A Comparative Experimental Study of IOR Potential in Fractured Shale Reservoirs by Cyclic Water and Nitrogen Gas Injection

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Abstract

Oil production from tight and shale formations accounted for more than half of total U.S. oil production in 2015 (EIA, 2016). Such amount is expected to grow significantly as the active development of low permeability reservoirs continues. Since the primary recovery is becoming less effective and large amounts of oil are locked in matrix, IOR techniques should be considered to face such challenge. Many recent studies have evaluated the potential of gas injection in shale plays. However, few studies discussed the feasibility of water huff-n-puff process. This study evaluated the potential of cyclic water injection (CWI) in shale plugs and compared it with the performance of cyclic gas injection (CGI).

Eagle Ford core samples were used in this study and saturated with dead shale oil. X-ray diffraction (XRD) technique was employed to analyze the mineral composition of the sample. To reduce clay swelling, 5 wt.% of potassium chloride (KCl) solution was used as the injection fluid in CWI tests. Two groups of experiments were performed to examine the effects of soaking time and injection pressure (P_{in}) on the recovery performance. For one cycle of huff-n-puff, after reaching the P_{in} , the core plug was soaked with water for a certain time, then the surrounding pressure was released to enter the production period. Under the same operating conditions, CGI tests were conducted to compare the two IOR performances.

The CWI experimental results show that soaking time affects the recovery factor (RF) of a single cycle within a certain range, which was similarly concluded from the CGI tests. Injection pressure can affect the recovery performance of CWI significantly. For example, after performing 12 cycles of water huff-n-puff, the RF for tests with P_{in} of 1,000 psi and 5,000 psi were 14% and 21%, respectively. When applying 5,000 psi, fractures were created on the plug and the size enlarged with further cycles operated. Comparing the two processes of CWI and CGI, different recovery characters can be observed. CWI showed the recovery potential at the first four cycles, and then the incremental oil recovery decreased dramatically in the subsequent cycles. By contrast, CGI presented a more continuous and steady recovery performance with high incremental RF, and then gradually diminished after seven cycles of huff-n-puff processes.

Keywords:

Water huff-n-puff; Gas huff-n-puff; Shales; Improved oil recovery

Nomenclature

CGI = cyclic gas injection

CWI = cyclic water injection

P_i = injection pressure, psi

RF = recovery factor

V_o = oil-in-place of the plug after saturation, cm^3

W_{dry} = dry weight of the core plug, g

W_{exp} = weight of the plug measured after each huff-n-puff cycle, g

W_{sat} = oil saturated weight of the plug, g

XRD = X-ray diffraction

ρ_o = oil density, g/cm^3

ρ_w = 5% KCl solution density, g/cm^3

1. Introduction

Cyclic injection can be related to either well-to-well or a single-well process, and the injected fluids involve in liquid, gas, or steam. For the well-to-well process, a recovery enhancement fluid is cyclically injected to the reservoir formation to displace the residual oil to adjacent production wells, such process is also described as cyclic flooding.

The cyclic injection for a single-well consists of three stages, which is also known as huff-n-puff. The first stage (huff phase) is injection, during which the fluid is introduced into the reservoir under a certain injection rate. The reservoir pressure is building up and such stage will be continuously operated until the desired soaking pressure achieved. The second stage (soak phase) requires that the well be shut in for a certain period to allow time for pressure equilibration and fluids interaction in porous media. Finally, during the third stage (puff phase), the well is reopened and production is resumed with the depletion of reservoir pressure. The cycle is repeated as long as the oil production profitable. This paper focuses on evaluating the water huff-n-puff process for a single-well in fractured shale reservoirs by experimental work.

The recovery performance of cyclic water flooding in conventional reservoirs has been demonstrated by lots of experimental and simulation studies as well as field practice reports (Li et al., 1995; Stirpe et al., 2004; Shchipanov et al., 2008; Surguchev et al., 2008). The concept of such cyclic injection is based on (1) pulsed injection and (2) alternating waterflood patterns. It presents the greatest potential for improved recovery in heterogeneous, high-permeability contrast sandstones and in naturally fractured carbonates, and dolomites (Surguchev et al., 2002). However, few publications reported the response of cyclic water injection (CWI) recovery process in a single well. In addition, due to the poor injectivity of water in shale formations, there have been no experimental or simulation studies performed on evaluating CWI in such cases. This study is proposed to explore the feasibility of water huff-n-puff in shale plays.

