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Visualized study of thermochemistry assisted steam flooding to improve oil recovery in heavy oil reservoir with glass micromodels

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Abstract

Steam channeling, one serious problem in the process of steam flooding in heavy oil reservoir, decreases the sweep efficiency of steam to cause a lower oil recovery. Viscosity reducer and nitrogen foam, two effective methods to improve oil recovery with different mechanism, present a satisfactory result after steam flooding. In this article, a 2D visualized device was introduced to investigate the synergistic development effect of two different chemical additives and intuitively study their flowing characteristic in porous media, as well as macroscopic and microscopic mechanism of improving heavy oil recovery by chemical additives after steam flooding. The results showed that the fingering phenomenon was generated obviously in the process of steam flooding, which restricted the swept area of steam. Due to decreasing oil-water interface tension, O/W emulsion with lower viscosity was formed to enhance the oil flow capacity and polish up the displacement efficiency of steam after injecting viscosity reducer. And the synergistic effect of viscosity reducer & foaming agent was more conductive to improve displacement efficiency of steam, with 4.3% of oil recovery higher than purely viscosity reducer assisting steam flooding in this process. Microscopic results indicated that thermal foams can be trapped in the porous media to improve injection profile effectively and displace the residual oil caused by steam flooding. The ultimate oil recovery of synergistic development is 65.6%, 11.0% higher than one additive (viscosity reducer). This article can provide reference for the study of thermochemistry assisted steam flooding in heavy oil reservoir.

Key Words: thermochemistry; steam flooding; 2D visualized physical model; synergistic development; microscopic mechanism analysis; physical simulation

1 Introduction

Recently, with the gradual depletion of conventional oil, the exploitation of unconventional crude oil has attracted much attention, and heavy oil, as a kind of important energy, accounts for a large proportion of oil and gas resources in the world [1-3]. However, with the remarkable characteristic of high viscosity, high density and low mobility, it is quite difficult to produce heavy oil economically efficient using conventional techniques [4-7]. In general, cyclic steam stimulation and steam flooding play a vital role in developing these resources at home and abroad, and steam flooding is an effective measure to improve oil recovery in the late period of steam huff and puff [8-11]. Also, SAGD is another attractive methods for heavy oil or oil-sands[12]. Unfortunately, due to the large difference of oil-water viscosity, the phenomenon of fingering is serious in the process of steam flooding, which forms preferential channeling passage and leads to the lower oil and gas ratio and limited swept area [13-14]. Nowadays, many experts had carried out plenty of investigations on how to improve heavy oil recovery.

Obviously, viscosity reducer is a good choice to reduce the viscosity and improve the mobility of heavy oil. Cash et al.[15] found that viscosity reducer had a strong capacity for reducing viscosity by changing viscous oil or water/oil emulsions into oil/water emulsions of which the viscosity is close to that of water. Yaghi[16] had presented in 2002 that the formation of the emulsions by the use of viscosity reducer forming an oil-in-water (O/W) emulsion could reduce the apparent viscosity. Ezeuko et al.[17] delivered that emulsion was a colloidal system of immiscible fluids, with one fluid as the dispersed phase (usually micrometer-sized drops) and the other as the continuous (non-dispersed) phase. Lu C et al.[18] studied the effects of viscosity-reducer (VR) concentration, salinity, water/oil ratio (WOR), and temperature on the performance of emulsions and found that high VR concentration, high WOR, and low salinity are beneficial to form stable oil/water emulsions and VR solution is beneficial for the oil dispersion and further viscosity reduction.

Steam override and steam channeling, two other significant problems which probably decrease the sweep efficiency of steam, could reduce the oil recovery in heavy oil reservoirs[19]. The use of foams to improve the mobility ratios of oil displacing agents arose from laboratory work in the 1950's and 1960's. In 1968, L.W. [20]described the mechanisms by which foams move through porous media. Friedmann F[21] investigated the high-temperature surfactant foams by modifying gas-phase mobility in conventional thermal simulator and studied foam generation by leave-behind and snap-off as well as foam coalescence and trapping mechanism.

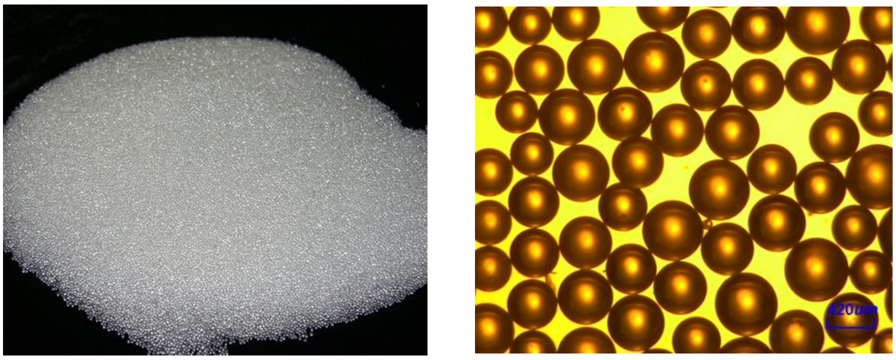
Pang[22] found that thermal foam flooding, an effective EOR method, presented a satisfactory and efficient production in laboratory and field pilot, because thermal foams could restrain steam injection from gravity override and steam channeling in reservoirs and foaming agent was an vital component of decreasing oil-water interface tension and increasing the stability of foam in thermal foam flooding. Furthermore, Zhang[23] selected N_2 and CO_2 as noncondensing gas injected respectively with self-produced foaming agent system called DQS and found two noncondensing gas could improve oil displacement efficiency greatly and CO_2 was the better choice compared with N_2 to be injected with DQS. And nitrogen-assisted CSS had been conducted in the Henan oil field, China, and achieved good results.

Although both viscosity reducer and foams can improve heavy oil recovery to some extent and attract more and more attention, to our knowledge, very little information is provided in the literature on the research of viscosity reducer and foams utilized together. In this paper, the objectives were to investigate the interact relations between different kinds of chemical agents and identify which developing method was suitable for field pilots. So, a two-dimensional visualization device with high temperature and high pressure was used to study the process of steam flooding development in heavy oil reservoir with different chemical agents, including viscosity reducer and foam agents. And the mechanism of different methods improving developing effects of steam flooding was discussed from macroscopic and microscopic phenomena.

