FEASIBILITY STUDY OF GAS-EOR USING CO_2 AND N_2 MIXTURE IN A HEAVY OIL RESERVOIR: EXPERIMENTS AND PILOT TEST

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Introduction

Since shallow-buried oil reservoirs of Nanpu Block, Jidong Oil Field, China belong to complex fault-block oil reservoirs, effective flooding networks are difficult to be established compared with other conventional oil reservoirs. Although horizontal wells are widely used in the field to expand drainage area, severe water invasions still happened after years of development **[1,2]**. Cyclic CO_2 injection, also known as CO_2 huff-n-puff, was then conducted to enhance oil recovery (EOR) since 2010, and great profits has been brought with 109.5×10^4 t of oil productions until the year of 2018. As a kind of solvent, CO_2 can dissolve with the heavy oil, and then cause oil swelling and viscosity reduction **[3, 4, 5, 6, 7]**. However, production problems such as wellbore corrosions, gas channeling, etc. still cannot be avoided during the operation of CO_2 injection, which then reduce the oil yielding and lower the CO_2 utilization. N_2 can also be used to enhance oil recovery according to the literatures **[8, 9, 10]**, more importantly, it is not corrosive and usually cheaper than CO_2 for EOR applications. Thus, CO_2 and N_2 mixture is proposed as an alternative gas-EOR technique for those shallow-buried heavy oil reservoirs.

In order to figure out the interaction mechanisms between CO_2/N_2 mixture and heavy oil, a feasibility study is firstly evaluated using a PVT cell in the laboratory. Mixtures with different CO_2/N_2 molar ratios (1:0, 4:1, 7:3, 1:1, 0:1) are designed, and the high-pressure properties of gas/oil system including saturation pressure, volume factor and viscosity are investigated. Then, a series of cyclic gas injection experiments are conducted using outcrop cores to compare the oil recovery factors of CO_2, N_2, and CO_2/N_2 mixtures. A pilot test of CO_2/N_2 mixture injection is also introduced in this paper.

Experiments

PVT analysis for gas/oil system

A PVT cell and a viscometer are used in the laboratory as shown in **Fig.1** and **Fig.2**. The operation pressure and temperature of the PVT cell is 200 MPa and 200 °C, and the viscometer's measurement range is from 0.3 mPa·s to 20000 mPa·s. The oil and water samples are collected from one block of Nanpu Oil Field, China. The density of formation oil is 0.89 g/cm^3, and the oil viscosity is 52.13 mPa·s under formation conditions (65 °C, 16.24 MPa). Both of the injected CO_2 and N_2 are with purities of 99.99 mol%.

The CO_2/N_2 molar ratio is set as 1:0, 4:1, 7:3, 1:1, 0:1, respectively, and the procedures for PVT analysis are as follows. (1) The PVT cell and the viscometer are cleaned and evacuated using a vacuum pump. (2) A specific volume of formation oil is injected into the cell and the viscometer, followed by a specific volume of gas. (3) Increase the pressure and temperature of the cell and the viscometer, then stir the gas/oil mixture for 12 h. The viscosity of formation oil (μ_o) can be measured at formation conditions

(65 ℃, 16.24 MPa). (4) Decrease the pressure step by step, and record the oil volume at a specific pressure. The saturation pressure (P_b) of the gas/oil system can be determined when the first gas bubble is observed in the PVT cell. (5) Change the injecting gas/oil ratio to another value, and repeat (1) to (4), then another P_b value and μ_o value can be obtained. (6) After the changes of gas/oil ratio for five to eight times, a series of P_b values and a series of μ_o value can be obtained as the changes of CO_2/N_2 ratio. (7) During the experiment procedure, the oil and gas volumes under different pressures can also be recorded, and then a series of volume factor (B_o) values versus different gas/oil ratios can be obtained.

Fig.1. Picture of PVT analysis apparatus

Fig.2. Picture of the viscometer

Cyclic gas injection experiments

cyclic gas injection experiments are designed to compare the oil recovery factors of CO_2, N_2 and CO_2/N_2 mixture, and the experimental setup is shown in **Fig.3**. The cores used in the experiments are outcrop cores with an average size of 300×45×45 mm^3, the average permeability of the core is 497.3×10^{-3} μm^2, and the average porosity is 17.02%. The formation oil and water samples are collected from the block, and the injected CO_2 and N_2 are with purities of 99.99 mol%.

