Performance Evaluation of the Multifunctional Variable-Viscosity Slick Water for Fracturing in Unconventional Reservoirs

Erdong Yao, Hao Bai, Fujian Zhou,* Mengchuan Zhang, Jie Wang,* and Fuyuan Li

ABSTRACT: The traditional guar gum fracturing fluid system has the drawbacks of the fracturing process of unconventional oil and gas deposits, such as high drag resistance and large residuum harm, which is gradually replaced by the system of the slick water fracturing fluid. The conventional slick water system, however, still has the features of low sand-carrying capability. Therefore, high-viscosity slick water is often used in fracturing operations, but most of the high-viscosity slick water is difficult to prepare, dissolve, and break gels, which needs to be improved. Based on the abovementioned problems, a new type of multifunctional variable-viscosity slick water is proposed in this paper. The self-made loop drag test unit, a dynamic crack sand-carrying model, a multifunctional core flow device, and other equipment were used for testing, and a set of systematic evaluation methods for the performance of multifunctional variable-viscosity slick water are established. In addition, the mechanism of improving sand-carrying capacity and increasing viscosity and solubilization was explained through the macroevaluation experiment of polymer properties and the analysis of the polymer microstructure. The experimental results show that compared with high-viscosity slick water, the multifunctional variable-viscosity slick water has good drag-reducing performance, the drag-reducing rate can reach more than 75%; the intersection value of viscoelastic modulus is about 0.01 Hz, the sand carrying capacity is higher; the gel-breaking time is faster, the residue content is lower, 38.5 ppm; it has the characteristics of low harm, the harm rate to the core is 18.30%; and it also has the performance of enhancing oil recovery.

1. INTRODUCTION

Unconventional oil and gas reservoirs refer to hydrocarbon (or non-hydrocarbon) resources that are different from conventional oil and gas in terms of reservoir-forming mechanism, occurrence state, distribution law, exploration, development mode, and so forth. It mainly refers to shale gas, coal-bed methane, tight oil, tight sandstone gas, and gas hydrate. At present, a considerable part of conventional oil and gas deposits has been extracted. In comparison, the output of unconventional oil and gas deposits is negligible.1−3 According to research, unconventional oil and gas reservoirs are widely distributed in the world and it is necessary to enhance the exploitation of unconventional oil and gas reservoirs because it is the most potential oil and gas reservoirs in the world. However, from conventional oil and gas to unconventional oil and gas development, the technical requirements increase, the cost increases, and the development difficulty increases. The successful application of the fracturing fluid in shales in the 1990s gradually formed the concept of hydraulic fracturing.4,5 After years of field operation and laboratory experiments, it is generally considered that the slick water fracturing fluid is more suitable for the exploitation of unconventional oil and gas deposit resources and it is easy to form large-scale complex cracks. The slick water fracturing fluid is composed of drag-reducing agents combined with bactericide, clay stabilizer, cleanup additives, and other auxiliary agents to form a complete formulation system, which has a good drag-reducing effect.6,7 The drag resistance of the fluid restricts the flow of the fluid in the pipeline, resulting in low pipeline throughput and increased energy consumption. The polymer drag-reducing method is to inject a small amount of high-molecular hydrocarbon polymers into the fluid and reduce the drag resistance in the turbulent state. The chemical agent used to reduce the flow resistance in turbulent conditions is called the drag-reducing agent, which is a kind of non-Newtonian fluid viscous substance. It has an extremely long chain structure, which is soft and elastic. If it is a spiral structure, the molecular weight is more ideal. The general requirement is 10⁶ and above.8−10

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The traditional guar gum fracturing fluid, the conventional slick water, and the high-viscosity slick water all have their own advantages and disadvantages: most of the traditional fracturing fluid has a higher viscosity, strong sand-carrying capacity, less filtration, and good compatibility; however, the stability of the traditional fracturing fluid is poor, and the drag is difficult to control. For example, gelled fracturing fluids use cross-linking techniques to improve the sand-carrying capacity of fracturing fluids, the common cross-linking agents are borate (mainly borax) cross-linker, organic transition-metal cross-linker, organic boron cross-linker, organic zirconium cross-linker, and so forth, but the rate of cross-linking is affected by many factors.11–13 Besides, polymer resida can cause serious harm. The conventional slick water mainly plays the role of drag reducing, and it is easy to form long fractures and extend into a network of joints when fracturing, to enhance the conductivity. It has low harm to the formation, fast flow-back speed, less proppant consumption, and low construction cost.14–16 However, because the conventional slick water is used as the fracturing fluid by adding active water and other additives such as a drag-reducing agent, the sand-carrying capacity of the fracturing fluid is poor. Therefore, the sand-carrying capacity of the fracturing fluid with a high sand ratio cannot be used during the fracturing operation; otherwise, it will cause the proppant to settle and premature sand plugging. Although the pump speed and displacement can be increased, it is easy to increase the drag loss, and at the same time, the reservoir protection measures should be fully considered.17–19