2 Experimental Apparatus and Procedure

2.1 Materials

In this experiment, square quartz glasses with holes on four corners could withstand high temperature and high pressure. The thickness of the sand layer was determined by the mesh size of the glass bead. In this study, the glass bead with 420μm (40 mesh) diameter was used to form unconsolidated transparent porous media as shown in Fig.1. The stock tank oil obtained from Biqian10 area in Henan oil reservoir had a viscosity of 1250 mPa·s at 60°C and a density of 0.951 g/cm^3 at 25°C. Two kind of fluids used in this set of experiments were distilled water used to generate steam and brine with 5000ppm of NaCl used to saturate the model. Industrial-grade nitrogen was used as gas with the purity of 99.99%. And a kind of hydrophilic VR called AE-121 and one foam agent called ADC were selected due to the best application effects in the field. For all processes in this study, the concentration of the injected VR and foam agent solution was kept at 0.5% by volume.



(a) original glass beads (b) glass beads under microscope

Fig.1 Glass beads used in this experiment

2.2 Experimental setup

The schematic diagram of the experimental setup was shown in Fig.2. The whole equipment can be divided into three subsystems: fluid-supply system, 2D visualized displacement system, and data-acquisition system. The 2D visualized model contained two pieces of quartz glass plates and two layers of glass beads. The dimensions of the quartz glass plate with a good transparency were 250mm×250mm×30mm, and it can endure the maximum pressure at 3MPa and the highest temperature at 280°C, as shown in Fig.3. While the actual visual area is 200mm×200mm, and the margin is sealed by high temperature resistant glass cement. The glass bead with 420μm (40 mesh) diameter was used to form the effective thickness is 840μm. Canon EOS70D digital camera and

Sweden Optilia optical microscope (the largest magnification is 150 times) were installed above the model to observe the macroscopic and microscopic flow characteristics in the model. A plane light source was mounted under the model to make images much clearer. High temperature steam was generated by a steam generator which was able to produce a maximum of 300°C steam. ISCO micro-gear pump was used to inject different fluids stored in different intermediate vessel into the visualized model.

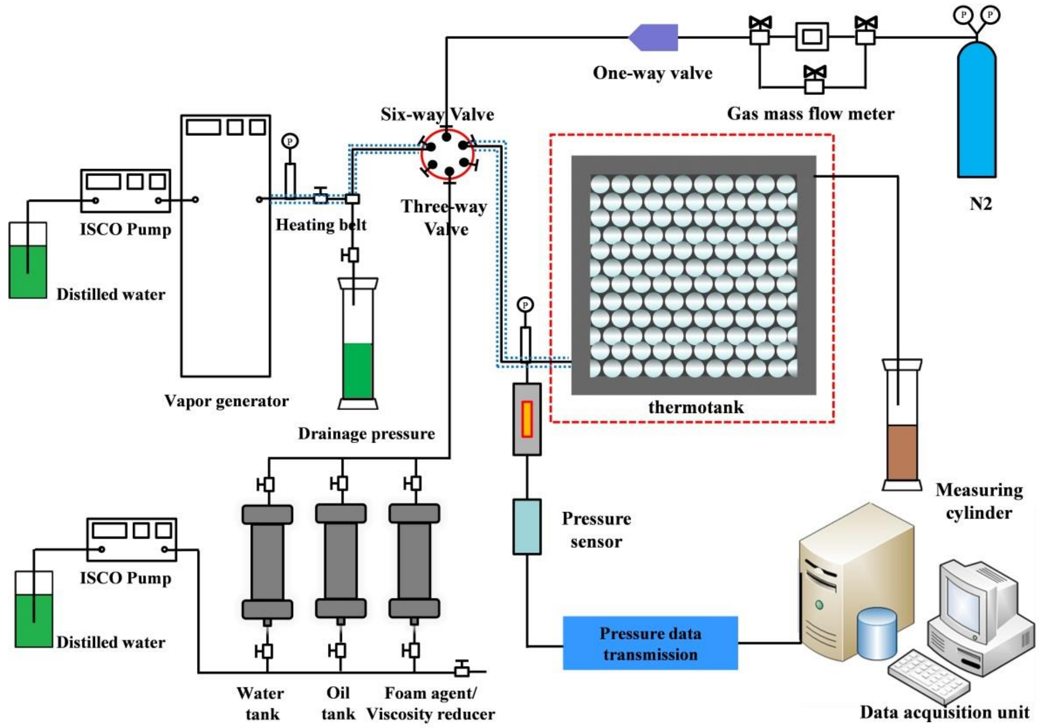
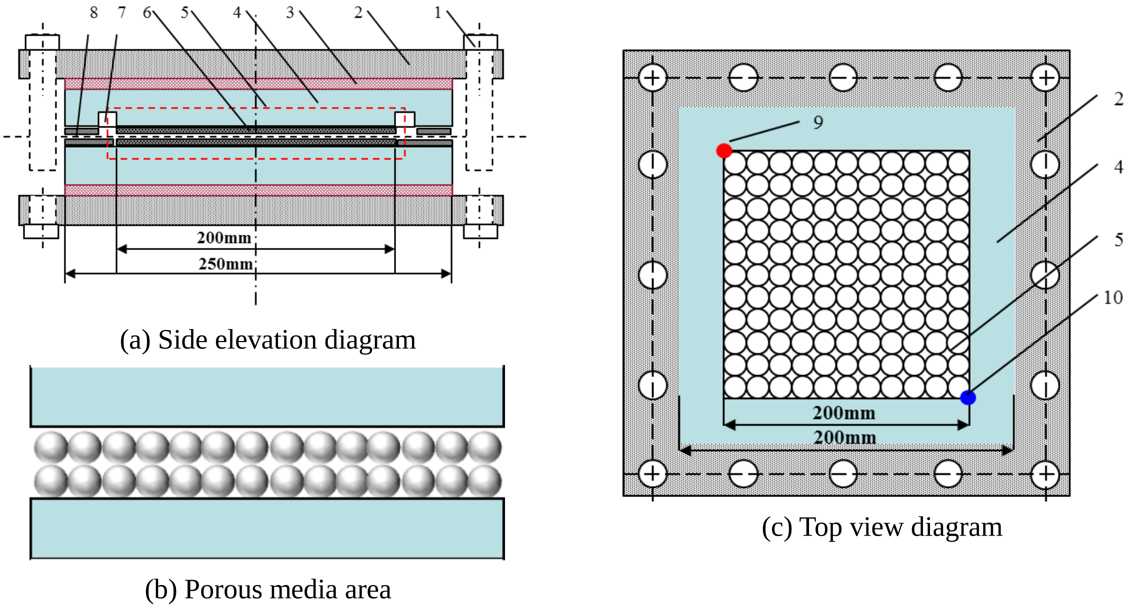


Fig.2 The schematic diagram of the experimental setup



(a) Side elevation diagram

(b) Porous media area

(c) Top view diagram

Fig.3 Structure diagram of the visualized model

1-nut; 2-model holder; 3-silicone pad; 4-quartzglass; 5- porous media; 6-glass beads; 7-draining trench; 8-tape; 9-injection pot; 10- production pot. (a)Side elevation diagram. (b) Porous media area. (c) Top view diagram.

