Arabian Journal of Geosciences (2018) 11: 660
https://doi.org/10.1007/s12517-018-3993-5

ORIGINAL PAPER

Experimental study on feasibility and mechanisms of N_2/CO_2 huff-n-puff in the fractured-cavity reservoir

Fenglan Zhao[1] · Wei Su[1] · Jirui Hou[1] · Yuanyuan Xi[1] · Teng Zhao[1]

Received: 18 July 2017 / Accepted: 10 October 2018 / Published online: 31 October 2018

Abstract
The purpose of this experimental study is to evaluate the efficiency and performance of gas huff-n-puff in the single well on recovery of light oil from a multi-well fractured-cavity reservoir and to reveal the feasibility of gas mediums huff-n-puff. In order to reveal the production performance characteristics and mechanisms of gas huff-n-puff on activating the remaining oil, a visualized and pressure resistant two-dimensional (2D) fractured-cavity model and a three-dimensional (3D) multi-wells model were designed and fabricated respectively based on the similarity theory. With the simulated oil and brine reservoir samples in Tahe oilfield, five groups of tests in 3D model and five groups in 2D model were performed, each of which included bottom water energy depletion driving, gas injection stage, soaking stage, and gas puff stage. The production performances of N_2, CO_2, and N_2/CO_2 mixture huff-n-puff in the 3D model were firstly analyzed. Then the remaining oil recovery principles of each gas were compared and analyzed in the 2D model. Finally, the influence of gas injection position was studied both in the 2D and 3D models. The experiment results from 3D model demonstrated that higher oil recovery factor could be achieved through N_2 huff-n-puff which had shown enormous advantages than CO_2 and N_2/CO_2 mixture. Furthermore, the results from 2D model indicated that there were four types of the remaining oil, all of which could be recovered through N_2 huff-n-puff if it was implemented in the relative low-position well. The results from experiments on gas injection position conducted in the 3D physical model demonstrated the better oil recovery effect if N_2 was injected in low-position well which was consistent with the results concluded in the 2D model. This paper confirmed the effectiveness and advantages of N_2 huff-n-puff compared with CO_2 and gas mixture in the light oil-saturated fractured-cavity reservoir.

Keywords Fractured-cavity reservoir · Gas huff-n-puff · 2D visualized model · 3D pressure resistant model · Production performance · Gas injection position

Introduction

Carbonate reservoirs occupy an extremely important position in the world's oil/gas resources. And more than 30% of carbonate reservoirs are fractured-cavity reservoirs (Perez Rosales et al. 2002). The exploration and development of carbonate reservoirs in China present a rapid development trend as the increasing demand for energy resources (Chen et al. 2005). Due to the extremely low permeability of carbonate rock matrix (between 0.1 and 1 mD), the vugs and fractures are the fluid flow spaces. The flow pattern in the large vugs is recognized as pipe-flow mode which is much different with seepage in porous media. The flow pattern in fractures is sometime near to seepage in porous media, while sometime near to pipe-flow mode. Therefore, we cannot simply use the conventional parameter (permeability) to characterize the fractured-vuggy reservoir because of its complicated storage spaces (Zheng et al. 2010; Du et al. 2011; Xu et al. 2010). Strong heterogeneity, complex fracture-cavity structure, and connections are the main characteristics of fractured-cavity carbonate reservoir (Cruz Hernandez et al. 2001). Moreover, the main storage space and seepage path possess the features of discontinuity and randomness (Popov et al. 2009; Lu et al. 2010; Chen et al. 2010). After years of water-flooding

✉ Wei Su
suweicup@foxmail.com

[1] Institute of Enhanced Oil Recovery, China University of Petroleum, Beijing, China

development, many shortcomings such as short period of stable production, early water breakthrough, rapid increase of water cut, and high natural declining rate are exposed gradually.

Since current conventional recovery methods are no longer feasible, substantial portions of crude oil have remained uncovered. With the help of enhanced oil recovery (EOR) methods, which are part of the more general scheme of improved oil recovery (IOR), much of this oil could be recovery. However, the choice of the method and the expected ultimate recovery is dependent upon many considerations and economic factors, as well as technological factors (Firouz and Torabi 2014). The solvent gases can be carbon dioxide (CO_2), flue gas, and light hydrocarbon gases such as natural gas and methane. Cyclic solvent injection is a single-well EOR method which was initially considered to be an alternative technology to improve oil recovery. It is performed by injecting gas into a well (huff cycle), followed by a relatively short shut-in time, and then, the well is returned to production after a soaking time to allow for solvent interaction with the formation oil (puff cycle). Numerous laboratory and field tests have been performed, and the results reveal that the process is economically feasible (Qazvini Firouz 2011; Palmer et al. 1986; Simpson 1988; Haskin and Alston 1989; Alfarge et al. 2017; Cudjoe et al. 2016). However, most of the works reported, either in the laboratory or field trials, have been focused on the conventional single-porosity reservoirs (Torabi and Asghari 2010).

One of the first attempts to investigate the efficiency of the huff-and-puff technique on viscous oil was conducted by Schnitzler et al. They performed an experimental study on a laboratory-scale core having the dimensions of 3.8-cm diameter and 22.8-cm length. Based on their results, the ultimate recovery factor (URF) was increased by 14% during 2 cycles of CO_2 injection. A. Kantzas et al. (1993) designed a gravity-assisted immiscible cyclic gas (N_2) injection experiment applied in fractured-cavity rocks. The experiment was on the impact of heterogeneity and wettability on oil recovery using a two-dimensional micro-glass tube model. The experimental results showed that the gas displacement could increase the recoverable reserves of crude oil by 20% even though in strong heterogeneous and weak hydrophilic reservoirs. carried on a high-temperature emptying experiment with fractured-cavity rocks to investigate the mechanisms of cyclic gas injection. The study found that the N_2 EOR mechanisms include thermal expansion, thermal enhancing dissolved gas driving, dry distillation, and steam driving. Sanchez Bujanos et al. (2005) analyzed the production performance of N_2 injection in complex reservoir through the pressure monitoring system. The production and pressure data indicated that N_2 was isolated within the gas cap and complement energy for the formation. Zhao et al. (2010) designed a cavity-porosity core to research the impact of viscosity and angle on oil recovery and the effects of N_2 and CO_2 on oil/water and gas/water interface. In CO_2 injection, the effect of angle on oil recovery became more sensitive, and gravity differentiation was more important. In N_2 injection, it took more time to form the gas cap with the increase of pressure. CO_2 could efficiently alter the location of oil/water interface when there were the vertical fractures in fractured-cavity reservoirs. And N_2 gas cap could keep on the high-pressure production formation due to its low solubility in water and oil. Liu et al. (2012) and Yuan et al. (2015) designed and fabricated a visualized fractured-cavity model based on fracture-cavity relations of Tahe fourth block. The experiments indicated that there existed much remaining oil after bottom water breakthrough, and determined the five main types of the remaining oil. Li et al. (2008) researched the feasibility of N_2 injection on developing the attic oil of fractured-cavity reservoirs and analyzed its main mechanism including gravity differentiation, oil expansion dissolved gas, and altering the flow direction. They concluded that N_2 injection on improving oil recovery for single wells was feasible. Wang (2009) studied the flow mechanism of three phases (oil/gas/water) in fracture-cavity mediums combining the numerical simulation and theoretical analysis, which had provided the theoretical foundation on the gas injection for EOR.

This paper presents the results of an experimental study on the feasibility of gas medium huff-n-puff in the single well set up in a 3D physical simulation model. The influence and mechanisms of gas injection position were studied through 2D visualized model. Then two groups of N_2 huff-n-puff experiments were conducted in the three-dimensional resisted model to demonstrate the results concluded through the experiments conducted in the 2D model.