To maintain and maximize the oil production from shale reservoirs, IOR technology should be applied, and comprehensive evaluation of the performances of various potential approaches should be conducted. Many laboratory observations and numerical simulation studies (Song and Yang, 2013; Wan et al., 2013; Sheng, 2014; Sheng and Chen, 2014; Tovar et al., 2014; Fragoso et al., 2015; Wan and Sheng, 2015a, 2015b, 2015c; Li and Sheng, 2016; Meng and Sheng, 2016a, 2016b; Meng et al., 2016; Sheng et al., 2016) have evaluated and confirmed the IOR potential of gas huff-n-puff process in unconventional reservoirs. Experimentally, the operating parameters of injection pressure, soaking time, pressure depletion rate, and number of cycles in gas huff-n-puff have been studied in previous works (Gamadi et al., 2014; Wan et al., 2015; Yu et al., 2016a). Water injection is a successful IOR method that has been widely employed in conventional reservoirs for many decades, while the effectiveness of such method has almost not been tested in shale plays. This study evaluated the performance of water huff-n-puff process in shale plugs with the matrix permeability less than 1 μD . The effects of soaking time and injection pressure on oil recovery factor were investigated. For the comparison purpose, gas huff-n-puff tests were performed under the same operating conditions of injection pressure and soaking time as those applied in water huff-n-puff tests.

For gas injection EOR, methane could be a good option because it is readily available and it is compatible with the reservoir hydrocarbon fluids. However, methane is in high demand for industrial and home uses. Carbon dioxide can achieve miscibility at a lower pressure than other gases. But carbon dioxide is not always available in required volumes. Air is easy to access and cost-effective, but we may have safety issue and facility corrosion issue. Alternatively, nitrogen gas can serve as an abundant and economical agent to recover oil. In addition, considering the operation convenience and safety in lab, we choose N_2 as the gas source in gas huff-n-puff tests.

2. Experimental Work

2.1 Materials

The core samples used in this study were cut from the Eagle Ford shale outcrop parallel to the bedding planes. Total six core plugs with similar rock properties were used to conduct water huff-n-puff processes under designed operating conditions, and four of them would be used for the nitrogen gas huff-n-puff tests. **Table 1** gives the dimensions and measured helium porosities of the core samples.

The nitrogen permeabilities of the plugs varied from 320 nD to 390 nD, which were determined using the complex transient method (Boitnoot, 1997). The measurement system (AutoLab 1000) is developed by New England Research Inc. The system controls the pore pressure at one end of the sample (referred to as the upstream end) while the other end of the sample is attached to a fixed volume filled with pore fluid. The pressure is monitored at both the upstream and downstream ends of the sample. Starting with the system in equilibrium and then perturbing the pressure at the upstream end of the sample, the response at the downstream end of the sample is measured.

The oil sample used for core plug saturation was the dead shale oil with a density of 0.815 g/cm³ and a viscosity of 8.5 cp which were measured at the room temperature of 71 °F.

Table 1 Core plug specifications

Core No.	Dry Weight (g)	Length (mm)	Diameter (mm)	Porosity
WHP_2	127.0848	50.9	38.3	9.71%
WHP_3	125.6778	50.9	37.9	8.99%
WHP_4	125.2180	50.9	37.9	10.18%
WHP_5	125.1510	50.9	38.2	10.91%
WHP_6	124.7914	50.8	38.1	10.56%
WHP_8	125.2297	50.8	38.1	9.89%

2.2 Mineral Composition Analysis

Rock properties determine the fluid flow and oil recovery to a great extent. The physical (i.e., permeability, fracability, wettability) and chemical properties of shale rocks strongly depend on the type and amount of clay minerals present (Dargahi et al., 2013). In order to understand the mineral composition of the rock, X-ray Diffraction (XRD) technique was employed to identify and quantify the mineral phases present in the sample. A Rigaku Ultima III powder X-ray diffractometer was used for quantitative analysis. **Table 2** provides a summary of identified minerals and their abundance. Quartz and calcite are evident in the sample with the amount of 24.9 wt.% and 58.3 wt.%, respectively. The total content of clay mineral, kaolinite and illite, is 7.4 wt.%. Since shales and clays swell in the presence of fresh water, clay stabilizer is necessary to add into the treatment fluids. Potassium chloride (KCl) helps control clay swelling and helps minimize fines migration. Typical KCl concentrations are 2 to 7% by weight of water (Halliburton, 2007). Since the content of identified clay minerals in the core sample was low with 7.4 wt.%, and there were no mixed-layer clays detected, it can be estimated that the sample is not so sensitive to hydration swelling effect. So we selected a median concentration of 5 wt.% KCl solution as the injection fluid for water huff-n-puff tests.

