Influence Factors of Multifunctional Viscous Drag Reducers and Their Optimization for Unconventional Oil and Gas Reservoirs

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ABSTRACT: Owing to the problems of guar gum fracturing fluid and conventional slickwater fracturing fluid systems in hydraulic fracturing of tight oil reservoirs, such as bad fracture network capacity, high damage, and low sand-carrying performance, researchers are actively looking for new alternative fracturing fluids. This study takes four commonly used additives for hydraulic fracturing of tight oil and gas reservoirs in western China, including the conventional polyacrylamide friction reducer EM30S, bioglue, thickener CHS-1, and high-viscosity friction reducer HVFR-1. By testing the water solubility, rheological properties, drag reduction, sand-carrying performance, imbibition oil displacement effect, and residue content of the four additives, the best additives suitable for hydraulic fracturing of tight oil and gas reservoirs were selected, and a set of indoor evaluations and the experimental method of screening hydraulic fracturing additives for tight oil and gas reservoirs were established. The research results show that the high-viscosity slickwater system composed of CND + HVFR-1 is more suitable for hydraulic fracturing of tight oil and gas reservoirs. Compared with the other three types of additives, CND + HVFR-1 fracturing fluid has good water solubility, and the dissolution time is less than 30 s. Therefore, in order to save construction time, the CND + HVFR-1 high-viscosity slickwater system is first recommended for field application. The research results of rheological properties show that although the apparent viscosity of high-concentration HVFR-1 + CND is low, the cross value of $G'$ and $G''$ is the smallest (0.006 Hz) and the elastic modulus is the largest (4.554 Pa) corresponding to 1 Hz. HVFR-1 + CND has better sand-carrying performance when used as a sand-carrying liquid. CND + HVFR-1 not only achieves a friction reduction rate of more than 60% but also has the effect of imbibition oil displacement to improve oil recovery; it can easily break gels, and its low residue content can ensure rapid flowback after construction is completed, and the lower residue content also causes the least damage to the reservoir. At the same time, the establishment of this evaluation method provides a certain reference for other researchers who select fracturing fluids for tight oil and gas reservoirs.

1. INTRODUCTION

With the continuous progress of exploration and development technology and the breakthrough of horizontal well volume fracturing technology, tight oil and gas reservoirs have been successfully developed worldwide.1,2 Volume fracturing of tight oil and gas reservoirs is mainly characterized by low viscosity, high sand-carrying, and large-scale construction, and conventional fracturing fluid systems such as linear guar gum or crosslinked guar gum cannot meet the construction requirements.3,4 This is mainly due to the formation of a complex network of fractures after hydraulic fracturing of tight oil and gas reservoirs. Guar gum fracturing fluid has a high viscosity, and the fracturing fluid cannot carry proppants into the tiny fracture network, so the formed fracture network has poor conductivity. At the same time, the guar gum fracturing fluid has a higher residue content after gel breaking, which will damage the pores of tight reservoirs. Therefore, the guar gum fracturing fluid is gradually replaced by the polyacrylamide-based slickwater fracturing fluid system.5,6

The main agent of slickwater fracturing fluid is a friction reducer with a concentration of 0.05~0.2%. It mainly includes anions, nonions, and cations, which can be divided into hydrophobic and amphoteric. Most anionic friction reducers are made from 30% mol acrylic copolymers.7−9 Friction reducers are typically high molecular weight polyacrylamide copolymers. According to reservoir conditions and salinity requirements, they can be classified into polyacrylamide-based
polymers, acrylamide methyl propane sulfonate polymers (AMPSs), polyacrylic acid (PAAc), and hydrolyzed polyacrylamide (PHPA). The most common friction reducers are often provided in the form of water-in-oil emulsions in which the polymer is divided between the water and oil phases. When the emulsion is added to water, it quickly reverses and releases the polymer into the water, further hydrating it. In addition to friction reducers, slickwater also includes additives such as drainage aids, clay stabilizers, bactericides, and scale inhibitors. \(^{10,11,19,20}\) In the process of solution flow, slickwater achieves the drag reduction effect through the interaction of the polymer molecular structure of the drag reducer additive. \(^{14,15,21}\)

