Parameter optimization and field test of nano variable-viscosity slick water fracturing in Changqing shale reservoir

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Abstract. After the development of the directional and horizontal wells of Chang 7 shale reservoir in Ordos Basin, the formation pressure decreases rapidly and the production decreases naturally. There is an urgent need for fracturing fluid with oil displacement and enhancing oil recovery (EOR) function, and the on-site fracturing process parameters are optimized. Through laboratory experimental research, nano variable-viscosity slick water has the advantages of high drag reduction, strong sand-carrying, and imbibition oil displacement capacity, which significantly improves the deficiency of sand-carrying and oil displacement performance of conventional slick water. At the same time, the numerical simulation shows that when the injection displacement is 18 m³/min, the cluster spacing is 5 m, the number of perforation clusters is 7 and the sand addition intensity is 3 t/m, the fracturing reconstruction volume can be maximized, which is the optimal parameter for fracturing construction of Chang 7 reservoir. Combined with nano variable-viscosity slick water and optimal construction parameters, field fracturing tests were carried out in 13 wells, including 9 directional wells and 4 horizontal wells; The average daily oil production of horizontal wells is 17.77 t, the cumulative oil production is 377.33 t, and the production is increased by 10~15 times. It is a new and effective method for the development of Changqing shale reservoir to combine the nano variable-viscosity slick water system of strong oil displacement and sand-carrying capacity with high displacement construction technology.

1. Introduction

In recent years, shale oil has become the main unconventional stimulation resource of oilfields. Slick water volume fracturing is an effective means of shale reservoir development [1-2]. Chang 7 reservoir in Changqing Oilfield is the main section of shale oil development. The trap area is about 1600 km², the reservoir thickness is 4~7 m, and the average oil saturation reaches about 70 %. The reservoir is rich in oil and gas resources, so it is in urgent need of economic and effective exploitation means [3-4]. However, the wettability of Chang 7 reservoir is complex, with neutral-weak hydrophilic wettability and strong heterogeneity, micro-nano pores are the main reservoir space of shale oil in Ordos Basin [5], and the formation energy decays rapidly. Traditionally, water flooding is the main method to supplement formation energy. For example, polymer flooding [6] is used in Henan Oilfield.
and surfactant flooding [7] is used in Louden and other blocks in the United States, which has achieved good oil displacement effect; However, it is difficult to apply this method in unconventional reservoirs, which is easy to produce blockage, water lock and Jamin effect, and the injection pressure is high [8]. The micro-nano pore throats of unconventional reservoirs are developed. If polymer flooding is used, it will also cause the problem of unable injection and great damage to the formation. The specific surface area of unconventional reservoir is large, if surfactant flooding is used, it will face serious adsorption near the well zone and small action area, which can not produce an effect at the far end of the crack.

Therefore, with the gradual reduction of formation energy, the productivity of the single well decreases gradually. It is particularly important to supplement formation energy by fracturing, forming high-speed flow channels of oil and gas, enhancing fracture conductivity, and improving production[9]; Changqing and other oilfields have also conducted fracturing tests on shale reservoirs and put forward the concept of gel fracturing and mixed production, but there are still some problems, such as great damage to the formation, weak oil imbibition displacement capacity, complex process and difficult connection [10-11]. At the same time, the conventional slick water fracturing being implemented has the problem of weak sand-carrying capacity, and the proppant can not effectively support fracture making, resulting in the dilemma of low recovery [12-13].

Given the above problems, through the laboratory core experiment of Changqing shale reservoir, a kind of nano variable-viscosity sand-carrying slick water system with oil imbibition displacement function is developed and optimized to solve the problem of insufficient sand-carrying and oil displacement capacity of fracturing fluid in Changqing shale reservoir. At the same time, the unconventional fracturing model (UFM) is used to optimize and fit the parameters including injection displacement, cluster spacing, and perforation cluster number, to maximize the fracture volume. Combined with the construction technology of high displacement and the nano variable-viscosity slick water system of oil displacement and strong sand-carrying capacity, field fracturing tests were carried out in 13 wells, and good results of increasing production by 10~15 times were obtained.