Table 2 Mineral composition of the Eagle Ford shale sample

Phase	Quartz	Calcite	Anhydrite	Kaolinite	Gypsum	Acmite	Illite
Wt. %	24.9	58.3	2.3	4.0	3.6	3.5	3.4

2.3 Experimental Setup and Procedure

The experimental work consists of two parts: core plug saturation and water/gas huff-n-puff recovery process. Prior to each test, the core plug was placed in an oven and dried for 24 hr with the temperature of 248 °F and then weighted (W_{dry}). Subsequently, it was placed in a vessel and vacuumed for 24 hr. After that, it was saturated with dead oil for 24 hr for maximum saturation. Then, the core was removed from the oil and weighted (W_{sat}) after a few hours to stabilize the weight. The detailed setup, operation procedures of core saturation, evaluation of saturation degree, and data uncertainty analysis for individual huff-n-puff test can be referred to our previous paper (Yu et al., 2016b) and Yu's dissertation (Yu, 2016).

The experimental setup used for water huff-n-puff tests is shown in **Fig. 1**. It mainly includes: a Quizix pump (QX-6000), an accumulator with the maximum operating pressure of 10,000 psi, a high-pressure vessel, pressure gauges, and valves. For the water huff-n-puff case, the oil-saturated plug was placed in the vessel in the vertical position. There was 1.0 cm space between the inside wall of the vessel and the core outer boundary, such annular space represented fractures surrounding the matrix. The vessel was filled with 5 wt.% KCl solution. The Quizix pump was used to deliver the KCl solution from the accumulator to the fracture-matrix system (vessel). Firstly, the pump was operated in the mode of constant pressure delivery (set the injection pressure P_{in}). With the solution injected into the vessel, the matrix-fracture system pressure increased, which represented the huff phase of cyclic water injection process. Once the system pressure reached P_{in} , the three-way valve and the pump were closed. Thus, it entered the soaking phase of the cyclic injection. After a certain period of soaking time, the three-way valve was opened to allow the liquid flow out and bleed the pressure of the vessel. The plug was remained in the vessel for 3 hr to be in equilibrium with the system pressure. Such process was the puff phase of the cyclic injection, during which oil would come out from the plug. Subsequently, we took the plug out of the vessel, wiped the outside liquid and weighted it, record as W_{exp} , and then placed it back in the vessel for repeating next cycle. Such process is one cycle of water huff-n-puff process. Total 12 cycles were designed to perform for each huff-n-puff test, which aims to study whether significant oil can still be produced after many cycles. Similarly, when conducting the N_2 huff-n-puff tests, N_2 replaced the KCl solution as the injection medium, which could be directly introduced into the vessel from the gas cylinder without using the accumulator.

Fig. 1. Schematic of setup for water huff-n-puff tests

2.4 Experimental Design

As the injection fluid may cause the change in the rock properties of plugs, plus plugs could not be totally cleaned as the original conditions (before operating the tests), different plugs were used to perform CWI tests under different operating conditions. The effect of slight property difference in samples on recovery performance is considered not be significant, because those samples were cut from same area and presented similar rock properties.

In this study, a total of 10 series of huff-n-puff injection tests (performing 12 cycles for each test) were designed to analyze the effects of soaking time and injection pressure on the performance of CWI, and to compare the recovery efficiencies between CGI and CWI. The operating conditions are presented in **Table 3**. In order to study the soaking time effect, four plugs went through the gas/water huff-n-puff processes under a consistent injection pressure of 1,000 psi and different soaking times of 1-hr, 6-hr, 12-hr, and 24-hr, respectively. For each plug, the N₂ huff-n-puff process was performed initially, then the same plug was re-saturated with oil and perform water huff-n-puff tests. In addition, two more plugs were used to operate water huff-n-puff tests under a consistent soaking time of 12 hr, and different injection pressures of 3,000 psi and 5,000 psi, respectively. As the temperature effect was not the focus in this study and to simplify the experimental work, all tests were conducted at the room temperature of 72 °F.