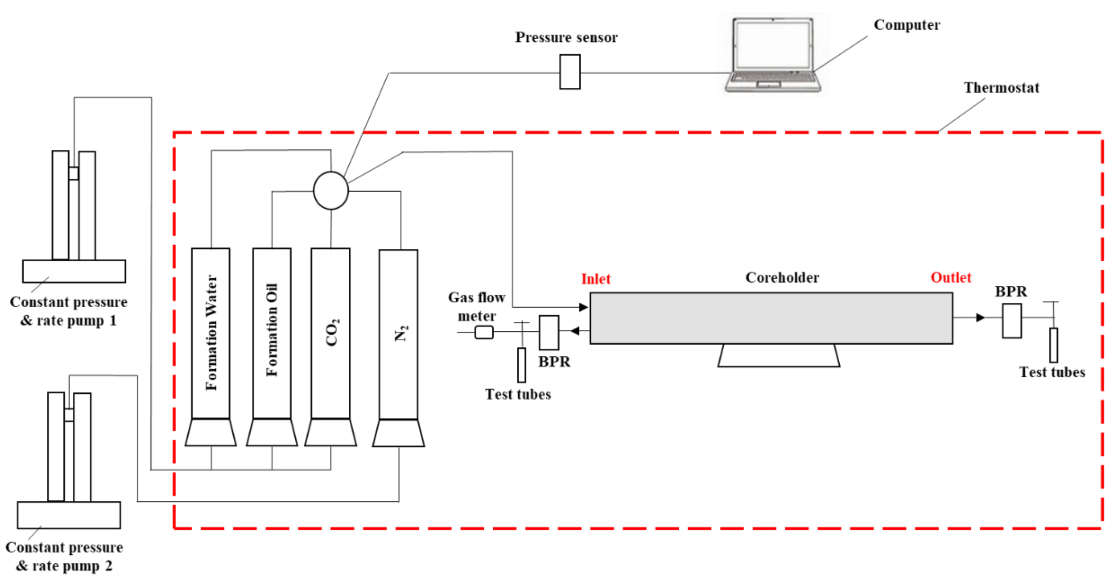

Fig.3. Flow chart for the cyclic gas injection experiments

Some preparations are conducted before the experiments as follows. (1) Epoxy resins are coated on the surface of the core to avoid CO_2 corruption, then the bulk volume of the core is measured. (2) The core is evacuated using a vacuum pump. After the core is saturated with formation water, the porosity is determined as the ratio of brine saturation volume to the bulk volume. (3) Brine is injected into the core to measure the permeability. (4) The core is displaced by oil to reach a residual water saturation, and the initial oil saturation is calculated as the ratio of injected oil volume to the pore volume.

CO_2, N_2 and CO_2/N_2 mixtures are injected into the core separately, and the procedures for the gas injection experiments are as follows. (1) The initial temperature is set as 65 ℃, and the initial pressure is set as 5 MPa using a back pressure regular (BPR). (2) Gas is injected into the core with a rate of 0.3 mL/min until the injection volume reaches 0.05 PV (Under formation conditions). (3) The inlet is shutoff with a soaking time of 12 h, and then opened to start a production process. When the pressure drops to 5 MPa again, one cycle is terminated. (4) Repeat procedure (2) and procedure (3) for another three times, and the whole experimental process is terminated after four cycles of gas injection. The pressure, the production of oil and gas are measured during the experiments. (5) Change the injecting CO_2/N_2 ratio as 1:0, 4:1, 7:3, 1:1 and 0:1, and repeat the procedures above, then the oil recovery factor for different gas injecting media can be calculated.