Methodology

Experimental physical models

A 2D visualized physical model and a 3D pressure resistant model were designed and fabricated according to the similar theories, which have been described in detail in previous documents (Li et al. 2014; Hou et al. 2014). Tahe oilfield in Tarim Basin of China is a typical fractured-vuggy carbonate reservoir. Large karst vugs, dissolved fracture-vugs, and multi-scale fractures are the main storage and flow spaces. Matrix does not have storage and permeability capabilities. Therefore, the flow pattern in the large vugs is recognized as pipe-flow mode which is much different with seepage in porous media. The flow pattern in fractures is sometime near to seepage in porous media, while sometime near to pipe-flow mode (Lyu et al. 2017; Hou et al. 2018). Therefore, we cannot simply use the conventional parameter (permeability) to characterize the fractured-vuggy reservoir because of its complicated storage spaces.

The 3D physical simulation model was designed and fabricated according to the research on geological model of S48 unit in Tahe oilfield; well group TK467-S48 was selected as the prototype for model design. Longitudinal sections of the geological prototype were divided into six layers. And carbonate powder and epoxy resin were used to suppress the six layers with the same diameter of 40 cm and a height of 5.6 cm. Caves and fractures were carved based on the geological prototype as were shown in Fig. 1. Six layers were bonded together and put into the cylindrical mold, encapsulated, and stereotyped with epoxy resin. Figure 2 shows the well locations and the surrounding fracture-cavity structures. Three wells were designed in the model based on geological wells (TK467 and S48). The red dotted portion in Fig. 2b was filled with sands, so the filling degree of well TK467 and S48 were fully-filling and half-filling. The wells' type and depth were shown in Table 1. The total volume of fractures and caves of the physical model is 3313 cm^3, among which the filling sands occupies 450 cm^3. The filling degree is 13.6%.

The 2D visualized model was designed based on the stratigraphic profile of well S48 and well TK467 in fourth block Ordovician fractured-cavity carbonate reservoir of Tahe oilfield, as shown in Fig. 3. Small-scale fractures and cavities were etched on the artificial carbonate core. The model was filled with sand and sealed by transparent epoxy resin. The size of the model is 30 cm × 30 cm × 5 cm, and entire volume of fractures and cavities is 345 mL, and filling degree is 30%.

Experimental materials

An oil sample representing the crude oil in Tahe oilfield, with density of 0.853 g/cm^3 and a dead oil viscosity of 24.7 cp at 65 °C, was used to saturate the 3D physical model. And another oil sample with the same viscosity at 25 °C used in two-dimensional visualized experiments was prepared with liquid

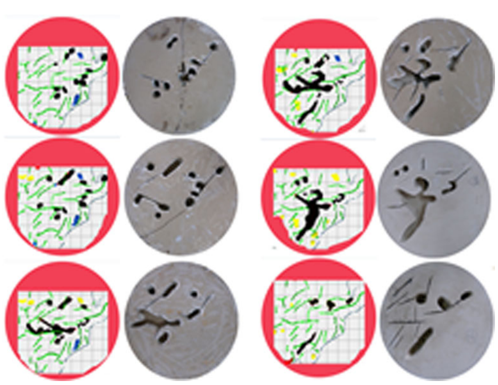
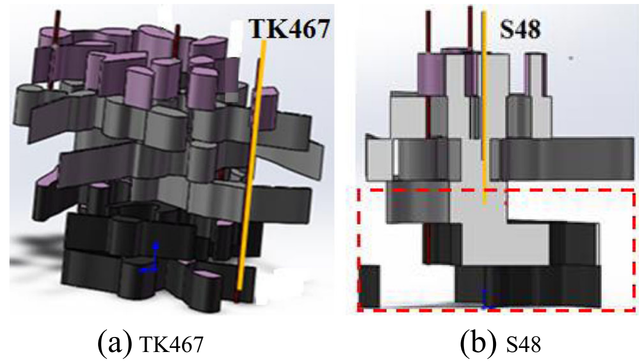


Fig. 1 Comparison of the fractured-cavity structures between the physical model and the real core for each layer



(a) TK467 (b) S48

Fig. 2 Well locations and the surrounding fractured-cavity connection structure

paraffin and kerosene. The oil composition was shown in Table 2. The brine phase in all experiments is the synthetic brine according to the reservoir water analysis results of well S48 in Tahe oilfield, and the salinity is 20 × 10^4mg/L (Mg^{2+} 1440 mg/L, Ca^{2+} 12,000 mg/L, Cl^- 132,000 mg/L, SO_4^{2-} 580 mg/L, HCO_3^- 105 mg/L). Carbon dioxide and nitrogen with stated purities of 99.99 and 99.97%, respectively, were used. And the gas mixture of CO_2 and N_2, volume ratio of which is 1:1, was pressured into a container. The carbonate powder and epoxy resin were used to fabricate the 2D visualized model and 3D physical model.

Experimental setup

Figure 4 shows the schematic of the huff-n-puff experimental setup in 3D physical model. It consists of the injection system, oil production system, and temperature controller system. In production system, a back pressure regulator and a gas-liquid separator were utilized to control the back pressure and measure oil/gas production rate. Besides, three highly sensitive digital pressure gauges, directly connected to the three production wells, were used to record the pressure throughout each experiment. It was also used to observe the pressure depletion during the soaking time, which is an indication of the diffusion process and the solubility of the gas in the oil phase and the fractured-cavity system. In addition, a separate vacuum setup was used to vacuum and saturate the model prior to each experiment.

Table 1 Well parameters of the 3D physical model

Well	Well depth (cm)	Well type	Filling percentage
TK467	18.0	Fracture-well	Fully-filling
S48	9.8	Cave-well	Half-filling

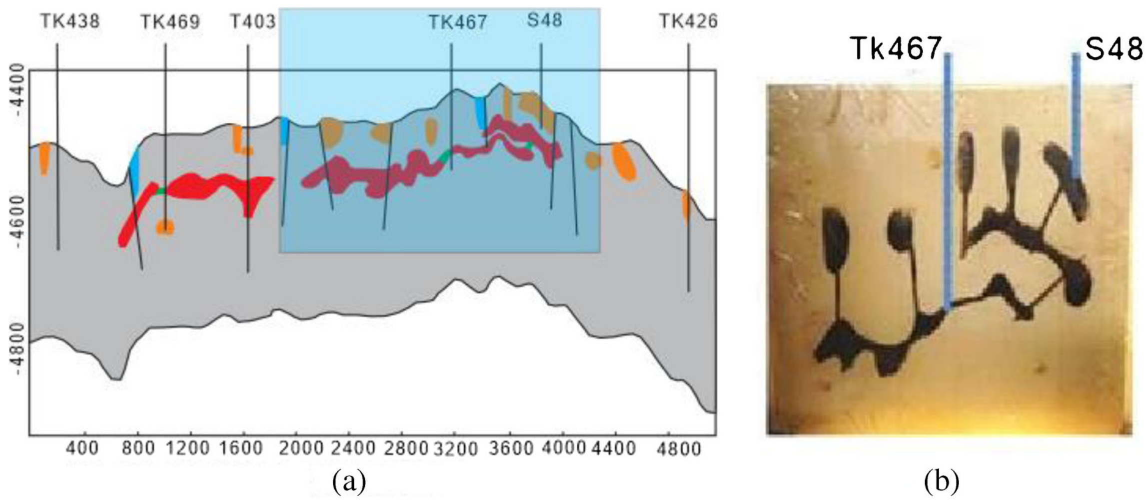


Fig. 3 Fracture-cavity connection of S48 unit (**a**) and the real figure of macroscopic visualized model (**b**)

The schematic diagram of the experimental setup used in 2D visualized huff-n-puff study is shown in Fig. 5. The main components of this setup are as the following:

(1) The injection stream: the main components of an injection stream are the injection line, a N_2 cylinder, a CO_2 cylinder, a gas mixture cylinder, two piston-cylinder apparatuses full of the crude oil and brine, and a high-pressure syringe pump (Teledyne ISCO). Besides, a gas flowmeter in inlet was used to control the gas injecting rate.
(2) Oil production stream: consists of a production line and production valve connected to the production well.
(3) The video system: a light video camera (distinguishability: 1920 × 1080) was used to record the phenomenon of oil/water interface change, the remaining oil distribution, and gas huff-n-puff to start the remaining oil. And a LED panel light was used to ensure the image quality.
(4) Temperature controller system: to maintain a constant temperature of 65 °C and to ensure that the temperature inside the air bath is uniform. A thermo-tank including one heater, two fans, and a digital temperature controlled was used.

