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A high temperature N2-foam assisted cyclic steam injection in Fuyv reservoir

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Steam stimulation has already been proved as an important thermal recovery technology. In Daqing, the development and management of high-heterogeneous heavy oil reservoirs plays an important role in stabilizing the oil output. To combine the good features of steam injection and cyclic injection, a cyclic steam flooding has been conducted in the Fuyv reservoir, Daqing. This paper aims to present a detailed process of the cyclic-steam injection. The target Fuyv reservoir in this research is located on the edge of the Songliao Basin. The reservoir characterized by high heterogeneity has a permeability range from 61.5 to 3650 mD. The viscosity of crude oil is averagely 3200 mPa.s. A simulation investigation was performed to instruct the pilot design. The nitrogen co-injected cyclic steam injection is also proposed and analyzed. The mechanisms of EOR by nitrogen assisted cyclic steam stimulation are studied. The pilot injection was fulfilled on the basis of fundamental investigation. The simulation results showed that the heated radius is a function of injection cycles. When the injected steam is only enough to forfeit the heat loss to caprock and beneath formation, the heated radius or heated area will not expand. The limited heated radius and steam overlapping vertically results in a poor sweep efficiency and oil-steam ratio, a large amount of oil untapped. The factors effecting production and injection performance are analyzed, and the injection parameters are optimized. The pilot injection has obtained foreseeable results.

Key words: Cyclic, steam inject, heavy oil, Fuyu reservoir, N_2-foam.

INTRODUCTION

The Fuyv reservoir in Daqing oilfield is a deep heavy oil reservoir (viscosity @ reservoir: 3200 mPa.s), which is located in the edge of Songliao Basin (Harris, 1987; Nguyen et al., 2003; Lin and Yang, 2006; Zhao et al., 2010). Hydrocarbon introduction is from the Fuyu sandstone, which is approximately 1070 m in depth and 21 m in thickness, the permeability is from 62.11 to 3650 mD and the effective porosity is from 23.0 to 39.49% (avg. 34.1%).

As of 2006, the reservoir was put into production by cyclic steam stimulation, which is the major development technology for heavy oil deposits (Zhao et al., 2011). While because of the high oil viscosity, formation heterogeneity and increased formation water due to muti-cycles of steam injection, the cyclic heat loss increases, cyclic production performance declines and oil recovery factor for CSS is limited (Kuehne et al 1990; Martinez et al., 2005; Liu et al., 2008; Liu et al., 2010; Li et al., 2012). Extensive literature investigation indicated that the N_2-foam assisted cyclic steam stimulation was successively applied in many heavy oil reservoirs throughout the world because of profile modification mechanism of nitrogen foam to control fingering and enhance oil recovery rate (Hudgins et al., 1990; Thomas et al., 1991; Bracho and Portillo, 1991; Svrcek et al., 2002; Ma et al., 2005). Therefore, taking the Fuyv reservoir as a research target,

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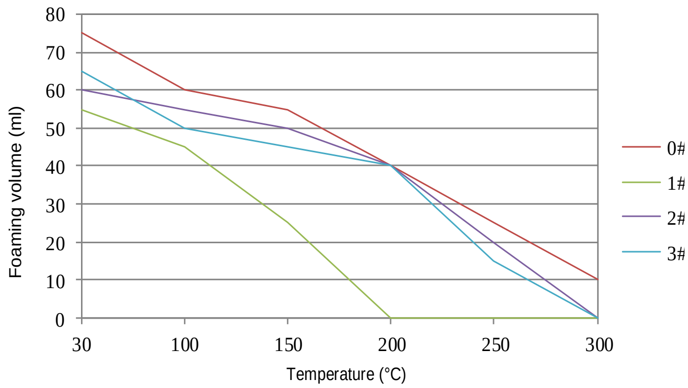


Figure 1. Foaming volume of different sets of N_2-foam system with temperature.

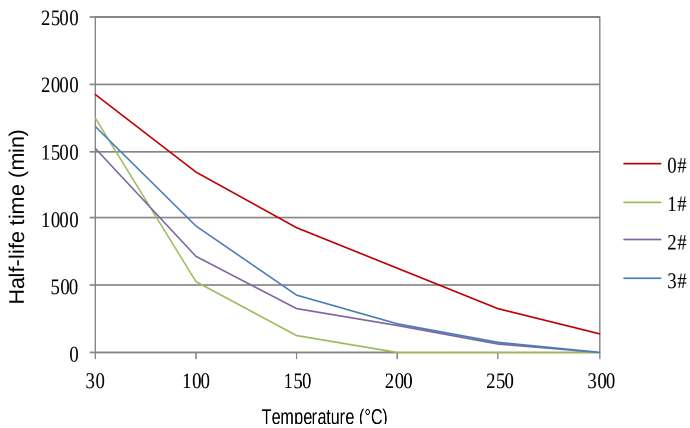


Figure 2. Half-life time of different sets of N_2-foam system with temperature.

four sets of N_2-foam system suitable for the Fuyv reservoi were screened by evaluation experiments and operation strategies of N_2-foam assisted CSS were optimized. The N_2-foam assisted CSS was carried out in two pilot test wells in 2010 and foreseeable results were obtained.

