UDC 622.276.43
IRSTI 52.47

https://doi.org/10.55452/1998-6688-2025-22-1-357-365

[1]**Haocong Li,**
Master' student, e-mail: 1244243374@qq.com
[1,2]***Hongbin Yang,**
PhD, Associate Professor, *e-mail: hongbinyang@upc.edu.cn
[1]**Haizhuang Jiang,**
PhD student, e-mail: 2737353467@qq.com
[1]**Ruichao Wang,**
PhD student, e-mail: wang_rchao@163.com
[1]**Kaixi Pang,**
Bachelor student, e-mail: 1940390250@qq.com
[1]**Zhao Li,**
Bachelor student, e-mail: 3276814563@qq.com
[3]**Wei Lian,**
Associate professor, e-mail: 2021592106@cupk.edu.cn
[3]**Derong Xu,**
Associate professor, e-mail: 2021592116@cupk.edu.cn
[4]**Jing Wei,**
Master student, e-mail: weijing@xjkeli.com
[4]***Wanli Kang,**
Professor, e-mail: kangwanli@upc.edu.cn

[1]School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, China
[2]Shandong Key Laboratory of Oil and Gas Field Chemistry, China University of Petroleum (East China), Qingdao, China
[3]College of Petroleum, China University of Petroleum-Beijing at Karamay, Karamay, Xinjiang, China
[4]Xin Jiang Keli New Technology Development Co.Ltd, Karamay, China

PERFORMANCE EVALUATION OF NANO-IMBIBITION OIL DISPLACEMENT AGENT SUITABLE FOR LOW-PERMEABILITY RESERVOIRS

Abstract

Low-permeability reservoir has low matrix permeability and small pore throat. Conventional enhanced oil recovery methods are difficult to effectively displace crude oil in low-permeability reservoirs. In this work, a new nano-imbibition oil displacement agent (NIAG) was developed by compounding nanoparticle (NI) and surfactant (APEG). The dispersion stability, interfacial tension and wettability were evaluated. Core imbibition and displacement experiments were carried out to study the imbibition and displacement effect of nano-imbibition oil displacement agent in low-permeability cores. The results show that the average particle size of NIAG is 70 nm. It reduces the oil-water interfacial tension to a certain extent, and the oil-water interfacial tension is 0.026 mN/m. It can change the wettability of rock wall, and the change degree of wetting angle can reach 70%. NIAG has good imbibition recovery effect for low-permeability cores. The spontaneous imbibition recovery rate can reach 21.5% at 60 °C, and the imbibition displacement efficiency can reach 37.5%. This work provides a theoretical basis and technical support for the efficient development of low-permeability reservoirs.

Key words: low-permeability reservoir; interfacial tension; wettability; spontaneous imbibition.

1 Introduction

With the continuous growth of global demand for oil and gas resources, the development of conventional reservoirs is gradually facing a bottleneck. The development of low-permeability reservoirs has received more and more attention [1–3]. Traditional water flooding is difficult to effectively use remaining oil due to low reservoir permeability, complex pore structure, high oil-water interfacial tension and unfavorable wettability of rock surface [4]. The recovery is generally less than 30%. Therefore, the development of new oil displacement agents to improve oil recovery in low-permeability reservoirs has become a research hotspot in the field of oil exploitation [5]. In recent years, nanoparticles have shown great potential in enhanced oil recovery (EOR) due to their unique interface effects and permeability regulation capabilities [6–7]. Nano oil displacement agents can significantly improve the oil displacement efficiency of low-permeability reservoirs by reducing the interfacial tension of oil and water, changing the wettability of rock and enhancing the mechanism of imbibition and oil displacement [8]. However, there are still some problems in the application of single nanoparticles, such as insufficient dispersion stability and low wetting reversal efficiency [9]. To this end, the researchers propose to combine nanomaterials with surfactants to optimize oil displacement performance through synergistic effects [10]. In this paper, a new nano-imbibition oil displacement agent NIAG was formed by compounding nanoparticle NI and surfactant APEG. The particle size distribution of NIAG was analyzed by Zeta potential and nano particle size analyzer. The oil-water interfacial activity of NIAG was evaluated using a rotary interfacial tensiometer. The change of wettability of NIAG on oleophilic surface was studied by contact angle meter. Finally, the effect of enhanced oil recovery during imbibition was studied by physical simulation of oil displacement device. This work has certain guiding significance for nano-imbibition oil displacement agent to improve the recovery of low-permeability reservoirs.

2 Materials and Methods

2.1 Materials

Nanoparticles NI were self-made in the laboratory. Non-ionic surfactant allyloxy polyoxyethylene ether (APEG) was provided by Aladdin Biochemical Technology Co., Ltd. Na_2SO_4, $CaCl_2$, $MgCl_2·6H_2O$, NaCl and $NaHCO_3$ were all analytical pure and provided by China Pharmaceutical Group Co., Ltd. Deionized water was self-made by the laboratory. The composition of simulated formation water used in the experiment was shown in Table 1. The experimental core parameters were shown in Table 2.

Table 1 – The ion compositions of simulated formation water

Ion species	Na+	K+	Ca2+	Mg2+	SO42-	HCO3-	Cl-	Total
Concentration/ mg·L-1	10996.2	364.5	370.1	1246.9	3380.3	207.7	19001.7	35567.4

Table 2 – Core detailed parameters

Number	Length/mm	Diameter/mm	Porosity/%	Permeability/mD
1	10	25	15.50	30.2
2	10	25	13.61	32.4
3	10	25	13.61	31.5
4	10	25	14.66	30.7

2.2 Methods

2.2.1 Measurement of particle size and Zeta potential

Nano-imbibition oil displacement agent NIAG (0.1% NI + 0.1% APEG) was prepared using simulated formation water. Stirred with a magnetic stirrer for 10 min and subjected to ultrasonication for 20 min until the solution was completely dispersed. The prepared NIAG was put into Zeta potential and nano particle size analyzer (Zetasizer Nano ZS90，Britain) to test the particle size distribution and Zeta potential of the system.

2.2.2 Determination of interfacial tension

The oil-water interfacial tension was measured by interfacial tension meter (TX-500C, China). The interfacial tension was measured at the formation temperature of 60°C and the rotation speed of 6000 r/min. The data were measured and recorded every 2 min. When the interfacial tension reached equilibrium, the experiment was completed.

2.2.3 Wettability experiment

The quartz glass sheet was soaked in crude oil at 60°C for 48 h to simulate the rock surface. The initial wetting contact angle of the surface of the lipophilic quartz glass was measured by a contact angle measuring instrument (SL200KS, American). The lipophilic quartz glass sheet was immersed in nano-imbibition oil displacement agent solution, and the quartz glass sheet was taken out at 60°C for different time to measure the wetting contact angle.

2.2.4 Imbibition oil discharge experiment

The core imbibition experiment was carried out by Amott imbibition bottle method, and the imbibition recovery efficiency of nano-imbibition oil displacement agent was measured. The steps of imbibition experiment were as follows.

1) The core after dry weight was saturated and weighed by vacuum method. After saturated with crude oil, the core was placed in a container containing crude oil and aged at 60 °C for use.

2) Preparing imbibition fluid with simulated formation water. The prepared imbibition fluid was placed in an oven at 60 °C for at least 1 h.

3) After the imbibition fluid reached the target temperature, the core was removed from the crude oil. The oil on the surface of the core was wiped clean with oil absorption paper, the mass of saturated crude oil core was weighed, and the volume of saturated crude oil was calculated.

4) Put the core into the imbibition bottle and quickly submerged the core in the imbibition liquid. The time of core submergence was recorded as the initial imbibition time. The imbibition liquid was added until the liquid level reached 1/3 to 1/2 of the imbibition bottle’s capillary scale to facilitate measuring the volume of produced crude oil.

5) The imbibition experiment was carried out in an oven at 60 °C. The volume of crude oil produced stopped increasing, and the imbibition experiment was terminated. The volume of crude oil produced by imbibition was measured and the imbibition recovery was calculated.

2.2.5 Physical simulation core displacement experiment

Through physical simulation of oil displacement experiments, the effect of nano-imbibition oil displacement agent NIAG on improving oil recovery in low-permeability cores was studied. The displacement experiment steps were as follows.

1) After removing the oil, removing the salt, and drying, the treated core was set aside.

2) The above cores were vacuumized and saturated with formation water, and the pore volume, porosity, and initial permeability were calculated.

3) The core was loaded into the core holder in the high-temperature and high-pressure dynamic huff-and-puff imbibition oil displacement experimental device. The high pressure displacement method was used to saturate the simulated oil to a certain oil saturation.

4) A core was first used to simulate the formation water at an injection rate of 0.3 ml/min and 60°C until the water content reached 95%. The recovery rate from simulated formation water flooding was calculated.

5) Imbibition fluid with a certain pore volume multiple was injected. After shut-in at 60 °C and 2 MPa, the core was imbibed in the core holder for a certain time. The simulated formation water was continuously used to displace the core at an injection rate of 0.3 ml/min and 60°C. Until the water content in the produced liquid reached 95% again, the changes in the recovery rate were recorded.

3 Results and Discussion

3.1 Dispersion stability

The particle size distribution and Zeta potential of nano-imbibition oil displacement agent NIAG were measured, and the results were shown in Figure 1. The average particle size of nano-imbibition oil displacement agent was about 70 nm, and the particle size distribution range was 30–110 nm. Zeta potential measurement results showed that the Zeta potential of NIAG was -35 mV. It showed that the nano-imbibition oil displacement agent NIAG had excellent dispersion stability, was suitable for low-permeability reservoirs, and was resistant to coalescence and precipitation.

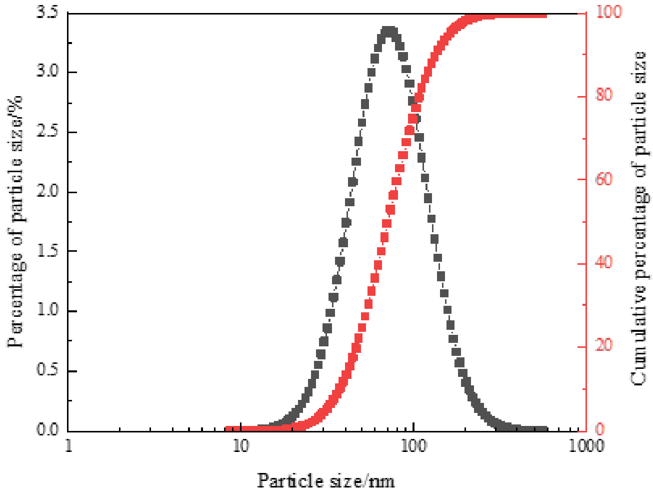

Figure 1 – Particle size distribution of NIAG nano-imbibition oil displacement agent

3.2 Oil water interfacial activity

The oil-water interfacial tension values of different systems at 60 °C were measured by interfacial tension meter, and the results were shown in Figure 2. The oil-water interface tension value of the simulated formation water was 0.44 mN/m. The oil-water interfacial tension of APEG was 0.16 mN/m, and the oil-water interfacial tension of NIAG was 0.026 mN/m. It showed that the nano-imbibition oil displacement agent NIAG significantly reduced the oil-water interfacial tension compared to the surfactant solution.

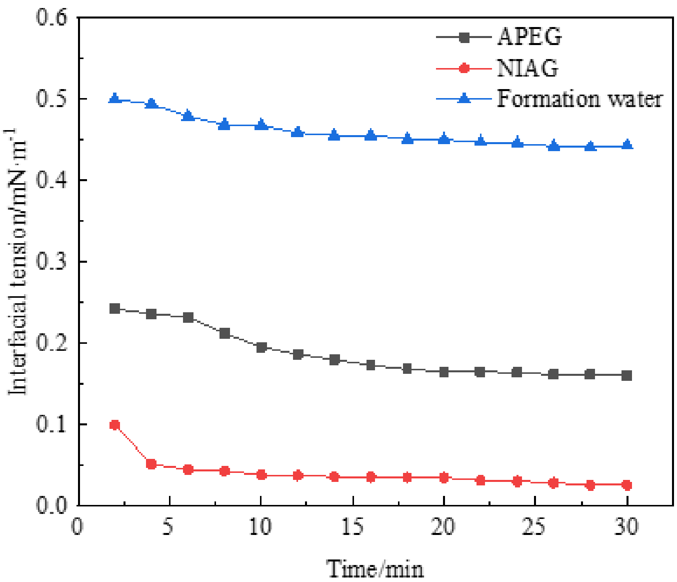

Figure 2 – Interfacial tension curves of different systems with time

3.3 Change rock wettability

The wettability reversal performance of simulated formation water, surfactant APEG solution and nano-imbibition oil displacement agent NIAG was compared by the experiment. The contact angle measurement results were shown in Figure 3. In the initial state, the surface of the quartz glass sheet was aged by crude oil, and the contact angle of the glass sheet pre-immersed in three solutions was about 90°. The surface of the glass sheet was in a lipophilic state. The contact angle of glass slides soaked in APEG solution and NIAG changed significantly faster than that of glass slides soaked in simulated formation water. The equilibrium contact angle of APEG was approximately 40°, which indicated that APEG could change the wettability of the glass surface from lipophilic to hydrophilic. In comparison to APEG, NIAG demonstrated a stronger ability to alter the wettability of the lipophilic surface, and the equilibrium contact angle was approximately 27°. The wettability reversal of the system was stronger after the combination of surfactant APEG and nanoparticle NI.

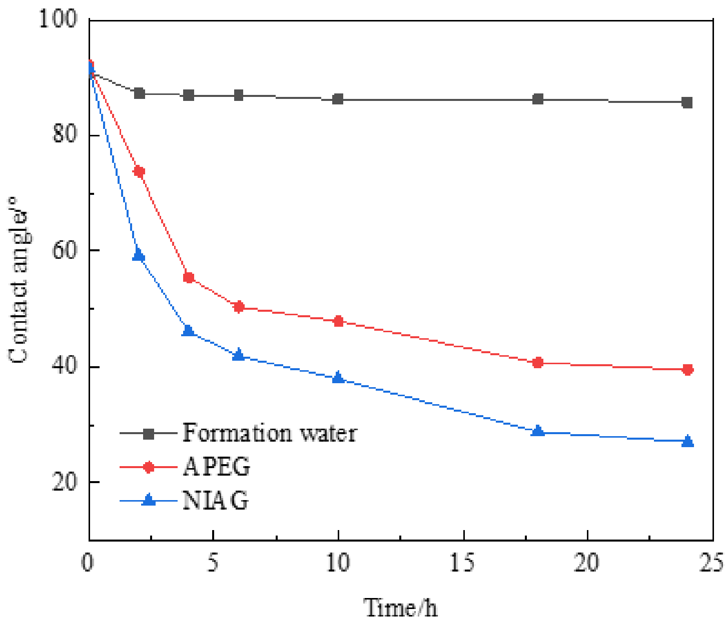

Figure 3 – Curves of contact angle of different systems with time

3.4 Imbibition to enhance oil recovery effect

The imbibition performance of simulated formation water, surfactant APEG solution and nano-imbibition oil displacement agent NIAG was investigated by using a static spontaneous imbibition experimental device. The imbibition temperature was 60 °C, and the imbibition experimental curves were shown in Figure 4. In a short time after the start of the experiment, the recovery degree of the three systems increased rapidly with time. However, the imbibition oil recovery rate of NIAG was significantly higher than that of the other two systems. NIAG nano-imbibition oil displacement agent had the best oil displacement performance. The ultimate recovery of NIAG imbibition displacement oil was 21.5%. The ultimate oil recovery of APEG solution was 18%. The final recovery rate of imbibition and oil drainage of simulated formation water was only 9.5%.

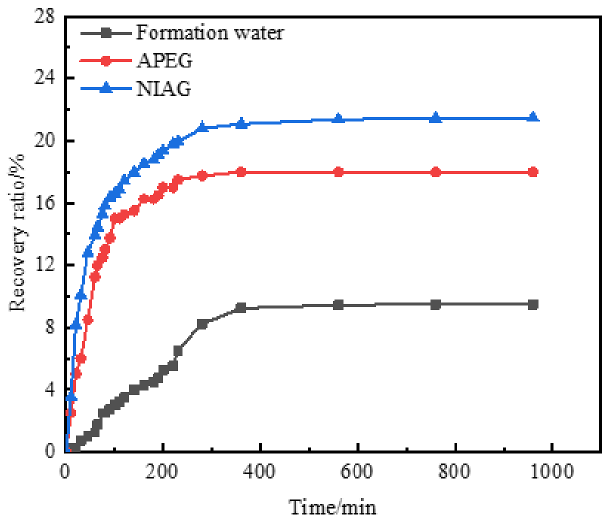

Figure 4 – Imbibition oil discharge performance of different systems

3.5 Effect of core displacement on enhanced oil recovery

The oil displacement effect of nano-imbibition oil displacement agent NIAG was evaluated according to the experimental method in 2.2.5. The results were shown in Figure 5. The experiments showed that during the initial water flooding stage, as water injection increased, the pressure rose rapidly, and crude oil was continuously displaced by water. After the water flooding recovery rate reached 20%, oil production ceased at the production end, and the maximum pressure during the initial water flooding stage reached 0.37 MPa. When the water content was 95%, the nano-imbibition oil displacement agent NIAG was injected. It showed that after the injection of the nano-imbibition oil displacement agent, the remaining oil, which was not recoverable by water flooding, was displaced, and the recovery rate reached 29.5%. During the subsequent water flooding stage, the NIAG in the core continuously displaced the crude oil from the pores and walls through imbibition. And it was carried out by the subsequent injection water. The final recovery rate reached 37.5%. It was observed that the nano-imbibition oil displacement agent NIAG exhibited a strong oil film stripping effect. And the system could be utilized as an effective oil displacement agent for low-permeability reservoirs.

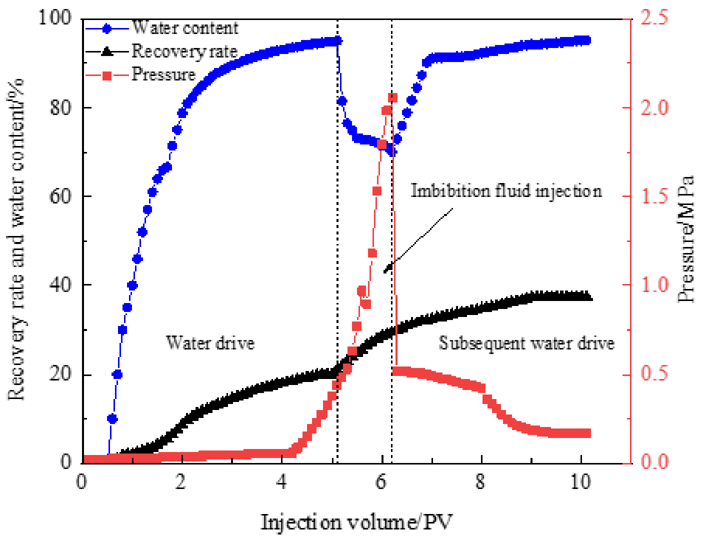

Figure 5 – Nano-imbibition oil displacement
agent NIAG oil displacement effect curve

4 Conclusions

1) The average particle size of nano-imbibition oil displacement agent NIAG was 70 nm, the particle size distribution ranged from 30 to 110 nm, and the Zeta potential was -35 mV, which indicated that it had good dispersion stability.

2) The nano-imbibition oil displacement agent NIAG could reduce the oil-water interfacial tension to about 0.026 mN/m under formation conditions. Furthermore, it could be adsorbed onto the rock surface, thereby converting oil-wet surfaces to water-wet surfaces and transforming imbibition resistance into imbibition drive, which facilitated imbibition and oil displacement.

3) The nano-imbibition oil displacement agent NIAG enhanced the capillary driving force through the synergistic effect of APEG and nanoparticles. Enhanced the imbibition and displacement effects and improved the recovery efficiency in low-permeability reservoirs. The spontaneous imbibition recovery rate reached 21.5%, and the imbibition displacement efficiency reached 37.5%.

REFERENCES

1 Zhao M., Cheng Y., Wu Y., et al. Enhanced oil recovery mechanism by surfactant-silica nanoparticles imbibition in ultra-low permeability reservoirs[J]. Journal of Molecular Liquids, 2022, vol. 348, p.118010.

2 Nwidee L.N., Lebedev M., Barifcani A., et al. Wettability alteration of oil-wet limestone using surfactant-nanoparticle formulation[J]. Journal of Colloid and Interface Science, 2017, vol. 504, pp. 334–345.

3 Paryoto S., Romdoni Y., Kurnia I., et al. Spontaneous imbibition of amphoteric-anionic surfactant and Fe3O4 nanoparticles colloidal mixture for enhanced oil recovery[J]. Journal of Molecular Liquids, 2023, vol. 392, pp. 123458.

4 Meng L., Dai Y., Zhao M., et al. Investigation of carbon-based nanofluid imbibition processes in low-permeability reservoirs using nuclear magnetic resonance[J]. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2024, vol. 695, p. 134310.

5 Kaushik A., Joshi D., Saw R.K., et al. Formation and characterization of nanoparticle assisted surfactant stabilized oil-in-water nanoemulsions for application in enhanced oil recovery[J]. Fuel, 2024, vol. 359, p. 130500.

6 Ahmadi Y., Ayari M.A., Olfati M., et al. Application of Green Polymeric Nanocomposites for Enhanced Oil Recovery by Spontaneous Imbibition from Carbonate Reservoirs[J]. Polymers, 2023, vol. 15, no. 14, p. 3064.

7 Song X.G., Zhao M.W., Dai C.L., et al. Mechanism of active silica nanofluids based on interface-regulated effect during spontaneous imbibition[J]. Petroleum Science, 2021, vol. 18, pp. 883–894.

8 Khosravi R., Chahardowli M., Keykhosravi A., et al. A model for interpretation of nanoparticle-assisted oil recovery: Numerical study of nanoparticle-enhanced spontaneous imbibition experiments[J]. Fuel, 2021, vol. 292, p. 120174.

9 Dai C., Wang X., Li Y., et al. Spontaneous imbibition investigation of self-dispersing silica nanofluids for enhanced oil recovery in low-permeability cores[J]. Energy & Fuels, 2017, vol. 31, no. 3, pp. 2663–2668.

10 Saien J., Bahrami M. Understanding the effect of different size silica nanoparticles and SDS surfactant mixtures on interfacial tension of n-hexane–water[J]. Journal of Molecular Liquids, 2016, vol. 224, pp. 158–164.

[1]Хаоконг Ли,
магистрант, e-mail: 1244243374@qq.com
[1,2]*Хунбин Ян,
PhD, қауымдастырылған профессор, e-mail: hongbinyang@upc.edu.cn
[1]Хайчжуан Цзян,
докторант, e-mail: 2737353467@qq.com
[1]Руйчао Ван,
докторант, e-mail: wang_rchao@163.com
[1]Кайси Панг,
бакалавр, e-mail: 1940390250@qq.com
[1]Чжао Ли,
бакалавр, e-mail: 3276814563@qq.com
[3]Вэй Лянь,
қауымдастырылған профессор, e-mail: 2021592106@cupk.edu.cn
[3]Деронг Сюй,
қауымдастырылған профессор, e-mail: 2021592116@cupk.edu.cn
[4]Цзин Вэй,
магистрант, e-mail: weijing@xjkeli.com
[4]*Ванли Канг,
профессор, e-mail: kangwanli@upc.edu.cn

[1]Мұнай инженериясы мектебі, Қытай мұнай университеті (Шығыс Қытай), Циндао қ., Қытай
[2]Мұнай және газ өндірістік химиясы бойынша Шаньдун зертханасы, Қытай мұнай университеті (Шығыс Қытай), Циндао қ., Қытай
[3]Мұнай колледжі, Қарамайдағы Қытай мұнай университеті – Пекин, Синьцзян қ., Қытай
[4]Xin Jiang Keli New Technology Development Co. Ltd, Синьцзян қ., Қытай

ТӨМЕН ӨТКІЗГІШТІ ҚАБАТТАР ҮШІН НАНО-СІҢІРГІШ МҰНАЙ ЫҒЫСТЫРУШЫ АГЕНТТІҢ ТИІМДІЛІГІН БАҒАЛАУ

Аңдатпа

Төмен өткізгіштікті коллекторлардың кеуектілік-құрылымдық ерекшеліктері, атап айтқанда, олардың төмен матрицалық өткізгіштігі мен ұсақ кеуек арналары, дәстүрлі мұнай өндіру әдістерінің тиімділігін шектейді. Осы мәселені шешу мақсатында бұл зерттеуде нанобөлшек (NI) пен беттік-белсенді зат (APEG) негізінде жаңа нано-сіңіргіш мұнай ығыстырушы агент (NIAG) әзірленді. NIAG-тың дисперсиялық тұрақтылығы, фазааралық кернеуін төмендету қабілеті және жыныс бетінің сулану қасиеттеріне әсері зерттелді. Төмен өткізгіштікті қабаттарда агенттің сіңіру және мұнай ығыстыру тиімділігін анықтау үшін өзек сіңіру және ығыстыру тәжірибелері жүргізілді. Зерттеу нәтижелері көрсеткендей, NIAG бөлшектерінің орташа өлшемі 70 нм құрайды. Ол мұнай-су фазааралық кернеуін белгілі бір деңгейде төмендетіп, оны 0,026 мН/м мәніне дейін азайтады. Сонымен қатар, жыныс қабырғасының сулануын жақсартып, сіңіру бұрышының өзгеру дәрежесін 70%-ға жеткізеді. NIAG төмен өткізгіштікті қабаттарда жоғары тиімділік көрсетіп, 60 °C температурада өздігінен сіңіру арқылы мұнайды қалпына келтіру коэффициентін 21,5%-ға, ал сіңіру-ығыстыру тиімділігін 37,5%-ға дейін арттырады. Бұл зерттеу төмен өткізгіштікті мұнай кен орындарын тиімді игеру үшін теориялық негіз бен техникалық шешімдер ұсынады.

Тірек сөздер: төмен өткізгіштікті коллектор, фазааралық кернеу, сулану, өздігінен сіңіру.

[1]Хаоконг Ли,
магистрант, e-mail: 1244243374@qq.com
[1,2]*Хунбин Ян,
PhD, ассоц.профессор, e-mail: hongbinyang@upc.edu.cn
[1]Хайчжуан Цзян,
докторант, e-mail: 2737353467@qq.com
[1]Руйчао Ван,
докторант, e-mail: wang_rchao@163.com
[1]Кайси Панг,
бакалавр, e-mail: 1940390250@qq.com
[1]Чжао Ли,
бакалавр, e-mail: 3276814563@qq.com
[3]Вэй Лянь,
ассоциированный профессор, e-mail: 2021592106@cupk.edu.cn
[3]Деронг Сюй,
ассоциированный профессор, e-mail: 2021592116@cupk.edu.cn
[4]Цзин Вэй,
магистрант, e-mail: weijing@xjkeli.com
[4]*Ванли Канг,
профессор, e-mail: kangwanli@upc.edu.cn

[1]Школа нефтяной инженерии, Китайский университет нефти (Восточный Китай), г. Циндао, Китай
[2]Шаньдунская ключевая лаборатория промысловой химии нефти и газа, Китайский университет нефти (Восточный Китай), г. Циндао, Китай
[3]Колледж нефти, Китайский университет нефти-Пекин в Карамае, г. Синьцзян, Китай
[4]Xin Jiang Keli New Technology Development Co.Ltd, г. Синьцзян, Китай

ОЦЕНКА ЭФФЕКТИВНОСТИ НАНОПРОПИТЫВАЮЩЕГО НЕФТЕВЫТЕСНЯЮЩЕГО АГЕНТА, ПОДХОДЯЩЕГО ДЛЯ НИЗКОПРОНИЦАЕМЫХ КОЛЛЕКТОРОВ

Аннотация

Коллекторы с низкой проницаемостью обладают низкой матричной проницаемостью и узкими поровыми каналами. Традиционные методы повышения нефтеотдачи затрудняют эффективное вытеснение нефти в низкопроницаемых коллекторах. В данной работе был разработан новый нанопоглощающий агент вытеснения нефти (NIAG) путем комбинирования наночастицы (NI) и поверхностно-активного вещества (APEG). Оценивались его дисперсионная стабильность, межфазное натяжение и смачиваемость. Были проведены эксперименты по пропитыванию и вытеснению в кернах для изучения эффекта нанопоглощающего агента в низкопроницаемых породах. Результаты показывают, что средний размер частиц NIAG составляет 70 нм. Он снижает межфазное натяжение на границе нефть – вода до 0,026 мН/м. Может изменять смачиваемость горной породы, а степень изменения угла смачивания достигает 70%. NIAG обладает хорошей эффективностью самопроизвольного пропитывания для низкопроницаемых кернов. Скорость самопроизвольного пропитывания достигает 21,5% при 60 °C, а эффективность вытеснения при пропитывании – 37,5%. Данное исследование предоставляет теоретическую основу и техническую поддержку для эффективной разработки низкопроницаемых коллекторов.

Ключевые слова: низкопроницаемый коллектор, межфазное натяжение, смачиваемость, самопроизвольное пропитывание.

Article submission date: 02.03.2025