Experimental Study of Core Size Effect on CH₄ Huff-n-Puff Enhanced Oil Recovery in Liquid-rich Shale Reservoirs

Lei Li and James J. Sheng

Texas Tech University, Lubbock, Texas, USA

*Corresponding author: james.sheng@ttu.edu, [Tel:806 834 8477](tel:8068348477)

ABSTRACT

Gas huff-n-puff injection, which avoids the viscous fingering phenomenon or gas channeling between connected wells, is a potential method to efficiently enhance oil recovery (EOR) in liquid-rich shale oil cores. In this paper, an experimental study of core size effect on the gas huff-n-puff EOR was implemented by using two groups of cores from the Wolfcamp field in West Texas. The first group contained core plugs with a length of 2", but different diameters varying from 1" to 4". The second group of core plugs had a diameter of 1.5", but differed in length from 1" to 3.5". CH₄ huff-n-puff EOR experiments with an injection pressure of 2000 psi were conducted to analyze the size effects. CT scan was also implemented to check the oil saturation and cumulative oil recovery for each cycle. The results show that after eight huff-n-puff cycles, the oil recovery of cores with 1", 1.5", 2", 3", 3.5" and 4" in diameter are 49.65%, 48.57%, 47.76%, 46.15%, 43.55%, and 42.64%, respectively. The core plug with a larger diameter yields a relatively smaller oil recovery due to its lower apparent surface-to-volume ratio (AS/V) and smaller pressure gradient ($\Delta P/\Delta r$). The core plugs with 1", 2", 2.75", and 3.5" achieve almost the same oil recovery during the huff-n-puff process. It is demonstrated that core length has no effect on final cumulative oil recovery. The result also shows that the oil recovered in one cycle decreases as the huff-n-puff cycle number increases. The first cycle gives the peak incremental oil recovery. The obtained CT scan images together with the analysis of CT number reveal the density and oil saturation change inside the core and reflect the cumulative oil recovery during the gas huff-n-puff process.

1. Introduction

The mechanism to enhance oil recovery (EOR) contains two parts: increasing the sweep efficiency, and improving the oil displacement efficiency (Latil, 1980; Thomas, 2008). Gas huff-n-puff has been used in heavy oil for decades (Sayegh and Maini, 1984; Ivory et al., 2009; Jia et al., 2015). This method uses one single well as both an injection well and a production well. It includes three steps: 1) Use this well as injection well to inject gas into the reservoir, 2) Shut in the well, let the gas swell with the heavy oil, reduce oil viscosity, and also increase the average reservoir pressure, and 3) Open the well to produce oil. This huff-n-puff EOR method avoids the gas viscous fingering phenomenon in the high viscosity reservoir (Thomas and Monger-McClure, 1991; Chen et al., 2014) and increases both the sweep efficiency and the oil displacement efficiency at the same time (Li et al., 2011).

In recent years, gas huff-n-puff has been used to increase oil recovery in liquid-rich shale oil reservoirs (Monger and Coma, 1988; Wan et al., 2013, 2014; Sheng and Chen, 2014; Sheng, 2015; Wan and Sheng, 2015; Meng et al., 2015). Numerous experiments have been conducted using this method. Gamadi et al. (2013) conducted N₂ cyclic injection experiments with three different core plugs from Barnett, Marcos, and Eagle Ford. They found that cycle gas injection could increase the recovery from 10 to 50% depending on the injection pressure and shale core type. They also tested the influence of soaking period on the ultimate recovery factor, and found the longer the shut-in period, the more the ultimate recovery achieved. Gamadi et al. (2014) replaced N₂ with CO₂ to implement the cycle gas injection. They claimed that injecting CO₂

at a miscible pressure has a great impact on the recovery factors compared to injection at immiscible conditions. However, in their experiments, they used mineral oil (Soltrol 130) instead of crude oil. As crude oil composition, viscosity, and density are all different from mineral oil, it causes differences in the EOR performance (Chen et al., 2014; Wan et al., 2014, Gamadi et al., 2014). Yu and Sheng (2015) conducted N₂ huff-n-puff on crude oil saturated shale core samples and analyzed the effect of pressure depletion rate on shale oil recovery. They found that oil recovery increases as the pressure depletion rate increases. The highest oil recovery can reach is 50.5% after 10 cycles under the pressure blowout condition.

Previous lab-scale experimental studies concentrated on the effects of operation parameters such as injection pressure, soaking time, pressure depletion time, and the number of cycles on the EOR performance of huff-n-puff in shale oil core plugs (Wenlong et al., 2008; Gamadi et al., 2013, 2014; Meng et al., 2015). The gas they used in the lab experiments are either CO₂ or N₂. As we know it is difficult to employ CO₂ in certain circumstances due to the cost, or corrosion problems and the difficulty with transportation when there is no CO₂ reservoir nearby. Compared with CO₂, CH₄ is a more readily available gas in the oil field after separating gas from the produced oil (Haines and Monger, 1990). Lino (1994) presented an extended evaluation of the results of natural gas huff-n-puff compared with CO₂ injection in Brazil, showing that the use of natural gas in substitution of CO₂ is very attractive because of its lower corrosion levels, lack of contamination in the produced fluid, and lower overall project costs. Zhang et al. (2006) did a laboratory investigation of enhanced light-oil recovery using the CO₂/flue gas huff-n-puff process and proved that enriched flue gas performed as well as, or better than pure CO₂. Thus, in this paper, we use CH₄ as the injection gas to analyze the performance of huff-n-puff EOR.

