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Research on Enhancing Heavy Oil Recovery Mechanism of Flue Gas Assisted Steam Flooding

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Abstract

Flue gas is industrial waste gas produced by the burning of fossil fuels. Its main compositions are 10% - 15% of carbon dioxide and 80% - 85% of the nitrogen, two key components needed for gas flooding. Adding a certain amount of flue gas into steam in displacement could decrease steam partial pressure, improve the steam quality and reduce heat loss, resulting in reduction of steam injection amount and improvement of development performance. The objective of the research is to investigate the mechanism of enhanced oil recovery (EOR) of flue gas assisted steam flooding which has a dual significance of reducing greenhouse gas emissions and improving oil displacement efficiency.

In this paper, PVT measurements at high temperature and high pressure (HTHP) were firstly conducted to analyze the effect of flue gas on property of heavy oil. Then sandpack displacement experiments containing 5 sub-experiments: steam flooding, flue gas assisted steam flooding, first steam flooding then flue gas assisted steam flooding, water flooding, flue gas assisted water flooding, were operated to compare the contribution of heat and gas on recovery. In the experiment of flue gas assisted steam flooding, the production rate and composition of gas were measured and analyzed, and the form of the produced oil was also compared with steam flooding.

The PVT measurements results show that with flue gas dissolved, viscosity of heavy oil declines and volume expands. The solubility of flue gas in heavy oil decreases with temperature and increases with pressure. The greater the solubility of flue gas, the lower viscosity of heavy oil, the larger volume. At the same solubility, as the temperature increases, the viscosity reduction effect of flue gas weakens and the volume expansion effect enhances.

The displacement experiments results indicate that the addition of flue gas to steam can significantly improve oil displacement efficiency compared with steam injected alone. In the test of flue gas assisted steam flooding, the heavy oil was produced in the form of foamy oil because of dissolution of flue gas, especially CO_2, which could expand oil volume and reduce the flow resistance of heavy oil to a certain extent. Besides, the cumulative volume of the produced gas was smaller than the injected gas, and in the produced gas the proportion of CO_2 was less than the injected proportion. Furthermore, the contribution of flue gas to recovery when injected with steam is greater than with water because of the synergistic effect of heat and gas.

This research reveals the interactions between flue gas and oil in displacement and the synergistic effect of steam and flue gas on EOR, which provides the theoretical support for the application of flue gas assisted steam flooding.

Introduction

In recent years, with greenhouse effect and global warming becoming increasingly serious, energy-saving and emission reduction has attached people's focus. Flue gas generated by the burning of fossil fuels is a major source of greenhouse gas. CCUS (CO_2 capture, utilization and storage) is an effective means to reduce greenhouse gas emissions, which has good application prospect in oilfield[1-6].

Steam flooding is a conventional exploiting method at present, but there are some issues including huge consumption of steam, high water cut and low oil recovery[7-8]. In order to improve the development performance of steam flooding, flue gas assisted steam flooding was proposed that flue gas is injected with steam together. The main components of flue gas are 80-85% of N_2 and 15-20% of CO_2. N_2 has the effect of increasing reservoir energy and heat insulation, and CO_2 has the effect of dissolution, viscosity reduction and volume expansion[9-10]. To inject flue gas with steam into reservoir not only improves the oil recovery of steam flooding, but also reduces the greenhouse gas emissions.

Now around flue gas assisted steam flooding, a lot of experiments and simulations have been carried out. Although many mechanisms of flue gas has been put forward to account for EOR, such as decreasing steam partial pressure, improving the steam quality and reducing heat loss and so on[11-14], no one is confirmed. So in order to investigate the effect of flue gas in displacement, PVT measurements at HTHP and sandpack flooding experiments were carried out in this paper. In PVT measurements, the dissolution law of flue gas into heavy oil was measured first and then the effect of flue gas on property of heavy oil was analyzed. Five tests of sandpack flooding were conducted to compare the contribution of heat and gas on recovery. The composition of the produced gas and the form of the produced oil in the experiments of flue gas assisted steam flooding were analyzed to study the interactions between flue gas and heavy oil in displacement.

