Laboratory Evaluation of Fluidity of Heavy Oil Emulsions in Formation Pores Medium

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ABSTRACT: Heavy oil emulsions such as water in oil (W/O), oil in water (O/W), and water in oil in water (W/O/W) would be formed during the development of heavy oil reservoirs. The key to the efficient development of heavy oil reservoirs is to clarify the fluidity of heavy oil emulsions in formation pores medium. In this study, the main factors that determine the fluidity of heavy oil emulsion were analyzed under the condition of simulating the formation pores medium. The reasons for the difference between the viscosity of heavy oil emulsions in formation pores medium and the viscosity measured by laboratory rheometer were analyzed. Then, experiments have confirmed the shortcomings of the current screening and evaluation method of emulsified viscosity reducer. Finally, through experimental research and mechanism analysis, the mechanism of the emulsified viscosity reducer was studied and suggestions were made to improve the effect of emulsified viscosity reducer in the oil field. When heavy emulsions flow in a formation pores medium, since the size of the droplets would be larger than the size of the pores medium, when the heavy emulsion passes through the pores medium, it would receive additional resistance brought by the Jamin effect. But when a rheometer is used for viscosity testing, this additional resistance is almost nonexistent. Therefore, the current method of viscosity test using rheometer cannot fully reflect the actual flow state of heavy oil emulsion in formation pores medium. The research in this paper proves that the larger the droplets of the emulsion, the less accurate the rheometer test results. Temperature, permeability, oil–water ratio, and the type of emulsified viscosity reducer all have a certain effect on the viscosity of heavy oil emulsion in formation pores medium. This article evaluated four types of emulsified viscosity reducers. When the viscosity test was performed by a rheometer, the results showed excellent viscosity-reducing effects. However, when simulating formation pores medium conditions, the effects of some types of emulsified viscosity reducers are not so good. It is no longer accurate to judge the effect of emulsified viscosity reducer by the way of measuring viscosity with a rheometer. It should be screened by the flow capacity of the heavy oil emulsions in formation pores medium. In oil field development, the contact area of heavy oil and emulsified viscosity reducer solution should be increased as much as possible and provide more time for the substitution effect of emulsified viscosity reducer molecules.

1. INTRODUCTION

The amount of heavy oil resources is more than 3 times that of conventional crude oil, and the development potential is huge. Over time, development of conventional oil fields in the world and their production have gradually declined and the importance of heavy oil extraction has become increasingly significant.1 Heavy oil resource in China are also abundant. The proved reserves are about 7.95 billion tons, and the recoverable reserves are about 1.91 billion tons, which is more than 20% of the total reserves. However, the low fluidity of heavy oil restricts its efficient development; therefore, the current main development methods are thermal recovery and chemical flooding.2,3

Heavy oil contains natural emulsifiers such as resin and asphaltene, which adsorbed on the oil–water interface film to form water in oil (W/O) emulsion4 and interconnected to form a three-dimensional (3D) network structure that accumulates on the surface of water droplets,5 thereby enhancing the mechanical properties of the interface film intensity.6,7 The development process provides the necessary shear reaction for the formation of the W/O emulsion. Therefore, the longer the development time, the more stable the W/O emulsion formed. Sjöblom et al. used the extraction method to separate the interfacial active substances from the heavy oil for analysis of the stability of the crude oil emulsions.8 They found that the composition of the interface-active components separated from crude oil is similar to...
asphaltenes. The strength of the interface film of the heavy oil emulsion increases with the increase of asphaltene content.\textsuperscript{3} The resin and aromatic hydrocarbons in heavy oil can disperse asphaltene aggregates, reducing the size of the structure of asphaltene aggregates, which can be better adsorbed at the oil–water interface. Therefore, the strength of the interfacial film is enhanced and the heavy oil emulsions are more stable.\textsuperscript{10}

