CMTC-486556-MS

Numerical Simulation and Performance Evaluation of CO_2 Huff-n-Puff Processes in Unconventional Oil Reservoirs

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This paper was prepared for presentation at the Carbon Management Technology Conference held in Houston, Texas, USA, 17-20 July 2017.

Abstract

Unconventional oil, such as tight oil and shale oil, has become one of the most significant contributors of oil reservoirs and production growth. Due to low porosity and ultra-low permeability, unconventional oil reservoirs require multistage hydraulic fracturing technique to maximize production. However, the primary recovery remains very low to narrow the profit margin heavily. Although CO_2 huff-n-puff process holds great potential to increase oil recovery and has a chance to sequester CO_2 to reduce environmental footprint, our current knowledge of the performance of this process is very limited.

With numerical simulation, we performed a series of sensitivity work to present the impacts of reservoir properties, fracture properties and operation parameters such as CO_2 injection rate, injection time, soaking time, number of cycle of CO_2 on enhanced oil recovery in the tight oil formation. What's more, the method of analysis of variance (ANOVA) was used to evaluate the performance of CO_2 huff-n-puff process and beneficial result from CO_2 EOR technology. Simulation results showed that bottom hold pressure and injection cycles impose more significant impose on oil recovery increment than injection time, injection rate and production time per cycle.Based on the typical reservoir and fracture properties from tight oil reservoir, the numerical models were estabilished to evaluate the performance of four EOR methods: CO_2 huff-n-puff, water huff-n-puff, nanofluids huff-n-puff and water alternating gas (WAG). With the camparison of oil recovery and its increment of four EOR methods and depletion method, it is found that CO_2 huff-n-puff method would lead to much more incremental oil recovery than other three methods, which reveals its huge potentials of enhancing oil recovery and improving development profit in unconventional reservoirs. The conclusion of this work has the potential to advance our understanding of the role of CO_2 in developing unconventional oil reservoirs, which will benefit both energy economy and environment with CO_2 geological sequestration.

Introduction

Recently, uncoventional oil reservoirs have attracted much more attention. Unfortunately, low permeability of the tight and shale oil formations prevents them from being developed effectively and benefitially. Generally speaking, even with long horizontal drilling and multistage hydraulic fracturing techniques, the primary revovery remains low to only 5-10% of original oil in place (Christensen JR et al, 2001). Song Chengyao et al (2012) thought the water alternating miscrible flooding process was the most favourable scheme for tight formations in terms of both recovery efficiency and fluid injectivity. Luky Hendraningrat et al (2013) proposed the optimizing nanofluids concentration to maximize oil recovery in the low-permeability Berea sandstone with the mechanism of wettability alternation and interfacial tension reduction. WAG and Nano-EOR have been proven to not only increase oil procudion, but also improve fluid injectivity, which would be nice way to extract oil from unconventional formations.With experimental researches and field applications in conventional oil reservoirs, CO_2 flooding schemes have shown favourable revovery potential of enhancing oil recovery (EOR). S.M. Ghaderi et al (2013) proposed the coupled methodology to evaluate profitability and the risk of failure for multiple recovery meahanism sequences as well as the need for incentives to make CO_2 EOR profitable in tight oil reservoir.H. Wang et al (2014) estabilished the compositional numerical model of CO_2 flooding in tight oil reservoir to show that the minimum miscrible pressure (MMP) and the total gas injection volume were two key factors of CO_2 flooding effect. However, fractured horizontal well requires huag CO_2 consumption to dissolve into the crude oil and erious early gas breakthrough occurs in the complex fractures network, which inhibits the performance of CO_2 flooding.K. Zhang et al (2015) presented an integrated method for CO_2 flooding reservoir criteria with the consideration of asphatene precipitation, oil recovery performance and rish analysis, which would be used as guidance to select suitable candidateds for CO_2 flooding. Bing Kong et al (2016) compared the performances of waterflooding and CO_2 huff-n-puff and studied the inter-well interference during CO_2 huff-n-puff process. Compared with synchronous CO_2 huff-n-puff, asynchronous pattern performed much better.Chengyao Song and Daoyong Yang (2017) combined experimental technique with numerical simulation method to evaluate the CO_2 huff-n-puff process in a tight oilfield in Bakken formation. Experimentally, oil recovery was significantly enhanced by CO_2 huff-n-puff much more than by waterfloodiung. Coreflooding simulation and reservoir simulation were developed to evaluate the revovery performance of CO_2 huff-n-puff by using the CMG GEM simulator. They found that injection pressure and production pressure influenced the ultimate oil recovery more significantly. Despite many attempts and efforts already made to eavulate recovery performance of CO_2 huff-n-puff, the mechainsms have not been well understood and there is little field trial of CO_2 huff-n-puff for tight oil exploitation. Escpecially under the condition of low oil prices, CO_2 projects have to take large investment risk. Fortunately, world’s largest carbon-capture project, the Petra Nova project, began commercial operation in 2017, which would attract much more interests from researches and field trials.