Experiments

Materials

The heavy oil used in the experiments was sampled from Liaohe oilfield, China. Its basic properties are shown in the Table 1.

The flue gas used in the experiments was prepared in laboratory with N_4 and CO_2 with mole fraction of 80% and 20% respectively.

In sandpack floodings, the sandpack models were packed by refined silica sand, the parameters of which are shown in Table 2.

Table 1 Properties of the heavy oil used in the experiments

Property	Value
Density at 20℃(kg/m^3)	936.8
Viscosity at 50℃(mPa·s)	8860
Saturate content (wt%)	44.23
Aromatic content (wt%)	30.76
Resin content (wt%)	21.60
Asphaltene content (wt%)	3.41

Apparatus

In the PVT test, a rotatable PVT device and a falling-ball viscometer were used, as is shown in Fig.1. The rotatable PVT device mainly consists of a heated piston cylinder, a hand-cranked pump and a temperature and rotation controller. Gas is mixed with oil and dissolved in the piston cylinder. The hand-cranked pump with scale is used to provide pressure and measure volume. The accuracy of the scale is ±0.05mL and the accuracy of the pressure gauge is ±0.01MPa. The falling-ball viscometer is connected with the piston cylinder, in which the viscosity of saturated oil is measured. Its measurement range is 100-100000 mPa s. The BPR is used to provide a pressure bigger than the saturation pressure to prevent solution gas from releasing.

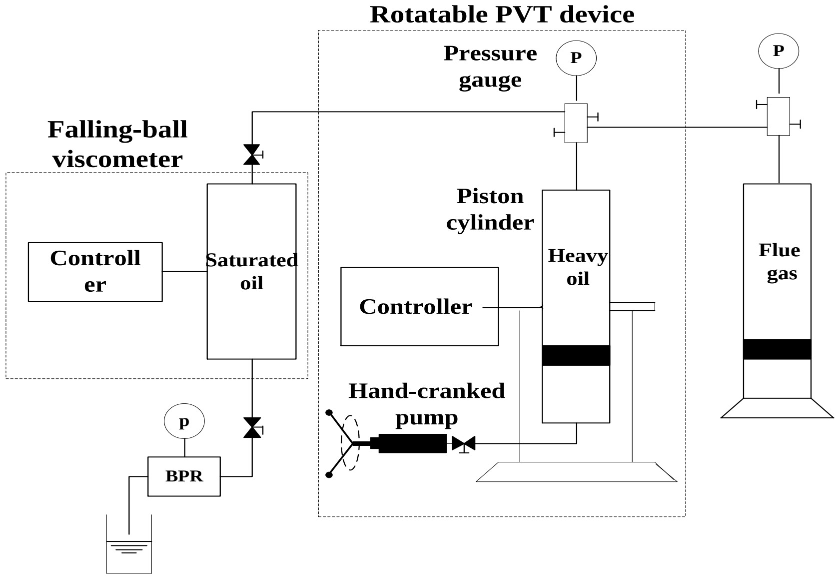


Fig.1 Schematic diagram of the PVT measurement apparatus

The schematic of the apparatus used in the experiments of sandpack flooding is shown in Fig.2. It mainly consists of injection system, multifunction displacement system, data acquisition system and production system. Injection system mainly includes an ISCO pump, a steam generator, a gas flowmeter , a gas cylinder and an oil cylinder. The injection rate of steam and oil are controlled by ISCO pump with accuracy of ±0.001mL. The gas injection rate is controlled by gas flowmeter with accuracy of 0.01Sccm. Multifunction displacement system mainly includes sandpack model, incubator and back-pressure regulator (BPR). Sandpack model has a length of 60.00cm and an inner diameter of 2.54cm, on which two pressure detecting points are distributed evenly. Data acquisition system records pressure by pressure transducers that are connected to a computer. Production system consists of liquid-gas separator, oil-water separator, gas mass-flow meter and balances. The produced gas is measured by gas mass-flow meter with accuracy of 0.01Sccm. The produced oil and water are measured separately by balance with accuracy of 0.01g.

