Research on Mechanism of Enhancing Recovery of Heavy Oil With N_2 Huff-n-Puff Assisted by Viscosity Reducer

Lei Tao[1], Sen Huang[1], Yali Liu[2], Hao Cheng[1], Huajun Du[3], Cheng Wang[1], Na Zhang[4]* and Jinlong Li[4]

[1]School of Petroleum Engineering, Changzhou University, Changzhou, China, [2]College of Petroleum Engineering, China University of Petroleum (East China), Qingdao, China, [3]Shandong Ruiheng Xingyu Petroleum Technology Development Co., Ltd., Qingdao, China, [4]School of Petrochemical Engineering, Changzhou University, Changzhou, China

In this paper, viscosity reducers with viscosity reduction ability and foaming ability and the recovery efficiency in N_2 huff-n-puff were studied. The optimal 4# viscosity reducer was selected by evaluating the viscosity reduction ability, emulsion stability, interfacial performance, and foaming. The huff-n-puff experiments of single sandpack and dual sandpack were carried out under the reservoir conditions. The results showed that the viscosity reduction rate of 4# viscosity reducer was more than 90% at 50–90°C, and it could form a stable oil/water emulsion when applied to heavy oil. Under the action of 4# viscosity reducer, the interfacial tension between oil and water decreased to 0.41 and 0.19 IFT/mN·m^{-1} at 50 and 80°C, respectively. In the single sandpack huff-n-puff experiment, the 4# viscosity reducer could inhibit N_2 bubbles coalesced in large channels and improve the mobility of heavy oil. Compared with N_2 huff-n-puff, the recovery rate of N_2 huff-n-puff assisted by 4# increased by 8.53%. In the dual sandpack huff-n-puff experiment, the N_2 was inhibited to flow from the low permeability sandpack to the high permeability sandpack by 4# viscosity reducer, and the gas production of the low permeability sandpack increased by 284.71%. Under the combined action of viscosification and plugging, the total oil production of the sandpack increased by 7.88%. Therefore, N_2 huff-n-puff assisted by viscosity reducer has a significant effect on enhancing oil recovery in heavy oil reservoirs.

Keywords: heavy oil, N_2 huff-n-puff, viscosity reducer, foaming ability, interfacial tension

INTRODUCTION

With the development of economy, the demand for oil resources is increasing. In the world oil reserves, heavy oil reserves account for more than 70% (Yu, 2001; Zhang et al., 2010). Poor mobility and serious formation heterogeneity are the main reasons for the difficulty of heavy oil development. Thermal recovery is a common method to improve heavy oil recovery. However, due to the energy-intensive emission of a large amount of carbon dioxide, the heavy oil thermal recovery was severely restricted by many countries (De Haan and Van Lookeren, 1969; Hanzlik and Mims, 2003; Ramlal, 2004; Ernandez, 2009). Thus, method of cold recovery of heavy oil has been used in many oil fields. The cold recovery methods of heavy oil mainly include CO_2 huff-n-puff and N_2 huff-n-puff Alvarado

and Manrique, 2010). Carbon dioxide can corrode the pipe networks and tubular columns, and the sources are limited (Dong et al., 2001; Jishun et al., 2015). N_2 can be separated from air, is difficult to dissolve in heavy oil, and has higher miscible pressure than CO_2. N_2 huff-n-puff recovers oil by increasing power of heavy oil with inject N_2. Compared to heavy oil thermal recovery, N_2 huff-n-puff is an effective heavy oil recovery method, which has low energy consumption and carbon emission (Clancy and Gilchrist, 1983; Hudgins et al., 1990; Zolghadr et al., 2013). Previous studies have found that N_2 reached low permeability channels during the first cycle of N_2 huff-n-puff and formed foamy oil flow. In the second cycle, the N_2 gradually accumulated in the continuous gas phase. In the third cycle, N_2 was produced mainly in the form of continuous gas phase. The oil recovery is mainly contributed by first cycle (Ma et al., 2015; Lu et al., 2017).

In view of poor dissolved viscosity reduction ability of N_2, serious gas channeling and low recovery rate may occur after multirounds of N_2 huff-n-puff. In the process of recovery, viscosity reducer and foam agent were usually applied to assist the heavy oil recovery. The active water film formed on the surface of oil by viscosity reducer, which can reduce the oil–water interfacial tension (IFT), and the O/W emulsion was formed in the near-well area, so as to reduce the viscosity of oil (Allenson et al., 2011). Foam can inhibit gas channeling, which is usual produced in the large channel. Foam has many excellent characteristics, such as blocking large channels firstly, water plugging, and oil defoaming. So foam was widely used in plugging water, profile control, and other aspects (Casteel and Djabbarah, 1985; Dalland and Hanssen, 1995; Hirasaki et al., 2005; Xu et al., 2012; Sun et al., 2016a; Li et al., 2019a; Li et al., 2019b). In order to solve the problems of poor mobility of heavy oil and serious gas channeling in N_2 huff-n-puff, a viscosity reduction agent was selected to assist N_2 huff-n-puff, which can not only reduce the viscosity of oil but also plug the larger channels.

In this paper, the oil used in the experiments was collected from ChengBei 15-351 reservoir. The four kinds of viscosity reducer were evaluated, including the viscosity reduction ability, emulsion stability, interfacial performance, and foaming. A viscosity reducer with the optimum comprehensive properties was chosen, which can not only reduce the viscosity of oil effectively, but also has good foaming performance. The N_2 huff-n-puff experiments were performed to investigate flow behaviors of different permeability levels and the effect of viscosity reducer on oil recovery.

EXPERIMENTAL EQUIPMENT AND METHODS

Experiment Material

In the N_2 huff-n-puff experiments, the heavy oil was collected from ChengBei 15-351 well (the properties of oil are shown in **Table 1**). The rheological properties of heavy oil were measured by high temperature and high pressure rheometer (model MCR302) in this experiment. The specific viscosity and temperature data were shown in **Figure 1**. Four different viscosity reducers were used in the experiment, labeled as 1#, 2#, 3#, and 4#. Industrial-grade N_2 with a

TABLE 1 | Properties of oil.

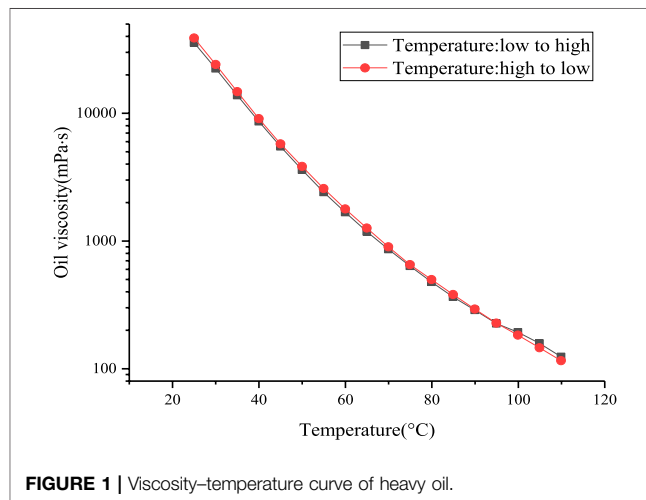|	
Viscosity at 80°C (mPa·s)	477.63
Density at 80°C (kg/m³)	958.3
Saturate content (wt%)	32.12
Aromatic content (wt%)	31.95
Resin content (wt%)	27.82
Asphaltene content (wt%)	6.74
Total acid number (mg KOH/g)	0.54

FIGURE 1 | Viscosity–temperature curve of heavy oil.

purity of 99.99% was used in the experiment. The simulated formation water was composed of a concentration of 10,668 mg/L NaCl and a concentration of 405 mg/L CaCl₂. And the sizes of silica sand which was used to simulate the dual sandpack models were 180 and 150 μm.

Physical Properties Evaluation Experiment of Viscosity Reducer

Viscosity Reduction Effect Evaluation Experiment

Apparatus: DV2TLV digital viscometer (BROOKFIELD, United States, measure range: 1–6,000,000 cP), magnetic stirrer (XiangTian, China, speed range: <2,400 rpm), thermostatic water bath (XiangTian, China, temperature range: <300°C).

Procedure: The temperature of experiment was measured at 50°C. The 1% viscosity reducer and the heavy oil were put into the thermostatic water bath at 50°C. Firstly, the 48 ml viscosity reducer and 112 ml heavy oil were stirred for 3 min by magnetic stirrer at a constant speed (800 rpm); then the emulsion was left to stand for 6 min. Next, the emulsion was stirred at a speed of 400 rpm for 3 min. Finally, the O/W emulsion was obtained. And the DV2TLV digital viscometer was used to measure the viscosity of the emulsion.