Table 2 Composition of crude oil of well TK467 in Tahe oilfield

Composition	mol%
CO_2	0.378
CH_4	38.103
C_2H_6	2.359
C_3H_8	0.792
iC_4	1.287
nC_4	0.835
iC_5	0.627
nC_5	3.569
C_6	0.712
C_{7+}	51.338
	Total 100
C_{7+} relative molecular mass: 254.8139	C_{7+}relative density: 0.8775 g/cm^3

Experimental procedures

In this paper, two kinds of experiments were conducted in 3D model: (a) the huff-n-puff experiments in the single well S48 to study the dynamic performance of three kinds of gas mediums including N_2, CO_2, gas mixture and (b) pure N_2 huff-n-puff experiments in two wells of TK467 and S48 to investigate the impact of gas injection position on the puff performance and EOR effect. The specific procedures are as follows:

(1) All the equipment was firstly set up according to Fig. 4.
(2) Vacuumize the 3D model, and then saturate the synthetic brine and simulated oil to calculate the original oil saturation and irreducible water saturation; finally, set up the back pressure regulator to 3 MPa.
(3) Bottom water displacement: connect "water gravity installation" to the bottom water well and open the well S48 at the same time to simulate the depletion bottom water driving. When the water content reached to 98%, well S48 was then transferred to gas injection well.
(4) The pressure of gas container, physical model, and back pressure was set up 3 MPa, and the gas medium was injected into well S48 at the speed of 5 mL/min.

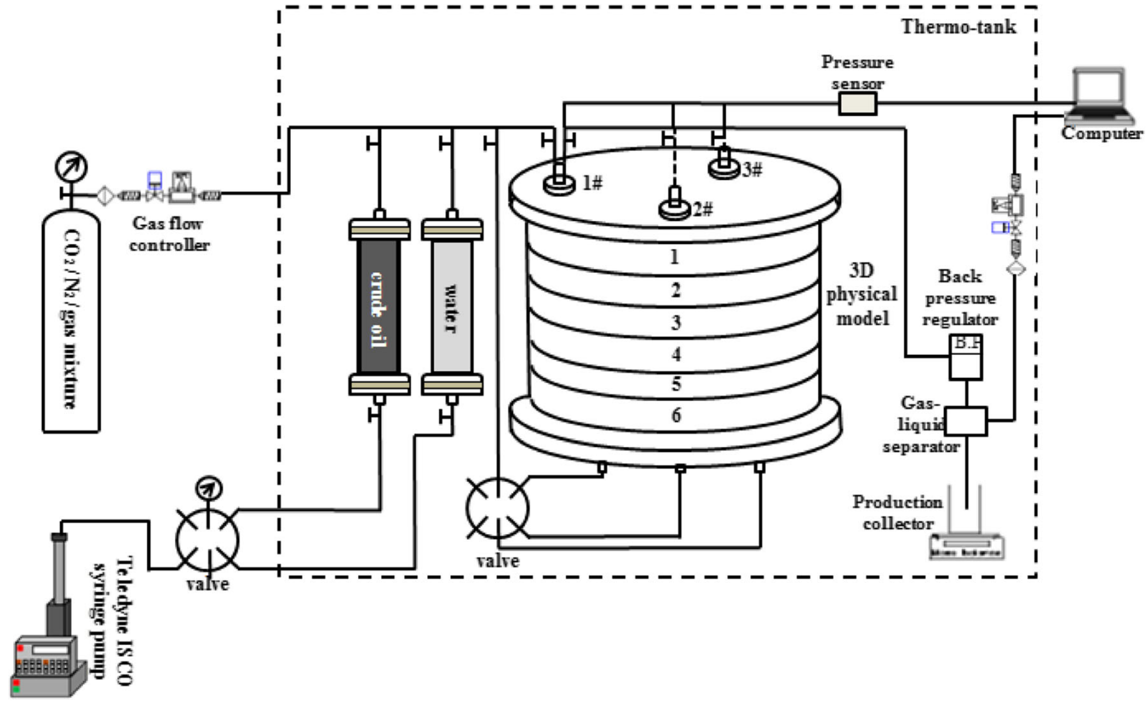


Fig. 4 The schematic diagram of gas huff-n-puff experiments in 3D physical model

The total amount was 100 mL at the condition of 3 MPa and 65 °C.

(5) Puff phase: well S48 was shut in for 24 h (soaking time) after gas medium was injected. Then the puff stage started. The oil/gas/water production rate and pressure were recorded.

Three kinds of experiments were conducted in 2D visualized model: (a) bottom water flooding; (b) oil recovery mechanisms analysis of N_2, CO_2, and N_2/CO_2 mixture injected in well TK467; and (c) oil recovery comparison of N_2 huff-n-puff in low (TK467) and high positional wells (S48). The pressure of back pressure was set up 1 MPa, and