In this paper, numerical simulation is conducted to evaluate the recovery performance of four EOR methos in tight oil reservoir: CO_2 huff-n-puff, water huff-n-puff, nanofluids huff-n-puff and water alternating gas (WAG). The method of analysis of variance (ANOVA) is carried out to present the impacts of operation parameters such as CO_2 injection rate, injection time, soaking time, number of cycle of CO_2 on enhanced oil recovery.

Numerical Simulation

A tight oil reservoir has been selected as the targeted reservoir. The reservoir covers an area of 2000 × 500 m with a payzone thichness 15 m. The formation matrix permeability is 0.015 mD and its porosity is 10%. The initial pressure is 45 MPa. The length of fractured horizontal well is 1800 m, while half length and numbers of fracture are 150 m and 23, respectively. The reservoir model is created by using the commercial software Eclipse. The model has a grid system of $200\times50\times3$, among which each grid is 10 m in the x and y direction, while it is 5 m in the z direction. With the constant oil production rate, the well produces for 2160 days and then it is converted to a CO_2 injection well with injection rates of 100000 m^3/d for 20 days. Then the well is shut-in and soaking for 20 days. Finally the well is put back into production for 300 days with constant bottom hole pressure, 6 MPa. This is one cycle of CO_2

huff-n-puff process. After that, another cycle of CO_2 huff-n-puff process continues. In this paper, the total times of cycles are 6 and the model is modelled totally for 5400 days.

The properties and parameters of the reservoir and the fractured horizontal well are presented in Table 1.

Table 1—Parameters of numerical simulation model

Parameters	Value	Parameters	Value
Reservoir length, m	2000	Length of horizontal well, m	1800
Reservoir width, m	500	Injection rate, m^3/d	100000
Effective thickness, m	15	Injection time per cycles, days	20
Initial reservoir pressure, MPa	45	Soaking time per cycles, days	20
Porosity, %	10	Production time per cycles, days	300
Permeability, mD	0.015	Cycles, times	6
Initial oil saturation	0.7	Bottom hole pressure, MPa	6
Fracture numbers	23	Modelling time, days	5400
Half length of fracture, m	150	CO_2 huff-n-puff time, days	3140

Figure 1 is the oil production profile and shows oil production as a function of production time. As it can be seen from the figure 1, the oil production starts to decrease after 1500 days and the well is shut-in at 2160 days to carry out CO_2 huff-n-puff injection. The profile indicates that oil production is largest in the first cycle and most oil is produced in the first two cycles. From the third cycle to the last cycle, the oil production during the puff process becomes less significant.