STATIC EVALUATION OF N_2-FOAM SYSTEM

In view of the geologic characteristics and fluid properties in Fuyv reservoir, four sets of N_2-foam system by different foaming agent are evaluated and screened in laboratory.

Foaming volume and half-life time with temperature

The tests of foaming volume and half-life time with temperature are carried out under the same conditions of test pressure (1 MPa) and foaming agent mass concentration (0.5%). The foaming volume test results (Figure 1) indicate that the foaming volumes of four sets of N_2-foam system decreases with increasing temperature. The 0# N_2-foam system can bear with temperature as high as 300°C, while the 1# is more sensitive with temperature and it cannot bear with temperature higher than 200°C. Meanwhile, the half-life time test results (Figure 2) show that the half-life time of 4 sets of N_2-foam system decreases gradually with increasing temperature. Generally, the half-life time of the 0# is higher than the other 3 sets at different temperature; therefore the 0# has the best high-temperature stability.

Adaptability of N_2-foam system to formation water

In the tests of adaptability of N_2-foam system to formation water, the formation water is replicated by sodium bicarbonate, anhydrous calcium chloride, magnesium chloride, sodium chloride, anhydrous sodium sulfate and other chemicals according to the fluid analysis of one well test result in the target area (Table 1). Four sets of N_2-foam system with 1 ml volume is dissolved separately into the replicated formation water to observe whether there occurs phenomenon of turbidity, insolubility or precipitation.

It is observed that the 4 sets of N_2-foam system are well adaptable to the formation water (Figures 3 and 4). Under the normal temperature (30°C), the phenomenon of turbidity, insolubility or precipitation is not observed within 6 days.

Adaptability of N_2-foam system to different formation oil samples

As the structure in Fuyv reservoir is the monocline structure, the formation oil in different position has different oil viscosity and oil composition; therefore it is necessary to test the adaptability of N_2-foam system to different formation oil samples. In view of the well placement in the target area, the oil samples from three different wells are selected to the adaptability test. The mass concentration of each foaming agent is 0.5%, the test pressure is 1 MPa and the test temperature is 30°C. The results (Figures 5 and 6) indicate that the set 0# has the largest foaming volume and longest half-life time in 3 oil samples compared with the other three sets of N_2-foam system. Therefore, the set 0# has a strong adaptability to different types of oil deposits in the target area.

DYNAMIC EVALUATION OF N_2-FOAM SYSTEM

The 1-D coreflooding system is used to carry out the influence of temperature and foaming agent concentration on the foam plugging performance; and

Figure 3. The formation water with dissolved foaming agent on the first day.

Figure 4. The formation water with dissolved foaming agent on the sixth day.

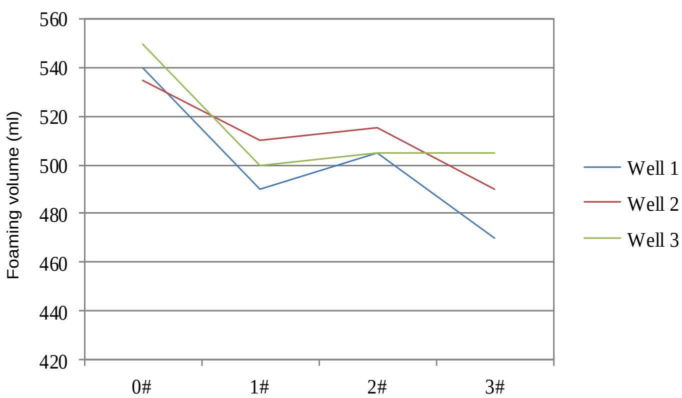


Figure 5. Foaming volume of different sets of N_2-foam system in different oil samples.

then, the oil displacement efficiency of different sets of N_2-foam system is tested and analyzed. The length of the quartz sand filled tube is 60 cm and the diameter is 3.8 cm. The tube is horizontally placed in the constant temperature oven. In the process of the experiment, the first step is to saturate water to test the porosity of the tube and water relative permeability; and then, injecting steam. The pressure difference between the inlet and outlet is recorded as the basic pressure difference; after that, the N_2-foam system is injected at the same volume injection rate with steam. The pressure difference between the inlet and outlet is recorded as the working pressure difference. The ratio between the working pressure difference and basic pressure difference is the foam resistance factor, which is used to evaluate the effectivenss of N_2-foam system. The higher the value of the resistance factor, the better the N_2-foam system performs in the field application.