2. The basic properties of nano variable-viscosity slick water
Nano variable-viscosity slick water mainly consists of nanoemulsion CNI-A synthesized in the laboratory and variable-viscosity drag reducing agent CNI-B. Among them, CNI-A contains surfactants, alcohols, oil cores, and other components, and CNI-B is composed of polyacrylamide or polyacrylamide copolymer. Compared with conventional slick water, nano variable-viscosity slick water can not only exhibit the imbibition effect of nanoemulsion CNI-A, but also reflect the low concentration drag reduction and high concentration sand-carrying ability of variable-viscosity drag reducing agent CNI-B, and carry out fracturing test in the field. The main ingredient of conventional slick water is similar to CNI-B, and the difference is that it is powdery and needs to be dissolved and prepared in advance. The above reagents are all from Changqing downhole oilfield additives company.

To test the related properties of nano variable-viscosity slick water (0.10 % nanoemulsion + different concentration drag reducing agent, the selected nanoemulsion concentration was considered by field economy), the drag reduction rate, dynamic sand-carrying, and imbibition modification tests were carried out and compared with the conventional slickwater.

2.1. Drag reduction performance
A self-made loop drag test device was used for the experiment [14]. As can be seen in Figure 1, when the drag reducing agent is 0.10 % (low concentration), the drag reduction rate of nano variable-viscosity slick water can reach more than 75 %, the drag reduction performance is slightly better than that of conventional slick water, and it can remain stable at the high flow rate, but the drag reduction effect of conventional slick water decreases.
2.2. Sand-carrying capacity

In the experiment, 30~50 mesh quartz sand with 10 % and 30 % sand ratio were selected respectively. The glass plate fracture model was used for dynamic sand-carrying experiment. The length and height of the model are 30 cm and 15 cm respectively, and the fracture width is 0.4 cm. The main experimental steps are to fully mix the fracturing fluid with sand, inject it into the fracture model with an air pump at a certain flow rate (10 L/min), the injection direction is from left to right, and then observe the sand-carrying condition of the liquid in the model.

As shown in Figure 2, in the simulated fracture, quartz sand is carried in both 0.30 % (high concentration) nano variable-viscosity slick water and conventional slick water, in which the sand at the end of conventional slick water is slightly settled, while nano variable-viscosity slick water is well carried.

Figure 3 shows two kinds of slick water with constant concentration. When the sand ratio increases to 30 %, it can be found that the nano variable-viscosity slick water still has a strong carrying effect, while the sand in the conventional slick water has settled down, and the front end of the sand embankment is high and the rear end is low, so it can not be carried. Compared with conventional slick water, the nano variable-viscosity slick water improves the sand-carrying capacity and can carry sand with 30 % sand ratio.

![Figure 1. Drag reduction rate test.](image)

![Figure 2. Comparison of dynamic sand-carrying situation of two kinds of slick water under 10% sand ratio.](image)

![Figure 3. Comparison of dynamic sand-carrying situation of two kinds of slick water under 30% sand ratio](image)
2.3. Wetting modification
The original wettability of core affects the imbibition quantity and speed of water phase, and restricts the process of imbibition and displacement. Water wetted cores are prone to imbibition displacement, while oil wetted cores are difficult to imbibition displacement. Therefore, wettability is the key factor of imbibition oil displacement in shale reservoirs, and water wettability is the favorable condition of imbibition oil displacement. A total of 21 cores from 7 wells in three blocks of Chang 7 reservoir were tested for wetting angle, porosity, and permeability [15]. It was found that the original wettability of the reservoir was neutral weak hydrophilic, and the average value of wetting angle was 83.47 ° (Figure 4); At the same time, under the action of nano variable-viscosity slick water fracturing fluid, the wettability of the reservoir changes, the wetting angle increases by 36.4~52.6 %, and the hydrophilicity of the reservoir is enhanced.

