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Heated Area and Well Performance Analysis of Injection N_2 and CO_2 in Cycle Steam Stimulation Process

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Abstract

Application of steam injection technology to heavy oil reservoirs is the most commercially successful EOR method. Cycle steam stimulation (CSS) is known as the most widely used and mature technology compared with various thermal methods. Because of various reasons, such as too high initial oil viscosity, excessive overburden heat loss and so on, in CSS, the radius of heated zone is small and the viscosity of heavy oil still cannot be lowered effectively, which leads to the low oil productivity and poor oil well performance. A variation on CSS process is to add N_2 and CO_2 in steam injection. Because of the influence of the N_2 and CO_2, the heated area and well performance of N_2 and CO_2 assisted CSS are different from that of steam stimulation. Therefore, this paper describes a detailed study of N_2 and CO_2 influence to cycle steam stimulation. In this paper, the physical simulation experiments of N_2 and CO_2 influence to the mixture of heavy oil are carried out at first. Through physical experiments, the enhancing oil mechanisms of N_2 and CO_2, the recovery mechanism of reducing oil viscosity by CO_2 dissolving, reducing interfacial tension between gas and heavy oil, which are different from the steam, are described respectively. Based on this, a numerical simulation model with a single horizontal well is built to carry out the quantitative and comparative study of heated area of formation. Results show that the development effect of N_2 and CO_2 assisted CSS is better than that of conventional steam stimulation in porous media. Next, the different well performance of the N_2 and CO_2 assisted CSS and conventional CSS are compared by numerical results. Finally, on the basis of the field data of two different heavy oil field, two typical wells of CSS and N_2 and CO_2 assisted CSS are analyzed in detail. Consequently, the N_2 and CO_2 injection together with steam is helpful to improve development effect in CSS process.

Key words: Heavy oil; Cycle steam stimulation; Heating mechanism; Enhancing oil mechanisms; Well performance

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INTRODUCTION

Because of the high viscosity of the heavy oil, the natural flow of heavy or viscous oils does not easily occur in the reservoir[1-2]. Application of steam injection technology to heavy oil reservoirs is the most commercially successful EOR method[3-6]. Nowadays, cycle steam stimulation, is known as the most widely used and mature technology[7]. In CSS, one of the most important goals is to lower the viscosity of heavy oil by raising formation temperature. Because of various reasons, such as excessive overburden heat loss[8], the radius of heated zone is small and the viscosity of heavy oil still cannot be lowered effectively, which leads to the low oil productivity, poor well performance and low oil recovery[9-10]. One improvement work of cyclic steam stimulation is to enlarge the heated radius by injection N_2 and CO_2 together with steam[11-12]. The greater the heating radius, the better development effect of CSS is.

Because of carrying higher heat, steam is the ideal and conventional heat medium for thermal recovery. The main mechanism of injection steam is to reduce oil viscosity, to eliminate the plugging, to reduce the interfacial tension. As for some deep buried reservoir, due to the relative high heat loss along the way, high formation pressure, the injection pressure in bottom hole is close to or above the critical pressure during steam injection process, so the steam quality in bottom hole is very low. Although the use of a high efficient heat insulation tube can reduce heat loss and improve the steam quality, it can increase the cost of the steam injection. In addition, during the steam injection process, sweep efficiency is reduced by steam overlap and steam channeling[13]. Moreover, to improve development effect by simply increasing the volume of cyclic steam injection is limited by the economical oil-gas ratio. So currently, the more feasible approach is that with same amount of steam injection, to inject non-condensate gas such as N_2 and CO_2 to change the distribution of formation fluid to improve the heating area and development efficiency[14].

1. EXPERIMENTAL RESEARCHES OF EOR MECHANISMS BY INJECTION N_2 AND CO_2

N_2 has weak solubility in both fresh and salt water. CO_2 can dissolve much more easily in water than N_2. This characteristic is very useful for keeping reservoir pressure by injecting N_2 into the reservoir. As can be seen in Figure 1, temperature has influence on solubility at a certain extent, but less affection when it becomes stable. Pressure and salinity are the main influence factors on solubility of N_2 in water. Solubility decreases with salinity and increases with pressure.