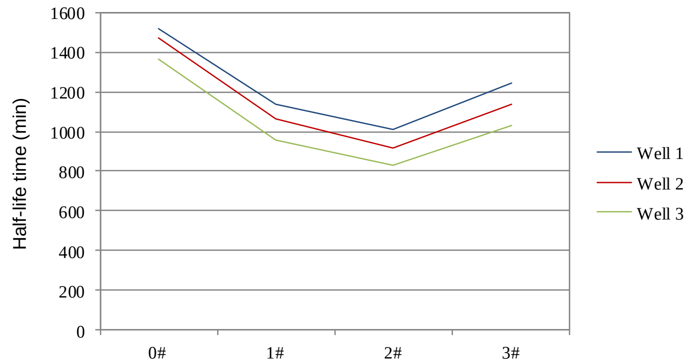


Figure 6. Half-life time of different sets of N_2-foam system in different oil samples.

Effects of temperature on foam plugging performance

The resistance factors of four sets of N_2-foam system under reservoir temperatures of 30, 60, 100, 150, 200, 250 and 300°C are tested. The mass concentration of foaming agent is 0.5%, the test pressure is 1 MPa.

The test results indicate that with increasing temperature, the resistance factor generally decreases, which is the results of smaller foaming volume and shorter half-life time of foam (Figure 7). The foam resistance factor of set 0# performs best at different temperature points, while the set 1# does not have evident resistance effects; therefore, set 1# is excluded from the foam candidates.

Effects of foaming agent concentration on foam plugging performance

The resistance factors of three sets of N_2-foam system (0#, 2# and 3#) are tested with foaming agent mass concentration of 0.3, 0.4, 0.5, 0.6 and 1.0% under experiment pressure of 1 MPa and temperature of 30°C.

The test results indicate that the resistance factor generally increases with increasing foaming agent mass concentration. When the mass concentration increases from 0.3 to 0.5%, the resistance factor increases dramatically. After the mass concentration reaches higher than 0.5%, the incremental resistance factor decreases, which means that when the mass concentration reaches a certain value, the foam resistance capacity becomes stable (Figure 8). Therefore, considering the influence of formation adsorption, the optimum mass concentration of foaming agent is between 0.5 and 0.6%.

Oil displacement efficiency under different injection patterns

In order to evaluate and compare different injection patterns on the performance of oil displacement efficiency,

Table 1. Ions in formation water from a typical well test results.

pH	Na^+	Mg^{2+}	CO_3^{2-}	Cl^-	SO_4^{2-}	HCO_3^-	Total salinity
7.2	1898.3	18.5	66.2	890.2	73.2	3707.6	6654.0

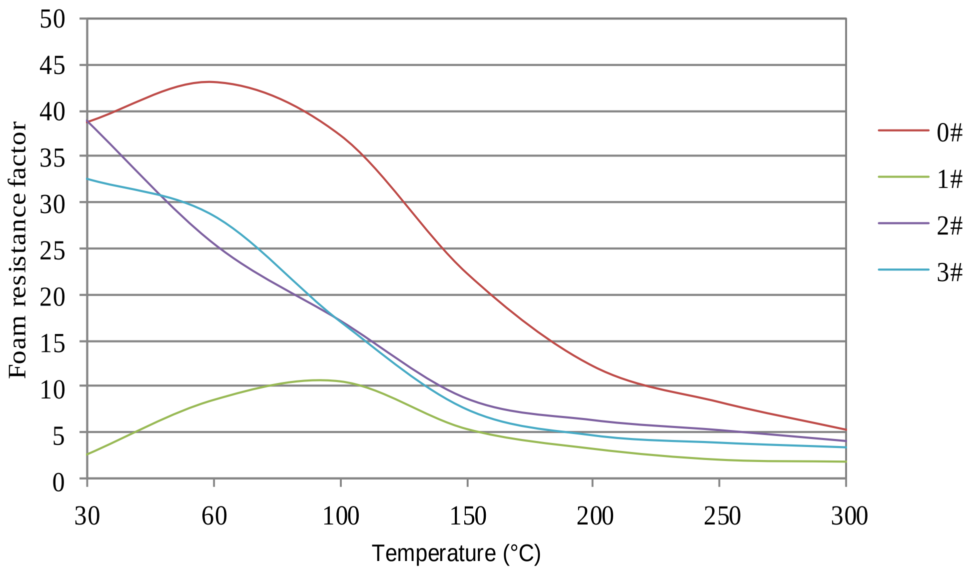


Figure 7. Effects of temperature on foam plugging performance of different sets of N_2-foam system.

