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DOI

[10.1016/j.fuel.2018.01.007](https://doi.org/10.1016/j.fuel.2018.01.007)

Publication date

2018

Document Version

Accepted author manuscript

Published in

Fuel: the science and technology of fuel and energy

Citation (APA)

Lyu, X., Liu, H., Pang, Z., & Sun, Z. (2018). Visualized study of thermochemistry assisted steam flooding to improve oil recovery in heavy oil reservoir with glass micromodels. *Fuel: the science and technology of fuel and energy*, 218, 118-126. <https://doi.org/10.1016/j.fuel.2018.01.007>

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1 **Visualized study of thermochemistry assisted steam flooding to improve oil** 2 **recovery in heavy oil reservoir with glass micromodels**

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8 **Abstract**

9 Steam channeling, one serious problem in the process of steam flooding in heavy oil reservoir,
10 decreases the sweep efficiency of steam to cause a lower oil recovery. Viscosity reducer and nitrogen
11 foam, two effective methods to improve oil recovery with different mechanism, present a satisfactory
12 result after steam flooding. In this article, a 2D visualized device was introduced to investigate the
13 synergistic development effect of two different chemical additives and intuitively study their flowing
14 characteristic in porous media, as well as macroscopic and microscopic mechanism of improving
15 heavy oil recovery by chemical additives after steam flooding. The results showed that the fingering
16 phenomenon was generated obviously in the process of steam flooding, which restricted the swept
17 area of steam. Due to decreasing oil-water interface tension, O/W emulsion with lower viscosity was
18 formed to enhance the oil flow capacity and polish up the displacement efficiency of steam after
19 injecting viscosity reducer. And the synergistic effect of viscosity reducer & foaming agent was more
20 conducive to improve displacement efficiency of steam, with 4.3% of oil recovery higher than purely
21 viscosity reducer assisting steam flooding in this process. Microscopic results indicated that thermal
22 foams can be trapped in the porous media to improve injection profile effectively and displace the
23 residual oil caused by steam flooding. The ultimate oil recovery of synergistic development is 65.6%,
24 11.0% higher than one additive (viscosity reducer). This article can provide reference for the study of
25 thermochemistry assisted steam flooding in heavy oil reservoir.

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

28 **1 Introduction**

29 Recently, with the gradual depletion of conventional oil, the exploitation of unconventional crude
30 oil has attracted much attention, and heavy oil, as a kind of important energy, accounts for a large
31 proportion of oil and gas resources in the world [1-3]. However, with the remarkable characteristic of
32 high viscosity, high density and low mobility, it is quite difficult to produce heavy oil economically
33 efficient using conventional techniques [4-7]. In general, cyclic steam stimulation and steam flooding
34 play a vital role in developing these resources at home and abroad, and steam flooding is an effective
35 measure to improve oil recovery in the late period of steam huff and puff [8-11]. Also, SAGD is

36 another attractive methods for heavy oil or oil-sands[12]. Unfortunately, due to the large difference of
37 oil-water viscosity, the phenomenon of fingering is serious in the process of steam flooding, which
38 forms preferential channeling passage and leads to the lower oil and gas ratio and limited swept area
39 [13-14]. Nowadays, many experts had carried out plenty of investigations on how to improve heavy
40 oil recovery.

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

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

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

68 Although both viscosity reducer and foams can improve heavy oil recovery to some extent and
69 attract more and more attention, to our knowledge, very little information is provided in the literature
70 on the research of viscosity reducer and foams utilized together. In this paper, the objectives were to
71 investigate the interact relations between different kinds of chemical agents and identify which

72 developing method was suitable for field pilots. So, a two-dimensional visualization device with high
73 temperature and high pressure was used to study the process of steam flooding development in heavy
74 oil reservoir with different chemical agents, including viscosity reducer and foam agents. And the
75 mechanism of different methods improving developing effects of steam flooding was discussed from
76 macroscopic and microscopic phenomena.

77 2 Experimental Apparatus and Procedure

78 2.1 Materials

79 In this experiment, square quartz glasses with holes on four corners could withstand high
80 temperature and high pressure. The thickness of the sand layer was determined by the mesh size of the
81 glass bead. In this study, the glass bead with $420\mu\text{m}$ (40 mesh) diameter was used to form
82 unconsolidated transparent porous media as shown in Fig.1. The stock tank oil obtained from Biqian10
83 area in Henan oil reservoir had a viscosity of $1250\text{ mPa}\cdot\text{s}$ at 60°C and a density of 0.951 g/cm^3 at 25°C .
84 Two kind of fluids used in this set of experiments were distilled water used to generate steam and
85 brine with 5000ppm of NaCl used to saturate the model. Industrial-grade nitrogen was used as gas
86 with the purity of 99.99%. And a kind of hydrophilic VR called AE-121 and one foam agent called
87 ADC were selected due to the best application effects in the field. For all processes in this study, the
88 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