The CT scan method is considered to be a nondestructive method to measure the cores' porosity, gas or oil saturation, and lithology characteristics within the cores (Siddiqui and Khamees, 2004; Yu et al., 2015). The CT scan method has been widely used in petroleum engineering applications for describing the core porosity (Siddiqui et al., 2005), relative permeability (MacAllister et al., 1993), investigating the performance during core flooding experiments (London, et al., 2014), or other EOR processes (Kovscek et al., 2008; Simjoo et al., 2013; Tovar et al., 2014; Yu et al., 2015). For this study, core plugs were scanned during the huff-n-puff tests to reflect the gas or oil saturation changes inside the core, and to help calculate the oil recovery in different stages.

The objective of this study is to explore core size (including the diameter and length) effects on the cumulative oil recovery factor. A series of ten experiments were conducted on Wolfcamp shale cores using the immiscible CH₄ huff-n-puff method. CT scans are applied to help analyze the properties of the core plugs.

2. Experimental methods

2.1. Experimental Materials

Crude oil and core plugs from the Wolfcamp formation in Apache's Lin field were used in these experiments. Table 1 illustrates the main properties of the Wolfcamp crude oil.

Table 1
Properties of Wolfcamp Crude Oil.

Density at 72°F, g/ml	Viscosity at 72°F, cp	API Gravity, °API	CT Number, Hounsfield
0.796	3.58	46.7	-184

The cores are horizontal core plugs, parallel to current, which can be divided into two groups. One contains six core samples with the same length of 2" but differing diameters of 1", 1.5", 2", 3", 3.5", and 4",

respectively, as shown in Fig. 1. The cores in the other group were taken from Well #SSH 31 in the Apache Corporation. As shown in Fig. 2, the four core samples have the same diameters of 1.5", but lengths of 1", 2", 2.75", and 3.5". The injection gas in these huff-n-puff experiments is CH₄ with purity greater than 99%.

Fig. 1. Shale oil cores in group 1 (the picture taken after first cycle).

Fig. 2. Shale oil cores in group 2 (the picture taken after first cycle).

2.2. Experimental equipment

Gas huff-n-puff apparatus. The main experimental flows for core saturation and cyclic CH₄ injection are shown in Fig. 3 and Fig. 4. The Quizix QX pump is a syringe pump with two cylinders, and it can pump fluids continuously. An accumulator cooperating with the QX pump pushes crude oil to the core container and maintains a high saturation pressure at the same time. Core plugs were placed vertically in the high pressure stainless steel accumulator, which were connected with two-way valves. A pressure gauge was placed directly on the top of the stainless core container to record the pressure around the core throughout the injection stage, soaking period, and pressure depletion time in each experiment. A syringe pump is used as a pressure boost to make sure that the injection gas pressure can reach 2000 psi. All of the experiments were conducted at a temperature of 95°F in the air bath oven.

The CereTom mobile CT scanner. The CT scanner, a small-bore portable device to deliver the highest quality non-contrast and contrast perfusion scans, is used as a separate component to axially scan the core plugs and provide core characteristics, shown in Fig. 5.

2.3. CH₄ huff-n-puff test

The huff-n-puff test contains two sections including the preparation of the saturate core sample with crude oil, and the conducting of the cyclic gas injection test. As the traditional saturation method for conventional reservoir cores is not suitable for these shale cores, a special saturation method applied in our research group's previous experiments was used in this study (Yu and Sheng, 2015; Li et al., 2015, 2016). Core plugs were named and dry weighted (W_d) after being put in the oven for one day prior to conducting the main experiment. As shown in Fig. 3, a core plug was placed in the core container and vacuumed for two days. Then we turned off the vacuum pump and used the Quizix QX pump to displace water into the

accumulator. The oil on the top of the plug was pushed into the core container by the force transient from the water. After the vessel was full of crude oil, 4000 psi of pressure was maintained for one week. The weight of the core plug after being saturated with oil was measured and recorded as W_s . After saturation, the core sample was put into the accumulator and the CH_4 huff-n-puff test was started.

The experiment shown in Fig. 4 was intended to simulate the gas huff-n-puff in the oil field. First, CH_4 was injected into the accumulator. If the gas pressure was lower than our designed pressure, the Syringe Continuous Pumping System (SCPS) was used to boost the pressure on top of the accumulator to the operation pressure of 2000 psi. A maximum of three cores can be implemented at the same time in this experiment, as shown in Fig. 4. After that, we shut in the well and let the gas soak with the crude oil inside the core plugs for a certain time. 24 hours of soaking time was applied in all of the experiments. Finally, we depressurized the core containers by using a backpressure regulator (BPR) system to control the production rate. The previous study by Yu and Sheng (2015) analyzed the effect of pressure depletion time on shale oil recovery. They found that more than 80% oil had been produced in the first 6 hours within the 24 hour monitored production period. So in this study we used 6 hours as the further depletion time. The core sample was weighed (W_i) after being kept in a sealed container under the atmosphere pressure for 6 hours. A second cycle of gas injection was started immediately after the further depletion of the first cycle, a third cycle was conducted after the second cycle, and so on. The same procedures were repeated in subsequent cycles using a similar manner to the first. During this process, the top and bottom areas of the core did not come directly in contact with the gas. Each core plug was weighed and recorded after each cycle to calculate the oil recovery with material balance using the following equation. The air bath is controlled at a temperature of 95 °F during all of the experiments.

