Research on Characterization Technology and Field Test of Biological Nano-oil Displacement in Offshore Medium- and Low-Permeability Reservoirs

Qing Feng, Jingchao Zhou, Shengsheng Li, Xianchao Chen,* Yanni Sun, Xiaorong Zhang, Ping Gao, Fan Zhang, and Yuehui She*

ABSTRACT: At present, the water displacement recovery in some medium- and low-permeability reservoirs that cannot be injected and produced in offshore oil fields because of small pores and complex structures is less than 18%. This amount is far lower than 25–40%, which is obtained after water displacement and chemical displacement in medium- and high-permeability reservoirs. Given the current situation of water injection in offshore medium- and low-permeability reservoirs, a new green and environmentally friendly nano-oil displacement technology must be urgently developed to improve the sweep coefficient and oil displacement efficiency of injected water. In this study, the experimental laboratory investigation of a biological nano-oil displacement system suitable for medium- and low-permeability reservoirs is performed. The oil displacement effects, such as changing interfacial tension, viscosity reduction, and oil flushing ability, are also evaluated. The partial differential mathematical model of multicomponent isothermal multiphase seepage is deduced, the mechanism of biological nano-oil displacement technology is finely characterized, and a set of numerical simulation optimization charts of the biological nano-oil displacement process parameters is established. Results show that the biological nano-oil displacement system has adsorption characteristics in porous media, effective miscibility with crude oil, and a minimum contact angle reaching 14.3°. Its interfacial tension can be reduced to the $10^{-3}$ level, the viscosity reduction efficiency can reach more than 90%, and the oil washing efficiency can reach more than 70%. Compared with the conventional water and chemical displacement systems, the displacement system in this study has a good oil rock flushing effect and improves oil recovery by 15%. When the injection–production ratio is comprehensively considered, the recommended injection cycle is 6000 ppm. The field test of the biological nano-oil displacement system has been completed, with a validity period of 1 year and a cumulative oil increase of $1.2 \times 10^4$ m$^3$, which is still effective. This study provides environmentally friendly solutions for the new chemical displacement of offshore medium- and low-permeability reservoirs. The established process parameter optimization chart has important guiding relevance for the optimization of technical schemes and improvement of the oil increase effect in chemical displacement.

1. INTRODUCTION

At present, more than 80% of offshore oilfields adopt secondary and tertiary oil recovery development methods to supplement formation energy and improve oil recovery. Some middle- and high-permeability reservoirs have achieved good effects through tertiary oil recovery methods, such as polymer displacement technology, multicomponent displacement technology, surfactant displacement technology and polymer

Received: August 4, 2022
Accepted: October 18, 2022
Published: October 28, 2022
displacement technology with microemulsions. However, the fluid is strongly affected by the phase interface when it flows in some medium- and low-permeability reservoirs because of the small pores and complex reservoir structure. This scenario results in high water injection pressure, low recovery, and poor development in low-permeability reservoirs. At present, a “no injection and no production” phenomenon exists. The degree of water drive production is low, most of the crude oil is retained in the reservoir, and the water drive recovery is less than 18%, which is much lower than the recovery rate of 25–40% after water displacement and chemical displacement in medium- and high-permeability reservoirs. Medium- and low-permeability reservoirs have great oil recovery potential. Increasing their recovery rate by 10% can considerably contribute to the economic and social benefits of offshore oilfield development and production.

In order to solve these problems, many scholars have proposed low salinity water flooding, steam flooding, microbial flooding, and adding catalysts and nanoparticles to the displacement fluid. Among them, nanoparticles have been widely studied by domestic and foreign scholars in recent years because of their environmental protection characteristics, and their application research in the field of petroleum exploration and development has become more and more extensive. Especially, the method of enhanced oil recovery by chemical flooding with nanoparticles is not only more environmentally friendly, but also, its application effect has been well verified in reservoirs with different lithology.

