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Investigation of cyclic CO_2 huff-and-puff recovery in shale oil reservoirs using reservoir simulation and sensitivity analysis

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ABSTRACT

Optimization of cyclic gas huff-and-puff recovery is challenging because there is a myriad of variables involved in the system, most of which have nonlinear and opposite effects. This study conducted a sensitivity analysis in order to find a set of primary depletion period, injection period, and production period which maximized the final oil recovery factor after a fixed length of production. Input data were based on the actual Bakken formation properties and field data. On the basis of numerical simulations, we found that short injection and production periods were favorable because they increased the overall huff-and-puff cycle number and adequately took advantage of the high initial injection rate and production rate during the huff-and-puff stage. When the injection period (production period) was fixed, a too short or too long production period (injection period) was not optimal for final oil recovery because of the interdependence between these two variables; a balance between them is needed. In addition, a too short or too long primary depletion period was not optimal for final oil recovery, and the optimal primary depletion period depends significantly on the combination of injection and production periods. If cyclic CO_2 huff-and-puff recovery starts too early, the recovery rate of primary depletion is higher than huff-and-puff; in this scenario the potential of reservoir pressure drive is not fully utilized. Conversely, if cyclic CO_2 huff-and-puff process starts too late, the recovery rate of primary depletion is already lower than huff-and-puff; in this scenario the remaining time is insufficient to take full advantage of cyclic CO_2 huff-and-puff process. This study aims to use a comprehensive sensitivity analysis to better demonstrate the interdependence and relationships between primary depletion period, injection period, and production period, as well as the influence on the final oil recovery. The outcome of this study has the potential to advance our understanding of the fundamental mechanisms underlying CO_2 huff-and-puff, which will benefit unconventional hydrocarbon energy recovery within shale reservoirs.

1. Introduction

The consumption of petroleum hydrocarbons in the world has been steadily increasing. To meet the rising demand for energy resources, hydrocarbon production from unconventional reservoirs, such as shale oil and gas, has attracted significant attention. Oil and gas reserves within shale reservoirs have widely been considered immense. For example, using a geology-based assessment methodology, the U.S. Geological Survey (USGS) estimated 3.65 billion barrels of oil, 1.85 trillion cubic feet of natural gas, and 148 million barrels of natural gas liquids in the Bakken Formation of the Williston Basin Province, Montana, and North Dakota [18].

The Bakken Formation underlies the Lower Mississippian Lodgepole Formation and overlies the Upper Devonian Three Forks Formation at the depth of about 10,000 ft. The formation has three distinct layers: Mississippian upper shale, Devonian middle dolomite, and Devonian lower shale. The upper shale is organic rich pyritic shale of about 8–12 ft thick [22]. It is the source rock for the Bakken Formation and the organic content is up to 40%. It is naturally fractured in some small parts of the reservoir with an effective permeability of a few millidarcies [22]; in other parts the permeability is much lower. The middle dolomite is the main reservoir facies consisting of silty and sandy dolomite. This layer is 6–15 ft thick with porosity of 6–8% and permeability of 10–40 microdarcies [22,19]. The lower shale is a brownish, noncalcareous, organic mudstone with an organic content of up to 21%. It is about 0–6 ft thick and very tight. The oil has an API gravity of 42 [24].

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Horizontal wells with multiple hydraulic fractures are needed to produce oil from shale reservoirs at an economically viable rate [9,13]. However, ultimate primary recovery factor is only 5–10% [14]. Improved oil recovery by water flooding may be too slow because of the low injection rate of water. In contrast, it may be possible to inject CO_2, N_2, and other gases because of their low viscosity. For instance, when pressure is higher than 1070 psi and temperature is higher than 31 °C, CO_2 exists in the supercritical (sc) phase. The density of supercritical CO_2 ($scCO_2$) is about 70% of water, and the kinematic viscosity is 10–25% of water [3]. Furthermore, given a high enough pressure, first contact miscibility between CO_2 and oil may be achieved, which means that any amount of CO_2 can be injected and exist as a single phase with the oil [15,23]. In this situation, the interfacial tension (IFT) between the oil and displacing fluid is reduced to zero, thus the hydrocarbons can migrate with the CO_2 in a single phase at a reduced viscosity, resulting in a higher recovery factor.

In CO_2 (or any well-to-well) flooding, because of the low permeability of shale matrix, it takes considerably long time for pressure to propagate from the injection well to the production well. Therefore, it might be more effective to adopt a CO_2 huff-and-puff approach to increase the recovery rate. CO_2 huff-and-puff refers to the process by which CO_2 is injected into a reservoir to achieve miscibility with the oil after a period of primary depletion recovery and the mixture is then produced from the same well after a period of soaking (well shut-in) time [4,5,25]. The length of primary depletion recovery before the start of the cyclic CO_2 huff-and-puff is referred to as the primary depletion period. One single CO_2 huff-and-puff cycle consists of three stages: injection, soaking, and production; the lengths of these three stages are referred to as the injection period, soaking period, and production period, respectively.