The high-viscosity slick water has high-viscosity, good sand-carrying capacity, and also the effect of drag reduction. However, most high-viscosity slick water is difficult to prepare, often in the form of powder. However, powder products are difficult to mix online and are not easy to dissolve. Sometimes, because the polymer viscosity is too high, the structure is too stable, and since it is not easy to break, it will cause great harm to the reservoir.20–22

In summary, to overcome the shortcomings of the traditional fracturing fluid, conventional slick water, and high-viscosity slick water, new multifunctional variable-viscosity slick water is proposed in this paper, which overcomes the low sand-carrying characteristics of the traditional fracturing fluid, forms a higher sand ratio, and improves the stable production stability and time. The advantages of the high drag-reducing performance of the conventional slick water and the good sand-carrying capacity of the high-viscosity slick water are inherited and maintained and formed a high flow supporting slit network to increase output. At the same time, the slick water is emulsion-like, easy to dissolve, and realizes the whole process of online mixing. The construction process is simple, and it can achieve fast breaking and low residue content.23,24

At present, there are little research studies on multifunctional variable-viscosity slick water. Wang et al.25 developed a functional slick water system, which is composed of a liquid functional drag-reducing agent and regulator. The low concentration functional drag-reducing agent solution can be used as slick water, which can be rapidly thickened within 15 s. The drag-reducing rate of slick water is as high as 74% and the viscosity of the system increases rapidly with the addition of the regulator, and the sand-carrying ratio is high. Wang et al.26 developed a set of formula systems of HL-C3 slick water. Based on drag reduction, the system specially added a surfactant. The surfactant is injected into the formation along with the base liquid throughout the entire process. Under the function of the protective agent, it can eliminate formation harm such as water blockage and water sensitivity; at the same time, it can increase the wettablity of the rock, clean and displace the crude oil around the fracture, the crude oil on the rock, and the scale, thus improving the percolation ability of the crude oil. Based on the abovementioned research, a multifunctional variable-viscosity slick water system is introduced in this paper, which has the characteristics of both conventional high-viscosity slick water and imbibition displacement, as well as the multiple effects of fracturing and enhanced oil recovery, it can realize the integrated characteristics of increased production and enhanced oil recovery.

2. MATERIALS AND METHODS

2.1. Chemical Additive Selection. It primarily contains two types of additives: nanoemulsion and high-viscosity drag-reducing agent. The high-viscosity drag-reducing agent can be made into high-viscosity slick water, and the nanoemulsion can mix with the high-viscosity drag-reducing agent to produce multifunctional variable-viscosity slick water.

Among them, the nanoemulsion CNI-A is made of a polymer homogeneous microemulsion which is fully diluted by water or brine. The polymer containing a homogeneous microemulsion is composed of the following raw materials: 8–40 wt % surfactant, 0.5–10 wt % polymer, 10–30 wt % alcohol, 3–30 wt % oil, 0–20 wt % salt, and water allowance. The water can be distilled water or deionized water. The high-viscosity drag-reducing agent is CNI-B. The main active ingredients and content are 0.10 wt % chitosan, 0.05 wt % paraformaldehyde, and 0.2 wt % polyacrylamide with a hydrolysis degree of 10 wt %. It is emulsion-like, which can be directly formulated into high-viscosity slick water. In addition, the viscosity of the high-viscosity drag-reducing agent can be changed by increasing its concentration.

It is found that after mixing CNI-A and CNI-B, CNI-A can enhance the viscosity of CNI-B. Meanwhile, CNI-A enters the reservoir pores with the filtrate of the fracturing fluid, which can achieve the effect of imbibition replacement and wetting modification of crude oil and improve the crude oil recovery after the fracturing fluid.

2.2. Experimental Equipment. The performance evaluation and mechanism research of the multifunctional variable-viscosity slick water mixed with nanoemulsion CNI-A and high-viscosity drag-reducing agent CNI-B were carried out. The experimental equipment was mainly composed of a ZNN-D6 six-speed rotary viscometer, Haake RS6000 rheometer, visual crack model, loop drag test unit, Zetasizer Nano ZS laser nanoemulsion size meter, JEM 2100 LaB6 transmission electron microscope, filtration drying device, multifunction core flow device, wetting angle testing device, BZY-2 automatic surface and interface tension meter, and imbibition bottle.

The experimental process includes five aspects: rheological characteristics, sand-carrying and drag-reducing properties, micromechanism research, low harm property, and enhancing oil recovery (EOR) property test. In the rheological test, the corresponding concentration of slick water is prepared, the viscosity change is measured using a six-speed rotary viscometer, and the viscoelastic test is carried out with a rheometer. The visual fracture model and the loop drag test unit are used to test the dynamic sand-carrying and friction resistance separately. The micromechanism mainly studies the nanoemulsion size and microstructure, using the nano laser
emulsion size meter and transmission electron microscope, respectively. The low harm characteristics are mainly tested using a filtration drying device, and the harm rate is measured using a multifunction core flow device. Finally, the extraction includes measuring the change in wetting angle using a wetting angle measuring device, measuring the surface and interface tension with a surface and interface tension meter, and measuring the recovery rate of the imbibition recovery using the imbibition bottle.