Results and discussion

PVT comparisons of CO_2/oil, N_2/oil, and CO_2/N_2/oil systems

Fig.4 shows the plot of saturation pressure (P_b) versus injecting gas molar ratio for the gas/oil system. The initial value of P_b for the formation oil is 11.2 MPa, which will raise as the increase of injecting gas ratio. P_b of the heavy oil is more sensitive with pure N_2 compared with pure CO_2. The saturation pressure influenced by CO_2/N_2 mixture is between pure CO_2 and pure N_2, which is also influenced by CO_2/N_2 molar ratio of the mixture. For example, with 20 mol% of CO_2/N_2 mixture injection, P_b influenced by the gas with a CO_2/N_2 ratio of 1:0, 4:1, 7:3, 1:1 and 0:1 is 13.6 MPa, 19.62 MPa, 22.63 MPa, 29.62 MPa and 51.39 MPa, respectively. The dissolving capacity for different injecting gas media can be also reflected through **Fig.4**. For example, when the pressure is 30 MPa, CO_2/N_2 mixture dissolved into the oil with a CO_2/N_2 ratio of 1:0, 4:1, 7:3, 1:1 and 0:1 is 12 mol%, 18 mol%, 29 mol%, 52 mol% and 57 mol%, respectively. CO_2 has a much better dissolving capacity into the heavy oil compared with N_2, which then influence the dissolving capacity of CO_2/N_2 mixture. The dissolving capacity of CO_2/N_2 mixture is enhanced dramatically as the increase of CO_2/N_2 molar ratio.

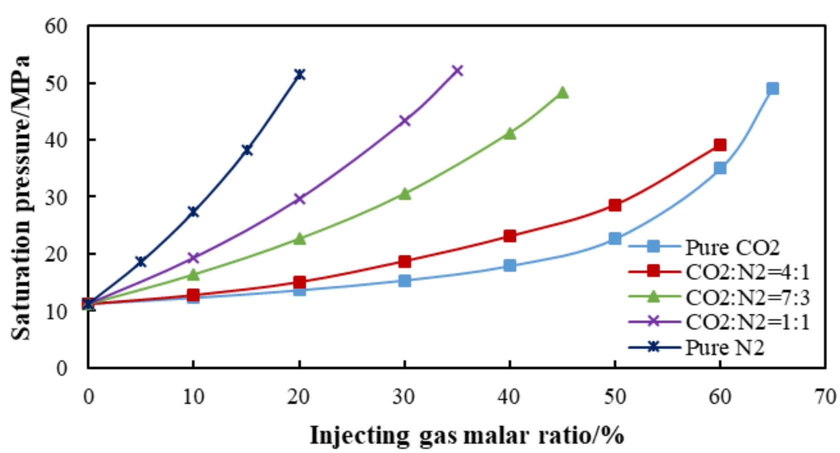

Fig.4. Saturation pressure (P_b) for the gas/oil system at 65 ℃

Volume factor (B_o) is used to evaluate oil swelling capacity, which is discussed as shown in **Fig.5**. The initial value of B_o for the heavy oil is 1.058 under formation conditions, which will also raise as the increase of injecting gas malar ratio. CO_2 has a better oil swelling capacity for the heavy oil compared with N_2. The volume factor influenced by CO_2/N_2 mixture is also between pure CO_2 and pure N_2, and is closely related to CO_2/N_2 molar ratio of the mixture. B_o raises as the increase of CO_2/N_2 molar ratio, and a better oil swelling capacity can be obtained with a higher CO_2 concentration for the mixture.

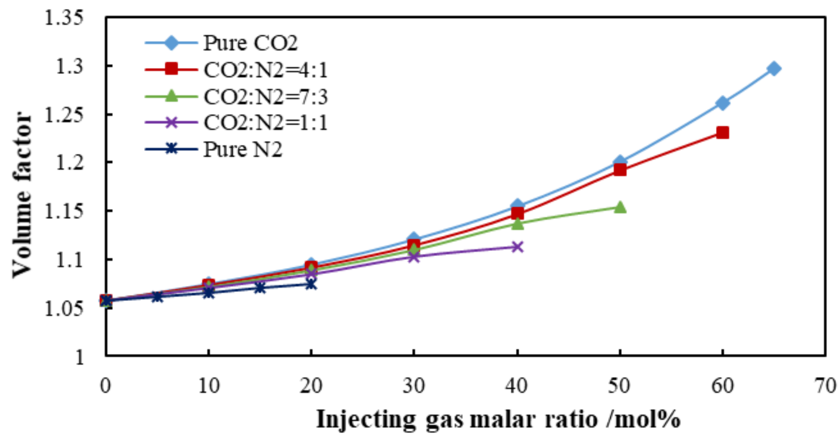

Fig.5. Volume factor (B_o) for the gas/oil system at 65 ℃ and 16.24 MPa

The oil viscosity (μ_o) reduction influenced by CO_2/N_2 mixture is shown in **Fig.6**. The initial value of μ_o for the formation oil is 52.13 mPa·s, which will decrease as the increase of injecting gas molar ratio. As more gas is dissolved into the formation oil, the viscosity reduction by the injecting gas is more obvious. CO_2 has a much better viscosity reduction capacity for the heavy oil compared with N_2. For the CO_2/N_2 mixture, the capacity of viscosity reduction is closely related to the CO_2/N_2 molar ratio. With a higher CO_2/N_2 ratio, a better viscosity reduction capacity will be obtained for the mixture.