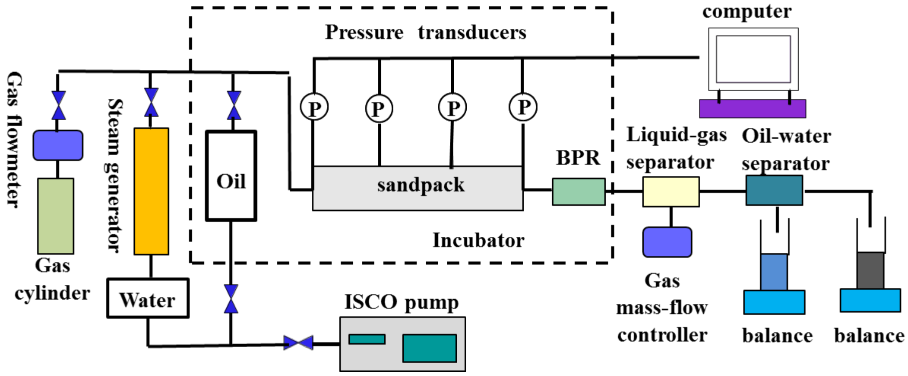


Fig.2 Schematic diagram of the sandpack flooding experiment

Experimental procedures

Experiment steps for PVT test

(1) A certain volume of gas was injected into the piston cylinder containing oil according to the solution gas-oil ratio.
(2) The mixture of oil and gas was provided a higher pressure by the hand-crank pump with the cylinder rotating to make sure the gas could be dissolved into the oil completely and quickly.
(3) Part of the saturated oil was injected into the falling-ball viscometer to measure the viscosity of the live oil first.
(4) For the remaining live oil, its volume and corresponding pressure were recorded with the piston withdrawing gradually.
(5) On the pressure curve against volume, the pressure at the inflection point could be regarded as saturation pressure. Meanwhile, the volume factor could be calculated according to known saturation volume and dead oil volume.

Experiment steps for sandpack flooding

(1) Sandpack model was prepared with proper permeability and porosities. Then it was saturated with water after evacuated for 4 hours. The pore volume and permeability could be measured and calculated.
(2) After the temperature of sandpack model reached stable in the incubator of 70℃, it was saturated with oil at the rate of 0.1mL/min for more than 2PV. Then the irreducible water saturation and initial oil saturation were calculated.
(3) For steam flooding, steam of 250℃ was injected at the rate of 2mL/min until the water cut of the produced liquid reached 98%. The produced gas, water and oil were measured respectively.
(4) For flue gas assisted steam flooding, flue gas was injected with steam together at the gas-water ratio of 1 with other parameters unchanged.
(5) For water flooding and flue gas assisted water flooding, the temperature of injection fluid was same as the temperature of the incubator. The detailed parameters are shown in Table 2.

Table 2 Parameters of the sandpack flooding

Test No.	Flooding pattern	Permeability (mD)	Porosity (%)	Initial oil saturation (%)	Injection rate (mL/min)	
					Water	Flue gas
1#	Steam flooding	3033	37.26	89.25	2	0
2#	Flue gas assisted steam flooding	3150	37.78	89.86	1	1
3#	First steam flooding then flue gas assisted steam flooding	3090	37.56	88.78	First 2 then 1	First 0 then 1
4#	Water flooding	3120	38.03	89.26	2	0
5#	Flue gas assisted water flooding	3065	37.73	89.52	1	1

Results and discussions

PVT measurements

The PVT tests were conducted at 60℃, 90℃ and 120℃ to study the effect of dissolution of flue gas on property of heavy oil. The dissolution law of flue gas at different temperature and pressure were analyzed first. Then the viscosity and volume of saturated oil were measured. On this basis, viscosity reduction factor and volume factor under different conditions were calculated.

Dissolution law of flue gas

Fig.3 shows the relationship of saturation pressure and solution gas-oil ratio at different temperatures. From the picture we can see, at the same temperature, as the saturation pressure increases, solution gas-oil ratio increases gradually. At the same saturation pressure, solution gas-oil ratio decreases with the increase of temperature. This is because at higher temperature, gas molecular thermal motion accelerates, which inhibits the dissolution of flue gas into oil.