2.3. Rheological Characteristic Test. The measurement of rheological characteristics mainly involves four indexes: the dissolution rate, the rising viscosity rate, the solution viscosity, and the solution viscoelasticity modulus of the multifunctional variable-viscosity slick water, reflecting the dissolution property and the increasing viscosity effect of the system.

2.3.1. Dissolution Rate and Rising Viscosity Rate. A total of 500 mL of distilled water was placed in an IKA six-speed magnetic stirrer, and CNI-A (0.00–0.10 wt %) and CNI-B (0.10 and 0.60 wt %) reagents were rapidly added at 1500 RPM (rotor magnetic stirrer diameter 5 cm, weight 21 g) and stirred evenly for 5 min and stopped, testing the slick water viscosity after 30 and 60 min with a ZNN-D6 six-speed rotary viscometer, respectively (at 25 °C and 100 RPM, i.e., 170.3 s⁻¹). 170.3 s⁻¹ usually represents the wellbore shear rate. At the same time, the time needed to fully dissolve the reagents without flocculating sedimentation was recorded and the corresponding speed of rotation was recorded.

2.3.2. Viscosity Test. The ZNN-D6 six-speed rotary viscometer was used to measure the viscosity at various concentrations of the slick water (0.00–0.10 wt % CNI-A and 0.00–0.80 wt % CNI-B), where the resulting viscosity at 100 RPM and 25 °C was the apparent viscosity of the solution, and the mean value was calculated three times at each concentration point. The viscosity is measured using eq 1

\[
\mu = \frac{0.511 \theta_N}{1.703N} \times 1000 = \frac{300 \theta_N}{N}
\]  

(1)

\(\mu\) refers to the apparent viscosity, mPa·s; \(\theta_N\) refers to the dial reading when the speed of the viscometer is \(N\); and \(N\) refers to speed, RPM.

2.3.3. Viscoelasticity Test. The elastic modulus reflects the polymer solution’s sand-carrying capacity, and the lower the intersection value of the viscous modulus and the elastic modulus, the greater the sand-carrying capacity of the corresponding solution. Consequently, the viscoelasticity of the polymer solution has to be checked. The viscoelasticity of slick water was tested, and the abovementioned experiment was replenished, using the Haake RS6000 rheometer to shear slick water from low-to-high frequency under some tension. The basic procedure of the experiment is as follows: first, the rheometer is used to scan the stress of the slick water, and afterward, the stress value at the inflection point is scanned by the frequency method. According to the value of the intersection point, the viscoelasticity of the slick water is determined.\textsuperscript{25,30}

2.4. Sand-Carrying and Drag-Reducing Properties. Two major features of slick water are sand-carrying and drag-reducing properties, but most conventional slick water is not effective at carrying sand. It is therefore important to research the performance difference between high-viscosity slick water and multifunctional variable-viscosity slick water in carrying sand and drag reducing.\textsuperscript{21–33}

2.4.1. Static Sand-Carrying Capacity. It applies specifically to the settling experiment of single-particle sand: preparing the high-viscosity slick water or multifunctional variable-viscosity slick water with a certain concentration (0.00–0.10 wt % CNI-A mixed with 0.05–0.80 wt % CNI-B), positioning them in a 1000 mL measuring cylinder, placing some mesh quartz sand of 30/50 into the measuring cylinder, tracking the time it takes for the sand to descend from 900 to 400 mL (i.e., 500 mL), and calculating the average time it takes for each grain of sand to settle at 25 °C.

2.4.2. Crack Dynamic Sand-Carrying Capacity. A pumping system and visual crack model are the main equipment in the crack dynamic sand-carrying experiment. Linked to the pumping system is the crack model. The multifunctional variable-viscosity slick water or variable slick water in the intermediate vessel is forced into the fracturing device at varying flow rates by regulating the airflow. The 30/50 mesh quartz sand with a certain sand ratio was placed, and then, the proppant migration state in the fracture was observed.

2.4.3. Drag-Reducing Property. Using a self-made loop drag test system, the drag-reducing rate of slick water was calculated. In this experiment, an 8 mm pipe was chosen. Next, the pressure drop of clear water flowing without a reagent has been measured. Then, to make multifunctional variable-viscosity slick water or high-viscosity slick water, a certain concentration of CNI-A and CNI-B reagents has been applied to clear water, the data of pressure drop of the fluid are obtained after going through the pipeline, and the solution’s drag-reducing rate is calculated.\textsuperscript{34,35} The drag-reducing rate is computed as eq 2

\[
DR\% = \frac{\Delta P_O - \Delta P_R}{\Delta P_O} \times 100%
\]  

(2)

DR refers to the drag-reducing rate, %; \(\Delta P_O\) refers to the pressure drop of clear water flow when no reagent is added, Pa; and \(\Delta P_R\) refers to the pressure drop of the slick water after the addition of the reagent, Pa.