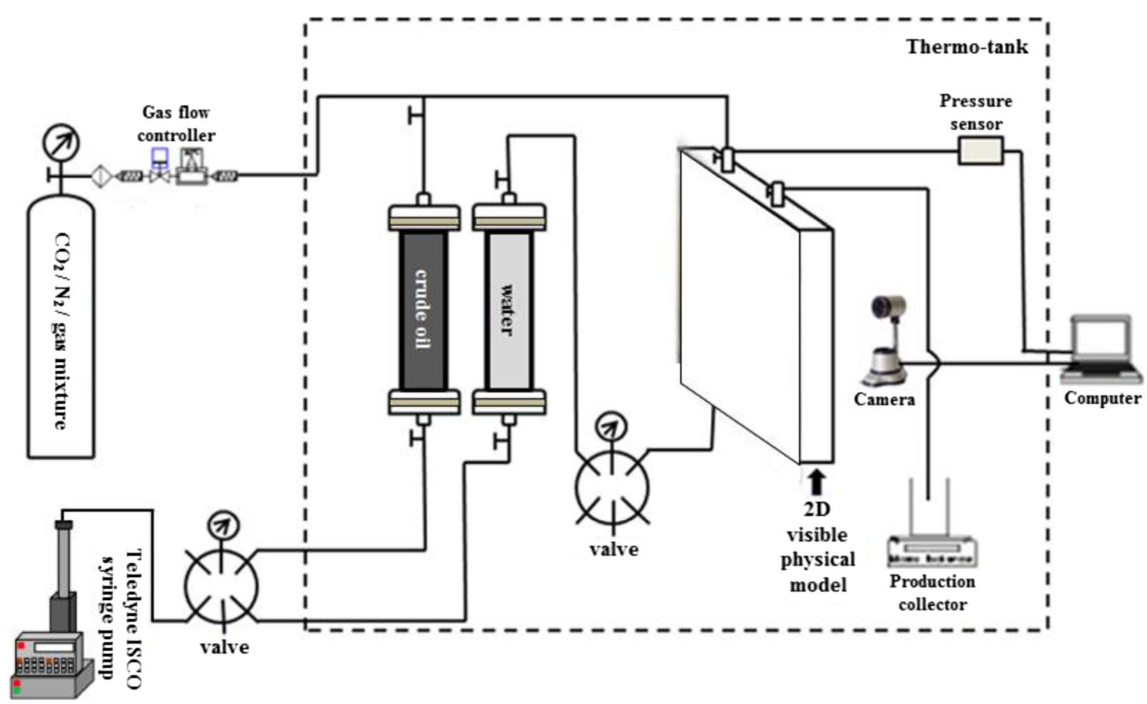


Fig. 5 The schematic diagram of 2D visualized huff-n-puff experiments

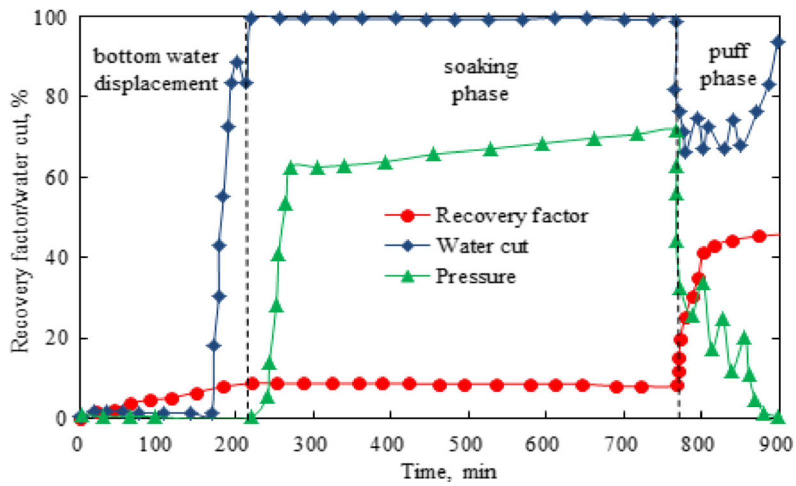


Fig. 6 Dynamic production performance of N_2 puff-and-puff

the gas medium was injected into well TK467 at the speed of 2 mL/min. The total amount was 25 mL (0.1 PV) at the condition of 1 MPa and 65 °C. The aim of bottom water flooding experiment is to investigate oil/water flowing mechanism, formation mechanism, and distribution of residual oil, which was fundamental to analyze the oil recovery mechanisms of N_2, CO_2, and N_2/CO_2 mixture. The influence of gas injection position on oil recovery in N_2 huff-n-puff process was then investigated.

Results and discussion

Oil/water/gas production analysis of N_2/CO_2 huff-n-puff experiments in the 3D model

The single well S48 of the 3D model was selected to study the dynamic performance of three kinds of gas mediums including N_2, CO_2, and gas mixture during huff-and-puff processes. The other well TK467 was shut in. Meanwhile, the parameters of gas/oil ratio, oil production rate, and gas production rate in the puff stage were analyzed and compared.

Oil/water production performance during the huff-and-puff process

The huff-n-puff experimental production curves of N_2, CO_2, and N_2/CO_2 mixture in the single well S48 were shown in Figs. 6, 7, and 8. The experimental procedures of each gas medium huff-n-puff were divided into three stages including bottom water displacement phase, soaking phase, and puff phase. At the beginning of the bottom water displacing phase, the well S48 produced oil stably and there was no water produced. At the time of 178 min, the bottom water occurred and the water cut suddenly reached 100%, which showed eruptible water breakthrough. And it could be inferred that the oil/water

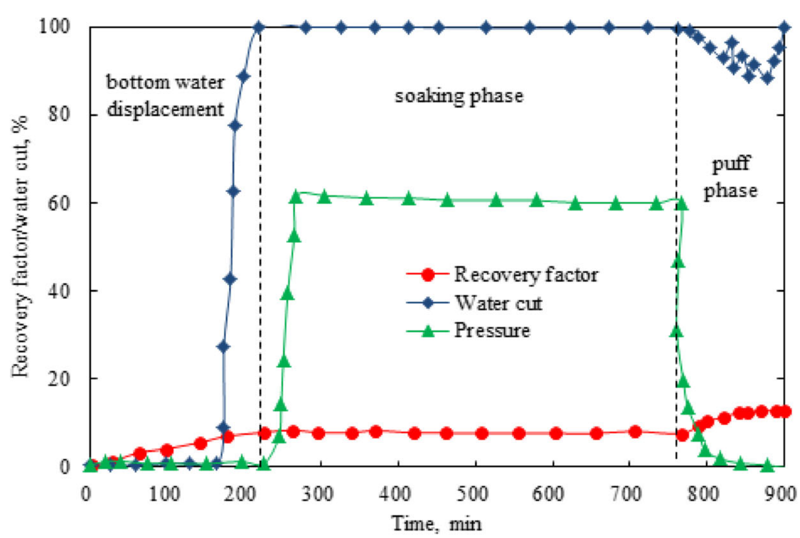


Fig. 7 Dynamic production performance of CO_2 puff-and-puff

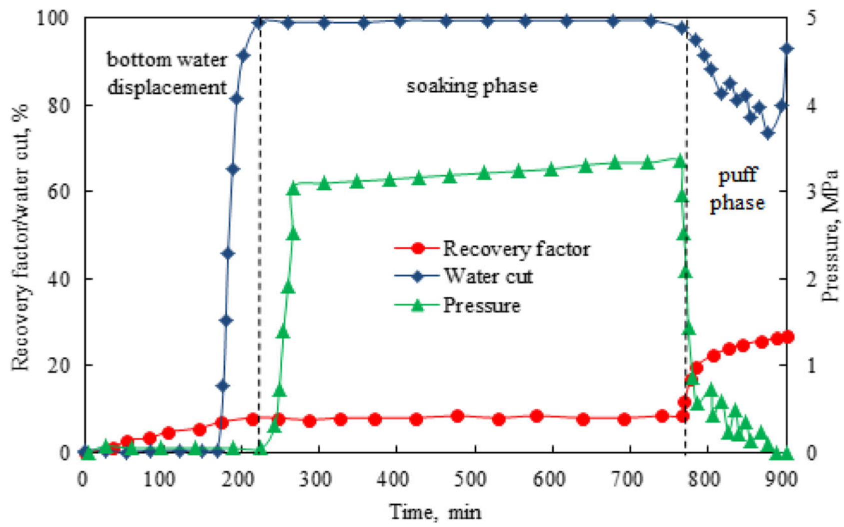


Fig. 8 Dynamic production performance of gas mixture of N_2/CO_2 puff-and-puff

interface went up horizontally before 178 min. The process of bottom water flooding was considered as piston displacement. The water occurred breakthrough within 20 min when the oil/water interface reached in the bottom of well S48. Finally, 9.8% OOIP was recovered in bottom water driving phase.

When the water cut of well S48 reached 100%, the well S48 was shut in and the bottom water was continued injected. Afterwards, the model pressure was quickly rose to 3 MPa. The injected water was to pressurize the model according to its extremely low compression coefficient. At this moment, the nitrogen container, the 3D model, and the back pressure regulator were all set to 3 MPa. Then the 100 mL nitrogen at the condition of 3 MPa and 65 °C was injected into the model. The soaking time started. The model pressure gradually rose and reached to the stable state within 10 h. The model pressure increased by 0.207 MPa and reached to 3.207 MPa finally in the soaking phase. Because pressure gradient along the model is very small, the flow process is primarily dominated by molecular diffusion and capillary forces (Hua et al. 1991). The injected gas volume expanded due to thermal effect. The pressure change after nitrogen injection reflected its effect on stratum energy complement. And the nitrogen gas could accumulate on the top of the model and form gas cap due to insolubility and oil/gas density variation. When the model pressure kept stably, the well and bottom water were both opened and the back pressure operator was set to 0 MPa. Overall, the puff phase was a short process and the pressure decreased to 1.488 MPa within 20 min. The water cut decreased rapidly to a stable state of average 68.5% which was due to the gas cap energy inhibiting bottom water coning. When the gas cap energy was less than that of bottom water, the water cut and the model pressure increased again with the injection of bottom water. When the gas cap energy was much more than that of bottom water, the water cut decreased.