Conventional friction reducers are mainly anionic polymers, which have the advantages of high solubility in water, high viscosity, small capacity loss, and low cost. \(^{12,13}\) The disadvantage of conventional drag reducers is poor sand-carrying capacity. In horizontal wells and complex fractures, the proppant cannot be effectively transported to the predetermined position, resulting in poor conductivity of the fracture network formed after fracturing. In recent years, the use of the high-viscosity drag reducer HVFR has become more and more popular. Its advantages include: (1) The effect of reducing the frictional resistance of the pipeline; (2) low cost, mixing on-the-fly, low concentration can be used as preliquid, and high concentration can be used as sand-carrying liquid; (3) strong sand-carrying capacity—the high-concentration HVFR slickwater solution has the same sand-carrying capacity as guar gum fracturing fluid, but the conventional slickwater solution does not have this feature; (4) the environmental pollution is small, the gel is easy to break, the residue content is low, and the damage to the reservoir is small; (5) quick to hydrate in fluid “on-the-fly” in the water; and (6) the reservoir has strong adaptability and good compatibility with other additives. \(^{14,15,22}\)

At present, the four additives commonly used in hydraulic fracturing of tight oil and gas reservoirs in western China include the conventional polyanionic friction reducer EM30S, biogels, thickener CHS-1, and high viscous friction reducer HVFR-1. By testing the water solubility, rheological properties, friction reduction, sand-carrying performance, imbibition displacement effect, and residue content of the four additives, the optimum additives for hydraulic fracturing in tight oil and gas reservoirs were selected, and an experimental method for evaluating and selecting hydraulic fracturing additives in tight oil and gas reservoirs has been established. The establishment of this evaluation method can be used for reference by other researchers who study the reservoir reconstruction of tight oil and gas reservoirs.

2. RESULTS AND DISCUSSION

2.1. Continuous Mixability. The difference between the additives of tight oil and gas reservoir fracturing fluid and guar gum fracturing fluid is that the above four additives can realize continuous mixing and there is no need for an early preparation tank for hydration treatment. A magnetic stirrer was used to prepare low-concentration and high-concentration fracturing fluids at the speeds of 800 and 1500 rpm, and a Fann flow viscometer was used to test the time required for the solution to reach a stable viscosity. The results are shown in Table 1. When the concentration of the four additives is low (as the preliquid), the dissolution rate in water is fast. When the concentration of additives is high (as sand-carrying liquid), the solution speed of the high-viscosity slippery water system composed of CND + HVFR-1 is the fastest (\( \leq 30 \) s) in water, and the water solubility of the EM30S + AS25 slippery water system is the worst (480 s). Therefore, in order to save construction time, the CND + HVFR-1 high-viscosity sliding water system is recommended in the field.

2.2. Viscoelasticity. Viscoelasticity is one of the main indicators to measure the sand-carrying performance of polymer solutions. Yang Bo, Haiyan Zhao and others think that the elasticity of polymer solutions is an important factor reflecting their sand-carrying performance. \(^{3,4}\) Therefore, it is necessary to test the viscosity modulus \( G' \) and elastic modulus \( G'' \) of the solution simultaneously, and the intersection of \( G' \) and \( G'' \) represents the relaxation time of the polymer network. The lower the intersection values, the stronger the suspension capacity of the proppant. Since the above four additives need to compare the viscoelastic modulus when they are used as sand-carrying liquid, the viscoelasticity of different types of fracturing fluids at high concentrations is tested by a HAKKE RS6000 rheometer. The results are shown in Figures 1 and 2, and Table 2. The cross

| Table 1. Dissolution Rates of Fracturing Fluids of Different Concentrations and Types |
|-------------------------------|--------------|--------------|--------------|--------------|
| recipe                        | 0.1 wt % CND + 0.1 wt % HVFR-1 | 0.05 wt % EM30S | 1.5 wt % CHS-1 | 0.8 wt % biogel |
| dissolution rate/(s, 800 rpm) | \( \leq 10 \) | \( \leq 10 \) | \( \leq 60 \) | \( \leq 30 \) |
| recipe                        | 0.1 wt % CND + 0.6 wt % HVFR-1 | 0.2 wt % EM30S + 0.25 wt % AS25 | 3.0 wt % CHS-1 | 1.5 wt % biogel |
| dissolution rate/(s, 1500 rpm)| \( \leq 30 \) | \( \leq 480 \) | \( \leq 180 \) | \( \leq 60 \) |