2.5. Synergistic Impact. Only the macroscopic properties of two forms of slick water have been studied, so further studies on its microscopic mechanism, which primarily covers two things, must be carried out: nanoemulsion size measuring and microstructure analysis.

2.5.1. Nanoemulsion Size. The nanoemulsion size of multifunctional variable-viscosity slick water or high-viscosity slick water was measured using the Zetasizer Nano ZS laser nanoemulsion size meter. Due to the poor transmittance of polymer solution at high concentration, the nanoemulsion size at a low concentration of two kinds of slick water (0.05–0.10 wt % CNI-A and 0.10 wt % CNI-B + 0.00–0.10 wt % CNI-A) can be measured to analyze the viscosity-increasing effect of a multifunctional slick water system. A 0.5 μm filter membrane was used for filtration before the test.

2.5.2. Microstructure Analysis. A low concentration of high-viscosity slick water (0.05 wt % CNI-B) and multifunctional variable-viscosity slick water (0.05 wt % CNI-A + 0.05 wt % CNI-B) was prepared. The liquid was drawn with a dropper, dropped on the carbon plate, and then allowed to dry on the glass dish. The abovementioned operation was repeated many times. A JEM 2100 LaB6 transmission electron microscope was used to observe its structure in vacuum, and the mechanism of improving sand-carrying capacity and increasing viscosity was analyzed.
2.6. Harm Test. The slick water joins the crack and brings sand during the fracturing process. The fast back-flow and low residual content help to reduce the harm to the reservoir from the drilling fluid. Therefore, the gel-breaking property, residual content, and harm rate of core displacement need to be checked. 36,37

2.6.1. Gel-Breaking Performance and Residual Content. In the beaker, the corresponding concentration of the slick water was prepared. 200 ppm (0.02%) of conventional breaker ammonium persulfate was added to the beaker. The beaker was placed in a constant-temperature water bath at 80 °C to record the change in slick water viscosity before and after breaking and its time. Then, the slick water after breaking was put into the filtering device for filtering. The filtering paper after being filtered was put into an oven to dry at 105 °C for 4 h, and then, the residual content was weighed.

2.6.2. Harm Rate of Core Displacement. The core displacement experiment is carried out using a multifunctional core flow unit. The Darcy formula is used to calculate the permeability of rock samples before and after harm. The method is as follows: first, the basic parameters of the core are measured for correction and comparison. Then, the initial permeability of the core is measured by positive displacement of 2% KCl solution, and the stable permeability $K_s$ is obtained. Darcy’s law is mainly used for permeability. Displacement is carried out under a constant flow rate, and the pressure difference at the inlet and outlet ends is measured under the stable state. After stopping the pump, the valve was switched on and a certain volume of the slick water gel breaker was back-driven. The valve is switched after the pump is stopped, the KCl solution of 2% is being driven again, and then, the stable permeability $K_s$ is obtained, according to the software, the harm value of permeability is $(K_i - K_s)/K_i$.

2.7. Enhanced Oil Recovery Performance. Compared with high-viscosity slick water, the advantages of multifunctional variable-viscosity slick water are not only reflected in high drag-reducing, good sand-carrying, and low harm properties. When the nanoemulsion CNI-A and drag-reducing agent CNI-B are mixed and broken. It also has its own properties. When the nanoemulsion CNI-A and drag-reducing water, and the multifunctional variable-viscosity slick water can be used as the sand-carrying fluid if it is increased to 0.60 wt %.

One of the major factors influencing the efficiency of the reagent is solubility. The higher the solubility, the quicker the rate of dissolution, the longer the acting time, and the better the effect of the reagent. It can be seen from Figure 1 that the dissolution time of the reagent (i.e., the time corresponding to the original viscosity) is 0.5 min and that the dissolution is accelerated by the addition of nanoemulsion CNI-A to the CNI-B drag-reducing agent, and it dissolved entirely in 0.417 min and played a solubilizing role.

3. RESULTS AND DISCUSSION

3.1. Rheological Characteristic Test. 3.1.1. Dissolution Rate and Rising Viscosity Rate. At 25 °C, the viscosity changes in the high-viscosity slick water and the multifunctional variable-viscosity slick water are measured at 30 and 60 min when the shear rate is 170.3 s$^{-1}$ and to examine the rising viscosity rate of the high-viscosity drag-reducing agent itself and the acceleration effect of nanoemulsion CNI-A on its rising viscosity, as seen in Figure 1. It can be found that high-viscosity slick water has the ability to increase viscosity, but the viscosity increases slowly. CNI-A will accelerate the speed of viscosity increase, and with the increase in CNI-A concentration, the viscosity of the fluid grows faster and faster. When the concentration of CNI-B is 0.10 wt %, it can be used as slick water, and the multifunctional variable-viscosity slick water can be used as the sand-carrying fluid if it is increased to 0.60 wt %.