In addition to natural emulsifiers in heavy oil, water content, temperature, shear strength, etc. also have a certain effect on the performance of W/O emulsion.\textsuperscript{11,12} Studies have shown that with the increase of the proportion of water in W/O emulsion, the stability of the heavy oil emulsion decreases.\textsuperscript{13,14} The W/O emulsion prepared at a higher temperature is more stable when observing the stability at the same temperature.\textsuperscript{15} For the W/O emulsion prepared at the same temperature, the stability would be reduced by increasing the temperature.\textsuperscript{16} The formation of W/O emulsion is not a spontaneous process, and stirring is one of the necessary conditions for the formation of emulsion. Shear strength can also affect the emulsification characteristics of oil–water two-phase systems. Many studies pointed out that when the shear strength is increased, the droplet size of the emulsion becomes smaller, making the W/O emulsion more stable.\textsuperscript{17−19} Other studies found that the stability of the W/O emulsion first increases with the increase of shear strength and then begins to decrease when the shear strength exceeded a certain value.\textsuperscript{20−22}

When the W/O emulsion formed, the viscosity would be increased and the flow resistance becomes larger, resulting in a rapid decline in the development of heavy oil reservoirs.\textsuperscript{23} Emulsified viscosity reducer molecules can adsorb on the interface of oil–water instead of active substances in heavy oil so that the oil in water (O/W) emulsion could be formed. The internal friction shifted from heavy oil-flowing medium to water-flowing medium, which can greatly reduce the flow resistance of the entire system and save the power consumption for heavy oil exploitation and transportation.\textsuperscript{24−26} Emulsified viscosity reducers are mainly divided into anionic, cationic, zwitterionic, and nonionic.\textsuperscript{27−30} Commonly used emulsified viscosity reducers are nonionic viscosity reducers such as OP, Span, and Tween, as well as anionic viscosity reducers such as petroleum sulfonate.\textsuperscript{31,32} At present, there are many studies on emulsified viscosity reducers, most of which can get better results in the laboratory experimental evaluation.

It is crucial to clarify the flow of heavy oil emulsion in the formation pores medium for the development of heavy oil reservoirs. In the formation pores medium, the flow mechanism of heavy oil emulsion is very complicated. Soo et al. found that emulsion droplets transported in the pores medium would be trapped, thereby ceasing the formation to a certain extent and causing a decrease in permeability.\textsuperscript{33,34} McAuliffe studied the flow of emulsion in a pore medium through a core displacement device.\textsuperscript{35} After the O/W emulsion is injected into the Berea sandstone, its emulsion droplets preferentially block high-permeability pores and restrict the flow of multiphase fluid in the high-permeability area, thereby increasing the displacement pressure difference. Liu et al. studied the microscopic seepage mechanism under alkali−surfactant−polymer (ASP) ternary flooding in Daqing Oilfield using a flat sand model and a microscopic simulation model of core slices.\textsuperscript{36} In the flow process of the composite system, the residual oil can be turned into flowable oil droplets, which are then further cut by the pore throat to form a fine O/W emulsion. Shi et al. used the sand-packed tube model to study the effect of shearing on the spontaneous emulsification flooding during the displacement process.\textsuperscript{37,38} Studies have shown that the size of emulsion particles is affected by the displacement velocity and the magnitude of shear forces. When the injection displacement speed is low and the shear force is small, the emulsion particle size becomes large; when the injection speed is high and the shear force is large, the emulsion particle size becomes small.

The development method commonly used in heavy oil reservoirs is steam injection thermal recovery. During steam injection and production, the flow of reservoir fluids is promoted, which also provides sufficient shear emulsification conditions for heavy oil–water emulsification. In addition, steam injection also increases the reservoir temperature, which is more suitable for W/O emulsion formation. After steam injection is complete, as the development progresses, the reservoir temperature gradually decreases and the viscosity of the W/O emulsion becomes high. At this time, the development method of chemically assisted steam is generally adopted. At present, screening and evaluation of emulsified viscosity reducers are carried out under laboratory stirring conditions. The different emulsified viscosity reducers can form different drop sizes of the O/W emulsion. When the O/W emulsion flows in the formation pores medium, the Jamin effect occurs when the oil droplets flow through the throats. The additional resistance of the flow greatly hinders the fluidity of the O/W emulsion in the pores medium. By all means, screening and evaluation of emulsified viscosity reducers should be carried out in formation pores medium.

