INTRODUCTION

Ceramic fracture proppants are extensively used for enhancing oil and gas well productivity in low-permeability reservoirs. The matrix/fracture interaction and its effect on well productivity and hydrocarbon recovery are described by Mao et al.,12 Longoria et al.,11 and Le et al.10 Zhang et al.18 and Zhu et al.19 give insights for understanding the mechanical behavior of proppants in hydraulic fractures. Among several fractures and proppant parameters to be optimized in fracturing
the impact of proppant’s surface wetting property on the behavior of oil and gas wells has also been observed in the energy industry but the mechanism behind it is not understood.

The water-oil 2-phase flow in homogeneous sandstones has been investigated for decades. The effect of sandstone surface wettability on oil recovery from oil reservoirs was first investigated in 1969. Anderson presented a summary of the effects of solid surface wettability on fluid flow in porous media. The conclusion is that sandstone surface wettability affects fluid relative permeability through spatial distribution of fluids in pore spaces. The effective oil permeability at a given initial water saturation decreases when the solid surface wettability is altered from water-wet to oil-wet. But Wang found that a strongly water-wet core ceases to produce oil as soon as water breaks through, while a mixed-wettability core continuously produced oil after water breakthrough, resulting in a very low residual oil saturation during waterflood. Humphry et al analyzed the impact of surface wettability on residual oil saturation and drawn a conclusion similar to that of Anderson. However, Mora et al’s study with fracturing proppants shows result that is opposite to what found in the experimental work with sandstone cores by Donaldson et al, that is, oil-wet proppant promotes oil flow in proppant packs. This tends to be consistent with Wang’s work. The investigations by Bestaoui-Spurr et al and Bestaoui-Spurr for the effect of proppant wettability on the water recovery during flowback and the flow in frac-packs in real wells show that neutral wettability surfaces reduce water saturation in the fracture and improve oil flow. Their findings seem to confirm the work of Mora et al. Apparently, the results from previous investigations about the effect of surface wetting property on oil flow are conflicting. More research work is needed to clarify this confusing issue.

Our interpretation about the discrepancy between the observations of the previous investigators is that the water-oil 2-phase flow from oil reservoir to hydraulic-fractured wellbore takes three steps: (a) flow from sandstone to the fracture surface, (b) flow across the fracture surface, and (c) flow through the proppant pack inside the fracture. For the flow in sandstone, the oil-wet surface of rock reduces oil flow in narrow pore spaces, as shown by Anderson’s work. For the flow in the proppant pack, the oil-wet surface of proppant promotes oil flow in large pore spaces, as shown by Mora et al’s work. For the flow across the fracture surface, oil-wet surface attracts oil and repels water from the sandstone, forming an oil channel across the fracture surface. The true effect of flow across the fracture face can be masked in the investigations by Bestaoui-Spurr et al and Bestaoui-Spurr where both sandstone reservoirs and hydraulic fractures are in much larger scale than the fracture faces.

Dong conducted a number of tests in small scale focusing on the interface between sandstone and proppant packs to study the effect of surface wettability of ceramic proppant on the oil flow efficiency from core samples to fractures filled with CC (code for major proppant provider) proppants. He observed that oil-wet proppant increased oil flow efficiency from sandstone to proppant packs. The mechanism is interpreted as the oil imbibition-induced oil flow channels across the sand-fracture interface. Dong et al investigated the effect of wettability of CC proppant surface in guar gum solution on the oil flow efficiency in fractures. They concluded that the residual guar gum in the fractures has negative effect on improving oil flow efficiency. Dong et al investigated the effects of oil-wet and mixed-wettability surfaces of ceramic proppants on the oil flow using SEM and energy-dispersive system and found that the resin-coated oil-wet proppant surface is much smoother than that of the mixed-wet proppant. Based on the result of oxide analysis, there is a layer of oleophilic materials which causes the oil affinity of the oil-wet proppants. However, the mixed-wet proppant presents dual affinity of oil and water due to capillary cohesion. They also concluded that the surface wettability plays a more essential role in determining the competing flow of oil and water in small size proppant than in large size proppant. As the proppant size increases, the effect of surface wettability on hydrogen transfer diminishes.

In summary, the effect of surface wettability of ceramic proppant on the completing flow of oil and water from sandstones to fractures is different from the effect of rock wettability on the oil flow in sandstone rocks. Oil-wet CC proppant has the attracting-oil-repelling-water (AORW) property that promotes oil flow from sandstones to fractures. The effects of proppant size, water content in the sandstone, and guar gum addition to the fracturing fluid have been studied with CC proppant. But, sandstones were not created equal and ceramic proppants are not made from the same materials. The effects of different sandstones on the effectiveness of oil-wet proppant from different proppant manufacturers in promoting oil flow have not been investigated. This work presents our result of studies of the effects of a new oil-wet proppant (from provider PC) on the completing flow of water and oil in two types of sandstones. We answer three questions in this study: (a) Does PC proppant have the same AORW effect to promote oil flow across the interface between sandstone and proppant pack? (b) If it does, is the AORW effect influenced by water content in the sandstone? (c) Does oil-wet proppant behave differently in different sandstones?