2.3 Experimental procedure

2.3.1 Evaluation of stability of bulk-foam

Considering the reaction of different chemical additives in the visual displacement experiments, foaming ability and stability should be evaluated to confirm the characteristics of chemical additives. Maximum foaming volume(V_m) and half-time($t_{1/2}$), two typical and vital factors reflecting the capability of foaming agent, can be obtained from a static experiment. The former is defined by shearing foaming agents for several minutes at a certain temperature, and the latter is the time when the foam decrease to half of maximum foaming volume at the same temperature.

In this part, foaming volume and half-time of different additives (foam agent with the volumetric concentration of 0.5%, viscosity reducer 0.5%, foam agent 0.5%&viscosity reducer 0.5% and foam agent 0.5% & viscosity reducer 1%) were tested respectively. In this experiment, the apparatuses including visual reaction oven, automatic mixer, glass rod, 1000mL breaker and stopwatch are used to carry out this process. During the experiment, 200mL chemical solution was injected into the reaction oven where the solution was kept at a certain temperature (40℃) for three hours. Then the surfactant solution was stirred by the automatic mixer at a rotating speed of 1600 r/min for 5 minutes. Finally, the foaming volume and half-life of different surfactant solution were measured with the stopwatch.

2.3.2 Visualized displacement experiments

Before the experiments, the visualized models should be cleaned up thoroughly. After the visualized model was prepared, it was mounted horizontally to minimize the effect of gravity. Simultaneously, a series of parameters such as porosity, permeability and initial oil saturation were determined when the models were prepared well as shown in Table 1. The depth of Biqian10 area was relatively shallow, and the reservoir temperature is 35°C ~45°C, so the temperature was controlled at 40°C during the experiment process to achieve a better simulation.

Experimental procedures were as follows: (1) The prepared formation water was injected into the model by ISCO micro-gear pump at a constant volumetric-flow rate (0.5mL/min), and the model was saturated until the water outflowed from the outlet steadily, then the model porosity can be acquired through the material balance method; (2) The crude oil was injected into the visualized model at a constant volumetric-flow rate (0.2mL/min), and the process was completed when the fluid flowing out from the outlet was only the crude oil, then the initial oil saturation was obtained and a connate-water saturation condition was created; (3) Thereafter, the model was undisturbed for 24 h to equilibrate the distribution of fluids. (4) Steam produced from steam generator was injected into the model at a constant volumetric-flow rate (0.5mL/min), and the temperature of steam was 200°C, and the dryness was kept in 0.8. When the oil and steam ratio reached to 0.1 in the stage of steam flooding, the steam and VR solution were injected into the model together at a rate of 0.5mL/min, and if oil and steam ratio of this stage was up to 0.1, steam was injected at a rate of 0.5mL/min with foam agents and N_2 (10mL/min) to simulate foam assisted steam flooding. And the process of steam and VR solution injection was repeated after the oil and steam ratio was 0.1 in the last stage. (5) Two sets of same visualized model were prepared to achieve the comparative experiments, and the designed patterns and property parameters were listed in Tab.1, and the operation process (1) to (4) was repeated.

Tab.1 The experimental parameters of different designed visualization model

No.	Fluid compositions			porosity /%	permeability /$10^{-3}\mu m^2$	Saturated oil volume/mL
	stage	flow-rate /(mL/min)	termination condition(Oil and steam ratio)			
Scheme I	steam flooding	0.5	0.1	45.0	2190	15.12
	steam &VR	0.5	0.1			
	steam &foam	0.5	0.1			
	steam &VR	0.5	0.1			
Scheme II	steam flooding	0.5	0.1	45.8	2120	15.40
	steam &VR &foaming agent	0.5	0.1			
	steam &foam	0.5	0.1			
	steam &VR	0.5	0.1			

3 Experimental Results and Discussion

3.1 Static performance of different surfactant

The results of evaluation on the static performance of different surfactants were shown in Fig.4. Results showed that the viscosity reducer had a little effect on the maximum foaming volume. The maximum foaming volume of foaming agent solution with the concentration of 0.5% by volume was about 750 mL no matter how much the viscosity reducer was, and the maximum foaming volume of viscosity reducer was just about 340mL due to the low ability of foaming. In this paper, the foaming mechanism of different surfactants was not discussed. From the variation curve of foaming volume, the viscosity reducer has a little effect on the half-time of foam and the half-time of foaming agents was about 190min, 15min more than that with viscosity reducer. And the different concentration of viscosity reducer made hardly any difference on the half-time of foam. Nevertheless, the defoaming rate of viscosity is rather quick with the half-time of about 50min. As a result, a rule can be obtained from this experiment that foam still stays stable although the viscosity reducer remains in the layers.