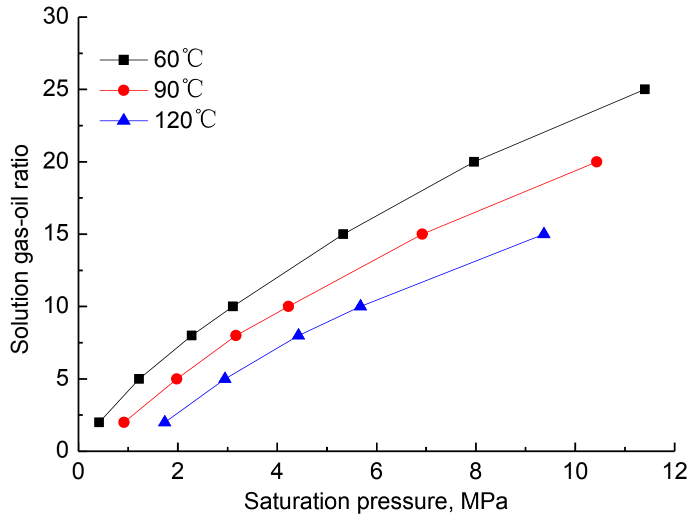


Fig.3 Relationship of solution gas-oil ratio and saturation pressure at different temperatures

Viscosity reduction property of flue gas on heavy oil

To investigate the viscosity reduction effect of flue gas on heavy oil, the viscosity reduction rate was used and defined as the ratio of reduction of viscosity to original viscosity, as is shown in equation (1):

$$Y = \frac{X_1 - X_2}{X_1} \times 100\% \tag{1}$$

Where Y is viscosity reduction rate, %; X_1 is the viscosity of original oil, mPa·s; X_2 is the viscosity of saturated oil, mPa·s.

The relationship of viscosity reduction rate and solution gas-oil ratio at different temperatures is shown in Fig.4. As solution gas-oil ratio increases, viscosity reduction rate increases, meaning that the viscosity of saturated oil decreases gradually with more flue gas dissolved. Under the same solution gas-oil ratio, the higher the temperature, the lower the viscosity reduction rate, which indicates that the effect of viscosity reduction of flue gas is weakened at higher temperature.

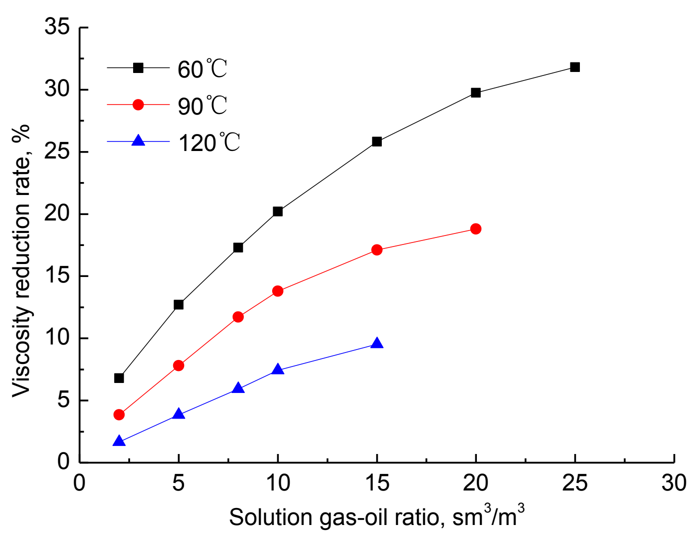


Fig.4 Relationship of solution gas-oil ratio and viscosity reduction rate at different temperatures

Volume expansion property of flue gas on heavy oil

In order to analyze the expansion effect of solution gas on heavy oil, the volume factor is used and defined by the equation (2),

$$B = \frac{V_2}{V_1} \times 100\% \tag{2}$$

Where B is volume factor; V_1 is the volume of oil on the ground, mL; V_2 is the volume of saturated oil at saturation condition, mL.

The relationship of volume factor and solution gas-oil ratio is shown in Fig.5. It can be seen that at the same temperature, as solution gas-oil ratio increases, the volume factor increases gradually. Although the pressure increases with the increase of solution gas-oil ratio, the expansion effect of solution gas on oil is greater than the compression of pressure. Under the same solution gas-oil ratio, the volume factor increases with the temperature, for the thermal-expansion effect becomes bigger.