Stability Evaluation Experiment

Apparatus: Magnetic stirrer (XiangTian, China, speed range: range: <2,400 rpm), thermostatic water bath (XiangTian, China, temperature range: <300°C).

Procedure: In this experiment, the stability evaluation parameter S_V was measured. The four kinds of prepared heavy oil emulsions were maintained in the thermostatic water bath at 50°C and then the volume of the drained water from emulsion was recorded every 10 min. The water drained rate f_v was calculated by the following formula:

$$f_v = \frac{V_1}{V_2} \times 100\%.$$

In the formula, V_1 and V_2 refer to the volume of the drained water and the total volume of water in the emulsion, respectively,

$V_2 = 48$ ml. Then, the stability S_V of the emulsion was calculated by the following formula:

$$S_V = \sum K_i \left[1 - (f_v)_i \right].$$

In the formula, K_i refers to the weighted coefficient, and the K_i was set as 1, 2, 3, 4, 5, and 6 for 10, 20, 30, 40, 50, and 60 min, respectively. With the increase of the S_V, the stability of the heavy oil emulsion was enhanced.
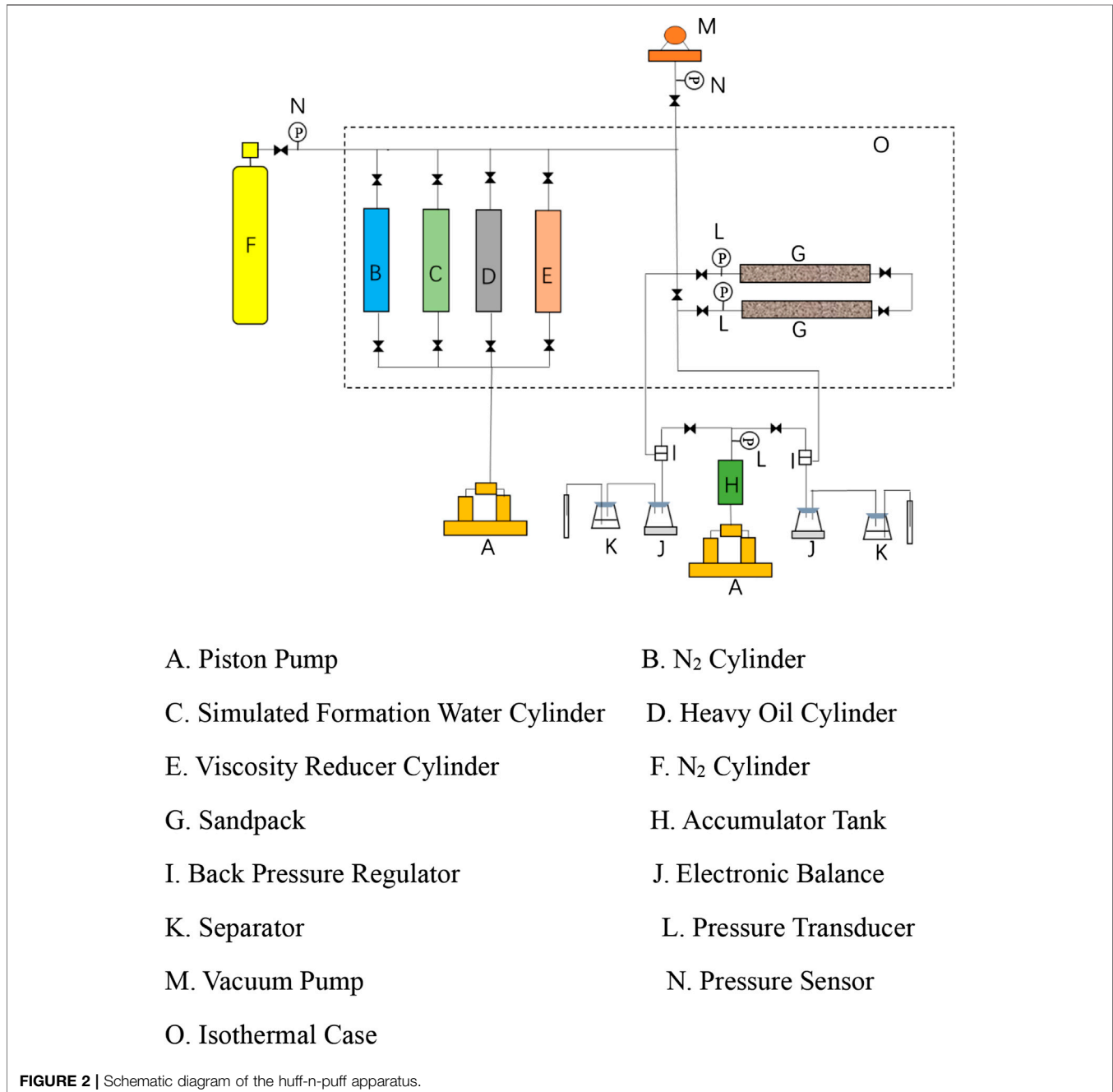

FIGURE 2 | Schematic diagram of the huff-n-puff apparatus.

A. Piston Pump

B. N₂ Cylinder

C. Simulated Formation Water Cylinder

D. Heavy Oil Cylinder

E. Viscosity Reducer Cylinder

F. N₂ Cylinder

G. Sandpack

H. Accumulator Tank

I. Back Pressure Regulator

J. Electronic Balance

K. Separator

L. Pressure Transducer

M. Vacuum Pump

N. Pressure Sensor

O. Isothermal Case

Oil–Water Interfacial Tension Evaluation Experiment

Apparatus: TX-500C rotating IFT apparatus (CNG, Co., United States, speed range: 1,000–10,000 rpm, IFT range: 10^{-5}–10 mN/m, accuracy <± 10^{-6} mN/m, temperature range: 20–100°C), thermostatic water bath (XiangTian, China, temperature range: <300°C).

Procedure: First of all, the 1% solution of four types of viscosity reducer and two heavy oil samples were prepared. The two heavy oil samples were placed in thermostatic water bath at 50°C and 80°C for 24 h, respectively. Then, the 1% viscosity reducer solution and the heavy oil sample were placed into TX-500C rotating IFT apparatus at a constant speed of 5,000 rpm, and the oil–water IFT at 50 and 80°C was measured.

Foaming Ability Evaluation Experiment

Apparatus: High temperature and high pressure foam evaluation instrument (FoamEvalue, Haian Group, China; pressure range <32 MPa and temperature range <200°C).

Procedure: The 100 ml 1% viscosity reducer solution was placed in the high temperature and high pressure foam evaluation instrument. The liquid height H_0 was recorded, and high-pressure N$_2$ was injected until the pressure of the foam evaluation instrument was up to 15 MPa. The temperature was set at 80°C for 60 min. The foam was manufactured at speed of 1,000 rpm for 1 min. The foaming height h_1 and liquid height h_2 were recorded. Foam half-life t_{50} was measured which is based on the time required to drain half of the liquid from the foam.

N$_2$ Huff-n-Puff Experiment

Apparatus: The apparatus of the huff-n-puff experiment was described in **Figure 2**. According to the different experiment requirements, single sandpack and dual sandpack experiment was carried out. A variety of fluids in the experiment were delivered by ISCO pumps (Model 100DX, Teledyne Technologies, United States, flow accuracy <0.25 μl/min, pressure accuracy <±0.5%). The sandpack model had a length of 600 mm and a diameter of 25 mm. Pressure gauges (Haian Group, China, measurement range <50 MPa, accuracy <0.1% FS), pressure sensors (Model 3210PD, Haian Group, China, measurement range <50 MPa, accuracy <0.1% FS), and vacuum gauge (Haian Group, China, measurement range < −0.1 MPa, accuracy <0.1% FS) were used to measure pressure. The electronic balances (Model PL 2002, Mettler Toledo, Switzerland, measurement range <2,100 g, accuracy <0.01 g) were used to measure the weight of produced oil.

Single sandpack: The experiment procedures for single sandpack were as follows: 1) Silica sand with the same size

TABLE 2 | Sandpack parameters of single sandpack/dual sandpack.

NO.	Type	Particle size (μm)	Porosity (%)	Permeability (mD)	Original oil saturation (%)
1	Single sandpack	180	0.44	3,018	88.88
2	Single sandpack	180	0.43	3,112	91.24
3	Dual sandpack	180	0.45	3,241	84.63
4		150	0.44	1,123	86.27
5	Dual sandpack	180	0.46	3,439	80.34
6		150	0.44	1,167	86.39

TABLE 3 | Experimental data on viscosity reduction effect.