This study used experiments to simulate the conditions in which heavy oil emulsions formed in formation pores medium. The main factors that determine the fluidity of the heavy oil emulsion and the reasons for the difference in viscosity during the flow in the formation pores medium and that measured by the laboratory rheometer are analyzed. Four kinds of emulsified viscosity reducers were screened and evaluated in formation pores medium. Then, the mechanism of the emulsified viscosity reducer in formation pores medium is analyzed combined with theoretical research. Finally, the effect of two different emulsified viscosity reducer injection methods on improving oil recovery was studied by experimental simulation, which provided guidance for designing the construction process of an oil field emulsifying viscosity reducer.

2. RESULTS AND DISCUSSION

2.1. Factors Affecting Fluidity of the W/O Emulsion. 2.1.1. Temperature. The dynamic curve of the injection pressure of the heavy oil when the permeability of the tube is 5000 mD and the water content of the heavy oil is 0% is shown in Figure 1. As the temperature increases, the stable pressure during injection decreases. The stable injection pressure is 2725 kPa at 50 °C, while the stable injection pressure is only 135 kPa at 100 °C and the injection pressure is reduced by 95%. The higher the temperature, the better the fluidity of heavy oil in the formation. This is because as the temperature increases, the thermal motion between the molecules of the heavy oil intensifies and the layered stacking effect of resin and asphaltene weakens so that the viscosity decreases dramatically. Therefore, thermal recovery is currently the most commonly used method for heavy oil development.
2.1.2. Permeability. Figure 2 and Table 1 show the experimental results of fluidity of heavy oil emulsion at different permeabilities (temperature, 70 °C; oil−water ratio, 7:3). As the permeability increases, the stable pressure during displacement becomes smaller. This means that the higher the permeability, the better the W/O emulsion flow performance in the formation. When the permeability increased from 3000 to 8000 mD, the pressure during steady displacement decreased from 2615 to 923 kPa and the stable displacement pressure decreased by 64.7%. In addition, as the permeability increases, the difference between the viscosity of W/O emulsion in formation pores medium and the viscosity measured by laboratory rheometer decreases. This is because the higher the permeability and the larger the pore space, the smaller the additional resistance of the W/O emulsion when flowing through the pores medium and the closer the viscosity is to the laboratory rheometer test results.

Table 1. Viscosity Data Statistics of Heavy Oil Emulsion at Different Permeabilities

| Permeability (mD) | 3000  | 5000  | 8000  |
|-------------------|-------|-------|-------|
| Viscosity by Rheometer (mPa·s) | 1845  | 1845  | 1845  |
| Viscosity in Pores Medium (mPa·s) | 2079  | 2026  | 1958  |
| Viscosity Deviation (%) | 12.68 | 9.81  | 6.12  |

2.1.3. Oil−Water Ratio. W/O emulsion would be formed by controlling the injection rate of heavy oil and water so as to simulate the different water content periods in the development process. The microscopic state of the different W/O emulsions and their flow capacity in the formation pores medium have been studied. The micro-emulsified state of the produced fluid, the injection pressure dynamics, and the calculated results of the produced fluid viscosity by different test methods are shown in Figures 3 and 4 and Table 2, respectively. The experimental temperature was 70 °C, and the permeability of the sand-packed tube was 5000 mD.

Figure 3. Photomicrograph of O/W emulsion with different oil−water ratios. Emulsified state when the oil−water ratio is (a) 9:1, (b) 8:2, (c) 7:3, and (d) 5:5.

Figure 4. Injecting dynamics of heavy oil emulsion fluidity experiment (70 °C).
medium and are divided into small droplets when they flow in the formation pores medium. W/O emulsion (Figure 5) would be formed when the active substances in the heavy oil migrate and adsorb onto the interface. The more complex the formation pores are and the longer the shearing time is, the more stable is the W/O emulsion formed. As the water–oil ratio decreases, the average adsorption amount of the active substance in the interface decreases. To reach a stable state, the size of droplets in emulsions at this time becomes larger.