Zargartalebi et al. found that adding hydrophilic and hydrophobic silica nanoparticles to sodium dodecyl sulfate (SDS) anionic surfactants can greatly enhance their original EOR (enhance oil recovery) performance. Its mechanism is that silica nanoparticles reduce the adsorption of IFT (interfacial) tension and surfactants on rock surface. In foam flooding, experiments have shown that adding nanoparticles can also make foam more stable and obtain higher oil recovery.

In addition, it has become a consensus that nanoparticles can change the wettability of the rock surface. After changing the wettability, the nanoparticles will form a separation pressure on the surface of oil and rock, which makes it easier to separate the oil attached to the surface of rock. Some nanoparticles can change the viscosity of crude oil or displacement fluid, improve the mobility ratio, and increase oil displacement efficiency. It can also form a layer of nanoparticle film between oil and water, reducing the occurrence of fingering phenomenon. Many scholars have carried out experiments on the influence of nanoparticles on sweep efficiency, and they found that the small size of nanoparticles enables them to enter many small pores and throats so that the residual oil, which cannot be recovered by conventional EOR processes, can be recovered. Although there are few reports on the application of nanoparticles in oil fields, there are related precedents, and the EOR operation was successfully carried out in Columbia oil fields by using anionic surfactants and nanoparticles. However, it is more widely used in China, such as in the Changqing Oilfield, the Bohai Oilfield, and other oilfields, in terms of production and application.

In a recent numerical simulation field, the E-amin research group has done some research on the transfer and mass transfer of nanoparticles in porous media and established a systematic flow coupling equation method of nanoparticles in porous media. Pryazhnikov and Guzei et al. simulated the oil displacement process of nanoparticles from the micropore point of view, studied the flow characteristics of the oil displacement process of nanoparticles, and optimized the influencing factors of oil displacement by nanoparticles. However, there are still few reports about nanoparticles used in the field, and the numerical simulation of reservoir scale in this area is even rarer. Therefore, most of these studies are still confined to laboratory tests or theoretical stages, and there is no verification of relevant field information reports.

In this study, a kind of nanoparticle used in the field is introduced, named biological nanoparticles. When injected underground as a medium, biological nanoparticles have more advantageous properties than the polymer chemical displacement used in a traditional EOR process. When polymer chemical displacement is used, injecting polymer into the reservoir can easily block the formation pores, reduce formation permeability, and increase the water injection and injection agent costs. The particle size of biological nanoparticles is small. Biological nanoparticles can easily pass through porous media without reducing formation permeability, thereby increasing the effectiveness of biological nanodisplacement in enhancing oil recovery. They can reach some small voids that traditional displacement media cannot enter because of their ultrasmall size. Therefore, biological nanoparticles can play a role in a wide area and improve macroscopic efficiency. In this study, we briefly introduced biological nanoparticles, and then, based on the partial differential equation mathematical model of isothermal multiphase seepage in a multicomponent system and many indoor experimental evaluation results, this study performs numerical
simulation research to characterize biological nano-oil displacement technology.

2. EXPERIMENTAL SECTION

Biological nano-oil displacement consists of the modified nanoparticles, biosurfactant, and biological emulsifier. Biological nano-oil displacement technology uses chemical modification in integrating multiple functions on the same nanomaterial to achieve “one agent with multiple functions” and “one agent with multiple uses”. These functions include wetting, amphiphilicity, emulsification, viscosity reduction, reducing interfacial tension, and expanding spread.

The relevant indoor experimental evaluation of the biological nano-oil displacement agent and the physical model experiment are conducted in this study to improve the accuracy of the numerical model and obtain the relevant parameters of the biological nano-oil displacement technology characterized by the numerical simulation method. The specific experiments are as follows.