Temperature (°C)	Initial oil viscosity (mPa·s)	1# (mPa·s)	2# (mPa·s)	3# (mPa·s)	4# (mPa·s)
50	3,610	67.8	66.5	87.8	64.2
60	1,680.4	56	57.2	77.5	55.4
70	862.44	44	42.4	64.1	40.1
80	477.63	38	39.3	58.6	36.8
90	288.14	30	32.2	41.2	27.3

TABLE 4 | Experimental data of viscosity reduction rate.

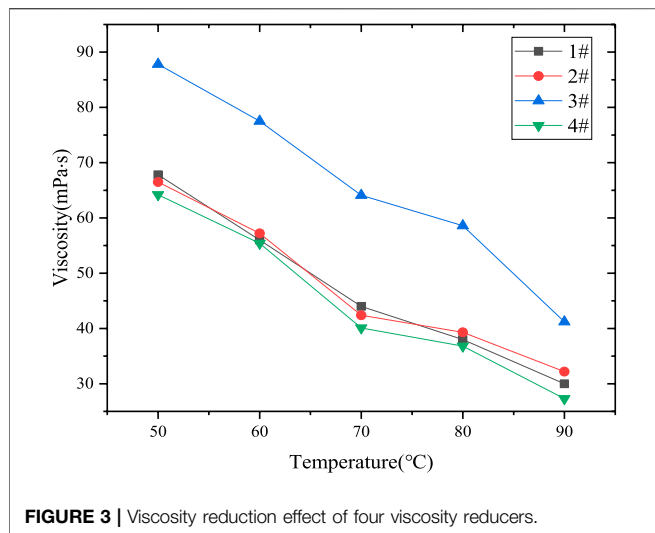| Temperature (°C)	1# viscosity reduction rate (%)	2# viscosity reduction rate (%)	3# viscosity reduction rate (%)	4# viscosity reduction rate (%)
50	98.12	98.16	97.57	98.22
60	96.67	96.60	95.39	96.70
70	94.90	95.08	92.57	95.35
80	92.04	91.77	87.73	92.30
90	89.59	88.82	85.70	90.53

FIGURE 3 | Viscosity reduction effect of four viscosity reducers.

distribution was used to make sure sandpacks are of similar permeability (2,500–4,000 md). 2) The sandpack was vacuumed for 6 h before being saturated by simulated formation water, and the permeability was measured by the Darcy law. 3) The experimental temperature was maintained at 80°C. The heavy oil was injected into the sandpack with a constant rate of 0.5 ml/min until no water came out at the outlet, and the original oil and water saturations were calculated. 4) The viscosity reducer was

pumped into sandpack; then N₂ was injected into the sandpack to 15 MPa; the huff process stopped. 5) After 12 h of soak time, the puff process started. 6) The sandpack was opened for a puff process, and the pressure gradually reduced at a rate of 0.2 MPa/min, which was controlled with a backpressure regulator and an ISCO pump at the outlet. The volumes of produced oil and gas were measured. 7) After the pressure at the outlet of first cycle was reduced to zero, the second cycle of the huff process was started and so on (**Table 2**).

Dual sandpack: The dual sandpack experiment procedures were as follows: 1) Two sandpacks were vacuumed for 6 h. 2) Under reservoir conditions, one sandpack was saturated with the simulated formation water to obtain its pore volume and the permeability of sandpacks was measured by the Darcy law. 3) The experimental temperature was maintained at 80°C. The original oil and water saturations were determined by pumping the heavy oil into the sandpack until no water came out. 4) The viscosity reducer was pumped into sandpack; then N₂ was injected into the sandpack to 15 MPa; the puff process stopped. 5) Another sandpack was operated in similar ways, that is, 2), 3), and 4). 6) After 12 h of soak time, the puff process started. 7) The sandpack was opened for a puff process, and the depletion rate of 0.2 MPa/min was controlled with two backpressure regulators and an ISCO pump at the outlet. The weight and volume of produced oil and gas were measured. 8) After the pressure of first cycle was reduced to zero, the second cycle of the huff process was started and so on (**Table 2**).
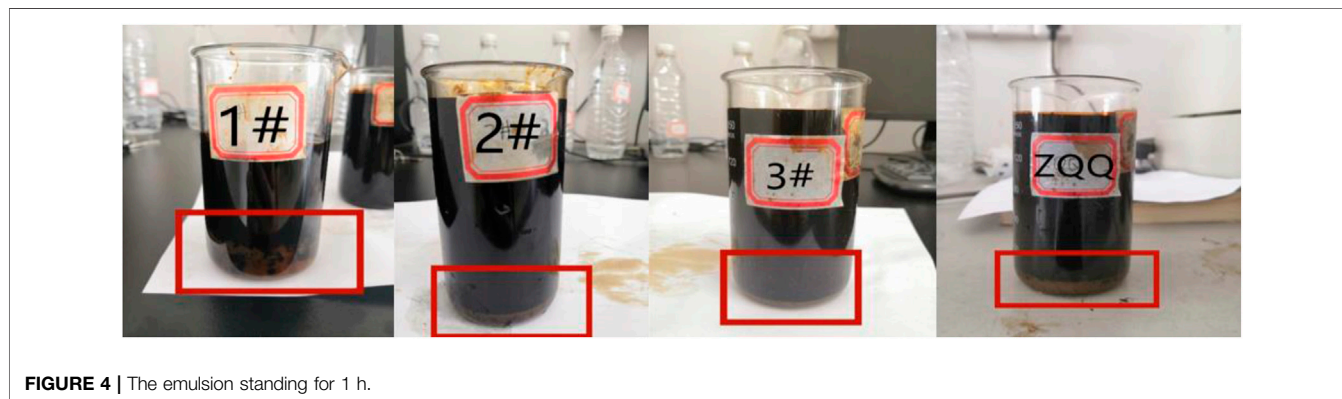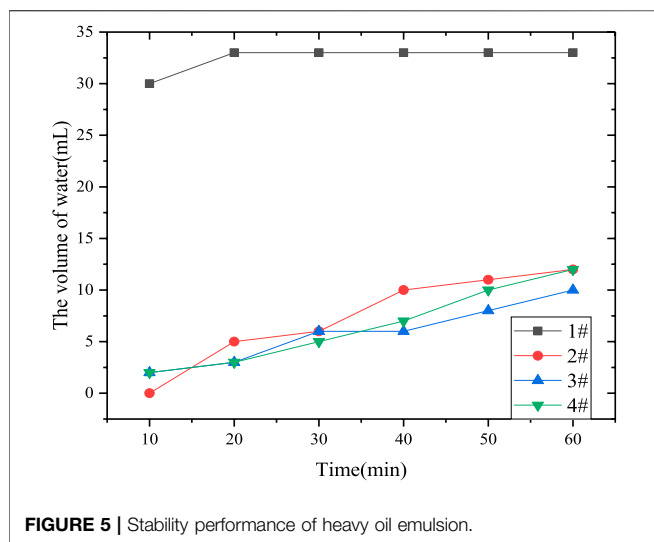

FIGURE 4 | The emulsion standing for 1 h.

TABLE 5 | Experimental results of stability performance of heavy oil emulsion.

Time (min)	1#		2#		3#		4#	
	Water volume (ml)	f_v(%)	Water volume (ml)	f_v(%)	Water volume (ml)	f_v(%)	Water volume (ml)	f_v(%)
10	24	50	0	0	1	4	1	2
20	25	52	3	6	2	4	2	4
30	25	52	4	8	2	4	3	6
40	26	54	6	13	4	8	5	10
50	26	54	7	15	5	10	5	10
60	26	54	7	15	5	10	6	13
S_V	9.74		18.52		19.29		19.02	

FIGURE 5 | Stability performance of heavy oil emulsion.

EXPERIMENTS, RESULTS, AND DISCUSSION

Evaluation of Viscosity Reduction Effect

Heavy oil was rich in resin and asphaltene, which results in high density and viscosity of heavy oil. The main reason for the difficulty of heavy oil recovery is poor mobility (Corbett, 1969). Since the viscosity of water was much less than oil, the viscosity of O/W emulsion was less than oil and W/O emulsion. Under the action of viscosity reducer, the mobility of fluid was improved, because the W/O emulsion was transformed into O/W (Kilpatrick, 2012; Liu et al., 2019). According to the experimental procedure and conditions, the experimental results were shown in **Tables 3 and 4**.

As shown in **Table 3**, when the temperature was less than 70°C, the viscosity reduction rate of the four viscosity reducers

FIGURE 6 | Experiment oil–water sample. **(A)** 50°C. **(B)** 80°C.

could be more than 90%. **Figure 3** shows the viscosity reduction effect of four viscosity reducers. It is observed that the viscosity decreased almost linearly with temperature. In terms of the viscosity reduction effect, 3# has the worst effect. 1#, 2#, and 4# viscosity reducers showed better performances of viscosity reduction effect as compared 3#.

