Research Article

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Study on the application of a steam-foam drive profile modification technology for heavy oil reservoir development

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Abstract: This paper introduces a steam-foam drive profile modification technology for heavy oil development in Block Qi40 based on an in-depth study of the characteristics of heavy oil reservoir and cross flow characteristics of injected steam in Block Qi40 of Liaohe Oilfield. The performance evaluation was carried out indoors for foaming agents. Influencing factors affecting profile modification and foam injection mode selection are studied. The results show that the CX-4 foaming agent system has excellent foaming properties and foam stability at 300°C. The plugging pressure difference of core can be increased by more than 15 times at 240°C. When a 0.5 PV foaming agent system is injected, the oil displacement efficiency can reach more than 68%. The optimal concentration of the foaming agent is 0.5% and the change of resistance factor is the largest in the range of oil saturation between 15 and 20%. Foam has better plugging ability in high permeability and large pores. Furthermore, after field application effect analysis, it confirms that the steam-foam profile modification technology has an obvious effect on enhancing oil recovery.

Keywords: heavy oil, steam drive, high-temperature foam, profile modification

1 Introduction

Steam channeling is the most difficult technical problem during steam huff & puff and steam drive processes for heavy oil development. The control effect of steam channeling is related to whether the steam flooding development can achieve good results.

Most heavy oil reservoirs in China were originated from continental deposits with severe heterogeneity and significant difference in steam channeling. There are channeling of large pore paths, the inrush of high permeability zones, and gravity override [1,2].

However, after many years of development, the main oil fields have entered into the multi-round huff & puff development stage, and there have been problems such as low reservoir pressure, high water content, low well yields, low recovery rates, and deteriorated physical properties, etc. The effect of huff & puff is getting worse. Laboratory study and field practice show that steam drive development is the most effective mode of further improving heavy oil reservoir recovery rates. The multi-round huff & puff development mode of Block Qi40 of Liaohe Oilfield is turned into the steam drive development mode, whereas new problems and conflicts constantly occur during the steam drive development process [3,4].

On the one hand, the viscous fingering is caused by the extremely unfavorable flow ratio of steam and high viscosity crude oil, and the steam superposition is caused by the extremely unfavorable density difference, resulting in low steam sweep efficiency during steam flooding; due to the existing reservoir heterogeneities, high permeability zones or fissures make steam flows into production wells along high-permeability zones rapidly [5–7]. The biggest hazard of steam channeling is that steam is produced from steam channeling wells directly, the heat injected cannot be fully and effectively used, steam flows bypassing the high-yield oil-bearing zones, and it is produced from production wells, the displacement swept volume is

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small, and the development effect is poor. Particularly, for blocks changed from cyclic steam injection development to steam drive development, distributions of thermal fields and pressure fields are uneven and the problem of steam channeling is extremely prominent. On the other hand, the steam swept zones still have high residual oil saturation. During the steam drive process, oil zones form different displacement zones, including the steam zone, the condensation miscible zone, the hot water zone, and the cold water zone from the front to the end of the steam. Due to the major interfacial tension between oil and water, the steam displacement efficiency is not high [8–10].

In order to increase the overall steam swept volume and the ultimate recovery ratio, effective measures are required to prevent a steam breakthrough. Foam has the ability to control the fluidity selectively, improve the displacement of injected fluid in the heterogeneous reservoir, reduce the fluid coning in high permeability reservoir, adjust the steam absorption profile of oil layer in the steam, block the channel of steam breakthrough, and improve the steam sweep coefficient and crude oil recovery [11–14]. Therefore, the foam profile control technology is a more effective means to solve steam overlay and breakthrough.

2 Experimental

2.1 Foaming agent indoor performance evaluation

According to the characteristics of the heavy oil reservoirs in Block Qi40 of Liaohe Oilfield, by using the oil sand samples, dewatered oil, and simulated formation water from the steam drive pilot test zone in Block Qi40, the main performance evaluation and selection were carried out indoors for the four foam agents (CX-1, CX-2, CX-3, CX-4), whose main component is α -olefin sulfonate anionic surfactant with an effective concentration of 20%.