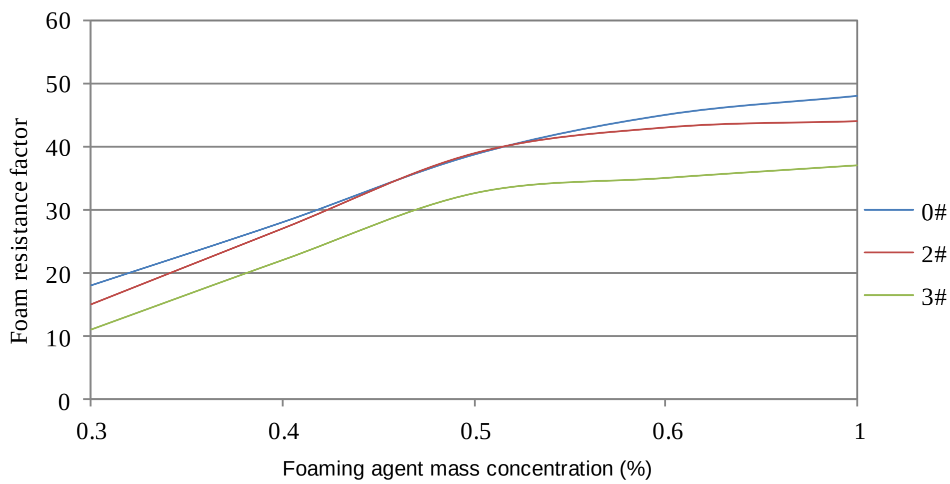


Figure 8. Effects of foaming agent concentration on foam plugging performance of different sets of N_2-foam system.

after reviewing the field conditions of cyclic steam stimulation, four injection patterns are selected and tested by 1-D coreflooding experiments. The sand filled tube has length of 30 cm and diameter of 2.5 cm. The four injection patterns are: steam, steam-nitrogen, steam-foaming agent, steam-nitrogen-foaming agent. The set 0# is selected as the foaming agent in these experiments.

The experiment results (Table 2) indicate that by only injecting steam, the oil displacement efficiency is only 35.4%; meanwhile, the oil displacement efficiency of Steam+Nitrogen injection is slightly higher than only steam injection, which means that the nitrogen itself could not act as a plugging agent to block the high permeability channels in the field application. The case of Steam-Foaming agent also does not yield high oil displacement efficiency, which is because of no resistance

Table 2. Oil displacement efficiency test results under different injection patterns.

Case No.	Injected fluid	Pore volume (ml)	Porosity (%)	Permeability (mD)	HCPV (ml)	So (%)	Oil displacement efficiency (%)
1	Steam	45.0	30.6	334	37.0	82.2	35.4
2	Steam+Nitrogen	43.0	29.2	316	36.0	83.7	38.1
3	Steam+Foaming agent	46.0	31.3	325	37.0	80.4	40.3
4	Steam+Nitrogen+Foaming agent	43.3	29.4	332	36.7	84.8	57.0

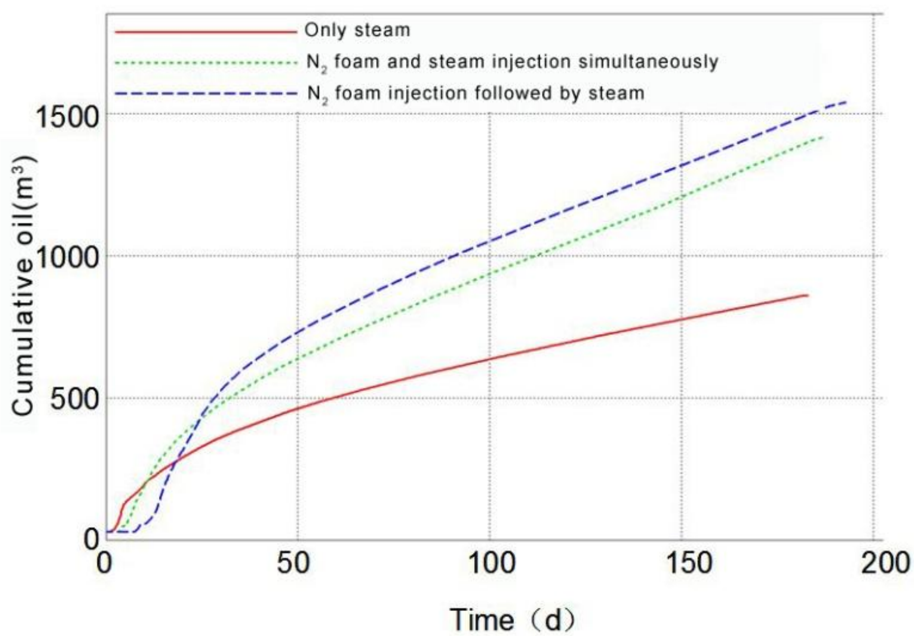


Figure 9. The cumulative oil comparison among different injection strategies.

effect by foaming agent itself; the foaming agent injected along with steam is largely adsorpted by reservoir rock surface. The optimum injection pattern is Steam-Nitrogen-Foaming agent, which can yield highest oil displacement efficiency compared with other injection patterns.