$$\text{Oil Recovery in cycle } i = \frac{W_i - W_d}{W_s - W_d} \times 100\% \quad (1)$$

2.4. X-ray CT scan test

The porosity and oil saturation can be measured by two methods: material balance (weight difference percentage) and the CT scan method. In our experiment, we used the CT scan on the core plugs after every huff-n-puff cycle. CT slices of a dry and oil saturated core plug were also recorded. The coverage of the scan is set based upon the core length. We used the minimum value (1.25mm) of scan slice space to observe the heterogeneity of the core plug. For the 2" (50.8mm) core, 40 images were obtained after each scan. The CT number reflects the core lithology properties, especially the core density. The density is different if the pore is saturated with oil or gas, and thus the CT number is also changed. When CT scanner method is used, the oil porosity can be calculated using the CT number of the sample at the conditions of dry and oil saturated data with the following equation (Aleidan and Mamora, 2011):

$$\emptyset = \frac{CT_s - CT_d}{CT_{oil} - CT_{air}} \quad (2)$$

Oil saturation in the core could be calculated as follows:

$$S_{oil} = \frac{CT_i - CT_d}{CT_s - CT_d} \quad (3)$$

Oil recovery should be:

$$R.F = \frac{S_{oi} - S_{oil}}{S_{oi}} \times 100\% \quad (4)$$

where CT_{oil} is the CT number for oil defined as -184 in Hounsfield units, and CT_{air} is the CT number of air defined as -1000 in Hounsfield units. CT_i is the CT number of the core after the i^{th} huff-n-puff cycle, CT_d is the CT number of the dry core plug, CT_s is the CT number of the oil saturated core plug, and S_{oi} is the initial oil saturation.

Fig. 3. Schematic diagram of the experimental equipment for oil saturation.

Fig. 4. Schematic diagram of the experimental equipment for gas huff-n-puff.

Fig. 5. CT scan system.

3. Results and discussion

3.1. CH_4 huff-n-puff results

3.1.1. Effect of core diameter size on oil recovery

Table 2 includes the recovery factors of cyclic CH_4 injection for shale cores at different core sizes with a length of 2", and differing diameters of 1", 1.5", 2", 3", 3.5", and 4" (as shown in Fig. 6). After eight huff-n-puff cycles, the oil recovery of the core plugs with diameter of 1", 1.5", 2", 3", 3.5", and 4" are 49.65%, 48.57%, 47.76%, 46.15%, 43.55%, and 42.64%, respectively. All the experiments were conducted under the same operation conditions (as shown in Table 3).

Table 2

Oil recovery data in gas injection cycles with different core diameters.

Core No.	Diameter, inches	AS/V, ft ² /ft ³	Cumulative Oil Recovery							
			Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8
1	1	24	12.63%	20.84%	29.11%	35.41%	40.07%	43.54%	46.91%	49.65%
2	1.5	16	11.26%	19.73%	27.34%	33.58%	39.17%	42.35%	45.95%	48.57%
3	2	12	10.53%	18.58%	25.90%	32.86%	38.34%	41.95%	45.21%	47.76%
4	3	8	9.77%	16.31%	24.23%	30.92%	36.08%	39.81%	43.57%	46.15%
5	3.5	6.9	9.34%	15.52%	23.14%	28.97%	33.79%	37.65%	41.48%	43.55%
6	4	6	8.62%	14.46%	21.15%	27.69%	32.31%	36.43%	40.42%	42.64%

Table 3

Operational schedule in a cycle.

Operations	Injection time	Soak period	Production time	Further depletion
Pressure, psi	2000	2000	14.7	14.7
Time, days	0.01	1	0.01	0.25

The results illustrate that the core with a bigger diameter has a lower oil recovery in the same injection cycle under the same operation schedule. One important factor causing the oil recovery difference is the apparent surface-to-volume ratio (AS/V). A smaller core has a relatively larger AS/V than that of a larger core. Table 2 shows that the AS/V for core the core plug with diameter of 1", 1.5", 2", 3", 3.5", and 4" are 24, 16, 12, 8, 6.9, and 6 ft²/ft³, respectively. Another parameter that will affect the oil recovery of different diameter cores is the pressure gradient ($\Delta P/\Delta r$). With the same pressure drop, a smaller diameter core will have relatively higher pressure gradients during production stage than that of a larger core. With greater surface area connected with gas and a higher pressure gradient, larger oil recovery will be achieved from the smaller diameter core plug. This experiment result showing higher oil recovery in smaller diameter cores is in line with expectations. Based on the experimental results, the oil recovery from a reservoir strongly depends on fracture density. As the fracture density is higher, relative matrix size becomes smaller, AS/V becomes larger and the oil recovery will be higher. Multi-stage fracturing with shorter fracturing space will result in high AS/V in the reservoir, which will be helpful to enhance oil recovery in liquid-rich shale reservoirs.

Fig. 6. R.F. data of different cores diameters for 5 injection cycles under the conditions of 2000psi with crude oil and CH₄ injection.

