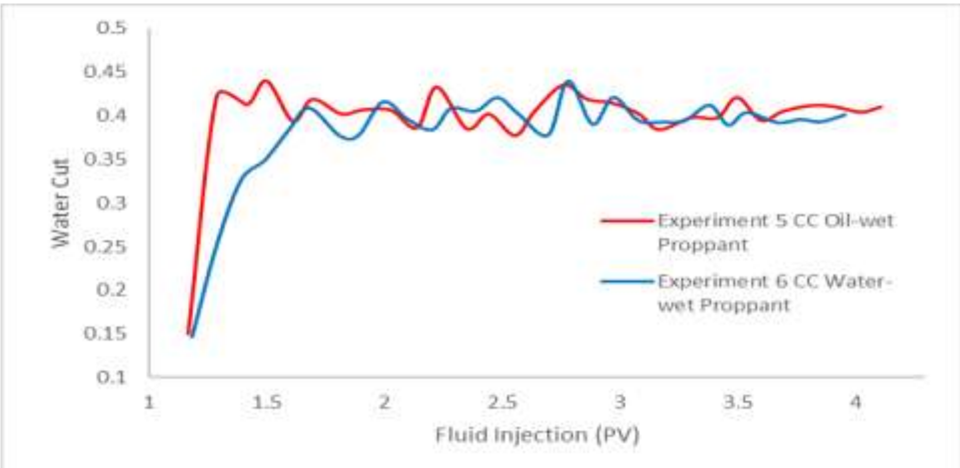

Figure 9:Comparison of 20/40 oil-wet proppant and 20/40 water-wet proppant with oil injectionfollowed by40% water Cuttwo-phase injection

Experiment 7: 12/18"Oil-Wet"Proppant withOil InjectionFollowed by40% Water-Cut Two-Phase Injection

This experiment was designed to investigate the effect of proppant size on the oil flow efficiency in oil-wet proppant packs in virgin oil reservoirs at early time of water flooding. A 22-inch long 2-inch diameter Parker Berea sand stone core was first tested for porosity and permeability with water. The porosity and water permeability were found to be of 15.0% and14.16 md, respectively. The water-saturated core was cut a slot of 6-inch long and 0.10-inch wide and the slot was then filled with 26 grams of SL 12/18 "oil-wet" proppant. The core was then transferred to the core holder and sealed with confining pressure. Oil was first injected into the core sample at 10 ml/min to achieve an initial water saturation of 0.3264. Water and oil were then injected into the core sample at 4 ml/min of water and 6 ml/min of oil, i.e., the water cut in the influent is 40%. The received water and oil in the effluent were continuously recorded as the injection time went on. The water cut data in the effluent is plotted in **Figure 10**, which shows that the water-cut in the effluent fluctuated before approach the influent water cut of 40%. Also plotted in the figure is the data from Experiment 5. A comparison of the two curves indicates that the level of effluent water cut for the 12/18 “oil-wet” proppant is slightly lower than that for the 20/40oil-wet proppant before they approach to the same influent water-cut 40%, meaning that using larger size of oil-wet proppant helps improve oil flow efficiency.

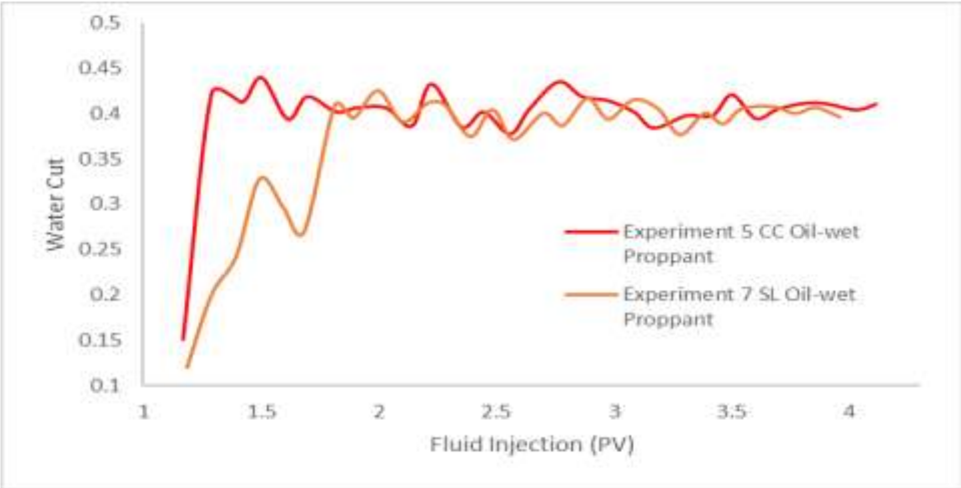

Figure 10:Comparison SL 12/18“oil-wet” proppant and CC 20/40 “oil-wet” proppant with oil injectionfollowed by40% water cuttwo-phase injection