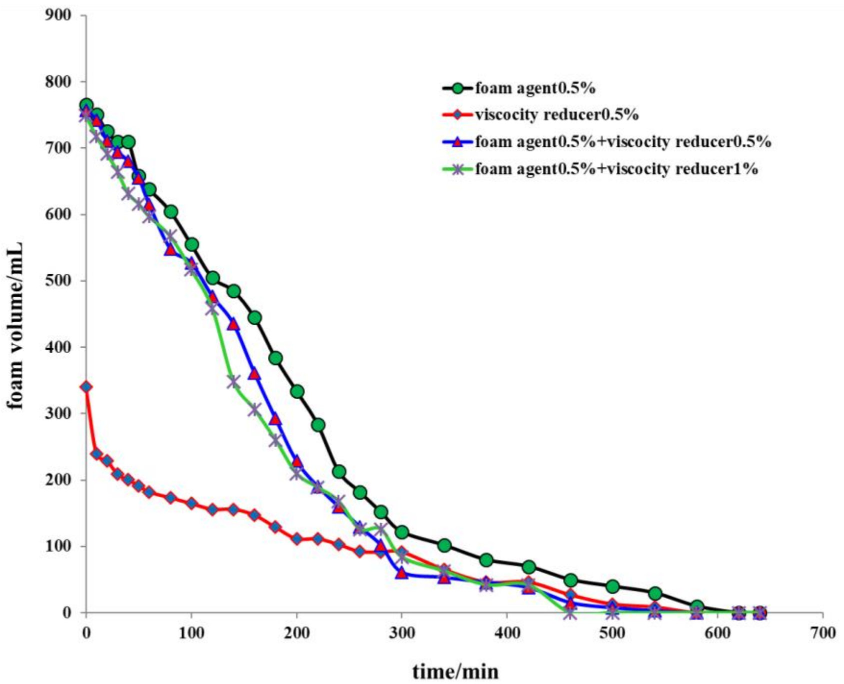
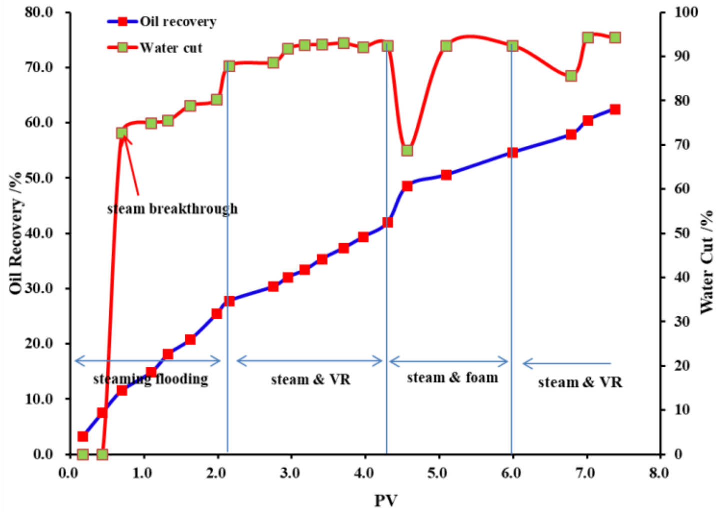


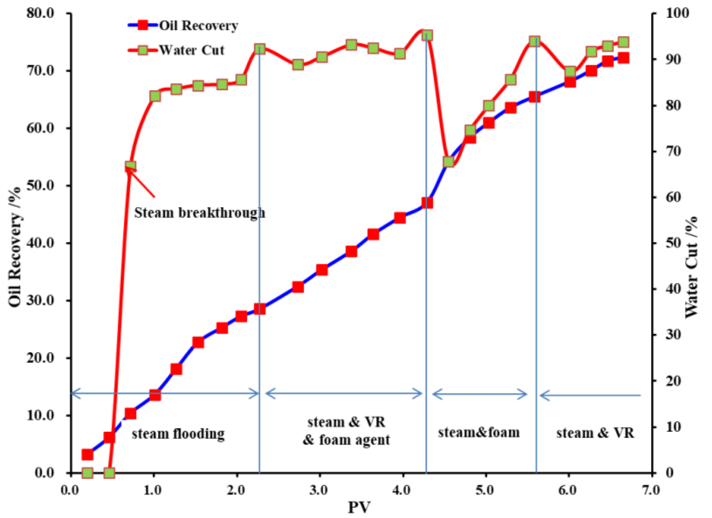
Fig.4 Foaming volume and half-life of different surfactant solution

3.2 Variation of dynamics characteristics

The variations of water cut and recovery with the change of injection liquids were shown as Fig.5(a) and Fig.5(b), during the process of displacement of scheme I and scheme II. According to Fig.5(a) and Fig.5(b), non-water production period existed in the early stage of steam flooding in both schemes, and after that, the water cut rose sharply. Then, the steam front reached the outlet of the model after 0.70PV and 0.74PV of steam were injected respectively in scheme I and scheme II. Thereafter, the recovery of heavy oil increased slowly. In scheme I, the process of steam flooding was ended after 2.10PV of steam injection with 95% of water cut and 27.8% of stage recovery. In the next sequence, viscosity reducer assisted steam flooding was carried out, and the water cut had a little change with the significant increment of oil recovery. The oil recovery increased by 14.2%. Then foam assisted steam flooding was going on to enhance the oil recovery. The injection of nitrogen foam directly contributed to the oil recovery (up to 54.6%) with a rapid reduction of water cut (from 92.5% to 68.8%) and an effective augment of the instantaneous oil production rate. Finally, viscosity reducer assisted steam flooding was repeated to investigate the effectiveness of foam. When the water cut reached to 95%, the experiment was terminated with 62.5% cumulative oil recovery. The difference between two schemes was the foam agent and viscosity reducer assisted steam flooding was conducted after the ending of steam flooding. It was observed that the ultimate oil recovery of Scheme II researched to 72.4%, 9.9% higher than Scheme I. The foam agent was injected into the model with viscosity reducer together, and it can distribute uniformly in the steam channeling. When nitrogen foams were injected, the redundant nitrogen can form stable foams again with the previous foam agent under the shearing action. Although nitrogen was rather difficult to dissolve into heavy oil not like carbon dioxide, the nitrogen foam could be trapped in porous media to change the flow direction of the following liquid. In this case, more unswept previously oil could be mobilized by subsequent displacing liquid.



a. The variation curve of water cut and oil recovery (Scheme I)

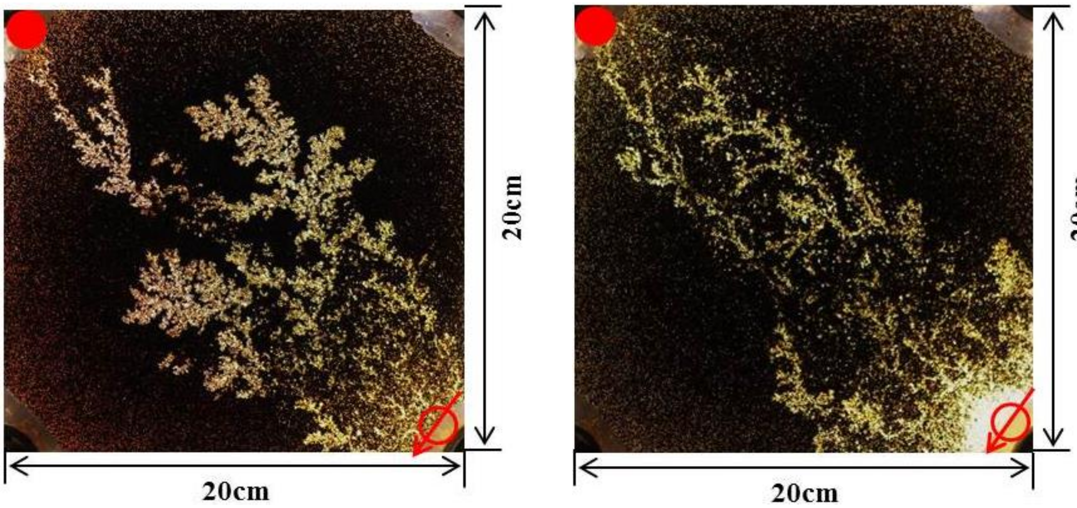


b. The variation curve of water cut and oil recovery (Scheme II)

