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An Experimental Investigation of Feasibility of Gas Huff and Puff for Recovering Crude Oil with Different Viscosities

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ABSTRACT

Investigating multi cyclic gas (N_2 and CO_2) huff and puff have been conducted by long sandpack simulations with four different crude oils from Jiangsu oilfield. According to the production differential pressure and the production regularity during huff and puff, the production process was divided into three sections; the first one is free gas production section; the second section is low viscous oil production section, and the third one is gas driving exploitation section. According to the results, the production decreases with the increase of cycle times at a certain backpressure, and the effect of multi-cycle huff and puff is improved as the backpressure decreases. In the same cycle, the oil production increases as the backpressure declines. In the first huff and puff cycle, positive synergistic effects are generated while CO_2 and N_2 are being mixed, and there is an optimum ratio between them. The amount of CO_2 in the optimum ratio increases as the backpressure rises. The effect of single gas is better than that of mixed gas in multi-cycle huff and puff, and the effect of CO_2 is better than that of N_2. The effect of huff and puff is not influenced by the injection mode. At a high backpressure, the huff-and-puff effect becomes better as the oil viscosity increases, but at low backpressure, it becomes worse with an increase in oil viscosity. The huff-and-puff effect also gets worse as the temperature rises. The oil recovery degree is improved as the CO_2 injection amount increases, but there is an optimal oil exchange ratio. The depressurization process should be neither too quick nor too slow in the CO_2 huff-and-puff process. The cyclic oil production is improved with the increase of injection rate while the average injection rate is lower than 90 L/min. The equilibrium time of CO_2 is shorter than that of N_2. The economic return of N_2 huff and puff is better than that of CO_2 at high producing pressure drop, and light oil has higher economic returns than heavy oil.

Keywords: Depressurization, Free Gas Production, Huff-and-Puff Effect, Injection Mode, Oil Reservoirs.

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INTRODUCTION

The investigation of CO_2 huff-n-puff applicability to the enhanced recovery of light oil began in 1984. It accounts for nearly 60 percent of EOR production in the United States. Cyclic injection could be the good EOR option for small or discontinuous reservoirs because the single-well process does not demand well-to-well displacement. The application of huff and puff process has been tested as a means of implementing variety of enhanced oil recovery processes such as CO_2 and hydrocarbon solvent injection in conventional oil reservoirs. Huff and puff process improves oil recovery through oil swelling, hydrocarbon extraction, viscosity reduction, and relative permeability effects [1, 2]. Information on the performance of CO_2 huff-n-puff in these conditions is provided in a laboratory core flood study, case histories, field-test evaluations, and a numerical simulation. Tang et al. [3] used gas huff-n-puff in a case study in Sudan, in which they found the production rate could be optimized using a nodal analysis. Rubin [4] simulated non-Darcy flow in stimulated fractured shale reservoirs. Wan et al. [5] first evaluated the huff and puff process in a shale oil reservoir using the Rubin's simulation method to set the fracture in the numerical model. He found out that huff-n-puff could increase shale oil recovery by 29% more than the primary gas flooding method. Sheng and Chen [6] also performed a comparison study to compare huff-n-puff with gas flooding. They found out that lower bottom-hole pressure leads to a relative higher oil recovery. Yu et al. [7, 8] also built a fracture model to simulate CO_2 huff-n-puff in Bakken tight oil reservoirs. They compared the CO_2 flooding in two horizontal wells with CO_2 huff-n-puff in a horizontal well. Then, they analyzed the influences of parameters such as an injection rate, time, the number of cycle, and CO_2 diffusivity on well performance. They claimed that the most important parameter is CO_2 injection rate which is followed by CO_2 injection time, number of cycle, and CO_2 diffusivity. Chen et al. [9] used the compositional models of Bakken formation to simulate CO_2 huff and puff which was stimulated in both homogenous and heterogeneous reservoirs. In their model, the huff-and-puff process is from 300 to 1000 days, which might be too long for industrial production. Vinassa et al. [10] applied CO_2 huff-n-puff injection in Chattanooga shale formation. They found out that the injection rate and injection time have the largest impact on incremental oil recovery. They thought that the injection time is directly related to the injected CO_2 volume and the changes in reservoir pressure and fluid properties during huff-n-puff. However, in the industrial production, the well is constraint to not only the injection rate and injection time, but also the maximum injection pressure. The performance of gas huff-n-puff will be influenced by many operation parameters such as the injection time and rate, production time and rate, soaking time, and so on.

During this low oil price period, researchers have gradually applied cyclic gas injection recovery to unconventional resources in recent years. Now, it is a big issue to enhance the oil recovery using a more efficient approach in a low permeability reservoir especially the unconventional oil reservoirs, and it has been proven to be an effective recovery method to enhance oil recovery in laboratory experiments for shale oil production [11,12,13]. Meng et al.