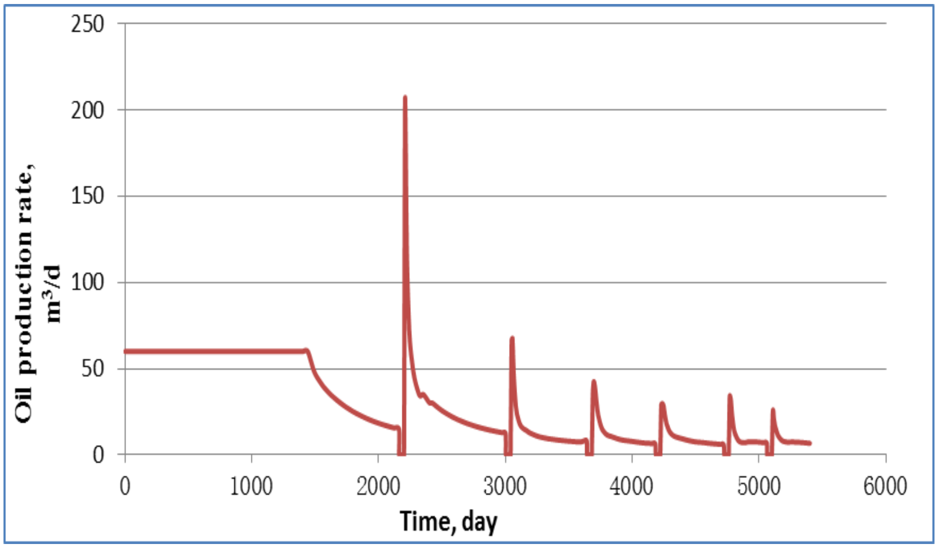

Figure 1—Oil production rate of CO_2 huff-n-puff process

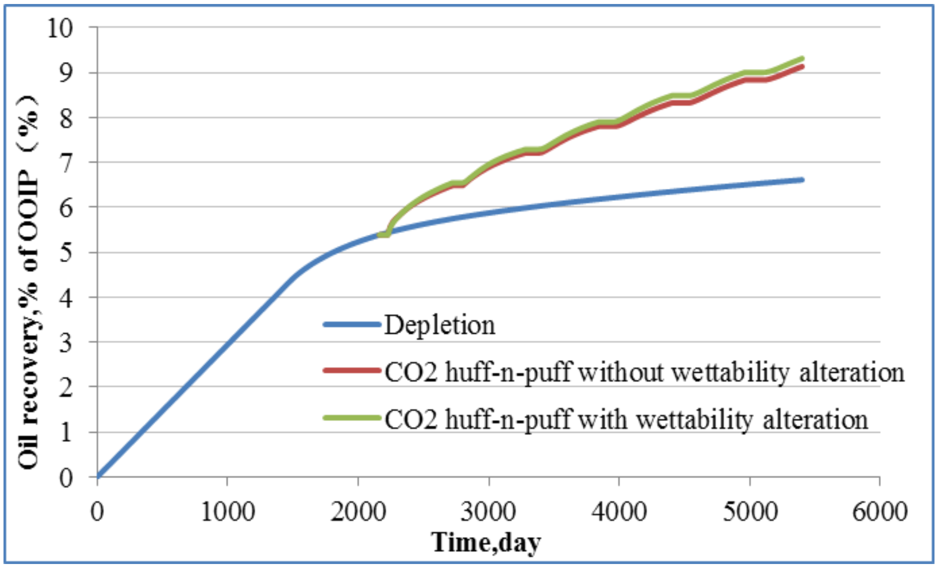

Figure 2—Comparison of oil recovery for depletion and CO_2 huff-n-puff

Figure 2 is the oil recovery profile of three scenarios: depletion, CO_2 huff-n-puff without wettability alternation and CO_2 huff-n-puff with wettability alternation. First of all, it is obviously found that CO_2 huff-n-puff brings significant recovery increment, about 3%. What's more, with the consideration of the mechanism of wettability alternation, the oil recovery is increased further, which suggests that wettability alternation is an important mechanism of enchancing oil recovery.