Evaluation of Oil–Water Emulsion Stability

Stability was the significant property of heavy oil emulsion, which requires the heavy oil emulsion to remain stable without phase separation and transformation during recovery. The stability of emulsion depends on the strength of oil–water interface. And the viscosity fluctuation of heavy oil O/W emulsion over time depends on its stability (Maneeintr et al., 2013; Yang et al., 2018). The stability of heavy oil emulsion was an important index to evaluate the performance of viscosity reducer. The four kinds of emulsions were prepared and placed in an oven at 50°C. The volume of the drained water was recorded every 10 min (**Figure 4**). The experimental results were shown in **Table 5**.

The performance of O/W emulsion stability was measured at 50°C. The stability performance of heavy oil emulsion is shown in **Figure 5**. The volume of water drained from heavy oil emulsion was increased with time. 2#, 3#, and 4# emulsions have good stability performance, in which the volume of water drained emulsions was similar. 1# emulsion drained out 50% water in 5 min; then, the volume of the drained water has no obvious change. After 60 min (**Figure 4**), all of emulsion was stable; according to S_V, 2#, 3#, and 4# showed a better performance of O/W emulsion stability as compared to 1#.

Evaluation of Oil–Water Interfacial Tension

The oil–water IFT is an important parameter for heavy oil recovery (Sakthivel et al., 2016; Sakthivel et al., 2017). As shown in **Figure 6**, it is observed that length of oil drop was increased with temperature. Based on the experiment results, shown in **Figure 7**,the IFT between oil and water was the highest; it reached 6.65 and 6.08 N/m at 50 and 80°C, respectively. Under the action of 4#, the IFT between oil and water decreased to 0.41 and 0.19 IFT/mN·m^{-1} at 50 and 80°C, respectively. The 4# viscosity reducer was the best at reducing oil–water IFT.

Evaluation of Foaming

Foam performance evaluation of viscosity reducer includes foaming ability and drainage half-life (Liu et al., 2010; Sun et al., 2016b). The foaming ability and drainage half-life of four viscosity reducers were measured at 15 MPa and 80°C; the results were shown in **Figure 8**.

Figure 9 indicated that the foaming volume of 2# viscosity reducer was the largest, 4# viscosity reducer ranks the second, and that of 3# viscosity reducer was the smallest. However, as for the half-life, the 3# has the longest half-life, 4# ranks the second, and the half-life of the 2# and 1# viscosity reducer was shorter. Although 2# viscosity reducer had the largest foaming volume, its half-life was short; similarly 3# viscosity reducer had the longest half-life, but the foaming volume was small. According to the foaming ability and drainage half-life of four kinds of
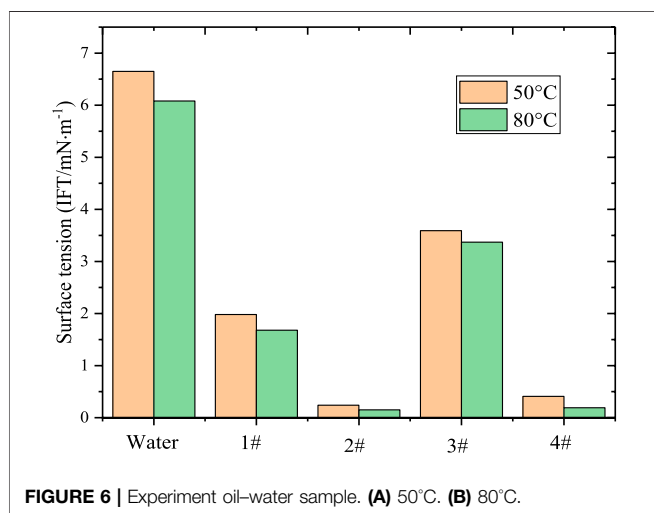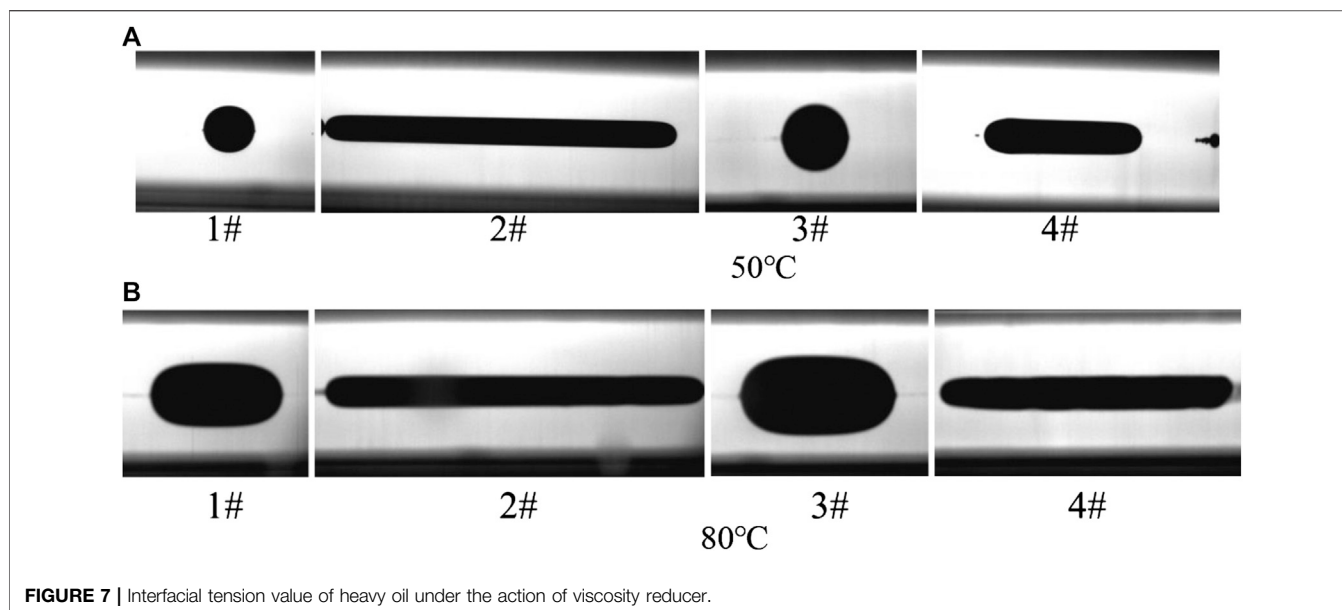
FIGURE 7 | Interfacial tension value of heavy oil under the action of viscosity reducer.

viscosity reducers, the foaming performance of 4# viscosity reducer was the best.

By measuring the viscosity reduction ability, emulsion stability, interfacial performance, and foaming ability at different concentrations, the 4# viscosity reducer with best performance was selected to conduct the huff-n-puff experiments.

Results and Analysis of Huff-n-Puff Experiment
Analysis of Oil Production
In the huff-n-puff experiment, the N$_2$ was injected into the sandpack until the pressure increased to 15 MPa, while the soaking time was 12 h. The puff process was started at pressure depletion rate of 0.2 MPa/min. The experimental results are shown in **Table 6**.

The oil recovery of N$_2$ huff-n-puff process was shown in **Table 6**. It can be seen that the oil recovery was mainly concentrated in the first and second cycles. Among them, the oil recovery in the first and second cycles was 6.86 and 6.85%, respectively. And the oil recovery in the third and fourth cycles was only 2.83 and 0.94%, respectively. Therefore, the total recovery of N$_2$ huff-n-puff process was 17.5%.

According to **Figure10B**, in the N$_2$ huff-n-puff assisted by viscosity reducer experiment, the oil recovery in the first and second cycles was 10.13% and 8.56%, and in the third and fourth cycles was 5.78% and 1.56%, respectively. As shown in **Figures 10A,B**, it is observed that the recovery performance of the first and second cycles was good. However, with the increase of the cycles, the cumulative oil production decreased rapidly. And the recovery performance of N$_2$ huff-n-puff assisted by viscosity reducer was better than N$_2$ huff-n-puff in each cycle.

In the N$_2$ huff-n-puff of dual sandpack process, the total oil recovery of high permeability sandpack was 18.98% and that of the low permeability sandpack was 11.90%. We note that the

permeability of sandpack (NO. 1) and that of sandpack (NO. 3) were similar; however, the oil recovery of sandpack (NO. 3) was increased 1.48%. In the N$_2$ huff-n-puff assisted by viscosity reducer of dual sandpack process, the total oil recovery of high permeability sandpack was 29.00%, and that of the low permeability sandpack was 17.82% **Figure 11**.