As the injection oil–water ratio increases, the stable pressure gradually increases. The stable pressure during injection is 824 kPa as the oil–water ratio was 9:1, and the stable pressure during injection is as high as 3709 kPa as the oil–water ratio was 5:5. The stable pressure is increased by nearly 3.5 times. The external phase is oil when the heavy oil emulsion is W/O emulsion. When it is subjected to shearing, the frictional resistance is the internal frictional resistance of heavy oil. Therefore, the oil-phase film is thinner and the internal friction resistance is greater when the oil–water ratio decreases. The viscosity of the W/O emulsion increases, and its fluidity decreases. Darcy’s law can be used to calculate the viscosity of the W/O emulsion when it flows in the formation pores medium due to the stable pressure during injection and the property of the sand-packed tube. The viscosity when flowing in the medium is higher than the viscosity measured by the rheometer, and as oil–water ratio decreases, the difference gradually increases. The viscosity of the W/O emulsion when flowing in the formation pores medium is 8.67% higher than the viscosity tested by the rheometer when the oil–water ratio was 9:1. The viscosity when flowing in the formation pores medium is 13.54% higher than the viscosity measured by the rheometer when the oil–water ratio is 5:5. As the size of droplets in the W/O emulsion increases, the oil–water ratio decreases. Therefore, the viscosity of the W/O emulsion by the laboratory rheometer test method is not accurate, and it should be tested in the condition of pores medium in the simulated formation environment.

### 2.2. Evaluation of Emulsified Viscosity Reducer

The evaluation of the viscosity-reducing rate of the emulsified viscosity reducer is carried out in the laboratory by the extent to which the viscosity of the heavy oil decreases after adding the emulsified viscosity reducer solution. This evaluation method cannot fully reflect the formation conditions because the structure of the formation pores medium is very complicated. When the O/W emulsion flows in the formation pores medium, there is additional resistance caused by the Jiamin effect. Therefore, design experiments were used to evaluate four different types of emulsified viscosity reducer in a conventional laboratory (rheometer test viscosity) and the viscosity-reducing effect in the formation pores medium. This is used to study the difference between the current evaluation method and the viscosity reduction in formation pores medium. The oil–water ratio is 7:3, and the emulsified viscosity reducer content is 1% in the experiments. The experimental temperature and the permeability of the sand-packed tube were 50 °C and 5000 mD, respectively, and the experimental results are shown in Figures 6–8 and Table 3.

### Table 2. Viscosity Data Statistics of Heavy Oil Emulsion (70 °C)

| oil–water ratio | 9:1 | 8:2 | 7:3 | 5:5 |
|----------------|-----|-----|-----|-----|
| viscosity test by rheometer (mPa·s) | 1004 | 1225 | 1845 | 4556 |
| viscosity in porous medium (mPa·s) | 1094 | 1337 | 2026 | 5173 |
| viscosity deviation (%) | 8.67 | 8.98 | 9.81 | 13.54 |

![Figure 5. Schematic diagram of heavy oil–water emulsification process in the formation pores medium.](image)

![Figure 6. Injecting dynamics of heavy oil emulsion fluidity experiment with four kinds of viscosity reducers.](image)

### Table 3. Viscosity Data Statistics of Heavy Oil Emulsion

| viscosity reducer | rheometer test | pores medium |
|-------------------|----------------|--------------|
|                   | viscosity (%)  | viscosity (%) |
|                   | mPa·s          | mPa·s        |         |
| 1#                | 147            | 95.99        | 146     | 92.40 |
| 2#                | 279            | 92.39        | 497     | 86.43 |
| 3#                | 147            | 95.99        | 146     | 92.40 |
| 4#                | 279            | 92.39        | 497     | 86.43 |

Figure 6 shows the injection pressure dynamics of the four kinds of emulsified viscosity reducer emulsified with heavy oil in the formation pores medium. Figure 9 shows the micro-emulsification state of four emulsified viscosity reducers and heavy oil in the formation pores medium, and Figure 10 shows the drop size distribution of O/W emulsions. Although all of the four emulsified viscosity reducers can form O/W emulsion in the formation pores medium, the droplet size of the O/W emulsion varies greatly. It can be seen from the micro-emulsification state that the O/W emulsion carried out by emulsifying viscosity reducer 3# is smaller and uniform. Emulsified viscosity reducer 2# has the largest O/W emulsion droplets, and the average droplet size exceeds 30 μm. The average droplet sizes of the O/W emulsions formed by emulsified viscosity reducers 1# and 4# are larger than 20 μm. The emulsion droplets formed by emulsifying viscosity reducer...
3# have the smallest O/W emulsion droplets (less than 10 μm). The additional resistance of different sizes of O/W emulsion droplets when flowing through the pores medium is also different, so the stable pressure during injection also varies greatly. The stable pressure of emulsified viscosity reducer 3# is only 210 kPa, but that of emulsified viscosity reducer 2# is as high as 751 kPa.