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3.1.2. Viscosity Test. The viscosity effect is one of the metrics for assessing if the viscosity of slick water with multifunctional variable viscosity is higher than that of the high-viscosity slick water at the same concentration. After mixing and stirring of various concentrations of CNI-B (0.00–0.80 wt %) with CNI-A (0.00–0.10 wt %), the viscosity of slick water at 170.3 s$^{-1}$ (i.e., 100 RPM) and 25 °C was calculated using a ZNN-D6 six-speed rotary viscometer, and the results are shown in Figure 2.

The viscosity of slick water increases with the increase in the drag-reducing agent concentration. The viscosity of slick water increases with the increase in the concentration of nanoemulsion CNI-A at the same CNI-B drag-reducing agent concentration. It can be shown that CNI-A has the characteristics of increasing CNI-B drag-reducing agent viscosity.
3.1.3. Viscoelasticity Test. What is seen above is the relationship between the concentration of the drag-reducing agent and viscosity of the slick water and the viscosity-increasing influence of nanoemulsion CNI-A on the drag-reducing agent. While polymer and nanoemulsion concentrations play an important role in fluid viscosity, the increase in viscosity does not explicitly indicate the amelioration in sand-carrying capability, so it is appropriate to measure the viscoelasticity of slick water.

First of all, the slick water (0.60 wt % CNI-B mixed with 0.00−0.10 wt % CNI-A) was scanned using an RS6000 rheometer to assess the stress of frequency scanning, and the scanning stress value of the two kinds of slick water is 0.10 Pa by stress scanning.

The frequency scanning of two kinds of slick water fluids is carried out under the chosen scanning frequency stress. As shown in Figure 3a, there is an intersection value between the elastic modulus $G'$ and the viscous modulus $G''$ in different slick water, and Figure 3b is a comparison of the intersection values of the two types of slick water.

As seen in Figure 3, the multifunctional variable-viscosity slick water has a lower intersection value, and if the CNI-A concentration increases, the intersection value will decrease accordingly, implying that its sand-carrying capacity is stronger.29

3.2. Sand-Carrying and Drag-Reducing Properties.

3.2.1. Static Sand-Carrying Capacity. High-viscosity slick water and multifunctional variable-viscosity slick water (0.10 wt % CNI-A mixed with 0.00−0.80 wt % CNI-B) were chosen for the experiment at 25 °C. At 500 mL height, the falling time of sand with 30/50 mesh was recorded and averaged. The results are shown in Figure 4. When the content is less than 0.60 wt %, the settling time of the proppant in two kinds of slick water is approximately the same, and when the concentration is greater than 0.60 wt %, the settling time of the multifunctional variable-viscosity slick water is significantly longer than that of the high-viscosity slick water.

3.2.2. Crack Dynamic Sand-Carrying Capacity. The dynamic sand-carrying experiment was performed using multifunctional variable-viscosity slick water and high-viscosity slick water. Figure 5a,b shows the proppant migration in two kinds of slick water, respectively. Figure 5a shows the selection of 0.60 wt % CNI-B and 0.10 wt % CNI-A, and Figure 5b shows the selection of 0.60 wt % CNI-B drag-reducing agent for the experiment.

By the airflow in the pump, the multifunctional variable-viscosity slick water with sand is pumped into the crack model and is forced forward at the inlet from top to bottom. The sand-carrying fluid’s front edge travels forward in an elliptical fashion. A small amount of sand will be left due to the uneven
condition of the crack wall, and throughout the process, a certain trapezoid will be seen by the sand-carrying fluid and then eventually advance and fill the whole crack, as shown in Figure 5a, there is no sand settlement.

The sand-carrying situation is close when the high-viscosity slick water enters the crack model, but it does not carry sand entirely as it flows to the back end of the crack model and is simple to settle separate, as seen in Figure 5b. It can be shown that multifunctional variable-viscosity slick water has stronger sand-carrying capacity and high dynamic sand-carrying capacity, and the dynamic sand-carrying capacity of multifunctional variable-viscosity slick water can be increased with the increase in the drag-reducing agent and nanoemulsion concentration.

By comparing Figures 4 and 5, the sand-carrying capacity of multifunctional variable-viscosity slick water can be found to be greater than that of conventional and high-viscosity slick water. It, therefore, has strong sand-carrying capacity, both static and dynamic.

3.2.3. Drag-Reducing Property. Using a self-made loop drag test system, the drag-reducing property of two kinds of slick water is measured and compared. The relationship between the drag-reducing rate and flow rate in 8 mm pipes for high-viscosity slick water and multifunctional variable-viscosity slick water is seen in Figure 6. The curves demonstrate that the drag-reducing rate of the multifunctional variable-viscosity slick water increases with the increase in the flow rate and stays constant at 1.50 m³/h at the same CNI-B drag-reducing agent concentration, while the drag-reducing rate of the high-viscosity slick water increases all the time, could not keep it steady.