2.1. Microadsorption of the Nanoparticles. The core treated by the biological nano-oil displacement system was observed using a scanning electron microscope (SEM). The clay mineral edge of the core was serrated, and nanoadsorption was observed on most core surfaces. The microscopic SEM pictures (Figures 1 and 2) show that nanoparticles are adsorbed on the end face of fractured clay minerals, whereas the surface has slight adsorption without dissolution of clay minerals. This observation indicates that the dissolution of the end face of the core results in strong adsorption of nanoparticles after the action of biological nano-oil displacement agent.

The exposure of Al³⁺ ions at the end face greatly increases the charge of the end face and results in strong adsorption capacity for the nanoparticles in the biological nano-oil displacement system. The adsorption capacity of the nanoparticles, and the adsorption strengths between the nanoparticles and minerals are both increased because of the electrostatic interaction between particles. This phenomenon complicates the desorption of nanoparticles and increases erosion resistance. A long effective period of oil displacement was also observed in the field experiment.

2.2. Evaluation of the Wetting Modification. The contact angle tester was used to measure the contact angle of the oil-saturated core of offshore well block A, the core after water injection displacement of offshore well block A, and the core (0.3%) after displacing the biological nano-oil displacement system.

According to the measurement results (Figure 3), the contact angle between the treated core and the injected water can be effectively adsorbed on the rock surface after the displacement by the biological nano-oil displacement system. The rock wettability changes, and the oil wetted rock interface transforms into an amphoteric wetted interface. This scenario is conducive to oil rock stripping and reduces the flow resistance of crude oil.

2.3. Performance Evaluation of Interfacial Tension Reduction. The interfacial tension between the oil and water added at different concentrations in the biological nano-oil displacement system and oil wells in offshore well block A was measured using an interfacial tension meter.

The test results (Figure 4) show that the oil phase cannot maintain a complete spherical state under the system when a 0.5% concentration of the biological nano-oil displacement system is added to the injection water of the water injection well in offshore well block A. Moreover, the oil–water interfacial tension can be reduced to 10⁻³ under the simulated formation temperature.

2.4. Evaluation of the Viscosity Reduction Rate of Crude Oil. The viscosity reduction rate of different concentrations of the biological nano-oil displacement system on heavy oil samples of oil wells in offshore well block A was measured. The results are shown in Table 1. The viscosity reduction rate of heavy marine oil can reach more than 90% by
adding a 0.3% concentration of the biological nano-oil displacement system. Therefore, the biological nano-oil displacement system has a good viscosity reduction effect on crude oil.

2.5. Influence Evaluation of the Concentration on Crude Oil Dehydration. The experiment on the influence of the concentration of biological nano-oil displacement system (0−1000 ppm) on crude oil dehydration was conducted for the oil and water samples of oil wells in offshore well block A. The influence degree classification was determined (grades I−IV; Table 2) through the test results of crude oil dehydration and the two-phase apparent state after oil−water separation. No obvious effect on crude oil dehydration was observed when the concentration of the grade I agent was below 300 ppm. Moreover, the interface was clear after oil−water separation. The results are shown in Figure 5.

The test results are shown in Figure 6. Compared with a chemical oil displacement agent, a biological agent has good demulsification performance because of its unique structure and spatial effect. After the crude oil is recovered, oil and water can be effectively separated.

2.6. Evaluation of Crude Oil Displacement Capacity and Oil Washing Efficiency. In this study, 30 mL of 0.1% biological nano-oil displacement system and 30 mL of formation water in offshore well block A were taken. Then, 20 g of aged oil sand containing 20% offshore heavy oil was added to the bottle. Two beakers were placed on the constant-temperature heating pad and heated to the formation temperature of 60°C. The dynamic changes of oil sand were observed and recorded as shown in Figure 7.