Figure 1. Viscoelastic modulus test results of EM30S + AS25 and HVFR-1 + CND.

Figure 2. Test results of viscoelastic modulus of CHS-1 and biogel.
values of $G'$ and $G''$ in the CND + HVFR-1 system were the smallest (0.006 Hz), the cross values of $G'$ and $G''$ in the biocolloid system were the largest (0.046 Hz). At 1 Hz, the elastic modulus of the CND + HVFR-1 system was the largest (4.554 Pa), and the elastic modulus of the EM30S + AS25 system was the smallest (0.563 Pa). From the point of view of viscoelasticity, CND + HVFR-1 has the strongest sand-carrying performance.

Four high-concentration solutions of different types of fracturing fluids were prepared, and glass rods were used for hanging to observe the viscoelasticity of fracturing fluids, as shown in Figure 3. CND + HVFR-1 fracturing fluid has better viscoelasticity, when using a glass rod hanging, the ductility of the solution is higher, and the ductility of other solutions is worse.

Furthermore, the apparent viscosity of four additives as sand-carrying liquid was tested. The results are shown in Table 3. The CND + HVFR-1 system has the lowest apparent viscosity (38 MPa·s). Although the apparent viscosity of the CND + HVFR-1 system is the lowest, the viscoelastic results show that it has the strongest sand-carrying performance.

2.3. Friction Reduction and Sand-Carrying Properties. Furthermore, in order to determine which additive is more suitable for hydraulic fracturing in tight oil and gas reservoirs, the friction reduction rate and static sand-carrying performance of four additives as the sand-carrying liquid are tested, respectively. The results are shown in Figures 4 and 5.

As can be seen from Figure 4, when the experimental flow velocity is 0.25 m³/h, the friction reduction rate of the four solutions is quite different and the drag reduction effect is poor. In the actual construction process, the pumping rate of fracturing fluid reached 10 m³/min. Therefore, compared with the friction reduction rate at the experimental flow rate of 2.0 m³/h, the friction reduction rate of the four additives was similar, and all had a friction reduction rate of more than 60%. Therefore, from the effect of friction reduction, it can be concluded that the fracturing fluid prepared by four additives has a better friction reduction effect and can be used as fracturing fluid in tight oil and gas reservoirs.

As can be seen from Figure 5, the static sand-carrying time of 0.10 wt % CND + 0.60 wt % HVFR-1, 0.20 wt % EM30S + 0.25 wt % AS25, 3.00 wt % CHS-1, and 1.50 wt % biogel are 269, 221, 265, and 245 s, respectively. The static sand-carrying capacities of the four additives are similar, and the static sand-carrying capacity of CND + HVFR is slightly higher than that of other types of fracturing fluids. Therefore, four types of fracturing fluid can be used as sand-carrying liquid in terms of static sand-carrying performance.

2.4. Enhanced Oil Recovery Properties. From the study of 2.1~2.3, considering the water solubility and rheological properties of four kinds of fracturing fluids, the high-viscosity slickwater prepared by the CND + HVFR-1 system is more...
suitable to be used as fracturing fluid in tight oil and gas reservoirs, and considering the friction reduction rate and sand-carrying performance, all four additives are suitable for fracturing in tight oil and gas reservoirs. Here is an analysis of which type of fracturing fluid is more suitable for hydraulic fracturing in tight reservoirs by testing the effectiveness of the fluid enhanced oil recovery of each of the four fracturing fluids after gel breaking. The test includes the surface interfacial tension value (the crude oil of a tight oil block in Changqing oil field, China), the wetting modification effect, the demulsification rate of the gel breaker mixed with the crude oil, and the imbibition oil displacement effect.17,18