At the same concentration of the CNI-B drag-reducing agent (0.40 or 0.60 wt %), the results of the drag-reducing rate are measured, as shown in Figure 7. By contrast, it can be observed that the drag-reducing effect of multifunctional variable-viscosity slick water is marginally greater than that of high-viscosity slick water, and the drag-reducing rate can exceed 75% when the flow is high. Thus, concerning the traditional fracturing fluid, the conventional slick water, and the high-viscosity slick water, the multifunctional variable-viscosity slick water has better sand-carrying capacity and drag-reducing performance and can be widely used.

3.3. Synergistic Impact. 3.3.1. Nanoemulsion Size. The emulsion sizes of high-viscosity slick water and multifunctional variable-viscosity slick water (0.10 wt % CNI-B mixed with 0.00–0.10 wt % CNI-A) were measured. Figure 8 demonstrates the findings. The emulsion size of 0.10 wt % CNI-A is 11 nm, 0.10 wt % CNI-B is 112 nm, 0.10 wt % CNI-B + 0.05 wt % CNI-A is 125 nm, and 0.10 wt % CNI-B + 0.10 wt % CNI-A is 143 nm. Through contrast, it can be observed that nanoemulsion CNI-A can increase the emulsion size of the polymer, thereby playing a role in increasing the viscosity and thickening of the CNI-B drag-reducing agent.

3.3.2. Microstructure Analysis. According to 3.1 and 3.2, there are some variations between high-viscosity slick water and multifunctional variable-viscosity slick water: (1) the dissolution rate and the rising viscosity rate of multifunctional variable-viscosity slick water far exceed that of high-viscosity slick water. (2) The viscosity of multifunctional variable-viscosity slick water is much greater than that of high-viscosity slick water. The higher the concentration of CNI-A is, the more obvious the effect of the CNI-B drag-reducing agent is. (3) The intersection value of the $G'$ and $G''$ of the multifunctional variable-viscosity slick water is lower, suggesting that the multifunctional variable-viscosity slick water has a stronger sand-carrying efficiency. (4) Compared with the high-viscosity slick water, the multifunctional variable-viscosity slick water has better sand-carrying capacity and drag-reducing property which can replace the traditional fracturing fluid and the conventional slick water.

To further establish the impact of the nanoemulsion CNI-A on the microstructure of the polymer, to improve the drag-reducing and sand-carrying efficiency, the microstructures of the two kinds of slick water were scanned by transmission electron microscopy (TEM). Figure 9a,b, respectively, show images of high-viscosity slick water at low concentrations and multifunctional variable-viscosity slick water. By comparison, it
can be found that there are random coil and network-like polymer structure in the high-viscosity slick water, and the random coil-like polymer presents bubble shape after compression, and it has viscoelasticity and stability. After adding 0.05 wt % CNI-A, the surface (interface) tension of slick water decreases, the bubble-like structure inside is broken and fused, which can play the role of solubilization. In addition, paraformaldehyde strengthens the chemical cross-linking of polymers, and the nanoemulsion enhances the physical cross-linking of polymers by making them more entangled and more complex, with larger emulsion sizes and more stable structures, as well as greater viscoelasticity and viscosity, the sand-carrying capacity would be improved accordingly.

3.4. Harm Test. 3.4.1. Gel-Breaking Performance and Residual Content. During fracturing, as the slick water carries the sand into the crack, the key criteria for determining the degree of harm are whether the gel is easy to break and leaves less residuum. Therefore, the gel-breaking performance and residuum content of multifunctional variable-viscosity slick water and high-viscosity slick water were tested under laboratory conditions. A conventional gel breaker at 200 ppm was added to 200 mL of high-viscosity slick water (0.60 wt % CNI-B) or multifunctional variable-viscosity slick water (0.60 wt % CNI-B mixed with 0.10 wt % CNI-A) and thoroughly agitated. According to API specification, two kinds of slick water were heated at constant temperature and their viscosity was measured at various times. Whether or not the gel was broken was determined according to the difference in viscosity and the residuum content was calculated after breaking.

The fluid viscosity curve at the 10.22 s⁻¹ shear scale at various times is seen in Figure 10. The reason why we choose a low shear rate is to show the gel-breaking performance of the product. High shear rate measurement will cause shear harm to slick water and reduce viscosity. To reduce this effect and show viscosity, a low shear rate of 10.22 s⁻¹ was chosen. In addition, the viscosity of the fracturing fluid will gradually become the same as that of water, and it is difficult to observe the change in viscosity at the later stage with a high shear rate. When the breaker concentration was 200 ppm, the viscosity of multifunctional variable-viscosity slick water or high-viscosity slick water is changed to 1 mPa·s in 30 or 40 min. Therefore,
multifunctional variable-viscosity slick water has better gel-breaking efficiency. Moreover, the gel-breaking time of multifunctional variable-viscosity slick water is faster than that of high-viscosity slick water because the hydrogen bond cross-linking produced is more easily damaged using the breaker. The gel was ruptured and filtered, and the residuum was measured after drying. The residual content of slick water with multifunctional variable viscosity and high-viscosity slick water is 38.5 and 33 ppm, respectively, which is well below API requirement 550 ppm. Therefore, multifunctional variable viscosity slick water has low residual content and less harm to reservoirs and cracks, so it has a good application prospect.