Table 3 shows the results of the viscosity and viscosity reduction rate of O/W emulsion calculated by two methods. The viscosity reduction rates are very high, i.e., above 92%, when the viscosity reduction effect of the four emulsified viscosity reducer agents is evaluated with a rheometer. However, the viscosity reduction effect in formation pores medium is not as satisfied as the results of the rheometer test. The viscosity reduction rates of the four emulsified viscosity reducers all decreased to a certain extent during the evaluation of the formation pores medium, of which the viscosity reduction rate of emulsified viscosity reducer 2# was the most obvious. The viscosity reduction rate of emulsified viscosity reducer 2# was 93.02%, as tested by the rheometer, but the viscosity reduction rate in the formation pores medium was only 73.04%.

From the view of emulsification state, emulsification viscosity reducer 3# has the best emulsification effect and the O/W emulsion droplets are the smallest, with an average diameter of less than 10 μm (Figure 7a). The diameter of emulsion droplets formed by reducers 1# and 4# is about 15 μm (Figure 7b,d), while the diameter of emulsion droplets formed by reducer 2# is the largest, reaching more than 20 μm (Figure 7b).

Different test methods lead to different experimental results, because although all of the four emulsified viscosity reducers form O/W emulsion in the formation pores medium, the emulsification states are very different (Figure 8). On the one hand, when the viscosity is tested by a rheometer, the distance between the test plates (1 mm) is larger than the diameter of the emulsion droplets. The external phase of the O/W emulsion is water phase, where slippage is likely to occur, which leads to inaccurate test results. On the other hand, when the O/W emulsion flows through the formation pores medium, due to the difference in the size of the emulsion droplets, it produces different degrees of Jamin effect, as shown in Figure 9. When the diameter of the oil droplets is much larger than the diameter of the pore throat (Figure 9a), the additional resistance caused by the Jamin effect is very large when the O/W emulsion flows in the formation pores medium, and the pressure during steady flow is also high. The formation viscosity reduction effect is poor under this condition. As the O/W emulsion droplet size decreases (Figure 9b), the Jamin effect gradually weakens, the additional resistance decreases, the flow pressure during steady flow also decreases, and the viscosity reduction rate becomes better. When the diameter of O/W emulsion droplets is smaller than the diameter of the pore throat (Figure 9c), the Jamin effect is almost nonexistent. The viscosity reduction rate is the best, and the stable pressure during injection is also the smallest under this condition.

The viscosity reduction rate calculated by the conventional rheometer to evaluate the emulsified viscosity reducer is far inaccurate compared to the viscosity reduction effect in the formation of pores medium. Conventional methods are inaccurate in evaluating emulsified viscosity reducer, whose viscosity-reducing effect should be evaluated in the formation pores medium. In addition to the emulsifying ability of the emulsified viscosity reducer, the relationship between the diameter of the oil-phase droplets in the O/W emulsion and the diameter of the formation pore throats is also the main basis for the evaluation of the emulsified viscosity reducer.

2.3. Mechanism of Viscosity Reduction of Emulsified Viscosity Reducer. As the development progresses, when emulsified viscosity reducers are used, the formation heavy oil generally has a certain water content. To explain the adsorption effect of emulsified viscosity reducer molecules replacing the active substances of heavy oil at the oil–water interface, the emulsification process of the emulsified viscosity reducer solution was studied. The emulsified viscosity reducer solution was used to continuously wash the W/O emulsion. The change in the oil–water interface is continuously recorded.
by a microscope. The microscopic observation results of the action process on the contact surface are shown in Figure 10.