[14] conducted an experimental study about the effect of huff-n-puff gas injection on enhancing condensate recovery in shale gas reservoirs. They analyzed the parameters such as huff-n-puff cycles and soaking time and found out that soaking time slightly affects condensate recovery. Yu and Sheng [15] analyzed the effect of pressure depletion time on shale oil recovery and found out that the oil recovery increased as the pressure depletion rate rose. Gamadi et al. [16, 17] compared N_2 with CO_2 huff–n-puff performances on shale core plugs in different regions such as Barnett, Marcos, and Eagle Ford. He claimed that the huff-n-puff method could enhance oil recovery by 10 to 50% in a laboratory study. They also tested the influence of soaking period on ultimate recovery factor and found out that the longer the shut-in-period was, the more the ultimate recovery became.

While the sequential steam huff-and-puff technique can significantly increase the oil recovery from heavy oil reservoirs, cyclic CO_2 injection has also been proposed as an alternative to cyclic steam stimulation for the heavy oil reservoir. Moreover, in China, gas huff-n-puff was widely used in heavy oil reservoirs such as in Liaohe and Henan oilfield with oil viscosity higher than 10000 mPa.s in reservoir conditions. Recently, petroleum operators have shown increasingly an interest in taking CO_2 huff-n-puff process as a preferred option to extract light oil in low-pressure and low-permeability reservoirs [18]. The problem of CO_2 huff-and-puff technique application was lack of CO_2 source in China. In addition, the precipitation of scale during immiscible CO_2 injection is another challenge encountered during CO_2 huff-n-puff process. Evidence of such a problem was seen in Crooks Gap field, Wyoming, during immiscible CO_2 injection [19]. Dissolution of CO_2 in the formation water results in the formation of carbonic acid, which in turn can dissolve formation minerals during injection and soak period; also, this process improves formation permeability [20]. However, if calcium carbonate precipitates near the wellbore, this will lead to reduced productivity.

N_2 has been successfully used as the injection fluid for the recovery of crude oil, with the advantages of being more cost-effective than CO_2 or hydrocarbon-gas and being non-corrosive; in addition, N_2 becomes an economical alternative for oil recovery using a gas miscible displacement (Hudgins et al., 1990). Lots of literature discussed the recovery of crude oil by N_2 injection into fractured reservoirs based on the findings from the experimental and simulation studies [21-23]. The very good agreement between experimental and numerical simulation results showed that N_2 was a feasible injection gas for recovering crude oil by gravity floods. Also, the performance of N_2 and enriched N_2 injections, which were applied as the secondary and tertiary oil recovery processes, was tested and analyzed.

The objective of this study is to investigate the influence of multi cyclic gas (N_2 and CO_2) huff and puff on enhancing oil recovery. First, oils with different viscosities (from light oil to heavy oil) were utilized. Second, the same oil was used to study the effect of mixing N_2 with CO_2 at different ratios. Third, long sandpacks were used instead of short cores so as to truly reflect the influence of gas diffusion and oil saturation on huff and puff. We hope that this work may expand the application of gas huff and puff.

EXPERIMENTAL PROCEDURES

Materials

The properties of crude oils and formation waters from Jiangsu oilfield are shown in Table 1.

The viscosity-temperature curves of the oils are shown in Figure 1. The mainly used gases in this paper are CO_2 (purity of 98.1%) and N_2 (purity of 99.9%). CO_2 is the greenhouse gas which comes from the power plants near the reservoir, and N_2 is a commercial product from gas producers.

they were filled in the sandpack. The permeability of the sandpack ranges from 90 to 200 mD.

Table 1: Oil and water properties of the tested oilfield

Crude oil	Density (formation condition), g/cm³	Viscosity (50℃), mPa·s	Viscosity (formation condition), mPa·s	Formation temperature, ℃	Average permeability, $\times10^{-3}\mu m^2$	Chloride content, mg/L	Salinity, mg/L	Water type
Tai5	0.8167	46.0	4.89	100	75.4	23487	50245	Na_2SO_4
Zhen177	0.6850	14.8	1.60	93	77.4	4017	8631	$NaHCO_3$
Xu27	0.8559	192.0	10.0	87	11.1	3752	11027	$NaHCO_3$
Wei5	0.9019 -0.9062	562.0	218.9 -292.3	60-70	192.3	8693	16264	$NaHCO_3$

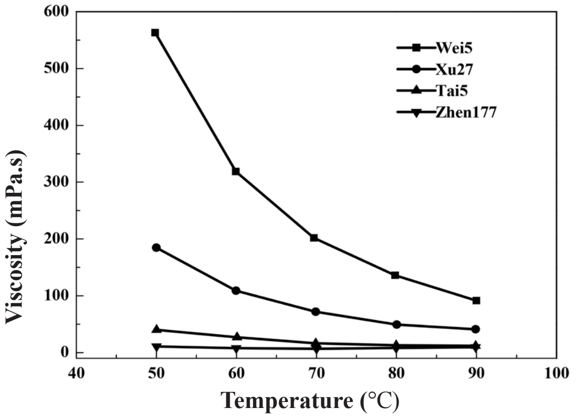

Figure 1: Viscosity-temperature relationship of the crude oils from Jiangsu Oilfield.