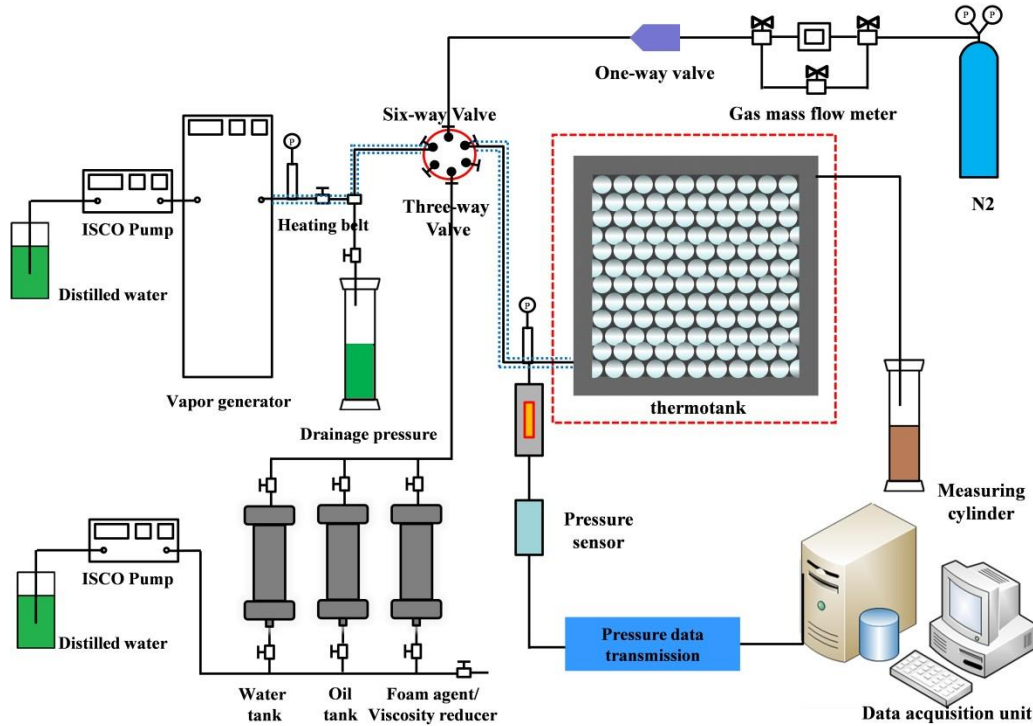
Fig.1 Glass beads used in this experiment

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90 2.2 Experimental setup

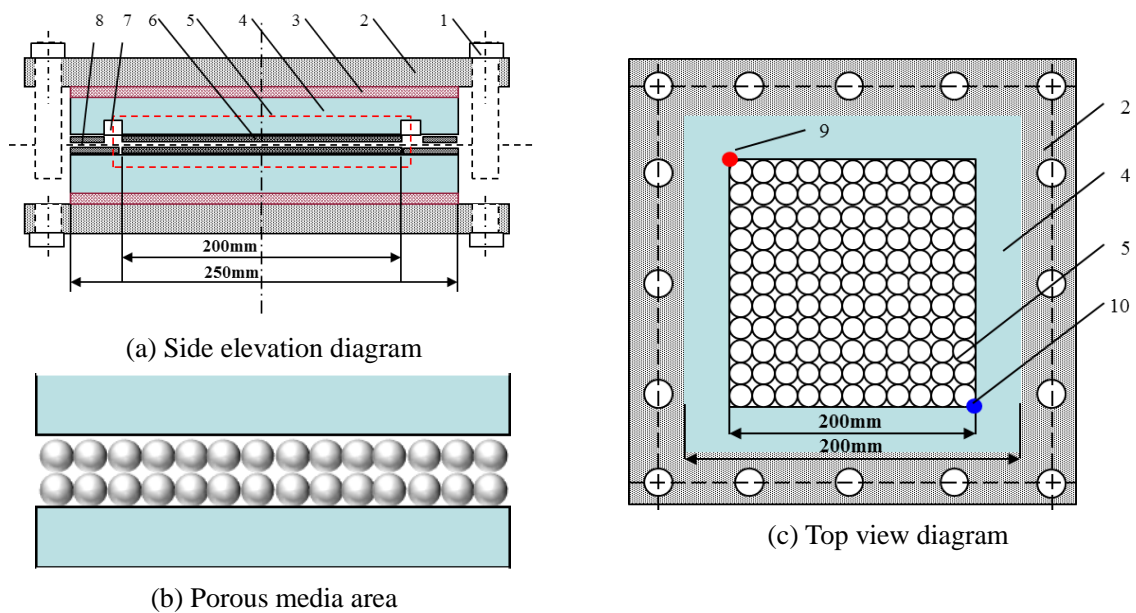
91 The schematic diagram of the experimental setup was shown in Fig.2. The whole equipment can
92 be divided into three subsystems: fluid-supply system, 2D visualized displacement system, and
93 data-acquisition system. The 2D visualized model contained two pieces of quartz glass plates and two
94 layers of glass beads. The dimensions of the quartz glass plate with a good transparency were
95 $250\text{mm}\times 250\text{mm}\times 30\text{mm}$, and it can endure the maximum pressure at 3MPa and the highest
96 temperature at 280°C , as shown in Fig.3. While the actual visual area is $200\text{mm}\times 200\text{mm}$, and the
97 margin is sealed by high temperature resistant glass cement. The glass bead with $420\mu\text{m}$ (40 mesh)
98 diameter was used to form the effective thickness is $840\mu\text{m}$. Canon EOS70D digital camera and

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



105
 106

Fig.2 The schematic diagram of the experimental setup



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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.