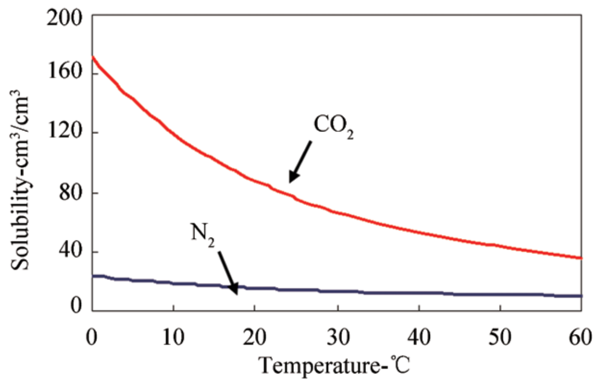


Figure 1
Solubility of N_2 and CO_2 in Water Under Standard State

Table 1
Influence of PVT Properties of Heavy Oil in NY with N_2

Temperature/℃	Dissolved gas/oil volume ratio	Saturation pressure / MPa	Formation oil gravity	Viscosity/ mPa·s	Volumetric factor
56	0	6.32	0.94	494.8	1.00
	5	9.33	0.91	490.6	1.01
	10	10.93	0.88	484.6	1.04
	20	11.8	0.85	435.0	1.08
	30	12.14	0.83	646.8	1.15
180	0	7.93	0.91	11.4	1.04
	3	9.84	0.91	10.9	1.04
	6	11.7	0.86	10.8	1.09
	9	12.58	0.81	10.7	1.17

1.1 Reducing Oil Viscosity by Dissolving

According to the laboratory experiment of oil sample in NY oil field, at original reservoir temperature of 56 ℃, when dissolved gas oil ratio is 0, the saturated pressure is 6.32 MPa. The more gas dissolved in the heavy oil, the higher saturation pressure is. When dissolved gas oil ratio is 20, N_2 can make the viscosity of heavy oil reduced from 494.8 mPa·s to 435 mPa·s with dropping about 10%, which is shown in Table 1. In the same temperature, CO_2 can make the viscosity of heavy oil from 460 mPa·s to 80 mPa·s, reducing nearly 80%, which is shown in Table 2.

Table 2
Influence of PVT Properties of Heavy Oil in NY With CO_2

Temperature/℃	Dissolved gas/oil volume ratio	Saturation pressure / MPa	Formation oil gravity	Viscosity / mPa·s	Volumetric factor
56	0.0	8.08	1.01	463.87	1.00
	12.7	8.32	0.97	325.6	1.01
	25.5	9.15	0.93	240.19	1.04
	43.3	10.2	0.91	78.88	1.06
180	0.0	8.6	0.92	14.09	1.05
	12.7	12.41	0.85	11.3	1.13
	20.4	14.25	0.84	10.15	1.14
	28.0	15.65	0.82	8.48	1.17
	40.7	18.17	0.80	7.32	1.20

1.2 Reduce Interfacial Tension

The interfacial tension between the fluids or fluids and rock in reservoir directly affects the fluids distribution in the rock, capillary force and fluid flow. Laboratory study showed that the interfacial tension between oil and gas is nearly 30% of the interfacial tension between oil and water (Figure 2), which thereby improves the displacement efficiency.

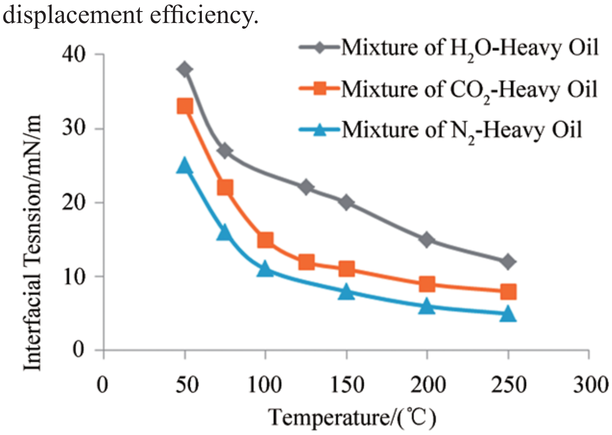


Figure 2
Interfacial Tension of Different Temperature

2. QUANTITATIVE RESEARCHES OF N_2 AND CO_2 BY NUMERICAL MODEL

2.1 Establishment of Single Well Model

Here, the commercially available thermal reservoir simulator, STARS, developed by Computer Modeling Group (CMG), is adopted. The basic reservoir and fluids properties, including simulation input parameters, can be obtained from Bohai heavy oil field, as listed in Table 3. In addition, the grid size is 41 × 41 × 11 and the corresponding block dimensions in *I*, *J* and *K* directions are 5.0 m, 5.0 m and 1.0 m, respectively. And the border is a closed border. The reservoir thickness is 11 m in the model, and the horizontal well located in the center of reservoir with horizontal section length of 200 m.