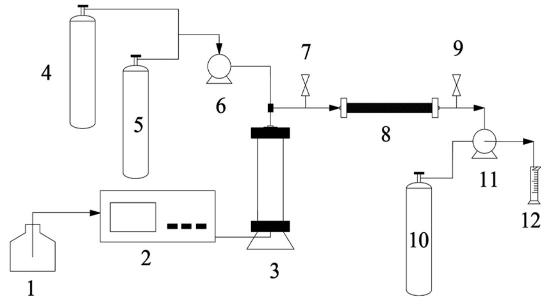

Figure 2: A schematic of the experimental setup; 1) Water source; 2) Pump; 3) Intermediate container; 4) CO_2 cylinder; 5) N_2 cylinder; 6) Backpressure valve; 7) Valve; 8) Sandpack; 9) Valve; 10) N_2 cylinder; 11) Backpressure valve; 12) Cylinder.

Apparatus

The schematic of an experimental set-up is shown in Figure 2. The sandpacks used in the experiment were 1500 mm in length and 45 mm in inner diameter. Quartz sands with a mesh of 20 to 70 were dried after they had been cleaned with distilled water, and then

Water/Oil Saturation

Firstly, the sandpack was saturated with simulated formation water which has the same salinity with the formation water, and the pore volume was calculated. Then, it was put in the thermostatic water bath, and the permeability was measured at a flow rate of 1.0 mL/min.

After the water saturation, the sandpack was saturated with crude oil at a flow rate of 1.0 mL/min at the formation temperature. The process was stopped until there was no water production at the outlet end, and then the oil saturation as well as the irreducible water saturation was calculated.

The Depressurization Process

The outlet valve of the sandpack was closed when the oil saturation was finished, and the inlet was closed when the pressure reached 20 MPa after the oil saturation. The pressure of the back-pressure valve at the outlet was increased to 20 MPa with gas right before the outlet valve was opened, and it was then reduced gradually to atmospheric pressure (in each step, the pressure was reduced by 2 MPa until there was no production). The liquid production, the water production, and the oil production were recorded.

The Gas Huff-and-Puff process

Gas Injection

The gas was injected into the intermediate container (at 60 °C) with a piston by a gas booster pump until the pressure reached 20 MPa. The valve of the intermediate container was opened, and the gas flowed into the sandpack that had been depressurized. The piston was displaced by water with a high pressure piston pump in order to keep the gas pressure at 20 MPa, and this equilibrium state was maintained for 6 hours (the pressure was increased repeatedly during this process). The injected gas volume was calculated through measuring the volume of the water that had been injected into the intermediate container.

Huff and Puff

The depressurization development was carried out as noted below.

Multi-cycle Huff and Puff

Step (1) and step (2) were repeated to conduct the multi-cycle huff and puff.

RESULTS AND DISCUSSIONS

The Production History Curve of Depressurization Development

The production history curve of the gas huff and puff depressurization production was studied with Zhen177 crude oil at 93 °C as shown in Figure 3. It shows that the curve can be divided into three sections as follows:

Section 1 (Pressure Reduces from 20 to 14 MPa): Free Gas Production Section

In this section, the main production is free gas, with little oil. It is because the flow channel for crude oil is occupied by the early gas production, and thus the flow of crude oil is hindered. The viscosity of free gas is much lower than that of crude oil, and gas has higher saturation and relative permeability near the outlet of the core, making the flow resistance of the gas lower than that of the oil; this leads to the priority production of gas.

By comparing the mixed gas of N_2-CO_2 with a different composition, it shows that the free gas production stage is extended with the increase of N_2 content. This is because N_2 has a lower solubility in crude oil as well as a smaller molecular weight compared to CO_2, and thus the free gas has a larger volume at the same pressure.

Section 2 (Pressure Drops from 14 to 5.0 MPa): Low-viscosity Crude Oil Production Section

The main production in this section is crude oil, accompanied with the discontinuous production of free gas. The oil production in this section accounts for 35-50% of the total oil production. The viscosity and the flow resistance of crude oil are reduced because of the dissolution of gas. Meanwhile, the volume expansion and the increase of driving energy change the immobile oil into movable oil.

The oil production in this section rises with higher CO_2 proportion of the mixed gas since CO_2 has a stronger ability to reduce the oil viscosity compared to N_2.

Section 3 (Pressure Drops from 5.0 to 0.1 MPa): Gas Driving Exploitation Section

In this section, the oil production accounts for 50-65% of the total amount. Gases are produced mainly in the form of bubbles or slugs and have two effects on displacing the oil. The first type is free gas driving. When the outlet pressure drops below 5 MPa, the free gas is segmented into clusters by crude oil. Furthermore, the gas expands with a decrease in pressure, resulting in the slug-type flow of oil and gas, which drives the oil to the outlet constantly. Since the volume factor and compressibility of N_2 is higher than that of CO_2, the driving effect of N_2 as free gas is better. Another type is dissolved gas driving. The dissolved gas spills over and then forms bubbles inside the oil at a low pressure. Therefore, the bubbles expand as the pressure decreases, and the crude oil, as well as gas, is produced in the form of foam. CO_2 is more able in dissolved gas driving than N_2 due to its higher solubility.