![Figure 4. Wetting angle test before and after modification.](image1)

2.4. Imbibition efficiency
After taking Changqing core and saturated crude oil, the nano variable-viscosity slick water (0.10% nanoemulsion +0.30% drag reducing agent) and conventional slick water gel breaker were used to carry out the imbibition experiment by imbibition bottles [15] The experimental results are as shown in Figure 5, the recovery rate of the nano variable-viscosity slick water gel breaker is up to 30 %, which is 7 % higher than that of conventional slick water, and the oil displacement effect is obvious.

![Figure 5. Laboratory imbibition recovery test of Changqing core.](image2)
sand-carrying capacity at high concentration, and obvious imbibition oil displacement effect. Therefore, it is used for fracturing trials on site.

3. Optimization of fracturing parameters in horizontal well section

3.1. Model establishment and scheme design
To study the effect of nano variable-viscosity slick water fracturing under different construction parameters, UFM model (unconventional fracturing model) is used for hydraulic fracturing numerical simulation in this paper [16-17]. Based on the field data of Changqing shale reservoir, this paper establishes the geological model and horizontal well model. Among them, the thickness of the target layer of the reservoir is 60 m, which is divided into 20 small layers, and the thickness of a single layer is 2~5 m. The vertical depth of horizontal well is 1580 m and the length of horizontal section is 1450 m. The geological model and single well diagram are shown in Figure 6. At the same time, to reflect the effect of low viscosity slick water fracture making and high viscosity slick water sand carrying, the first 40％ fluid of fracturing fluid is low viscosity slick water, and then 60％ fluid is variable-viscosity slick water. According to the indoor test experiment, the viscosity of low viscosity slick water is 10 mPa·s, while the viscosity of high viscosity slick water is 80 mPa·s. To analyze the influence of different construction parameters on the effect of hydraulic fracturing, this paper compares the hydraulic fracture propagation law under different displacement, cluster spacing, cluster number, and sand addition strength. See Table. 1 for the specific scheme setting.

![Figure 6. Geological modeling based on petrel.](image)

| Scheme   | Displacement (m³/min) | Cluster spacing (m) | Number of clusters | Sand addition strength (t/m) |
|----------|-----------------------|---------------------|--------------------|-----------------------------|
| Scheme 1 | 8                     | 3                   | 3                  | 2                           |
| Scheme 2 | 12                    | 5                   | 5                  | 3                           |
| Scheme 3 | 14                    | 7                   | 7                  | 4                           |
| Scheme 4 | 18                    | 10                  | 10                 | 5                           |

3.2. Research of fracturing parameters
In this paper, the effects of parameters such as displacement, cluster spacing, perforation cluster, and sand addition strength on the fracturing effect of nano variable-viscosity slick water are compared and optimized.
To study the improvement effect of different displacements on nano variable-viscosity slick water fracturing, this paper compares the hydraulic fracture propagation patterns under four different displacements: 8 m³/min, 12 m³/min, 14 m³/min, and 18 m³/min. Figure 7 shows the corresponding support fracture morphology. Under low displacement, the width of fracture support fracture near the fracture is large, and proppant is accumulated near the well, which is easy to cause sand plugging near the well (Figure 7(a)); Under high displacement, the width of the support joint in the fracture is more uniform (Figure 7(d)). In addition, under the influence of stress interference between fractures, the expansion of hydraulic fractures does not simply expand along the direction of the maximum horizontal principal stress, but there is bending and deflection. There is no obvious change in fracture deflection under different displacements, but there are differences in the distribution of fracture length. The average fracture length under high displacement (the average length is 438.8 m) is generally higher than the fracture length at low displacement (the average length is 326.8 m). The above fracture morphology results show that high injection displacement is not only conducive to the uniform placement of proppant but also conducive to the increase of fracture length. When the displacement is 18 m³/min, the fracture reconstruction area is the largest, but it should be determined according to the power of field construction equipment.

Figure 7. Fracture morphology under different injection displacements.