The other basic parameters of the reservoir model are as follows: The initial formation oil viscosity is 500 mPa·s, the horizontal permeability is 5,000×10^{-3} μm^2 and the vertical to horizontal permeability is 500×10^{-3} μm^2, the original oil saturation is 0.728, the porosity is 35%, the reservoir depth is 1,000 m, the initial formation pressure is 10.0 MPa, the reservoir oil density is 0.96 g/cm^3.

Table 3
Rock and Fluid Thermal Parameters in Numerical Model

Parameter name	Value	Parameter name	Value
Rock compressibility/kPa^{-1}	15×10^{-6}	Specific heat for oil/（kJ·kg^{-1}·$℃^{-1}$）	2.12
Rock volume heat capacity/（kJ·m^{-3}·C^{-1}）	2,575	Relative density of crude oil	0.956
Upper and lower rock thermal conductivity /（kJ·m^{-1}·d^{-1}·C^{-1}）	105	Upper and lower rock volume heat capacity/（kJ·m^{-3}·C^{-1}）	2,200
Initial reservoir temperature/℃	56	Oil compressibility/MPa^{-1}	5.3×10^{-4}
Oil thermal expansion coefficient/$℃^{-1}$	1.0×10^{-6}	Rock thermal conductivity/（kJ·m^{-1}·d^{-1}·C^{-1}）	163

2.2 Numerical Simulation Project Design

According to the geological reservoir parameters of typical offshore oil field, two test programs were designed to simulation of cycle steam stimulation and cycle N_2 and CO_2 assisted steam stimulation, respectively. And the injection parameters are shown in Table 4.

Table 4
Thermal Recovery Injection Parameters

Test #	Injection media	Cumulative water injection (m^3)	Water injection rate (m^3/d)	Gas injection rate (Nm^3)	Steam quality (/)
Test 1	Steam	3,000	150	0	0.4
Test 2	Steam+50%CO_2+50%N_2	3,000	150	30,000	0.4
Test 3	Water	3,000	150	0	0.0
Test 4	Water+50%CO_2+$50_{\%}N_2$	3,000	150	30,000	0.0

3. RESULTS AND DISCUSSION

3.1 Heated Radius of Numerical Results

Using the above model, the heated radius and temperature field of test1 is simulated for 10 cycles. And the figures of temperature field of the 6^{th} layer (K = 6) after the end of the soak are shown in Figure 3. The original reservoir temperature of the model is 56 ℃, when the heating temperature is higher than 100 ℃ the display area is shown in blank.

Another model, the heated radius and temperature field after N_2 and CO_2 assisted steam injection was simulated. And the comparison of temperature field of the 6^{th} layer (K = 6) after the end of the soak are shown in Figures 4 and 5.