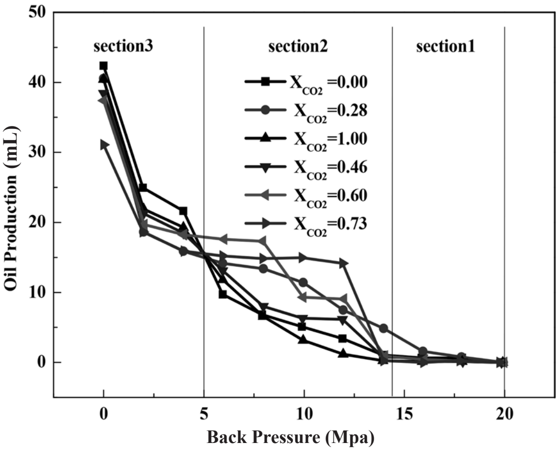

Figure 3: Recovery curve of depressurizing production of gas huff and puff.

The Effect of Multi-cycle Gas Huff and Puff at Different Backpressure

The effect of multi-cycle gas huff and puff at different back pressures was studied with Zhen177 crude oil at 93 °C. The results are shown in Figures 4-7.

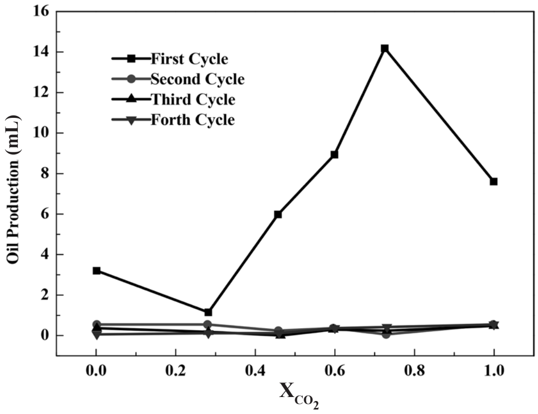

Figure 4: The effect of multi-cycle gas huff and puff at the backpressure of 12 MPa.

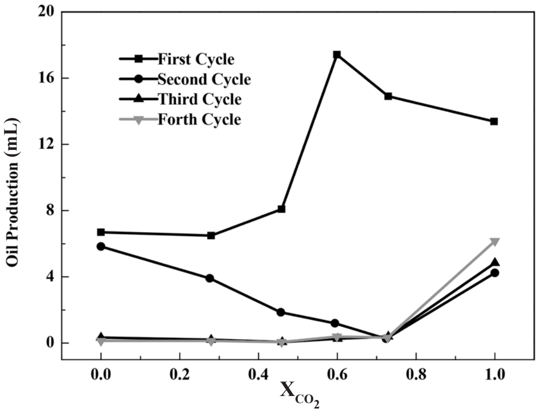

Figure 5: The effect of multi-cycle gas huff and puff at the backpressure of 8 MPa.

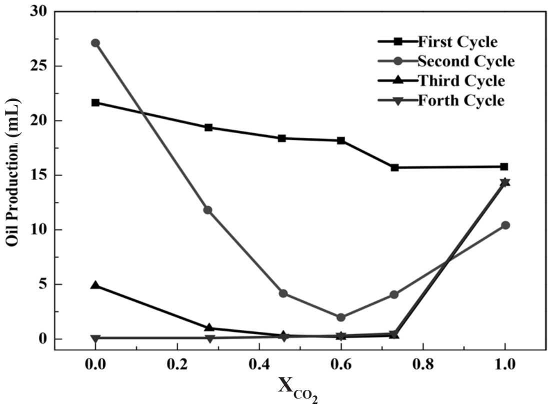

Figure 6: The effect of multi-cycle gas huff and puff at the backpressure of 4 MPa.

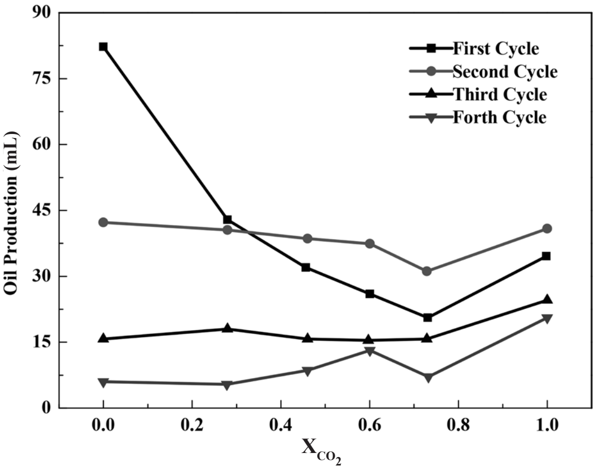

Figure 7: The effect of multi-cycle gas huff and puff at the backpressure of 0.1 MPa.

The figures show that the production decreases with an increase in cycle times at a certain backpressure. This is because the oil saturation decreases with an increase in cycle times. Meanwhile, gas channels are formed in the core when oil saturation is reduced to a certain degree, so the displacement effect of free gas is significantly weakened.