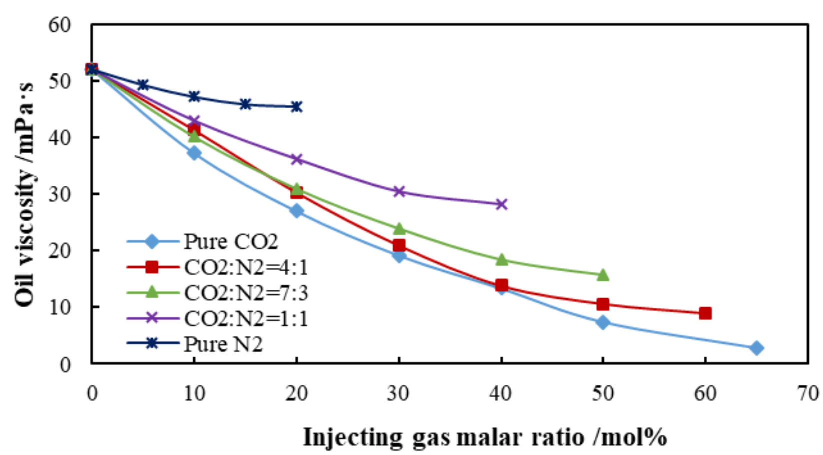

Fig.6. Oil viscosity (μ_o) for the gas/oil system at 65 ℃ and 16.24 MPa

The PVT analysis reveals that CO_2 has a better interaction with the heavy oil compared with N_2. For the CO_2/N_2 mixture, its interaction with formation oil is always between pure CO_2 and pure N_2. A higher CO_2/N_2 molar ratio for the mixture can always lead to better capacities of dissolution, oil swelling and viscosity reduction, which are the dominant mechanisms for the heavy oil extraction.

Recovery factor comparisons of CO_2, N_2 and CO_2/N_2 mixtures

Table 1 shows the total oil recovery factors after four cycle of gas injection using different gas media. After four cycles of gas injection, pure CO_2 and the 4:1 (CO_2/N_2 molar ratio) mixture achieve higher oil recovery factors. The oil recovery of 4:1 mixture is 17.31%, which is close to the oil recovery of 19.03% achieved by pure CO_2. 7:3 mixture achieves the middle oil recovery of 13.27%, and the 1:1 mixture and the pure N_2 achieve the lowest oil recovery factors, which are less than 10%. As discussed above, the oil extraction mechanisms for CO_2/N_2 mixture is closely related to the injecting CO_2/N_2 ratio. Since the concentration of N_2 component increases as the CO_2/N_2 ratio decreases, the interactions between gas and oil is weakened, which then affects the oil extraction of the CO_2/N_2 mixture. For the mixture with a CO_2/N_2 molar ratio of 4:1, CO_2 accounts for a large proportion of the mixture, and the superior performances of gas dissolution, oil swelling and viscosity reduction dominated by CO_2 are highly reserved for enhanced oil recovery.

Table 1. Total oil recovery of cyclic gas injection using different gas media

CO_2/N_2 molar ratio	**1:0**	**4:1**	**7:3**	**1:1**	**0:1**
Total oil recovery/%	19.03	17.31	13.27	9.09	8.09

Fig.7 shows the oil recovery for each cycle during gas injection experiments. It can be observed that although the oil recovered by 4:1 mixture is less than the oil recovered by pure CO_2 during the first and the second cycle, a better oil recovery can still be obtained for the 4:1 mixture during the third and the fourth cycle. **Fig.8** shows the pressure of cyclic gas injection using different gas media. The pressure enhancement using pure N_2 is much higher than the pressure using CO_2/N_2 mixture and pure CO_2, however, the oil recovery factor is still the poorest. This reveals that the critical factors for gas-EOR is to use enough CO_2 to interact with the heavy oil, while the pressure enhancement using N_2 could act as a supplementary role for the oil extraction. Although pure CO_2 has the best interactions with the heavy oil, 4:1 mixture can reach a higher pressure enhancement compared with pure CO_2. The gas/oil interactions dominated by CO_2 coupled with the pressure supplement by N_2 lead to a favorable oil recovery for the 4:1 mixture injection.