3.4.2. Harm Rate of Core Displacement. The abovementioned experiments of gel breakage and residuum content only reflect the harm degree of slick water from the side, while the core displacement experiment can directly observe the harm degree of the slick water gel breaker and measure the harm rate. Two tight cores were selected to carry out displacement experiments. The results of relevant parameters are shown in Table 1. After displacement, it can be seen from

Table 1. Basic Parameters of the Experimental Core

| core number | length (cm) | diameter (cm) | porosity (%) |
|-------------|-------------|---------------|--------------|
| 1           | 2.20        | 2.52          | 8.41         |
| 2           | 2.00        | 2.51          | 4.39         |

Table 2. Harm Rate Results of the Core Displacement Experiment

| core number | fracturing fluid gel breaker | pre-damage permeability $K_1$, mD | post-damage permeability $K_2$, mD | damage rate, % |
|-------------|-----------------------------|-----------------------------------|-----------------------------------|----------------|
| 1           | 0.6% CNI-B                  | 0.01328                           | 0.01111                           | 16.37          |
| 2           | 0.6% CNI-B + 0.1% CNI-A     | 0.01050                           | 0.00858                           | 18.30          |

Table 2 that the harm rates of two kinds of slick water gel breakers are 16.37 and 18.30%, respectively, which are lower than 30% required by the API standard. The harm rates of the multifunctional variable-viscosity slick water gel breaker are slightly higher, which is mainly affected by the molecular structure.

3.5. Enhanced Oil Recovery Performance. From the abovementioned experiments, we can see that the multifunctional variable-viscosity slick water not only breaks the gel quickly but also has low residuum and low harm. After the slick water is injected into the formation, the slick water gel breaker is easily filtered through the pores and enters into the inside of pores and the multifunctional variable-viscosity slick water gel breaker also has the characteristics of enhanced oil recovery, which is mainly demonstrated by the following experiments.

3.5.1. Wetting Modification. The experimental results show that the high-viscosity slick water (0.60 wt % CNI-B) and the multifunctional variable-viscosity slick water (0.60 wt % CNI-B mixed with 0.10 wt % CNI-A) gel breaker can be used for the experiment. The wettability angle of two cores (oil drop angle in water) was tested using the wettability angle testing device. The results are shown in Figure 11a. It can be found that the angle is about 80°, which belongs to the weak lipophilic core. From Figure 11b, it can be found that the wetting angle changes to about 110° after soaking in the multifunctional variable-viscosity slick water gel breaker, and the weak lipophilic core changes to the hydrophilic core, which can play a very good role in oil displacement, enhanced oil recovery. After being soaked in the high-viscosity slick water gel breaker, the wetting angle has no change, that is, it does not have the ability to wet modification. According to Ju,39 Dai,41 and others, wetting modification is one of the main driving forces to promote imbibition. The change in wettability changes the direction of capillary force, according to the formula of capillary force, and under hydrophilic conditions, capillary force plays a more important role in oil recovery, which can improve the efficiency of self absorption and oil displacement.

3.5.2. Surface and Interfacial Tension. High-viscosity slick water and multifunctional variable-viscosity slick water (0.00–0.10 wt % CNI-A mixed with 0.00–0.80 wt % CNI-B) were selected and the surface (interfacial) tension was tested after gel breaking. The results are shown in Figure 12a, after comparison, it can be found that no nanoemulsion CNI-A is added, the surface tension of the high-viscosity slick water gel breaker becomes the largest and increases with the increase in the concentration of the drag-reducing agent; after adding the nanoemulsion CNI-A, the surface tension decreases with the increase in the concentration of CNI-A. The test results of interfacial tension with kerosene, as shown in Figure 12b, can be found that the situation of interfacial tension of the slick water gel breaker is similar to that of surface tension. When comparing the surface tension of the slick water gel breaker with the same concentration of the drag-reducing agent, it can be found that the surface tension is much higher than the interfacial tension. This is because when measuring the surface tension, the upper layer of the testing medium is air, the density is 0 g/cm³, and when measuring the interfacial tension, it is kerosene, the density difference with the slick water gel
breaker becomes smaller. Li,42 Xu,43 and others think that low interfacial tension is one of the main driving forces to promote imbibition. Under low interfacial tension, the adhesion between the oil and the solid surface decreases. Due to the electrostatic repulsion and the Brown motion between the nanoemulsion molecules, the force from the aqueous phase to the oil phase is produced, and the oil is easily stripped from the solid surface due to the decrease in the force and adhesion.

3.5.3. Imbibition Displacement. In this paper, the experiments of imbibition were carried out with the fluid of high-viscosity slick water (0.60 wt % CNI-B), multifunctional high-viscosity slick water (0.10 wt % CNI-A mixed with 0.60 wt % CNI-B), and clear water. The recovery factor results are shown in Figure 14.