Analysis of Gas Production
As shown in **Figure 12**, with the increase in the huff-n-puff cycles, the gas production increased rapidly. The oil was produced and the oil position in the sandpack was occupied by N$_2$ injection in the next huff process, which increased the gas injection volume in each cycle. In the first and second cycles, when the production pressure was in the range of 8–15 MPa, the gas production per unit pressure drop was relatively flat. And when the production pressure was in the range of 0–6 MPa, the gas production increased per unit pressure drop, which was similar to the oil
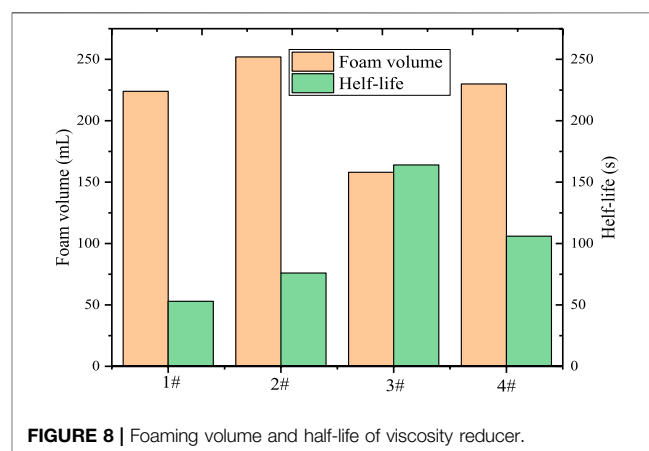

FIGURE 8 | Foaming volume and half-life of viscosity reducer.
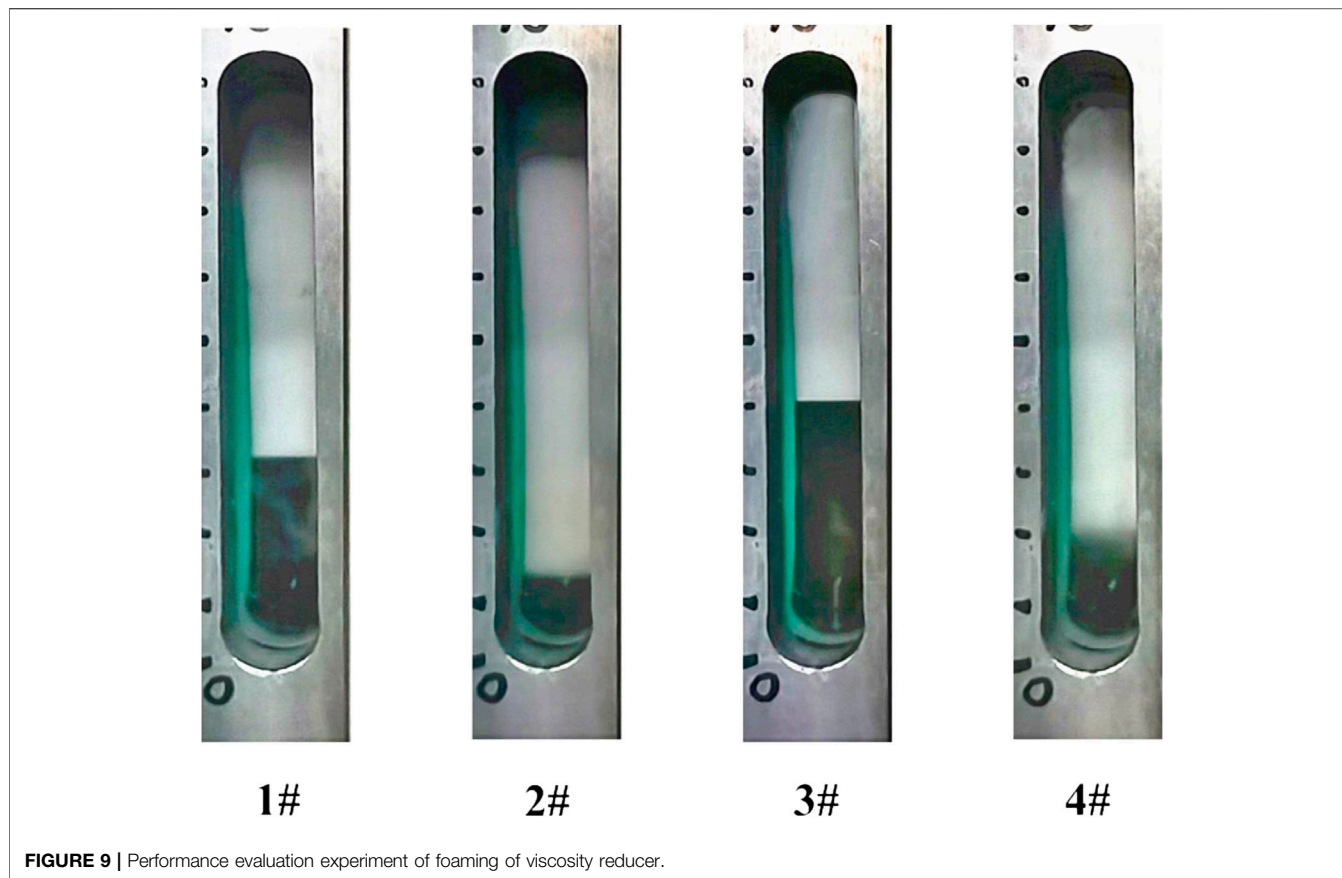
FIGURE 9 | Performance evaluation experiment of foaming of viscosity reducer.

production. The third and fourth cycle production processes were relatively stable.

As shown in **Figures 13A,B**, the gas production of the high permeability sandpack was higher than that of the low permeability sandpack. This is because the flow resistance of the gas in the high permeability sandpack was less than that in the low permeability sandpack. In the N₂ huff-n-puff experiment, the gas production in the first and second cycles was more than that of the third and fourth cycles. In the first and second cycles, one reason is the higher oil saturation in the low permeability sandpack, and the other reason is the effect of the resistance of N₂ flowing out in the high permeability sandpack less than that in the low permeability sandpack. In the third and fourth cycles, due to the low oil saturation of the low permeability sandpack, the N₂ gas volume was more than the

oil in the channel, and the gas was more likely to flow out from the high permeability sandpack.

As shown in **Figures 13C,D**, in the N₂ huff-n-puff assisted by viscosity reducer experiment, the gas production of low permeability sandpack was increased, especially in the third and fourth cycles. This is because of the foaming pugging effect of 4# viscosity reducer. The foam plugged the large channel, which increased the resistance of N₂ flow in the channel, but did not affect the N₂ displacement of oil (Zhu et al., 1998; Li et al., 2017). Finally, the oil production of low permeability sandpack was improved.

Analysis of Huff-n-Puff Process

In the process of soaking, N₂ was dispersed in the pores of the sandpack. This is because of the concentration difference of N₂ in

TABLE 6 | Results of huff-n-puff experiment.

| Sandpack NO.	Type	First cycle oil recovery (%)	Second cycle oil recovery (%)	Third cycle oil recovery (%)	Fourth cycle oil recovery (%)	Total oil production (ml)	Total cycle oil recovery (%)
1	Single sandpack	6.86	6.85	2.83	0.94	20.14	17.5
2	Single sandpack	10.13	8.56	5.78	1.56	30.06	26.03
3	Dual sandpack	6.99	6.99	3.00	2.00	21.28	18.98
4		4.06	4.84	2.33	0.66	13.3	11.9
5	Dual sandpack	9.07	9.36	5.96	4.61	31.55	29.00
6		6.55	6.51	2.38	2.37	19.94	17.82
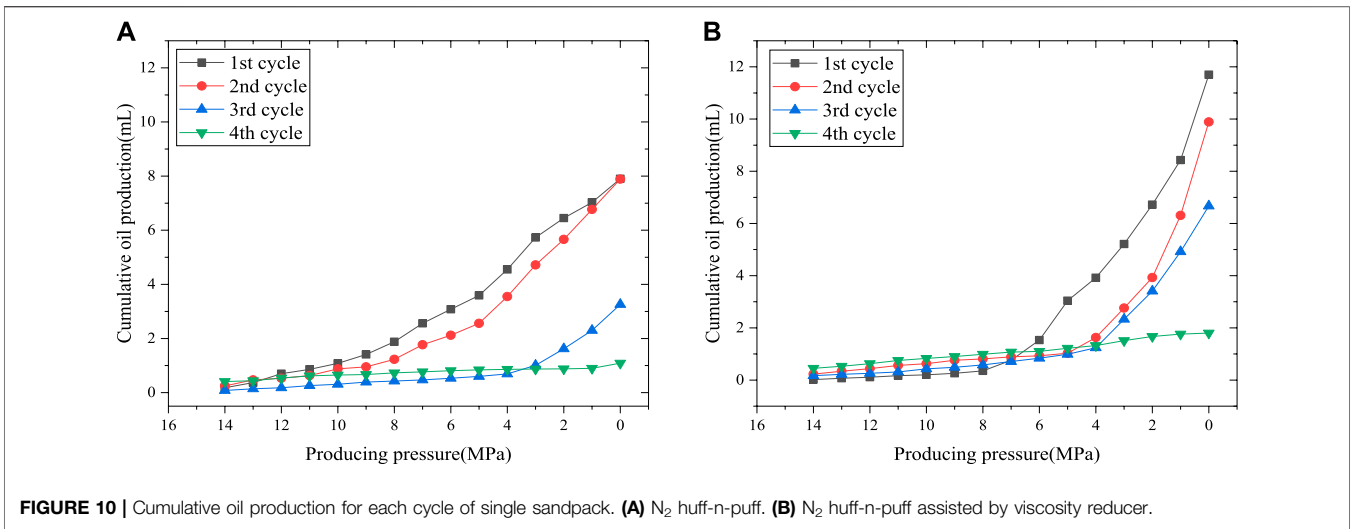
FIGURE 10 | Cumulative oil production for each cycle of single sandpack. (A) N$_2$ huff-n-puff. (B) N$_2$ huff-n-puff assisted by viscosity reducer.