Table 3 Operating conditions for huff-n-puff tests

Test No.	Core No.	Recovery Strategy	Soaking Time (hour)	Injection Pressure (psi)
1	WHP_8	Gas huff-n-puff	1	1,000
2	WHP_8	Water huff-n-puff	1	1,000
3	WHP_6	Gas huff-n-puff	6	1,000
4	WHP_6	Water huff-n-puff	6	1,000
5	WHP_4	Gas huff-n-puff	12	1,000
6	WHP_4	Water huff-n-puff	12	1,000
7	WHP_2	Gas huff-n-puff	24	1,000
8	WHP_2	Water huff-n-puff	24	1,000
9	WHP_5	Water huff-n-puff	12	3,000
10	WHP_3	Water huff-n-puff	12	5,000

2.5 Determination of Oil Recovery Factor

After the saturation process, the volume of oil in the plug (oil-in-place) can be calculated from the weight of saturated core, the weight of dry core, and the value of the density of oil, as Eq. 1:

$$V_o = \frac{W_{sat} - W_{dry}}{\rho_o}, \dots\dots\dots(1)$$

For gas huff-n-puff test, after each cycle, the weight of the plug was measured until no more oil coming out, recorded as W_{exp} . Ignoring the gas weight in the plug and based on mass balance, we have

$$W_{exp} = W_{sat} - RF \cdot V_o \cdot \rho_o, \dots\dots\dots(2)$$

Therefore, the cumulative RF after performing each cycle of gas huff-n-puff can be written as

$$RF(G) = \frac{(W_{\text{sat}} - W_{\text{exp}})}{(W_{\text{sat}} - W_{\text{dry}})}, \dots\dots\dots(3)$$

Recovery factor for water huff-n-puff test was determined by the weight gain of the plug (before and after the CWI process) and the density difference of the two fluids that occupied the pore spaces of the plug, oil and water. With the increase of surrounding pressure provided by the injected fluid, water penetrated into the plug during the soaking phase. After that, during the puff phase, the system pressure began to decline, oil came out from the plug along with the water, and partial of water remained in the plug. The weight of the plug would increase as the density of water is greater than that of oil. Sample weight was measured after each cycle. The volume ratio of produced oil (same as the volume of water remained in the plug) to the oil-in-place (V_o) is the recovery factor (RF). According to mass balance equation,

$$W_{\text{exp}} = W_{\text{sat}} - RF \cdot V_o \cdot \rho_o + RF \cdot V_o \cdot \rho_w, \dots\dots\dots(4)$$

Recombining Eq. 1 and Eq. 4, RF of CWI process can be determined using the following equation:

$$RF(W) = \frac{(W_{\text{exp}} - W_{\text{sat}}) \cdot \rho_o}{(W_{\text{sat}} - W_{\text{dry}}) \cdot (\rho_w - \rho_o)}, \dots\dots\dots(5)$$

where ρ_w is the 5% KCl solution density (1.12 g/cm³) and ρ_o is the oil density.

3. Results and Discussion

In this study, six sets of water huff-n-puff tests and four sets of N₂ huff-n-puff tests were performed orderly. The results of cumulative recovery factor (RF) obtained after each cycle for each test are presented in **Table 4**. **Figs. 2 and 3** reflect the recovery responses to soaking time for water huff-n-puff and N₂ huff-n-puff processes, respectively.

For water huff-n-puff, the oil can be extracted effectively from the first four or five cycles, during which the incremental RF was stable compared with the oil yielded from subsequent cycles. After that, the recovered oil from each cycle decreased (less than 1% of incremental RF), thus the effectiveness of such process was diminished. By contrast, **Fig. 3** shows that the N₂ huff-n-puff was much more productive that oil could be effectively recovered from the initial seven cycles. The main reason that causes the obvious difference in recovery performance is that the low viscosity gas can penetrate shale matrix easier than water when displacing oil. Considering that the recovery evaluation based on core-scale test are usually overestimated compared with the field-scale conditions, the potential of water huff-n-puff as an IOR solution in shale plays is limited compared with gas huff-n-puff injection.