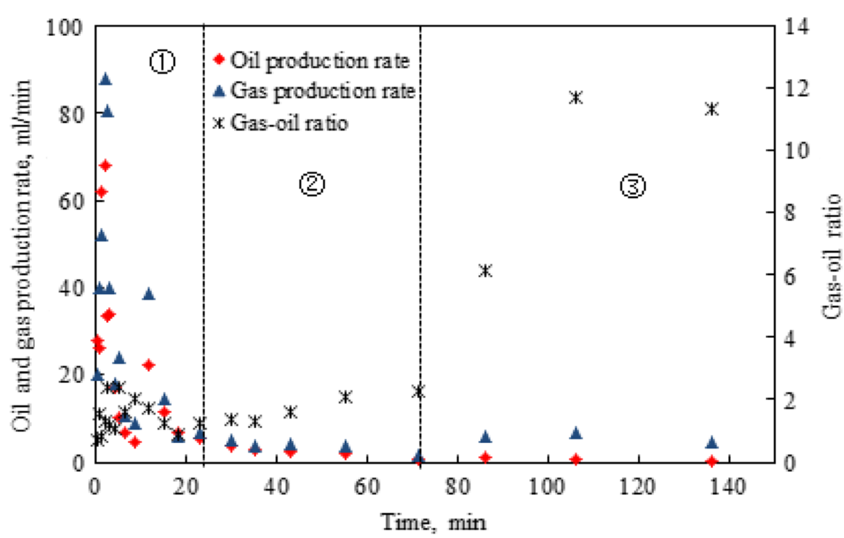


Fig. 9 Oil/gas production rate and gas-oil ratio of N_2 huff-and-puff

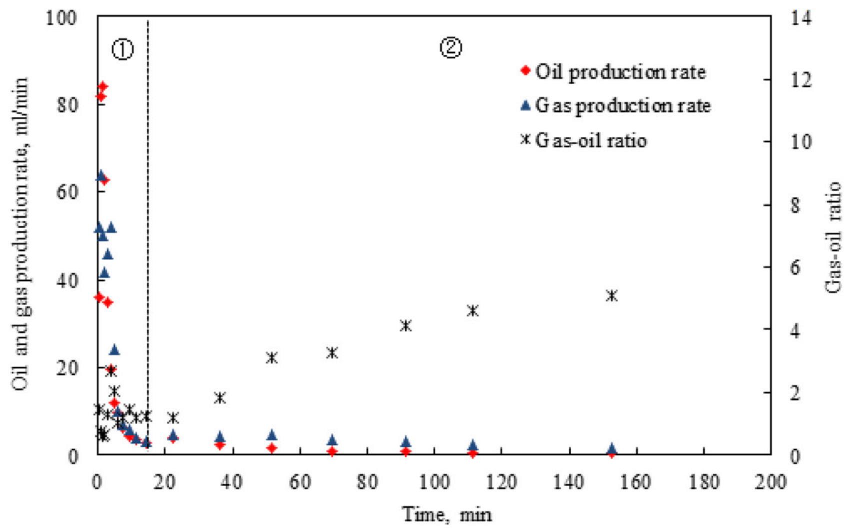


Fig. 10 Oil/gas production rate and gas-oil ratio of CO_2 huff-and-puff

Therefore, both the pressure and the water cut presented the state of fluctuating. The puff phase lasted for 120 min and the final oil recovery during puff stage increased by 35.53%. The fluctuating curve of model pressure and water cut proved nitrogen functions of gravitational differentiation, water coning controlling, and stratum energy complement.

The dynamic production curve of CO_2 huff-n-puff in well S48 was shown in Fig. 7. The experimental procedures were similar to N_2 huff-n-puff. Compared with that of N_2 huff-n-puff, the model pressure in soaking phase decreased gradually a little bit to 2.96 MPa. Molecular diffusion contributes to enhanced oil recovery in puff period (Jia et al. 2018). In this study, molecular diffusion contributed to 0.2–0.3% of oil recovery factor. It could be inferred that the oil viscosity remain unchanged and viscosity reduction with CO_2 dissolution was not apparent. The apparent oil viscosity reduction after CO_2 dissolved reflected the remarkable pressure decrease. Adversely, the slight soaking pressure change reflected tiny oil viscosity reduction. In puff stage, the model pressure decreased to 0 quickly, and it did not show the fluctuated characteristic. Besides, the water cut could merely decrease to an average value of 92.5% and the oil recovery during puff stage improved only by 4.78%, which was far less than that of N_2 huff-n-puff. Therefore, the effect of CO_2 dissolving in oil and reducing oil viscosity was taking the second place while the energy complement of inert gas was in dominant position.

Given the limitation of the single gas, the gas mixture of N_2 and CO_2 was injected simultaneously to investigate whether the synergistic effect existed. The experimental result was shown in Fig. 8. The model pressure also gradually increased by 0.128 MPa, which was less than the single nitrogen. The water cut decreased to an average value of 80% and the oil recovery during puff stage increased by 17.85%, both of which were less than single N_2 huff-n-puff while much more than the single

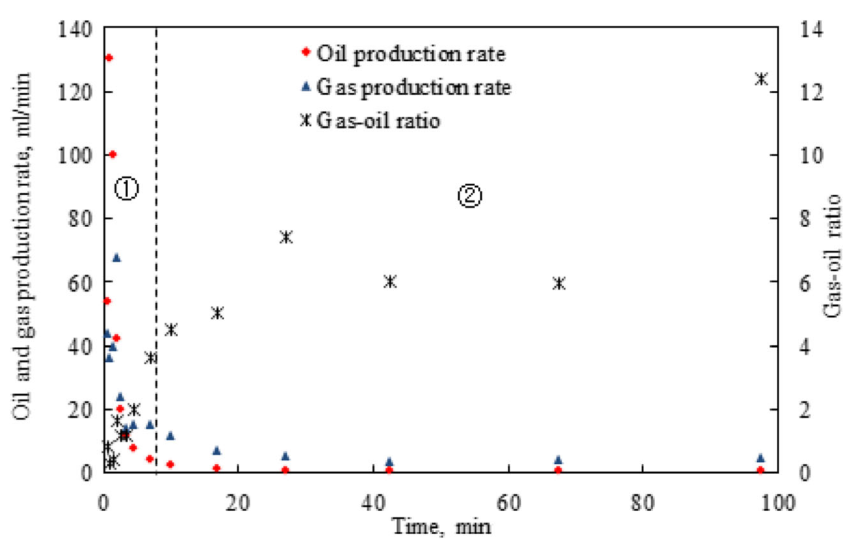
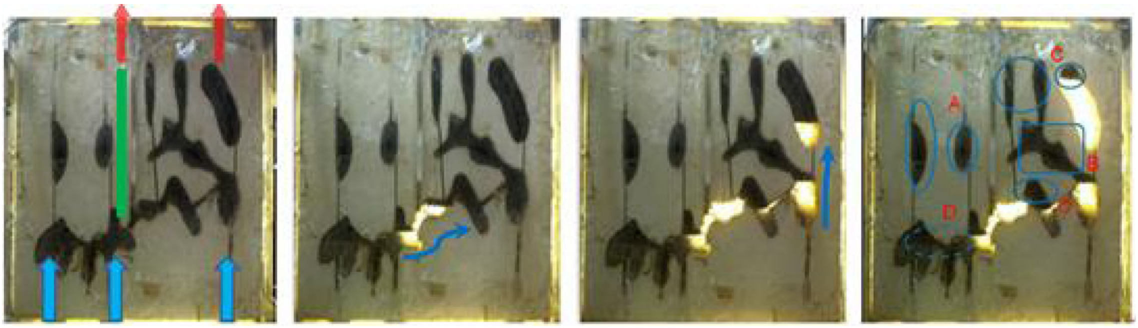


Fig. 11 Oil/gas production rate and gas-oil ratio of N_2/CO_2 mixture huff-and-puff



(a) Oil saturated (b) Piston displacement (c) Forming water channeling (d) Final state

Fig. 12 Oil/water distribution during bottom water flooding process

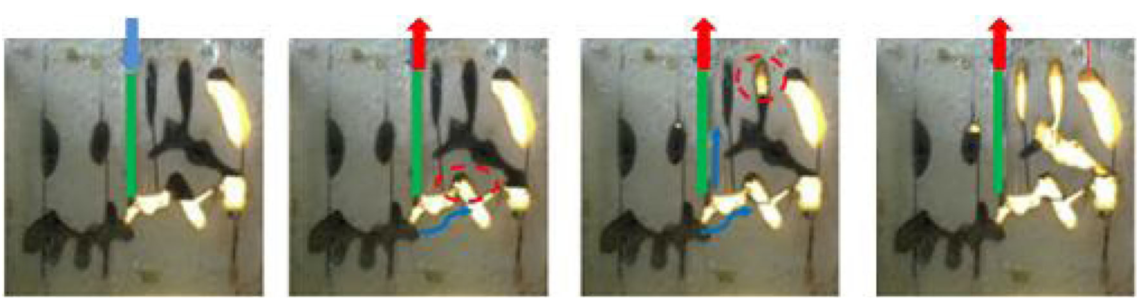
CO_2 huff-n-puff. Overall, the nitrogen in the gas mixture played a major role in reducing water cut and improving oil recovery.