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113

114 **2.3 Experimental procedure**

115 **2.3.1 Evaluation of stability of bulk-foam**

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

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

130 **2.3.2 Visualized displacement experiments**

131 Before the experiments, the visualized models should be cleaned up thoroughly. After the
132 visualized model was prepared, it was mounted horizontally to minimize the effect of gravity.
133 Simultaneously, a series of parameters such as porosity, permeability and initial oil saturation were
134 determined when the models were prepared well as shown in Table 1. The depth of Biqian10 area was
135 relatively shallow, and the reservoir temperature is 35°C ~45°C, so the temperature was controlled at
136 40°C during the experiment process to achieve a better simulation.

137 Experimental procedures were as follows: (1) The prepared formation water was injected into the
138 model by ISCO micro-gear pump at a constant volumetric-flow rate (0.5mL/min), and the model was
139 saturated until the water outflowed from the outlet steadily, then the model porosity can be acquired
140 through the material balance method; (2) The crude oil was injected into the visualized model at a
141 constant volumetric-flow rate (0.2mL/min), and the process was completed when the fluid flowing out
142 from the outlet was only the crude oil, then the initial oil saturation was obtained and a connate-water
143 saturation condition was created; (3) Thereafter, the model was undisturbed for 24 h to equilibrate the
144 distribution of fluids. (4) Steam produced from steam generator was injected into the model at a
145 constant volumetric-flow rate (0.5mL/min), and the temperature of steam was 200°C, and the dryness

146 was kept in 0.8. When the oil and steam ratio reached to 0.1 in the stage of steam flooding, the steam
 147 and VR solution were injected into the model together at a rate of 0.5mL/min, and if oil and steam
 148 ratio of this stage was up to 0.1, steam was injected at a rate of 0.5mL/min with foam agents and N₂
 149 (10mL/min) to simulate foam assisted steam flooding. And the process of steam and VR solution
 150 injection was repeated after the oil and steam ratio was 0.1 in the last stage. (5) Two sets of same
 151 visualized model were prepared to achieve the comparative experiments, and the designed patterns and
 152 property parameters were listed in Tab.1, and the operation process (1) to (4) was repeated.

153 Tab.1 The experimental parameters of different designed visualization model

No.	Fluid compositions			porosity /%	permeability /10 ⁻³ μm 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			