Analysis of Variance

The above numerical model with the consideration of wettability alternation is further applied to evaluate the recovery performance of CO_2 huff-n-puff under various operation parameters such as CO_2 injection rate, injection time, soaking time, number of cycle of CO_2. The simulated results of ANOVA are shown in Figure 3-8, respectively.

As can be seen in Figure 3, the ultimate oil recovery factors under injection rate of 40000 m^3/d, 60000 m^3/d, 80000 m^3/d, 100000 m^3/d and 120000 m^3/d are found to be 8.1%, 8.3%, 8.4%, 8.9%, 8.4%.

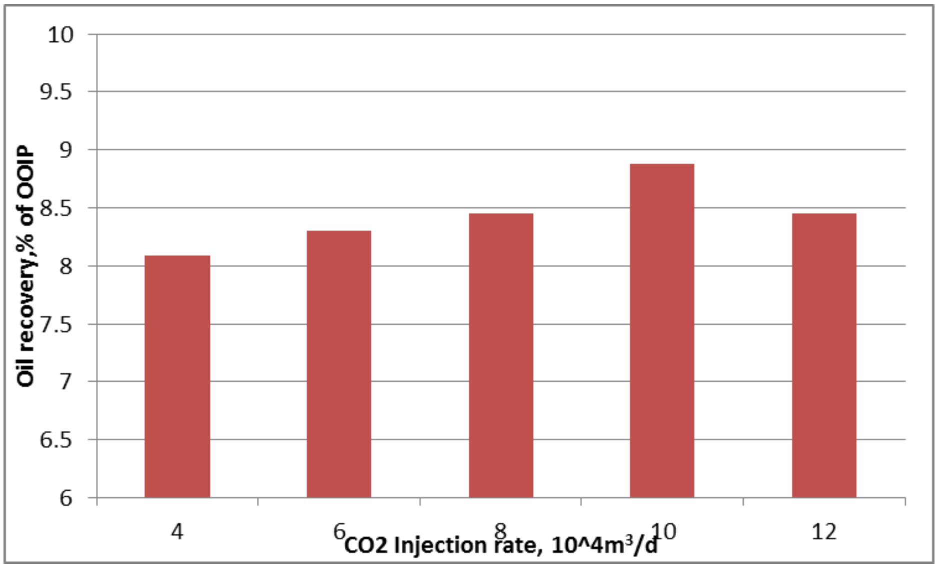

Figure 3—Oil recovery versus different injection rate

The oil recovery under various injection time is shown in Figure 4. The ultimate oil recovery factors under injection time of 5 days, 10 days, 15 days, 20 days and 25 days are found to be 7.5%, 7.8%, 8.7%, 8.9%, 8.4%.

Figure 5 shows the oil recovery under various soaking time. When the soaking rate is set to be 10 days, 15 days, 20 days and 25 days, the factor is 8.1%, 8.1%, 8.9%, and 8.5%, respectively.