Gas/oil production rate and gas/oil ratio

The experimental production parameters including gas/oil ratio, oil production rate, and gas production rate in the puff stage were analyzed and compared of N_2, CO_2, and N_2/CO_2. The three parameters could reflect and prove that the nitrogen gas was more suitable to improve oil recovery for light oil in fractured-cavity reservoirs. The production parameters of N_2, CO_2, and N_2/CO_2 were shown in Figs. 9, 10, and 11. The production process in N_2 puff stage could be divided into three phases. The period of first 20 min was the early stage in puff process, the features of which were that the gas and oil production rate reached to 100 mL/min rapidly, but the gas/oil ratio maintained around 15. The produced oil in the first stage accounted for 56.2%. The first stage was similar to the energy failure stage and huge quantity of the crude oil was produced in a short period time. The second stage was in relative stable period in which the oil and gas production rate was low. But it maintained a long production time when 32.3% of the total improved oil in the whole puff stage was produced. The third stage was the later and short period in which the gas/oil ratio increased and only 11.5% of oil was produced. It could be inferred that the gas/oil interface reached to the bottom of well S48 and the gas breakthrough was formed.

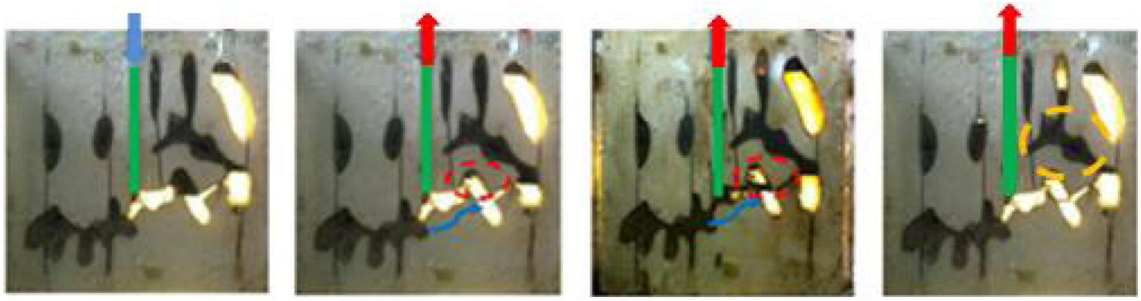
As was shown in Fig. 10, the puff process of carbon dioxide was divided into two stages. Of the oil, 75% was produced in the first stage in which pressure was released immediately. The dissolved gas overflowed and carried huge quantities of crude oil. The production mode in first stage was similar to energy failure production and solution gas driving. And the average production rate of oil and gas kept relative high (around 50 mL/min). While the oil and gas production rate declined sharply in the second stage. The gas/oil ratio increased gradually and kept relative stable, which inferred that a small amount of dissolved gas played a role of the dissolved gas driving in the second stage. Only 25% of the oil was produced in this stage. The puff process of the gas mixture was similar to that of pure carbon dioxide. The gas ratio in the second stage changed a lot, which was different from the stable state of pure carbon dioxide, which indicated the mechanism of energy accumulation and release due to the mixed nitrogen. The oil recovery of gas mixture was much more than that of pure carbon dioxide, but less than that of pure nitrogen, as was shown in Fig. 11.

Therefore, it could be concluded that nitrogen for energy complement and carbon dioxide for dissolved gas driving were the two mechanisms contributed to enhanced oil recovery. Here, energy complement, accumulation, and release



(a) N_2 injection (b) starting bottom attic oil (c) starting bypass oil (d) final state

Fig. 13 Remaining oil startup principle during N_2 huff-n-puff in well TK467



(a) N_2 injection (b) starting bottom attic oil (c) CO_2 breakthrough (d) final state

Fig. 14 Remaining oil startup principle during CO_2 huff-n-puff in well TK467

triggered by nitrogen played a dominant role. Whether the cap energy could be formed play a decisive role on the effect of improved oil recovery in fractured-vuggy reservoirs, which was different from the conventional sandstone reservoir that the dissolved gas driving triggered by carbon dioxide may be the main mechanism.

Remaining oil starting analysis of N_2/CO_2 huff-n-puff in the 2D model

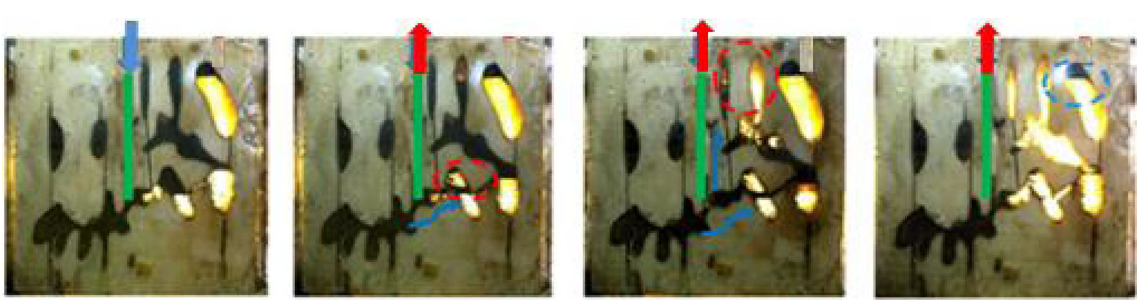
The huff-n-puff experiments in the fractured-cavity 3D model illustrated that the gravitational differentiation of N_2 played a dominant role in improving light oil recovery. Three groups of huff-n-puff experiments were conducted in the designed 2D model to study the oil recovery mechanisms of N_2, CO_2, and N_2/CO_2 mixture. The remaining oil type and distribution after bottom water flooding were firstly analyzed.

Distribution of remaining oil after bottom water flooding in 2D model

Oil/water interface change with bottom water flooding was shown in Fig. 12, from which the residual oil formation and distribution can be observed clearly. At the beginning of bottom water flooding, the oil/water interface went up horizontally when the bottom water was injected. The process of bottom water flooding was considered as piston displacement and pressured pipe flow (Fig. 12b). With the injection of bottom water, the oil/water interface was elevated to step up. When it was higher than the narrow cave in the middle side, the oil could not be displaced. The reason is due to the complex shape of caves and water flow deviated from the breakthrough channel (Fig. 12c). As a result, different types of the remaining oil were formed and distributed in different position (Fig. 12d). The formation mechanisms of the remaining oil are poor connectivity between caves which bottom water could not sweep. The types of remaining oil include those trapped in the closed fractures and caves (A), bypass oil (B), attic oil (C), and oil film absorbed on the surface of fractures (D). Remaining oil was trapped in the closed caves due to bad connectivity between fractures and caves. Because the minimum resistance was the fluid flow direction as was shown by blue arrow in Fig. 12, the bypass oils were easy to form due to the poor swept volume. The attic oils were trapped in the top of caves because of the oil/water density difference. In the caves filled with sands, the oil films formed and affected by wettability, oil viscosity, and temperature.