154 3 Experimental Results and Discussion

155 3.1 Static performance of different surfactant

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

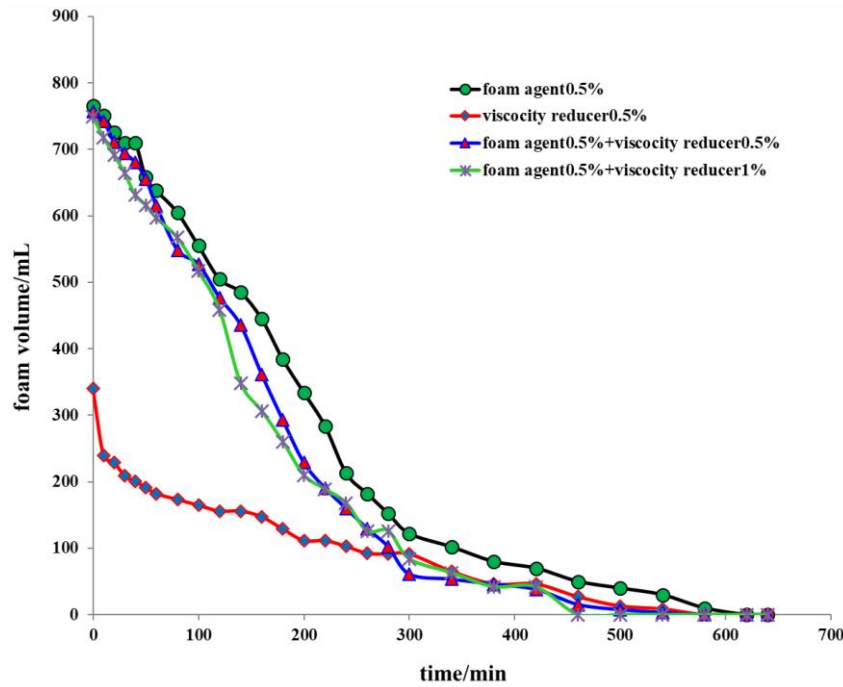


Fig.4 Foaming volume and half-life of different surfactant solution

167

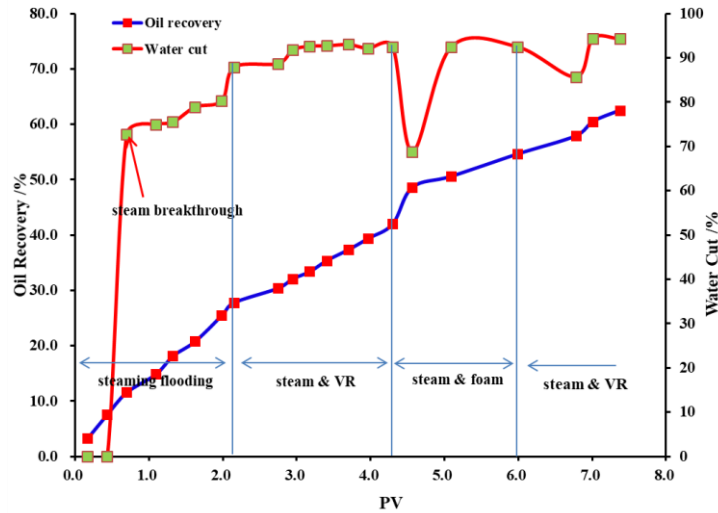
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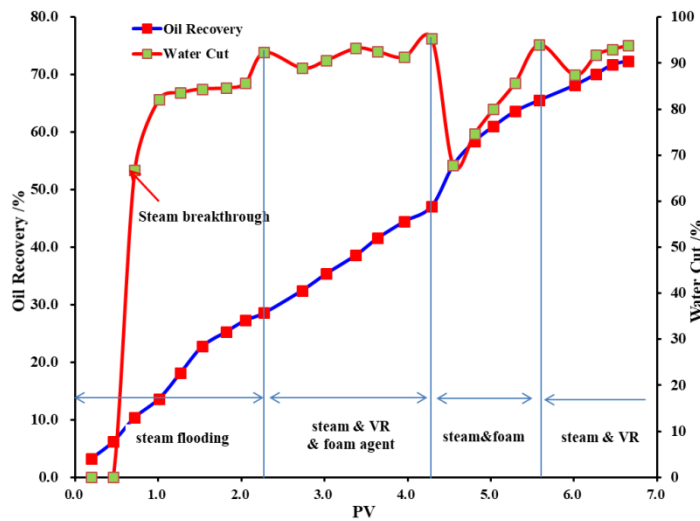
170 3.2 Variation of dynamics characteristics

171 The variations of water cut and recovery with the change of injection liquids were shown as
 172 Fig.5(a) and Fig.5(b), during the process of displacement of scheme I and scheme II. According to
 173 Fig.5(a) and Fig.5(b), non-water production period existed in the early stage of steam flooding in both
 174 schemes, and after that, the water cut rose sharply. Then, the steam front reached the outlet of the
 175 model after 0.70PV and 0.74PV of steam were injected respectively in scheme I and scheme II.
 176 Thereafter, the recovery of heavy oil increased slowly. In scheme I, the process of steam flooding was
 177 ended after 2.10PV of steam injection with 95% of water cut and 27.8% of stage recovery. In the next
 178 sequence, viscosity reducer assisted steam flooding was carried out, and the water cut had a little
 179 change with the significant increment of oil recovery. The oil recovery increased by 14.2%. Then foam
 180 assisted steam flooding was going on to enhance the oil recovery. The injection of nitrogen foam
 181 directly contributed to the oil recovery (up to 54.6%) with a rapid reduction of water cut (from 92.5%
 182 to 68.8%) and an effective augment of the instantaneous oil production rate. Finally, viscosity reducer
 183 assisted steam flooding was repeated to investigate the effectiveness of foam. When the water cut
 184 reached to 95%, the experiment was terminated with 62.5% cumulative oil recovery. The difference
 185 between two schemes was the foam agent and viscosity reducer assisted steam flooding was conducted
 186 after the ending of steam flooding. It was observed that the ultimate oil recovery of Scheme II
 187 researched to 72.4%, 9.9% higher than Scheme I. The foam agent was injected into the model with
 188 viscosity reducer together, and it can distribute uniformly in the steam channeling. When nitrogen
 189 foams were injected, the redundant nitrogen can form stable foams again with the previous foam agent

190 under the shearing action. Although nitrogen was rather difficult to dissolve into heavy oil not like
 191 carbon dioxide, the nitrogen foam could be trapped in porous media to change the flow direction of the
 192 following liquid. In this case, more unswept previously oil could be mobilized by subsequent
 193 displacing liquid.