Table 4 Cumulative RF determined after each huff-n-puff cycle for all tests

Test No. (Type)	Test 1 (CGI)	Test 2 (CWI))	Test 3 (CGI)	Test 4 (CWI)	Test 5 (CGI)	Test 6 (CWI)	Test 7 (CGI)	Test 8 (CWI)	Test 9 (CWI)	Test 10 (CWI)
Soaking Time (hour)	1	1	6	6	12	12	24	24	12	12
P _{in} (psi)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	3,000	5,000
Cycle 1	1.28%	0.38%	1.21%	0.98%	3.54%	1.95%	4.54%	3.60%	3.70%	6.06%
Cycle 2	3.18%	1.83%	4.49%	3.50%	8.11%	4.04%	9.14%	5.59%	6.61%	10.15%

Cycle 3	4.91%	3.31%	7.43%	5.25%	11.35%	5.89%	13.42%	7.66%	9.84%	13.58%
Cycle 4	7.00%	4.87%	10.52%	6.70%	14.93%	7.49%	16.81%	9.00%	11.91%	16.86%
Cycle 5	8.42%	5.75%	12.51%	7.33%	16.45%	8.69%	19.32%	10.08%	13.17%	18.74%
Cycle 6	10.54%	6.29%	14.22%	7.95%	18.10%	9.50%	20.70%	10.65%	14.52%	19.88%
Cycle 7	12.54%	6.46%	15.76%	8.29%	19.40%	10.33%	21.98%	11.28%	15.03%	21.03%
Cycle 8	14.27%	6.80%	17.43%	8.80%	20.13%	11.29%	22.63%	12.32%	15.83%	-
Cycle 9	15.54%	7.12%	18.36%	9.14%	21.43%	12.49%	23.32%	13.11%	16.13%	-
Cycle 10	16.74%	7.46%	19.28%	9.39%	21.97%	13.22%	24.20%	14.14%	16.53%	-
Cycle 11	17.74%	7.55%	19.85%	9.61%	22.62%	13.87%	24.59%	14.80%	17.12%	-
Cycle 12	18.21%	7.67%	20.47%	9.69%	22.94%	14.04%	24.75%	15.03%	17.33%	-

Fig. 2. Oil recovery performance of the water huff-n-puff with different soaking times

Fig. 3. Oil recovery performance of the N₂ huff-n-puff with different soaking times

3.1 Effect of Soaking Time

Soaking time influences the recovery performance of a single cycle of water huff-n-puff within a certain range. According to the oil recovery response to the number of cycles in **Fig. 2**, when applying different soaking times, the recovery difference was generated since the first cycle. For this study, with the condition of rapid build-up of injection pressure (short huff phase), a longer soaking period gave a higher RF of a single cycle. When increasing such period from 1-hr to 12-hr, after the completion of 12 cycles of CWI, an obvious improvement in cumulative oil recovery was achieved with RFs of 7.67% and 14.04%, respectively. While for the test with 24-hr soaking time, the increased cumulative RF was only about 1%, compared with 12-hr. It implies that an extra longer soaking time might not be beneficial to improve the RF more effectively, thus there exists a soaking period that corresponds to the maximum oil recovery. After a certain period of soaking time, it has no positive effect on the oil recovery. Overall, the role of soaking time becomes less significance with the increase of such period. Since the process of pressure build-up in fracture area was very fast in this study, a soaking period is necessary to transfer the surrounding pressure into the matrix and equilibrate the matrix-fracture system pressure.

If it is assumed that the ultimate RF was achieved when the incremental RF less than 0.5%, **Fig. 2** indicates that for the cases of 1-hr and 6-hr soaking periods, the ultimate RF was reached after 6 cycles of CWI; for the cases of 12-hr and 24-hr soaking periods, it took about 11 cycles to achieve the ultimate RF. Therefore, within a certain range, a longer soaking duration can improve the ultimate RF with more huff-n-puff cycles operated.

3.2 Effect of Injection Pressure

Fig. 4 presents the effect of injection pressure on the recovery performance of water huff-n-puff process. It shows that RF increased with the injection pressure, which can be identified since the first cycle. In the first five cycles, with an increase in injection pressure, the incremental RF increased with the performed cycle number. The increased RF was credited from the greater pressure gradient between the matrix and

fracture during the production period. In addition, when 5,000 psi injection pressure was applied (Test #10) and after about six cycles of CWI, we observed that fractures were generated in the core plug (see **Fig. 5**). Those fractures provided the extensive flow channel for the injected fluid, which increased the matrix permeability and promoted oil and water exchange during the periods of pressure buildup and drawdown. Test #10 was terminated after conducting 7 cycles of water huff-n-puff as the developed fractures could cause the overestimation of the recovery performance.