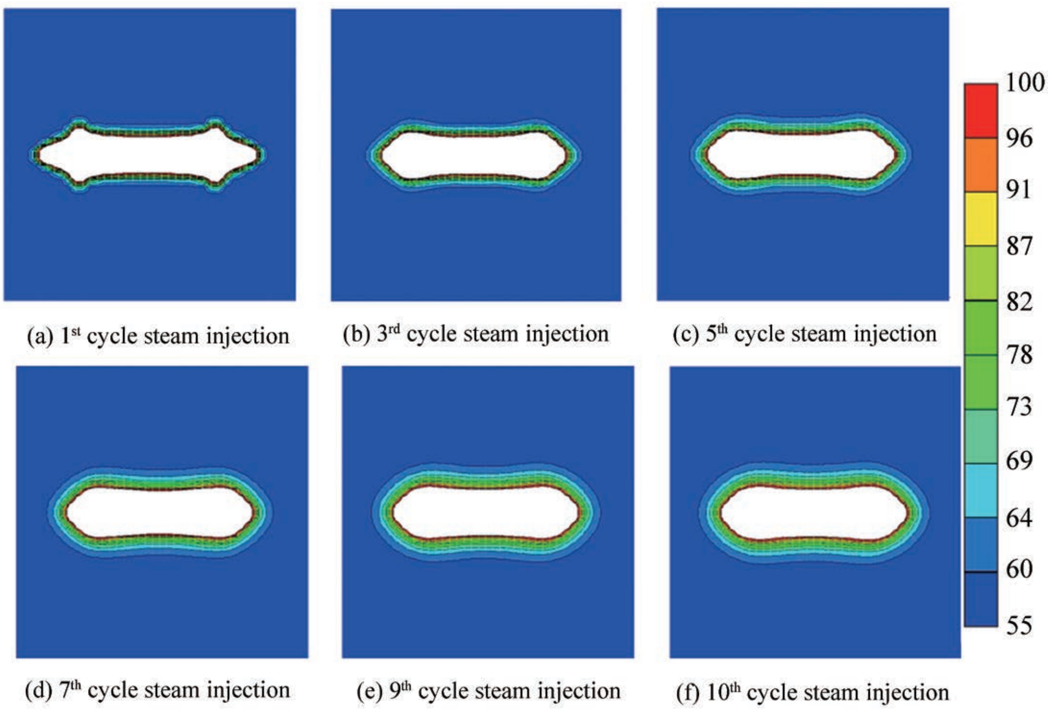


Figure 3
Temperature Field Distribution of Injection Steam (Blank Represent Temperature Higher Than 100 ℃)

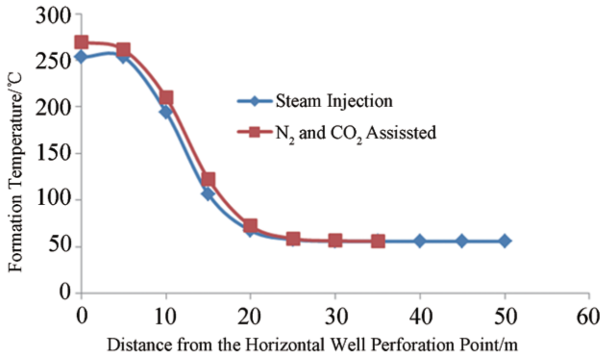


Figure 4
Temperature of 2nd Cycle Injection

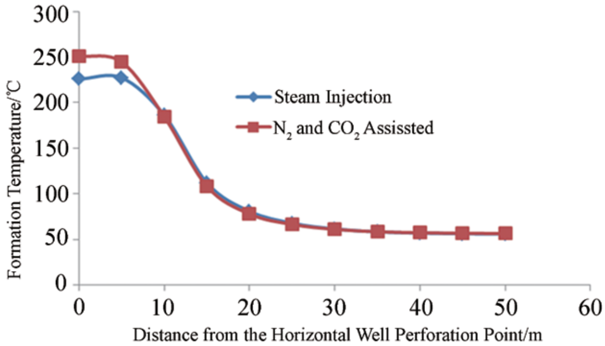


Figure 5
Temperature of 9nd Cycle Injection

It can be concluded from Figures 4 and 5, the temperature of N_2 and CO_2 assisted steam injection is much higher than that of the steam injection in the same location, which has the same distance from the horizontal well. That is because, N_2, as an inert gas, has a low thermal conductivity coefficient (shown in Table 5) and a lower density than steam.

Table 5
Thermal Conductivity of Varied Thermal Media

Thermal media	Thermal conductivity/ W/(m·K)
Heavy oil	0.5~0.8
Rock (no oil)	2.0~3.5
Rock (contains oil)	1.5~2.5
Water	0.4~0.5
Steam	0.02~0.025
CO_2	0.01~0.25
N_2	0.01~0.05

The N_2 would spread upward and crate a heat preservation zone at the top of formation. On one hand, it would obviously reduce heat loss of steam injected to rock in the top of layer and improve heat efficiency; on the other hand, it would reduce overlapping of steam, which might extend steam chamber laterally and enhance swept volume. N_2 injection in the casing tubing annulus at low temperature would have an effect of heat insulation, which could reduce the heat loss of steam injected in the casing tubing annulus.