When the emulsified viscosity reducer solution contacts the W/O emulsion, the substitution effect gradually occurs (Figure 10). First, the emulsified viscosity reducer solution “cuts” the W/O emulsion and forms a large bulk of water in oil in water (W/O/W) emulsions by which the contact area is increased. Then, in the process of “peeling off” the large W/O emulsion, it is further cut to form a W/O/W emulsion with smaller droplets. Figure 11 shows the reduction mechanism of the emulsified viscosity reducer. The mechanism of emulsified viscosity reducer is to replace the adsorption of active substances in heavy oil on the interface to form an O/W emulsion by which the viscosity of heavy oil emulsion can be greatly reduced. When the emulsified viscosity reducer contacts the W/O emulsion, the emulsified viscosity reducer can pass through parts of the heavy oil film, connecting a part of the water-phase droplets, increasing the contact area of the emulsified viscosity reducer with the heavy oil. It enhanced the substitution on the interface, which is shown as the cutting effect on the W/O emulsion. When the bulk W/O emulsion was peeled off, the substitution of viscosity reducer molecules on the active substance of the heavy oil on the interface film continued and the bulk W/O emulsion droplets continued to be cut. Eventually, a stable smaller W/O/W emulsion is formed.

2.4. Suggestions on Improving the Effect of Emulsified Viscosity Reducer in the Oil Field. When an emulsified viscosity reducer is used in the oil field, the effect is usually worse than the effect evaluated in the laboratory. On the one hand, when the O/W emulsion droplets flow in the formation pores medium, the additional resistance increases due to the Jamin effect. On the other hand, in laboratory evaluation, the experiments are usually carried out by stirring. In this way, the contact area is large, which accelerates the substitution effect at the interface. However, the substitution efficiency is often low under formation conditions.

It is crucial to study the effect of different emulsified viscosity reducer injection methods on enhanced oil recovery (EOR in short). Experiment V-1 was developed by means of
water flooding (1PV) + emulsified viscosity reducer solution (0.5PV) + subsequent water flooding (1PV). Experiment V-2 was developed using water flooding (1PV) + emulsified viscosity reducer solution flooding (1.5PV). The amount of water injected and the quality of the emulsified viscosity reducer were the same in both experiments. The other experimental conditions of the two experiments are the same. The emulsified viscosity reducer used during the experiments is 4#, the injection rate of water and emulsified viscosity reducer solution is 0.5 mL/min, and the experiment temperature is 50 °C. The design and oil recovery of the two development methods are shown in Table 4, and the development dynamics are shown in Figures 12 and 13.

Table 4. Design of Viscosity Reducer Injection Method and Experiment Result Statistics

| Experiment | Injection Method | Water Flooding Recovery (%) | Ultimate Recovery (%) | EOR (%) |
|------------|-----------------|-----------------------------|-----------------------|--------|
| V-1        | Water flooding + 0.5PV emulsified viscosity reducer solution (concentration is 1%) + water flooding | 37.5                  | 44.3                  | 6.8    |
| V-2        | Water flooding + low concentration emulsified viscosity reducer solution (same quality of viscosity reducer) | 38.4                  | 54.1                  | 15.7   |

Figure 12. Development dynamics of experiment V-1.

Figure 13. Development dynamics of experiment V-2.

The difference between the two types of development methods for EOR is quite different (Table 4). The heavy oil recovery of the water flooding + emulsified viscosity reducer solution + subsequent water flooding development method increased from 37.5 to 44.3%, and the EOR was 6.8%. The heavy oil recovery of the water flooding + emulsified viscosity reducer solution flooding development method increased from 38.4 to 54.1%, and the EOR was 15.7%. In the case of same water volume and quality of emulsified viscosity reducer injection, the difference between the two development methods to EOR is as high as 8.9%. Studies have shown that the injection method of emulsified viscosity reducer also has a great influence.

Due to the difference in viscosity between heavy oil and water, water would undergo fingering in the reservoir. When the water flow channel reaches the oil well, the water cut rises rapidly, and the development rapidly decreases when the injection of emulsified viscosity reducer is a better choice to enhance heavy oil recovery. However, emulsification of the emulsified viscosity reducer and heavy oil is also a gradual process. Therefore, when an emulsified viscosity reducer was used for EOR, sufficient contact emulsification time should be ensured. As shown in Figure 12, when the development method of water flooding + emulsified viscosity reducer solution + subsequent water flooding is adopted, the contact time of the emulsified viscosity reducer with the heavy oil after injection into the formation is short. Most emulsified viscosity reducer molecules would not participate in the interface replacement and directly flow out with water. The pressure of the subsequent water flooding quickly decreased, the water content rapidly increased again, and the EOR was poor. Figure 13 is the development of water flooding + emulsified viscosity reducer solution flooding. Although the emulsified viscosity reducer concentration in this development mode is low, it provides more time for the interfacial substitution of the emulsified viscosity reducer molecules. As the heavy oil on the contact surface is peeled off by emulsification, more molecules participate in the interface replacement. As the development progresses, the heavy oil was emulsified and produced, the water channel gradually became larger, the displacement pressure slowly decreased, and the water content increased slowly. Therefore, in the oil field development process, the contact area should be increased as much as possible, or more time should be provided for emulsification. This can effectively result in EOR of emulsified viscosity reducer on oil field application.