3.1.2. Effect of core length size on oil recovery

Table 4 and Fig. 7 show the relative oil recovery results of the experiments for core plugs in group two, which have a diameter of 1.5 inches, but differing lengths of 1", 2", 2.75", and 3.5". After eight huff-n-puff cycles, the oil recovery of the core plugs with length of 1", 2", 2.75", and 3.5" are 48.54%, 48.28%, 50.31%, and 50.54%, respectively. The oil recovery differences are only 0.26% for the core plugs with lengths of 1" and 2", and 0.23% for the ones with lengths of 2.75" and 3.5". This means the lengths do not have significant influence on the oil recovery of shale core during huff-n-puff process. From Table 4, the AS/V is the same value for all the different length cores. As all the cores have the same diameter, $\Delta P/\Delta r$ is also the same for different core plugs during experiment process. With the same AS/V and $\Delta P/\Delta r$, the core plugs yield similar oil recovery in each gas huff-n-puff cycle.

However, when we compare the oil recovery of cores with lengths of 1" and 2.75", the longer length core even has a higher oil recovery than the short core plug. When we checked the texture of these core plugs, we find a reasonable explanation for this phenomenon. The core plugs in this group are taken from different

depths of the same well, SSH #31 in Apache Corporation. Thus, the structure properties of the core plugs with length of 1" or 2" are different from that of the core plugs with length of 2.75" and 3.5", as shown in Fig. 2. The length does not affect the oil recovery, but the structure parameters such as permeability, heterogeneity, and anisotropy will cause some differences in the oil recovery during the gas huff-n-puff process. Under the condition that all the core plugs have the same permeability, the homogenous core plug will have the highest oil recovery. The oil recovery is the result of sweep efficiency times the displacement efficiency. The homogenous core has the largest sweep efficiency. With keeping all the other properties unchanged, the displacement efficiency is assumed to be the same for every core plug. Thus, the high lever heterogeneity will lead to a smaller sweep efficiency, which will result in a lower oil recovery. The core anisotropy will also cause differences in oil recovery in this experiment. If the gas was injected from the high permeability direction, the oil recovery may be higher than that from the lower permeability direction, because the oil will be produced from these high permeability channels during the puff phase. In order to study the size effect and eliminate these uncontrollable factors, we use similar horizontal core plugs from the same area of Wolfcamp field for all the experiments.

Table 4

Relative oil recovery data in gas injection cycles with different core diameters.

Core No.	Length, inches	AS/V, ft ² /ft ³	Cumulative Oil Recovery							
			Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8
7	1	16	12.98%	20.83%	27.79%	34.27%	40.48%	43.26%	46.24%	48.54%
8	2		12.97%	20.27%	27.31%	34.06%	39.86%	43.39%	46.02%	48.28%
9	2.75		13.67%	23.30%	31.13%	36.77%	41.63%	45.45%	48.12%	50.31%
10	3.5		13.60%	23.37%	30.89%	36.64%	42.17%	45.65%	48.33%	50.54%

Fig. 7. R.F. data of different core lengths for 8 injection cycles under the conditions of 2000psi with crude oil and CH₄ injection.

3.1.3. Effect of gas huff-n-puff number

The incremental oil in one cycle decreased as the number of cycles increased. Taking the No.3 core plug (with diameter of 2" and length of 2") as an example, Fig. 8 shows the oil production capability pictures which were taken after each huff-n-puff cycle (from 1st to 8th cycle). Lots of oil came out to the surface of

the core plug in the first five cycles, while in the last two cycles, little oil was produced. The incremental oil recovered in each cycle of all the 10 core plugs are calculated and shown in Table 5. The first cycle yielded the highest incremental oil recovery from 8.62% to 13.67% for the different size core plugs. This is because it is easier for the oil near the surface of the core to be produced owing to the large pressure gradient and high oil saturation gradient. Then the incremental oil recovered in one cycle decreases as the number of huff-n-puff cycle increases.

Fig. 8. Pictures of No.3 core plug (diameter 2" and length 2") taken from 1st - 8th cycle.

The first five cycles can give an incremental oil recovery above 5% for most of the core plugs. After that, the oil recovered in one cycle is around 2% to 3%. The space between the accumulator and the core can be considered as a fracture section which is full with huff gas. Oil saturation in the core circumference reduced faster than that in the center section because it was near the high permeability fracture section and has the highest oil saturation gradient. The oil in the center core plug would transport to the surface owing to convection and dispersion caused by the oil concentration differences and pressure gradient. The oil in the center core needs to overcome higher force than the oil in the core circumference. The pressure gradient is also lower due to the long distance between the central core and the fracture, which leads to lower incremental oil recovered in the later cycle. The oil saturation gradient between the core and fracture decreases as the oil saturation inside the core reduces during the production process. Thus the driving forces of convection and dispersion become lower than before. These also contribute to the decline in incremental oil recovery.

Table 5

The incremental oil recovered in each cycle of all the 10 core plugs.