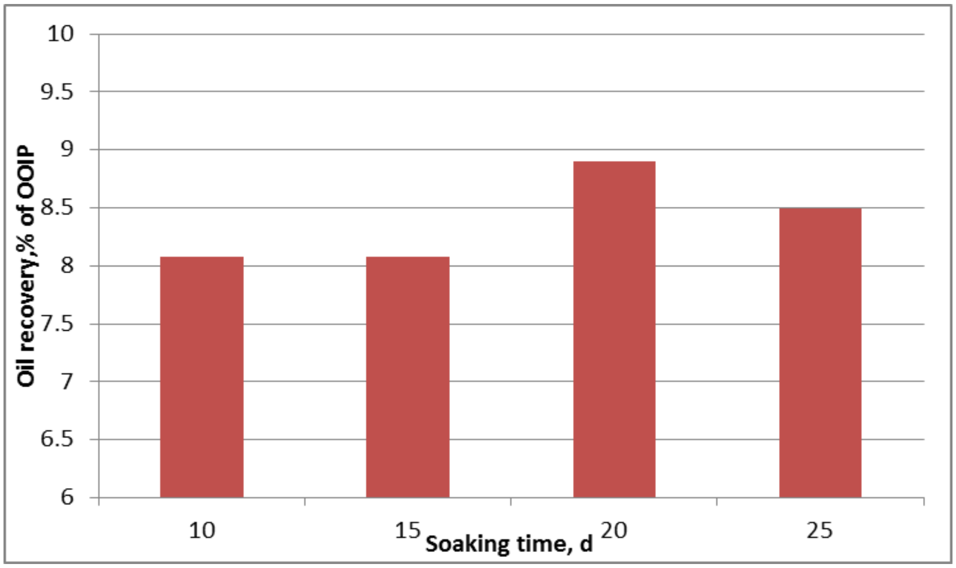

Figure 4—Oil recovery versus different soaking time

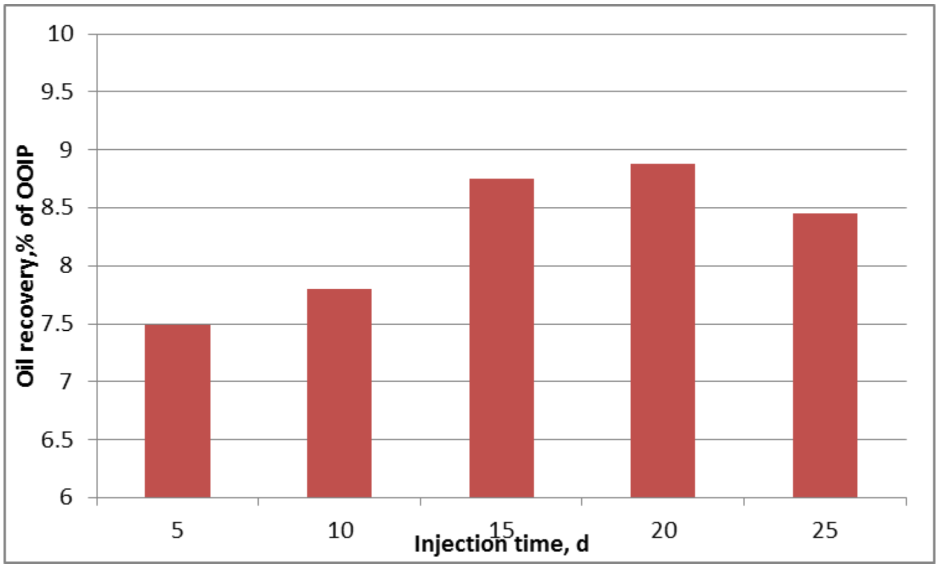

Figure 5—Oil recovery versus different injection time

The oil recovery performance is shown in Figure 6, where oil recovery is increased by a longer production tiem per cycles from 100 days to 500 days.