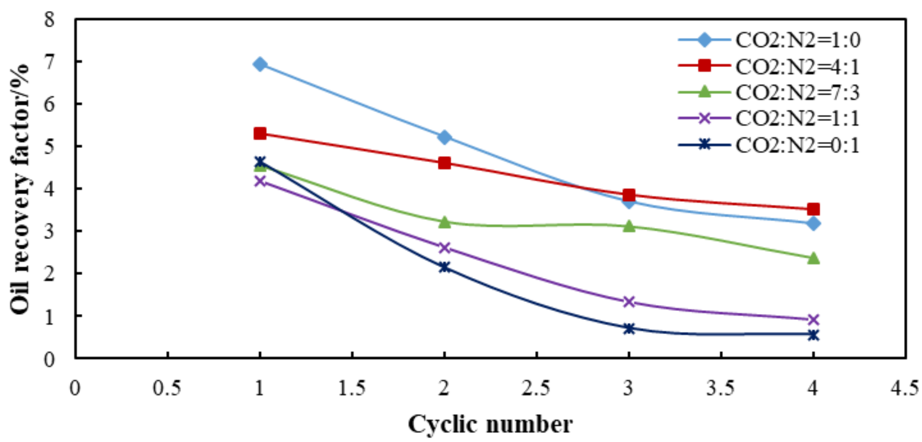

Fig.7. Oil recovery factor of each cycle for different gas injection experiments

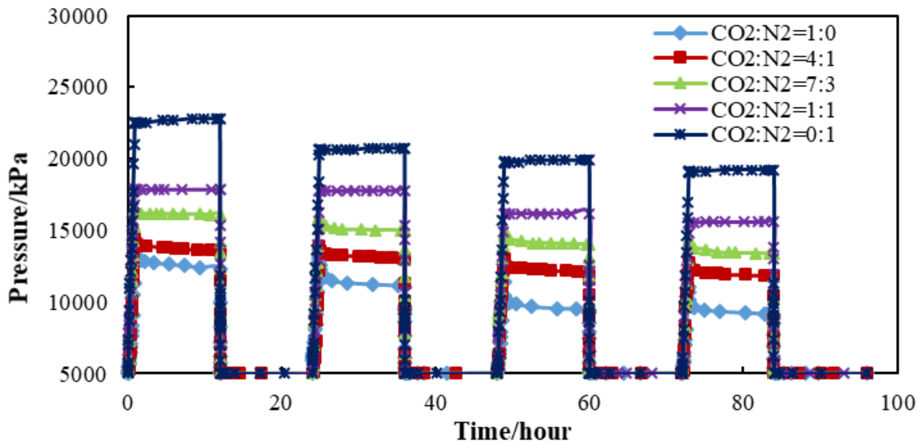

Fig.8. Pressure data of cyclic gas injection using different gas media

A pilot test results for the CO_2/N_2 mixture

Well G104-5P101 was chosen as a test well for CO_2/N_2 mixture injection at the year of 2016. The water cut of the well is 99% before the mixture injection, and CO_2/N_2 mixture was then injected into the test well with 40000 m^3 of N_2 and 300 t of CO_2 (CO_2/N_2 molar ratio = 4:1). When the well was re-produced after 1 months of soaking time, the water cut dropped from 99% to 72.3%, and the daily oil rate increased from 0.17 m^3/d to 2.95 m^3/d at the initial producing process (As shown in **Fig.9**). After 279 days of production, the CO_2/N_2 mixture recovered 275 t of heavy oil from the test well.