Experiment 8: 20/40 “Oil-Wet”Proppant withOil InjectionFollowed by70% Water-Cut Two-Phase Injection

This experiment was designed to investigate the oil flow efficiency in oil-wet proppant packs in virgin oil reservoirs at late time of water flooding. A 22-inch long 2-inch diameter Parker Berea sand stone core was first tested to obtain porosity of 15.7% and water permeability of 13.22 md. A slot of 6-inch long and 0.1-inch wide was cut and filled with 27 grams of CC 20/40 “oil-wet” proppant. The core was then transferred to the core holder and sealed with confining pressure. Oil was first injected into the core sample at 10 ml/min to achieve an initial water saturation of 0.3210. Water and oil were then injected into the core sample at 7 ml/min of water and 3 ml/min of oil, i.e., the water cut in the influent is 70%. The received water and oil in the effluent were continuously recorded as the injection time went on. The water cut in the effluent is plotted in **Figure 11.** It indicates that the water-cut in the effluent dropped quickly and then gradually approached the influent water cut 70%.

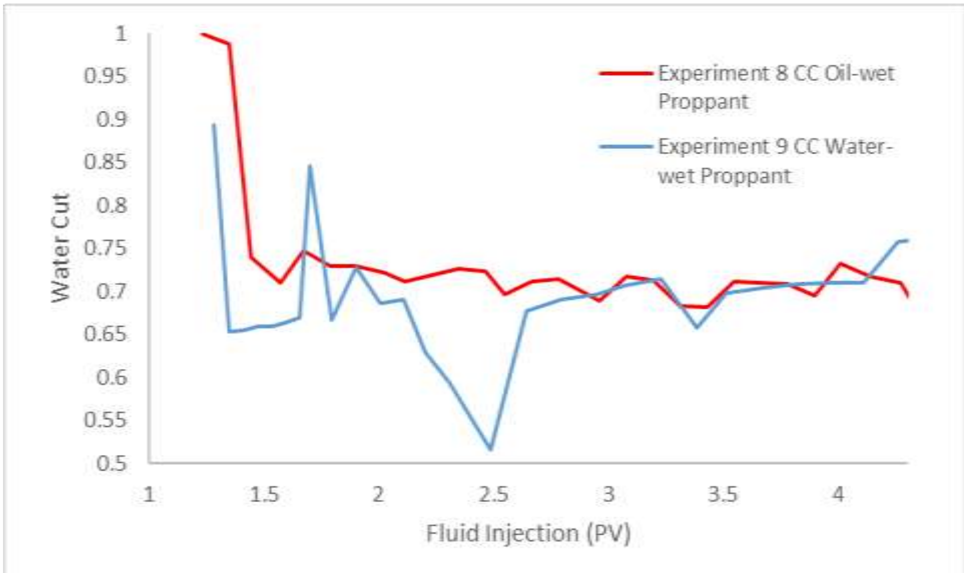

Figure 11: Comparison of 20/40 water-wet proppant and 20/40 oil-wet proppant with Oil InjectionFollowed by70% Water Cut Two-Phase Injection

Experiment 9: 20/40 “Water-Wet”Proppant withOil InjectionFollowed by70% Water-Cut Two-Phase Injection

This experiment was designed to investigate the oil flow efficiency in water-wet proppant packs in virgin oil reservoirs at late time of water flooding. A 22-inch long 2-inch diameter Parker Berea sand stone core was first tested for porosity and permeability with water. The porosity and water permeability were found to be of 16.1% and14.51 md, respectively. The water-saturated core was cut a slot of 6-inch long and 0.10-inch wide and the slot was then filled with 26 grams of CC 20/40 “water-wet” proppant. The core was then transferred to the core holder and sealed with confining pressure. Oil was first injected into the core sample at 10 ml/min to achieve an initial water saturation of 0.3162 Water and oil were injected into the core sample at 7 ml/min of water and 3 ml/min of oil, i.e., the water cut in the influent is 70%. The received water and oil in the effluent were continuously recorded as the injection time went on. The water cut data in the effluent is also plotted in **Figure 11**, which shows that the water-cut in the effluent fluctuated before reaching the influent water cut of 70%. A comparison of the two curves in Figure 11 indicates that the level of effluent water cut for the oil-wet proppant is similar to that for the water-wet proppant, meaning that the oil-wet proppant does not significantly improve oil flow efficiency in high water-saturation oil reservoirs.