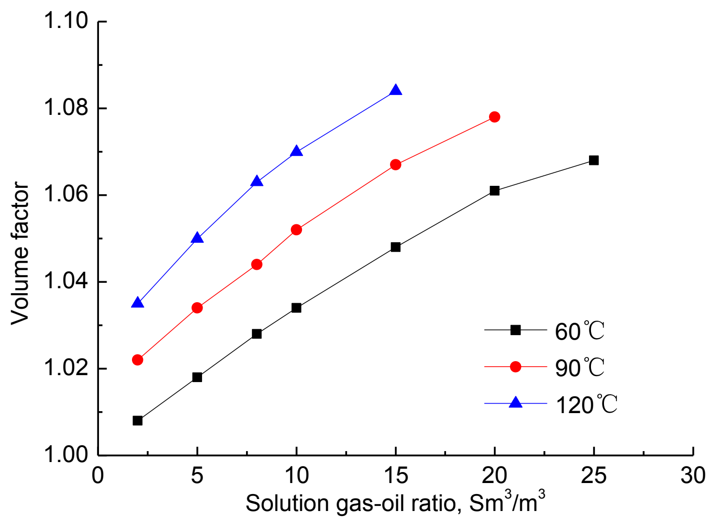


Fig.5 Relationship of solution gas-oil ratio and volume factor at different temperatures

Sandpack flooding

In order to investigate the effect of flue gas on the displacement law, three experiments of steam flooding, flue gas assisted steam flooding and first steam flooding then flue gas assisted steam flooding, were conducted, as shown in Table 2 (No.1, No.2 and No.3). The production law of oil, water and gas were compared in the three experiments. In order to investigate the synthetic effect of flue gas and heat on EOR, two more experiments of water flooding (No.4) and flue gas assisted flooding (No.5) were conducted to compare the contribution of different factors on recovery.

Oil production rate and form of produced oil

Fig.6 shows the change curves of oil production rate along with injection volume in different displacements. As we can see, with fluid injected, oil production rate first rises quickly then declines rapidly in all three experiments. But in the experiment of flue gas assisted steam flooding, the oil production rate is greater than in steam flooding. And in the experiment of No.3, when the flue gas is injected with steam subsequently, the oil production rate increases significantly. This shows the addition of flue gas is really beneficial to the production of oil no matter when the gas is injected.

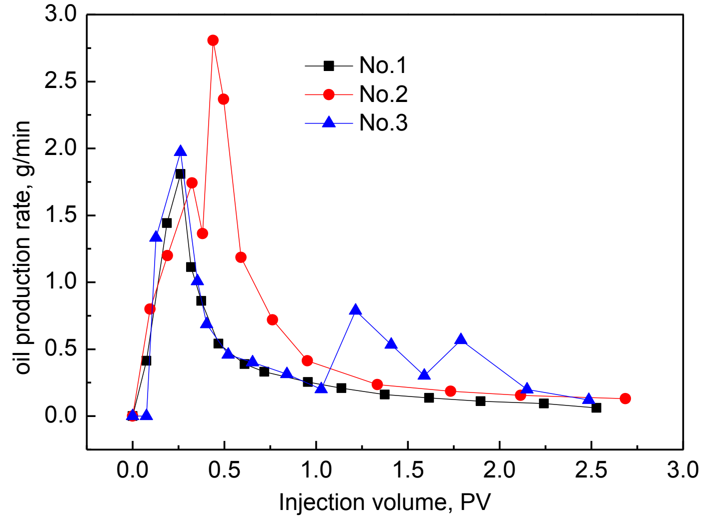
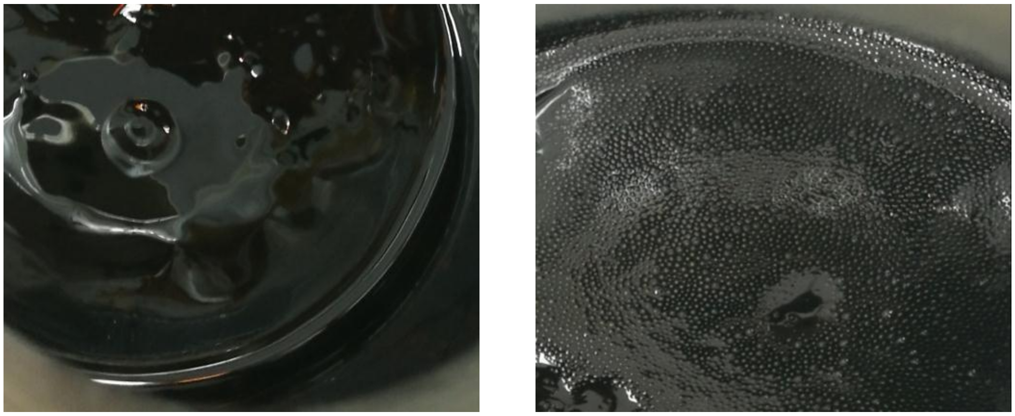


