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Research Article

Experimental Study on Enhancing Heavy Oil Recovery by Multimedia-Assisted Steam Flooding Process

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Aiming to reduce the negative effect of steam channeling in the late stage of steam flooding applied in heavy oil reservoirs, experimental studies were carried out on selective plugging of solid particles, added to single-medium- and multimedia-assisted steam flooding. This work also explored the mechanisms of enhancing heavy oil recovery by applying plugging agent- and multimedia-assisted steam flooding and its optimized injection parameters. Through solid particle plugging experiments, this study clarifies the high-efficiency solid particle plugging mechanism, with an optimized slug size of 0.40 PV and plugging ratio of over 98%. Through single-medium- and multimedia-assisted steam flooding experiments, this study confirms that gas-assisted steam flooding has an effect of synergistic oil displacement and that a CO_2 with urea solution-assisted steam flooding method achieves the best production performance. Its oil recovery factor is 10.7% higher than that of the steam flooding process. Parallel sand pack models with a permeability difference of more than 10 times were used to mimic a heavy oil reservoir with high-permeability channels, and the selective plugging of solid particles was carried out. The plugging ratio of high-permeability formation reached 91.20%, playing an effective plugging role. Solid particle plugging is less effective to the low-permeability formation, with the plugging ratio at only 32.39%. Based on the selective plugging of solid particles, a plugging agent- and multimedia-assisted steam flooding experiment was conducted, the high-permeability formation was effectively plugged, and the swept volume of the low-permeability formation increased significantly. The final recovery factor of the high-permeability formation was enhanced by 11%, and the recovery factor of the low-permeability formation increased by 3 times, reaching 36.38%. Therefore, solid particle plugging effectively alleviates the impact of high-permeability formation caused by permeability difference during steam flooding.

1. Introduction

Heavy oil resources are becoming increasingly essential to meet the growing energy demand in the world [1]. At present, thermal-based heavy oil recovery methods, including SAGD, steam huff-n-puff, and steam flooding, are still effective methods for the exploitation of heavy oil resources [2, 3], which is why they are dominant in oil fields. However, because of the significant differences in density and viscosity between heavy oil and steam [4, 5], conventional enhanced oil recovery methods lead to problems such as steam fingering and channeling [6, 7]. In this situation, the injected steam only flows through high-permeability areas and bypasses most of the remaining oil [8], resulting in a low recovery factor [9]. Particularly for the reservoir with thin oil pay zone, the SAGD process cannot be applied in this reservoir economically. So that in order to develop the oil reserves in this reservoir, steam flooding process is usually carried out. To boast the oil recovery, it is important to alleviate the negative effect of steam channeling in heavy oil development, in terms of how to plug the channel and increase the steam sweep volume. Scholars have carried out studies on injecting different media to enhance oil recovery, such as solid particle plugging, gas-phase foam plugging, and liquid-phase plugging.

Solid particle plugging has the following advantages: low cost, high-temperature resistance, high plugging strength, long-acting time, etc. Zhao et al. prepared coated particles suitable for high-temperature, high-salinity reservoirs. They believed particle migration to be closely related to reservoir permeability [10]. Zhao et al. developed an expandable quartz particle that can effectively block high-permeability channels under high-temperature conditions and force steam into the low-permeability area. This study showed that under the action of polymers, the suspension performance of the solid particle plugging system is greatly improved [11].