IV. DISCUSSION

The result from this study shows that oil-wet proppant is favorable to improve oil flow efficiency from Berea sandstone to hydraulic fractures. Although this is consistent with the theory of oil relative permeability that increases with oil saturation that is promoted by oil wettability of solid surface, it is contradicting to the findings from two-phase flow in reservoir rock. Previous investigations with rock core samples has concluded that the effective oil permeability ata given initial water saturation decreases as the wettability is variedfrom water-wet to oil-wet (Donaldson et al.,1969;Anderson, 1987c; Wang, 1988). Thiscan be interpreted as the effect of adhesion/affinity of oil to the solid surface. In proppant packs where the void spaces are much larger than the pore spaces in rock core samples, the affinity effect may not be significance because the center of stream of oil flow is away from the solid surface. This was evidenced byMora at el.’s (2010) workwhere his result shows opposite to the experimental work by Donaldson et al. (1969). The discrepancy was explained by the significant difference in absolute permeabilities of reservoir rocks and proppant packs. In porous media with very high permeability, such as proppant packs and the bead packs, wettability becomes a less relevant factor in determining the fate of fluid mobility when compared with permeability. However, in our experimental studies, all core samples have similar permeabilities, suggesting that the difference in oil flow efficiency is due to proppant wettability. We interpret the effect of proppant wettability on the oil flow efficiency as the formation of oil channel at the fracture face. As illustrated in **Figure 12**,when water-wet proppant is used (Case A in the figure), the water in the core imbibes into the water-wet surface of the proppant, initiating a water flow channel between the two porous media and thus promoting water flow from the core to the fracture. When oil-wet proppant is used (Case B in the figure), the oil in the core imbibes into the oil-wet surface of the proppant, initiating an oil flow channel between the two porous media and thus promoting oil flow from the core to the fracture.

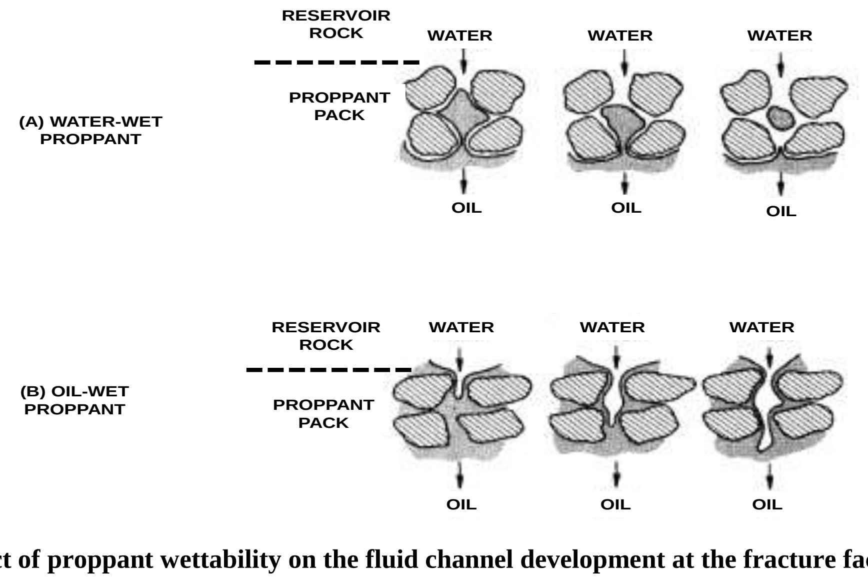

Figure 12: Effect of proppant wettability on the fluid channel development at the fracture face (Modified from Raza et al. 1968)

A comparison of Figures 7 and 8 indicates that the oil-wet proppant is more effective for improving oil flow efficiency in low-water saturation cores than in high-water saturation cores. This is also evidenced by a comparison of Figures 9 and 11. The mechanism behind it is not clear. Figure 10 implies that using larger size of oil-wet proppant helps improve oil flow efficiency. This may be explained by the more significant effect of adhesion/affinity of oil to the narrow corners of the solid surface in larger-size proppant packs.

V. CONCLUSIONS

Ten experiments were conducted to investigate the effect of wettability of ceramic proppant on the oil flow efficiency from core samples to "fractures" filled with the proppant in this study. Result of this allows for drawing the following conclusions:

1. Oil-wet ceramic proppant promotes oil flow efficiency from sandstone core samples to proppant packs and thus should promote oil well productivity. The mechanism behind this phenomenon is believed to be the formation of oil flow channels across the fracture face due to the imbibition of oil in the core onto the oil-wet surface of the proppant, promoting oil flow from the core to the fracture.
2. Oil-wet proppant is more effective in improving oil flow efficiency in low-water saturation cores than in high-water saturation cores. The principle behind it is not clear and needs more in-depth investigations.
3. Using larger size of oil-wet proppant helps improve oil flow efficiency. This may be explained by the more significant effect of adhesion/affinity of oil to the narrow corners of solid surface in small-size proppant packs.The mechanism is not clear and needs more in-depth investigations.

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