CO2 huff and puff pilot with staged-fracturing horizontal well in tight oil reservoirs

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Abstract: CO2 huff and puff has been considered as one of the most successful processes to increase oil recovery, however, this stimulation technology is yet to be widely used in tight oil reservoirs. In this paper, a production model is developed to describe the CO2-soak process in tight oil reservoirs, providing a guidance to optimize the production parameters for CO2-soak pilot in the staged-fracturing horizontal well. The result shows that the CO2 huff and puff process helps to improve the reservoir energy, the fluid mobility, and thus the reserves-to-production ratio. To be specific, the recovery factor of tight oil reservoirs stimulated with CO2 huff and puff technology is 2.0% higher than that produced with natural energy. The success in CO2 soak pilot is of importance significance to the effective development of tight oil reservoirs.

1. Introduction

As an important part of unconventional oil and gas resources, tight oil reservoirs have receive more and more attention in China. However, oil field practice shows that water drive is ineffective in tight oil reservoirs. Horizontal well with staged-fracturing has been adapted in tight oil reservoirs to generate the oil highway, enhance the reservoir seepage capacity, and thus obtain better production performance at the initial. However, the subsequent production decrease rapidly, and the energy supplement become a key to tight oil reservoir development.

2. Pilot Overview

The pilot area is located in the central depression of the Songliao Basin. The block structure is gentle and is an important exploration and reserve area in the south of the Songliao Basin. The target Fuyu oil layer is the complex lithologic reservoir, which is mainly composed of rivers and delta subaqueous distributary channels. Therein the thickness of oil-bearing sandstone is 5~15.0 m, the thickness of the single sand body is 2.0~4.0 m, the size of the sand body is 200~600 m, and the depth of the reservoir is about 1700 m. The density of the crude oil is 0.7996 g/cm³, and the viscosity of the crude oil is 7.02 Pa.s. The reservoir has an average porosity of 14.6% and an average permeability of 1.54 mD, and therefore it is a low-porosity and ultra-low permeability reservoir[1].

The tight oil pilot project has been developed on the combination of horizontal well and multi staged-fracturing. The average sandstone drilled along horizontal wellbores is 970 m. The well was fractured into 8.9 segments and 18.8 clusters, and 9257.2 m³ liquid and 905.8 m³ sand were used during the fracturing. The initial daily oil production was 27.1 t per well on average. The production has lasted for 1456 days, producing 1.1×10⁴ t oil in total. However, the production has been dropped to 3.5 t due to the lack of external energy supplement. Since the effective fractures are becoming shorter with production, some wells have to turn to batch production mode, and extend the shut-in cycle gradually.

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The energy supplement is urgent to the tight oil reservoir development.

3. **The mechanism of CO₂ huff and puff process**

The CO₂ solubility in crude oil is 4.4 times than that in water. The dissolution of CO₂ in crude oil will increase the crude oil volume while greatly reduce the viscosity of crude oil. Compared with not CO₂ dissolution situation, the saturated case has an increase of 10-30% in oil volume, and a decrease of 1-10% in oil viscosity. The dissolution of CO₂ in crude oil has several advantages for oil recovery, including gas drive energy increase, residual oil reduction, oil phase permeability improvement. The interfacial tension between oil and water is about 30~35 mN/m. However, this interfacial tension value will decrease 30%~40% when water is saturated with the CO₂. The reduction in interfacial tension will reduce the capillary force so that the fracturing fluid and the bound water can be returned in time[2]. The dissolution of CO₂ in water can also form a low-pH carbonic acid, which can dissolve the oil scale and inhibit the expansion of the clay, thereby facilitating the permeability of the formation.

3.1 **Viscosity reduction and energy increase**

Under formation pressure and temperature, the CO₂ can be dissolved in crude oil quickly, changing the physical properties of crude oil and greatly reducing the viscosity of crude oil. T.

3.2 **Anti-swelling and unblocking effect**

The CO₂ enters the oil layer and reacts with the formation water to form carbonic acid. The saturated carbonated water has a pH of 3.3~3.7, which can reduce the expansion of the clay mineral and release the blockage in the near-well zone.

3.3 **Wettability inversion**

The higher well pressure can improve the water wettability of the rock and make the rock develop in a hydrophilic direction, which is conducive to water flooding and improve oil recovery.

3.4 **Interfacial tension reduction**

Reducing the interfacial tension of the crude oil, even the miscible phase, reducing the displacement resistance, increasing the energy of the dissolved gas flooding, is conducive to returning to the discharge after the measure.

Since the CO₂ huff and puff is a single well treatment, it does not have to rely on the fluid drive between the well. Therefore, it can achieve a certain yield increase effect for small inter-well connectivity, other small-block reservoirs that can’t improve the recovery.

4. **Injection and production parameters optimization**

Based on the method of artificial cracking, numerical simulation, pressure recovery, and well testing, the oil change rate are used as the basis for evaluation, and the CO₂ huff and puff parameters are optimized in combination with reservoir geological conditions.

4.1 **CO₂ injection pressure**

Experiments show that under the higher injection pressure, the carbon dioxide crude oil has a higher degree of dissolution and higher oil displacement efficiency. Therefore, the upper-end pressure limit is set to the reservoir fracture pressure, and the lower-end pressure limit is more suitable than the mixed-phase pressure. The fracture pressure of the reservoir is 36.47 MPa, the average depth of the Fuyu oil reservoir is 1582 m, and the maximum injection pressure of the wellhead is 22.61 MPa. The upper injection pressure is calculated according to the critical pressure of 0.95, and the designed gas injection pressure at the wellhead should be lower than 21.48 MPa. The pressure at the end of injection should be greater than 17.51 MPa to reach the miscible pressure[3].
4.2 CO₂ injection rate
It is generally believed that the faster the injection speed, the easier it is to form a finger so that the CO₂ enters the deep part of the reservoir and dissolves more crude oil. However, the injection speed of each well should be within the allowable injection pressure range of the reservoir. As the injection speed continues to increase, the bottom hole temperature decreases, resulting in freezing blockage and oil change rate decreases. Numerical simulation is applied based on horizontal well 1. When the other parameters are constant, the overall oil change rate is higher when the injection speed is 120 t/d–140 t/d.

