Study on Oil Recovery Potential of Nitrogen Huff-N-Puff in Yanchang Tight Oil Reservoir

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Abstract. Tight oil is considered as the most expecting alternative resource after the conventional fossil energy exploration. In this work, the oil recovery efficiencies of nitrogen huff-n-puff process in ten cylinder cores and in a three dimensional model from Yanchang tight oil reservoir were investigated. The results indicated that the pressure propagation in nitrogen huff–n-puff process was much deeper and faster, which contributed to the higher oil recovery, compared to water huff–n-puff. The pressure depletion rate was the dominating factor for enhancing oil recovery, meanwhile, the injection velocity and the closed time had little effect on oil recoveries. Moreover, the evidence from numerical simulation showed that natural energy exhaustion was remarkably supplemented at the first circle of nitrogen injection; and around 25% of the oil saturation was recovered by nitrogen huff-n-puff. Our study implied that nitrogen huff–n-puff process might have robust application for enhancing oil recovery in Yanchang tight oil formation.

1. Introduction
The increasing requirement of hydrocarbons but with the decline of primary production in conventional oil recovery has led to the development of crude oil originating from low permeable reservoirs such as tight reservoirs and shale reservoirs. The crude oil is first raised to the surface through producing wells by the natural pressure of a reservoir. Second, water is injected the oil-based formation to maintain the reservoir pressure and to sweep out oil. Water is the most convenient and cheapest displacement substance in comparison to other displacement materials. However, as for the low permeable reservoirs, defined pores-throats of porous media result in the abnormal pressure for water injection. A widely used enhanced oil recovery (EOR) method is gas injection, which involves the injection of natural gases, carbon dioxide (CO\textsubscript{2}), air or nitrogen (N\textsubscript{2}) to displace oil under either immiscible or miscible condition. Compared to the water flooding, gas injection could have higher oil recovery efficiency. The main oil recovery mechanisms of immiscible gas injection are reservoir pressure supplement to displace oil towards the production wells and gas dissolution into the oil phase to somehow make it less viscous. For a miscible gas injection, besides the above mechanisms, the interfacial tension between the injected gas and oil phase is ultralow even zero, which significantly increases the microscopic displacement efficiency.
CO₂ injection is the most non-thermal EOR processes. It is a promising set of technologies for EOR processes of low permeable reservoirs. CO₂ achieves supercritical condition at low pressure (7.38 MPa) and low temperature (31.3 ℃). Supercritical CO₂ has high density which eliminates gas fingering, and has a strong capability of extract light component of crude oil under reservoir condition which facilitates the miscibility in oil under reservoir condition. CO₂-based process has a successful application in United States and Canada whose have abundant CO₂ resource underground. In 1980s, CO₂ process was implemented in Little Knife and South Pine oil field, the recovery improved 13% in the pilot experiment. CO₂ flooding method was proved to be efficient by Ghedan in 2009 in the low permeability reservoir [1-3]. However, the main challenges for the worldwide application of CO₂ EOR processes are the availability of CO₂, corrosion in the surface facilities and wells, and the high cost of CO₂ for use. Nitrogen has long been successfully used as the injection fluid for EOR purpose in the terms of gas recycling, reservoir pressure maintenance and gas lift. The costs and limitations on the availability of natural gas and CO₂ made nitrogen a desirable alternative for recovery because nitrogen is more widely available, cheaper and environmental friendly. Moreover, nitrogen has no corrosion in the surface facilities and wells. Notably, the miscible displacement is not the main mechanism because the press required for nitrogen to become miscibility is significantly high compared with CO₂ and natural gas displacement [4-6].

Tight oil accounts for the largest part in Yanchang oilfield (Shannxi Yangchang Petroleum Co., LTD), which is the most expecting alternative resource after the conventional fossil energy exploration. To elucidate the potential of nitrogen EOR process in tight oil formation, nitrogen huff-n-puff process was investigated in comparison to that of water in the study. The parameter corresponding to huff-n-puff process such as injecting flow rate, close time and pressure depletion were optimized. A three dimensional model was carried out to compare the oil recovery efficiency of nitrogen and water huff-n-puff. Moreover, to confirmed the oil recovery potential of nitrogen in a certain block formation, numerical simulation is considered to describe the residual oil occupation after nitrogen huff-n-puff process.

