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Enhanced light oil recovery from tight formations through CO_2 huff 'n' puff processes

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HIGHLIGHTS

- The viability of pressure-depleted cyclic CO_2 EOR technique was investigated.
- Operating parameters of pressure-depleted CO_2 huff 'n' puff processes were optimized.
- The favorable light oil recovery was achieved in tight formations.

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ABSTRACT

The major objective of this paper was to evaluate the viability of CO_2 huff 'n' puff processes as primary means to enhance oil recovery in low-pressure tight reservoirs and thereby optimize the corresponding key operating parameters of the process. In this study, CO_2 huff 'n' puff corefloods were conducted by using a 973 mm-long composite core with an average porosity of 9.6% and an average permeability of 2.3 mD. The effects of primary parameters, such as slug size, injection rate, and the maximum and minimum pressures during production, chasing gas (N_2) and soaking time on the performance of the process were investigated and operating strategies were optimized to lead to successful field applications. The experimental results indicate that 0.1 reservoir pore volume (PV) seems to be an optimal slug size for the first cycle, with the cycle recovery factor (RF) up to 14.52% when reservoir pressure is depleted from the maximum pressure to 8 MPa. RF is suggested to be sensitive to the maximum pressure and therefore, a maximum pressure should be built up to as high as the formation can hold. In the subsequent cycles, injecting N_2 as a chasing gas flowing CO_2 slug has great potential to significantly improve the cycle performance while reducing the CO_2 utilization. The optimal operation should have three cycles and the ultimate RF for these three cycles could reach above 30%. The observations of this study suggest that the CO_2 huff 'n' puff process is a viable technique to enhance light oil recovery in low-pressure tight reservoirs.

1. Introduction

Greenhouse gas (GHG) emissions are commonly identified as a major contributor to global warming. CO_2-based enhanced oil recovery (EOR) techniques have shown great potential to enhance oil recovery while offsetting the GHG emissions by means of sequestrating CO_2 underground. Widely used CO_2-based EOR techniques can be categorized into CO_2 flooding and the cyclic CO_2 injection process (also known as CO_2 huff 'n' puff). The applicability of these CO_2-based EOR techniques depends heavily on reservoir conditions, like reservoir pressure and temperature, properties of reservoir fluids and formation, as well as the availability of local CO_2 sources.

This study targeted a reservoir located in Ordos sedimentary basin, northwestern China. The reservoirs in this basin generally feature low initial reservoir pressure and low permeability. The initial reservoir pressure is about 12.9 MPa, far below its measured minimum miscible pressure (MMP) value of 23 MPa. The permeability of the reservoir formation averages out to 2.3 mD, in some regions even below 1 mD. Due to the low initial reservoir pressure which resulted in insufficient energy for the reservoir's primary production, the primary oil recovery was very low in this formation. Furthermore, the application of waterflooding was not

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successful for this tight reservoir as the injectivity leading to a successful waterflood could not be achieved technically. CO_2-based EOR techniques were proposed as key approaches to develop this tight light oil reservoir, since (1) there are abundant CO_2 sources available from local large-scale coal chemical plants for CO_2 EOR injection; and (2) as far as CO_2 injection processes are concerned, injectivity will not be an issue for low-permeability reservoirs. For CO_2 flooding in reservoirs with an initial pressure far below the corresponding MMP, the displacement process is expected to be immiscible to avoid the disadvantages of maintaining the reservoir pressure at a level high enough to meet the requirement for miscible displacing processes, such as CO_2 channeling or early breakthrough. Based on their extensive review of previous papers, Dyer and Farouq Ali [1] summarized that the immiscible EOR technique is only applicable to reservoirs with certain characteristics, specifically the viscosity, gravity, and density of the oil ranging from 100 to 1000 cp, from 10 to 25 °API, and from 904 to 1000 kg/m^3, respectively. However, not only is the candidate reservoir a light reservoir of 33 °API gravity, but also it has a tight formation with natural fractures. Several pilot applications of immiscible CO_2 flooding in this area showed poor performance as a direct result of the early breakthrough of CO_2 resulting from the existing natural fractures. In this case, the CO_2 huff 'n' puff process, therefore, might be a rational option as it could benefit from these natural fractures.

The CO_2 huff 'n' puff process is a typical single well operation, usually involving three portions: injecting a pre-determined slug of CO_2, a soaking time allowing the gas phase to mix with the oil phase in place, and the production portion immediately following the soaking operation. Efforts to investigate the applicability of this process to enhance oil recovery have been made for several decades with encouraging results, ranging from laboratory coreflood investigations and field test evaluations to numerical simulations.