Core No.	Diameter inches	Length inches	Incremental Oil Recovered in Each Cycle							
			Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8
1	1		12.63%	8.21%	8.27%	6.30%	4.66%	3.47%	3.37%	2.74%
2	1.5		11.26%	8.47%	7.61%	6.24%	5.59%	3.18%	3.60%	2.62%
3	2	2	10.53%	8.05%	7.32%	6.96%	5.48%	3.61%	3.26%	2.55%
4	3		9.77%	6.54%	7.92%	6.69%	5.16%	3.73%	3.76%	2.58%
5	3.5		9.34%	6.18%	7.62%	5.83%	4.82%	3.86%	3.83%	2.07%
6	4		8.62%	5.84%	6.69%	6.54%	4.62%	4.12%	3.99%	2.22%
7		1	12.98%	7.85%	6.96%	6.48%	6.21%	2.78%	2.98%	2.30%
8		2	12.97%	7.30%	7.04%	6.75%	5.80%	3.53%	2.63%	2.26%
9	1.5	2.75	13.67%	9.63%	7.83%	5.64%	4.86%	3.82%	2.67%	2.19%
10		3.5	13.60%	9.77%	7.52%	5.75%	5.53%	3.48%	2.68%	2.21%

Due to the limitation of the huff-n-puff experiments that the core plug's weight is needed to be measured after each gas huff-n-puff cycle, the in situ measurements with three principle stresses cannot be implemented during these experiments. When considered the tectonic regimes, the grains are assumed to be incompressible, while the porosity and permeability are stress-dependent (Mckee et al., 1988; Pang et al., 2016). The total volume of core plug can be expressed as:

$$V_t = V_g + V_p \quad (5)$$

where, V_t is the total volume of the core plug, V_g is the volume of the grain or solid in the core plug, and V_p is the pore volume of the core plug. Walsh (1981) gave the following general relationship between effective stress, σ , total stress, σ_t , and pore pressure, P_p :

$$\sigma = \sigma_t - \alpha P_p \quad (6)$$

where, P_p is the pore pressure, psi, and α is Biot's constant, a measure of the ratio of the fluid volume squeezed out to the volume changed of the rock. The Carman-Kozeny equation is assumed valid, and changes in total porosity are proportional to changes in porosity effective stress. The equation for pore compressibility C_p is shown in the following:

$$C_p = \frac{1}{V_p} \cdot \left(\frac{\partial V_p}{\partial P_p} \right)_{P_c} = \frac{1}{\phi} \cdot \left(\frac{\partial \phi}{\partial P_p} \right)_{P_c} \quad (7)$$

where, C_p is the pore compressibility, psi^{-1} , ϕ is the porosity of the core plug, and P_c is the confining pressure, psi. After simplification, Eq. 7 can be expressed in the following formant (Pang et al., 2016):

$$\frac{\phi}{\phi_i} = 1 + C_p \cdot (P - P_i) \quad (8)$$

where, ϕ_i is the initial porosity at initial reservoir pressure, ϕ is the porosity during production process, and P and P_i are pore pressures corresponding to ϕ and ϕ_i , respectively.

According to Gu and Chalaturnyk (2006), the permeability multiplier (k/k_i) can be calculated by:

$$\frac{k}{k_i} = \left(\frac{\phi}{\phi_i}\right)^3 \quad (9)$$

where, k is the permeability during the production process, md, and k_i is the permeability at initial reservoir pressure, md.

For the experiment condition, the effective stress is zero. However, the effective stress cannot be zero at the reservoir condition. According to Eqs. 5-8, as the pore pressure decreases during the production process, the effective stress increases. Thus, the porosity of the core becomes smaller than the initial porosity. Based on Eq. 9, the permeability declines as the porosity decreases. The reduced porosity and reduced permeability may affect oil recovery differently. Probably the reduced porosity increases oil recovery and the reduced permeability decreases oil recovery. As a result, the overall effect may not be significant, but more research is needed.

3.2. CT scan results

Fig. 9 and Fig. 10 show the CT axially scanned images of the core plug before and after oil saturation. The core plug in these images is the No.3 core plug with diameter of 2" and length of 2". For the 2" long core, we used 40 slices along the axial direction. From the scale, the black color means the lowest density region whose CT number is -1024, and the white color represents the highest density region with the largest CT number 3947 in this case. The color close to the right end has higher density than the one in the left. For example, the red color part inside every slide represents that this area has relatively higher density minerals than other areas. These color differences indicate the density differences inside the core plug, which also illustrate that the core plug is heterogeneous in mineral contents. Comparing the two series of images, the colors of oil saturation core slices are lighter than that of the dry cores, which means the saturated core has a bigger CT Number or heavier density than that of the dry core (Meng et al., 2015; Yu et al., 2015). This reflects that oil has been saturated into the core plugs. Fig. 10 also illustrates that the core is not equally saturated. The center of the core plug is not as saturated as that in the circumference. The reason is that the pores and pore throats inside the shale core sample are in nano-scale. It's difficult for the oil to equally saturated into the center of the core. This unequally saturated condition gives a good explanation for the effect of gas huff-n-puff number. In the first 5 cycles, the incremental oil recovered in each cycle is more than that of the later cycles. The oil in the circumference of the core plugs was first produced, then the oil inside the center core was produced in the later cycles. Because the oil saturated in the core center is relatively less than that in the circumference, the incremental oil recovered in later cycle is less than that of the first several cycles. Of course, in later cycles the distance oil transports is also longer, resulting in less oil produced.

Fig. 9. CT slices images of a dry core plug (No.3 core plug with diameter of 2" and length of 2").