2. Experimental Section

2.1. Materials
Crude oil and injected water were obtained from a certain block in Yanchang oilfield (China). This formation is a typical tight formation with permeability ranking 0.18-0.37mD and porosity. The viscosity and density of crude oil in reservoir condition (original pressure of 11.3MPa, temperature of 53℃) were 3.75 MPaꞏs and 0.856 g/cm³. The SARA fractions of the crude oil were as follows: saturated hydrocarbon 76.22-78.9%, aromatic hydrocarbon 11.5-12.4%, resin 4.07-7.5% and asphaltene 0.78-1.74%. The paraffin content was around 2.3-3.7%. The total salinity of injected water was 15220 mg/L and the inorganic composition is listed in Table 1. The injected water was double filtered using 3.0 μm nucleopore membrane to remove undissolved particles, such as clay and physical impurities. Cylinder cores (2.5 cm × 48 cm), used in this study were artificial cores that were consolidated cuboids or natural cores. The injection gas is nitrogen with the purity of 99.95%.
Table 1. Physical parameters of cores used in this study.

| Core no. | Permeability (mD) | Length (cm) | Diameter (cm) | Porosity (%) | Oil saturation (%) |
|----------|-------------------|-------------|---------------|--------------|-------------------|
| 1        | 0.180             | 49.427      | 2.48          | 9.7          | 58                |
| 2        | 0.220             | 47.144      | 2.51          | 10.0         | 56.3              |
| 3        | 0.220             | 47.054      | 2.47          | 9.6          | 56.7              |
| 4        | 0.237             | 47.446      | 2.43          | 10.7         | 57.4              |
| 5        | 0.228             | 47.196      | 2.49          | 11.0         | 52.8              |
| 6        | 0.237             | 47.677      | 2.45          | 10.6         | 54.2              |
| 7        | 0.250             | 49.924      | 2.41          | 10.2         | 54.4              |
| 8        | 0.300             | 51.527      | 2.42          | 10.3         | 54.0              |
| 9        | 0.340             | 52.168      | 2.49          | 10.5         | 57.7              |
| 10       | 0.370             | 49.890      | 2.51          | 10.7         | 56.7              |

ISCO pump, resistance saturation detection device and pressure detection device are required in this experiment. The maximum temperature and pressure for the replacing system is 150°C and 70MPa. The flow rate range of ISCO pump is 90 ml/min.

Figure 1. The experimental set-up in this study.

2.2. Experimental Procedure

2.2.1 Measurement of physical parameters of long cores. Physical parameters of cores are measured according to the following steps.

(1) Cores were treated with acetone, under the vacuum environment for 1 week, then dried at 80°C for 12 h, the dry weight and core size were measured. The gas permeability was measured. Each core was vacuumized for 12 h again and saturated with reservoir formation water, the wet weight was measured, calculated the pore volume (PV) and porosity. (2) The formation water saturation cores were vacuumized under crude oil condition for 2 weeks, the weight of oil saturated cores were calculated, and the oil saturation was calculated according to the mass balanced rule.

2.2.2 Water huff-n-puff processes. Five cycles of water huff-n-puff with three variables were carried out. Three parameters are water injection velocity, pressure depletion rate and close time, respectively.
These experimental results would provide the initial parameters of the simulation model, which are the permeability, porosity, initial water and oil saturation. The dynamic parameters supplied are pressure, water injection volume, and the production of oil and water in each stage.

2.2.3 Nitrogen huff-n-puff processes. Five cycles of gas huff-n-puff with three variables were carried out. Three parameters are gas injection velocity, pressure depletion rate and close time, respectively. These experimental results would provide the initial parameters of the simulation model, which are the permeability, porosity, initial water and oil saturation. The dynamic parameters supplied are pressure, gas injection volume, and the production of oil and water in each stage.

2.2.4 Three dimensional huff-n- puff experiment. The optimal parameters are optimized through long core water and nitrogen huff-n- puff experiments. Combined with the conditions of field well pattern and construction feasibility, three-dimensional (3D) physical simulation experiments of water and nitrogen huff-n-puff are designed. The size of the 3D model is 40cm*40cm*4cm. As shown in Figure 1, the red point is stand for huff–n-puff well surrounding by four wells (blue points) which are regarded as the pressure detection points during the experiment.

![Three dimensional huff–n-puff model](image)

**Figure 2.** Three dimensional huff–n-puff model.

1. The initial back pressure of the 3D model was set 15 MPa. It was saturated with formation water, and then crude oil is injected to the model at the flow rate of 0.5 ml/min to obtain the irreducible water saturation and oil saturation. The amount of liquid production was calculated after the first depletion stage with pressure decreasing from the initial pressure to 5MPa.