Based on solid particle plugging, researchers conducted CO_2-assisted steam flooding to enhance heavy oil recovery. Li et al. studied the effect of CO_2 on the physical properties of a heavy oil-water system [12]. During the steam flooding process, the crude oil was generally emulsified and water-in-oil (W/O) emulsion was formed, which increased the viscosity of crude oil. However, CO_2 has a de-emulsification effect that significantly decreases the viscosity of emulsified crude oil [13, 14]. Another plugging agent is urea solution; once urea solution is injected into the reservoir, it reacts to generate NH_3 and CO_2 under high temperature. This improved heavy oil recovery factor occurs through in situ gas production [15]. Liu et al. used three-dimensional (3D) physical models to carry out experimental research on urea-assisted steam flooding and urea foam agent-assisted steam flooding [16]. The results showed that urea reacts in situ, generating NH_3 and CO_2 and increasing oil recovery factor by 9.85% and 16.08%, respectively, compared with steam flooding. Wang et al. carried out experimental research on urea-assisted steam flooding with high-pressure, high-temperature models [17]. The results showed the injection of urea solution to enhance the oil recovery factor between 2.4% and 18.8%. Li et al. conducted urea-assisted steam flooding experiments and numerical simulation studies using a one-dimensional (1D) physical model [9]. The results showed the gas generated by the urea reaction to maintain pressure in an oil reservoir and to increase oil recovery factor by 10% to 20%. Dahbag carried out a numerical simulation study to improve heavy oil recovery using a 5% to 10% hot urea solution [18]. The results showed the urea solution to change the formation wettability, improve the relative permeability of the oil phase, and delay water breakthrough.

Urea-assisted steam flooding improves heavy oil recovery factor mainly by the following mechanisms: (1) CO_2 generated in situ expands the steam sweep volume and enhances the thermal efficiency [19, 20]. (2) The generated ammonia and the acidic compounds in heavy oil asphaltene react to form surfactants [21]. (3) The generated surfactants reduce the oil-water interfacial tension and change the reservoir rock wettability. (4) The generated surfactant in situ forms W/O emulsion bounded in porous media, which relieves the effect of steam channeling in high-permeability reservoirs and increases the sweep volume [12]. (5) The generated surfactants combine with CO_2 to generate foam [22], which plugs the high-permeability channel and increases the steam sweep coefficient [19]. (6) The urea solution reacts with naphthenic acid in the asphalt under high temperature to form an in situ surfactant that emulsifies the oil phase [23] and to form W/O emulsion at the displacement front, which restricts viscous fingering and channeling [24]. (7) Because the polar charges in the solution will be adsorbed on the rock surface [25], the use of urea solution will change reservoir wettability and make it more water wet; this is good for displacing crude oil out of the reservoir.

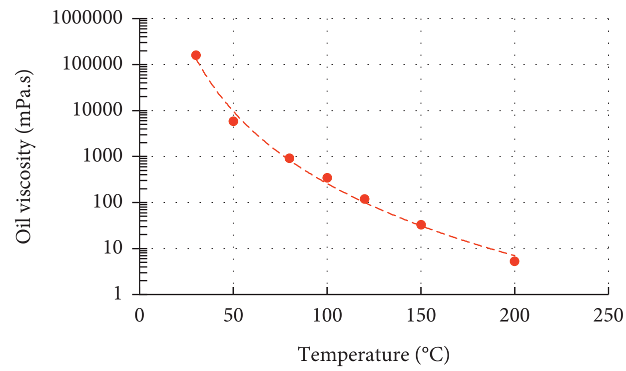


Figure 1: Crude oil viscosity-temperature curve.

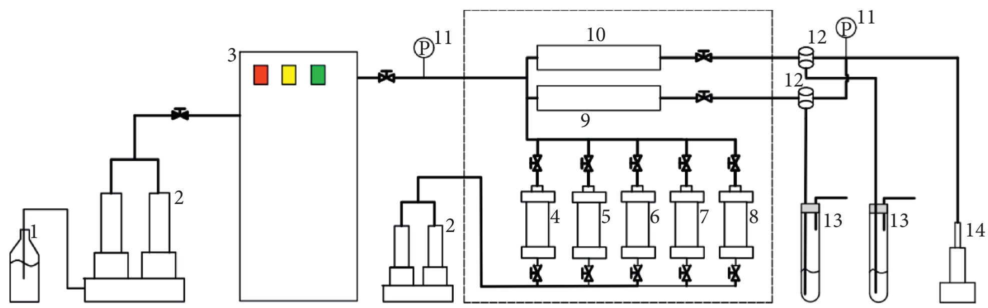
Analyzing the mechanism of urea-assisted steam flooding to enhance heavy oil recovery, it has been found that urea combines the mechanisms of condensate gas, non-condensate gas, and chemical agents, making urea a great choice for assisting steam flooding, but in the process of replenishing formation energy, urea exhibits a pattern different from that of non-condensate gas. For the non-condensate gas injection process, pressure spreads from surface to reservoir, and sweep efficiency is very limited. However, for the urea solution, pressure maintenance is based on the reaction in the reservoir. The urea solution can move to the deep formation of the reservoir to increase the remote pressure. Further, the gas generated after the reaction has a longer distance action, which reaches more residual oil and improves the sweep efficiency [26, 27]. It can be seen that in enhancing heavy oil recovery, urea-assisted steam flooding has broader application prospects.