During the injection stage, because of the high CO_2 injection pressure, first-contact or multiple-contact miscibility occurs and CO_2 mixes with the oil, resulting in single phase flow of which viscosity and IFT are significantly reduced. During the soaking stage, the injection well is shut down in order to let CO_2 diffuse deeper and broader into the reservoir and mix with oil as intimately as possible. During the production stage, the well is re-opened to produce at a lower pressure, which causes the mixture of CO_2 and oil to expand and flow out. The huff-and-puff cycle can be repeated to achieve a cyclic gas huff-and-puff process. In a previous study [4], we found that a shorter soaking period led to a higher recovery factor because of the higher huff-and-puff cycle number. Thus, a shorter soaking period is preferable when the total production time is fixed, which has recently been confirmed by Li et al. [17] because they found that adding soaking time will decrease oil recovery. It was also observed that the recovery rate of CO_2 huff-and-puff peaked right after the well was re-opened and then declined dramatically, and recovery rate decline depended primarily on the degree of reservoir heterogeneity [5]. Therefore, multiple cycles of huff-and-puff are desired to maintain a sufficient stimulation; adequate characterization of reservoir heterogeneity is necessary to assess the effect of cyclic CO_2 huff-and-puff recovery.

Other experimental and numerical studies were conducted to investigate gas huff-and-puff as an enhanced oil recovery approach in shale oil reservoirs. Gamadi et al. [11] conducted an experimental study of cyclic gas injection to improve shale oil recovery. In their study, nitrogen gas was used and the recovery factors in the laboratory were relatively high when the injection pressure was near the miscibility condition for nitrogen. They observed that oil recovery rate peaked in the first two cycles of gas huff-and-puff and then stabilized after the sixth cycle; this implied that re-pressurization is an important oil recovery mechanism for multiple cycles of gas huff-and-puff. Gamadi et al. [12] also used compositional simulations to find that shorter shut-in periods with more huff-and-puff cycles led to higher oil recovery factors compared to using longer shut-in periods with fewer cycles, which agrees with our previous finding [4]. Yu et al. [26] used CMG-GEM to numerically illustrate that the most important parameters in CO_2 huff-and-puff is CO_2 injection rate, injection time, and number of cycles; other parameters such as fracture conductivity, CO_2 soaking time, and fracture length are less important. Sanchez-Rivera et al. [20] used CMG-GEM to study various design components of the huff-and-puff process in order to identify the parameters with the largest impact on oil recovery and understand the reservoir's response to cyclical gas injection. They found that starting huff-and-puff too early in the life of the well diminished its effectiveness and also confirmed that shorter soaking periods were preferable over longer soaking periods.

Molecular diffusion is the primary driving mechanism to distribute CO_2 in the reservoir when the well is shut in. In fact, both mechanical dispersion and molecular diffusion are taken into account in this study and our previous work [4,5]. Several groups (e.g., [26,20]) found that increasing molecular diffusivity led to enhanced oil recovery factors. In addition, pre-existing natural fractures has an important role as well; they are pathways for injected CO_2 to migrate deep into the shale formation and conduits for CO_2-oil mixtures to reach the well during production [20].

Optimization of cyclic gas huff-and-puff recovery is challenging because there is a myriad of variables involved in the system, most of which have nonlinear and opposite effects. Previous studies showed that the most influential variables are primary depletion period, injection period, and production period, when other physical and operational conditions are fixed. Specifically, it is unclear how to determine the optimal time to start cyclic huff-and-puff and the optimal injection and production periods. It is difficult to find a balance between these three variables to achieve the optimal solution, because they might be interdependent and interconnected; simple variation of one variable might impact the effectiveness of the other two. For example, when solving for the optimal primary depletion period, existing studies usually test a few values of the primary depletion period while fixing the injection and production periods. This simple strategy is problematic because the solution will likely change when a different combination of injection and production periods is used, which will be demonstrated later in this paper. Therefore, these three variables should be considered as a whole in order to maximize the final oil recovery factor.

This study conducted a sensitivity analysis in order to find a set of primary depletion period, injection period, and production period which maximized the final oil recovery factor after a fixed length of production. Other parameters, such as fracture conductivity and soaking period, are less important (e.g., [4,12,26]), thus they were not included in the current study. UTCOMP, an equation-of-state (EOS) based compositional reservoir simulator [2], was used to conduct reservoir simulations. Input data were based on the actual Bakken formation properties and field data [4,5]. This study aims to use a comprehensive sensitivity analysis to better demonstrate the interdependence and relationships between primary depletion period, injection period, and production period, as well as the influence on the final oil recovery. The outcome of this study has the potential to advance our understanding of the fundamental mechanisms underlying CO_2 huff-and-puff, which will benefit unconventional hydrocarbon energy recovery within shale reservoirs.

2. Reservoir modeling

2.1. Model geometry

Similar model geometry was adopted as in a previous work [5]. A 3D reservoir simulation domain was built in the middle dolomite