2. According to the pre-set water and gas injection velocity, gas is injected into the model to maintain the pressure as high as 20MPa. The simulated well begins to produce after shutting off for 1h by controlling the rate of liquid and gas production to maintain the pre-set pressure depletion speed until the pressure deceased to 5MPa. The amount of produced liquid was calculated during the first cycle of nitrogen huff-n-puff process.

3. Repeat this step and continue to huff n-- puff for two cycles and measurement of the amount of produced liquid during each cycle.

   Notably, the starting pressure in non-Darcy flow of low permeability core, there will be huge differences of the pressure among inlet, middle part and outlet during multiphase flow in low permeable porous media due to the existence of staring pressure in non-Darcy flow. It would be solved through a pure water huff-n- puff experiment because there is no starting pressure gradient in single-phase flow.

3. Results and discussion

0.0559 PV liquid needs to be produced when the pressure is reduced from 15MPa to 5MPa by using volume equivalent principle. And when the pressure changes from 5MPa to 20MPa, it needs to supplement 0.08PV liquid.
3.1. Water huff-n-puff experiments

The average permeability, pore volume and porosity of the five long cores of water injection experiments are shown as follows. The physical properties are similar after the combination.

Table 2. Water huff-n-puff Injection Experiment Schedule.

| Core no. | Average Permeability (mD) | Saturated Oil Volume (ml) | Initial Oil Saturation (decimal) | Pressure Depletion Rate (MPa/h) | Water Injection Velocity (ml/min) | Close Time (h) |
|----------|---------------------------|---------------------------|----------------------------------|---------------------------------|----------------------------------|---------------|
| 1        | 0.180                     | 13.649                    | 0.580                            | 1                               | 0.025                            | 3.000         |
| 2        | 0.220                     | 13.166                    | 0.563                            | 2                               | 0.025                            | 3.000         |
| 3        | 0.220                     | 13.270                    | 0.567                            | 3                               | 0.025                            | 3.000         |
| 4        | 0.237                     | 13.420                    | 0.574                            | 1                               | 0.050                            | 3.000         |
| 5        | 0.228                     | 13.420                    | 0.528                            | 1                               | 0.050                            | 9.000         |

In the experiment of water injection huff and puff, the final recovery with the exhaustion speed of 1MPa/h is higher than 12% (Figure 3). And the recovery with exhaustion speed in 2MPa/h is 10.44%. The lowest recovery is that with exhaustion speed of 3MPa/h, which is only 8.92%. As time goes on, the fastest water injection velocity and the longest close time do the worst to the recovery (Figure 4). To close time, ultimate recovery after shutting in three hours is higher than 9 hours, but almost the same. The velocity of water injection with 0.025ml/min does better than 0.05ml/min in enhancing oil recovery.

Figure 3. Relationship between recovery and water injection pore volume.
In the first circle, water cut rate runs the first in the fifth experiment which has the highest water injection rate. At the second and third circles, water cut is located in the first with the fastest pressure depletion in experiment three (Figure 5). The final water cut rate is basically the same after three rounds of water huff and puff. The experiment with fastest pressure depletion has the shortest water breakthrough time (Figure 6).

The optimal parameter settings for the first set of experiments with 0.025ml/min water injection velocity, pressure depletion rate 1MPa/h and closed time 3h is the best.
3.2. Gas injection experiment analysis of long core

The average permeability, pore volume and porosity of the five long cores of gas injection experiments are shown as follows (Table 3). The physical properties are similar after the combination.

| No. | Average Permeability (mD) | Core length (cm) | Pore Volume (ml) | Porosity (decimal) | Saturated Oil Volume (ml) | Initial Oil Saturation (decimal) | Pressure Depletion Rate (MPa/h) | Gas Injection Velocity (ml/min) | Close Time (h) |
|-----|------------------------|-----------------|-----------------|-------------------|--------------------------|-------------------------------|-------------------------------|-------------------------------|----------------|
| 6   | 0.237                  | 47.677          | 24.760          | 0.106             | 13.420                   | 0.542                         | 1                             | 2.000                         | 3.000          |
| 7   | 0.250                  | 49.924          | 24.852          | 0.102             | 13.520                   | 0.544                         | 2                             | 2.000                         | 3.000          |
| 8   | 0.230                  | 51.527          | 26.105          | 0.103             | 14.100                   | 0.540                         | 3                             | 2.000                         | 3.000          |
| 9   | 0.340                  | 52.168          | 26.360          | 0.103             | 15.200                   | 0.577                         | 1                             | 4.000                         | 3.000          |
| 10  | 0.370                  | 49.890          | 26.110          | 0.107             | 14.800                   | 0.567                         | 1                             | 4.000                         | 9.000          |