RESERVOIR ENGINEERING DESIGN OF N_2 FOAM ASSISTED CSS

Injection strategy of N_2 foam and steam during N_2 foam assisted CSS

Three injection strategies are simulated: only injecting steam, N_2 foam injection followed by steam injection, injecting N_2 foam and steam simultaneously (Figure 9). The results show that injecting N_2 foam and steam simultaneously is not the best injection strategy. This is because the half-life time of foaming agent is dramatically reduced when it is injected simultaneously with the high-temp steam, therefore initially the N_2 foam is not fully mixed with steam, the nitrogen fingering during injection period occurs and consequently, the CSS performance is poorer than N_2 foam injection followed by steam injection. It is also indicated that the N_2 foam injection followed by steam injection yields cyclic oil 125 m^3 more than by injecting N_2 foam and steam simultaneously, and 679 m^3 more than by conventional CSS. The performance comparison of N_2 foam assisted CSS and conventional CSS is listed in Table 3.

Optimization of the proportion between Nitrogen and steam

The proportion between nitrogen and steam is optimized to determine the optimal nitrogen injection. The results show that the cyclic oil production increases with increase of nitrogen proportion (Figure 10). When the proportion is higher than 35:1, the incremental oil deceases with further increase of nitrogen, and the optimum

Table 3. The CSS performance comparison of different injection strategies.

Injection strategy	Cumulative oil (m^3)	Cumulative liquid (m^3)	Cumulative steam (m^3)	Cumulative Nitrogen (m^3)	Production time (day)	Producers (n)	Average oil (m^3/day)
Only steam	832	4963	2547	0	180	4	1.15
N_2 foam injection followed by steam	1511	8177	2547	101882	180	4	2.10
N_2 foam and steam injection simultaneously	1386	5708	2547	101882	180	4	1.92

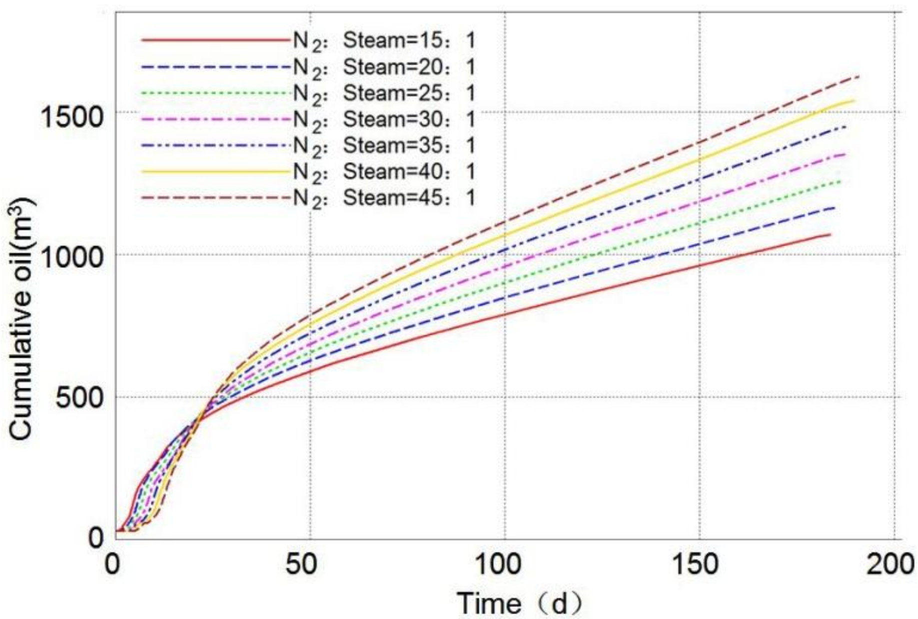


Figure 10. Cumulative cyclic oil production by different proportion between Nitrogen and steam.

proportion is 35:1 (Table 4).

Nitrogen foam injection rate optimization

Four cases of nitrogen foam injection rate are simulated: 2000, 3000, 4000 and 5000 Nm^3/day (Figure 11). The results show that when nitrogen is injected at the rate of 3000 Nm^3/day, the cumulative cyclic oil production is the highest; therefore the optimum nitrogen foam injection rate is 3000 Nm^3/day (Table 5).