Moreover, the effect of multi-cycle is improved with a decrease in backpressure. It shows that little oil is produced during the 2-4 cycle; furthermore, the backpressure is higher than 12 MPa, which illustrates that the oil production displaced by the free gas mainly depends on the oil saturation near wellbore area. However, when the backpressure is lower than 8 MPa, the oil production obviously corresponds to a decrease in backpressure due to the effect of the dissolved gas driving and viscosity reduction mechanism. Additionally, in the first huff and puff cycle, positive synergistic effects are generated with the mixture of CO_2 and N_2, and there exists an optimum ratio between these two gases. The amount of CO_2 at this optimum ratio increases with a decrease in backpressure. This is because CO_2 has a higher solubility in crude oil than N_2, making the oil viscosity lower, which is beneficial to increasing the production in the second section (Low-viscosity crude oil production section). N_2 has higher compression ratio and volume expansion ability during the pressure drop process, which contributes to an increase in the production in the third section (gas driving exploitation section). It is the main reason that the oil production of the single N_2 huff and puff is higher than that of the single CO_2 or CO_2-N_2 mixture at low backpressure in the first and second cycles. Also, the effect of single gas is better than that of mixed gas in multi-cycle huff and puff, and the effect of CO_2 is better than that of N_2. Since the oil saturation near wellbore is reduced during the multi-cycle huff and puff, the effect of the first two sections becomes less, and the increment of oil production mainly relies on the gas driving period. However, free gas exists continuously in the porous medium during the depressurizing process due to the oil saturation reduction, making the gas clusters dispersed in crude oil become less, and the effect of oil displacement by gas expansion is weakened. Therefore, the main mechanism of increasing oil production is dissolved gas driving.

The Influence of Injection Mode

The influence of injection mode on huff-and-puff effect was studied with Tai5 crude oil and formation water at 95 °C. In this experiment, the molar ratio of CO_2 and N_2 was 1:1. The shut in time was 6 hrs and the equilibrium pressure of mixed gas was 20 MPa. Five kinds of injection modes were studied:

Pattern a: N_2 was injected first, followed by CO_2.

Pattern b: Half of CO_2 was injected first, followed by half of N_2; then, the other half of CO_2 was injected, followed by the other half of N_2.

Pattern c: Half of N_2 was injected first, followed by half of CO_2; then, the other half of N_2 was injected, followed by the other half of CO_2.

Pattern d: Half of N_2 was injected first, followed by CO_2; then, the other half of N_2 was injected.

Pattern e: Half of CO_2 was injected first, followed by N_2; then, the other half of CO_2 was added.

The results are listed in Table 2. It shows that oil recovery was not influenced by the injection mode. This is because the gas-gas as well as the gas-liquid has achieved an equilibrium state within the shut-in time. When composition, temperature, and pressure are at certain values, the distribution of the gas in gas phase and liquid phase is constant regardless of the injection mode.

Table 2: Influence of injection mode on oil recovery

Injection Mode	a	b	c	d	e
Pore Volume (mL)	576	591	587	563	584
Porosity (%)	32.4	31.8	32.6	33.4	31.9
Permeability ($10^{-3}\mu m^2$)	159.4	173.6	118.6	133.7	164.2
Saturated Oil (mL)	406	411	404	396	417
Oil Saturation (%)	70.5	69.5	68.8	70.3	71.4
Oil Production in Elastic Exploitation Process (mL)	23.7	22.3	21.8	23.4	22.9
Oil Recovery in Elastic Exploitation Process (%)	5.84	5.43	5.40	5.91	5.49
Oil Production in Gas Huff and Puff (mL)	47.3	46.9	44.2	46.5	47.1
Oil Recovery in Gas Huff and Puff (%)	11.65	11.41	10.94	11.74	11.29

The Influence of Oil Viscosity

The influence of oil viscosity was studied at 93 °C. The results are shown in Table 3 and Figure 8.

Table 3: Influence of oil viscosity on huff and puff effect

Crude oil	Oil viscosity (mPa·s)	Oil production at the backpressure of 0.1 MPa (mL)		Oil production at the backpressure of 10 MPa (mL)	
		CO_2	N_2	CO_2	N_2
Zhen 177	5.51	58.55	65.65	9.75	0.25
Tai5	9.61	54.45	61.05	9.07	0.23
Xu27	32.8	48.90	49.00	11.50	2.45
Wei5	81.8	40.50	42.25	14.50	5.15

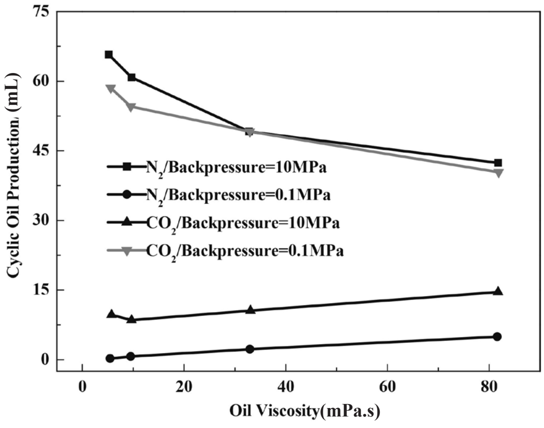

Figure 8: The influence of oil viscosity on cyclic oil production.