3.2 Performance Comparison of Numerical Results

The cumulative oil production result of test 3 and test 4 is compared in Figure 6. It can be concluded from Figure 6 that the N_2 and CO_2 assisted steam injection can get better development effect than that of the steam injection. The reason is that, CO_2 can dissolve in the heavy oil; this can reduce the viscosity of heavy oil sharply, which is shown in Figure 7.

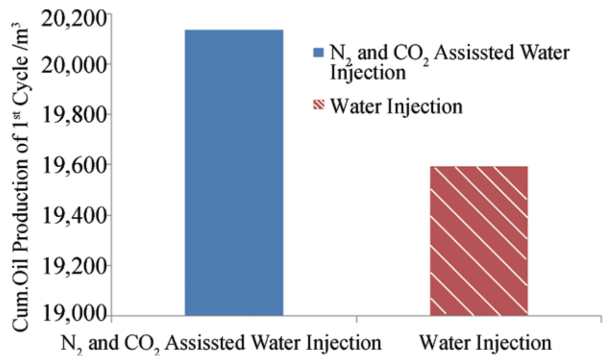
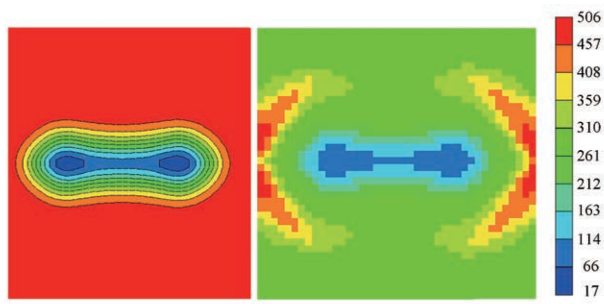


Figure 6
Cumulative Oil Production Comparison of 1st Cycle Injection



(a) After 10th cycle water injection (b) After 10th cycle water and CO_2 injection

Figure 7
Oil Viscosity in Place Comparison of 10th Cycle Injection

The block volume weighted average of water injection after 10th cycle water injection is 464 mPa•s (a of Figure 7), and that of water and CO_2 injection is 338 mPa•s (b of Figure 7). Through the example of horizontal well thermal recovery single well numerical simulation results, if the steam quality was zero, which often happens in deep buried reservoir, CO_2 was helpful to improve the effect of thermal recovery. Thermal recovery of Test 3 and Test 4 is 23.8% and 24.9% respectively, that is, CO_2 and N_2 can improve the oil recovery with one percent point.

3.3 Well Performance Comparison of Field Data

3.3.1 History of N_2 and CO_2 Assisted Cycle Steam Stimulation

The first pilot test of N_2 and CO_2 assisted cycle steam stimulation was carried out at NY oilfield with compact thermal recovery equipment since 2008. There have been 11 test wells in the pilot test area, and there are 8 wells located in the same major oil layer (shown in Figure 8). And most of them have been carried out the first cycle of stimulation, that is, most the well has complete co-injection N_2 and CO_2 for almost 20 days, shut down the well for 3~5 days, and open the well for flowing production, and put on pump when the formation pressure is too low to flow.