FIELD TEST PERFORMANCE ANALYSIS

The field test is carried out based on the foaming agent screening in laboratory and numerical simulation for reservoir engineering parameters. Producers with 5 to 7 cycles of conventional CSS are selected and the injection and production parameters of CSS are optimized according to the reservoir and fluid properties: the proportion between nitrogen and steam is 35:1 and the nitrogen foam injection rate is 3000 N m^3/day as of December 2010; the N_2 foam assisted CSS has been carried out in 16 wells, and the staged performance is encouraging.

Fluid absorption profile improvement

The fluid absorption profiles in 16 wells have been tested and analyzed, which shows an encouraging improvement of the fluid absorption profile vertically. As can been seen from the test results of a typical well that by only steam injection during previous conventional CSS, the zone 1 absorbs most of the steam, which accounts for 83.81% of the total steam injection rate, while for zone 2, the steam absorption percentage is only 16.19%; during steam injection phase of N_2 foam assisted CSS, the fluid absorption profile is improved: for zone 1, the fluid absorption percentage reduces from 83.81 to 43.4%, while for zone 2, the fluid absorption percentage increases from 16.19 to 56.6% (Figure 12). Therefore, it can be seen that by injecting N_2 foam assisted CSS, the vertical oil deposits can be evenly developed. Meanwhile, the pressure data also shows that during injection phase

Table 4. Optimization results of the proportion between Nitrogen and steam.

Proportion (N_2/Steam)	Cumulative oil (m^3)	Cumulative liquid (m^3)	Cumulative steam (m^3)	Cumulative Nitrogen (m^3)	Production time (day)	Producers (n)	Incremental oil (m^3)
15:1	1039	6213	2547	38205	180	4	
20:1	1134	6619	2547	50941	180	4	94.32
25:1	1225	7064	2547	63676	180	4	91.65
30:1	1322	7449	2547	76411	180	4	97.03
35:1	1421	7824	2547	89147	180	4	98.66
40:1	1511	8177	2547	101882	180	4	89.73
45:1	1594	8556	2547	114617	180	4	83.47

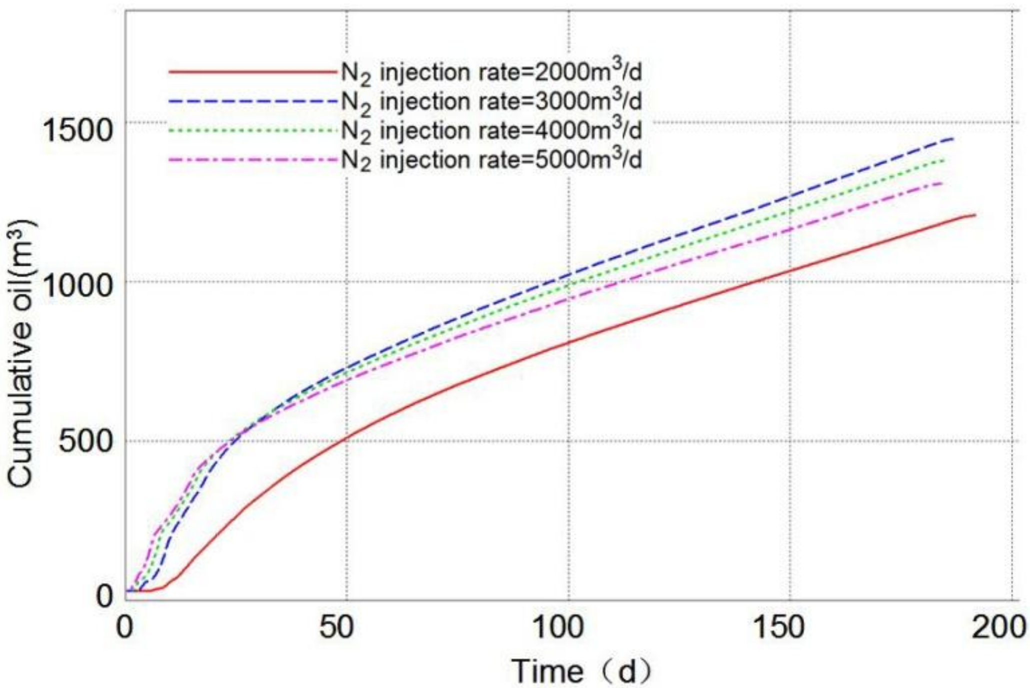


Figure 11. Cumulative cyclic oil production comparison by different nitrogen foam injection rate.