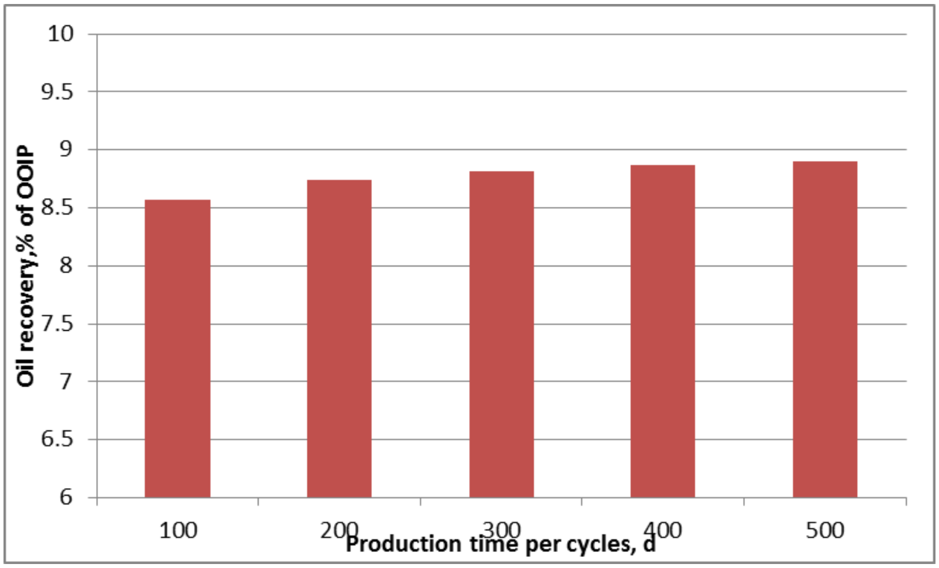

Figure 6—Oil recovery versus different production time per cycles

In Figure 7, where oil recovery factor decreases with increasing bottom hole pressure from 6 MPa to 12 MPa, the difference of oil recovery between the highest and the lowest value is about 3%.

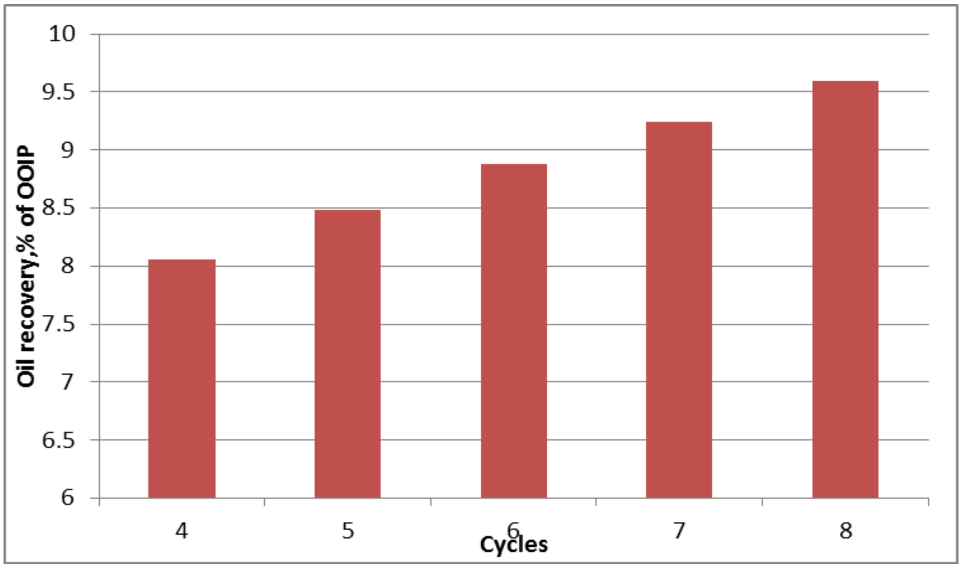

Figure 7—Oil recovery versus different cycles

In figure 8, with the increading of cycles, the oil recovery factor increases from 8% to 9.6%.