the sandpack. By this diffusion way, N$_2$ was almost unaffected by permeability, so N$_2$ can reach the channel with low permeability (Nguyen et al., 2018). In the first cycle (**Figure 14**), the N$_2$ existed

in the sandpack in the form of dispersed small bubbles. In the production process, it was difficult for N$_2$ to form continuous gas phase, and oil of existence enables the sandpack to maintain a
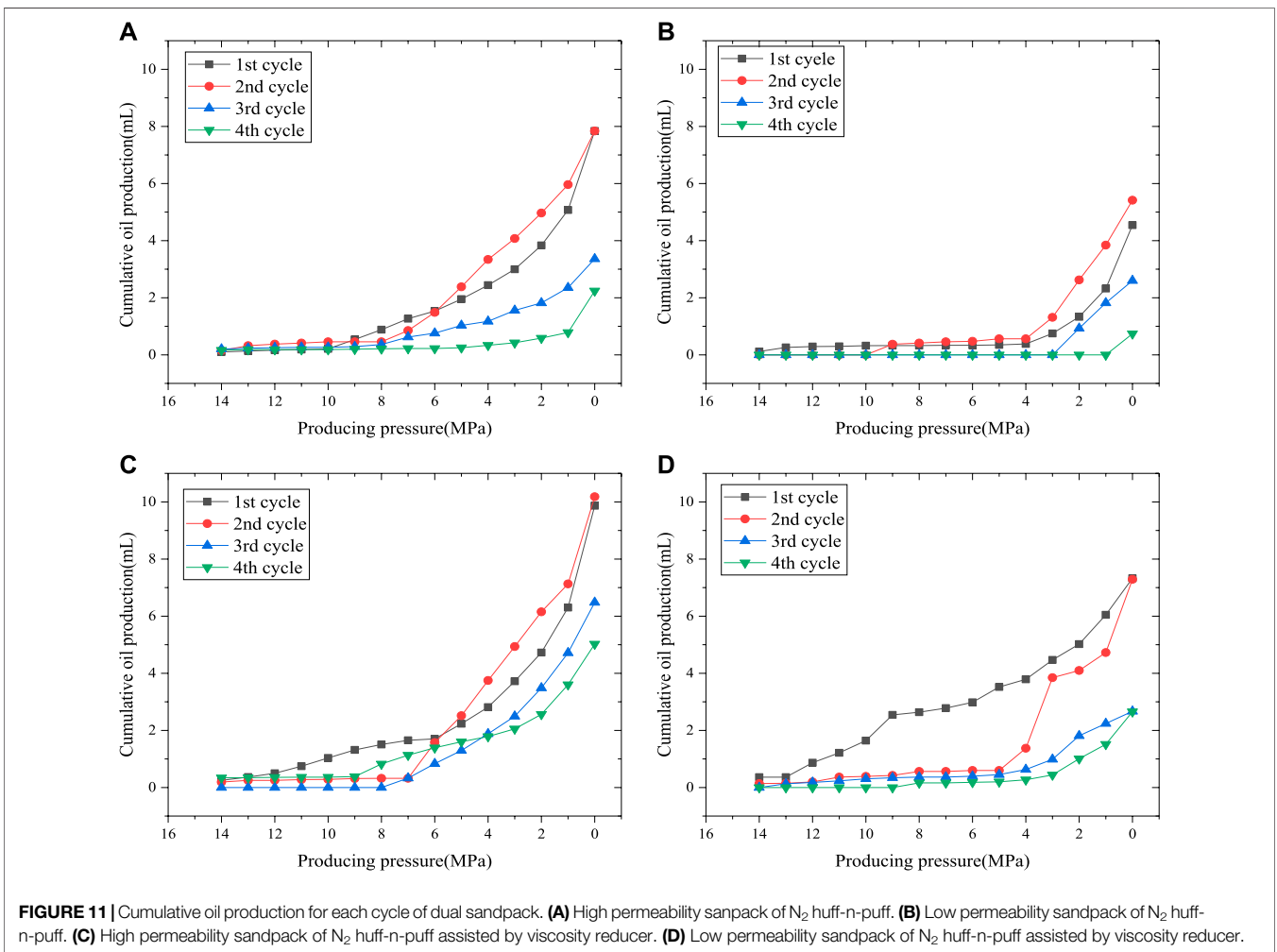
FIGURE 11 | Cumulative oil production for each cycle of dual sandpack. (A) High permeability sanpack of N$_2$ huff-n-puff. (B) Low permeability sandpack of N$_2$ huff-n-puff. (C) High permeability sandpack of N$_2$ huff-n-puff assisted by viscosity reducer. (D) Low permeability sandpack of N$_2$ huff-n-puff assisted by viscosity reducer.
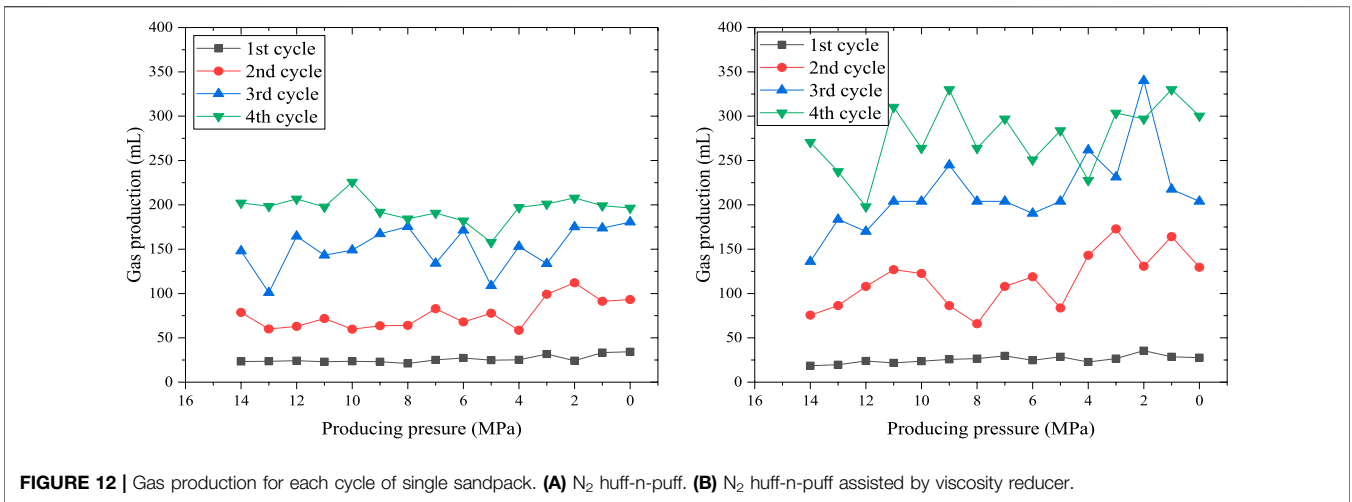
FIGURE 12 | Gas production for each cycle of single sandpack. **(A)** N$_2$ huff-n-puff. **(B)** N$_2$ huff-n-puff assisted by viscosity reducer.