As shown in Figure 8, when the experimental bottle was heated to the target temperature (formation temperature, 60°C), the oil sand remained stable in the formation water, the formation oil was always consolidated with the sand and settled at the bottom of the water, and the water phase could not break the oil phase and enter the oil sand. This finding proves that the oil phase is a wetting phase, the interfacial tension between the oil and water is great, and the water phase cannot wet the sand. The solution containing 0.1% of the biological nano-oil displacement system replaced the oil phase to become the wetting phase after the whole system reached the formation temperature. The oil sand system was broken. Under the slight gravity difference, the solution entered the

![Figure 4. Variation diagram of the interfacial tension test.](image)

![Figure 5. Physical diagram of dehydration rates of different biological nano-oil displacement systems.](image)

![Figure 6. Results of the influence of different concentrations of the bio-nano-oil displacement system on crude oil dehydration rate.](image)

| Table 1. Viscosity Reduction Rate of Crude Oil under Different Concentrations of the Biological Nanodisplacement System |
|---|---|---|---|
| concentrations of biological nanodisplacement system | crude oil of oil wells in offshore well block A | 0.3% | 0.5% |
| viscosity (mPa s) | 27 | 2.4 | 1.2 |
| viscosity reduction rate (%) | / | 91.1 | 95.2 |

| Table 2. Classification of Influence Degree of Different Agent Concentrations on Crude Oil Dehydration |
|---|---|---|---|---|
| agent concentrations (ppm) | <0.5 | 0.5−1.0 | 1.0−1.5 | 1.5−2.0 |
| water content in oil (%) | the oil−water interface is clear, and the water phase is transparent | the oil−water interface is slightly irregular and the water phase is transparent | a thin emulsion layer appears at the oil−water interface, and the water phase is translucent | the oil−water interface is slightly fuzzy, and the water phase is slightly brown |
| description of apparent phenomena classification | I | II | III | IV |

ACS Omega 2022, 7, 40132−40144
of biological nano-oil displacement technology by optimizing the keywords in the tNavigator reservoir numerical simulation software to evaluate the oil displacement effect of biological nanotechnology and predict the development effect of biological nano-oil displacement technology.

3.1. Establishment of the Mathematical Model of Biological Nano-oil Displacement. The biological nano-oil displacement process has many physical and chemical problems, such as the diffusion and migration of the biological nano-oil displacement system from solution to the oil phase and adsorption on the surface of sandstone particles. The model in this study is a set of partial differential equations for the isothermal multiphase seepage of multicomponent systems. The isothermal nonequilibrium seepage process of M-phase and N-component systems was studied. Given the diffusion of each component and the adsorption on the surface of porous media, the continuity equation of component $j$ in phase I can be written as follows:

$$
V [\phi D_{ij} \delta V(p_i C_i)] - V [p_i V C_i] = \sum_{a=1}^{m} \eta_{ai} (\varphi_j - \varphi_a)
$$

$$
\frac{\partial}{\partial t} (\phi p_i s C_i + \varphi_a q_i) = p_i C_i
$$

(1)

In the formula, $\phi$ is the reservoir porosity (%), $D_{ij}$ is the absolute permeability of component $j$ in phase $i$ (mD), $s_i$ is the saturation of the $i$ phase (%), $p_i$ is the pressure of component $i$ (MPa), $C_{ij}$ is the concentration of the biological nanosolution of component $j$ in phase $i$ (M/m3), $V_i$ is the seepage velocity of phase $i$ (m/d), $\eta_{ai}$ is the adsorption capacity of $a$ times mass fraction component $j$ in phase $i$ (mg/g sand), $\varphi_a$ is the number of component $j$ captured in phase $i$, $a_j$ is the number of catches of $a$ times mass fraction component $j$, $t$ is time (s), $a_j$ is the mass fraction of component $j$ in phase $i$ (mg/mg), and $q_i$ is the output of phase $i$ (m3/day).

For the treatment of saturation, pressure, and capillary force, the black oil model is used for reference. The numerical simulation model of the biological nano-oil displacement was obtained through the method of differential dispersion implicit pressure–explicit saturation or implicit pressure concentration–explicit saturation. Then, the oil displacement effect could be predicted.