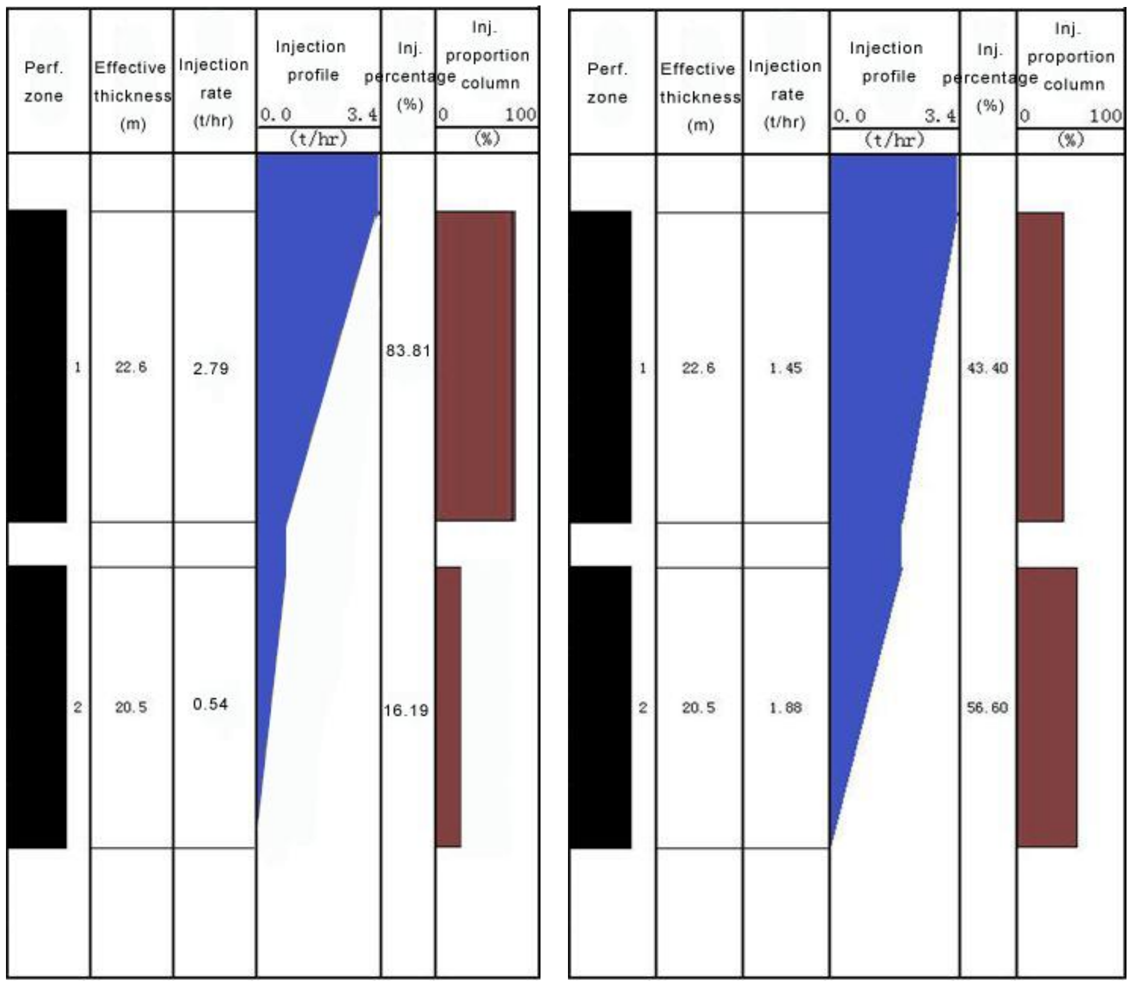
Table 5. Results of nitrogen foam injection rate optimization.

Injection rate (m^3/day)	Cumulative oil (m^3)	Cumulative liquid (m^3)	Cumulative steam (m^3)	Cumulative Nitrogen (m^3)	Production time (day)	Producers (n)
2000	1179	7812	2547	89147	180	4
3000	1421	7824	2547	89147	180	4
4000	1353	7291	2547	89147	180	4
5000	1278	6857	2547	89147	180	4

of N_2 foam assisted CSS, the injection pressure is evidently higher (avg. 3.9 MPa) than those wells injecting only steam due to the resistance effects of the N_2 foam, which could effectively reduce the steam fingering and enhance the cyclic production performance.

Cyclic oil production enhancement

The comparison between the previous conventional CSS and current N_2 foam assisted CSS shows that after nitrogen foam injected, the cyclic oil production and the



(a) (b)

Figure 12. Fluid absorption profile comparison before and after N_2 foam assisted CSS for a typical well. (a) Steam absorption profile (b) Steam and N_2-foam system absorption profile.