As can be seen from Figure 13, the displacement effect of clear water, high-viscosity slick water, and multifunctional variable-viscosity slick water on low permeability and hydrophilic core, especially the nanoemulsion CNI-A, has changed the core imbibition process. The polymer CNI-B can improve the heterogeneity and also can use its viscoelastic effect to improve oil displacement efficiency.

Therefore, the final recovery of the high-viscosity slick water gel breaker is higher than that of water. The nanoemulsion can reduce the surface interfacial tension, resulting in the reduction of capillary force, and the initial imbibition of nanoemulsion into the core of the power is insufficient. The hydrophilic core needs to soak in the nano emulsion for 4 h to reach the maximum imbibition velocity, while the clear water can reach the maximum imbibition velocity in a short time. However, the imbibition efficiency is affected not only by imbibition power but also by the resistance of oil phase migration.

The continuity of oil drainage channels in low permeability cores is poor, oil drops are easy to be trapped in the flow process, and lower surface interfacial tension can promote the activation of crude oil. More crude oil becomes movable oil to participate in the flow, and the final imbibition recovery of the hydrophilic low permeability core in the multifunctional variable-viscosity slick water gel breaker is significantly higher than that in the high-viscosity slick water gel breaker and the clear water alone.

4. FIELD APPLICATION

Shale oil field in Western China has implemented multifunctional variable-viscosity slick water fracturing for four directional wells, with a success rate of 100%. The field test of Yuan X well shows that the sand-carrying capacity is stable, the construction pressure is 17.0 MPa, the fracturing pressure is 27.6 MPa, the pump stopping pressure is 15.4 MPa, the fracturing fluid construction displacement is 8.0 m³/min, the total injected fracturing fluid is 668.6 m³, and the maximum sand concentration reaches 400 kg/m³. The construction curve is shown in Figure 14. After 26.5 t oil production per day, the fracturing fluid system test has achieved initial results.

5. CONCLUSIONS

The multifunctional variable-viscosity slick water not only has strong sand-carrying capacity as traditional fracturing fluid and high-viscosity slick water but also has the good drag-reducing property as conventional and high viscosity. At the same time, it can be mixed online in the whole process. Compared with high-viscosity slick water, the viscosity and the modulus of multifunctional variable-viscosity slick water are higher. The
intersection value of high concentration of the multifunctional variable-viscosity slick water (0.10 wt % CNI-A + 0.60 wt % CNI-B) is about 0.01 Hz, which has higher sand-carrying capacity, and can be used as a sand-carrying liquid; when the concentration is low (0.10 wt % CNI-A + 0.10 wt % CNI-B), the drag-reducing rate is higher, which can be used as slick water to realize the multieffect of one agent.

The TEM picture suggests that the variable viscosity of slick water has bubbles and a network structure. The bubble-like structure increases rupture and fusion overlap, which plays the role of solubilization, and more polymer structures are entangled and cross-linked together and the emulsion size increases, the system is more steady, and the sand-carrying performance is improved.

The multifunctional variable-viscosity slick water has the characteristics of low harm. The conventional gel breaker can break the gel rapidly, and the residuum content is 38.5 ppm. The harm rate to the core is 18.30%, which is also less than the conventional gel breaker can break the gel rapidly, and the residuum content is 38.5 ppm. The harm rate to the core is 18.30%, which is less than the API standard. Its gel breaker also has the characteristics of low harm. The conventional gel breaker can break the gel rapidly, and the residuum content is 38.5 ppm.

The harm rate to the core is 18.30%, which is also less than the API standard. Its gel breaker also has the characteristics of low harm. The conventional gel breaker can break the gel rapidly, and the residuum content is 38.5 ppm.

6. RECOMMENDATIONS

In the future fracturing fluid performance test, it is suggested that more attention should be paid to collaborative sand-carrying or elastic sand-carrying. In addition, multifunctional slick water may be the development direction of hydraulic fracturing in the future, which is worth studying.

AUTHOR INFORMATION

Corresponding Authors
Fujian Zhou — Unconventional Natural Gas Institute, China University of Petroleum Beijing, Beijing 102249, China; Email: zhoufj@cup.edu.cn
Jie Wang — Yangtze University, Wuhan 430100, China; Email: wangjie@yangtzeu.edu.cn

Authors
Erdong Yao — Unconventional Natural Gas Institute, China University of Petroleum Beijing, Beijing 102249, China
Hao Bai — Unconventional Natural Gas Institute, China University of Petroleum Beijing, Beijing 102249, China; orcid.org/0000-0002-3649-8942
Mengchuan Zhang — Unconventional Natural Gas Institute, China University of Petroleum Beijing, Beijing 102249, China
Fuyuan Li — Unconventional Natural Gas Institute, China University of Petroleum Beijing, Beijing 102249, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c01986

Notes
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