high relative permeability. In the process of pressure depletion, the bubbles were expanded to increase the elastic energy of oil. In the second cycle, the large channels in the sandpack were increased as the oil was produced, and the amount of N$_2$ injection increased. The sandpack has continuous gas phase and gas bubbles, the continuous gas phase was usually in the

large channel, and the gas bubbles were in the small channel. This kind of continuous gas contributing to the gas bubbles coalesced in the large channel (Adil and Maini, 2005; Zhang et al., 2018). In the third and fourth cycles, the gas bubbles were coalesced, resulting in channeling. After gas channeling, the gas flowed in the large channel with high permeability in the process of
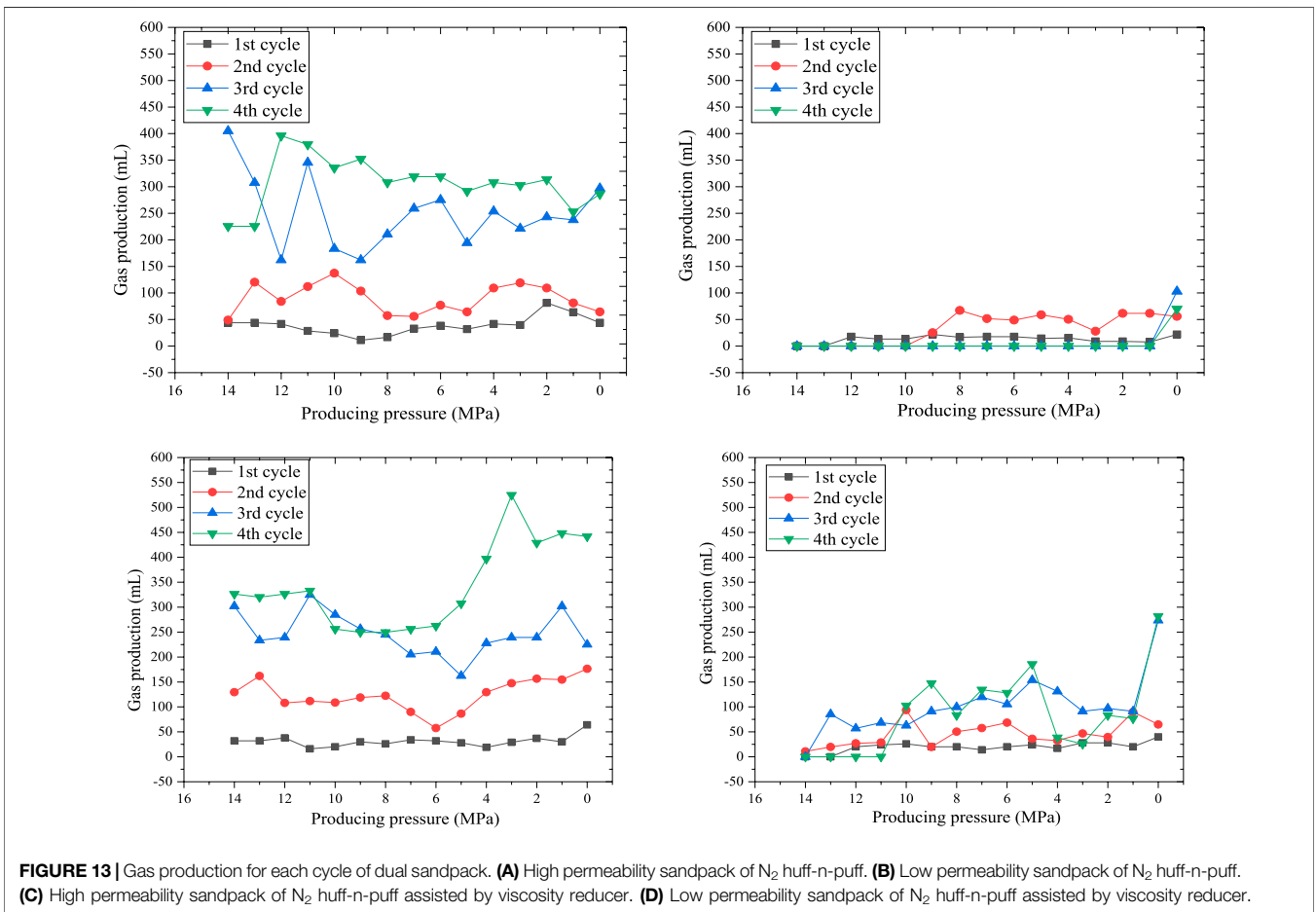

FIGURE 13 | Gas production for each cycle of dual sandpack. **(A)** High permeability sandpack of N$_2$ huff-n-puff. **(B)** Low permeability sandpack of N$_2$ huff-n-puff. **(C)** High permeability sandpack of N$_2$ huff-n-puff assisted by viscosity reducer. **(D)** Low permeability sandpack of N$_2$ huff-n-puff assisted by viscosity reducer.

FIGURE 14 | Diagram of single sandpack N$_2$ huff-n-puff production process.
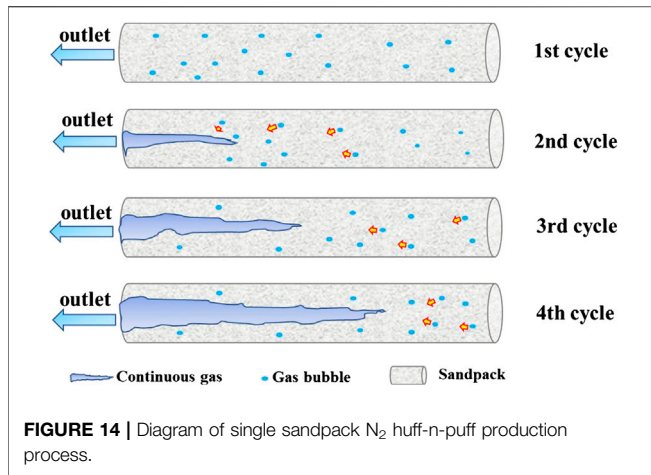
production, which led to the failure of N$_2$ to sweep the small channel with high oil saturation and low permeability. The viscous fingering caused by the adverse mobility ratio between the oil and the gas was not a benefit to oil production. When oil was produced, the gas channeling was serious, which was the main reason for low recovery in the third and fourth cycles (Shokri and Babadagli, 2017).

In the dual sandpack N$_2$ huff-n-puff experiment (**Figure 15**), the oil production and gas production of the high permeability sandpack (NO. 3) were higher than those of the low permeability sandpack (NO. 4). However, we found that the remaining oil content of the high permeability sand was higher than that of the low permeability (**Figure 16**). The main reason for this phenomenon was that the flow resistance of oil and N$_2$ in the high permeability sandpack was lower than that in the low permeability sandpack during the production process. In the process of pressure depletion, the oil and N$_2$ in the low permeability sandpack near the high permeability sandpack could flow to the high permeability sandpack with low resistance. Although the oil in the high permeability sandpack was produced, it was supplemented by the oil which was in the low permeability sandpack. In this case, the remaining oil content of the high permeability sandpack was higher than that of the low permeability sandpack.

In the first cycle of dual sandpack N$_2$ huff-n-puff experiment, the oil saturation in the sandpack was high, and the N$_2$ was dispersed in the high permeability and low permeability sandpack. After pressure depletion, in the low permeability sandpack, the oil was drove by the N$_2$ to the high permeability sandpack. The produced oil and N$_2$ in the high permeability sandpack were supplemented by the oil in the low permeability