Fig. 4. Oil recovery performance of the water huff-n-puff with different injection pressures

Fig. 5. Pictures of core WHP_3 in top and side view after the water huff-n-puff tests

3.3 Comparison of CWI and CGI

The four plots in **Fig. 6** present consistent trends that the N_2 huff-n-puff process has much better recovery performance than the water huff-n-puff process. Under the same operating conditions, similar amount of oil were produced in the first cycle from two IOR processes. The RF difference between two processes increased with the number of operated cycles. At the end of all tests, with the completion of 12 cycles, the cumulative RF of cyclic injection was 10% higher by using gas than that of water.

Fig. 6. Comparison of recovery performance between the water huff-n-puff and the N₂ huff-n-puff under different soaking times

3.4 Further Discussion

In this study, the dimensions of core plug samples were almost the same. The objective of this paper was to compare the IOR potentials by cyclic water injection and cyclic nitrogen injection. In a study from our group (Li and Sheng, 2016), the core plugs with different diameters and lengths were used in gas huff-n-puff tests to study the upscale issue. The samples had the similar rock properties as they were cut from the same area. The experimental setup and procedures were the same as those used in this study. The results from the work by Li and Sheng (2016) (2016) show that under the identical operating conditions, the core with a larger bulk volume yielded lower oil recovery factor than a smaller core. The simulation results illustrated that when upscaling the core size to the field level, the oil recovery decreased (Li et al., 2016). A further upscale work has been submitted for a journal review that establishes a relationship of shale oil recovery between the core-scale and the field-scale.

Some studies have reported the EOR performance of huff-n-puff process in shale plugs using other gases. Gamadi et al. (2014) conducted experimental work to evaluate the recovery efficiency of cyclic CO₂ injection in shale plugs. Under the condition of immiscible injection, the ultimate recovery factor

varied from 40% to 60% based on the changes in soaking times. Li and Sheng (2016) performed the CH₄ huff-n-puff tests to recovery oil from liquid-rich shale core samples. The experimental results show that more than 45% of oil-in-place could be extracted by cyclic CH₄ injection. The cyclic CH₄ injection outperformed cyclic N₂ injection in terms of oil recovery. It can be seen that under the identical operating conditions, using CO₂ or CH₄ will achieve a higher oil recovery factor than using N₂ by cyclic injection. A comprehensive study of the effect of gases is ongoing.

4. Conclusions

Cyclic water injection (water huff-n-puff) experiments were performed to recover oil from liquid-rich shale core plugs. The effects of soaking time and injection pressure on the recovery performance were examined. We also compared the recovery performances between the water huff-n-puff process and the N₂ huff-n-puff process. The following conclusions can be drawn from this study.

- The potential of water huff-n-puff in shale oil reservoirs is limited with a low ultimate recovery factor. The experimental results show that oil could only be effectively extracted in the first several (e.g. four) cycles.
- Within a certain range, a longer soaking period caused a higher ultimate recovery factor in water huff-n-puff process. Once the maximum RF was achieved, extra longer time had no contribution to the improvement of oil recovery.
- Increasing injection pressure in CWI is beneficial to improve oil recovery. The high pressure also results in a generation of fractures in the matrix after operating several cycles, thus the extended stimulated volume contributed to the additional oil recovery.
- The recovery performance of N₂ huff-n-puff outperformed water huff-n-puff greatly when operating the two processes under the same conditions, with an approximately 10% higher cumulative RF than that of water huff-n-puff.
- Gas huff-n-puff process would be more effective and promising than water huff-n-puff process in shale reservoirs with a longer period of steady production and a higher ultimate recovery factor.

Acknowledgments

This work was supported by the U.S. Department of Energy under Award Number DE-FE0024311.

References

1. Boitnott, G.N. 1997. Use of Complex Pore Pressure Transients to Measure Permeability of Rocks. Presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, 5-8 October. SPE-38717-MS. <http://dx.doi.org/10.2118/38717-MS>.
2. Dargahi, H.J., Rezaee, R., and Pejic, B. 2013. Clay Mineralogy of Shale Gas Reservoirs through Integrating Infrared Spectroscopy and X-Ray Diffraction. Presented at the Unconventional Resources Technology Conference, Denver, Colorado, USA, 12-14 August. SPE-168908-MS. <http://dx.doi.org/10.1190/URTEC2013-210>.
3. Energy Information Administration (EIA). 2016. Initial production rates in tight oil formations continue to rise, 11 February 2016, <https://www.eia.gov/todayinenergy/detail.cfm?id=24932> (accessed 30 March 2016).
4. Fragoso, A., Wang, Y., Jing, G., and Aguilera, R. 2015. Improving Recovery of Liquids from Shales through Gas Recycling and Dry Gas Injection. Presented at the SPE Latin American and Caribbean Petroleum Engineering Conference, 18-20 November, Ecuador, Quito. SPE-177278-MS. <http://dx.doi.org/10.2118/177278-MS>.
5. Gamadi, T.D., Sheng, J.J., Soliman, M.Y., Menouar, H., Watson, M. C., and Emadibaladehi, H. 2014. An Experimental Study of Cyclic CO₂ Injection to Improve Shale Oil Recovery. Presented at the SPE

- Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, 12-16 April. SPE-169142-MS. <http://dx.doi.org/10.2118/169142-MS>.
6. Halliburton. 2007. http://www.halliburton.com/public/cem/contents/Chem_Compliance/web/H02686.pdf.
 7. Li, Z., Shao, X., Qiu, Y., and Chen, X. 1995. Methods and Effects of Cyclic Waterflooding in the Southern Oilfields of Daqing Placanticline. *SPE Advanced Technology Series*, **5** (01): 20-23. SPE-30875-PA. <http://dx.doi.org/10.2118/30875-PA>.
 8. Li, L and Sheng, J.J. 2016. Experimental Study of Core Size Effect on CH₄ Huff-n-Puff Enhanced Oil Recovery in Liquid-rich Shale Reservoirs, *Journal of Natural Gas Science and Engineering*, **34**: 1392-1402. <http://dx.doi.org/10.1016/j.jngse.2016.08.028>.
 9. Li, L., Sheng, J.J., and Sheng, J. 2016. Optimization of Huff-n-Puff Gas Injection to Enhance Oil Recovery in Shale Reservoirs. Presented at the SPE Low Perm Symposium, Denver, Colorado, USA, 5-6 May. <http://dx.doi.org/10.2118/180219-MS>.
 10. Meng, X. and Sheng, J.J. 2016. Optimization of huff-n-puff gas injection in a shale gas condensate reservoir, *Journal of Unconventional Oil and Gas Resources*, **16**: 34-44. <http://dx.doi.org/10.1016/j.juogr.2016.09.003>.
 11. Meng, X. and Sheng, J.J. 2016. Experimental and Numerical Study of Huff-n-Puff Gas Injection to Re-vaporize Liquid Dropout in Shale Gas Condensate Reservoirs. *J. of Natural Gas Science and Engineering*, **35**: 444-454. <http://dx.doi.org/10.1016/j.jngse.2016.09.002>.
 12. Meng, X., Sheng, J.J., and Yu, Y. 2016. Experimental and Numerical Study on Enhanced Condensate Recovery by Huff-n-Puff Gas Injection in Shale Gas Condensate Reservoirs. *SPE Reservoir Evaluation & Engineering*, in press. <http://dx.doi.org/10.2118/183645-PA>.
 13. Shchipanov, A.A., Surguchev, L.M., and Jakobsen, S.R. 2008. Improved Oil Recovery by Cyclic Injection and Production. Presented at the SPE Russian Oil and Gas Technical Conference and Exhibition, Moscow, Russia, 28-30 October. SPE-116873-MS. <http://dx.doi.org/10.2118/116873-MS>.
 14. Sheng, J.J. 2014. Enhanced Oil Recovery in Shale Reservoirs by Gas Injection. *Journal of Natural Gas Science and Engineering*, **22**: 252-259. <http://dx.doi.org/10.1016/j.jngse.2014.12.002>.
 15. Sheng, J.J. and Chen, K. 2014. Evaluation of the EOR Potential of Gas and Water Injection in Shale Oil Reservoirs. *Journal of Unconventional Oil and Gas Resources*, **5**: 1-9. <http://dx.doi.org/10.1016/j.juogr.2013.12.001>.
 16. Sheng, J.J., Mody, F., Griffith, P.J., and Barnes, W.N. 2016. Potential to increase condensate oil production by huff-n-puff gas injection in a shale condensate reservoir. *J. of Natural Gas Science and Engineering*, **28**: 46-51. <http://dx.doi.org/10.1016/j.jngse.2015.11.031>.
 17. Song, C. and Yang, D. 2013. Performance Evaluation of CO₂ Huff-n-Puff Processes in Tight Oil Formations. Presented at the SPE Unconventional Resources Conference Canada, Calgary, Alberta, Canada, 5-7 November. SPE-167217-MS. <http://dx.doi.org/10.2118/167217-MS>.
 18. Stirpe, M.T., Guzman, J., Manrique, E., and Alvarado, V. 2004. Cyclic Water Injection Simulations for Evaluations of its Potential in Lagocinco Field. Presented at the 2004 SPE/DOE Fourteenth Symposium on Improved Oil Recovery, Tulsa, Oklahoma, USA, 17-21 April. SPE-89378-MS. <http://dx.doi.org/10.2118/89378-MS>.
 19. Surguchev, L., Koundin, A., Melberg, O., Rolfsvag, T.A., and Menard, P. 2002. Cyclic Water Injection: Improved Oil Recovery at Zero Cost. *Petroleum Geoscience*, **8** (1): 89-95. <http://dx.doi.org/10.1144/petgeo.8.1.89>.
 20. Surguchev, L.M., Giske, N.H., Kollbotn, L., and Shchipanov, A. 2008. Cyclic Water Injection Improves Oil Production in Carbonate Reservoir. Presented at the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, UAE, 3-6 November. SPE-117836-MS. <http://dx.doi.org/10.2118/117836-MS>.
 21. Tovar, F.D., Eide, O., Graue, A., and Schechter, D.S. 2014. Experimental Investigation of Enhanced Recovery in Unconventional Liquid Reservoirs using CO₂: A Look Ahead to the Future of Unconventional EOR. Presented at the SPE Unconventional Resources Conference, The Woodlands, Texas, USA, 1-3 April. SPE-169022-MS. <http://dx.doi.org/10.2118/169022-MS>.