2 EXPERIMENTAL DESIGN

2.1 Test setup

The test apparatus employed in this study is similar to that used by Dong et al shown in Figure 1. The central component is a
2-foot long core holder assembly that uses confining gas pressure for tightening a rubber sleeve to seal a 2-in. diameter, 20-in. long, sandstone core sample. A 6-in.-long slot is cut along the diameter of the core to simulate a hydraulic fracture. The “fracture” is filled with proppant particles before testing.

### 2.2 | Test procedure

The experimental procedure is outlined as follows:

1. Measure the dimension and dry weight of a sandstone 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, calculate pore volume (PV) and core sample porosity.
4. Transfer the wet core sample into the core holder, seal the core with confining pressure, inject water through the core, and calculate core permeability.
5. Inject oil into the core until the desired water saturation is reached.
6. Remove the core sample from the core holder and cut a 6-in. “fracture” along the diameter of the core.
7. Fill the “fracture” with proppant particles, transfer the core sample into the core holder, and seal the core with confining pressure.
8. Inject pure water and oil with deigned water-cut \( x \) at 5 cc/min through the core and record water and oil flow volumes every 1 minute at the outlet.
9. Stop fluid injection when the effluent water-cut \( y \) reaches the influent water-cut \( x \).

### 2.3 | Measure of AORW effect

When a test is completed, the effluent water-cut data vs total fluid injection (in PV) are plotted to identify the fluid injection volume at the time of water breakthrough at outlet. In comparison of results from two tests with different proppants, the proppant that delays water breakthrough is identified to have the AORW effect. To ensure that the difference in water breakthrough time is not masked by test accuracy, the fluid volume reading was taken every 1 minute of fluid injection. The pore volume of most core samples is around 180 cc. Dividing the fluid injection, rate of 5 cc/min by 180 cc gives a test data accuracy of 0.028 PV/min. If the difference between water breakthrough times is less than 0.028 PV, no conclusion should be made.

### 3 | EXPERIMENTAL RESULT

Two base tests were conducted to determine the AORW effect of PC proppants followed by further testing to identify factors affecting the AORW effect.

#### 3.1 | Effect of proppant surface wetting property on AORW

PC water-wet and oil-wet proppants were tested in Parker Berea sandstone core samples. The proppants from PC include water-wet and oil-wet samples of both 20/40 and 40/80 meshes. Images of the 20/40 mesh proppants are presented in Figure 2 where (A) shows that water was absorbed by the
proppant immediately, indicating water-wetting surface of the proppant, and (B) indicates that oil was not absorbed by the proppant immediately, indicating non–oil-wetting surface of the proppant. Therefore, the proppant in gray color is water-wet. Figure 2C indicates that water was not absorbed by the proppant immediately, indicating non–water-wetting surface of the proppant, and (D) shows that oil was absorbed by the proppant immediately, indicating strong oil-wetting surface of the proppant. Therefore, the proppant in green color is strong oil-wet.

The test result is presented in Figure 3. For the PC 20/40 strong oil-wet proppant, the curve shows that water breakthrough occurred at nearly 0.57 PV. For the PC 20/40 water-wet proppant, the curve indicates that water breakthrough occurred at 0.35 PV. A comparison of these two values implies that water breakthrough occurred later by nearly 0.22 PV in the strong oil-wet proppant than in the water-wet proppant, indicating strong AORW effect of the strong oil-wet proppant.

3.2 Influence of water cut on the AORW effect of oil-wet proppant

The influence of water cut on the AORW effect of the PC 20/40 strong oil-wet proppant was investigated in the Parker Berea sandstone with fluid injection of 70% water cut. Figure 4 presents the effluents' water-cut data obtained for the strong oil-wet and water-wet proppants. It shows that water breakthrough occurred at about 0.2 PV for the water-wet proppant and water breakthrough occurred at about 0.35 PV for the
strong oil-wet proppant. That is, the strong oil-wet proppant delayed water breakthrough by 0.15 PV. Comparing this value with the 0.22 PV from the 40% water-cut tests reveals that the AORW effect of the strong oil-wet proppant decreased in the 70% water-cut sandstone.