At a high backpressure, the oil recovery increases with an increase in oil viscosity, and the effect of CO_2 is superior to that of N_2. However, at a low backpressure, the huff and puff effect becomes worse as the oil viscosity increases, and the effect of CO_2 is about the same as that of N_2. This is because viscosity reduction is the main mechanism of gas huff and puff to improve oil recovery at a high backpressure, and the viscosity reduction efficiency is improved when the oil viscosity increases. Nevertheless, at a low backpressure, gas driving is the main mechanism to improve oil recovery; furthermore, the gas driving efficiency is improved when the oil viscosity decreases, and thus the huff-and-puff effect becomes better.

The Influence of Temperature

The simulated oil was prepared with Xu27 crude oil and diesel oil to study the influence of temperature on the huff-and-puff effect. The component of the simulated oil is shown in Figure 9.

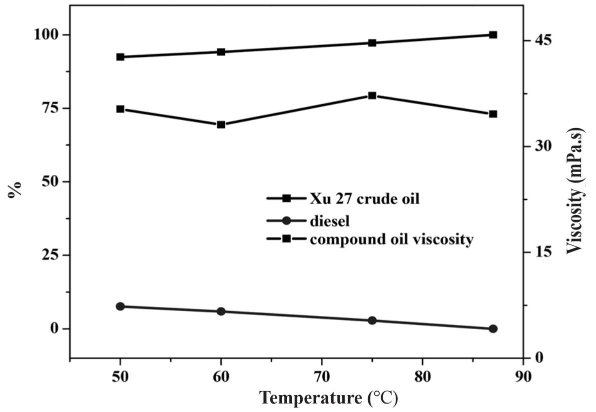

Figure 9: Simulated crude oil viscosity.

The viscosity of the used oil was maintained between 33.1 and 37.2 mPa.s, and the influence of temperature on CO_2 huff-and-puff effect was studied (see Figure 10).

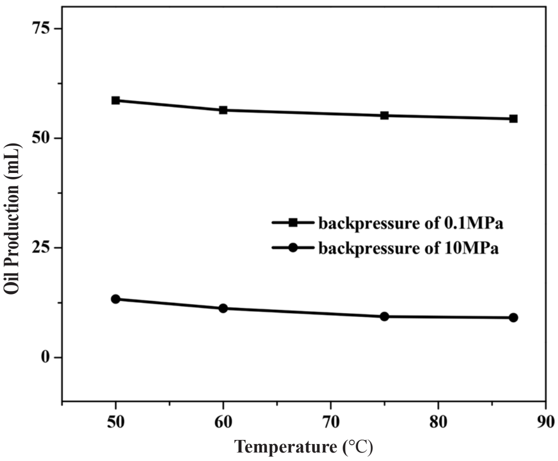

Figure 10: The influence of temperature on oil production.

The cycle production of CO_2 huff and puff decreases as the temperature rises. This is because the solubility of CO_2 in crude oil declines when temperature increases, and thus the viscosity reduction effect and dissolved gas driving effect are weakened, leading to a decline in oil production.

The Influence of Injection Pressure/ Injection Volume

The influence of CO_2 injection volume was studied with Tai5 crude oil at the backpressure of 0.1 MPa at 95 °C. The results are listed in Table 4 and Figure 11.

Table 4: Influence of CO_2 injection amount on huff and puff effect

CO_2 injection pressure (MPa)	20	15	10	5	3
Injection amount (mol)	0.5837	0.3336	0.2247	0.1668	0.1126
Oil production at the backpressure of 0.1MPa (mL)	57.3	49.1	47.5	37.55	21.34

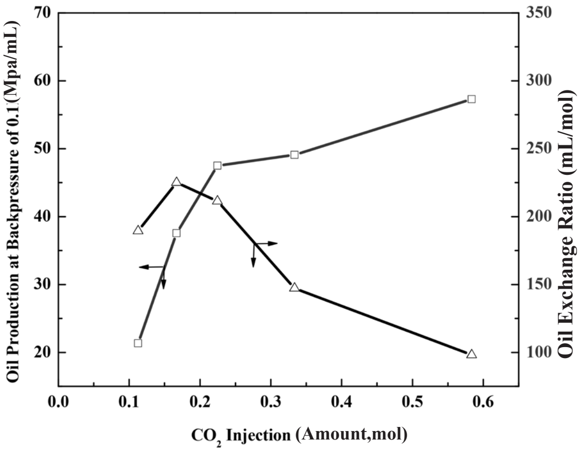

Figure 11: The influence of CO_2 injection amount on huff-and puff-effect.

It shows that the oil recovery is improved as the amount of injected CO_2 increases, while there is an optimal value of the oil exchange ratio. With an increase in the amount of CO_2 injection, the partial pressure of CO_2 in the core rises, leading to an increase in solubility in oil and a reduction in oil viscosity, which enhances the oil production. The incremental oil production of gas huff and puff mainly lies in the gas driving section (the third section), and thus the oil exchange ratio may reach the highest value as long as the conditions of the third section are obtained. In Figure 11, the oil exchange ratio is the highest when CO_2 injection pressure is 5 MPa, and this is corresponding to the result displayed in Figure 3.