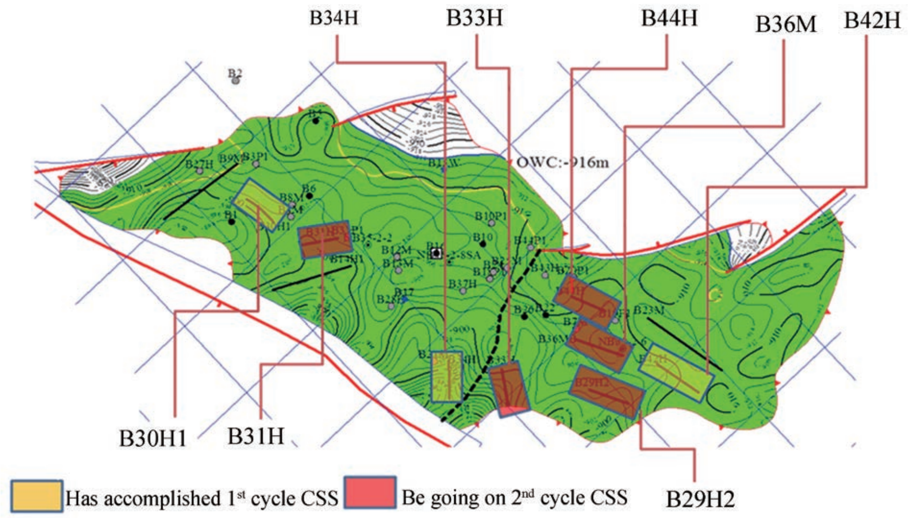


Figure 8
N_2 and CO_2 Assisted CSS Well Location in the Pilot Area of NY

From January 7th to January 13th in 2013, B29H2 injected thermal fluids for 17 days (shown in Table 6). During this period, 1 day were spend to inject multi-thermal fluid with wellhead temperature of 180 ℃, and 16 days to inject fluid with wellhead temperature of 220 ℃. The cumulative volume of injected multi-thermal medium as follows: 3,800 m³ of hot water, 107.0×10^4 Nm³ of N_2, and 18.8×10^4 Nm³ of CO_2 (in standard state), were injected into formation by oil tube. And 19.8×10^4 Nm³ of N_2 was injected to the formation through the annular insulation (shown in Table 7). Then it shut well for 3 days. Peak oil production was 72.7 m³/d and B29H2 well cold production capacity was 20 m³/d by prediction, that is, 3.6 times oil production capacity can be achieved by injection N_2 and CO_2 together with steam. And there was 6,400 m³ oil increment of the first cycle injection compared that with cold production.

3.3.2 History of Cycle Steam Stimulation

LX heavy oil field is a typical heavy oil reservoir with formation viscosity of 2,300 mPa•s, buried depth of 1,300 meters, average porosity of 34.4%, and average permeability of $3,786.5\times10^{-3}$ μm². There are several pattern reservoirs, such as edge water, bottom water and without water drive, most of which are too complex to develop economically[15]. Three reservoirs with 12 wells have been selected as cyclic steam pilot area, two of which are edge water reservoirs and one of which is bottom water reservoir.

Table 6
Reservoir Data of LX and NY Heavy Oil Field

Parameter name	LX	NY
Putting into operation date	2009	2005
Oil zone	Nm	Nm
Depth/(m)	1,272~1,526	900~1,100
Depositional facies	Shallow delta	Shcal water
Initial reservoir pressure/(MPa)	12.6	9.8
Initial reservoir temperature/(℃)	52	56
Net pay/(m)	6~18	4~10
Porosity/(%)	31	36
Permeability/(mD)	1,000~4,000	3,000
Initial oil saturation/(℃)	64	0.73
Dead oil viscosity of 50℃/(cp)	2,678	2,500
Oil viscosity in formation condition/ (cp)	400~2,400	450~650

At the moment, two wells located on 1-1308 reservoir have been carried out the CSS pilot test (shown in Figure 9). Well A22H and A23H have completed the first cycle steam huff and puff, and the Injection Parameters are shown in Table 7.

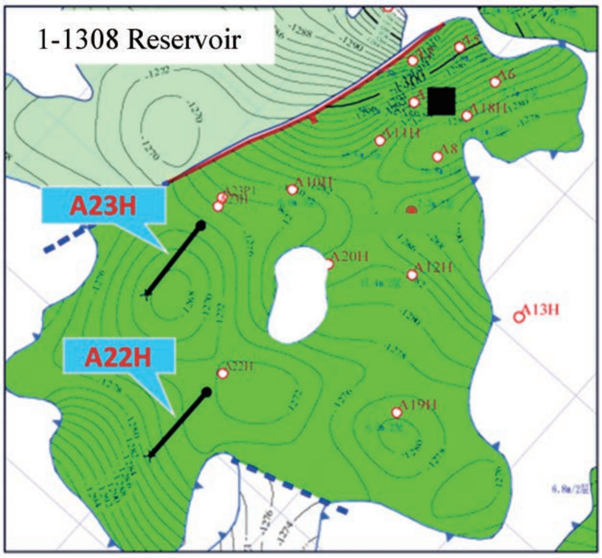


Figure 9
CSS Well Location in the Pilot Area of LX

Table 7
Comparison of Injection Parameters

Parameter name	LX-A23H	NY-B29H2
Well head temperature/(℃)	>340	220
Well head steam quality/(%)	80	0
Well bottom hole temperature/(℃)	350	240
Well bottom hole steam quality/(%)	0	0
Injection rate/(m^3/d)	190	224
Injection time/(d)	24	17
Injection volume of steam in 1st cycle/(m^3)	4,500	3,800
Injection volume of N_2 in 1st cycle/(Nm^3)	0	126.8
Injection volume of CO_2 in 1st cycle/(Nm^3)	0	18.8