![Figure 1 Simulation of the relationship between injection speed and bottom hole temperature](image1)

4.3 CO₂ injection volume
The results show that the higher the injection rate, the greater the cumulative oil production and cumulative oil production; however, as the periodic injection volume increases, the oil change rate decreases gradually[4].

Numerical simulations were applied based on horizontal well 1 with injection speed (120 t/d) and shut-in period (30 d) unchanged. During the period of validity, when the injection amount is low, the corresponding effective period is short, and the oil production is low. As the gas injection increases, oil production also increases. When the injection is about 3500 t, the oil change rate reaches the highest to 0.51. As the injection continues to increase, the increase becomes slower in oil production. However, considering that the bottom hole pressure reaches the miscible pressure, the CO₂ greatly reduces the viscosity of the crude oil, increases the dissolved gas drive energy, and increases the elastic energy of the reservoir. Although it is not possible to mix phases throughout the entire process, it has an increase in oil absorption performance.

![Figure 2 The numerical simulation predicts the relationship between injection volume and accumulated oil production and oil change rate](image2)

4.4 Soak period
It is predicted by numerical simulation that the oil change rate and the gas-oil ratio decrease with the
increase of the shut-in cycle. After carbon dioxide injection, it has a physical effect on the leading edge and the crude oil, such as viscosity reduction and extraction. The affected crude oil gradually becomes heavier, and the physical effects of newly injected carbon dioxide and crude oil are gradually weakened. The shut-in period is short, the formation pressure is high along the wellbore, the initial production is high, but the gas-oil ratio is high, and the physical reaction time is short. The long-term shut-off period pressure is transmitted to the formation direction, and the pressure near the wellbore is lower than that of the shut-in period. The initial output is low, but the final oil change rate is slightly higher.

5. **Pilot implementation**

Three horizontal wells in the mine test were carried out in the test area with the on-site injection construction has been completed. The average single well injection liquid is 610 m³, the injection of carbon dioxide is 9945 t, the end pressure is 12.1 MPa, and the well is opened after 55 days. The initial single well daily oil increase is 18.3 t. At present, the average single well daily oil increase is 4.4 t, the average cumulative production is 403 days, and the single well cumulative oil increase is 1761.5 t.

| Num | Well | Layer | The length of the oil layer (m) | preflush (m³) | Injection (m³) | Point at the end of the pressure (MPa) | Soak time (d) | Before the throughput | Post-measure initial period | At present | Meter production days (d) | Cumulative oil production (t) |
|-----|------|-------|-------------------------------|--------------|--------------|----------------------------------------|---------------|---------------------|--------------------------|------------|--------------------------|-------------------------------|
| 1   | H1   | FL1   | 925                           | 616          | 9891        | 11.2                                    | 58            | 5.0                 | 2.6                      | 50.0       | 28.0                     | 2.6                           | 723                         | 3370.6 |
| 2   | H2   | FL2   | 1434                          | 828          | 10061       | 12.0                                    | 40            | 2.2                 | 1.1                      | 25.0       | 24.5                     | 4.7                           | 310                         | 890.8  |
| 3   | H3   | FL3   | 845                           | 387          | 9884        | 13.0                                    | 67            | 0.7                 | 0.3                      | 8.1        | 6.3                      | 11.8                          | 9.7                          | 177    |
| 4   |      |       | 1068                          | 610          | 9945        | 12.1                                    | 55            | 2.6                 | 1.3                      | 27.7       | 19.6                     | 7.5                           | 5.7                          | 403    |
| summation | | | |     | | | | | | | | | 403 | 1761.5 |

5.1 **Injection rate, injection volume, and injection pressure**

In the test area, the influence of injection speed on injection pressure is mainly reflected in the early stage of injection. The injection pressure of higher injection speed has a significant rise. After the injection volume reaches 2000 t, the pressure increase range and injection speed have no obvious influence, while the injection reaching a certain value (5000 ~ 6500 t), continue to inject, the injection pressure is slowly increased (about 11 MPa), and the injection pressure of the CO₂ per 1000 t is increased by less than 0.5 MPa.

![Figure 3 Relationship between injection volume and injection pressure](image)

5.2 **Physical property change of crude oil after huff and puff**

After the comparison of the CO₂ huff and puff, the extraction of light components in crude oil was carried out. The crude oil changed after the injection, the content of light components below C13 was significantly reduced, and the content of heavy components above C19 was increased.
5.3 Stimulation effect
At the beginning of the production of test well 1, the daily oil production was stable at 11 t, and it has lasted for 742 days. The cumulative oil production is 4435 t and increases 3393 t. It is expected that the cumulative oil increase will be 3509 t, and the oil-increasing effect is effective.

6. Conclusions
(1) CO2 huff and puff process has a significant effect on crude oil extraction and viscosity reduction. The light components (C13 and below) decrease while the heavy components (C19 and above) increase after the CO2 huff and puff process.

(2) The increase in CO2 soak rate will improve the injection pressure at the initial, but then the injection rate will have little effect on injection pressure when the injection rate is larger than a critical value.

(3) The mixed-phase pressure of the block is relatively high. After the injection pressure reaches a certain value, the pressure rises slowly with injection rate. Therefore, the mixed-phase condition is too difficult to reach.

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