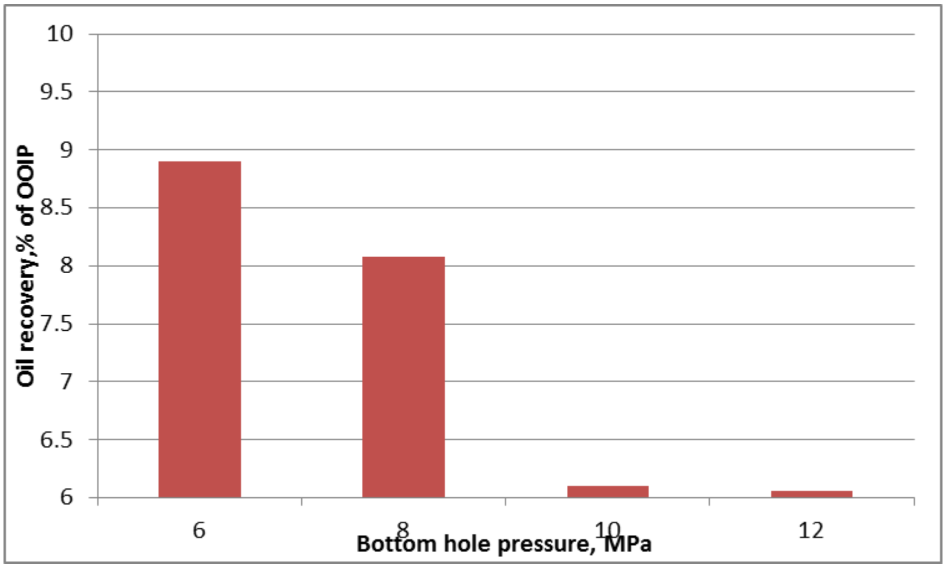

Figure 8—Oil recovery versus different bottom hole pressure

With comparison of oil recovery factor under various parameters, it can be found that the most important parameter is bottom hole pressure, followed by cycles, soaking time, injection time, injection rate, production time per cycle. Besides, the range of oil recovery factor is obtained as 6%-9.6%.

Performance Evaluation

There have been several EOR methods applied into conventional reservoirs development. According to the analysis of K. Zhang et al (2015), four typical EOR methods are highly possible to become favourable recovery potential for unconventional reservoirs exploitation: CO_2 huff-n-puff, water huff-n-puff, nanofluids huff-n-puff and water alternating gas (WAG).

Based on the above numerical model, five cases, including depletion (case #1), CO2 huff-n-puff (case #2), water huff-n-puff (case #3), nanofluids huff-n-puff (case #4) and WAG (case #5), are conducted to evaluate their recovery performance.

The oil recovery of five cases is presented in Figure 9. When compared with depletion (case #1), four methods could indeed enhance oil recovery of tight oil reservoir. In addition, tt can be suggested that CO2 huff-n-puff (case #2) leads to largest oil recovery, followed by WAG (case #5), nanofluids huff-n-puff (case #4) and water huff-n-puff (case #3).

