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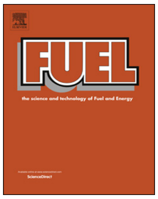

Full Length Article

Performance evaluation of CO_2 flooding process in tight oil reservoir via experimental and numerical simulation studies

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ABSTRACT

In this study, experimental and numerical simulation studies were conducted to enhance oil production in a tight oil reservoir using CO_2 injection processes. In experimental studies, three types of CO_2 injection experiments—CO_2 flooding (continuous CO_2 injection process), CO_2 flooding coupled with a soaking period, and CO_2 flooding coupled with pressure maintenance—were carried out in one-meter-long core plugs to investigate the effect of CO_2 flooding schemes on production performance. The properties of light oil–CO_2 systems with different CO_2 concentrations under different pressures were measured to study the phase behaviors of light oil–CO_2 systems. Test results indicate that the CO_2 flooding process is the best method to enhance oil recovery in tight formations, showing an oil recovery factor of 38.96% and a CO_2 utilization of 10.41 Mscf/STB. In numerical simulation study, the properties of light oil–CO_2 systems first were simulated using the WinProp module. Next, the GEM module was applied to implement history-matching studies on experimental results, and good agreement was achieved. Third, a sensitivity analysis was carried out to investigate the effect of parameters on the CO_2 flooding process. Finally, upscaling simulation studies were conducted at the field scale to optimize the well pattern and CO_2 injection rate to enhance oil recovery in the target reservoir. Important correlations on the effect parameters were generated for predicting the oil production performance in the reservoir with different operations. Among the studied well patterns, the inverted seven-spot well pattern with a CO_2 injection rate of 44.28 t/day/well achieved the best production performance in the field study. In the optimized case, the oil recovery factor reached 30.89% with a low CO_2 utilization of 5.69 Mscf/STB.

1. Introduction

With increasing oil consumption and depleting conventional oil production all over the world, scholars have focused on oil source reserves in tight reservoirs, and great recovery potential of tight oil can be found in previous studies [1–7]. However, producing oil is difficult in this type of reservoir using the conventional production method of water flooding for two reasons: (1) water fingering, overriding, and channeling occur in low-permeability reservoirs resulting from the viscosity difference between water and oil; and (2) water is difficult to inject into tight reservoirs because of the threshold pressure gradient and low permeability. To avoid the negative effects of the water flooding process, CO_2-based recovery methods have been investigated as an effective approach to enhance oil production in tight reservoirs [8–10]. CO_2-based recovery methods have been applied in tight oil reservoirs including continuous CO_2 injection, intermittent CO_2 injection, water-alternate CO_2 injection, and CO_2 huff 'n' puff. Among them, the continuous CO_2 injection process (CO_2 flooding) has been successful in both light oil reservoirs and heavy oil reservoirs, showing benefits in enhanced oil recovery and CO_2 storage [11–15]. Three techniques—immiscible, near-miscible, and miscible flooding—have been applied in light oil reservoirs because of different operation pressures.

In the CO_2 flooding process, operation pressure significantly affects production performance. The mechanisms of the CO_2 flooding process are different when operation pressure is higher or lower than minimum miscible pressure (MMP). When operation pressure is higher than MMP, miscible status is achieved. A highly improved oil recovery factor is obtained, mainly contributed by gas drive, oil viscosity reduction, oil swelling, CO_2 molecular diffusion, and dispersion [16–20]. When operation pressure is lower than MMP, this process is in the immiscible or

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near-miscible condition. Oil recovery is enhanced because of lower interfacial tension (IFT), reduced oil viscosity, oil swelling, solution gas drive, permeability improvement, etc. [17,21–24]. Previous studies have indicated that oil production performance in the miscible flooding process is higher than that in the immiscible and near-miscible flooding processes [25–28]. However, studying the immiscible CO_2 flooding process is essential because (1) not all tight oil reservoirs can meet the miscible condition because of technology issues and reservoir characters; and (2) other potential benefits (oil recovery enhancement and greenhouse gas reduction) can be achieved with the immiscible flooding process. Experimental and numerical simulation approaches are usually applied to investigate production performance in the immiscible CO_2 flooding process.

Experimental studies on immiscible CO_2 flooding have been conducted by previous scholars. The studies mainly have investigated both the operation parameters and properties of the reservoir and oil sample. Operation parameters have been investigated in terms of injection pressure, CO_2 breakthrough time, well pattern, etc. Injection pressure significantly affects oil recovery because injection pressure relates to flooding procedures (immiscible or near-miscible). In the same reservoir, the oil displacement efficiency in the immiscible process is lower than that in the near-miscible process such that the oil recovery factor increases with increased injection pressure [27,29]. In the CO_2 immiscible flooding process, CO_2 breakthrough time is considered a dividing line between the CO_2 flooding process and solution gas flooding process because after CO_2 breakthrough, the solution gas flooding mechanism plays an important role in oil production [30]. The highest portion of oil is produced before CO_2 breakthrough, so with an earlier CO_2 breakthrough time, a lower oil recovery factor is obtained. Gravity effect has been observed in a vertical flooding well pattern, especially in thick reservoirs. Vertical flooding under the near-miscible condition can gain 24% higher oil recovery than the horizontal flooding process, and more light oil components have been observed in the vertical flooding process [31–34]. The above-mentioned operation parameters have been studied and optimized, with results gained in some special reservoirs (rather than in a general reservoir) that can be applied to most situations. The effect of maintenance pressure in the CO_2 flooding process has not been investigated before, so studies in the target reservoir are necessary. To gain a better understanding of the mechanisms of CO_2 flooding, the effects of the properties of the reservoir and oil samples require examination.