Fig.5 Variation curves of water cut and recovery with injection volume

3.3 Variation of macroscopic swept area

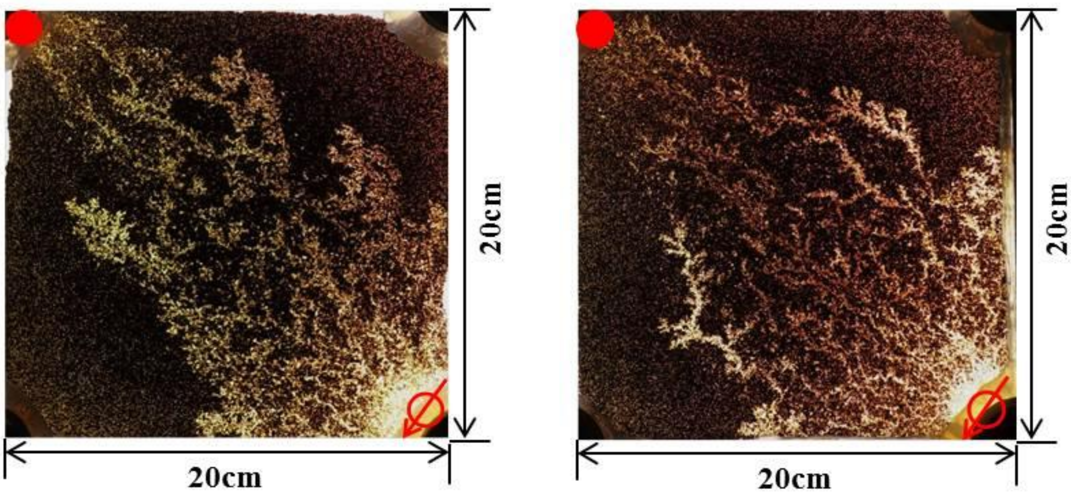
Fig.6~Fig.10 illustrated the effect of macro displacement at the end of different stages under different schemes. As shown in Fig.6~Fig.10, the small spheres and white highlights represent glass beads, and the black-brown area is the distribution of heavy oil, and the yellow ribbons area stands for the swept area of steam and condensation of water. Fig.6 illustrates the swept area at the end of steam breakthrough, and it is observed that the steam and condensate moved quickly along the main streamline. In the process of steam injection, the flowing capacity of heavy oil was enhanced due to the heating of high temperature steam. Meanwhile, the heating effect between main streamline was better. Once their front reached the outlet of the model, as shown in Fig.6a and Fig.6b, the extension of flowing branches left behind the mainstream channel was substantially restricted and some irregular bright bands standed around the main streamline.



a. steam flooding (scheme I) b. steam flooding (scheme II)

Fig6. Macroscopic swept area at the end of steam breakthrough

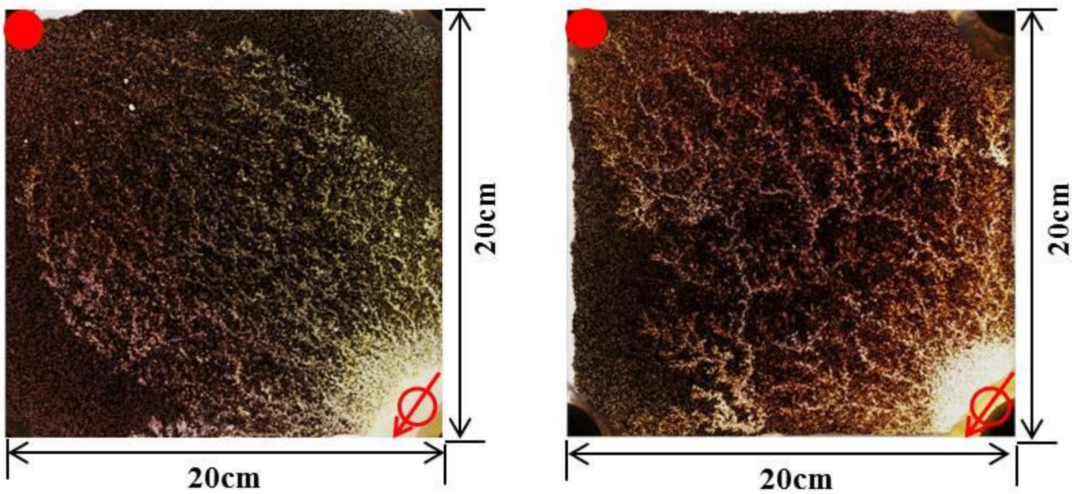
At the end of steam flooding, although the swept area expanded to some extent, there was still plenty of residual oil existing in oil layer, mainly locating on both sides of the mainstream channel, as shown in Fig.7. Due to the difference of viscosity between steam and heavy oil, a large amount of steam and condensate water moved along the main streamline, which maked the range of steam sweeping limited seriously. From Fig.7a and Fig.7b, it also could be observed that the oil recovery and sweep efficiency of these two schemes were basically equal in the process of steam flooding.



a. steam flooding (scheme I) b. steam flooding (scheme II)