Fig.6 Oil production rate of different flooding patterns

Fig.7 compares the form of produced oil in test No.1 and test No.2. Fig.7(a) presents the form of the produced oil in test No.1, and Fig.6(b) shows the form of the produced oil in test No.2. We can see that the produced oil in the two tests is quite different in form. A large number of bubbles exist in the produced oil of test No.2, which forms a special state of mixture of heavy oil and solution gas, namely foamy oil. Flue gas is dissolved into oil under high pressure in displacement and then releases when produced. But due to high viscosity of heavy oil, it is difficult for the released solution gas to coalesce and form continuous free gas phase. As a result, it exists in heavy oil in the form of micro-bubble. The formation of foamy oil can expand the volume of original heavy oil and reduce its flow resistance, which can greatly promote the production of heavy oil.



(a) Test No.1 **(b) Test No.2**

Fig.7 Form of produced oil

Water cut

Fig.8 shows the change curves of water cut along with injection volume in different displacement tests. From the picture we can see, there exists a brief period in which oil is produced without water. Once the injected water breaks through, water cut in produced liquid will rise sharply. And when the water cut exceeds 80%, corresponding to the injection volume about 0.5PV, water cut will increase slowly. Compared with steam flooding, the water cut in the experiment of flue gas assisted steam flooding is lower at the same injection volume, especially early in displacement. In the test of No.3, when flue gas is injected, the water cut first declines significantly then increases gradually. It can be concluded that when steam and flue gas flow together, the flue gas occupies the main flow channel and inhibits water channeling to some extent, resulting in lower water cut in the tests of No.2 and No.3.

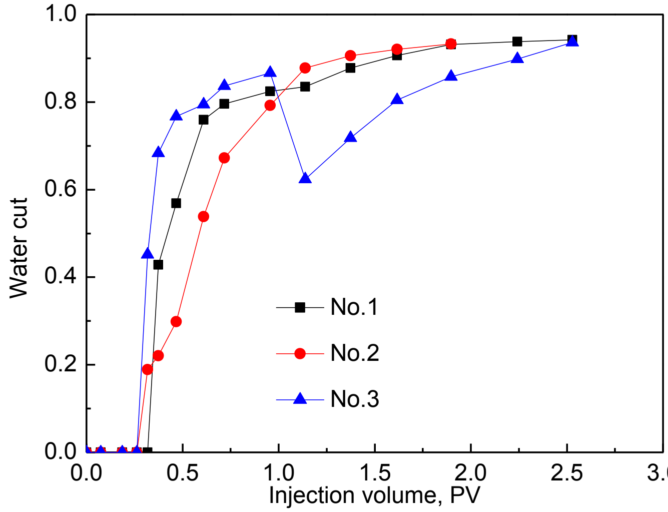


Fig.8 Water cut of different flooding patterns

Gas production and composition change

In flue gas assisted steam flooding (Test No.2), some complicated interactions happen between flue gas and oil, such as multiphase flow, gas dissolution and diffusion, gas retention, which has an important influence on EOR. So the gas production law and composition change of produced gas was investigated to analyze the effect and mechanism of gas on EOR.