The properties affecting CO_2 flooding production performance are formation heterogeneity, CO_2 diffusion, asphaltene precipitation, etc. Regarding formation heterogeneity, several scholars believe that it affects production performance significantly. It is especially more sensitive at permeability ratio ranges from 1.0 to 15.5 [35,36]. Also, oil recovery factor and CO_2 storage ratio increase with decreases in permeability [29]. However, some researchers have reported an opposite result, indicating that formation heterogeneity has an unremarkable effect on oil production [18]. Considering CO_2 diffusion in the oil phase during the CO_2 flooding process in composite cores, a previous study indicated observing a remarkable effect on oil production [18]. Asphaltene precipitation has a negative effect on tight oil production in the CO_2 flooding process because asphaltene firmly adheres to the surface of the rock, blocks the thin throat, and reduces the rock permeability [37]. Among the CO_2-based recovery approaches mentioned above, the CO_2 flooding process obtains the least asphaltene precipitation and the least formation permeability reduction percentage. Thus, less formation damage occurs [38]. Among the studies, long core plugs with heterogeneity rarely have been applied, and the soaking period has not been implemented. Therefore, experimental study using long (48-in.) core plugs is needed. Based on the experimental studies, numerical simulation studies were conducted to gain a further understanding of the CO_2 flooding process in a tight reservoir.

Numerical simulation is an important method to study oil production performance using CO_2 flooding in a tight reservoir. This method can be applied to gain a better understanding of the CO_2 flooding process with less experimental studies. Based on numerical simulation studies, operation parameters can be optimized, and then the optimized results can be used to design pilot tests. The procedure for numerical simulation studies on the CO_2 flooding process mainly contains a history match of the experimental or pilot results or a sensitivity analysis of the effect of parameters and prediction. In numerical simulation studies, operation parameters and reservoir properties are usually investigated. The studied operation parameters include injection pressure, injection rate, injection phase, well characteristics, etc. [16,26,39–41]. Parameters are considered optimized when the best production performance is obtained. For the effect of reservoir properties, simulation studies have been developed in both homogeneous and heterogeneous reservoirs, focusing on the differences between the two types of reservoirs. Simulation results indicate that oil production performance in the CO_2 flooding process is affected significantly by the heterogeneity. The higher the heterogeneity, the earlier the breakthrough time, and thus the lower the oil production [26,40–42]. Previous numerical simulation studies rarely have researched the combination of history matching, sensitivity analysis, and upscaling in the same target reservoir to gain more understanding of the CO_2 flooding process in tight reservoirs. Therefore, a study is necessary using history matching, sensitivity analysis, and upscaling using numerical simulation in the same reservoir.

In this study, the immiscible CO_2 flooding process was researched in long core plugs using experimental and numerical simulation methods. First, the properties (saturation pressure, viscosity, and density) of the light oil–CO_2 system at different pressures were measured. Second, three experiments were implemented in a 48-in.-long core holder. Oil production performance was investigated, and the effects of the parameters were studied. Third, the measured properties of the light oil–CO_2 system and CO_2 flooding experiments were history-matched. Then, sensitivity analyses were developed to study the effect of injection pressure, injection rate, capillary pressure, relative permeability curves, etc. Fourth, an upscaling study was conducted to optimize the operation parameters (well pattern and injection rate). Finally, the optimized case was selected to predict the CO_2 flooding process in the field case. Experimental results indicate that injection pressure, CO_2 diffusion, and maintenance pressure remarkably affect production performance. With good agreement of the history match, the sensitivity analysis indicates that the relative permeability curve significantly affects production performance, but that capillary pressure and CO_2 solubility in the water phase only slightly affect the CO_2 flooding process. The optimized CO_2 flooding case (with an inverted seven-spot well pattern and injection rate of 44.28 t/day/well) at the field scale can be an asset to designing a field application.

2. Experimental section

2.1. Materials

In this study, a typical light oil sample from western China was applied to conduct CO_2 flooding experiments in long tight core plugs, which were retrieved from the studied reservoir with a depth from 1639.1 to 1696.2 m. The properties of dead oil and live oil (by recombining produced gas into dead oil) are shown in Table 1, and the compositional analysis of the oil samples under the reservoir conditions (12.90 MPa, 44 °C) are listed in Table 2. CO_2 was recombined into a reservoir oil sample to generate light oil–CO_2 systems under different pressures for measuring phase behaviors. The MMP of the live oil sample recombined with CO_2 was measured using a traditional slim tube, and the MMP measured as 23 MPa [28,43]. The purities of CO_2 and N_2 (leakage-free test gas) were 99.98% and 99.999%, respectively. Brine collected from the targeted reservoir was used to saturate the core plugs, and the salinity of the brine was 71,340 mg/L with a pH of 5.5; the brine was filtered twice using filter papers.