Remaining oil recovery comparison of N_2, CO_2, and N_2/CO_2 mixture

The oil recovery principle of N_2, CO_2, and N_2/CO_2 mixture in puff stage was in Figs. 13, 14, and 15. Of the nitrogen gas, 0.1 pore volume was injected under the condition of 1 MPa and



(a) N_2 injection (b) starting bottom attic oil (c) starting partial bypass oil (d) starting bypass oi

Fig. 15 Remaining oil startup principle during N_2/CO_2 huff-n-puff in well TK467

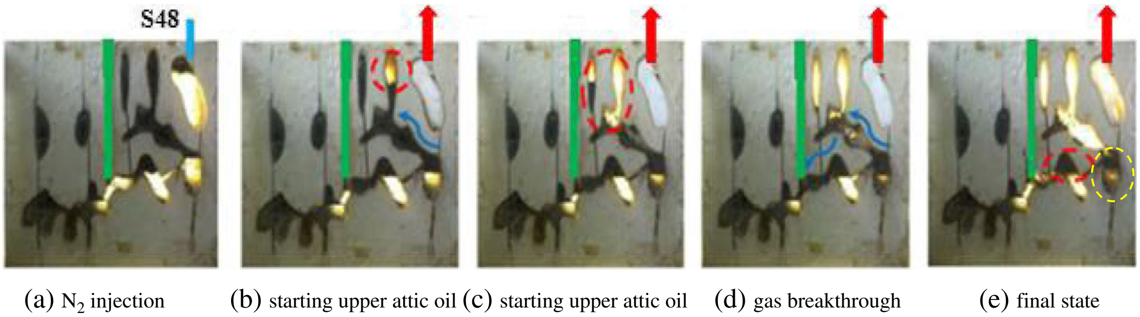


Fig. 16 Remaining oil startup principle of N_2 huff-n-puff in high positional well S48

65 °C. The soaking time ran for 1 h and the well TK467 was then changed into the production well. As was shown in Fig. 13b, the attic oil in the bottom cave was replaced as the majority of the injected nitrogen gas stored in the bottom part in the initial puff stage. Then nitrogen transferred to the cave in the upper part due to the density difference, and the gas/oil interface appeared gradually (Fig. 13c). The attic oil in the upper part and the bypass oil were totally activated (Fig. 13d). In CO_2 puff stage, the attic oil in the bottom cave was firstly activated as CO_2 gas stored and dissolved in the bottom part (Fig. 14b). With the puff went on, the gas/oil interface did not appear in the upper part and the gas breakthrough occurred in the production well TH467. The reason was that the majority of CO_2 dissolved in the bottom water and CO_2 could not move to caves in the upper part. Only small part of the upper attic oil and bypass oil were recovered (Fig. 14d). The oil recovery process of N_2/CO_2 mixture was shown in Fig. 15. In the puff stage, part of the nitrogen gas transferred to the upper part and replaced the attic oil and bypass oil. Part of CO_2 dissolved in the bottom water in the bottom cave, which was not beneficial to improve oil recovery. On the whole, the oil recovery effect of N_2/CO_2 mixture was close to that of N_2, but much better than the pure CO_2.

Effect of injection position on N_2 huff-n-puff

The 2D visualized model was designed to analyze the remaining oil distribution after bottom water flooding, in which two groups of N_2 huff-n-puff experiments were conducted in high-position well S48 and low-position well TK467 to study the effect of gas injection position on the remaining oil activity. Then two groups of N_2 huff-n-puff experiments were conducted in the 3D resisted model to demonstrate the results concluded through the experiments conducted in the 2D model.

Effect of N_2 huff-n-puff with different injection position in 2D model

The production performance of N_2 huff-n-puff in high-position well S48 in 2D model was shown in Fig. 16. In the process of gas injection, nitrogen tended to flow along the blue direction and accumulate on the top of the middle cave due to gravitational differentiation (Fig. 16b). But it could not flow into the caves in left side which were filled with sands. Thus, the resistant was much larger than the caves in the right side. In puff stage, the attic oil in the middle cave was recovered due to the effect of gas cap, as the red cycle showed in Fig. 16c. But it was easy to form gas breakthrough along the blue line to well S48 when the gas/oil interface reached the bottom of well S48 (Fig. 16d). Besides, part of the remaining oil was driven to the cave in the lower side and formed the new type of remaining oil, as the yellow cycle showed in Fig. 16e.

Similarly, the production process of N_2 huff-n-puff in single well TK467 was shown in Fig. 17. Nitrogen tended to

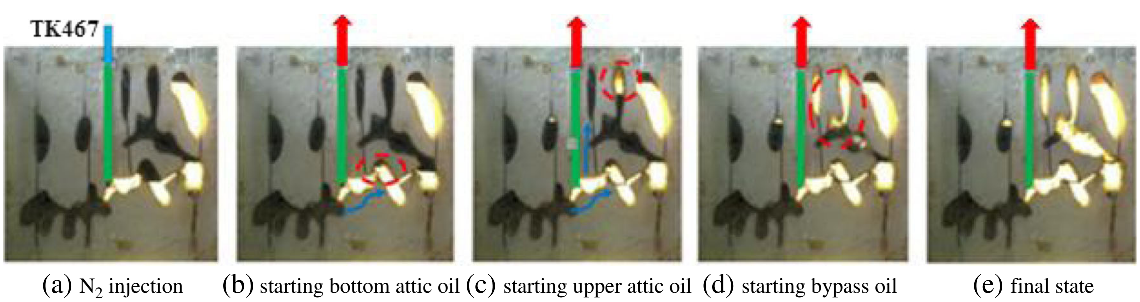


Fig. 17 Remaining oil startup principle of N_2 huff-n-puff in low positional well TK467

Table 3 Comparison of N_2 huff-n-puff oil recovery effect in different position

Position	Well	Injection volume, mL (3 MPa, 65 °C)	Oil production volume, mL	Oil recovery, %
High	S48	100	710.6	35.53
Low	TK467	100	865	43.25

accumulated on the top part of right-side caves in the process of gas injection. In puff stage, the gas/oil interface went down slowly and replaced the remaining oil, the displacing process of which was like the piston flooding. The gas was not formed breakthrough channel until the oil/gas interface reached the bottom of well TK467, as was shown in Fig. 17e. All types of the remaining oil in the right side were recovered. As a result, N_2 huff-n-puff should be implemented in the low-position well in case of the early gas breakthrough.

Oil production volume with different N_2 injection position in 3D model

N_2 huff-n-puff experiments in the single well S48 and well TK467 were conducted, respectively, in 3D physical model. The experimental condition and results were shown in Table 3. Overall, the oil recovery during nitrogen puff phase in the low-position well TK467 was 43.25%, while it was 35.53% in the high-position well S48. The results were consistent with that observed and concluded in the 2D visualized model. As was shown in Fig. 18, the gas production rate during puff stage in well S48 was much higher than that in well TK467. It reflected that the nitrogen gas was easy to form gas channeling if it was injected from high-position well, which resulted in relative lower gas utilization.