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



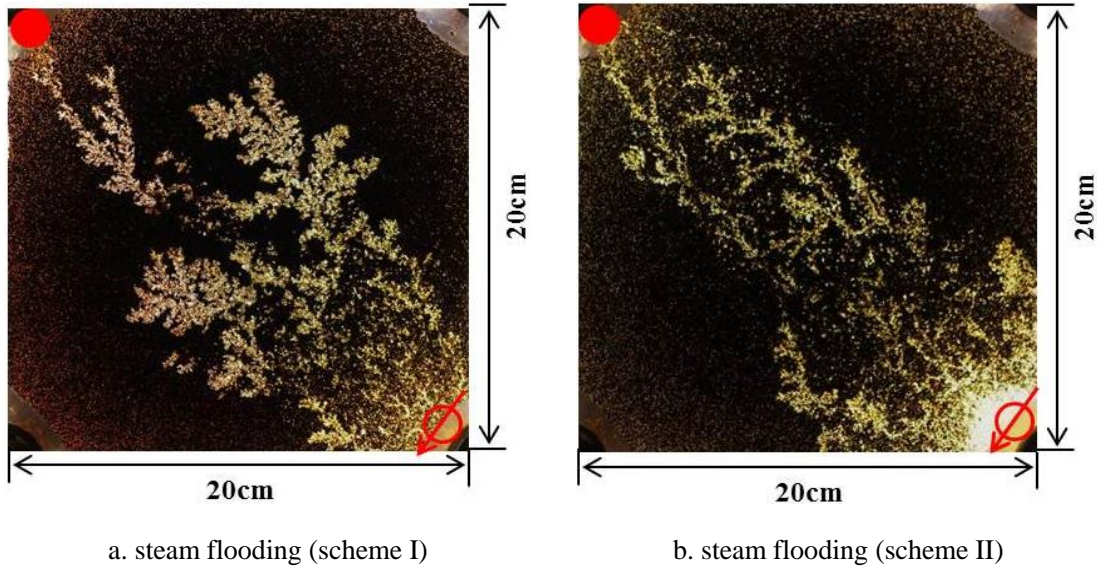
b. The variation curve of water cut and oil recovery (Scheme II)

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

195 **3.3 Variation of macroscopic swept area**

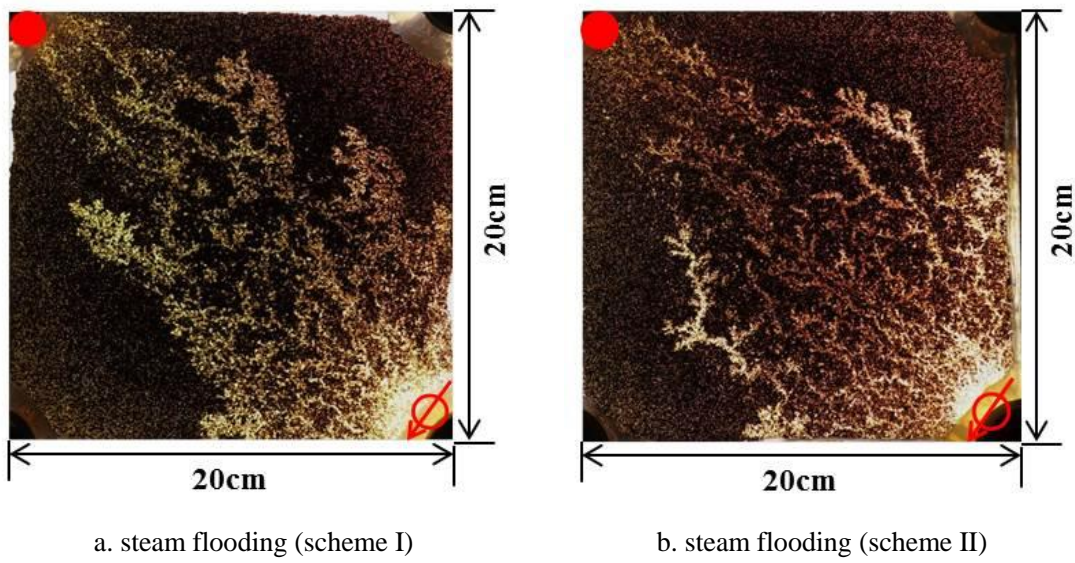
196 Fig.6~Fig.10 illustrated the effect of macro displacement at the end of different stages under
 197 different schemes. As shown in Fig.6~Fig.10, the small spheres and white highlights represent glass
 198 beads, and the black-brown is the distribution of heavy oil, and the yellow ribbons area stands for
 199 the swept area of steam and condensation of water. Fig.6 illustrates the swept area at the end of steam
 200 breakthrough, and it is observed that the steam and condensate moved quickly along the main
 201 streamline. In the process of steam injection, the flowing capacity of heavy oil was enhanced due to
 202 the heating of high temperature steam. Meanwhile, the heating effect between main streamline was

203 better. Once their front reached the outlet of the model, as shown in Fig.6a and Fig.6b, the extension of
 204 flowing branches left behind the mainstream channel was substantially restricted and some irregular
 205 bright bands stood around the main streamline.
 206