3.2. Establishment of the Reservoir Numerical Model in the Well Area. The density of crude oil in offshore well block A is 0.734–0.782 g/cm3. The viscosity of crude oil in this block is 27 mPa s before treatment, the viscosity of crude oil in the oilfield after treatment is 1.53–2.69 mPa s, and its average value is 2.11 mPa s in the numerical simulation. The reason why the viscosity of crude oil here is different from that in the laboratory may be that the site is more susceptible to the influence of additional impurities and temperature. The volume coefficient is 1.172–1.235, the dissolved gas–oil ratio is 35–65 m3/m3, the formation pressure is 22.670–29.668 MPa, and the saturation pressure is 9.29–11.10 MPa, including four injection wells and 14 production wells. The four injection wells were completed by casing perforation, and a layered water injection string was used for water injection.

The numerical simulation model was established using tNavigator reservoir numerical simulation software. The model adopts a corner grid, and the number of xy plane grids is 79 × 84. The grid sizes are all 25 m. The number of grid layers in the z-direction is 246. The grid size was set to 1 m. The top grid depth is 2535 m, and the reservoir porosity is 21.6.%.

3. NUMERICAL SIMULATION OF BIOLOGICAL NANO-OIL DISPLACEMENT

Numerical simulation is a good method to upgrade the scale from laboratory tests to field applications. Based on the partial differential equation mathematical model of isothermal multiphase seepage of the multicomponent system and a large number of indoor experimental evaluation results, this study constructed the characterization numerical simulation model...
total of 246 layers were divided vertically into three large layers of high, medium, and low permeability: (1) high: the average permeability is 571 md, the average porosity is 21.7%, and the thickness is 12.7 m; (2) medium: the average permeability is 80 md, the average porosity is 19.3%, and the thickness is 14.9 m; (3) low: the average permeability is 10 md, the average porosity is 16.1%, and the thickness is 16.8 m), as shown in Figure 9, which is the three-dimensional geological model of well block A. The Figure 10 shows the measured relative permeability curve of rocks in this block, which is also the relative permeability data used in the numerical simulation model.

The experimental results indicate that the biological nano-oil displacement has three main mechanisms: neutral wetting, emulsification and viscosity reduction, and interfacial tension reduction. The relative contents of the components of the three mechanism parts were presumed equal. In this case, the components corresponding to the three mechanism parts were injected to produce nanocomposite components through the following reaction:

\[ \text{nanoFN} + \text{nanoNQ} + \text{nanoQH} \rightarrow 3\text{nanoFH} \]  

where nanoFN is the modified nanoparticles (nanoparticles were selected as one of SiO\(_2\), TiO\(_2\), or Al\(_2\)O\(_3\)), nanoNQ is the biosurfactant (one of glycolipid, polysaccharide lipid, lipopeptide, or neutral lipid derivative), nanoQH is the biological emulsifier (one of biological anionic type, biological cationic type, or biological nonionic type), and nanoFH is the biological nano-oil displacement system.

Based on the water drive simulation, the above three mechanisms were added to establish the numerical model of well block A, and 21 sets of process schemes were designed. As shown in Table 3, the oil increase amplitude of scheme 21 is the highest. Under this process scheme, the biological nano-oil displacement system was injected for six rounds. Moreover, the injection concentration is 8000 ppm, the injection amount is 0.06 PV, the injection speed is 13.3 m\(^2\)/h, the number ratio of biological fluid flow diverter slug to oil displacement slug is 6:1, and the injection time is 30 days. The biological nano-oil displacement system was injected alternately. The simulation time is 200 days, and the oil increase of the well group is 33480.744 m\(^3\), as shown in Figures 11–13. The oil increase of schemes 19 to 21 can be more than 30,000 m\(^3\) within 200 days. Further comparison shows that the profile control operation of the two slugs (scheme 19) can significantly improve the effectiveness of the biological nano-oil displacement agent (scheme 18), with an increase of more than 1000 m\(^3\). Therefore, scheme 19 can be selected as the final scheme of on-site construction to obtain the best input–output effect.