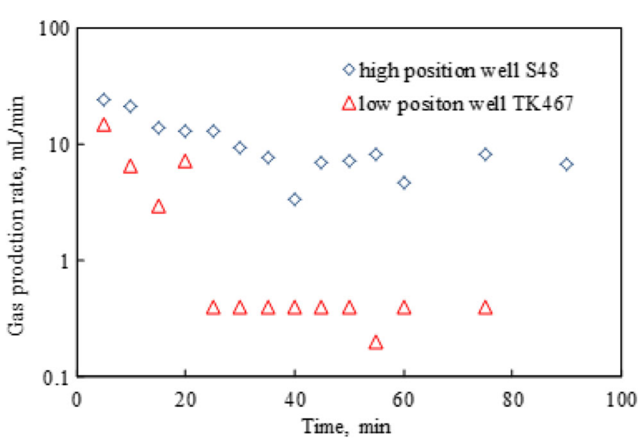


Fig. 18 Gas production rate during puff period of well S48 and well TK467

Conclusions

From this study, the following conclusions can be drawn:

(1) The designed and fabricated 2D and 3D models are closer to the reservoir situation of fourth block, Tahe oilfield. The production performance of gas huff-n-puff experiments could represent and instruct the real production condition.
(2) The effect of CO_2 dissolving in oil and reducing oil viscosity is taking the second place while the energy complement of N_2 is in dominant position. In the gas mixture, the nitrogen played a major role in reducing water cut and complementing formation energy. The nitrogen gas gradually migrates to the high structural position and forms gas cap for energy supplement. It replaces the attic oil in the top part and bypass oil in the bottom part, and redistributes the remaining oil.
(3) It could be concluded that there exist four types of the remaining oil including those trapped in the closed fractures and caves, bypass oil, attic oil, and oil film absorbed on the surface of fractures. All types of the remaining oil could be recovered if N_2 huff-n-puff measure is implemented in the low-position well in case of the early gas breakthrough.
(4) The 3D model with complicated fracture-vug structure could represent the fracture-vuggy reservoir to some extent. But the experimental pressure is not easy to reach the field condition (60 MPa), so we still need to improve the model both in the structure and in the pressure condition. Besides, the influencing parameters of soaking time, huff-n-puff cycles, production rate, and so on should be evaluated in the future work.

Acknowledgements The insightful and constructive comments of the anonymous reviewers are also gratefully acknowledged.

Funding The authors wish to thank the National Natural Science Foundation of China and State Key Science and Technology Project of China for their financial support to carry out this research.

References

Alfarge D, Wei M, Bai B (2017) Factors affecting CO_2-EOR in shale-oil reservoirs: numerical simulation study and pilot tests. Energy Fuel 2017:31(8)

Chen Z, Liu C, Yang J, Lu X (2005) Development strategy of fractured-vuggy carbonate reservoirs-taking Ordovician oil/gas reservoirs in main development blocks of Tahe oilfield as examples. Oil Gas Geol 26(5):623–629

Chen ZJ, Liu L, Wang W (2010) Characteristics and controlling factors of the Upper Ordovician petroleum reservoirs in the Tazhong No.1 fault belt, Tarim basin. Pet Explor Dev 37(4), 40(9)):415–429

Cruz Hernandez J, Islas Juarez R, Perez Rosales C, Rivas Gomez S, Pineda Munoz A, Gonzalez Guevara JA (2001) Oil displacement by water in vuggy fractured porous media. SPE Latin American and Caribbean petroleum engineering conference. In: Society of Petroleum Engineering

Cudjoe S, Vinassa M, Gomes JHB et al (2016) A comprehensive approach to sweet-spot mapping for hydraulic fracturing and CO_2 huff-n-puff injection in Chattanooga shale formation. J Nat Gas Sci Eng 33:1201–1218

Du J, Zhou X, Li Q, Wu G, Pan W, Yang T (2011) Characteristics and controlling factors of the large carbonate petroleum province in the Tarim basin, NW China. Pet Explor Dev 38(6):652–661

Firouz AQ, Torabi F (2014) Utilization of carbon dioxide and methane in huff-and-puff injection scheme to improve heavy oil recovery. Fuel 30(117):966–973

Haskin HK, Alston RB (1989) An evaluation of CO_2 huff-n-puff tests in Texas. J Pet Technol 41(02):177–184

Hou JR, Li HB, Jiang Y (2014) Macroscopic three-dimensional physical simulation of water flooding in multi-well fracture-cavity unit. Pet Explor Dev 41(6):784–789

Hou J, Luo M, Zhu D (2018) Foam-EOR method in fractured-vuggy carbonate reservoirs: mechanism analysis and injection parameter study. J Pet Sci Eng 164:546–558

Hua H, Whitsoll CH, Yuandiang Q (1991) A study of recovery mechanisms in a nitrogen diffusion experiment. Society of Petroleum Engineers

Jia B, Tsau JS, Barati R (2018) Role of molecular diffusion in heterogeneous, naturally fractured shale reservoirs during CO_2 huff-n-puff. J Pet Sci Eng 164:31–42

Kantzas A, Nikakhtar B, De Wit P, Pow M, Jha KN (1993) Design of a gravity assisted immiscible gas injection program for application in a vuggy fractured reef. J Can Pet Technol 32(10)

Li JY, Jiang HQ, Li JJ (2008) The feasibility study for fractured and cavernous carbonate reservoir by injection nitrogen. Inner Mongolia Petrochem Ind 34(23):84–87

Li HB, Hou JR, Li W (2014) Laboratory research on nitrogen foam injection in fractured-vuggy carbonate reservoir for enhanced oil recovery. Pet Geol Recov Effic 21(4):93–96

Liu Z, Hou J, Jianglong L, Qian C (2012) Study of residual oil in Tahe 4th block karstic/fractured heavy oil reservoir. North Africa technical conference and exhibition. Society of Petroleum Engineering

Lu M, Cai Z, Xu J, Wang S, Wei J, Song X (2010) Inverse-scattering imaging of cavern models. Pet Explor Dev 37(3):330–337

Lyu X, Liu Z, Hou J, Lyu T (2017) Mechanism and influencing factors of EOR by N_2 injection in fractured-vuggy carbonate reservoirs. J Nat Gas Sci Eng 40:226–235

Palmer FS, Landry RW, Bou Mikael S (1986) Design and implementation of immiscible carbon dioxide displacement projects (CO_2 huff-puff) in South Louisiana. SPE annual technical conference and exhibition. Society of petroleum engineering

Perez Rosales C, Mercado Diaz A, Cruz Hernandez J, Islas Juarez R (2002) Electric resistivity of vuggy fractured media. SPE international petroleum conference and exhibition in Mexico. In: Society of Petroleum Engineering

Popov P, Qin G, Bi L, Efendiev Y, Ewing RE, Li J (2009) Multiphysics and multiscale methods for modeling fluid flow through naturally fractured carbonate karst reservoirs. SPE Reserv Eval Eng 12(02): 218–231

Qazvini Firouz A (2011) Applicability of solvent based huff-n-puff method to enhance heavy oil recovery. Petroleum system engineering program, Faculty of Engineering and Applied Science, University of Regina

Sanchez Bujanos JL, Abundes A, Valeriano A, Morales J, Rodriguez Torres A (2005) Nitrogen injection in the Cantarell complex: results after four years of operation. SPE Latin American and Caribbean petroleum engineering conference. Society of Petroleum Engineering

Simpson MR (1988) The CO_2 huff-n-puff process in a bottom water drive reservoir. J Pet Technol 40(07):887–893

Torabi F, Asghari K (2010) Effect of operating pressure, matrix permeability and connate water saturation on performance of CO_2 huff-and-puff process in matrix-fracture experimental model. Fuel 89(10):2985–2990

Wang DS (2009) Flow mechanism experiment and numerical simulation research in fractured-cavity medium. China University of Petroleum, Beijing

Xu T, Lun Z, Zhang X, Cheng YL (2010) Gravity drainage in oil-wet carbonate matrix rock system. Pet Explor Dev 37(3):358–362

Yuan DY, Hou JR, Song ZJ, Wang Y, Luo M, Zheng ZY (2015) Residual oil distribution characteristic of fractured-cavity carbonate reservoir after water flooding and enhanced oil recovery by N_2 flooding of fractured-cavity carbonate reservoir. J Pet Sci Eng 129:15–22

Zhao R, Zhao H, Yue XA, Wu Y, Ke W (2010) Enhanced heavy oil recovery from fractured vuggy carbonated reservoir of Tahe oilfield with N_2/CO_2 gas mixture. International oil and gas conference and exhibition in China. Society of petroleum engineering

Zheng SQ, Li Y, Zhang HF (2010) Fracture-cavity network model for fracture-cavity carbonate reservoir. J China Univ Pet 34(3): 72–75 +79