Fig.7 Macroscopic swept area at the end of steam flooding

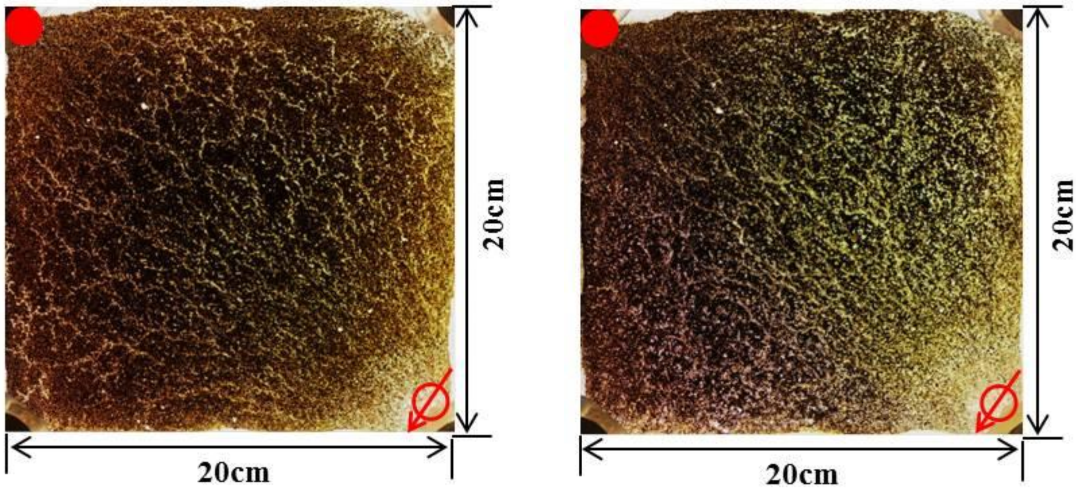
Fig.8a illustrated the variation of swept area when the viscosity reducer is injected into the model with steam. It can be seen that the color of the main streamline became bright, which indicated viscosity reducer can improve the displacement efficiency effectively. And the swept area extending to fusiform expanded to some extent. When the reducer viscosity was injected, the oil in water emulsion will be formed to be used for plugging because of the lower interface tension. Fig.8b showed the variation of swept volume with the injection of reducer viscosity and foam agent simultaneously. As shown in Fig.8b, the swept area also enlarged with an irregular shape. Considering the oil recovery(Fig.2), the Scheme II was higher than Scheme I (4.3% higher) mainly due to the function of reducing oil viscosity of viscosity reducer and foam agent. Both of them can lower the interface tension to form the O/W emulsion with an enhanced flow capability, which improved the displacement efficiency.



a. steam & VR (scheme I) b. steam & VR & foaming agent (scheme II)

Fig.8 Macroscopic swept area at the end of steam &VR flooding(steam & VR & foaming agent)

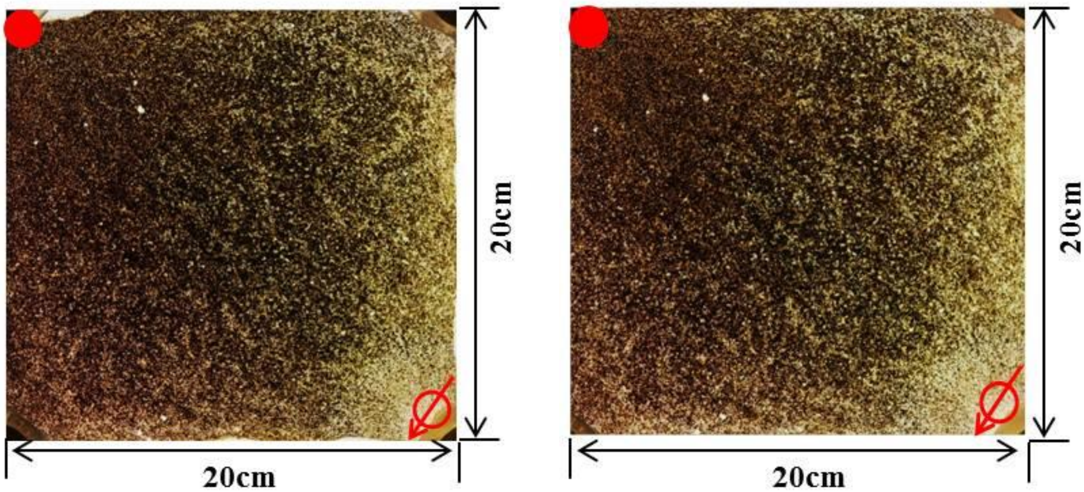
In the next sequence, 1.2PV of nitrogen slug was injected with foam agent and steam. As we can see from the Fig.9, the injection of nitrogen foam directly contributed to the expanding of swept area and promoted the displacement efficiency obviously. However, there were still some continuous black residual fritters. The nitrogen could be trapped in porous media and change the flow direction of following liquid although it was difficult to dissolve into heavy oil like carbon dioxide. From the oil recovery curve in Fig.2, the oil recovery of scheme II was higher than that of scheme I with 5.9% of OOIP. In Scheme II, after the second cycle of VR and foam agent injection, a large amount of foaming agent solution still remained in the pore and throat. When the nitrogen was injected into the model, more foams were formed to plug the bigger pore or throat and the majority of the model was swept.



a. steam & foam (scheme I) b. steam & foam (scheme II)

Fig.9 Macroscopic swept area at the end of steam & foam

In order to investigate the effect of plugging the bigger pore or throat of nitrogen foam, the viscosity reducer with steam was injected. At the end of the last cycle, the whole model was much brighter because more oil that was unswept previously could be mobilized by subsequent displacing liquid as shown in Fig.10. When the bigger pore or throat was plugged, the injected liquid started to change the direction, which caused more small pore swept and improved the displacement efficiency. And from the Fig2, there was still about 5% of OOIP produced.



a. steam & VR (scheme I) b. steam & VR (scheme II)

Fig.10 Macroscopic swept area at the end of steam & VR

For investigating the macro displacement effect quantitatively, the oil recovery of these two different schemes was compared. For a certain reservoir, oil recovery percentage (E_R) was based on oil displacement efficiency (E_D) and sweep efficiency (E_V). Namely,

$$E_R = E_V \cdot E_D \tag{1}$$

Combined with the experimental results, oil recovery percentage of different stages can be obtained, as shown in Table 2.

Tab.2 Displacement parameters under different displacement modes

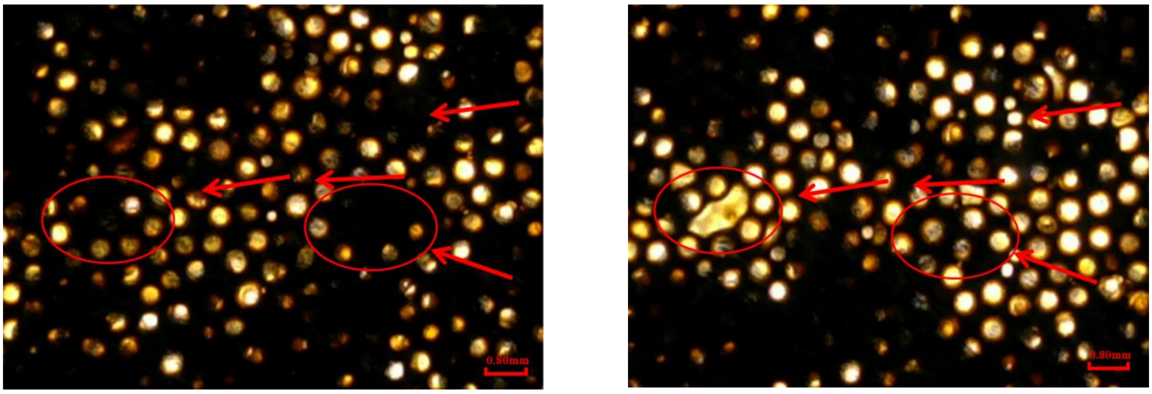
No.	stage	stage recovery %	sweep efficiency %	displacement efficiency %
Scheme I	steam flooding	27.8	49.1	56.6
	steam &VR	14.2	62.5	67.2
	steam &foam	12.6	83.7	65.2
	steam &VR	7.9	88.4	70.7
Scheme II	steam flooding	28.6	51.2	55.9
	steam &VR &foaming agent	18.5	68.4	68.9
	steam &foam	18.5	88.6	74.0
	steam &VR	6.8	92.7	78.1

3.4 Analysis of microscopic mechanism

The mechanism of thermochemistry assisted steam flooding to improve oil recovery mainly includes two points: macroscopic swept volume and microscopic displacement efficiency, and the latter is discussed in the following part.

