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Potential of carbon dioxide miscible injections into the H-26 reservoir

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ABSTRACT:

The H-26 reservoir in Liaohe oilfield has been subjected to water flooding for many years, and the reservoir has now reached the late water-flooding stage. At this stage, the production wells show the characteristic of high water-cut, and the oil production declines dramatically, resulting in unfavorable recovery. Therefore, improving oil recovery at this stage is a matter of concern. CO_2 injection is a potential alternative method that is widely used for realizing enhanced oil recovery (EOR), while simultaneously reducing greenhouse gases by storing them in the underground formation.

In order to determine the potential for CO_2 injection in the H-26 reservoir, the gas–liquid phase behavior and gas–oil minimum miscibility pressure (MMP) should be tested. In this study, PVT experiments were conducted with crude oil samples from the H-26 reservoir, and the corresponding oil properties were regressed through the equation of state (EoS). Two sets of EoS parameters (EoS-5 and EoS-15) were used to determine the CO_2–oil MMP. The results show that the cell-to-cell method is a convenient and accurate method to determine the MMP and verify that the H-26 reservoir can achieve miscible CO_2 flooding. In addition, a case study of a typical water flooded well group was performed with a compositional model. In this case study, the characteristics of the reservoir oil component composition were found to change after water flooding, and the impacts of these changes on the CO_2–oil MMP were investigated. The recovery factor of CO_2 flooding was found to be 8.5% greater than that in the water-flooding scenario. This work can be used as a reference for reservoirs facing similar problems related to high water cut or low recovery.

1. Introduction

Reservoir simulation studies have been carried out to examine the dynamic performance of conventional and unconventional reservoirs subject to acid gas injection (Zhang et al., 2012a and 2012b; Wu et al., 2014; Zhao et al., 2015a; 2015b), CO_2 sequestration or enhanced oil recovery (EOR) (Zhang et al., 2015), and multiphase flow regimes and several other mechanisms (Wu et al., 2010; Xiong et al., 2013). Coupled numerical simulation greatly aids the understanding of the driving mechanisms in the reservoir. In non-thermal gas EOR methods, one type of gas, such as CO_2, N_2, dry gas, enriched gas, air or flue gas, is injected into a reservoir. CO_2 flooding is not only an effective way to realize EOR, but also provides a way to reduce greenhouse gases by permanently trapping CO_2 in an underground formation (Yao and Ji, 2010; Zhang et al., 2014).

CO_2 is preferable for injection, especially for low-permeability oil reservoirs (Cinar et al., 2008; Wang et al., 2013; Duchenne et al., 2014; Srivastava and Huang, 1997). Experiments on water alternating gas (WAG) show that the injection pressure drops drastically in each CO_2 injection cycle, which indicates that fluid injection capacity can be greatly improved during the CO_2 injection process (Yang et al., 2015; Nuryaningsih et al., 2010). