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Study on the Plugging Effect of Novel Expandable Graphite as Plugging Agent for Steam Flooding

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Abstract: Steam flooding technology is widely applied in heavy oil development, yet steam channeling in high-permeability channels greatly reduces thermal efficiency and oil recovery. In this paper, a novel 500-mesh expandable graphite customized by Nanjing Gerifa Carbon Materials Co., Ltd. is adopted as a high-temperature plugging agent for steam flooding treatment. Three groups of sand-pack models with different initial permeability gradients were set up to systematically evaluate its plugging capacity and oil displacement performance. Experimental results demonstrate that the material expands rapidly above 180 °C under steam thermal conditions to block preferential flow paths, with outstanding thermal stability and anti-salinity ability compared with conventional polymer plugging agents. The average plugging rate of three groups of sand packs reaches 83.5%, and the incremental oil recovery ranges from 13.2% to 15.8%. Sand-pack displacement experiments confirm that expandable graphite can effectively adjust reservoir injection profile, restrain steam breakthrough and enlarge the swept volume of steam. This material is easy to prepare and friendly to formation environment, which provides a new option for profile control and channeling prevention during steam flooding exploitation.

Keywords: Expandable graphite; Steam flooding; Plugging rate; Profile control; Sand-pack model; Enhanced heavy oil recovery

1. Introduction

Steam flooding serves as a dominant thermal exploitation method for heavy oil reservoirs, which can greatly reduce crude oil viscosity and mobilize residual oil by continuously injecting high-temperature steam into the formation. Nevertheless, most heavy oil reservoirs feature prominent interlayer and internal permeability heterogeneity, and permeability difference is the core inducement of steam channeling. During continuous steam injection, steam preferentially rushes into high-permeability zones to form obvious channeling channels. A large amount of heat dissipates along the dominant seepage paths, leading to extremely low sweep range of steam in low-permeability oil-bearing regions. As a result, the overall oil recovery is restricted sharply, and excessive steam injection also causes unnecessary construction cost waste [1–5].

Traditional polymer-based profile control agents are prone to thermal degradation under long-term high-temperature steam environment (above 200 °C), resulting in failure of plugging effect and short effective period. Common inorganic particle plugging materials often suffer from poor injectability and are difficult to migrate deep into porous media. Therefore, it is urgent to develop a high-temperature resistant plugging material with favorable injection performance and durable plugging effect to suppress steam channeling and improve steam utilization efficiency [1–3,5,6].

Expandable graphite has outstanding high-temperature resistance and volume expansion characteristics under thermal stimulation, which can realize in-situ plugging after being transported into the formation with injection fluid. In this work, expandable graphite is proposed as a novel plugging agent for steam flooding. To simulate actual heterogeneous reservoir permeability differences, three groups of sand-pack models with different initial permeabilities were designed to carry out indoor flooding experiments, comprehensively testing its plugging ability and enhanced oil recovery effect. The research aims to provide a new technical choice for profile control and channeling prevention of steam flooding heavy oil reservoirs with multi-permeability interlayers [1–3,6–10].

2. Materials and Methods

2.1 Experimental Materials

The experimental materials mainly included expandable graphite, graded quartz sand, simulated formation water, and heavy crude oil.

Expandable graphite: Custom-produced by Nanjing Gerifa Carbon Materials Co., Ltd., particle size 500 mesh, initial expansion temperature 180 °C, maximum expansion volume 220 mL/g, pH value 6.5–7.2, inorganic carbon-based material without organic additives, resistant to high temperature above 250 °C. The graphite suspension for injection was prepared with simulated formation water, and the mass concentration was fixed at 1.5 wt% for all test groups.

Quartz sand: Four particle sizes (0.1–0.2 mm, 0.2–0.4 mm, 0.4–0.6 mm, 0.6–0.8 mm) were screened and proportionally mixed to construct sand packs with three gradients of initial permeability, simulating low, medium and high permeability layers of actual heavy oil reservoirs.

Simulated formation water: Prepared according to the ion composition of typical heavy oil reservoir produced water, total salinity 8560 mg/L, mainly containing Na^+, Ca^{2+}, Mg^{2+}, Cl^- and HCO_3^-, consistent with the water property of target steam flooding block.

Heavy crude oil: Sampled from a steam flooding development block, reservoir viscosity 1100 mPa/s at 50 °C, density 0.962 g/cm^3 at room temperature, medium-heavy oil without extra viscosity reducer addition during experiments.

2.2 Experimental Device

All experiments were carried out by a conventional one-dimensional sand-pack flooding experimental system. The main experimental equipment included a constant-flux injection pump, high-pressure sand-pack tube, constant-temperature heating oven, high-precision pressure sensor, back-pressure regulator, and oil–water separation metering device.

Sand-pack tube fixed specification: inner diameter 30 mm, effective length 300 mm (30 cm). Each sand-pack tube was filled layer by layer with graded quartz sand under continuous vibration to ensure uniform compaction; the average porosity of all sand-pack models was controlled at 32.1% ± 0.5%.

Three groups of sand-pack models with different initial permeability were set for comparative tests:

Group A (low permeability): Initial permeability 0.32 μm^2

Group B (medium permeability): Initial permeability 0.75 μm²

Group C (high permeability): Initial permeability 1.28 μm²

Graded quartz sand mixing ratio was adjusted separately for each group to form the above permeability gradients, which reproduced the interlayer permeability heterogeneity of on-site heavy oil reservoirs and different degrees of steam channeling risk [7,8,10].

2.3 Experimental Process

Three groups of sand-pack models (Group A/B/C) adopted identical experimental operation steps to guarantee comparability of results:

Saturation and oil establishing process

The sand-pack model was vacuumized for 2 h and fully saturated with simulated formation water at a constant flow rate of 0.5 mL/min, and the initial water phase permeability of each sand pack was measured and recorded. After water saturation, crude oil was injected at 0.3 mL/min to establish original reservoir oil saturation, and the average oil saturation of all models stabilized at 68.2%–70.1%. The prepared sand-pack model was placed in a constant-temperature oven at 50 °C for static aging for 12 h to restore the initial reservoir temperature and fluid distribution state.

Primary pure steam flooding stage

Continuous steam flooding was performed under a simulated reservoir temperature of 220 °C and back-pressure of 3.5 MPa, with a constant steam injection rate of 0.4 mL/min. The outlet produced liquid was collected in real time, and oil production data were recorded until daily oil output was less than 0.1 mL (steam flooding reached economic limit). The oil recovery factor of conventional pure steam flooding for each group was calculated based on the cumulative oil production data.

Expandable graphite plugging injection and high-temperature aging

After the primary steam flooding stage, 1.5 PV of 1.5 wt% expandable graphite suspension was slowly injected into each sand-pack model at a low injection rate of 0.2 mL/min to ensure uniform migration in the porous medium. After injection completion, the inlet and outlet valves were closed, and the model was aged at 220 °C for 6 h to realize in-situ thermal expansion of the 500-mesh expandable graphite in high-permeability channels and form stable physical plugging structures.

Secondary steam flooding and data statistics

Secondary steam flooding was carried out with completely consistent injection parameters (temperature, pressure, injection rate) as the primary stage. The real-time inlet-outlet pressure difference and oil–water production were continuously monitored and recorded until oil production was negligible again.

The residual permeability after plugging was measured for each sand pack, and plugging rate was calculated by the permeability difference before and after plugging; the incremental oil recovery of each group was counted to quantitatively evaluate the plugging and oil displacement performance of customized expandable graphite under different reservoir permeability conditions.

3. Results and Discussion

3.1 Plugging Performance of Expandable Graphite under Different Initial Permeability

The plugging performance of the customized 500-mesh expandable graphite (Nanjing Gerifa Carbon Materials Co., Ltd.) was evaluated through three groups of one-dimensional sand-pack flooding experiments with gradient permeability. All sand-pack models adopt uniform specifications of 30 cm length and 3 cm inner diameter, with average porosity controlled at about 32.1%.

After the injection and 6 h high-temperature aging of expandable graphite suspension, the permeability of all three sand-pack models decreased significantly, and the plugging rate showed a positive correlation with initial permeability:

Group A (low permeability, 0.32 μm^2): Plugging rate 76.2%

Group B (medium permeability, 0.75 μm^2): Plugging rate 83.1%

Group C (high permeability, 1.28 μm^2): Plugging rate 91.2%

The average plugging rate of the three groups reaches 83.5%, which matches the overall experimental conclusion.

This rule is mainly attributed to the matching relationship between graphite particle size and pore throat. The 500-mesh expandable graphite particles can easily enter the large pore throats of high-permeability sand packs, and fully expand above 180 °C to stack into dense plugging layers, resulting in extremely high plugging efficiency. For low-permeability models, small pore throats limit the deep migration of graphite particles, only forming shallow plugging at the inlet end, so the plugging rate is relatively lower.

Different from traditional polymer plugging agents that are easy to thermally degrade at high temperature, expandable graphite maintains stable plugging performance under 220 °C steam environment. After continuous secondary steam flooding for more than 10 PV, no obvious permeability recovery was observed in all three groups, indicating that the graphite plugging layer possesses high structural stability and can meet the long-term profile control requirements of steam flooding reservoirs with different permeability grades.

3.2 Enhanced Oil Recovery Effect of Profile Control for Multi-Permeability Sand Packs

The oil displacement effect before and after expandable graphite plugging was compared quantitatively based on sand-pack displacement data of Group A, B and C. The simulated heavy oil viscosity is fixed at 1100 mPa/s (50 °C), and the oil recovery data of each group are sorted as follows:

Primary pure steam flooding recovery

Group A (low permeability): 34.6%

Group B (medium permeability): 29.3%

Group C (high permeability): 24.1%

High-permeability sand packs suffer the most serious steam channeling, leading to premature steam breakthrough; most injected steam flows rapidly through dominant channels, low-permeability zones cannot be heated effectively, so the basic steam flooding recovery is the lowest. Low-permeability models have weak channeling phenomenon, and the original steam sweep efficiency is relatively higher.

Secondary steam flooding recovery after graphite plugging

Group A (low permeability): 47.8%, incremental recovery 13.2%

Group B (medium permeability): 43.8%, incremental recovery 14.5%

Group C (high permeability): 39.9%, incremental recovery 15.8%

After expandable graphite profile control treatment, the secondary steam flooding performance of all three groups was significantly improved. The blocked high-permeability channels force subsequent steam to divert into the untouched low-permeability reservoir areas, which greatly expands the steam sweep volume and improves displacement uniformity. It can be clearly seen that the higher the initial permeability and the more severe the original steam channeling, the greater the amplitude of enhanced oil recovery after plugging. This proves that expandable graphite has the most prominent application value for high-permeability channeling steam flooding blocks.

The experimental results verify that the customized expandable graphite can effectively solve the steam channeling problem of heavy oil steam flooding with different reservoir permeability. It has good injectability and in-situ plugging adaptability for sand-pack porous media. As a high-temperature resistant inorganic plugging material, it avoids formation damage and thermal failure problems of traditional organic polymer plugging systems, showing wide application prospects for profile control and enhanced oil recovery in heterogeneous thermal recovery heavy oil reservoirs.

4. Conclusions

In this study, a custom 500-mesh expandable graphite produced by Nanjing Gerifa Carbon Materials Co., Ltd. was adopted as a high-temperature plugging agent for steam flooding heavy oil reservoirs. Three groups of sand-pack models with gradient initial permeability (0.32 μm^2, 0.75 μm^2, 1.28 μm^2) were designed to simulate heterogeneous oil reservoirs, and systematic sand-pack flooding experiments were carried out to evaluate its plugging performance and oil displacement enhancement effect under simulated reservoir temperature of 220 °C. The main conclusions are summarized as follows:

(1) The customized expandable graphite has excellent high-temperature expansion performance, with an initial expansion temperature of 180 °C and maximum expansion volume of 220 mL/g. Prepared as 1.5 wt% water-based suspension, it possesses favorable injectability and can migrate into the deep pore channels of sand-pack models with different permeability without blockage at the inlet.

(2) The plugging capacity of expandable graphite is positively correlated with reservoir initial permeability. The plugging rates of low, medium and high permeability sand packs are 76.2%, 83.1% and 91.2% respectively, with an average plugging rate of 83.5%. The graphite plugging layer formed after 6 h high-temperature aging has stable structure and no permeability rebound under long-term steam scouring, which overcomes the thermal degradation defect of conventional polymer profile control agents.

(3) Expandable graphite plugging can significantly inhibit steam channeling and improve steam sweep efficiency. The incremental oil recovery of three groups ranges from 13.2% to 15.8%. The medium-permeability model (0.75 μm^2) increases the ultimate oil recovery from 29.3% to 43.8% with an incremental recovery of 14.5%; the high-permeability model with severe channeling obtains the largest oil increment of 15.8%, proving that this material is more suitable for steam flooding blocks with developed high-permeability channels.

(4) Compared with traditional organic polymer plugging agents, 500-mesh expandable graphite has superior high-temperature resistance and formation compatibility, will not cause secondary pollution or permanent reservoir damage, and the preparation and injection process is simple with low operation cost.

It is demonstrated that the customized expandable graphite is a reliable and efficient plugging material for heterogeneous steam flooding heavy oil reservoirs. This study provides complete experimental data and a feasible technical reference for profile control and channeling prevention to enhance heavy oil thermal recovery efficiency.

References

[1] G. Shao, Z. Shi, Y. Jia, Q. Cheng, N. Kang, X. Wang, Processes 2025, 13, 1319.

[2] G. Zhao, C. Dai, C. Gu, Q. You, Y. Sun, Chemical Engineering Journal 2019, 368, 668.

[3] L. M. Corredor-Rojas, A. Hemmati-Sarapardeh, M. M. Husein, M. Dong, B. B. Maini, Energy Fuels 2018, 32, 10628.

[4] J. Chang, Y. Tang, Z. Lun, B. Ji, Petroleum Science and Technology 2025, 1.

[5] Q. Wang, W. Zheng, J. Liu, B. Cao, J. Hao, X. Lu, K. Zheng, L. Cui, T. Cui, H. Sun, Energies 2022, 15, 7346.

[6] M. Wu, Z. Lun, Y. Tang, J. Dai, M. Liu, D. Wang, Z. Li, Processes 2023, 11, 2649.

[7] C. Dai, C. Gu, B. Liu, Y. Lyu, X. Yao, H. He, J. Fang, G. Zhao, Journal of Molecular Liquids 2019, 293, 111535.

[8] B. Xu, G. Zhao, C. Gu, C. Dai, W. Zhao, T. Ma, Energy Fuels 2023, 37, 1081.

[9] A. A. Jaber, S. A. Abbas, A. A. Farah, K. K. Kopeć, Y. M. Alsalik, M. A. Tayeb, N. Verghese, Polymers 2023, 15, 4678.

[10] K. Cheng, Z. Huang, J. Li, T. Luo, H. Li, Geofluids 2022, 2022, 1.