2.1.1 Foamability and foam stability

Foamability refers to the degree of difficulty of generating foam and the amount of foam generated. If measured by the volume of foam generated, the stability of foam refers to the lifespan of the foam; if measured by the half-life period of foam, it refers to the time required for the

Figure 1: Foaming volume of the foaming agent at 300°C.

Figure 2: Foam stability of the foaming agent at 300°C.

volume of foam to decrease to one-half its original volume. Figures 1 and 2 show that the CX-4 foaming agent not only has a large foam volume but also has a long half-life, so it is considered as a good foaming agent.

2.1.2 Morphological description of environmental scanning electron microscope

A Quanta450 FEG field emission environmental SEM is used to test the foaming agent before and after the high-temperature treatment. The SEM images of the original foaming agent are shown in Figure 3, and these images are magnified 800 times, respectively.

The SEM images of the foaming agent after high-temperature treatment at 300°C for 24 h are shown in Figure 4, and these images are magnified 800 times, respectively.

Figure 3: SEM images of the original foaming agent.

As shown in Figure 3, although the natural gas of the original high-temperature foaming agent has escaped in the drying process, the air-bubble voids remain intact; the size and shape of the void are similar to those of the bubble. The bubble has an irregular hexagonal structure.

Figure 4 shows the SEM images of the foaming agent after high-temperature treatment. After the air in the bubble is pumped, the absorbed film around the bubble has a bubble-centered ring structure, which intertwines and shows a spatially overlapping state. The absorbed film of the foam has kept the integrity, and it is relatively

Figure 4: SEM images of the foaming agent after high-temperature treatment at 300°C for 24 h.

thick. It is unevenly distributed in space, and the three-dimensional structure becomes slightly worse. This is mainly due to the uneven dispersion of the polymer compound in the foaming agent on the liquid film under the condition of high temperature. In areas where polymer compounds are concentrated, due to high viscosity, the volume of the foam is small, but there are many bubbles. Thus, a temporary polymer compound chain with a three-dimensional network is created, which increases the wall thickness of the foam and prevents film thinning. As a result, it has splendid barrier properties, which is conducive to the stability of the foam system.

2.1.3 High-temperature endurance performance

The foaming agent is mixed with simulated formation water to prepare a solution with a concentration of 0.5%, which is loaded into an HTHP (high temperature and high pressure) autoclave to carry out a temperature endurance test. Table 1 shows the evaluating indicators of high-temperature endurance performance of the foaming agents.

As can be seen from Table 1, CX-4 has satisfactory thermal stability to meet the requirements of a field test.

2.1.4 Flooding performance

Using cores to carry out displacement experiment, Figure 5 shows flooding performance evaluation curves of various foaming agents. It indicates from Figure 5 that after injecting 0.5 PV CX-4, oil displacement efficiency can reach above 68%; after injecting 1 PV CX-3, oil displacement efficiency reaches 64%, which is close to the former. Therefore, CX-4 and CX-3 have satisfactory oil displacement efficiencies. It indicates from performance evaluation on several foaming agents as mentioned above, CX-4 foaming agent has the best performance, followed by CX-3, CX-2, and CX-1.

2.2 Influence of Influence factors of steam-foam profile modification

2.2.1 Influence of foaming agent concentration

During the experiment on the influence of foaming agent concentration, we set the foaming agent as CX-4, temperature as 240°C, gas-oil ratio as 1:1, and foaming agent concentrations as 0, 0.2, 0.3, 0.5, and 1.0%, respectively, and the experimental results are shown in Figure 6.

Table 1: Indicators of high-temperature endurance performance of the foaming agents

Name of foaming agent	CX-1	CX-2	CX-3	CX-4
Experimental conditions	300°C, 1 day	310°C, 3 days	320°C, 10 days	340°C, 20 days
Thermal degradation rate (%)	12.1	9.95	8.87	0

Figure 5: Curves of steam drive efficiency. **Figure 6:** Influence of foaming agent concentration on the resistance factor.