2.4.1. Surface Interfacial Tension. Table 4 shows the test results of surface interfacial tension of different fracturing fluids after gel breaking. The surface tension and interfacial tension of the CND + HVFR-1 gel-breaking fluid were the lowest, surface tension = 35 mN/m and interfacial tension = 3–6 mN/m. After the CND + HVFR-1 gel-breaking fluid enters into the reservoir, it can reduce the surface tension of the gas—liquid or oil—water interface, improve the capillary resistance of fluid flow, and be beneficial to releasing water lock damage in the tight gas reservoir or water drive crude oil in the tight oil reservoir, to achieve the effect of enhanced oil recovery.

2.4.2. Angle of Wettability. Only HVFR-1 and EM30S fracturing fluids contain surfactants (CND and AS25) in the four types of fracturing fluids. Therefore, other types of fracturing fluids do not have the effect of wettability modification. The wettability modification effects of CND + HVFR-1 and EM30S + AS25 fracturing fluids (the cores are treated by demulsification, then the liquid and crude oil are mixed according to a 7:3 ratio and put into a 100 mL measuring cylinder, the measuring cylinder is covered and shaken for 200 times, then it is left still, and the separation time of crude oil and gel breaker is observed and recorded as shown in Figure 8. The...

| recipe                  | 0.1 wt %CND + 0.6 wt % HVFR-1 | 0.05 wt % EM30S | 0.2 wt % EM30S + 0.25 wt % AS25 | 1.5 wt % CHS-1 | 3.0 wt % CHS-1 | 0.8 wt % biogel | 1.5 wt % biogel |
|------------------------|-----------------------------|----------------|-------------------------------|---------------|---------------|---------------|---------------|
| surface tension (m N/m)| ≤35                         | ≤45            | ≤42                           | ≤45           | ≤75           | ≤35           | ≤35           |
| interfacial tension (m N/m) | 3–6                      | ≤15            | ≤12                           | ≤8            | ≤20           | ≤10           | ≤10           |

Figure 8. Test result of emulsion rates of four kinds of gel-breaking liquid.

Figure 6. 0.1 wt % CND + 0.6 wt % HVFR-1 gel breaker soaking cores.

Figure 7. 0.2 % EM30S + 0.25% AS25 gel breaker soaking cores.
wettability modification, and interfacial tension reduction between oil and water, it can be concluded that adding CND into FR-900 can not only improve the performance of HVFR slickwater as a fracturing fluid, but also at the same time, it has the effect of imbibition oil displacement to enhance tight oil recovery and achieves the goal of multieffect.

2.5. Low Damage Property. Since tight oil and gas reservoirs are all micro–nano pore throats, the injected fracturing fluid must have a low residue content in order to have low damage to the reservoir. At the same time, the fracturing fluid can easily break the gel, which is beneficial to increase the flowback rate after fracturing, and reduce the formation of liquid lock damage to the reservoir after the fracturing fluid enters the reservoir. Therefore, the gel breaking and residue content of the four fracturing fluids were evaluated indoors.

Two hundred milliliters of four kinds of fracturing fluids with high concentration were prepared in a laboratory, and then 500 ppm of conventional gel breaker ammonium persulfate was added into the solution and fully stirred. According to the API standard, the solution was put into an 80 °C water bath to test the viscosity of the solution at different times. According to the change of solution concentration, it can be judged whether the solution breaks the gel. The residue content after gel breaking of the solution was tested, and the results are shown in Table 5. The gel-breaking time (18 min) and residue content (38.5 ppm) of the CND + HVFR-1 fracturing fluid are the smallest. This shows that when CND + HVFR-1 is used as a fracturing fluid, faster gel breaking after construction is conducive to flowback, and at the same time, lower residue content has minimal damage to the reservoir.