3.3.3 Well Performance Comparison

Compared with well of LX-A23H, the flowing period of well NY-B29H2 is shorter. But the well NY-B29H2 has higher oil rate than that of A23H. It was analyzed that N_2 and CO_2 injected played a great role in keeping pressure and help increase the flow production rate (shown in Figure 10).

The oil productivity decline rate of a thermal well might be also characterized by the decline factor. The decline rate curve presented exponential decrease, as shown in Figure 11. Daily Decline Rate of LX-A23H was 0.39%, and that of NY-B29H2 was 0.33%.

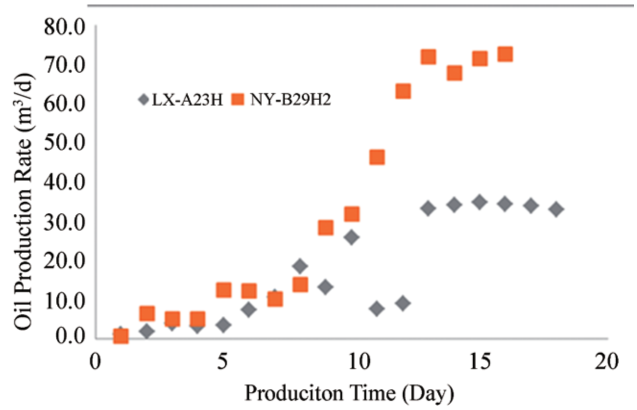


Figure 10
Oil Production Rate Comparison During Flowing Stage of 1st Cycle

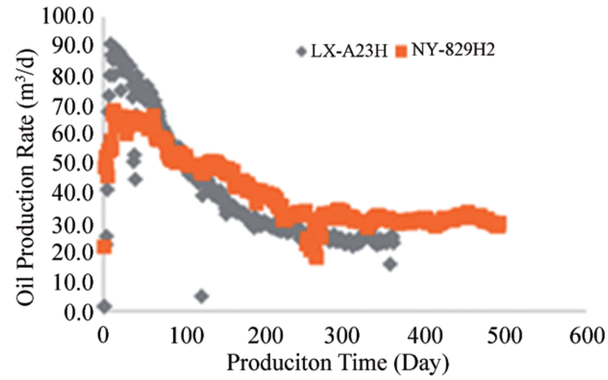


Figure 11
Oil Production Rate Comparison of 1st Cycle

Cycle incremental oil production is equal the cumulative oil production volume of thermal cycle minus the cumulative oil production of conventional develop. It is an important indication for offshore thermal development. Predicated cumulative oil production of well A22H is 0.42×10^4 m^3 if it's produced by natural energy development. According to the Valid period evaluation and declining rate and the production capacity, we can get the cycle cumulative oil production of steam huff and puff is 0.88×10^4 m^3, so the cycle incremental oil production is 0.46×10^4 m^3. But the NY-B29H2 has a cycle incremental oil production of 0.64×10^4 m^3.

CONCLUSION

(a) Through the physical experiment researches of mixture N_2 and CO_2 of heavy oil, the results showed that CO_2 and N_2 can reduce the viscosity of heavy oil by 80% and 10% respectively, and reduce the interfacial tension between oil and water which can improve the oil displacement efficiency by 5.1~6.2% at 250 ℃. We can make full use of vary mechanisms to extract heavy oil with depth buried.

(b) A numerical model for single horizontal well is built up to simulate injecting water alone, water mixed with N_2 and CO_2, steam and steamed mixed with N_2 and

CO_2 separately. The results demonstrate that injection N_2 and CO_2 together with steam can get higher cumulative oil production and higher oil recovery factor, nearly improve recovery one percentage point on the base of injection water only.

(c) By comparison the well performance of two different heavy oil field, it can be concluded that N_2 and CO_2 assisted steam stimulation can obviously improve oil recovery. It is an efficient way to enhance steam sweep zone and slow down the production decline for heavy oil.

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