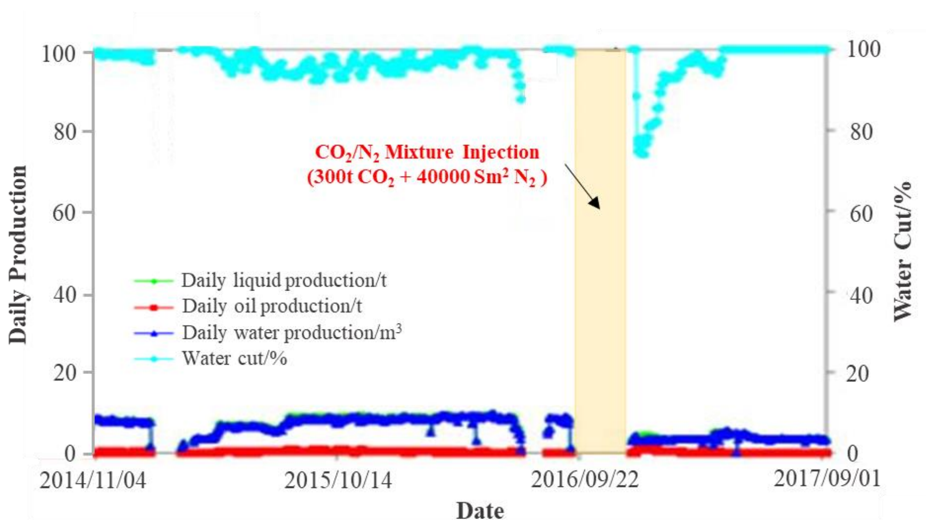

Fig.9. Test results for CO_2/N_2 mixture injection

Conclusions

A feasibility study of gas-EOR using CO_2 and N_2 mixture is evaluated to enhance the heavy oil recovery. Gas/oil interactions are firstly evaluated using a PVT analysis, then cyclic gas injection experiments using different gas media are conducted in the laboratory, and a pilot test for CO_2/N_2 mixture is also introduced in this paper. Some conclusions can be summarized as follows.

(1) The oil saturation pressure, volume factor and viscosity are highly related to CO_2/N_2 ratio of the injecting mixture. CO_2/N_2/oil interactions are usually between CO_2/oil interactions and N_2/oil interactions, and a higher CO_2/N_2 ratio can always lead to better capacities of dissolution, oil swelling and viscosity reduction.

(2) The mixture with a CO_2/N_2 moalr ratio of 4:1 can achieve an oil recovery of 17.31%. The gas/oil interactions dominated by CO_2 coupled with energy supplement provided by N_2 can effectively enhance the heavy oil recovery.

(3) A pilot test of CO_2/N_2 mixture injection is successfully conducted in a test well. An oil increment of 275 t is obtained after 40000 m^3 of N_2 and 300 t of CO_2 injection, which shows a potential EOR application of CO_2/N_2 mixture for the heavy oil.

References

1. Yu S., Li B., and Zhang Q. (1995), "Development of Jidong Oilfield with complicated fault-blocks", in *International Meeting on Petroleum Engineering*, Beijing, China.
2. Zhou H., Hao J., and Zheng J. (2006), "Development technique and practice of horizontal wells for complex fault-block reservoirs in Jidong Oilfield", in *International Oil & Gas Conference and Exhibition in China*, Beijing, China.
3. Miller J. and Jones R. (1981), "A laboratory study to determine physical characteristics of heavy oil after CO_2 saturation", in *SPE/DOE Enhanced Oil Recovery Symposium*, Tulsa, Oklahoma.
4. Mokrys I. and Bulter R. (1993), "In-situ upgrading of heavy oils and bitumen by propane deasphalting: The vapex process", in *SPE Production Operations Symposium*, Oklahoma City, Oklahoma.
5. Ivory J., Chang J., Coates R., et al. (2010), "Investigation of cyclic solvent injection process for heavy oil recovery", *Journal of Canadian Petroleum Technology*, 49 (9), pp. 22-33.
6. Shokri A. and Babadagli T. (2017), "Feasibility assessment of heavy-oil recovery by CO_2 injection after cold production with sands: Lab-to-field scale modeling considering nonequilibrium foamy oil behavior", *Applied Energy*, 205, pp. 615-625.
7. Ahadi A. and Torabi F. (2018), "Effect of light hydrocarbon solvents on the performance of CO_2-based cyclic solvent injection (CSI) in heavy oil systems", *Journal of Petroleum Science and Engineering*, 163, pp. 526-537.
8. Hudgins D., Llave F., and Chung F. (1990), "Nitrogen miscible displacement of light crude oil: A laboratory study", *SPE Reservoir Engineering*, 5 (1), pp. 100-106.
9. Sadooni M., and Zonnouri A. (2015), "The effect of nitrogen injection on production improvement in an Iranian rich gas condensate reservoir", *Petroleum Science and Technology*, 33, pp. 422-429.
10. Yuan D., Hou J., Song Z., et al. (2015), "Residual oil distribution characteristic of fractured-cavity carbonate reservoir after water flooding and enhanced oil recovery by N_2 flooding of fractured-cavity carbonate reservoir", Journal of Petroleum Science and Engineering, 129, pp. 15-22.