### Table 5. Breaking Time and Residue Content of Four Fracturing Fluids

| Recipe | 0.1 wt % CND + 0.6 wt % HVFR-1 | 0.2 wt % EM30S + 0.25 wt % AS25 | 3.0 wt % CHS-1 | 1.5 wt % biogel |
|--------|-------------------------------|-------------------------------|----------------|----------------|
| Gel-breaking time, (300 ppm gel breaker), min | 18 | 90 | 360 | ≥1800 |
| Residue content, ppm | 38.5 | 71 | 405 | 60 |

3. CONCLUSIONS

This study was tested by parameters such as water solubility, rheological properties, friction reduction, sand-carrying performance, imbibition oil displacement effect, and residue content of four additives, and the optimum additives for hydraulic fracturing in tight oil and gas reservoirs were selected; an experimental method for evaluating and selecting hydraulic fracturing additives in tight oil and gas reservoirs has been established. The main conclusions and recommendations are as follows:

1. The study shows that by testing the water solubility, rheological properties, friction reduction effect, sand-carrying properties, imbibition oil displacement effect, gel-breaking time, residue content of different fracturing fluids, etc., the additives suitable for hydraulic fracturing in tight oil and gas reservoirs were selected. The establishment of a systematic evaluation method can be used for reference by other researchers who study the reconstruction of tight oil and gas reservoirs. The high-viscosity slickwater system composed of CND + HVFR-1 is more suitable for hydraulic fracturing in tight oil and gas reservoirs.

2. Compared with the other three types of additives, the CND + HVFR-1 fracturing fluid has good water solubility and the dissolution time is ≤30 s. Therefore, in order to save construction time, the CND + HVFR-1 high-viscosity slickwater system is recommended. The results of rheological properties show that although the high concentration of CND + HVFR-1 has a low apparent viscosity, the cross value of G' and G" is the smallest (0.006 Hz) and the elastic modulus is the largest (4.554 Pa) when corresponding to 1 Hz. It shows that CND + HVFR-1 has better sand-carrying properties when used as a sand-carrying liquid.

3. The study of friction reduction rates and static sand-carrying performance shows that the four kinds of fracturing fluids all have good friction reduction performance at a high flow rate of 2.0 m³/h and the friction reduction rate is over 60%, and the high-viscosity slickwater formed by CND + HVFR-1 has slightly higher sand-carrying performance than the other three fracturing fluids.

4. Because CND is a kind of nanosurfactant for imbibition oil displacement, it can improve the imbibition oil displacement effect of the HVFR-1 fracturing fluid, but the other three fracturing fluids do not have the function of enhancing oil recovery. The results of gel-breaking time and residue content show that the gel-breaking time (18 min) and residue content (38.5 ppm) of the CND + HVFR-1 fracturing fluid are the minimum. It shows that when CND + HVFR-1 is used as fracturing fluid, faster gel breaking after operation is beneficial to backflow, and lower residue content is also the least harmful to the reservoir.

4. MATERIALS AND METHOD

4.1. Materials. The four additives in the experiment include the conventional polyacrylamide friction reducer EM30S, biological glue, thickener CHS-1 (the above three additives are provided by Chongqing Oilfield Chemical Company), and high viscous friction reducer HVFR-1 (provided by Beijing Comex Chemical Company). The samples are shown in Figure 10.

1. The EM30 friction reducer is a kind of polyacrylamide polymer with a comb-shaped molecular structure, which uses acrylamide as the main chain structure to synthesize...
Four additives of low concentration and high concentration were prepared according to the actual use situation in the reservoir, mainly includes the following five aspects: field mixing on-the-fly, rheological properties, friction reduction effect, amount of gel-breaking residue, and imbibition oil displacement effect. The following four main fracturing fluid agents are tested from five aspects, and the best fracturing fluid system in tight oil and gas reservoirs is selected. The equipment and procedures for the laboratory are shown in Figure 12.