It indicates from Figure 6 that when the foaming agent concentration is greater than 0.3%, the resistance factor is greater than 4; with foaming agent concentration continuously increasing, the resistance factor of the foam generated also increases rapidly. When the foaming agent concentration is greater than 0.5%, the amplitude of foam resistance factor increment is decreased.

Foaming agent concentration has a major influence on the plugging performance of the foam. When the foaming agent reaches a certain concentration, it can reduce the flowability. With the increment of concentration, surface tension is rapidly reduced and more active molecules show oriented arrangement along the liquid–gas interface, and the liquid film strength is increased, and thus the plugging effect is improved. Generally, the appropriate application concentration of the foaming agent is 0.5%.

2.2.2 Influence of oil saturation

Figure 7 shows the experimental curves of the influence of oil saturation values on foam resistance factor using foaming agent CX-4. It is observed from the experimental results as shown in Figure 7 that when oil saturation in the oil-bearing zone is greater than 20%, the resistance factor of N_2 foam is always less than 4, i.e., it has no profile modification capability; when oil saturation is smaller than 20%, the resistance factor of N_2 foam increases rapidly. When oil saturation reaches around 15%, the resistance factor of N_2 foam is close to the resistance factor when there is no oil. When oil saturation is in the range from 15 to 20%, the resistance factor has the greatest change. Thus, foam plugging is selective, which is also favorable for the application of foam profile modification. As for the steam drive, oil saturation in steam channeling pores is generally low, and foam can be generated in steam channeling pores. Therefore, reducing steam mobility can control steam channeling effectively.

2.2.3 Influence of core permeability

Figure 8 shows the test curve of the influence of permeability on the foam resistance factor. It indicates from Figure 8 that as permeability increases, the foam flow resistance factor increases and so does the plugging capacity. The foam has better plugging capacity in high permeability and large pore paths. It is concluded that foam is generated mainly in large pore paths in the cores, plugging these pore paths.

Figure 7: Influence of oil saturation on the foam resistance factor.

Figure 8: Influence of permeability on the foam resistance factor.

2.3 Injection mode selection

Currently, there are mainly three kinds of steam-foam profile modification injection modes both at home and abroad, namely slug injection, continuous injection, and intermittent injection.

The slug injection method is to inject a certain amount of foam and nitrogen (or other non-condensable gases) into the steam injection well, then inject steam. After some time, re-inject the foaming agent and nitrogen. The method is generally used for plugging steam channeling between plugging cyclic steam injections. The effect is not ideal for steam channeling well groups.

The continuous injection method is to inject a certain amount of foam and nitrogen continuously into the formation. Though it has a good effect of plugging profile

modification, it needs strict requirements on equipment and it is not economical.

The intermittent injection method is to combine and optimize the above two methods. For a steam injection well, it is to mix a foaming agent with a certain concentration and nitrogen evenly, then inject a small slug along with the steam and then stop for some time, and inject foaming agent and a small slug again, and then stop for some time, using such a cycle to carry out foam profile modification with an average interval of 12–36 h.

Steam-foam profile modification for steam drive well groups adopts the intermittent injection method that is the most cost-effective. Field test shows that after stopping injecting foaming agent and nitrogen, the pressure of steam injection in the steam injection well is still rising in 8 h, i.e., foam plugging is still effective. Selecting the interval of 12 h for Block Qi40 of Liaohe Oilfield is the best option, and in addition, the on-site injection equipment can meet the requirements of the above process design.

Ethical approval: The conducted research is not related to either human or animal use.

3 Steam-foam profile modification flow design

The flow rate of the foaming agent is calculated according to the amount of foaming agent in the bottom hole, accounting for 0.5 to 1% of the effective concentration of the steam-liquid phase, and the flow rate of nitrogen is calculated according to 1% molar fraction of the steam phase.

3.1 Operation process

Connect the process according to Figure 9, then start the foaming agent injection pump and the nitrogen generator system, regulate flow rates of foaming agent and nitrogen, and control injection pressure of both devices strictly to keep them match as best as possible. The intermittent injection method is adopted, namely, to inject 12 h, stop for 12 h, and then inject for 12 h again and stop for 12 h again for 10 cycles altogether, keeping injecting steam throughout the entire operation process without stopping.