The Influence of Depressurization Mode

The influence of depressurization mode was studied with Xu27 crude oil at 87 °C as shown in Table 5. The four kinds of modes are studied as follows:

A: depressurization step: 20-18-16-14-12-10-8-6-4-2-0.1;

B: depressurization step: 20-16-12-8-4-0.1;

C: depressurization step: 20-10-0.1;

D: onetime depressurization: 20-0.1.

Table 5: Influence of depressurization mode

Depressurization method	A	B	C	D
Oil production (mL)	54.45	63.42	56.38	49.22
Recovery (%)	11.71	13.32	11.87	10.61

It shows that the depressurization should be neither too fast nor too slow in the CO_2 huff-and-puff process, with the existence of a reasonable value. If the production pressure drop is too large, CO_2 will have a high fingering speed and make a breakthrough easily, which diminish the driving effect of free gas. If the production pressure drop is too small, gas-liquid stratified flow will occur under the action of gravity, which can also diminish the driving effect of free gas. Therefore, a reasonable production pressure is to ensure that the gas-liquid is produced in the form of slug flow.

The Influence of CO_2 Injection Rate

The influence of CO_2 injection rate was analyzed with the result of the first gas huff and puff applied to Xu27 crude oil at the backpressure of 0.1 MPa and at a temperature of 87 °C. The average injection rate is defined as the time spends for the pressure to reach 20 MPa by injecting CO_2. The results are shown in Tables 6 and 12.

Table 6: Influence of CO_2 injection rate

Injection time (min)	45	90	120	150	200
Average injection rate (L/min)	184	93.6	70.3	55.3	41.5
Oil production (mL)	59.33	54.45	48.27	46.16	45.17
Recovery degree (%)	12.76	11.71	10.60	9.88	9.93

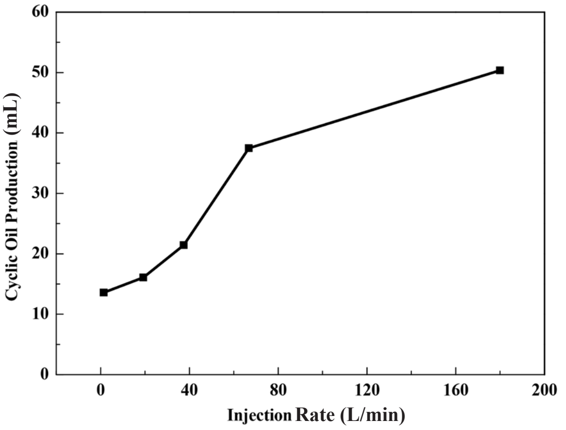

Figure 12: The influence of CO_2 injection rate on huff-and-puff effect.

The cyclic oil production is improved with an increase in the average injection rate. However, once the average injection rate is larger than 90 L/min, the cyclic oil production increases slowly as the injection rate rises. This is because the gas is easier to finger into the deep reservoir along the high permeability layers when the injection rate is larger. On the one hand, the viscosity reduction mechanism as well as the gas driving mechanism will have a larger action radius while more oil is in touch with the gas, resulting in a better huff-and-puff effect. On the other hand, the partial pressure of the gas will decline while the injection amount is certain and the action radius becomes larger, which can weaken the effect of viscosity reduction and gas driving.

The Influence of Shut-in Time

The influence of shut-in time was described with the result of the first gas huff and puff applied to Xu27 crude oil at the backpressure of 0.1 MPa and at a temperature of 87 °C. The results are shown in Table 7 and Figure 13.

Table 7: Influence of shut in time on huff and puff effect

Shut in time (hr.)	0	2	4	6	8	10
Recovery of first CO_2 huff and puff cycle (%)	3.10	4.32	9.01	10.76	10.58	10.69
Recovery of first N_2 huff and puff cycle (%)	1.31	2.16	7.43	11.84	11.99	11.73

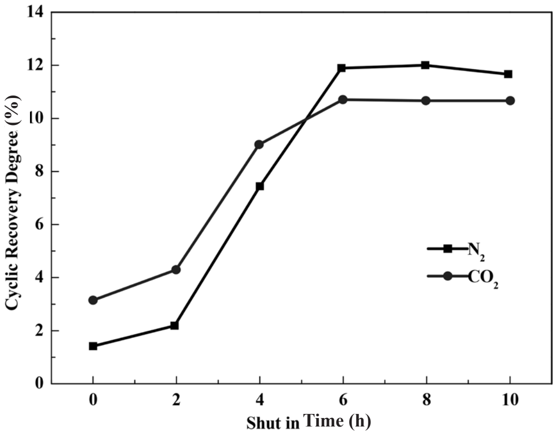

Figure 13: The influence of shut in time on huff-and-puff effect.