Under the influence of stress interference factors, the fracture cluster spacing has a great influence on the effect of hydraulic fracturing. To study the influence of cluster spacing on the effect of nano variable-viscosity slick water fracturing, this paper compares the hydraulic fracture propagation patterns under the conditions of cluster spacing of 3 m, 5 m, 7 m, and 10 m. When the cluster spacing is small, due to the strong interaction between fractures, the sand-carrying performance of high viscosity slick water is reduced, and the fractures can not be evenly supported (Figure 8(a)). Under large cluster spacing, the fractures have bending and deflection (Figure 8(d)); As shown in Figure 8(c), when the cluster spacing is 5 m, the proppant is laid relatively evenly in the fracture, and the fracture width distribution is relatively uniform.

Figure 8. Fracture morphology under different cluster spacing.
In addition to the influence of cluster spacing, the size of stress interference should also consider the influence of the number of perforation clusters in the fracturing section. Therefore, four hydraulic fracture propagation patterns with different cluster numbers of 3 clusters, 5 clusters, 7 clusters, and 10 clusters/segment are compared. When the number of clusters is low, the hydraulic fractures have serious bending and deflection near the well, resulting in the uneven distribution of fracture width (Figure 9(a)). With the increase of the number of clusters, the width is gradually uniform; As shown in Figure 9(c), when the number of perforation clusters is 7 clusters/section, the proppant is relatively evenly laid in the fracture, and the fracture width distribution is relatively uniform.

Figure 9. Fracture morphology under different cluster number.

Larger sand addition strength is conducive to increasing the fracture support area and increasing the fracture conductivity, but at the same time, larger sand addition strength and easy to cause sand plugging events, which cause great harm to the field construction. In this paper, the hydraulic fracture propagation patterns under four different sand adding intensities of 2 t/m, 3 t/m, 4 t/m, 5 t/m are compared. Under low sand adding strength, the overall fracture width is small, but the distribution of proppant is relatively uniform, and the phenomenon of wide local fractures does not occur (Figure 10(a)). With the increase of sand addition strength, the fracture width in the joint area gradually increases, but the local fracture width in the joint is large, which indicates that proppant accumulates here, which will cause sand plugging in the fracture, thus affecting the normal construction on site. As shown in Figure 10(c), with the increase of sand strength, the fracture reconstruction area first increases and then decreases, and the fracture reconstruction area is the largest at 3 t/m.

Figure 10. Fracture morphology under different sand addition strength.
3.3. Optimization of fracturing parameters

To quantitatively evaluate the effect of hydraulic fracturing construction parameters and optimize the field fracturing construction scheme, this paper summarizes the fracture reconstruction area under different parameters, as shown in Figure 11. When the displacement is 18 m$^3$/min, the fracture reconstruction area is the largest, but it should be determined according to the power of field construction equipment. With the increase of cluster spacing, the fracture reconstruction area first increases and then decreases. When the cluster spacing is 5m, the fracture reconstruction area is the largest. Similar phenomena also exist in parameters such as perforation cluster number and sand addition strength. Therefore, according to the results of maximizing the volume of fracturing reconstruction, the optimization results of fracturing parameters for this block are as follows: the injection displacement is 18 m$^3$/min, the cluster spacing is 5 m, the number of perforation clusters is 7, and the sand addition strength is 3 t/m.

Through comparison, it can be found that displacement is the main control factor affecting the fracture reconstruction area, which will also be highlighted in the field fracturing experiment.

4. Analysis of field and stimulation mechanism

4.1. Fracturing curve analysis

Nano variable-viscosity slick water system has been used for fracturing trials in Changqing, China. At present, 13 wells have been successfully fractured. Figure 12 is the fracturing operation curve of the first three sections of one horizontal well.

Taking the horizontal well of Changqing field experimental well 1 as an example, the horizontal section is 1450 meters long, and 22 sections of volume fracturing are subdivided through DMS soluble ball socket. As shown in Figure 10, the fracturing fluid construction displacement is 12.0 m$^3$/min. It can be found that the sand addition is stable, the sand concentration can reach more than 30 %, the pressure fluctuation range is small, the total liquid amount into the ground is 25911 m$^3$, and the total sand addition is 2488.7 m$^3$. 