3.3. Evaluation of the Biological Nano-oil Displacement Effect

The numerical simulation model performs the simulation process after the normal water displacement and the biological nanosystem oil displacement.

As shown in Figure 14, the continuous advancement of water displacement gradually emphasizes the interlayer contradictions caused by the reservoir heterogeneity in the normal water displacement production process. Moreover, the oil saturation difference of each layer is obvious, the sweep effect of the low-permeability reservoir is poor, and the residual oil saturation at the edge of each small layer is high because of the imperfect well pattern.

Compared with Figure 14, Figure 15 clearly shows the oil displacement effect of the biological nano-oil displacement system after the injection of the biological nano-oil displacement system. Moreover, the utilization degree of each layer is further improved, particularly the sweep and oil washing effect of medium- and low-permeability reservoirs.

4. FIELD APPLICATION

Of course, in addition to indoor experiments and numerical simulation studies, biological nanotechnology has also begun to be used in the field. Well B15 (Figure 16) is a water injection well in offshore well block A. The vertical thickness of the injection layer is 24 m, which is divided into four sand control sections. The vertical depth in the middle of the reservoir is 2617.65 m, the average permeability of the low-permeability reservoir is poor, and the residual oil saturation at the edge of each small layer is high because of the imperfect well pattern.
distributed adequately, and the sweep efficiency of the water injection level is low.

According to the plane contradiction of the B15 well group and the low degree of water drive control, the biological nano-oil displacement system was selected to improve the plane oil displacement effect of the B15 well group. The process parameters are as follows. The biological nano-oil displacement system is injected for four rounds, the injection concentration is 6000 ppm, the injection volume is 0.04 PV, the injection speed is 12.5 m$^3$/h, the ratio of biological fluid flow diverter slug to oil displacement slug is 5:1, the injection time is 30 days, and the injection method is alternate injection. The construction curve of the biological nano-oil displacement in well B15 is shown in Figure 17.

The biological nano-oil displacement measures were taken for well B15 in August 2020. The corresponding oil wells began to take effect about 1 month after injection. The oil production and liquid production change curve of the affected oil wells are shown in Figure 18. The daily liquid production is stable, the daily oil production is increased by 1.5–2 times, the water content is reduced by 3–10%, and the effect of single-well precipitation and oil increase is remarkable.

Figure 19 shows that after the biological nano-oil displacement measures were taken, the actual oil production and that predicted by numerical simulation have increased significantly, and the effect is remarkable. The validity period has reached 1 year, and the cumulative oil increase is $1.2 \times 10^4$ m$^3$.

### 5. RESULTS AND DISCUSSION

#### 5.1. EOR Mechanism of Biological Nano-oil Displacement Technology

From the experiments in this study, we can easily get that biotechnology can change the wettability of rocks and the interfacial tension between oil and water. Changing wettability will make it easier for nanoparticles to