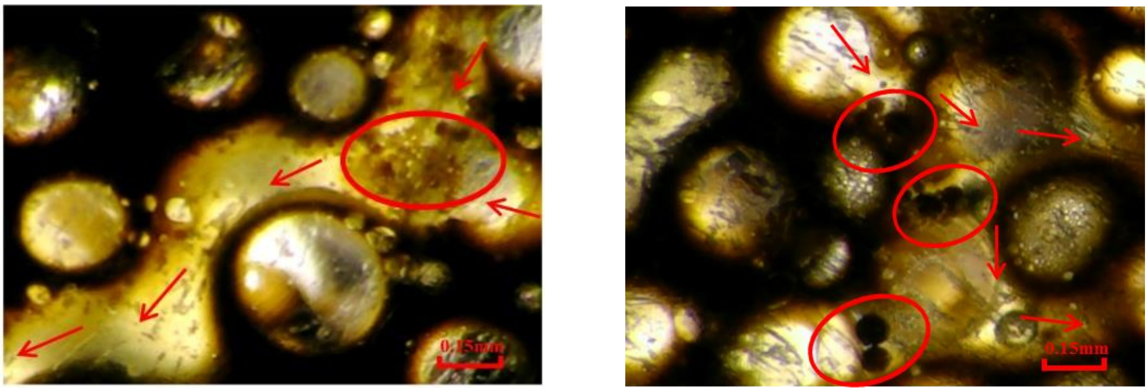
3.4.1 Emulsion of viscosity reducer

The area marked in red circle (Fig.11a) is residual oil generated by steam flooding. As shown in Fig.11a, there was still a large amount of residual oil existing in the pore and throat. When the viscosity reducer was injected, the interface tension between oil and water was decreased and the oil in water (O/W) emulsion was formed, which improved the flow capacity of crude oil. Later, the oil adhering to the surface of glass bead was cleaned gradually (Fig.11b). Compared Fig.11a with Fig.11b, we can see that the viscosity reducer can improve displacement efficiency obviously, but the swept area didn't change a lot. Also, a thin film of oil was formed around the glass bead as shown in Fig.11c. However, most steam and condensate water still bypassed the main area of residual oil. Due to the emulsion of O/W, some bigger throat can be blocked temporarily, as shown in Fig.11d. Although these emulsion cannot block the higher permeable channel thoroughly, they can change the direction of injected liquid and increase the flow resistance to some extent.



a. swept area before VR

b. swept area after VR



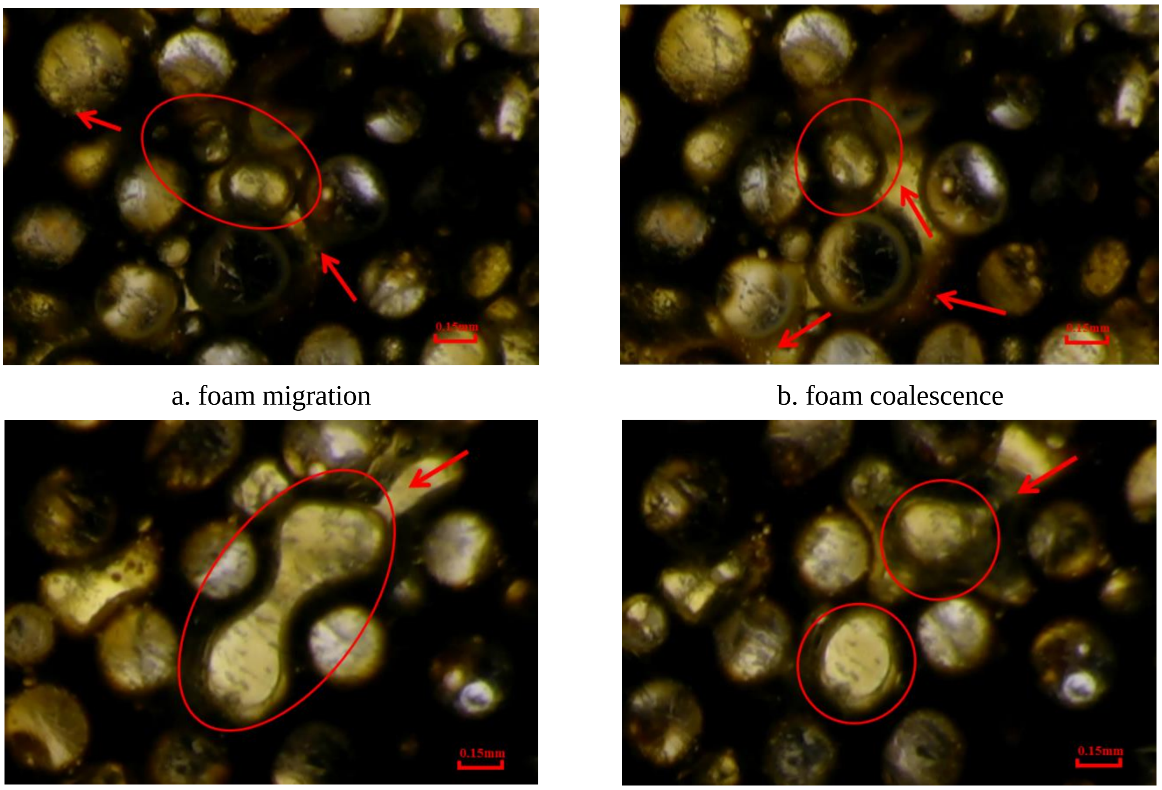
c distribution of floccule emulsion

d. distribution of sphere emulsion

Fig.11 Microscopic displacement process of VR assisting steam flooding

3.4.2 Mobility control of nitrogen foam

The mobility-control process, which must treat a large fraction of reservoir volume, places a heavier emphasis on rapid foam propagation [24]. As shown in Fig.12, foam can improve the sweep efficiency significantly. When nitrogen was injected into the model, the bubble gradually moved from the inlet to the outlet, and with the increase of the amount of bubble, two bubbles will coalescence into a larger bubble due to the lower interfacial tension (Fig. 12a and Fig. 12b). The bigger bubble can be trapped in the pore and throat because of Jamin effect, which can inhibit the flow of water and gas phase with higher flowing capability and change the flowing direction of subsequent liquid. If a larger bubble passed through narrow throat, it can change its shape under the shear force. In this process, the larger bubble was cut off into two small bubbles at the throat under the increasing resistance force and blocked the throat finally, as shown in Fig. 12c and Fig. 12d.