2. Experimental Section

According to the realities of the on-site steam flooding process for heavy oil fields, the injected high-temperature steam causes dominant channels or high-permeability formation in the reservoir, which leads to the channeling of subsequent medium injection and makes further enhancing heavy oil recovery impossible. This study used solid particles to carry out experiments on plugging ratio for high-permeability formation to clarify the effect of solid particle plugging on a parallel sand pack model with a significant difference in permeability. Meanwhile, this study conducted research on medium-assisted steam flooding to improve heavy oil recovery, including CO_2, urea solution, and other single-medium-assisted steam flooding experiments, as well as research on multimedia-assisted steam flooding experiments.

Table 1: SARA of the crude oil sample.

Property	Saturates	Aromatics	Resins	Asphaltenes	Unrecovered
Measured (%)	36.97	22.25	19.92	18.81	2.05



1. De-iron water;
2. Iso pump;
3. Steam generator;
4. Crude oil;
5. Formation water;
6. CO_2;
7. Urea solution;
8. Solid-plugging agent solution;
9. High-permeability sand-pack;
10. Low-permeability sand-pack;
11. Pressure gauge;
12. Back pressure regulator;
13. Oil-gas separator;
14. Constant pressure pump.

Figure 2: Schematic of multimedia-assisted steam flooding process. (1) De-iron water; (2) iso-pump; (3) steam generator; (4) crude oil; (5) formation water; (6) CO_2; (7) urea solution; (8) solid plugging agent solution; (9) high-permeability sand pack; (10) low-permeability sand pack; (11) pressure gauge; (12) back pressure regulator; (13) oil-gas separator; and (14) constant pressure pump.

2.1. Materials. Crude oil was collected from heavy oil fields in western China. The viscosity of crude oil at 50°C was 5862 MPa, the crude oil viscosity-temperature curve is shown in Figure 1. A saturate-aromatic-resin-asphaltene (SARA) analysis of the crude oil is shown in Table 1. The salinity of the formation water was 9586 mg/L. The CO_2 gas concentration was 99.9%, and the urea purity was 99.99%.

2.2. Experimental Setup. In this study, the experimental setup of multimedia-assisted steam flooding to improve heavy oil recovery is shown in Figure 2. The device included the following:

(1) Injection system: constant speed displacement pump, steam generator, transfer containers.
(2) Displacement system: sand pack model, pressure sensor, high-temperature and high-pressure oven.
(3) Data collection system: computer, data converter.
(4) Gas-liquid separation system: gas-liquid separator, back pressure regulator, constant pressure control pump.

The sand packs and transfer containers were located in the oven, and the pressure in the models was maintained using the back pressure regulars. The test range of the oven was 20 to 300°C with an accuracy of ±0.5°C. The range of the steam generator was 20 to 400°C with an accuracy of ±0.5°C. The liquid meter accuracy was 0.1 mL. The inner diameter of the 1D sand pack model was 3.8 cm, and the length was 30 cm. The particle size of quartz sand was 20 to 100 mesh.

2.3. Experimental Procedure. To study the role played by multimedia in the multimedia-assisted steam flooding process, it was applied in high-permeability formation for plugging and profile control. This study carried out the following experiments: high-permeability sand pack model plugging experiments and single-medium and multimedia-assisted steam flooding experiments. The specific experimental processes can be summarized as follows.