Fig.9 shows cumulative gas injection volume, cumulative gas production volume and cumulative gas retention volume against injection volume. Cumulative gas retention volume can be defined as the difference between cumulative injection volume and cumulative production volume. As can be seen from the picture, cumulative gas injection volume begins to increase gradually, while cumulative gas production volume has little change. This indicates that injected gas is captured in the model with dissolution and diffusion occurring. As the gas injected volume increases, gas breaks through and gas production rises sharply with quantities of oil carried out in the form of foamy oil. After breakthrough, the injected gas was almost all produced in the steady displacement stage. when the displacement was over, the cumulative gas production volume was less than the cumulative gas injection volume, with about 200mL gas, one-fourth of the cumulative gas injection volume, remaining in the sandpack model or captured in the produced oil in the form of micro-bubble.

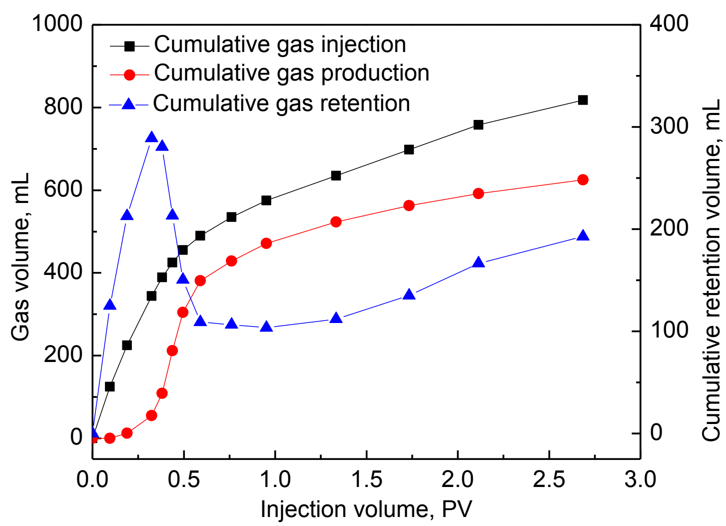


Fig.9 Gas production law in Test No.2

Table 3 and Fig.10 show the composition of produced gas at different displacement stage of Test No.2. We can see that the proportion of flue gas is always less than 1 and decreases with time. This is because some hydrocarbon gas generated at high temperature condition. As the displacement progresses, the proportion of N_2 in the produced gas declines and the proportion of CO_2 increases gradually. Before gas channeling the proportion of N_2 is greater than the injected proportion, while the proportion of CO_2 is less than the injected proportion. It might be because the solubility of CO_2 in heavy oil is greater than N_2, more CO_2 is dissolved into heavy oil. But after gas channeling, the previous dissolved CO_2 releases and is produced, leading to an opposite proportion of N_2 and CO_2 to before gas channeling. The change of the produced gas composition reflects the interactions of dissolution, diffusion and release between flue gas and heavy oil in displacement.

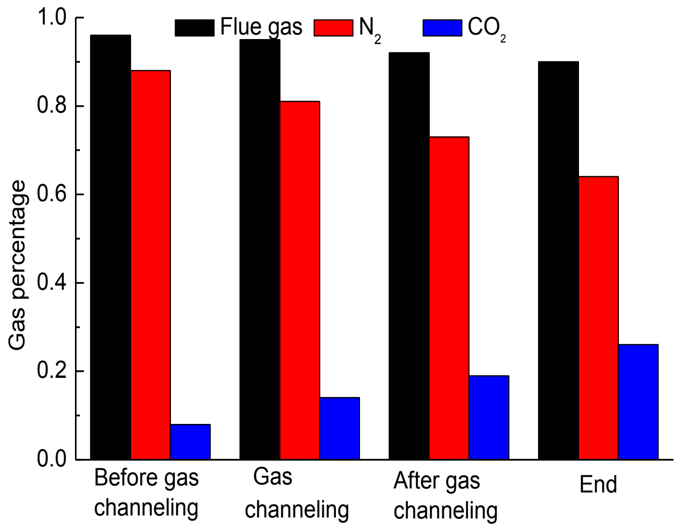


Fig.10 Composition Change of produced gas of Test No.2

Table 3 Proportion of different gas in produced gas at different stages

Stage	Proportion of flue gas	Proportion of N_2	Proportion of CO_2
Before gas channeling	0.96	0.88	0.08
Gas channeling	0.97	0.81	0.16
After gas channeling	0.95	0.75	0.2
End of displacement	0.91	0.64	0.27

