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## Heated Area and Well Performance Analysis of Injection N<sub>2</sub> and CO<sub>2</sub> 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<sub>2</sub> and CO<sub>2</sub> in steam injection. Because of the influence of the N<sub>2</sub> and CO<sub>2</sub>, the heated area and well performance of N<sub>2</sub> and CO<sub>2</sub> assisted CSS are different from that of steam stimulation. Therefore, this paper describes a detailed study of N<sub>2</sub> and CO<sub>2</sub> influence to cycle steam stimulation. In this paper, the physical simulation experiments of N<sub>2</sub> and CO<sub>2</sub> influence to the mixture of heavy oil are carried out at first. Through physical experiments, the enhancing oil mechanisms of N<sub>2</sub> and CO<sub>2</sub>, the recovery mechanism of reducing oil viscosity by CO<sub>2</sub> 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<sub>2</sub> and CO<sub>2</sub> assisted CSS is better than that of

conventional steam stimulation in porous media. Next, the different well performance of the N<sub>2</sub> and CO<sub>2</sub> 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<sub>2</sub> and CO<sub>2</sub> assisted CSS are analyzed in detail. Consequently, the N<sub>2</sub> and CO<sub>2</sub> 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<sup>[1-2]</sup>. Application of steam injection technology to heavy oil reservoirs is the most commercially successful EOR method<sup>[3-6]</sup>. Nowadays, cycle steam stimulation, is known as the most widely used and mature technology<sup>[7]</sup>. 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<sup>[8]</sup>, 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<sup>[9-10]</sup>. One improvement work of cyclic steam stimulation is to enlarge the heated radius by injection N<sub>2</sub> and CO<sub>2</sub> together with steam<sup>[11-12]</sup>. 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<sup>[13]</sup>. 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<sub>2</sub> and CO<sub>2</sub> to change the distribution of formation fluid to improve the heating area and development efficiency<sup>[14]</sup>.

## 1. EXPERIMENTAL RESEARCHES OF EOR MECHANISMS BY INJECTION N<sub>2</sub> AND CO<sub>2</sub>

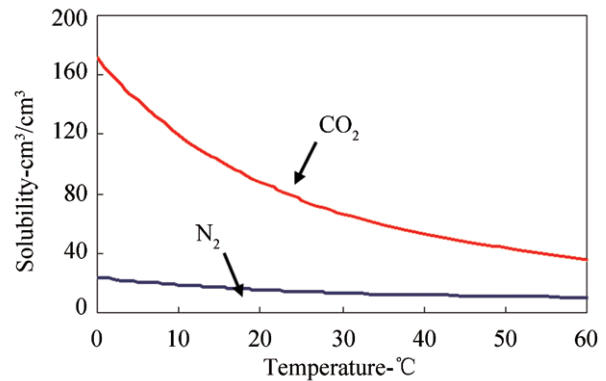
**Table 1**  
Influence of PVT Properties of Heavy Oil in NY with N<sub>2</sub>

Temperature/°C	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 °C, 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<sub>2</sub> has weak solubility in both fresh and salt water. CO<sub>2</sub> can dissolve much more easily in water than N<sub>2</sub>. This characteristic is very useful for keeping reservoir pressure by injecting N<sub>2</sub> 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<sub>2</sub> in water. Solubility decreases with salinity and increases with pressure.



**Figure 1**  
Solubility of N<sub>2</sub> and CO<sub>2</sub> in Water Under Standard State

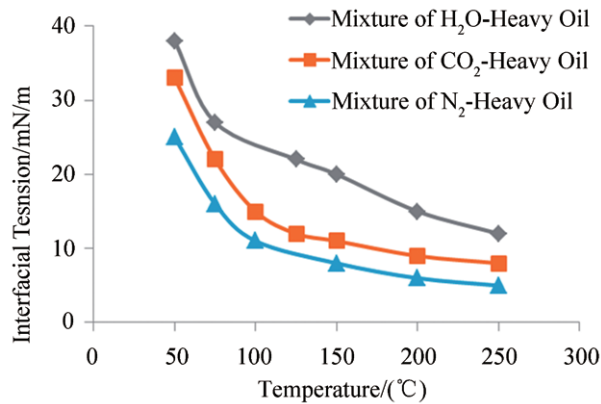
N<sub>2</sub> can make the viscosity of heavy oil reduced from 494.8 mPa·s to 435 mPa·s with dropping about 10%, which is shown in Table 1. In the same temperature, CO<sub>2</sub> can make the viscosity of heavy oil from 460 mPa·s to 80 mPa·s, reducing nearly 80%, which is shown in Table 2.