2.3.1. Plugging Experiment

(1) The one-dimensional (1D) sand pack model is filled with quartz sand to establish a high-permeability model.
(2) Then, the measurement of the physical properties of the model (pore volume, porosity, and permeability) was conducted.
(3) The sand pack was vacuumed, and then, the pore volume and porosity were determined by the water volume saturated in the sand pack. Different injection rates were employed in the sand pack, and Darcy's law was applied to determine the average permeability under the different injection rates.

(4) Solid plugging agent solutions in different pore volumes (PVs) are injected, the permeability of the plugged sand pack is measured, and the plugging ratio is calculated.

(5) The injection volume of the solid plugging agent is changed, the above experimental steps are repeated, and the injection volume is optimized.

2.3.2. Single-Medium-Assisted Steam Flooding Experiment

(1) The packed sand pack model is saturated with crude oil until no water is displaced out of the model, and the original oil saturation and original water saturation are calculated. In total, 2 PV of crude oil was injected.

(2) Steam and single medium are injected into the sand pack model, and the single-medium-assisted steam flooding experiments are conducted. The experiment is stopped once water cut of the steam flooding reaches 95%.

2.3.3. Multimedia-Assisted Steam Flooding Experiment

(1) Two sand pack models with a significant permeability difference as a parallel model system are packed. The higher-permeability sand pack is used to mimic the formation where steam channeling is dominant during steam injection.

(2) The properties (PV, porosity, permeability, oil saturation, water saturation) of the physical model are measured using the above methods.

(3) The steam flooding experiment is conducted as the base case. Solid particle plugging agent is used to plug high-permeability sand pack model, and then, multimedia-assisted steam flooding experiment and plugging agent with multimedia-assisted steam flooding experiment are carried out.

3. Results and Discussion

3.1. Experiment on Solid Particle Plugging Ratio. Five sets of physical sand pack models were filled with 20 to 100 mesh quartz sand. After sand packing, the permeability of the model was measured in the range of 2576 to 2718 mD. Different sand pack models were injected with different volumes of plugging agent, and then, the permeability was measured and plugging ratio was determined. The experimental results are shown in Table 2 and Figure 3.

From the experimental results, one can find that good plugging performance by the plugging agent in the high-permeability sand pack model was achieved. With the volume increase in injected solid particle plugging agent, the plugging ratio increased. When the injection volume reached 0.10 PV, the plugging ratio was 88.28%, essentially successfully plugging the high-permeability formation to a large extent. With the injection of the plugging agent, the plugging effect was significantly improved. When 0.40 PV plugging agent was injected, the plugging rate reached 98.75%. When the injected plugging agent volume exceeded 0.40 PV, the plugging ratio of the sand pack model did not increase too much. Therefore, the optimized injection volume of the plugging agent in this study was found to be 0.40 PV, and the permeability of the sand pack model decreased from 2633 to 63 mD.

Table 2: Plugging effect experiments with different sand pack models.

PV_{inj} (PV)	K_{ini} (mD)	K_{plug} (mD)	R_{plug} (%)
0.1	2576	302	88.28
0.2	2631	185	92.97
0.3	2596	127	95.11
0.4	2633	63	97.61
0.5	2718	45	98.34

Note. PV_{inj}—injection volume of solid particle plugging; K_{ini}—initial permeability; K_{plug}—permeability after plugging; R_{plug}—plugging ratio.

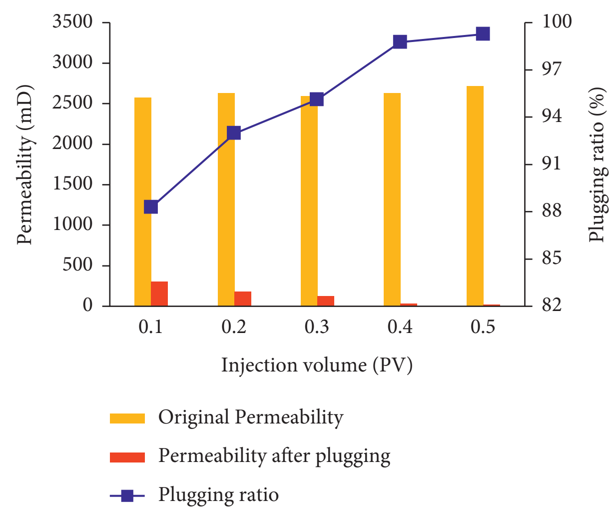


Figure 3: Plugging ratio with different models under different conditions.