![Figure 11. Comparison of fracture reconstruction area under different parameters.](image-url)
4.2. Fracturing production effect

At the initial stage of the pilot test of nano variable-viscosity slick water fracturing in Changqing shale reservoir, several times of stimulation effects can be achieved. The reasons for good results are as follows: first, the oil saturation of shale oil reservoir is high, which can reach about 70% on average; Second, after the implementation of volume fracturing in shale reservoir, the reservoir fluid channel forms a fracture network, the contact area between fracturing fluid and reservoir is large, and the oil-water exchange is fast and sufficient; Third, shale oil reservoir belongs to mixed wetting, nano-emulsion can be modified to water wetting, core pore throats and surface crude oil are easy to be driven out. In addition, the presence of polymers can prolong the time of imbibition of nano-emulsion.

As shown in Figure 13, the oil production changes of experimental well 1 and adjacent wells are compared. The adjacent well is fractured with conventional slick water. The construction parameters are injection displacement of 8 m³/min, cluster spacing of 3 m, number of perforation clusters of 5, and sand addition intensity of 2 t/m. Well experiment 1 uses nano variable-viscosity slick water for fracturing. After optimization, its construction parameters are injection displacement of 12 m³/min, cluster spacing of 5 m, number of perforation clusters of 7, and sand addition intensity of 3 t/m; Compared with adjacent well, experiment well 1 significantly improves the displacement parameters. The average daily oil production of experimental well 1 is 17.77 t, and the cumulative oil production is 377.33 t, which is much higher than that of conventional slick water fracturing. The fracturing of nano variable-viscosity slick water system has achieved initial results.
4.3. Discussion on yield increasing mechanism

Hydraulic fracturing mainly has several functions: increasing or maintaining formation pressure, water absorption and oil drainage by capillary force, gravity differentiation of fluid in fracture, etc; Changqing shale oil reservoir rocks are suitable for wetting modification, and the soaking process mainly plays the role of imbibition replacement and gravity replacement.

The capillary force decreases with the decrease of interfacial tension, especially low interfacial tension is not conducive to imbibition, but the increase of interfacial tension will increase the adhesion work. Therefore, to improve the imbibition oil displacement effect of shale reservoirs, appropriate interfacial tension should be selected. The interfacial tension of nanoemulsion and crude oil can be measured to be 2.80 mN/m by the surface tension tester. In addition, the average porosity of Chang 7 reservoir core is 8.24 % and the permeability is 0.02953 mD.

By substituting the above experimental data into formula (1) [18], it can be obtained that the Bond number $N_B^{-1}$ is 1373.22, which is much greater than 5, indicating that capillary force displacement is dominant and dominates the imbibition recovery.

$$N_B^{-1} = C \frac{2 \sigma \cos \theta \sqrt{\phi/k}}{\Delta \rho g H}$$  \hspace{1cm} (1)

Where, $C$ is related to the geometric size of porous media, for circular capillary model, $C = 0.4; \sigma$ is oil-water interfacial tension, mN/m; $\theta$ is the wetting angle, °; $\phi$ is the porosity of porous media; $k$ is the permeability of porous media, mD; $\Delta \rho$ is the density difference between oil and water, g/cm$^3$; $g$ is the gravitational acceleration, cm/s$^2$; $H$ is the height of porous media, the standard 5 cm core is used in this experiment.

5. Conclusions

(1) Nano variable-viscosity slick water has the characteristics of wetting modification, high drag reduction, high sand-carrying, and strong imbibition performance. It is a multifunctional fracturing fluid system. Its drag reduction rate can be greater than 75 %, sand-carrying ratio can exceed 30 %, and oil displacement rate can reach more than 30 %.

(2) Displacement is the main controlling factor of Changqing shale oil pressure fracture affecting the fracture reconstruction area. Cluster spacing, perforation cluster number, and sand addition strength have little influence on it. The optimal fracturing parameters are: the injection discharge is 18 m$^3$/min, the cluster spacing is 5 m, the number of perforation clusters is 7, and the sand addition intensity is 3 t/m.