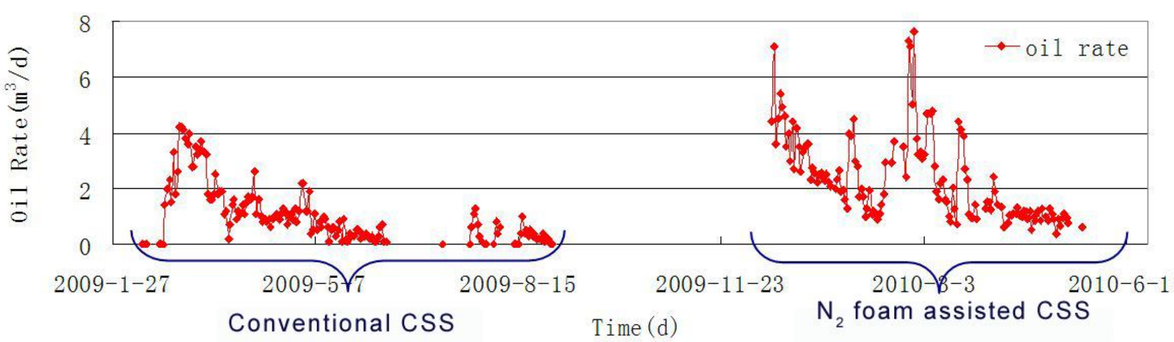


Figure 13. Comparison between conventional CSS and nitrogen assisted CSS in well 1.

cyclic OSR enhanced effectively (Figures 13 and 14). Most wells performed poor and were uneconomic during conventional CSS, while after nitrogen assisted CSS, the performance improved greatly: the cyclic production time increased by 51 days, the OSR enhanced by 0.105 ~ 0.137, the recycling ratio of water enhanced by 12 ~ 141%. Especially, the cyclic oil production in typical well 1 is 114 t and the OSR is 0.144 (Table 6), while after

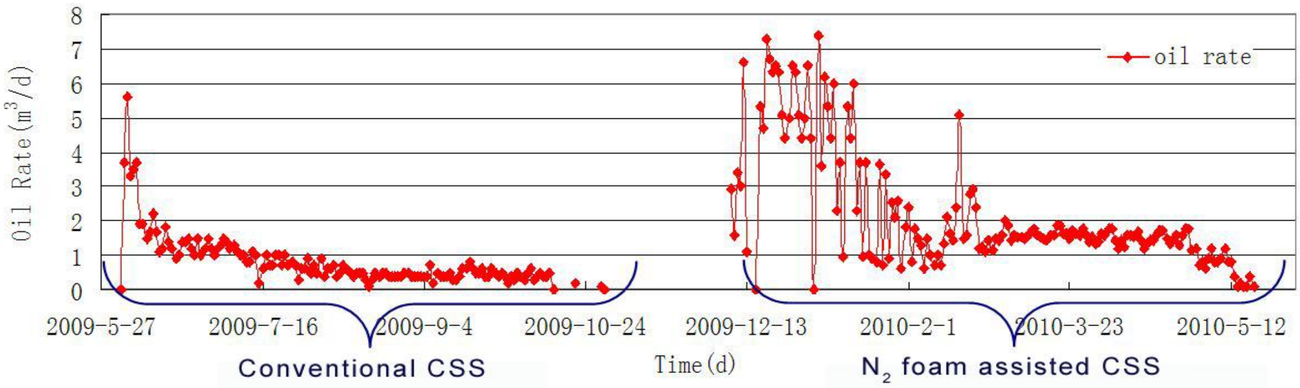


Figure 14. Comparison between conventional CSS and nitrogen assisted CSS in well 2.

Table 6. Incremental oil of well 1 and well 2.

Well No.	CSS method	Cycle	Cyclic oil (m^3)	Incremtnal oil (m^3)	Cyclic liquid (m^3)	Average oil (m^3/day)
Well1	Conventional CSS	6	114	240	284	0.83
	N_2 foam assisted CSS	7	354		655	2.58
Well2	Conventional CSS	6	160	156	613	1.06
	N_2 foam assisted CSS	7	316		902	2.10

nitrogen assisted CSS, the cyclic oil production is enhanced to 354 t and the OSR is enhanced to 0.277. The field tests show that the N_2 foam assisted CSS is an effective technology to enhance the performance of multi-cycle heavy oil wells, and an effective means to enhance the oil recovery factor.

Conclusions

1) Detailed literature investigation is carried out on profile modification mechanism of nitrogen foam to control fingering and enhancing oil recovery rate.
2) Static tests of foam adaptability to temperature, salinity and different oil samples are evaluated using four sets of N_2 foam system.
3) Effects of temperature and foaming agent concentration on foam plugging performance are analyzed and compared, by which the set 0# is selected to carry out the pilot test.
4) The operation parameters regarding injection pattern, injection rate, etc. are obtained by reservoir engineering design, which guided the implementation of N_2 foam assisted CSS successively.
5) Pilot test in 16 wells gave the positive results, which indicate that the fluid absorption profile is improved, consequently the oil deposits could be evenly tapped vertically, and the cyclic production performance is much better than previous conventional CSS, which shows potentials for future tests with larger scale in the Fuyv heavy oil reservoir.

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