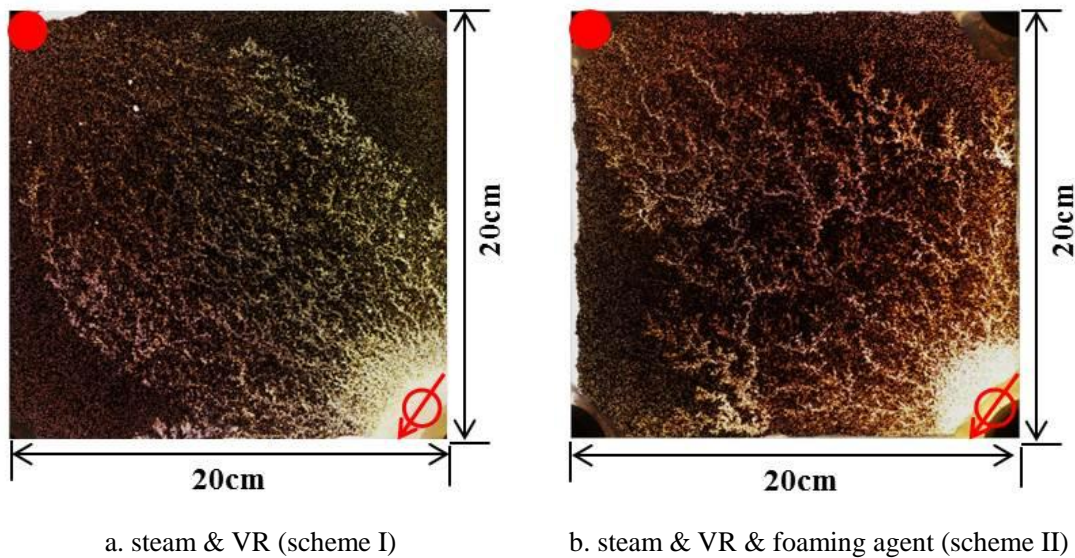
207 Fig6. Macroscopic swept area at the end of steam breakthrough

208 At the end of steam flooding, although the swept area expanded to some extent, there was still
 209 plenty of residual oil existing in oil layer, mainly locating on both sides of the mainstream channel, as
 210 shown in Fig.7. Due to the difference of viscosity between steam and heavy oil, a large amount of
 211 steam and condensate water moved along the main streamline, which made the range of steam
 212 sweeping limited seriously. From Fig.7a and Fig.7b, it also could be observed that the oil recovery and
 213 sweep efficiency of these two schemes were basically equal in the process of steam flooding.
 214



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

216 Fig.8a illustrated the variation of swept area when the viscosity reducer is injected into the model
 217 with steam. It can be seen that the color of the main streamline became bright, which indicated
 218 viscosity reducer can improve the displacement efficiency effectively. And the swept area extending to
 219 fusiform expanded to some extent. When the reducer viscosity was injected, the oil in water emulsion
 220 will be formed to be used for plugging because of the lower interface tension. Fig.8b showed the
 221 variation of swept volume with the injection of reducer viscosity and foam agent simultaneously. As
 222 shown in Fig.8b, the swept area also enlarged with an irregular shape. Considering the oil
 223 recovery(Fig.2), the Scheme II was higher than Scheme I (4.3% higher) mainly due to the function of
 224 reducing oil viscosity of viscosity reducer and foam agent. Both of them can lower the interface
 225 tension to form the O/W emulsion with an enhanced flow capability, which improved the displacement
 226 efficiency.
 227



228 Fig.8 Macroscopic swept area at the end of steam &VR flooding(steam & VR & foaming agent)
 229 In the next sequence, 1.2PV of nitrogen slug was injected with foam agent and steam. As we can
 230 see from the Fig.9, the injection of nitrogen foam directly contributed to the expanding of swept area
 231 and promoted the displacement efficiency obviously. However, there were still some continuous black
 232 residual fritters. The nitrogen could be trapped in porous media and change the flow direction of
 233 following liquid although it was difficult to dissolve into heavy oil like carbon dioxide. From the oil
 234 recovery curve in Fig.2, the oil recovery of scheme II was higher than that of scheme I with 5.9% of
 235 OOIP. In Scheme II, after the second cycle of VR and foam agent injection, a large amount of foaming
 236 agent solution still remained in the pore and throat. When the nitrogen was injected into the model,
 237 more foams were formed to plug the bigger pore or throat and the majority of the model was swept.