**Table 2**  
**Influence of PVT Properties of Heavy Oil in NY With CO<sub>2</sub>**

Temperature/°C	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
	0.0	8.6	0.92	14.09	1.05
180	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**

**Table 3**  
**Rock and Fluid Thermal Parameters in Numerical Model**

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

## 2. QUANTITATIVE RESEARCHES OF N<sub>2</sub> AND CO<sub>2</sub> 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<sup>-3</sup> μm<sup>2</sup> and the vertical to horizontal permeability is 500×10<sup>-3</sup> μm<sup>2</sup>, 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<sup>3</sup>.

## 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<sub>2</sub> and CO<sub>2</sub> 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 <sup>3</sup> )	Water injection rate (m <sup>3</sup> /d)	Gas injection rate (Nm <sup>3</sup> )	Steam quality (l)
Test 1	Steam	3,000	150	0	0.4
Test 2	Steam+50%CO <sub>2</sub> +50%N <sub>2</sub>	3,000	150	30,000	0.4
Test 3	Water	3,000	150	0	0.0
Test 4	Water+50%CO <sub>2</sub> +50%N <sub>2</sub>	3,000	150	30,000	0.0

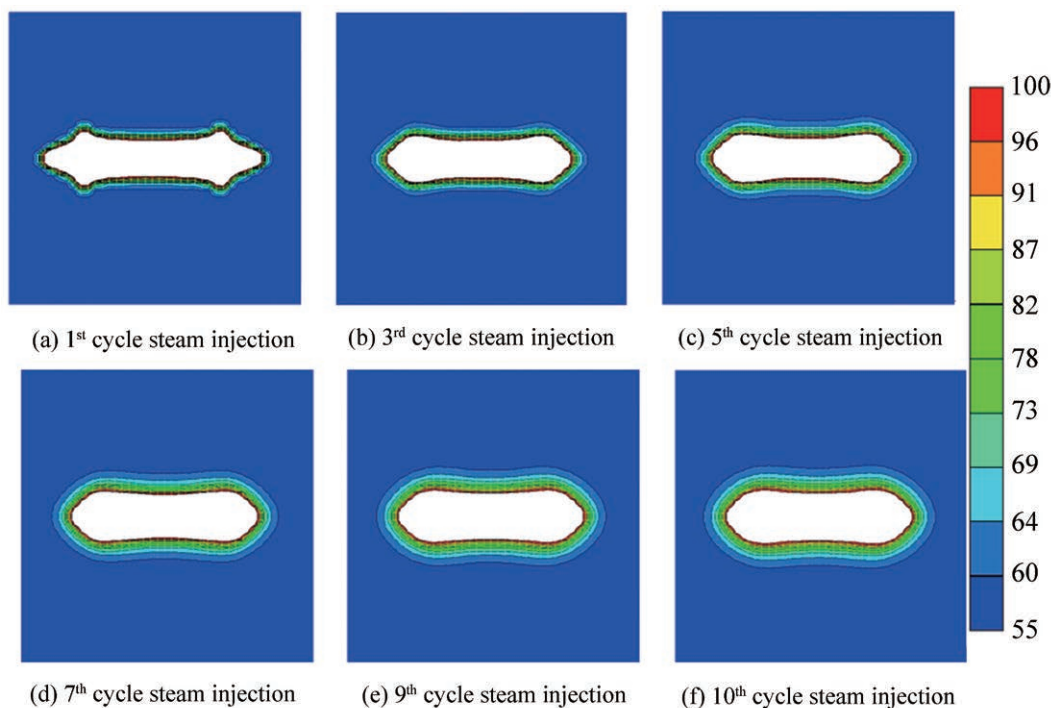
## 3. RESULTS AND DISCUSSION

### 3.1 Heated Radius of Numerical Results

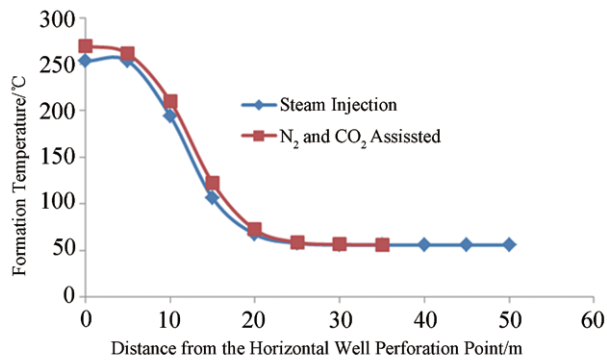
Using the above model, the heated radius and temperature field of test1 is simulated for 10 cycles. And the figures of temperature field of the 6<sup>th</sup> layer ( $K = 6$ ) after the end of the soak are shown in Figure 3. The original reservoir