3. CONCLUSIONS

In this study, the following conclusions were obtained through experimental research and mechanism analysis on the fluidity of heavy oil emulsion in formation pores medium.

(1) The main factors determining the flowability of heavy oil emulsion are temperature, reservoir permeability, water content, and the addition of emulsified viscosity reducer. The stable injection pressure decreases 95% when the temperature rises from 50 to 100 °C. When the permeability of sand-packed tube increased from 3000 to 8000 mD, the stable displacement pressure decreased by 64.7%. The stable pressure is increased by nearly 3.5 times when the oil–water ratio is decreased from 9:1 to 5:5. When the emulsified viscosity reducer is added (3#, 1%), the stable injection pressure is reduced by 86% (70 °C, oil–water ratio is 7:3).
(2) The viscosity of the W/O emulsion flowing in formation pores medium is higher than the viscosity tested in the laboratory rheometer, and the proportion of viscosity increase is greater when the oil−water ratio decreases. The viscosity when flowing in the formation pores medium is 8.67% higher than the viscosity tested by the rheometer (oil−water ratio, 9:1). The viscosity when flowing in the formation pores medium is 13.54% higher than the viscosity tested by the rheometer (oil−water ratio, 5:5). This is because as the oil-to-water ratio increases, the droplets of the W/O emulsion increase and the additional resistance obtained when passing through the pore throat increases.

(3) Different types of emulsified viscosity reducers have different O/W emulsions formed by emulsification in the formation pores medium, and their flowability in formation pores medium is also different. When the diameter of the oil-phase droplets is larger than the diameter of the pore throat, the additional resistance caused by the Jamin effect is large when droplets flow in the formation pores medium. The larger the droplets, the greater the influence of the Jamin effect and the higher the additional resistance during the flow. The emulsified viscosity reducer should be screened to evaluate the formation pores medium.

(4) The substitution effect occurs as soon as the W/O emulsion contacts with the emulsified viscosity reducer solution. First, the emulsified viscosity reducer solution cuts the W/O emulsion to a large bulk of W/O/W emulsion, then the contact area is increased. Then, in the process of peeling off the large W/O emulsion, it further cuts to form a W/O/W emulsion with smaller droplets.

(5) The injection method of emulsified viscosity reducer also has a great influence on its effect. With the same volume of water injection and quality of emulsified viscosity reducer, the enhanced oil recovery of the development method of water flooding + emulsified viscosity reducer solution flooding is 8.9% higher than that of water flooding + emulsified viscosity reducer solution + subsequent water flooding. The contact area of the emulsified viscosity reducer solution and heavy oil should be increased as much as possible, or more time should be provided for emulsification in the oil field development process. This can effectively improve the EOR of emulsified viscosity reducer on oil field application.

4. EXPERIMENTAL SECTION

4.1. Materials. The heavy oil used in experiments was provided by Bohai Oilfield (saturated hydrocarbon, 53.6%; aromatic hydrocarbon, 25.0%; resin, 20.5%; and asphaltene, 0.9%). The viscosity−temperature curve of heavy oil is shown in Figure 14. The water used in all experiments was deionized.