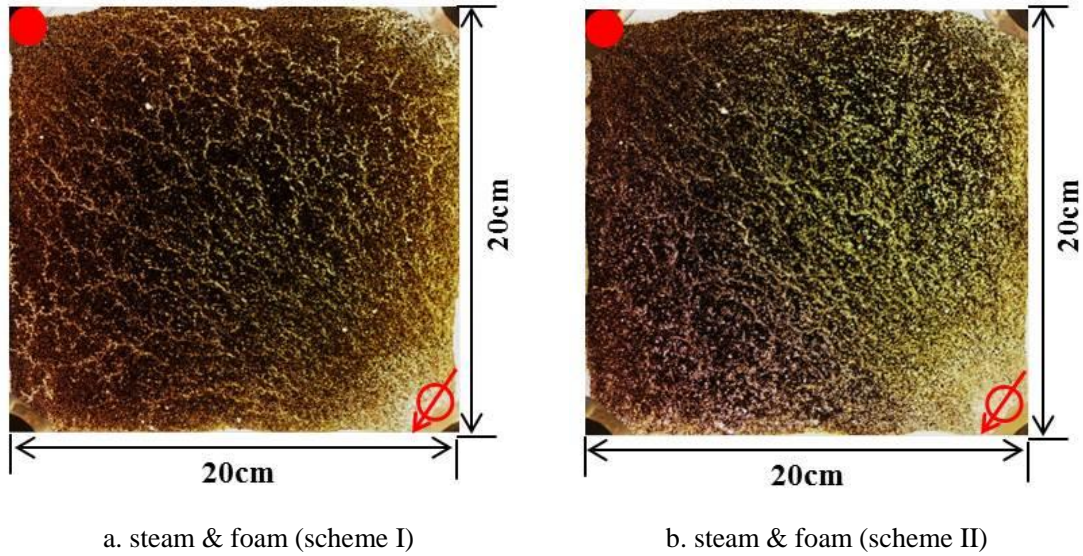


Fig.9 Macroscopic swept area at the end of steam & foam

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.

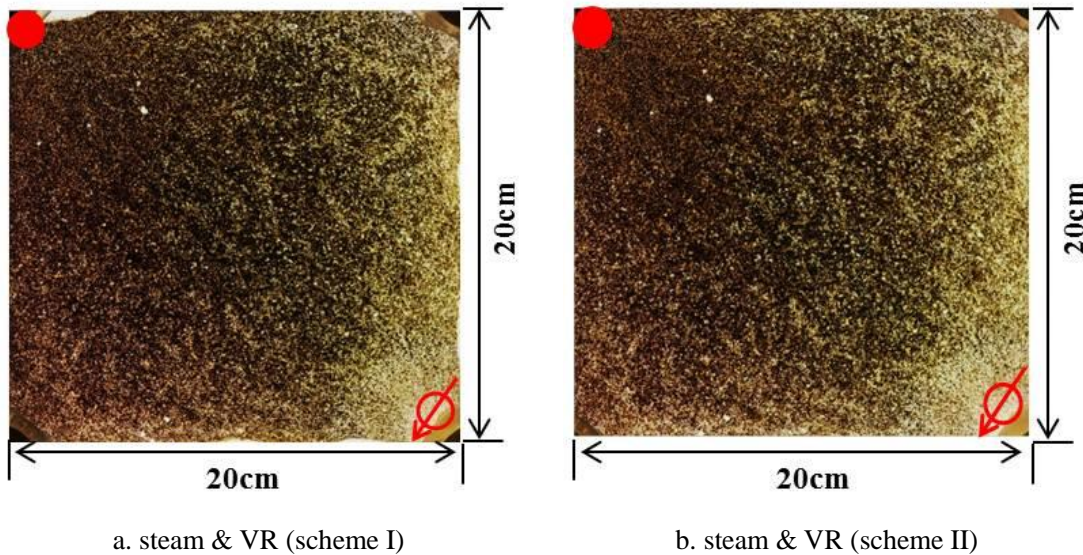


Fig.10 Macroscopic swept area at the end of steam & VR

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,

250

$$E_R = E_V \cdot E_D \quad (1)$$

251

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

253

254

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

255

256 3.4 Analysis of microscopic mechanism

257

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.

259

260 3.4.1 Emulsion of viscosity reducer

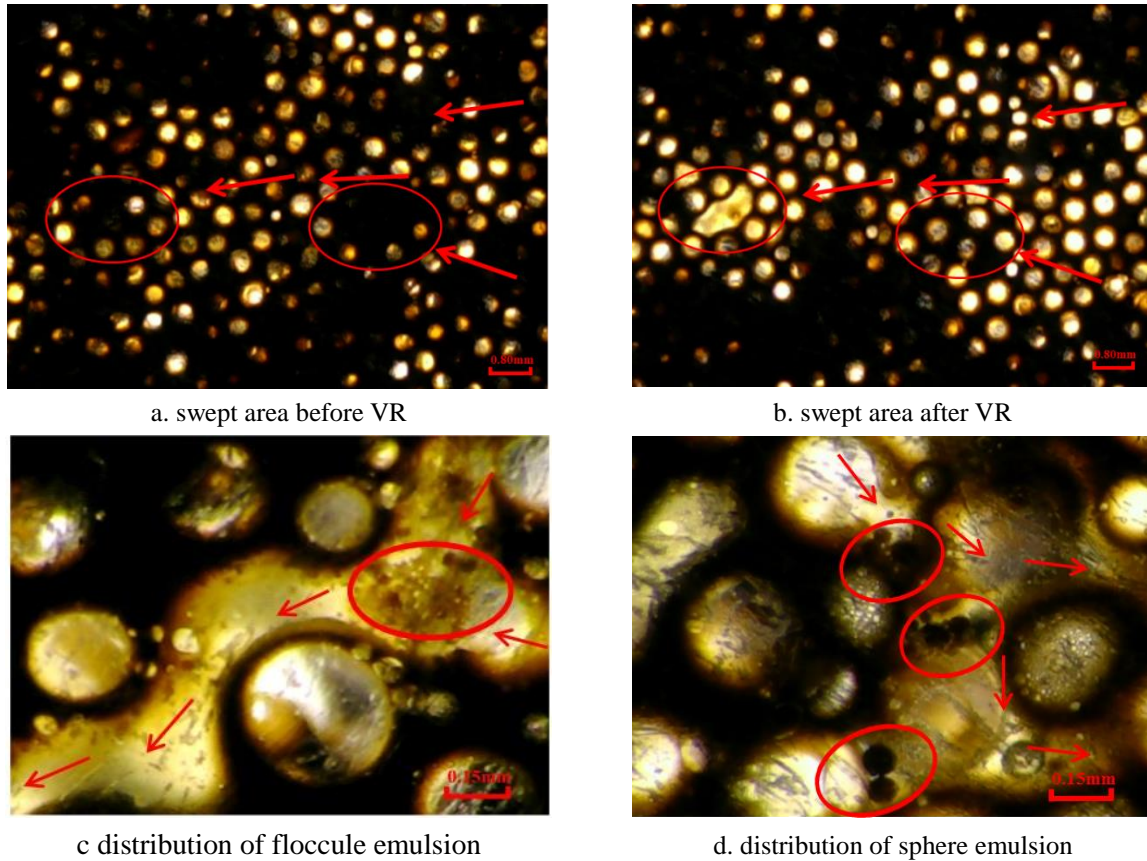
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The area marked in red circle (Fig.11a) is residual oil generated by steam flooding. As shown in Fig.11a, there was still a large amount of residual oil existing in the pore and throat. When the viscosity reducer was injected, the interface tension 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.