| scheme | injection round | injection concentration (ppm) | injection volume (PV) | injection rate (m$^3$/day) | ratio of biological fluid flow diverter slug to oil displacement slug | injection time (days) | oil increase (m$^3$) |
|---------|-----------------|-------------------------------|-----------------------|-----------------------------|-------------------------------------------------|----------------------|---------------------|
| case 1  | /               | /                            | /                     | /                          | /                                              | /                    | /                   |
| case 2  | 1               | 2000                          | 0.01                  | 100                         | 1:01                                           | 10                   | 5752.0              |
| case 3  | 1               | 3000                          | 0.01                  | 120                         | 2:01                                           | 10                   | 6832.0              |
| case 4  | 1               | 4000                          | 0.02                  | 120                         | 2:01                                           | 10                   | 7577.5              |
| case 5  | 2               | 4000                          | 0.02                  | 120                         | 2:01                                           | 15                   | 7755.8              |
| case 6  | 2               | 5000                          | 0.02                  | 120                         | 3:01                                           | 15                   | 5942.7              |
| case 7  | 2               | 5000                          | 0.02                  | 140                         | 3:01                                           | 15                   | 8235.5              |
| case 8  | 3               | 5000                          | 0.03                  | 140                         | 3:01                                           | 20                   | 8549.0              |
| case 9  | 3               | 7000                          | 0.03                  | 220                         | 4:01                                           | 20                   | 8110.7              |
| case 10 | 5               | 7000                          | 0.05                  | 220                         | 4:01                                           | 20                   | 8217.7              |
| case 11 | 5               | 7000                          | 0.05                  | 160                         | 4:01                                           | 25                   | 7955.7              |
| case 12 | 6               | 7000                          | 0.06                  | 180                         | 6:01                                           | 25                   | 13,061.4            |
| case 13 | 6               | 7000                          | 0.06                  | 160                         | 6:01                                           | 35                   | 18,851.1            |
| case 14 | 6               | 7000                          | 0.06                  | 180                         | 6:01                                           | 35                   | 22,449.0            |
| case 15 | 7               | 8000                          | 0.07                  | 200                         | 7:01                                           | 35                   | 22,548.6            |
| case 16 | 7               | 8000                          | 0.07                  | 200                         | 7:01                                           | 40                   | 26,319.3            |
| case 17 | 4               | 8000                          | 0.04                  | 140                         | 5:01                                           | 40                   | 27,731.8            |
| case 18 | 5               | 7000                          | 0.05                  | 140                         | 4:01                                           | 40                   | 28,113.5            |
| case 19 | 4               | 6000                          | 0.04                  | 160                         | 5:01                                           | 30                   | 31,528.9            |
| case 20 | 6               | 6000                          | 0.06                  | 160                         | 6:01                                           | 30                   | 32,763.1            |
| case 21 | 6               | 8000                          | 0.06                  | 180                         | 6:01                                           | 30                   | 33,480.7            |

**Figure 11.** Effect of injection rounds and injection concentration on oil increase.

**Figure 12.** Effect of injection rounds and injection concentration on oil increase.
form a wedge-shaped structure between rock and oil (as shown in Figure 20). This wedge-shaped structure will produce separation pressure, which makes the crude oil on the wall of the inner channel of the rock easier to peel off. Our experiment shows that its oil washing efficiency exceeds 70%, which greatly improves the oil recovery ratio. Nanoparticles can greatly reduce the viscosity of crude oil, increase the crude oil fluidity, effectively improve the phenomenon of viscous fingering, and improve the law of fluid seepage in medium- and low-permeability reservoirs (Figure 21).

Figure 12. Effect of injection PV and injection speed on oil increase.

Figure 13. Effect of slug number and injection time on oil increase.

Figure 14. Oil saturation distribution of each layer after normal water drive in well block A. (A) High permeability; (b) medium permeability; (c) low permeability.
Bio-based polymer materials are cross-linked under the action of in situ biological nanoparticles in the formation to form a temporary plugging with a certain strength. Thus, the subsequent displacement fluid flows to the low-permeability/deep formation. Our numerical simulation results show that compared with conventional water flooding, the spreading coefficient after using biological nanotechnology has increased by more than 13% (Figures 14 and 15). At the same time, the cross-linking process can be regulated by microbial nutrient supply and biodegradation to realize the adjustability of plugging strength and time.

5.2. Discussion on Biological Nanotechnology Based on Field Application. As we can know from Figure 19, since the application of biotechnology in July, 2020, its oil production has greatly increased, and the oil production in the following year has exceeded 12,000 cubic meters. After one year, it still maintains a good oil-increasing effect. In fact, as of July 2022, the well group treated by biotechnology still maintains a certain oil-increasing effect, and its effective period is far beyond our expected time.

At the same time, according to the on-site feedback data we got, the liquid production and liquid production of each well in the well group increased obviously after the use of biotechnology, but the water cut did not increase significantly, and some wells with oil production close to 0 even had obvious production improvement, which indicated that the application of biotechnology could improve the sweep efficiency and reduce the viscosity fingering effect. Biotechnology has other advantages over traditional chemical flooding methods. It will not pollute the environment, and we have not detected some environmentally unfriendly substances exceeding the standard.