4.2. Fluidity of W/O Emulsions in Formation Pores Medium. Emulsification of heavy oil and water occurred when they flowed in the formation pores medium. To study the true emulsification process and emulsification state of heavy oil−water under formation conditions, the experimental device shown in Figure 15 was used to conduct W/O emulsion fluidity experiment. Two intermediate containers were filled with dehydrated heavy oil and water. The total injection rate is 0.5 mL/min, and the injection rate is distributed between two constant pumps to obtain W/O emulsions with different oil−water ratios (9:1, 8:2, 7:3, 6:4, and 5:5). For example, when the injection rate of dehydrated heavy oil is 0.45 mL/min and the injection rate of water is 0.05 mL/min, the oil/water ratio of the W/O emulsion is 9:1. The fluidity experiment under different temperature conditions is also studied, i.e., 50, 70, and 100 °C. After the heavy oil and water were injected into the sand-packed tube, they are fully emulsified and form W/O emulsions by the shear action of the formation pores medium. The pressure dynamics during the injection process was measured by a pressure sensor installed at the entrance of the sand-packed tube. The heavy oil emulsions were sampled by a liquid sampling device. In addition, the viscosity test and micro-emulsified state calculations were carried out on the emulsions of the outlet.

4.3. Fluidity of O/W Emulsions in Formation Pores Medium. The effect of emulsified viscosity reducer is usually measured by the viscosity-reducing rate of heavy oil when it was added into the heavy oil and tested by a rheometer. The emulsification method is usually agitated. This evaluation method could not fully reflect the actual emulsification in the formation conditions. Therefore, the experimental device of Figure 2 was used for the formation of O/W emulsions due to the shear action of the formation pores medium by heavy oil and emulsified viscosity reducer. The viscosity-reducing effects of the four types of emulsified viscosity reducers were evaluated. During the experiment, the injection speed of the heavy oil was 0.35 mL/min and the injection speed of the emulsified viscosity reducer solution was 0.15 mL/min (the ratio of oil−water was 7:3). The emulsified viscosity reducer concentration in the water solution was 3.33% so that the emulsified viscosity reducer accounts for 1% of the total mass of the emulsion. The pressure dynamics during the injection process was measured by a pressure sensor installed at the entrance of the tube. The heavy oil emulsion was sampled by a liquid sampling device. In addition, viscosity test and micro-emulsified state calculations were carried out on the emulsions.
of the outlet. The temperature during the experiments was 50 °C.

4.4. Viscosity Determination of Heavy Oil Emulsion. Rheometers are used to test the viscosity of fluids during laboratory studies. For heavy oil emulsions (W/O or O/W), the dispersed water-/oil-phase droplets all have a certain size. The Jamin effect is generated when the droplets pass through the small pore of the formation, which increases the flow resistance of the heavy oil emulsion. When using a rheometer for viscosity testing, the influence of the Jamin effect produced by the dispersed-phase droplets passing through the porous medium cannot be reflected. To clarify the influence of the actual flow resistance of the heavy oil emulsion in the formation pores medium, the viscosity of the heavy oil emulsion in different conditions was tested. On the one hand, by sampling heavy oil emulsions at the outlet of the above experiments, their viscosity is tested using a HAAKE MARSIII rheometer (the commercial modular rheometer with a 20 mm plate/plate system, the gap was 1.0 mm, and the shear rate was 5 s⁻¹). On the other hand, by stabilizing the pressure during injection and the property of the sand-packed tube, Darcy’s law can be used to calculate the viscosity of emulsions flowing in the formation pores medium.

4.5. Micro-emulsification State of Heavy Oil Emulsion. To explain the micro-emulsification state of the heavy oil emulsions formed by the shear action of the formation pore medium from a microscopic perspective, the micro-emulsion state of the emulsion was observed by using an electron microscope. For the heavy oil emulsions (O/W and W/O) formed during the experiments, the micro-emulsification states were observed. The molecules of emulsified viscosity reducer can be adsorbed on the interface when its solution is in contact with heavy oil and divides the heavy oil into oil droplets that disperse in water solution. The heavy oil droplets in the O/W emulsion can be carried by the water solution so that heavy oil recovery can be improved. When conducting evaluation experiments in the laboratory, stirring is generally used to fully mix the heavy oil and water solution. However, the oil phase is usually relatively static and a flowing water phase is used to emulsify the heavy oil under actual reservoir conditions. Therefore, the emulsification process and emulsification state may be different from the routine evaluation in the lab. To simulate the actual emulsification process in the reservoir, the emulsified viscosity reducer solution was used to continuously wash the W/O emulsion (The W/O emulsion is relatively static, and the emulsified viscosity reducer solution continuously flows through.) The change in the interface is continuously recorded by a microscope to study the mechanism of the emulsified viscosity reducer.

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Notes
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