272

273

274



a. swept area before VR

b. swept area after VR

c distribution of floccule emulsion

d. distribution of sphere emulsion

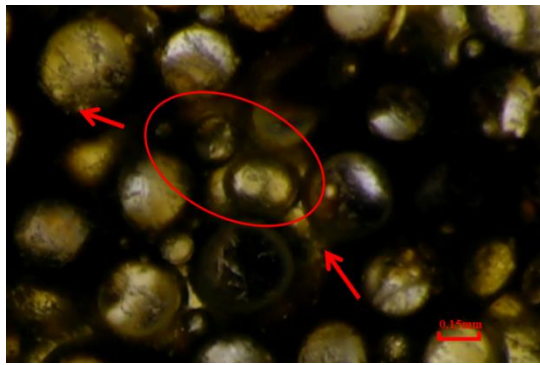
Fig.11 Microscopic displacement process of VR assisting steam flooding

275

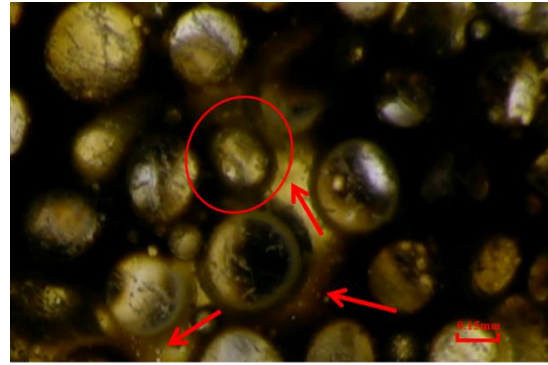
276 3.4.2 Mobility control of nitrogen foam

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

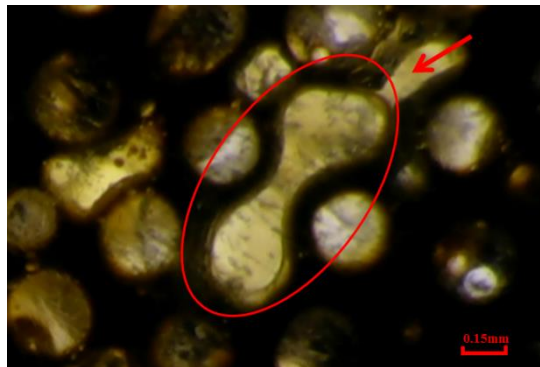
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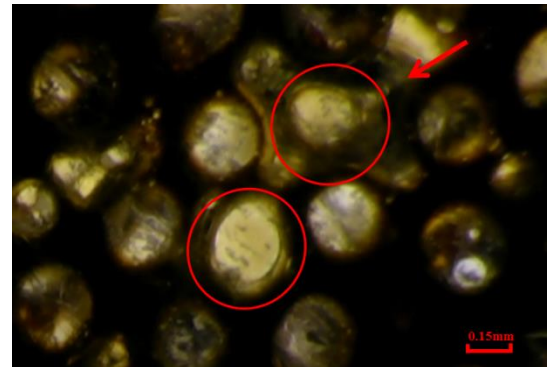
a. foam migration



b. foam coalescence



c. shear distortion



d. snap off two bubble

Fig.12 Microscopic displacement process of foam assisting steam flooding

288

289 4 Conclusion

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

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

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

302 5 Acknowledgment

303 Financial support received from the National Natural Science Foundation of China (No. 51504264 and
 304 No. 51274212), and the Outstanding Young Teachers' Research Funds of China University of Petroleum,
 305 Beijing (2462015YQ0202) is gratefully acknowledged.

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