3.2. Screening Injected Medium. To optimize the injection medium for the media-assisted steam flooding process, this study implemented experimental research on different medium-assisted steam flooding processes. When the water cut reached 95% in the steam flooding process, different types of media, such as CO_2, urea solution (30% concentration), and CO_2 + urea solution, were used in the flooding experiments. The slug size was 0.20 PV, the experimental temperature was 200°C, a back pressure regulator was used to make sure that the pressure in the model was lower than the steam-saturated vapor pressure at 200°C, which is 1.55 MPa, and the steam displacement rate was 3 mL/min. The oil displacement volume was recorded, and the recovery factor was calculated. The production performances are shown in Table 3 and Figure 4.

The experimental results indicate that, when the medium was injected for displacement after steam flooding, good production performance was obtained, with the recovery factor being 3.37% to 10.70% higher than the steam flooding process. CO_2-assisted steam flooding improved heavy oil

Table 3: Statistics of physical properties and displacement performance for different sand pack models.

Test	PV (cm^3)	Φ (%)	K (mD)	So (%)	IM	Rs/o (cm^3/cm^3)	RF (%)
#1	117.68	34.59	3089	75.36	Steam	0.073	48.68
#2	106.15	31.20	2756	70.81	CO_2 + steam	0.074	52.05
#3	125.13	36.78	3261	72.65	Urea + steam	0.084	57.73
#4	116.87	34.35	2938	68.77	CO_2 + urea + steam	0.082	59.38

Note. PV—pore volume; Φ—porosity; K—permeability; So—oil saturation; IM—injection medium; Rs/o—oil-steam ratio; RF—recovery factor.

recovery to a certain extent. Urea-assisted steam flooding greatly increased the recovery factor by 9.05%. This can be attributed mainly as follows:

(1) The mechanisms of CO_2-assisted steam flooding process are viscosity reduction, dissolution, and expansion, CO_2 extraction of light hydrocarbons, enhanced steam sweep volume, gravity differentiation, etc.

(2) CO_2 has an overlap and thermal insulation effect. Because of the difference in density between CO_2 and steam, CO_2 will flow to the upper formation. Because CO_2 is a non-condensate gas and its thermal conductivity is relatively low, the heat transmission rate of steam overlying formation is reduced, and the heat loss is reduced significantly. Thus, the heat efficiency of steam injection is improved effectively.

(3) The generated free gas merges with crude oil in the reservoir to form foamy oil, which plays a role of plugging to a certain extent, as shown in Figure 5.

From Figure 4, one can find that the CO_2 + urea solution-assisted steam flooding process achieves the best production performance, with the recovery factor being 10.7% higher than that of the steam flooding process. This is mainly due to the following:

(1) Urea decomposes into NH_3 and CO_2 under high temperature (200°C), and CO_2 could reduce steam condensation. Meanwhile, gas volume expansion under high temperature supplements formation energy and greatly increases displacement pressure.

(2) The NH_3 generated from the decomposition of urea reacts with acidic substances in the crude oil after being dissolved in water to form a surfactant. The surfactant reduces the capillary force at the oil-water interface and promotes the flow of residual oil.

(3) The generated CO_2 in the urea decomposition process and the injected CO_2 have a synergistic oil displacement in the steam flooding process.

(4) Emulsification occurs in the process of urea-assisted thermal recovery. The emulsified oil droplets block the pore throats, which block the high-permeability zone. The displacement fluid then flows into the unswept throats, and thus, the sweep coefficient is increased.

3.3. Multimedia-Plugging-Assisted Steam Flooding. For heavy oil reserves developed by steam flooding process, high-permeability channels are formed by long-term steam flooding process, which seriously affects the heavy oil production performance. To study the influence of different high-permeability formations on the production performance of steam injection, parallel displacement experiments of different sand pack models with a permeability difference of 10 times were conducted in this study. The properties and displacement effects are shown in Table 4.