Fig. 10. CT slices images of an oil saturated core plug (No.3 core plug with diameter of 2" and length of 2").

Due to some of the core pore size being less than 10nm, the resolution of the CT scan images can only give the macroscopic saturation change of the core. We need to analyze the data of CT number in order to get the accurate oil saturation change inside the core. The CT number detail for every slice is shown in Fig. 11, which demonstrates that the CT number in every slice of the oil saturated core is larger than that of the dry core. The data for 40th slice is deleted as it is distorted by the boundary effect. After analyzing the CT number for all the slices in every cycle, the cumulative distribution plot during the whole huff-n-puff process is shown in Fig. 12.

Fig. 11. CT number comparison between dry and oil saturated core plug (No.3 core plug with diameter of 2" and length of 2").

Fig. 12. CT number cumulative distribution plot for all the cycles (No.3 core plug with diameter of 2" and length of 2").

Fig. 12 shows that dry core has the lowest CT number while the oil saturated core has the highest CT number by comparing the CT numbers at the cumulative 50% distribution. The CT number decreases as the huff-n-puff process is implemented. By comparing the distance between each curve, we can see that the CT number declines faster in the first five cycles than that in the later cycles. This is the same tendency that we got by using the weight difference method. The average CT number of the whole 40 slices is shown in Table 6. The porosity is calculated to be 8.0% by analyzing the average CT number for every slice in the dry and oil saturated tests. Oil saturation and oil recovery can also be calculated, as shown in Fig. 13. As the huff-n-puff cycle number increases, the average CT number decreases, which represents the density decreasing as the oil is replaced by gas. The oil saturation decreases and the cumulative oil recovery increases. Fig. 14 compares the cumulative oil recovery calculated using the weight difference method and CT scan method. The cumulative oil recovery change tendency is the same, although the oil recovery factor measured by CT is lower than that calculated from weight difference. Yu et al. (2015) measured a higher oil recovery from the CT method. The difference of the oil recovery results may be caused by the selection of the calculation region when applying the CT method. As shown in Fig. 9 and Fig. 10, we need to separate the dark region from the core occupied region when we try to analyze the CT number. Also, the boundary of the core will make a difference in the CT number. Thus a minor difference in the analysis region selection will cause a difference in oil recovery. Although the CT number method is not accurate enough, it provides a good tool for us to observe the oil saturation changes inside the core.

Table 6

Average CT number during huff-n-puff process.

	dry core	saturated core	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8
Average CT Number	1890.1	1955.4	1949.6	1944.1	1940.5	1935.8	1932.8	1930.9	1929.3	1928

Fig. 13. CT number, oil saturation and cumulative oil recovery in every huff-n-puff cycle using CT number method for No.3 core plug with diameter of 2" and length of 2".

Fig. 14. Cumulative oil recovery in every huff-n-puff cycle using CT number method and weight difference method for No.3 core plug with diameter of 2" and length of 2".

4. Conclusions

This work presented and discussed the size effect (including core diameter and length) and cycle number effect on oil recovery factor during huff-n-puff process. Some new and important findings can be summarized as follows:

1. Experiment results show that using the identical operation schedules, a core with a larger diameter will have a lower oil recovery in the same injection cycle and lower cumulative oil recovery after all the huff-n-puff cycles. The core length has no influence on the oil recovery.
2. Based on the analysis of weight difference, the oil recovered in the later cycle is smaller than that of the former cycle for all different size core plugs. The majority of oil is produced in the first five huff-n-puff cycles.
3. The two main parameters determining the oil recovery are the apparent surface-to-volume ratio and the pressure gradient along the radial of the core. With greater surface area contact with gas and higher pressure gradient as the driving force, greater oil recovery will be achieved.
4. The core porosity, oil saturation and oil recovered at each cycle can be calculated based on the CT number method. Although the CT number method is not accurate enough for the oil recovery, it provides a better way to observe the oil saturation changes inside the core during huff-n-puff process.

Nomenclature

α	=	Biot's constant
C_p	=	pore compressibility, psi^{-1}
D	=	pore diameter, μm
k	=	permeability during the production process, md
k_i	=	permeability at initial reservoir pressure, md
k/k_i	=	permeability multiplier
P	=	applied pressure, psi
P_c	=	confining pressure, psi

P_p	=	pore pressure, psi
V_t	=	total volume of the core plug
V_g	=	volume of the grain or solid in the core plug
V_p	=	pore volume of the core plug
$\emptyset$	=	porosity during production process
$\emptyset_i$	=	initial porosity at initial reservoir pressure
σ	=	effective stress, psi
σ_t	=	total stress, psi
γ	=	surface tension of the mercury, 480 dyne cm ⁻¹
θ	=	contact angle between mercury and the pore wall, usually taken as 140°
W_d	=	dry core plug weight, gram
W_s	=	oil saturated core plug weight, gram
W_i	=	core plug weight after i th huff-n-puff cycle, gram
CT_{oil}	=	CT number for oil defined as -184, Hounsfield
CT_{air}	=	CT number for air defined as -1000, Hounsfield
CT_i	=	CT number of the core after the i th huff-n-puff cycle, Hounsfield
CT_d	=	CT number of the dry core plug, Hounsfield
CT_s	=	CT number of the oil saturated core plug, Hounsfield
S_{oi}	=	initial oil saturation
S_{oil}	=	oil saturation after i th huff-n-puff cycle
AS/V	=	apparent surface-to-volume ratio, ft ² /ft ³
$\Delta P/\Delta r$	=	pressure gradient

Acknowledgments

Crude oil and cores were provided by Apache Corporation. The work presented in this paper is supported by the Department of Energy under Award Number DE-FE0024311.