(3) The on-site fracturing of nano variable-viscosity slick water has achieved 10~15 times production increase effect. Large displacement construction, enhanced sand-carrying, and imbibition oil displacement are considered to be three main production increase mechanisms, which are being popularized and applied in the field at present.

Acknowledgments

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References

[1] Cox S A, Cook D and Dunek K Unconventional Resource Play Evaluation: A Look at the Bakken Shale Play of North Dakota 2008 SPE
[2] Wang J Study on high efficiency slick water fracturing fluid system suitable for shale gas reservoir 2019 Energy Chem Ind
[3] Fu J H, Li S X, Niu X B, Deng X Q and Zhou X P Geological characteristics and exploration of shale oil in Chang 7 Member of Triassic Yan chang Formation, Ordos Basin, NW China 2020 Pet Explor Dev 47(05) 931-945
[4] Han W X, Hou L H, Yao J L and Ma W J Characteristic and formation mechanism of Chang 7 tight sandstone reservoir in Ordos basin 2016 *J China Univ Min Technol*

[5] Long S, Peng Y and Liu H Micro- and nano-scale geological characteristics of the shale in the first Member of Lower Silurian Longmaxi Fm in SE Sichuan Basin 2017 *Nat Gas Ind* 37 23-30

[6] Lin Y, Huang H Q and Wang Q Laboratory research and field application of polymer flooding technology with high concentration and large pore volume 2014 *Oilfield Chem* 31 274-7

[7] Pursley S A and Production E A Field Test of Surfactant Flooding, Loudon, Illinois 1973 *J Pet Technol* 25(07) 793-802

[8] Bertoncello A, Wallace J and Blyton C Imbibition and Water Blockage in Unconventional Reservoirs: WellManagement Implications During Flowback and Early Production 2014 *SPE Reservoir Eval Eng* 17(04) 497-506

[9] Duan H, Li H T and Dai J Q Horizontal well fracturing mode of "increasing net pressure, promoting network fracture and keeping conductivity" for the stimulation of deep shale gas reservoirs: A case study of the Dingshan area in SE Sichuan Basin 2019 *Nat Gas Ind* 6(5) 497-501

[10] Guan B S, Liu J and Zhou X Q Gel breakdown of hydrofracturing fluids by using enzyme preparation GLZ-1 at changqing oil/gas fields 2008 *Oilfield Chem*

[11] Li X, Yin Q and Li Z Temporary plugging and mixed water volume fracturing technology of tight oil reservoirs in An83 block, Ordos basin 2016 *Pet Geol Recovery Effic*

[12] Wang J, Zhou F J and Bai H A new approach to study the friction-reduction characteristics of viscous/conventional slickwater in simulated pipelines and fractures 2020 *J Nat Gas Sci Eng* 83

[13] Wen Q Z, Lan X H and Zhai H L Study on the rule of forming sand bank in fractures of slickwater fracturing 2013 *Spec Oil Gas Reservoirs*

[14] Sun J, Yang Z and Qu H A new approach to predict field-scale performance of friction reducer based on laboratory measurements 2017 *J Pet Sci Eng* 159 927-933

[15] Liu J, Sheng J J and Tu J Effect of spontaneous emulsification on oil recovery in tight oil-wet reservoirs 2020 *Fuel* 279 118456

[16] Kresse O, Weng X and Gu H Numerical Modeling of Hydraulic Fractures Interaction in Complex Naturally Fractured Formations 2013 *Rock Mech & Rock Eng* 46(3) 555-568

[17] Yong R, Zhou F J and Li M H Effects of Fracturing Parameters on Fracture Unevenness During Large-Stage Multi-Cluster Fracturing in Horizontal Wells 2021 *Frontiers in Energy Research*

[18] Schechter D S, Zhou D and Orr F M Low IFT drainage and imbibition 1994 *J Pet Sci Eng* 11(4) 283-300