4.2.2. Continuous Mixability Test. When conventional guar fracturing fluid is mixed in the field, a large number of water tanks need to be used for hydration in advance, which not only increases the construction cost but also increases the construction difficulty. In order to reduce the construction cost and simplify the construction difficulty, the additives suitable for hydraulic fracturing in tight oil and gas reservoirs should have real-time continuous miscibility. A mixture of magnetic stirring 800 rpm at low speed and 1500 rpm at high speed was used, and then a Fann Model 35 rotational viscometer was used to test the time it took for the apparent viscosity of the solution to stabilize and to determine the dissolution time of the different additives in the water.

4.2.3. Rheological Property Test. 4.2.3.1. Viscosity Test. The static sand-carrying performance of the viscosity reaction solution was studied. Distilled water was used to prepare fracturing fluid systems of low concentration and high concentration, and the apparent viscosity of different concentrations and different types of fracturing fluids was tested with a Fann Model 35 six-speed viscometer.

4.2.3.2. Viscoelastic Test. First, stress sweeping of polymer fluid was performed with a HAKKE RS6000 rheometer. Then, the stress values in the linear region near the inflection point of the stress sweep were used to scan the fluid frequency to obtain the elastic modulus $G'$ and viscosity modulus $G''$ of the solution to determine the viscoelasticity of different solutions.

4.2.4. Friction Reduction and Sand-Carrying Property Test. 4.2.4.1. Friction Reduction Rate Test. Friction reduction is an important parameter that differentiates the HVFR system from linear gel and cross-linked gel fracturing fluids. The laboratory friction reduction test system consists of three parts: a pumping system, pipeline test system, and data acquisition system. In this study, 8 mm pipeline was used to test the drag reduction rate. The drag reduction rate is calculated by the following formula 1:

$$\text{FR} \% = \left( \frac{\Delta P_1 - \Delta P_2}{\Delta P_2} \right) \times 100$$  

(1)

where FR% is the friction reduction rate of the friction reducer solution; $\Delta P_1$ is the pressure difference generated when clean water passes through the ends of the 8 mm pipe at different flow rates; and $\Delta P_2$ is the pressure difference generated when the friction reducer passes through the ends of the 8 mm pipe at different flow rates.

4.2.4.2. Hydrophilic Property Test. The static sand-carrying performance of the viscosity reaction solution was studied. Distilled water was used to prepare fracturing fluid systems of low concentration and high concentration, and the apparent viscosity of different concentrations and different types of fracturing fluids was tested with a Fann Model 35 six-speed viscometer.
4.2.5. Sand-Carrying Property Test. This paper mainly tests the static sand-carrying performance of different types of high-concentration fracturing fluids. A certain concentration of friction reducer agent fluid was prepared and poured into a 1000 mL graduated cylinder, then 3–4 40/70 mesh quartz sand proppants were put into the graduated cylinder. The time taken for 3–4 sands to fall from 900 to 400 mL was recorded, and then the average time of the 500 mL length of single sand sinking was calculated.

4.2.6. Enhanced Oil Recovery Property Test. The mechanism of surfactant enhancing oil recovery is to reduce oil—water interfacial tension, change rock surface wettability, and demulsification to achieve the effect of oil displacement by imbibition. In order to verify whether different types of fracturing fluid systems have enhanced oil recovery characteristics, the interfacial tension between different types of fracturing fluids and crude oils, the demulsification rate after mixing with crude oils, the wettability of reservoir rocks, and the imbibition displacement efficiency were tested.

4.2.7. Low Damage Property Test. The fracturing fluid has fast gel-breaking performance and low residual content, which can improve the flowback rate of the postfracturing fluid and reduce the damage rate of the fracturing fluid to the reservoir. Since the low-concentration fracturing fluid is used as the preliquid, it has low viscosity and does not require gel breaking, so it is only necessary to test the gel-breaking performance, residual content, and core damage rate of the high-concentration fracturing fluid.

Different types of fracturing fluid systems with high concentration were prepared. A 500 ppm gel breaker was added to the fracturing fluid to test the gel-breaking time of the solution and then the residual content of the gel-breaking fluid was tested.

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