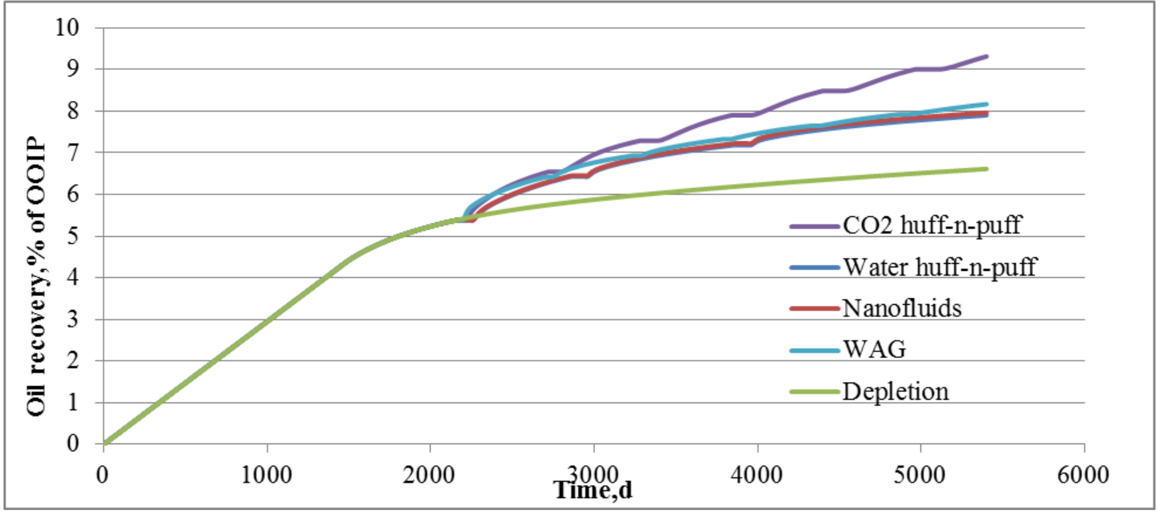

Figure 9—Oil recovery of five cases

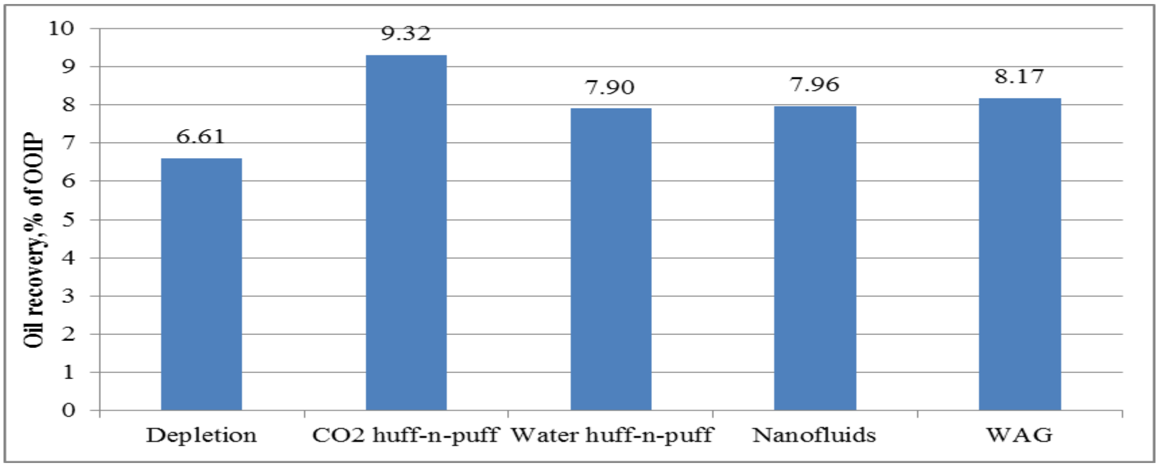

Figure 10—Ultimate oil recovery of five cases

In Figure 10, without any EOR method, the oil recovery of depletion at 5400days of production is 6.61%, which is the primary recovery. When water huff-n-puff, nanofluids huff-n-puff and water alternating gas (WAG) is applied respectively, the oil recovery is less than 8.2% and the range of the incremental factor is 1.3%-1.5%. However, CO_2 huff-n-puff could enhance oil recovery factor to 9.32% with the incremental facor 2.7%.

Conclusions

This paper conduted numerical simulation to model CO_2 huff-n-puff process and evaluate the recovery performance in targeted tight oil reservoir. With the method of analysis of variance, operation paratmeters, such as CO2 injection rate, injection time, soaking time and number of cycles, are anyalyized to evaluate the impacts on the performance. Five cases are modeled to study the application of four EOR methods: CO2 huff-n-puff, water huff-n-puff, nanofluids huff-n-puff and WAG.

In our work, the primary recovery in tight oil reservoir is 6.61%. It's found that CO_2 huff-n-puff brings significant recovery increment, about 3%. With the results of ANOVA, it can be seen that bottom hole pressure is the most important parameter, followed by cycles, soaking time, injection time, injection rate, production time per cycle. Through the five cases calculation and comparsion, CO_2 huff-n-puff reveals the greatest advantages of enhancing oil recovery in unconventional reservoirs against other three EOR mehods. As a result, it is suggested that CO_2 huff-n-puff process should attract more attention to make greater contribution to the exploitation of unconventional reservoirs and carbon geological sequestration

Acknowledgments

This research is supported by the National Program onKey Basic Research Project (973 Program, 2015CB250906). We would like to thank the Computer Modeling Group (CMG) Foundation for its support to this work. And we also thank the assistance of Key Laboratory of Petroleum Engineering of China University of Petroleum-Beijing.

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