References

- Aleidan, A., Mamora, D., 2011. Comparative Study of Oil Recovery during Miscible CO₂ Injection in Carbonate Cores and Slimtube. SPE 155411 presented in SPE Saudi Arabia section Young Professionals Technical Symposium held in Dhahran, Saudi Arabia, 14-16 March.
- Chen, C., Balhoff, M. T., Mohanty, K. K., 2014. Effect of Reservoir Heterogeneity on Primary Recovery and CO₂ Huff'n'Puff Recovery in Shale-Oil Reservoirs. SPE Reservoir Evaluation and Engineering. 17 (03), 404-413.
- Gamadi, T.D., Elldakli, F., Sheng, J.J., 2014b. Compositional Simulation Evaluation of EOR Potential in Shale Oil Recovery by Cyclic Natural Gas Injection. SPE 1922690 (URTeC 1922690) presented at the Unconventional Resources Technology Conference held in Denver, Colorado, USA, 25-27 August.
- Gamadi, T.D., Sheng, J.J., and Soliman, M.Y., 2013. An Experimental Study of Cyclic Gas Injection to Improve Shale Oil Recovery. SPE 166334 presented at the SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana, USA, 30 September - 2 October.
- Gamadi, T.D., Sheng, J.J., Soliman, M.Y., Menouar, H., Watson, M.C., Emadibaladehi, H., 2014. An Experimental Study of Cyclic CO₂ Injection to Improve Shale Oil Recovery. SPE 169142 presented at the SPE Improved Oil Recovery Symposium held in Tulsa, Oklahoma, USA, 12-16 April.

- Gu, F., Chalaturnyk, R. J., 2006. Numerical simulation of stress and strain due to gas sorption/desorption and their effects on in situ permeability of coalbeds. *Journal of Canadian Petroleum Technology*. 45 (10), 52-62.
- Halnes, H. K., Monger, T. G., 1990. A Laboratory Study Of Natural Gas Huff 'n' Puff. SPE 21576 presented at CIM/SPE International Technical Meeting held in Calgary, Alberta, Canada, 10-13 June.
- Ivory, J., Chang, J., Coates, R., Forshner, K., 2009. Investigation of cyclic solvent injection process for heavy oil recovery. PETSOC 2009161 presented at Canadian International Petroleum Conference held in Calgary, Alberta, Canada, 16-18 June.
- Jia, X.; Zeng, F., Gu, Y., 2015. Gasflooding-assisted cyclic solvent injection (GA-CSI) for enhancing heavy oil recovery. *Fuel*. 140 (0), 344-353.
- Kovscek, A.R., Tang, G.Q., Vega, B., 2008. Experimental Investigation of Oil Recovery from Siliceous Shale by CO₂ Injection. SPE 115679 presented at SPE Annual Technical Conference and Exhibition held in Denver, Colorado, USA, 21-24 September.
- Latil, M., 1980. Enhanced oil recovery. Éditions Technip.
- Li, G., Moridis, G. J., Zhang, K., Li, X. S., 2011. The use of huff and puff method in a single horizontal well in gas production from marine gas hydrate deposits in the Shenhu Area of South China Sea. *Journal of Petroleum Science and Engineering*. 77 (1), 49-68.
- Li, L., Sheng, J. J., Sheng, J., 2016. Optimization of Huff-n-Puff Gas Injection to Enhance Oil Recovery in Shale Reservoirs. SPE 180219 presented at SPE Low Perm Symposium held in Denver, Colorado, USA, 5-6 May.
- Li, L., Sheng, J.J., Watson, M., Mody, F., 2015. Experimental and Numerical Upscale Study of Cyclic Methane Injection to Enhance Shale Oil Recovery. AIChE 425710 presented at AIChE Annual Conference held in Salt Lake City, Utah, 8-13 November.
- Lino, U. de R. A., 1994. An Evaluation of Natural Gas Huff 'n' Puff Field Tests in Brazil. SPE 26974 presented at SPE Latin America/Caribbean Petroleum Engineering Conference held in Buenos Aires, Argentina, 27-29 April.
- London, M., Cameron, S. M., Donald, J., Wassmuth, F. R., 2014. Waterflooding Experiments with X-ray CT Imaging. SPE 170147 presented at SPE Heavy Oil Conference-Canada held in Calgary, Alberta, Canada, 10-12 June.
- MacAllister, D. J., Miller, K. C., Graham, S. K., Yang, C.-T., 1993. Application of X-ray CT scanning to determine gas/water relative permeabilities. *SPE Formation Evaluation*. 8 (03), 184-188.
- McKee, C. R., Bumb, A. C., Koenig, R. A., 1987. Stress-dependent permeability and porosity of coal. In *International Coalbed Methane Symposium*. University of Alabama, Tuscaloosa, Alabama, 183-193.
- Meng, X., Sheng, J. J., Yu, Y., 2015. Evaluation of Enhanced Condensate Recovery Potential in Shale Plays by Huff-n-Puff Gas Injection. SPE 177283 presented at SPE Eastern Regional Meeting held in Morgantown, West Virginia, 13-15 October.
- Meng, X., Yu, Y., Sheng, J. J., 2015. An Experimental Study on Huff-n-Puff Gas Injection to Enhance Condensate Recovery in Shale Gas Reservoirs. SPE 178540 presented at SPE Unconventional Resources Technology Conference held in San Antonio, Texas, 20-22 July.
- Monger, T. G., Coma, J. M., 1988. A Laboratory and Field Evaluation of the CO₂ Huff'n'Puff Process for Light-Oil Recovery. *SPE Reservoir Evaluation and Engineering*. 3 (04), 1-168.
- Pang, Y., Soliman, M. Y., Deng, H., Emadi, H., 2016. Effect of Methane Adsorption on Stress-Dependent Porosity and Permeability in Shale Gas Reservoirs. SPE 180260 presented in SPE Low Perm Symposium held in Denver, Colorado, USA, 5-6 May.