In the experiment of gas injection huff and puff, the final recovery with the exhaustion speed of 1MPa/h is higher than 15% (Figure 7). And the recovery with exhaustion speed in 2MPa/h is 14.25%. The lowest recovery is that with exhaustion speed of 3MPa/h, which is only 14.11%. To close time (Figure 8), ultimate recovery after shutting in three hours is higher than 9 hours, but there are not too many differences between them. The velocity of gas injection with 2ml/min does better than 4ml/min in enhancing oil recovery.

![Figure 7. Relationship between recovery and gas injection pore volume.](image1)

![Figure 8. Relationship between recovery and gas injection time.](image2)
The optimal parameter settings for the sixth set of experiments with 2ml/min gas injection velocity, pressure depletion rate 1MPa/h and closed time 3h is the best. The gas oil ratio increases with the time. When the depletion pressure is 3MPa/h, the gas oil ration ranked the first (Figure 9).

3.3. Three dimensional huff and puff experiment analysis

The average permeability, pore volume and saturated oil volume of the three dimensional huff and puff experiments are shown as follows (Table 4). The initial temperature and pressure for the three dimensional model is 53℃ and 15MPa separately. Experiment 11 is water injection and experiment 12 is gas injection.

Table 4. Three Dimensional Huff and Puff Experiment.

| Core no. | Average Permeability (mD) | Model Size (cm) | Pore Volume (ml) | Initial Temperature (℃) | Saturated Oil Volume (ml) | Initial Pressure (MPa) | Pressure Depletion Rate (MPa/h) | Water/Gas Injection Velocity (ml/min) | Close Time (h) |
|----------|---------------------------|-----------------|------------------|--------------------------|--------------------------|------------------------|-----------------------------------|--------------------------------------|---------------|
| 11       | 1.360                     | 40*40*4         | 646.56           | 40                       | 323.214                  | 15                     | 1                                | 0.025                  | 3.000         |
| 12       | 1.410                     | 40*40*4         | 672.15           | 40                       | 333.520                  | 15                     | 1                                | 2.000                  | 3.000         |

According to the pressure in the middle of the model or at the end, under the same conditions, the pressure in the process of gas injection can spread farther and faster. The production process can exploit the residue oil production far away from the well, which is an important reason why the effect of gas injection is better than water injection (Figures 10-11).
The numerical simulated results of three-dimensional huff and puff experiments indicate that the natural energy is the single-phase flow of oil phase under the action of elastic energy from the results of the residual oil saturation field. The oil is continuous phase during this period and the development effect is the best. Nature depletion exploiting is adopted until the reservoir pressure decreases to 5MPa.

The first round of water injection (gas injection) supplemented energy. The sweeping volume accounts for a quarter of total by injecting water (gas). The injected water (gas) replace the crude oil in the pores during the process of elastic mining, which do benefits to the recovery. The oil saturation field after the first round and the second round is shown as follows (Figure 13).
Figure 13. Oil saturation field at the end of first round and the second round.

The second round and third round of injecting water (gas) cannot greatly improve the degree of sweeping inefficiency. What more, the residual oil in sweep area has already been segmented and blocked during the first round of injecting water (gas). That is the reason why the effect is unsatisfied after two rounds of injecting water (gas). The oil saturation field after the second round and the third round is shown as follows (Figure 14).

Figure 14. Oil saturation field at the end of second round and the third round.

4. Conclusions
(1) The pressure propagation in the nitrogen huff–n-puff process is much deeper and faster, compared to water huff–n-puff, which is contribution to the higher oil recovery.
(2) The pressure depletion rate is the prime factor for enhancing oil recovery. Meanwhile, the injection velocity and the closed time have little effect on oil recoveries.
(3) Natural energy exhaustion is an important mining stage during the exploitation of low permeability reservoir, which was remarkably supplemented at the first circle of nitrogen injection; and therefore, around a quarter of the oil saturation was recovered by nitrogen huff-n-puff.

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