In the experiments, the permeabilities of the parallel sand pack models were 5713 and 565 mD. Steam flooding was firstly implemented on the parallel sand pack model. After the water cut at the outlet of the sand pack model achieved 95%, the steam flooding process was stopped. Then,

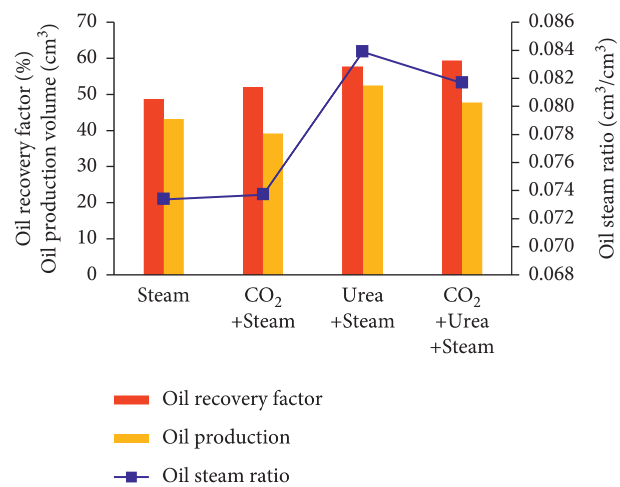


Figure 4: Comparison of production performance with different medium-assisted steam flooding processes.

Figure 5: Foamy oil in the experiment.

Table 4: Physical properties and development effects of sand pack models with different permeabilities.

Test	PV cm^3	Φ (%)	So (%)	K (mD)		RF (%)		
				K_{ini}	K_{plug}	SF	SF/plug	SF/CO_2/urea
#5	115.03	33.81	75.08	5713	503	50.15	52.78	61.13
	98.32	28.9	71.26	565	382	10.08	28.96	36.38

Note. PV—pore volume; Φ—porosity; So—oil saturation; K—permeability; RF—recovery factor; K_{ini}—initial permeability; K_{plug}—permeability after plugging; SF—steam flooding; SF/plug—steam flooding after plugging; SF/CO_2/urea—mixture of CO_2 and urea-assisted steam flooding.

the solution of solid plugging agent was injected into the sand pack models, and in total, 0.40 PV plugging agent was employed, and the differences in the permeabilities are shown in Figure 6.

This was reflected in the experiments when steam flooded the parallel sand pack model; the high-permeability sand pack model (5713 mD) was prone to steam channeling. The injected steam passed by the high-permeability formation directly to the production end, resulting in low oil displacement efficiency in the low-permeability sand pack, with the recovery factor at only 10.08%. To relieve steam channeling, it is suggested to use the aforementioned optimized solid particle plugging agent to plug the sand pack model. Because the plugging agent has certain selective plugging properties, it will first plug high-permeability sand pack models. Figure 6 indicates that the plugging ratio of the high-permeability sand pack reached 91.20% after injecting 0.40 PV plugging agent. This effectively plugged the high-permeability formation, and thus, steam channeling was controlled. Solid particle plugging agents were less harmful to low-permeability formation, with the plugging ratio at only 32.39%.

Once the solid plugging agent was injected into the model, 0.20 PV of CO_2 + urea was combined for multimedia-assisted steam flooding. The experimental temperature was 200°C, and the steam displacement rate was 3 mL/min. The production performance of the plugging agent + multimedia combination was evaluated, as shown in Figure 7.

It can be seen from the results (as shown in Figure 7) that after steam flooding process, the oil recovery factors for high-permeability and low-permeability sand packs were 50.15% and 10.08%, respectively. Once the sand pack model was plugged, the recovery factor of high-permeability reservoir was increased by 2.63%, and the recovery factor of low-permeability reservoir was improved by 18.88%, which is because the steam injected in the early stage preferentially flowed into the high-permeability formation, leading to a higher recovery factor of the high-permeability sand pack model and resulting in less improvement in recovery factor after plugging. Before plugging, the steam sweep efficiency of the low-permeability sand pack model was low, with the recovery factor at only 10.08%. After plugging, the permeability difference in parallel sand pack models was reduced, with greatly improved sweep efficiency and recovery factor.