Khatib et al. [2] reviewed results of previous cyclic coreflood tests and field applications of miscible CO_2 injection and indicated that the use of CO_2 can achieve desirable recovery for both heavy and light oil. Monger-McClure and her colleagues [3–6] developed extensive research work on the feasibility of the CO_2 huff 'n' puff process on light oil recovery. They investigated the influence of various critical parameters, including CO_2 slug size, the number of cycles, operating pressures, the impurity of CO_2, reservoir gas, and gravity segregation and remaining oil saturation, by conducting laboratory coreflood tests on watered-out cores in conjunction with comprehensive reviews of hundreds of field applications. It was suggested that light oil recovery by CO_2 huff 'n' puff either in pressure-depleted reservoirs or waterflooded reservoirs is promising. In addition, they also compared the recovery mechanisms between CO_2 injections on light oil with heavy oil. On the basis of field-treatment evaluations, several authors [7,8] developed two correlations to predict the process performance and some criteria to evaluate whether a cyclic CO_2 injection process is successful or not. One important economic indicator presented with successful implementations is CO_2 utilization, defined as the volume of CO_2 used for per unit volume of incremental oil produced, in the unit of Mscf/STB. The favorable range for CO_2 utilization is from 0.5 to 0.8 Mscf/STB for field cases. Torabi et al. [9,10] investigated the performance of the CO_2 huff 'n' puff process in naturally fractured reservoirs by conducting experimental and simulation studies. Even though the volume ratio between the fracture and the matrix used in their laboratory models was much larger than that in real reservoir scenarios, their research work filled the gap in information relevant to the application of the CO_2 huff 'n' puff process in naturally fractured reservoirs.

Numerical simulations by history-matching field performance revealed that the reduction of oil viscosity, oil swelling, and gas relative permeability hysteresis are the principal mechanisms contributing to the CO_2 huff 'n' puff response [11,12].

However, nearly all the available experimental studies on light oil recovery by CO_2 huff 'n' puff simulated the displacement process for the remaining oil of the waterflooded reservoir. During these processes, the reservoir pressure can be maintained at a certain level by means of inducing a water flux from the end opposite to the production port and thereby ensuring the displacement process is miscible, near-miscible or immiscible [3–6,13]. Injecting water can mimic either the water flux from the aquifer connecting to the reservoir or the constant outer boundary of the reservoir, both of which contribute to the maintenance of the reservoir pressure. However, it is common in reality, just as with the candidate reservoir in this study, that a reservoir has neither a constant pressure boundary nor an aquifer available but has a closed boundary and also has insufficient reservoir energy for primary production. Furthermore, pressure waves travel within a low-permeability reservoir so slowly that during the production phase, there is no effective pressure support to the wellbore vicinity from the other portion of the reservoir. Therefore, the displacement occurring within the wellbore vicinity is actually a pressure-depleted process. The pressure depletion production process should have some distinct differences in performance from those pressure maintained processes mentioned above. The proper strategy of CO_2 huff 'n' puff corefloods for simulating that physical process is to use the portion of a core near the injection end saturated with CO_2 to mimic the wellbore vicinity while allowing the other end of the core to be closed to mimic the other portion of the reservoir beyond the wellbore vicinity.

The objective of this study was to investigate the viability of the CO_2 huff 'n' puff process as a primary production means for light oil recovery in low-pressure tight reservoirs and to optimize operating strategies of the injection in terms of the combination of RF and CO_2 utilization. This study mainly focused on examining the role of key operating parameters in affecting the performance of the process and thereby optimizing the operating parameters to achieve the maximization of the process performance of CO_2 huff 'n' puff treatment in the candidate reservoir by conducting a series of coreflood tests. The investigations of this study created an extended insight of cyclic CO_2 treatment at the primary production stage in a tight reservoir with closed boundary or without an aquifer connecting to it. The results suggest that the recovery factor of a three-cycle huff 'n' puff gas injection can be as high as 34.65%, that a 0.1 PV CO_2 slug seems to be an optimal injection slug for the first cycle operations with favorable CO_2 utilization as low as 0.324 Mscf/STB, and that injecting N_2 as chasing gas can significantly improve the overall economy of operations. The optimal operations should have three cycles and the ultimate RF for these three cycles could reach above 30%.

2. Properties of dead-oil, live-oil and the mixture of live-oil andCO_2

2.1. Crude oil sample

In this study, cyclic coreflood tests were conducted to investigate the performance of the CO_2 injection process in a low-pressure, low-permeability, and light oil reservoir. A light crude oil sample from an oilfield located in northwestern China used in this study has an API gravity of 40.34. The dead oil and reservoir gas samples were obtained through flashing the crude oil sample down to atmospheric conditions. Properties of the dead oil are listed in Table 1. The average molecular weight of gases produced is 32.125 kg/kmol and its molar fraction in reservoir fluids is 46.95%.