a. foam migration　　b. foam coalescence

c. shear distortion　　d. snap off two bubble

Fig.12 Microscopic displacement process of foam assisting steam flooding

4 Conclusion

(1) The phenomenon of fingering is obvious in the process of steam flooding in heavy oil reservoir due to the difference of pressure gradient between injection and production wells and oil-water viscosity, resulting in a limited swept area of steam. O/W emulsion could be formed when the viscosity reducer is injected into the model, which can reduce the viscosity of oil and improve its mobility significantly. The synergistic effect of viscosity reducer & foaming agent is more conductive to improve displacement efficiency of steam due to their ability of lowering interface tension.

(2) Foam in the porous media could block the larger pore and throat to change the direction of subsequent injected liquid, resulting in a more attractive sweep efficiency. And the effect of foam flooding after synergistic development of viscosity reducer & foaming agent is more effective with a higher stage recovery of 9.9% due to the left foaming agent in the model.

(3) Foam still stays stable although the viscosity reducer remains in the layers, which provide an alternative way for field plot.

5 Acknowledgment

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6 References

[1] Demaison G J. Tar sands and supergiant oil fields[J]. AAPG Bulletin, 1977, 61(11): 1950-1961.

[2] Ma C. Heavy oil development key to china's oil production growth[J]. China Oil & Gas, 2006, 13(4):18-19.

[3] Meyer R F, Attanasi E D, Freeman P A. Heavy oil and natural bitumen resources in geological basins of the world[R]. 2007.

[4] Briggs P J, Baron P R, Fulleylove R J, et al. Development of heavy-oil reservoirs[J]. Journal of Petroleum Technology, 1988, 40(02): 206-214.

[5] Dilgren R E, Deemer A R, Owens K B. The laboratory development and field testing of steam/non-condensible gas foams for mobility control in heavy oil recovery[C]. SPE California Regional Meeting. Society of Petroleum Engineers, 1982.

[6] Butler R M, Stephens D J. The gravity drainage of steam-heated heavy oil to parallel horizontal wells[J]. Journal of Canadian Petroleum Technology, 1981, 20(02).

[7] Butler R M, Mokrys I J. Recovery of heavy oils using vapourized hydrocarbon solvents: further development of the VAPEX process[J]. Journal of Canadian Petroleum Technology, 1993, 32(06).

[8] Wang Y, Ren S, Zhang L, et al. Numerical study of air assisted cyclic steam stimulation process for heavy oil reservoirs: Recovery performance and energy efficiency analysis[J]. Fuel, 2018, 211: 471-483.

[9] Beattie C I, Boberg T C, McNab G S. Reservoir simulation of cyclic steam stimulation in the Cold Lake oil sands[C]. SPE California Regional Meeting. Society of Petroleum Engineers, 1989.

[10]Hongfu F, Yongjian L, Liying Z, et al. The study on composition changes of heavy oils during steam stimulation processes[J]. Fuel, 2002, 81(13): 1733-1738.

[11]Yang G, Butler R M. Effects of reservoir heterogeneities on heavy oil recovery by steam-assisted gravity drainage[J]. Journal of Canadian Petroleum Technology, 1992, 31(08).

[12]Huang S, Xiong H, Wei S, et al. Physical simulation of the interlayer effect on SAGD production in mackay river oil sands[J]. Fuel, 2016, 183:373-385.

[13]Eson R L, Cooke R W. A successful high-temperature gel system to reduce steam channeling[C].SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 1992.

[14]Wang C, Liu H, Wang J, et al. A novel high-temperature gel to control the steam channeling in heavy oil reservoir[C]. SPE Heavy Oil Conference-Canada. Society of Petroleum Engineers, 2014.

[15]Cash Jr R L, Cayias J L, Hayes M, et al. Spontaneous emulsification-a possible mechanism for enhanced oil recovery[C]. Fall Meeting of the Society of Petroleum Engineers of AIME. Society of Petroleum Engineers, 1975.

[16]Yaghi B M, Al-Bemani A. Heavy crude oil viscosity reduction for pipeline transportation[J]. Energy sources, 2002, 24(2): 93-102.

[17]Ezeuko C C, Wang J, Gates I D. Investigation of Emulsion Flow in Steam-Assisted Gravity Drainage[J]. SPE Journal, 2013, 18(03): 440-447.

[18]Lu C, Liu H, Zhao W, et al. Experimental investigation of in-situ emulsion formation to improve viscous-oil recovery in steam-injection process assisted by viscosity reducer[J]. SPE Journal, 2017, 22(01): 130-137

[19]Liu P, Li W, Shen D. Experimental study and pilot test of urea- and urea-and-foam-assisted steam flooding in heavy oil reservoirs[J]. Journal of Petroleum Science & Engineering, 2015, 135:291-298.

[20]Holm L W. The mechanism of gas and liquid flow through porous media in the presence of foam[J]. Society of Petroleum Engineers Journal, 1968, 8(04): 359-369.

[21]Friedmann F, Chen W H, Gauglitz P A. Experimental and simulation study of high-temperature foam displacement in porous media[J]. SPE reservoir engineering, 1991, 6(01): 37-45.
[22]Pang Z, Liu H, Zhu L. A laboratory study of enhancing heavy oil recovery with steam flooding by adding nitrogen foams[J]. Journal of Petroleum Science and Engineering, 2015, 128: 184-193.
[23]Zhang X, Liu Y J, Che H C, et al. An experimental study on injecting noncondensing gas and chemical agent during steam flooding for enhanced oil recovery[J]. Lithologic Reservoirs, 2010, 22(2):116-119.
[24]Farajzadeh R, Andrianov A, Krastev R, et al. Foam-oil interaction in porous media: implications for foam assisted enhanced oil recovery.[J]. Advances in Colloid & Interface Science, 2012, 183-184:1.