This study introduced a biological nanotechnology for EOR. However, this study also has some defects; for example, in the process of numerical simulation, the fluid−solid coupling after biological nanoinjection has not been studied and analyzed. At the same time, although some experimental studies have been carried out, the microscopic behavior of the bio-nano-oil displacement process has not been continuously observed and simulated.

6. CONCLUSIONS

(1) Given the addition of bioactive groups, bio-modified nanoparticles show high oil rock stripping and oil−water emulsifying activities to achieve a good oil displacement effect. The biological nano-oil displacement system has adsorption characteristics in porous media and effective mutual solubility with crude oil. The minimum contact angle can reach 14.3°, the interfacial tension can be reduced to the 10⁻³ level, the viscosity reduction rate can reach more than 90%, and the oil washing efficiency can reach more than 70%. The oil rock stripping effect of the biological nano-oil displacement system is better than that of the conventional water displacement and chemical displacement systems. Compared with the latter, the former improves oil recovery by 20%.

(2) The partial differential equation mathematical model of the isothermal multiphase seepage in the multicomponent system is established. On this basis, the keywords in the tNavigator reservoir numerical simulation software are optimized, and the numerical simulation model is...
constructed. This model can accurately characterize the biological nano-oil displacement technology.

(3) In the numerical simulation and optimization of the biological nanotechnology parameters, the biological nanotechnology oil displacement system is injected for four rounds under the condition that the requirements of the optimal input–output ratio are met. Moreover, the injection concentration is 6000 ppm, the injection
amount is 0.04 PV, the injection speed is 12.5 m$^3$/h, the number ratio of the biological fluid flow diverter slug to oil displacement slug is 5:1, the injection time is 30 days, and the process scheme of alternating injection is the best construction scheme. The combination of biological nano-oil displacement agent and biological fluid flow diverter slug can improve the spread range of the biological nanofluid in medium- and low-permeability reservoirs and fully show the oil displacement effect of the biological nanofluid.

(4) In August 2020, well B15 in well block A of the offshore oilfield took biological nano-oil displacement measures. The field test results show that the biological nano-oil displacement technology achieves a good oil increase effect. The validity period has reached 1 year, and the oil increase is $1.5 \times 10^4$ m$^3$, which is still effective.

**AUTHOR INFORMATION**

**Corresponding Authors**

Xianchao Chen – College of Energy, Chengdu University of Technology, Chengdu 610059, China; orcid.org/0000-0003-0576-5259; Email: chenxianchao2005@126.com

Yuehui She – College of Petroleum Engineering, Yangtze University, Wuhan, Hubei 430100, China; Hubei Key Laboratory of Drilling and Production Engineering for Oil and Gas, Wuhan 430010, China; Email: sheyuehui@163.com

**Authors**

Qing Feng – Oilfield production optimization institution of China Offshore Oilfield Services Limited, Tianjin 300459, China

Jingchao Zhou – College of Energy, Chengdu University of Technology, Chengdu 610059, China

Shengsheng Li – Oilfield production optimization institution of China Offshore Oilfield Services Limited, Tianjin 300459, China

Yanni Sun – GuangDong NanYou Service Co., Ltd. TianJin Branch, Tianjin 300450, China

Xiaorong Zhang – GuangDong NanYou Service Co., Ltd. TianJin Branch, Tianjin 300450, China

Ping Gao – College of Energy, Chengdu University of Technology, Chengdu 610059, China

Fan Zhang – School of Energy Resources, China University of Geosciences (Beijing), Beijing 100083, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c04960

**Notes**

The authors declare no competing financial interest.
ACKNOWLEDGMENTS

The authors are grateful for funding from the National Natural Science Foundation of China (grant no. 51804048).

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