temperature of the model is 56 °C, when the heating temperature is higher than 100 °C the display area is shown in blank.

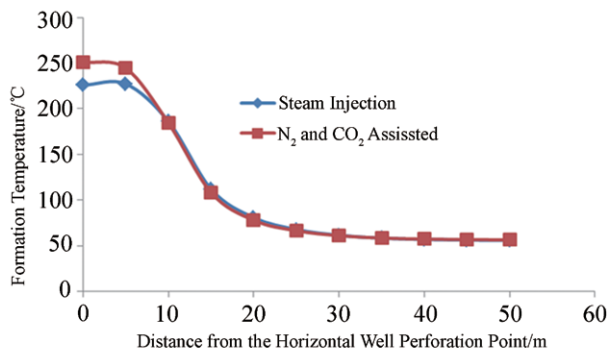
Another model, the heated radius and temperature field after N<sub>2</sub> and CO<sub>2</sub> assisted steam injection was simulated. And the comparison of temperature field of the 6<sup>th</sup> layer ( $K = 6$ ) after the end of the soak are shown in Figures 4 and 5.



**Figure 3**  
Temperature Field Distribution of Injection Steam (Blank Represent Temperature Higher Than 100 °C)



**Figure 4**  
 Temperature of 2<sup>nd</sup> Cycle Injection



**Figure 5**  
 Temperature of 9<sup>th</sup> Cycle Injection

It can be concluded from Figures 4 and 5, the temperature of N<sub>2</sub> and CO<sub>2</sub> 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<sub>2</sub>, 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

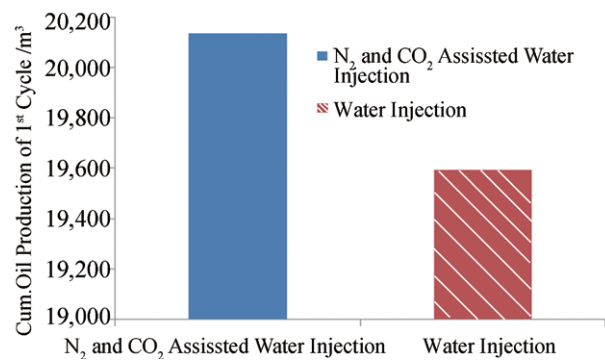
Thermal media	Thermal conductivity/ W/(m·K)
Heavy oil	0.5~0.8
Rock (no oil)	2.0~3.5
Rock (contains oil)	1.5~2.5
Water	0.4~0.5
Steam	0.02~0.025
CO <sub>2</sub>	0.01~0.25
N <sub>2</sub>	0.01~0.05

The N<sub>2</sub> 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,

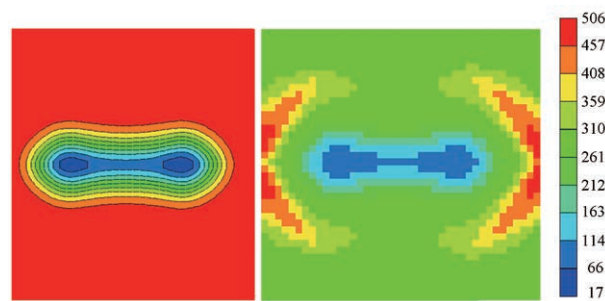
which might extend steam chamber laterally and enhance swept volume. N<sub>2</sub> injection in the casing tubing annulus at low temperature would have an effect of heat insulation, which could reduce the heat loss of steam injected in the casing tubing annulus.