- Sayegh, S., Maini, B., 1984. Laboratory Evaluation Of The CO₂ Huff-n-Puff Process For Heavy Oil Reservoirs. *Journal of Canadian Petroleum Technology*. 23 (03), 29-36.
- Sheng, J. J., 2015. Increase liquid oil production by Huff-n-Puff of produced gas in shale gas condensate reservoirs. *Journal of Unconventional Oil and Gas Resources*. 11 (0), 19-26.
- Sheng, J. J., 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 (0), 1-9.
- Siddiqui, S., Grader, A. S., Touati, M., Loermans, A. M., Funk, J. J., 2005. Techniques for extracting reliable density and porosity data from cuttings. SPE 96918 presented at SPE Annual Technical Conference and Exhibition held in Dallas, Texas, 9-12 October.
- Siddiqui, S., Khamees, A. A., 2004. Dual-energy CT-scanning applications in rock characterization. SPE 90520 presented at SPE Annual Technical Conference and Exhibition held in Houston, Texas, 26-29 September.
- Simjoo, M., Dong, Y., Andrianov, A., Talanana, M., Zitha, P., 2013. CT scan study of immiscible foam flow in porous media for enhancing oil recovery. *Industrial & Engineering Chemistry Research*. 52 (18), 6221-6233.
- Thomas, G. A., Monger-McClure, T. G., 1991. Feasibility of cyclic CO₂ injection for light-oil recovery. *SPE Reservoir Engineering*. 6 (02), 179-184.
- Thomas, S., 2008. Enhanced oil recovery-an overview. *Oil & Gas Science and Technology-Revue de l'IFP*. 63 (1), 9-19.
- Tovar, F. D., Eide, O., Graue, A., Schechter, D. S., 2014. Experimental Investigation of Enhanced Recovery in Unconventional Liquid Reservoirs using CO₂: A look Ahead to the Future of Unconventional EOR. SPE 169022 presented at SPE Unconventional Resources Conference held in The Woodlands, Texas, USA, 1-3 April.
- Walsh, J. B., 1981. Effect of pore pressure and confining pressure on fracture permeability. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. 18 (05), 429-435.
- Wan, T., Meng, X., Sheng, J. J., Watson, M., 2014. Compositional modeling of EOR process in stimulated shale oil reservoirs by cyclic gas injection. SPE169069 presented at SPE Improved Oil Recovery Symposium held in Tulsa, Oklahoma, 12-16 April.
- Wan, T., Sheng, J. J., 2015. Evaluation of the EOR Potential in Hydraulically Fractured Shale Oil Reservoirs by Cyclic Gas Injection. *Petroleum Science and Technology*. 33 (7), 812-818.
- Wan, T., Sheng, J.J., Soliman, M.Y., 2013a. Evaluation of the EOR Potential in Shale Oil Reservoirs by Cyclic Gas Injection. Paper SPWLA-d-12-00119 presented at the SPWLA 54th Annual Logging Symposium held in New Orleans, Louisiana, USA, 22-26 June.
- Wenlong, G., Shuhong, W., Jian, Z., Xialin, Z., Jinzhong, L., Xiao, M., 2008. Utilizing Natural Gas Huff and Puff to Enhance Production in Heavy Oil Reservoir. SPE 117335 presented at International Thermal Operations and Heavy Oil Symposium held in Calgary, Alberta, 20-23 October.
- Yu, Y., Sheng, J.J., 2015. An Experimental Investigation of the Effect of Pressure Depletion Rate on Oil Recovery from Shale Cores by Cyclic Nitrogen Injection. SPE 178494 in SPE Unconventional Resources Technology Conference held in San Antonio, Texas, 20-22 July.
- Yu, Y., Sheng, J.J., Mody, F., 2015. Evaluation of Cyclic Gas Injection EOR Performance on Shale Core Samples Using X-Ray CT Scanner. AICHE 407411 presented at the AICHE Annual Meeting held in Salt Lake City, UT, 8-13 November.
- Zhang, Y. P., Sayegh, S. G., Huang, S., Dong, M., 2006. Laboratory Investigation of Enhanced Light-Oil Recovery By CO₂/Flue Gas Huff-n-Puff Process. *Journal of Canadian Petroleum Technology*. 45 (2): 24-32.