Oil recovery of different flooding patterns

Fig.11 shows the change curves of oil recovery with injection volume in different displacement patterns. As can be seen from Fig.11, it can improve oil recovery significantly to inject flue gas both for steam flooding and for water flooding. Especially in the test No.3, the oil recovery rose dramatically when flue gas was injected with steam together, considering the recovery no longer increased clearly when steam injected alone. This fully demonstrates it is effective for EOR to add flue gas in steam flooding.

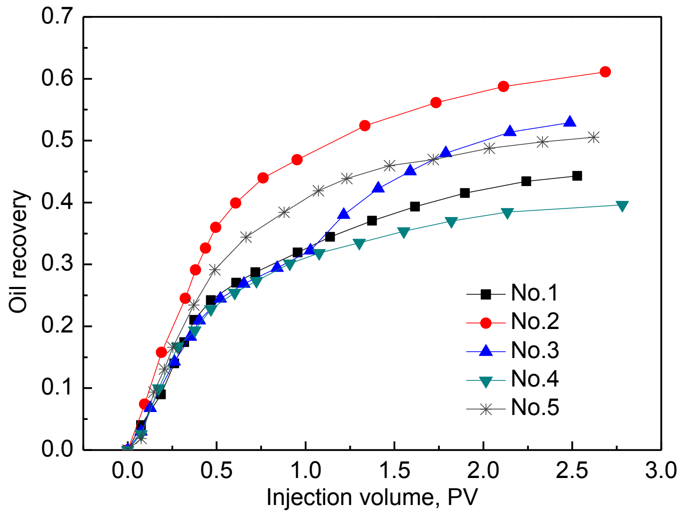


Fig.11 Oil recovery of different flooding patterns

In order to analyze the EOR mechanism of flue gas, the contribution of different factors on oil recovery was compared in Table 4. By comparing the recovery of steam flooding and water flooding, the contribution of heat on recovery without flue gas can be obtained, which is 4.7%. By comparing the recovery of flue gas assisted steam flooding and flue gas assisted water flooding, the contribution of heat with flue gas can be obtained, which is 10.6%. It is obvious that the contribution of heat with flue gas is larger than without flue gas, which indicates heat can play a greater role in displacement in the presence of flue gas. Similarly, the contributions of flue gas with and without heat were obtained by comparison, 16.8% and 10.9% respectively. The difference represents the synergistic effect of flue gas and heat that flue gas can carry steam into deep core, decrease heat loss along the model and expand heat-swept zone, and the heat in turn can facilitate gas drive.

Table 4 Contribution of different factors on recovery

Flooding pattern	Oil recovery /%	Contribution of different factors/%		
		Flue gas	Heat	Synergistic effect
Steam	44.3	16.8	4.7	5.9
Steam+flue gas	61.1		10.6	
Water	39.6	10.9	/	
Water+flue gas	50.5		/	

Conclusion

(1) The solubility of flue gas in heavy oil increases with pressure, and decreases with temperature. With the flue gas dissolved, the viscosity of heavy oil declines and the volume expands, which is a significant EOR mechanism.

(2) When flue gas injected in displacement, the heavy oil was produced in the form of foamy oil. The formation of foamy oil can expand the volume of original heavy oil and reduce its flow resistance, which can greatly promote the production of heavy oil.

(3) The composition of the produced gas changes with time. Before gas channeling, the proportion of CO_2 in the produced gas was less than the injected proportion because of its dissolution. The proportion of CO_2 increased and the proportion of N_2 decreased gradually with time. At last, a quarter of cumulative injected gas was captured in the core approximately.

(4) Oil recovery can be improved significantly in the test of flue gas assisted steam flooding. A synergistic effect of heat and gas is generated when steam and flue gas is injected together.

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