**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<sub>2</sub> and CO<sub>2</sub> assisted steam injection can get better development effect than that of the steam injection. The reason is that, CO<sub>2</sub> 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 1<sup>st</sup> Cycle Injection



(a) After 10<sup>th</sup> cycle water injection (b) After 10<sup>th</sup> cycle water and CO<sub>2</sub> injection

**Figure 7**  
 Oil Viscosity in Place Comparison of 10<sup>th</sup> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> and N<sub>2</sub> can improve the oil recovery with one percent point.

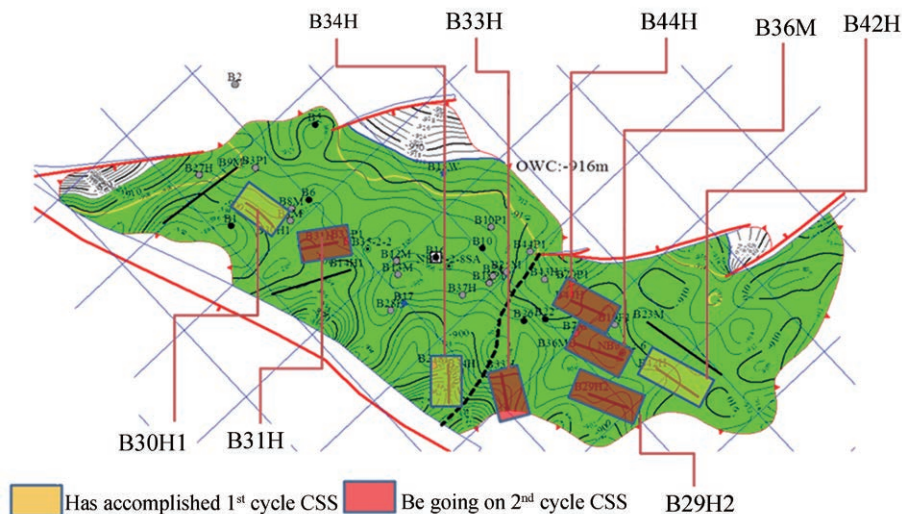


### 3.3 Well Performance Comparison of Field Data

#### 3.3.1 History of N<sub>2</sub> and CO<sub>2</sub> Assisted Cycle Steam Stimulation

The first pilot test of N<sub>2</sub> and CO<sub>2</sub> 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<sub>2</sub> and CO<sub>2</sub> 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<sub>2</sub> and CO<sub>2</sub> Assisted CSS Well Location in the Pilot Area of NY

From January 7<sup>th</sup> to January 13<sup>th</sup> 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 °C, and 16 days to inject fluid with wellhead temperature of 220 °C. The cumulative volume of injected multi-thermal medium as follows: 3,800 m<sup>3</sup> of hot water, 107.0×10<sup>4</sup> Nm<sup>3</sup> of N<sub>2</sub>, and 18.8×10<sup>4</sup> Nm<sup>3</sup> of CO<sub>2</sub> (in standard state), were injected into formation by oil tube. And 19.8×10<sup>4</sup> Nm<sup>3</sup> of N<sub>2</sub> 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 m<sup>3</sup>/d and B29H2 well cold production capacity was 20 m<sup>3</sup>/d by prediction, that is, 3.6 times oil production capacity can be achieved by injection N<sub>2</sub> and CO<sub>2</sub> together with steam. And there was 6,400 m<sup>3</sup> oil increment of the first cycle injection compared that with cold production.