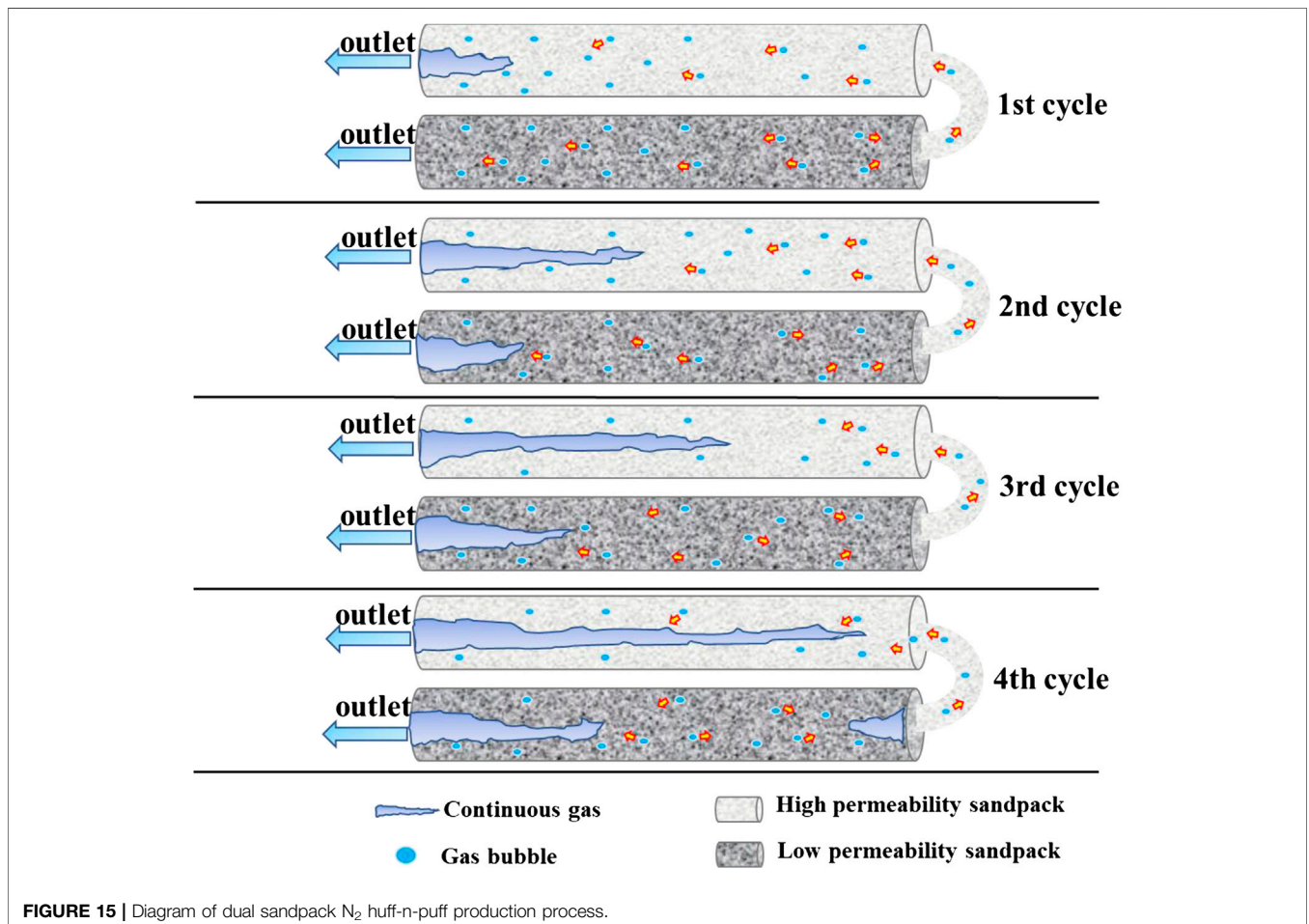**FIGURE 15 |** Diagram of dual sandpack N$_2$ huff-n-puff production process.

FIGURE 16 | Oil sands after huff-n-puff production process.

sandpack. As a result, the gas concentration in the high permeability sandpack was increased, and the relative permeability of gas was increased, resulting in the gas channeling. In the second and third cycles, gas channeling became more and more serious in the high permeability sandpack, and the relative permeability of gas in the low permeability sandpack was increased. In the fourth cycle, the N_2 saturation increased in dual sandpack, the relative permeability of gas increased significantly, and the relative permeability of oil decreased.

From the above analysis, in the single sandpack N_2 huff-n-puff experiment, we can know that the main reason for low oil production was that a large amount of N_2 collects in the high permeability channel to form a continuous gas after the second cycle. Continuous gas flows in large channel with low flow resistance and becomes unable to sweep into low permeability channel with high oil content. In addition, with the relative permeability of gas phase increasing, the relative permeability of oil phase decreases. It is indicated that the oil mobility was

decreased and gas mobility was increased. In dual sandpack N_2 huff-n-puff experiment, the oil and N_2 near the high permeability sandpack in the low permeability sandpack flowed to the high permeability sandpack with low flow resistance. However, there were a large number of channels with high permeability in the high permeability sandpack. In the high permeability sandpack, with the supplement of N_2, the gas channeling becomes more serious. In order to solve these problems, 4# viscosity reducer with foaming ability was used to assist N_2 huff-n-puff, the large channel was plugged by foam to reduce the collection of N_2, and the viscosity of oil can be reduced to increase the mobility.

In the process of N_2 huff-n-puff experiment, with the reduction of sandpack pressure, N_2 was collected in the large channel (**Figure 17A**), and the continuous N_2 tended to flow into large channels. And the oil in small channels with low permeability was difficult to drive. At the same time, because the mobility of oil was lower than that of N_2, and the relative permeability of oil decreased continuously, it was difficult for the oil to flow. In order to reduce the collection of N_2 in the
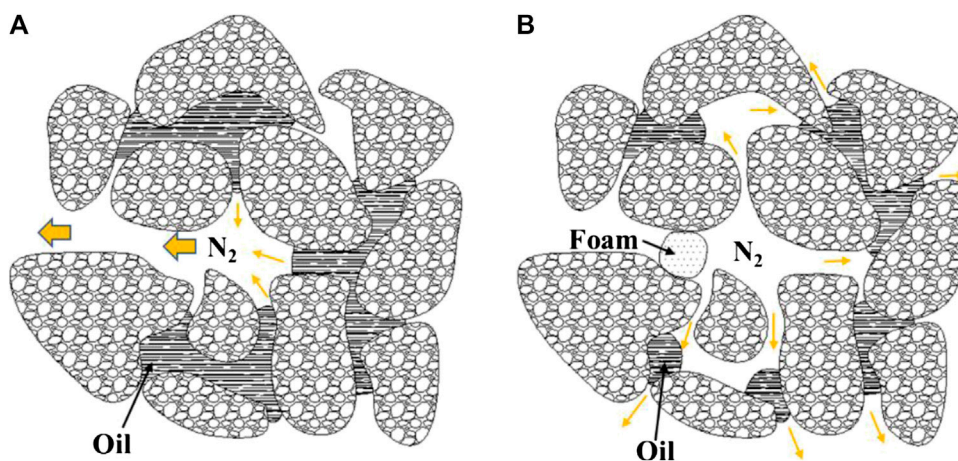

FIGURE 17 | Foam plugging process.

production process and improve the mobility of oil, the 4# viscosity reducer was used. In the process of N_2 flow, the 4# viscosity reducer was stirred and foamed, and the foam plugged the large channel (**Figure 17B**). The N_2 was forced to flow to the small channel by gas, and the gas phase relative permeability was reduced.

In the dual sandpack N_2 huff-n-puff assisted by viscosity reducer experiment, the gas production of the low permeability sandpack was obviously increased (**Figure 13D**). It indicated that the 4# viscosity reducer plugged the large channel in the low permeability sandpack and inhibited the flow of N_2 to the high permeability sandpack. The oil production of high permeability sandpack and low permeability sandpack increased by 10.02 and 5.92%, respectively. This is due to the foam of 4# viscosity reducer, which plugged the larger channel, reduced the viscosity of oil, and improved the mobility of oil. The flow of N_2 from the low permeability sandpack to the high permeability sandpack was inhibited by foam, while the flow of oil to the high permeability sandpack was difficult to inhibit. There were a large number of high permeability channels in the high permeability sandpack, and the foam inhibited the gas channeling and improved the oil production of the high permeability sandpack. It is the reason that the oil production of the high permeability sandpack is more than that of the low permeability sandpack.

CONCLUSION

(1) The optimized 4# viscosity reducer has good viscosity decreasing effect, which decreases viscosity rate of oil more than 90% at 50–90°C, which can form stable oil emulsion. The oil–water IFT was 0.41 and 0.19 IFT/mN·m^{-1} at 50 and 80°C, respectively. What's more, the 4# viscosity reducer has good foaming ability at high temperature and pressure.

(2) In the single sandpack huff-n-puff experiment, compared with N_2 huff-n-puff, the oil recovery rate of N_2 huff-n-puff assisted by viscosity reducer increased by 8.53%. In the dual sandpack N_2 huff-n-puff experiment, compared with N_2 huff-n-puff, oil production of high permeability sandpack

of N_2 huff-n-puff assisted by viscosity reducer increased by 10.02%, the oil production of low permeability sandpack increased by 5.92%, and total oil production increased by 7.88%.

(3) After the second cycle of single sandpack N_2 huff-n-puff experiment, the N_2 bubbles coalesced in the large channel, resulting in the gas channeling. In the dual sandpack N_2 huff-n-puff experiment, the oil and N_2 in the low permeability sandpack, near the high permeability sandpack, flowed to the high permeability sandpack, so the oil production of the high permeability sandpack was increased and the remaining oil was higher than the low permeability sandpack.

(4) The 4# viscosity reducer can reduce the viscosity of oil and plug large channel by foaming. N_2 was forced to flow to small channel, which alleviated the generation of continuous gas phase and increased the oil recovery of small channel. In the dual sandpack huff-n-puff experiment, the foam can effectively inhibit the N_2 flow from the low permeability sandpack to the high permeability sandpack and increase the N_2 displacement efficiency.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The authors LT and SH have equally contributed to this work.

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