3.2 Actual operation situation

Field tests for steam-foam profile modification were carried out in the 19-K028 steam drive well group in Block Qi40 of Liaohe Oilfield. The foaming agent used was CX-4 agent, and 9.6 tons was injected. Profile modification tests were carried out in the three-wide spacing steam drive well groups. The foaming agent, HR89o3, was adopted for profile modification in the well group of Cao 20-11-17, and 12 tons was injected. F240B foaming agent was adopted for other well groups.

4 Field test and effect analysis of steam-foam profile modification

High-temperature profile modification tests were carried out selecting the well groups with the most severe steam

channeling in the tops and distribution of much-remaining oil in the lower parts. By the end of October 2012, the four well groups with an inverted nine-spot rhombus pattern, 19-K028, 18-027, 18-027, 18-k029, and 17-028 in Block Qi40 of Liaohe Oilfield were taken as test well groups for steam drive high-temperature profile modification. The success rate was 100%. The accumulative total oil recovery increased was 33,225 tons. The recovery rate of reserves of the current stage under the basis of the steam drive is 21.91%; the recovery rate of reserves in the current huff and puff + steam drive stage is 49%; the ultimate recovery rate can reach 70.91%; and the ultimate recovery rate in the planning program can be 61%. It is analyzed as follows taking the 19-k028 well group in Block Qi40 as an example.

4.1 Steam injection pressure changes

Figure 10 shows the pressure curves of steam injection before and after profile modification in the Qi40-19-K028 well group. It indicates from Figure 10 that the wellhead steam injection pressure was 7.89 MPa before operation and the steam injection pressure was 9.13 MPa after the operation, and after the operation was completed, the pressure energy was sustained and stable for some time. The increment in steam injection pressure indicates that the foam profile modification decreased the mobility of steam and increased plugging pressure difference, achieving the purpose of plugging steam channeling paths, adjusting steam entry profile, and improving displacement and sweep efficiency.

Figure 9: Steam-foam profile modification operation flow chart. (1) Air compressor; (2) air buffer tank; (3) filter; (4) heater; (5) N₂ generator; (6) N₂ buffer tank; (7) N₂ booster; (8) foaming agent storage tank; (9) calibration tank; (10) double plunger metering pump; (11) foam generator; (12) check valve; (13) pressure gauge.

Figure 10: Steam injection pressure curve before and after profile modification.

4.2 Production changes

Figure 11 shows the curves of production performance of Qi40-19-k028 steam injection well. It is indicated from Figure 11 that as the intermittent steam injection measure was taken, the total water cut significantly decreased to about 75% and the crude production rate increased significantly. Therefore, peak steam injection rates were designed according to different steam channeling degrees in the well group. For well groups with steam channeling, in order to suppress steam channeling, increase the injection rate of nitrogen-foamed system slug and reduce the injection rate of a steam slug; for well groups without severe steam channeling, the size of the steam slug equals the size of the air foam system slug.

Figure 11: Curves of steam drive production performance of Qi40-19-k028 well group.

5 Conclusion

- (1) The steam-foam profile modification technology can not only improve displacement and sweep efficiency but also improve oil displacement efficiency. The CX-4 foaming agent system has good foaming property and foam stability at 300°C. The plugging pressure difference of core can be increased by more than 15 times at 240°C. When a 0.5 PV foaming agent system is injected, the oil displacement efficiency can reach more than 68%.
- (2) Steam-foam profile modification has a significant effect on wells in which steam channeling occurred, but for wells, without steam channeling, it has no obvious effect. The change of resistance factor is the largest in the range of oil saturation between 15 and 20%. Foam has better blocking ability in high permeability and large pores.
- (3) An ideal foaming agent, a reasonable foam injection process, and an optimal injection opportunity are key factors of successful steam-foam profile modification.

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Conflict of interest: We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled “Study on the Application of a Steam-Foam Drive Profile Modification Technology for Heavy Oil Reservoir Development.”

Data availability statement: Raw data were generated at facility name: Foam evaluation instrument, FEI Quanta 450 ESEM, etc. Derived data supporting the findings of this study are available from the corresponding author on request.

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