During the shut-in time, the gas diffuses into the deep reservoir and reduces the viscosity of the oil. The oil recovery is constant while the dissolution and diffusion processes are researching equalization. It shows that the gas-liquid equilibrium time of CO_2 is shorter than that of N_2.

The Huff-and-puff Results of Different Oils

For different kinds of oils, the relationship between the cost per ton oil and backpressure during the first huff-and-puff cycle is shown in Figure 14 (CO_2 huff and puff) and Figure 15 (N_2 huff and puff).

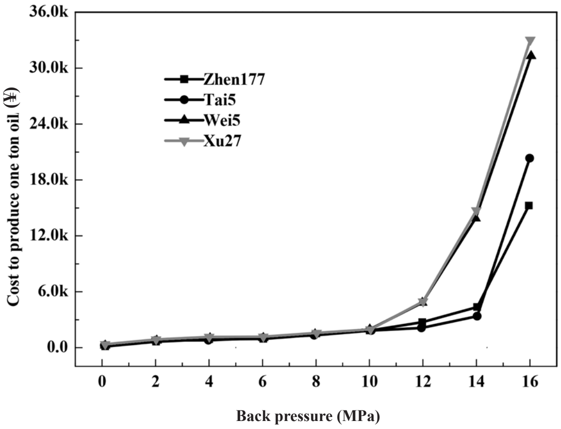

Figure 14: A relationship between the cost per ton oil and backpressure in CO_2 huff and puff.

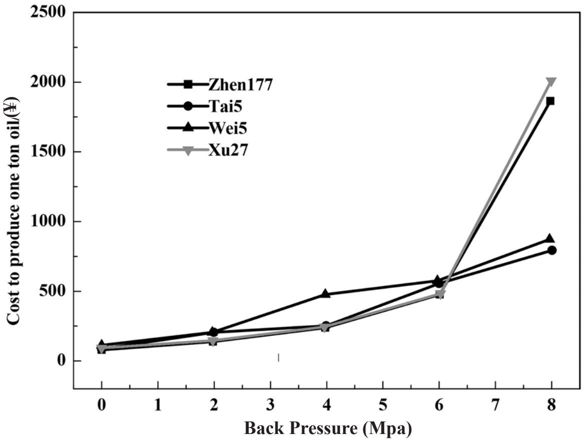

Figure 15: A relationship between the cost per ton oil and backpressure in N_2 huff and puff.

The calculation was conducted by consulting that the price of CO_2 and N_2 are respectively 1000¥ per ton and 2¥ per cubic meter in a standard condition. It can be seen that there is a turning point in the cost-backpressure curve. The turning point is corresponding to the starting point of the second section (as shown in Figure 3), which is the end point of the free gas production section.

The turning point backpressure of the heavy oils (Xu27 and Wei5) is lower than that of the light oils (Zhen177 and Tai5). This is because the mobility ratio between gas and oil rises with an increase in the oil viscosity, leading to the lag of oil production. Meanwhile, the oil with low viscosity is easily displaced by gas at high backpressure.

The turning point backpressure of CO_2 is larger than that of N_2 because CO_2 has the better viscosity reduction ability and enhance the recovery at higher backpressures.

CONCLUSIONS

The recovery curve of the gas huff-and-puff depressurization production can be divided into three sections; Section 1 free gas production (pressure reduces from 20 to 14 MPa), in which the main production is free gas, with little oil; Section 2 low-viscosity crude oil production (pressure drops from 14 to 5.0 MPa), in which the main production is crude oil, accompanied with the discontinuous production of free gas. The oil production in this section accounts for 35-50% of the total amount. Section 3 gas driving exploitation section (pressure drops from 5.0 to 0.1 MPa), in which the oil production accounts for 50-65% of the total amount. Gases are produced mainly in the form of bubbles or slugs. Moreover, the production decreases with an increase in cycle times at a certain backpressure, and the effect of multi-cycle huff and puff is improved with a decrease in backpressure. In the same cycle, the oil production increases as the backpressure declines. In the first huff-and-puff cycle, positive synergistic effects are generated after CO_2 and N_2 are mixed together, and there is an optimum ratio between these two gases. The amount of CO_2 in this optimum ratio increases as the backpressure rises. The effect of single gas is better than that of mixed gas in multi-cycle huff and puff, and the effect of CO_2 is better than that of N_2. Furthermore, the effect of gas huff and puff is not influenced by the injection mode. At high backpressures, the huff and puff effect becomes better as the oil viscosity increases, but at low backpressures, the huff and puff effect becomes worse with an increase in oil viscosity. The effect of gas huff and puff worsens with an increase in the temperature. The oil recovery degree is improved as the CO_2 injection amount increases, but there is an optimal value of the oil exchange ratio. The depressurization development should be neither too quick nor too slow in the CO_2 huff and puff process. The cyclic oil production is improved with an increase in injection rate, while the average injection rate is lower than 90 L/min. The equilibrium time of CO_2 is shorter than that of N_2. Finally, the economic return of N_2 huff and puff is better than that of CO_2 at a high producing pressure drop. Moreover, the light oil has a larger economic return compared to heavy oil which needs a high producing pressure drop.

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