#### 3.3.2 History of Cycle Steam Stimulation

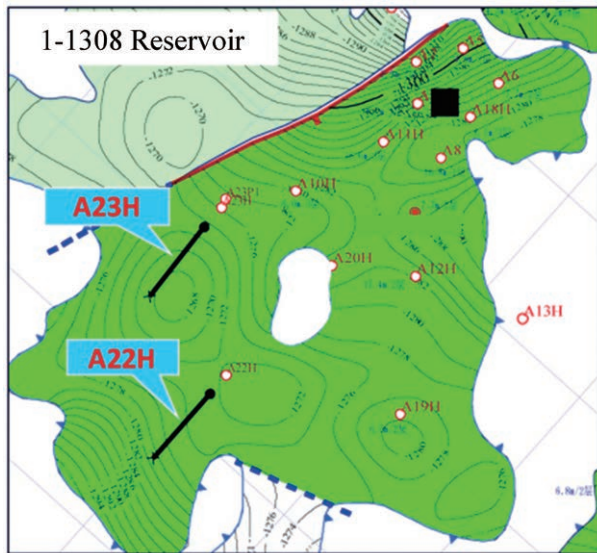
LX heavy oil field is a typical heavy oil reservoir with formation viscosity of 2,300 mPa·s, buried depth of 1,300 meters, average porosity of 34.4%, and average permeability of 3,786.5×10<sup>-3</sup> μm<sup>2</sup>. There are several pattern reservoirs, such as edge water, bottom water and without water drive, most of which are too complex to develop economically<sup>[15]</sup>. 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/(°C)	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°C/(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

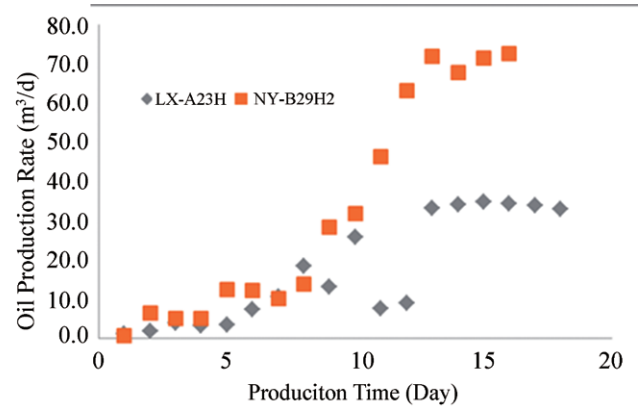
**Table 7**  
 Comparison of Injection Parameters

Parameter name	LX-A23H	NY-B29H2
Well head temperature/(°C)	>340	220
Well head steam quality/(%)	80	0
Well bottom hole temperature/(°C)	350	240
Well bottom hole steam quality/(%)	0	0
Injection rate/(m <sup>3</sup> /d)	190	224
Injection time/(d)	24	17
Injection volume of steam in 1 <sup>st</sup> cycle/(m <sup>3</sup> )	4,500	3,800
Injection volume of N <sub>2</sub> in 1 <sup>st</sup> cycle/(Nm <sup>3</sup> )	0	126.8
Injection volume of CO <sub>2</sub> in 1 <sup>st</sup> cycle/(Nm <sup>3</sup> )	0	18.8

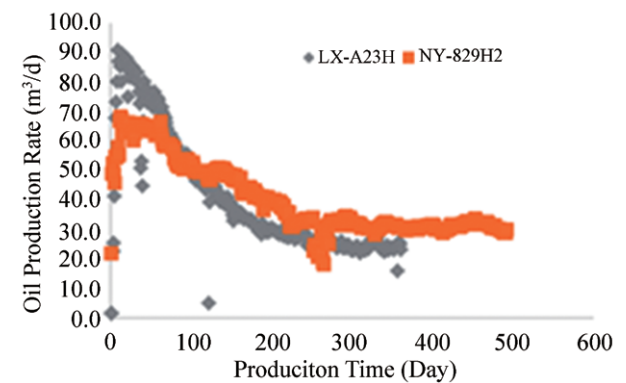
### 3.3.3 Well Performance Comparison

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<sub>2</sub> and CO<sub>2</sub> 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 1<sup>st</sup> Cycle



**Figure 11**  
 Oil Production Rate Comparison of 1<sup>st</sup> Cycle

Cycle incremental oil production is equal the cumulative oil production volume of thermal cycle develop. It is an important indication for offshore thermal development. Predicated cumulative oil production of well A22H is  $0.42 \times 10^4$  m<sup>3</sup> 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  $0.88 \times 10^4$  m<sup>3</sup>, so the cycle incremental oil production is  $0.46 \times 10^4$  m<sup>3</sup>. But the NY-B29H2 has a cycle incremental oil production of  $0.64 \times 10^4$  m<sup>3</sup>.