Based on the profile improvement of the sand pack model, 0.20 PV CO_2 + urea solution combined media were

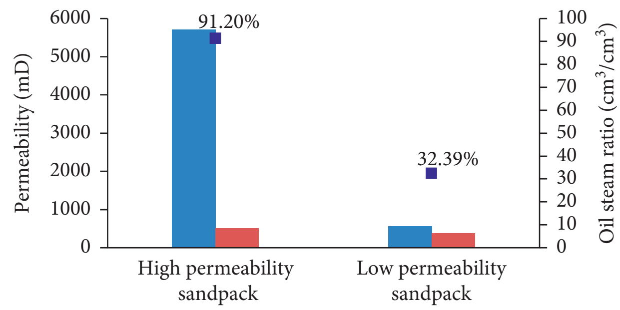


Figure 6: Comparison of plugging ratio before and after plugging with different-permeability sand pack models.

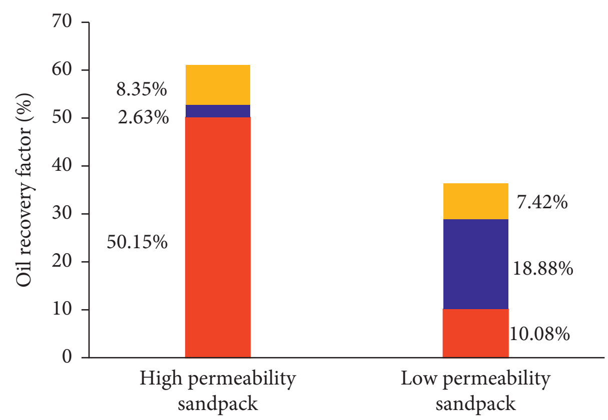


Figure 7: Comparison of production performance before and after plugging with different-permeability sand pack models. AP—after plugging.

injected to carry out the plugging agent + multimedia oil displacement experiment shown in Table 4 and Figure 7. It can be seen from the results that the oil recovery factor of the two sand pack models was improved after the injection of multimedia. The recovery factor of the high-permeability formation increased by 8.35%, and the recovery factor of the low-permeability formation improved by 7.42%. It can be seen by these experiments that the plugging agent + multimedia channeling obviously improves oil recovery factor for highly oil-saturated reservoirs. Crude oil in low-permeability reservoirs is swept effectively with this method. The experimental results indicate that under the condition of a significant permeability difference, the plugging agent and multimedia can still produce crude oil in medium- and low-permeability reservoirs. The solid particle plugging agent still has good plugging performance for high-permeability formation and obviously improves reservoir recovery.

4. Conclusions

In this study, plugging agent study, single-media-assisted steam flooding experiment, and multimedia-assisted steam flooding experiment were conducted with the following conclusions obtained:

(1) The solid particle plugging agent has good injection ability, the optimized slug size is 0.40 PV, and the plugging ratio is above 98%.

(2) The medium-assisted steam flooding process improves heavy oil recovery factor compared with steam flooding, and gas-assisted steam flooding meets synergistic oil displacement effect. The CO_2 + urea solution-assisted steam flooding method achieves the best production performance, with the recovery factor of 10.70% higher than that of the steam flooding process.

(3) With the selective plugging properties of the solid particle plugging agent, the plugging ratio of the high-permeability formation can reach 91.20%, playing a role in plugging effectively. The solid particle plugging agent is less harmful to low-permeability formation with a plugging ratio of 32.39%.

(4) After plugging, the permeability difference in the parallel sand pack model is remarkably reduced, which improves the sweep efficiency, and thus, the recovery factor is greatly enhanced. Compared with the original sand pack model and the sand pack model after plugging, the oil recovery factor for high-permeability sand pack is improved by 10.98%, and the recovery factor for low-permeability sand pack is improved by 26.30%.

Data Availability

All data and research results supporting this study are included in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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