22. Wan, T. and Sheng, J.J. 2015a. Compositional Modelling of the Diffusion Effect on EOR Process in Fractured Shale-Oil Reservoirs by Gas flooding. *J Can Pet Technol* **54** (2): 107-115. SPE-2014-1891403-PA. <http://dx.doi.org/10.2118/2014-1891403-PA>.
23. Wan, T. and Sheng, J.J. 2015b. Evaluation of the EOR Potential in Hydraulically Fractured Shale Oil Reservoirs by Cyclic Gas Injection. *Petroleum Science and Technology*, **33** (7): 812–818. <http://dx.doi.org/10.1080/10916466.2015.1010041>.
24. Wan, T. and Sheng, J.J. 2015c. Enhanced Recovery of Crude Oil from Shale Formations by Gas Injection in Zipper-Fractured Horizontal Wells. *Petroleum Science and Technology*, **33** (17-18): 1605-1610. <http://dx.doi.org/10.1080/10916466.2015.1079536>.
25. Wan, T., Sheng, J.J., and Soliman, M.Y. 2013. Evaluate EOR Potential in Fractured Shale Oil Reservoirs by Cyclic Gas Injection. Presented at the Unconventional Resources Technology Conference, Denver, Colorado, USA, 12-14 August. SPE-168880-MS. <http://dx.doi.org/10.1190/URTEC2013-187>.
26. Wan, T., Yu, Y., and Sheng, J.J. 2015. Experimental and Numerical Study of the EOR Potential in Liquid-rich Shales by Cyclic Gas injection. *Journal of Unconventional Oil and Gas Resources* 12: 56-67. <http://dx.doi.org/10.1016/j.juogr.2015.08.004>.
27. Yu, Y. 2016. Experimental Study of Enhanced Liquid Oil Recovery from Shale Reservoirs by Gas Injection (Doctoral dissertation). Texas Tech University, Lubbock, Texas, May.
28. Yu, Y., Li, L., and Sheng, J.J. 2016a. Further Discuss the Roles of Soaking Time and Pressure Depletion Rate in Gas Huff-n-Puff Process in Fractured Liquid-rich Shale Reservoirs. Presented at the SPE Annual Technical Conference and Exhibition, Dubai, UAE, 26-28 September. SPE-181471-MS. <http://dx.doi.org/10.2118/181471-MS>.
29. Yu, Y., Meng, X., and Sheng, J.J. 2016b. Experimental and Numerical Evaluation of the Potential of Improving Oil Recovery from Shale Plugs by Nitrogen Gas Flooding. *Journal of Unconventional Oil and Gas Resources*, **15**: 56-65. <http://dx.doi.org/10.1016/j.juogr.2016.05.003>.