## CONCLUSION

(a) Through the physical experiment researches of mixture N<sub>2</sub> and CO<sub>2</sub> of heavy oil, the results showed that CO<sub>2</sub> and N<sub>2</sub> 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 °C. 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<sub>2</sub> and CO<sub>2</sub>, steam and steamed mixed with N<sub>2</sub> and

CO<sub>2</sub> separately. The results demonstrate that injection N<sub>2</sub> and CO<sub>2</sub> 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<sub>2</sub> and CO<sub>2</sub> 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.

## REFERENCES

- [1] Liu, D., Zhang, Y. C., Li, Y. P., Zhang, L., Hou, D. M., Li, J. M., & Liu, Y. C. (2014, May). *Multi-thermal fluids stimulation production characteristics: A case study of the first thermal recovery pilot test for offshore heavy oil in China*. Paper presented at 2014 World Heavy Oil Congress, WHOC2014-186, New Orleans, USA.
- [2] Liu, D., Ma, K. Q., Zhang, L., Nie, L. L., & Li, J. M. (2015). *The research and first application of multi-thermal fluids huff and puff technology in Bohai bay offshore heavy oil in China*. Paper presented at 2015 World Heavy Oil Congress, WHOC2015-153, Edmonton, Alberta, Canada.
- [3] Patzek, T. W., & Koinis, M. T. (1990). Kern river steam-foam pilots. *J. Pet. Technol.*, (4), 496-503.
- [4] Yang, C. Z., & Han, D. K. (1991). Present status of EOR in the Chinese petroleum industry and its future. *J. Pet. Sci. Eng.*, (6), 175-189.
- [5] Fatemi, S. M., & Jamaloei, B. Y. (2011). Preliminary considerations on the application of toe-to-heel steam flooding (THSF): Injection well-producer well configurations. *Chem. Eng. Res. Des.*, 89, 2365-2379.
- [6] Pang, Zhanxi, Liu, Huiqing, & Zhu, L. (2015). A laboratory study of enhancing heavy oil recovery with steam flooding by adding nitrogen foams. *J. Pet. Sci. Eng.*, 128, 184-193.
- [7] Liu, H. Q., Fan, Y. P., & Zhao, D. W. (2000). *Principles and methods of thermal oil recovery technology* (pp.138-141). Dongying: China University of Petroleum Press.
- [8] Boberg, T. C., & Lantz, R. B. (1966). Calculation of the production rate of a thermally stimulated well. *J. Petrol. Technol.*, 1613-1623.
- [9] Liu, C. Z., Cheng, L. S., Liu, Y., & Pang, Z. X. (2008). Calculating models for heating radius of cyclic steam stimulation and formation parameters in horizontal well after soaking. *Acta Petrolei Sinica*, 29(1), 101-105.
- [10] Gu, H., Cheng, L. S., Huang, S. J., Li, B. K., & Shen, F. (2015). Steam injection for heavy oil recovery: Modelling of wellbore heat efficiency and analysis of steam injection performance. *Energy Conversion and Management*, 97, 166-177.
- [11] Li, F., Zhang, F. S., & Ding, J. M. (2001). Application of assistant chemical viscosity reducing technology in steam soaking in shallow layer viscous oil reservoir in Xinjiang. *Oil Drilling & Production Technology*, 23(1), 67-68.
- [12] Huang, Y. H., Liu, D., & Luo, Y. K. (2013). Research on multiple thermal fluid stimulation for offshore heavy oil production. *Special Oil & Gas Reservoirs*, 20(2), 164-165.
- [13] Van Lookeren. J. (1983). Calculation methods for linear and radial steam flow in oil reservoirs. *Society of Petroleum Engineers Journal*, 23(3), 427-439.
- [14] Zhang, F. Y., Xu, W. K., & Liu, X. H. (2015). Study of mechanisms of enhanced oil recovery by multi-thermal fluids. *Advances in Petroleum Exploration and Development*, 9(1), 1-8.
- [15] Wang, S. T., Li, Y. P., & Ma, K. Q. (2015, August). *Evaluation of the first cyclic steam pilot in offshore oilfield of China*. Paper presented at SPE Asia Pacific Enhanced Oil Recovery Conference, Kuala Lumpur, Malaysia.