3.3 Influence of sandstone type on the AORW effect of oil-wet proppant

The AORW effect of the strong oil-wet PC 20/40 proppant was investigated with Parker Berea and Upper Gray Berea sandstones with fluid injection of 40% water cut. Table 1 presents a summary of the Parker Berea sandstone core samples filled with proppants. The sandstone core samples have water permeabilities from 7 md to 14 md. Table 2 shows a summary of the Upper Gray Berea sandstone core samples filled with proppants. The sandstone core samples have water permeabilities from 62 md to 85 md. The test results are presented in Figure 5. It shows that the water breakthrough occurred at 0.44 PV of fluid injection in to the Upper Gray sandstone and the water breakthrough occurred at 0.54 PV of fluid injection in to the Parker sandstone. This implies that the strong oil-wet PC 20/40 proppant has higher AORW effect in low-permeability sandstones than in high-permeability sandstones.

### Table 1 Parker Berea sandstone core samples with different proppants

| PC proppants in Parker Berea sandstone cores | 20/40 water-wet | 20/40 strong oil-wet |
|---------------------------------------------|-----------------|---------------------|
| Geometry and property                       |                 |                     |
| Diameter (in.)                              | 2               | 2                   |
| Length (in.)                                | 24              | 22.25               |
| Dry weight (g)                              | 2641.4          | 2406.9              |
| Wet weight (g)                              | 2836.6          | 2584.8              |
| Proppant (g)                                | 24.3            | 24.1                |
| Fracture width (in.)                        | 0.1             | 0.1                 |
| Fracture length (in.)                       | 6               | 6                   |
| Porosity (%)                                | 15.80           | 15.53               |
| Permeability (md)                           | 14              | 7                   |
| Water saturation (%)                         | 45.4            | 45.7                |

4 RESULT DISCUSSION

This experimental study shows that oil-wet proppant has AORW effect on the water-oil two-phase flow from sandstones to fractures. The proppant's AORW effect drops with water cut in the sandstone. Oil-wet proppant behaves differently in different types of sandstones. It has better AORW
capacity in low-permeability sandstones. These phenomena maybe interpreted as follows.

Although this AORW effect 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. The mechanism of the oil-wet proppant promoting oil flow from sandstone to fractures may be interpreted by the theory of flow channels. As illustrated in Figure 6, there may exist channels for water and oil flow in sandstones. Figure 6A depicts a situation where water-wet proppants are used. Wherever a water-wet proppant particle contacts a water channel in sandstone, owing to the nonaffinity between the water-wet surface of proppant particle and the water in the channel, the particle surface will repel the water in the channel, resisting the water flow from the water channel to the fracture. Wherever an oil-wet proppant particle contacts an oil channel in the sandstone, owing to the affinity between the oil-wet surface and the oil in the oil channel, the surface will attract the oil, promoting the oil flow from the oil channel to the fracture.

Because there are more water channels in high water-cut sandstones than in low water-cut sandstones, the AORW effect of oil-wet proppant will be lower in high water-cut sandstones than in low water-cut sandstone. It is expected that there exist more oil channels in low-permeability sandstones than in high-permeability sandstones. This explains why oil-wet proppant has higher AORW effect in low-permeability sandstones than in high-permeability sandstones.

5 | CONCLUSIONS

The effects of oil-wet and water-wet fracture proppants on the competing flow of water and oil from Parker and Upper Gray sandstones to fracture were investigated in this study using PC (code for provider) proppants. The following conclusions are drawn:

1. Similar to the CC oil-wet proppants, the PC oil-wet ceramic proppants have the property of AORW effect on the water-oil two-phase flow from sandstones to proppant-packed fractures. This effect is attributed to the surface property of the oil-wet proppants. Wherever an oil-wet proppant particle contacts an oil channel in the sandstone, owing to the affinity between the oil-wet surface and the oil in the oil channel, the proppant surface will attract oil and repel water, promoting the oil flow from the oil channel in the sandstone to the fracture.
FIGURE 6 Effect of proppant surface wetting behavior on fluid flow from sandstone to fracture

2. The AORW effect of PC oil-wet proppant drops as the water cut in the sandstone increases. This is explained by the fact that there are more water channels in high water-cut sandstones than in low water-cut sandstones, reducing the chance for the oil-wet proppant to contact oil channels and attract oil.

3. The PC oil-wet proppant behaves differently in different types of sandstones. Its AORW effect is higher in low-permeability sandstones than in high-permeability sandstones. This may be because there are more oil channels in low-permeability sandstones than in high-permeability sandstones, increasing the chance for the oil-wet proppant to contact oil channels and attract oil.

ACKNOWLEDGMENT
The authors are grateful to PetroChina for its financial support to the project YL2017-001 “An Investigation of Oil Flow Efficiency under Different Fracture Conditions.”

ORCID
Dong Xiao https://orcid.org/0000-0002-9389-8002
Boyun Guo https://orcid.org/0000-0003-2086-5338

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How to cite this article: Xiao D, Wang M, Guo B, Weng D. Effect of surface wetting behavior of ceramic proppant on the two-phase flow across the interface of sandstone and fracture. Energy Sci Eng. 2020;8:1330–1336. https://doi.org/10.1002/ese3.595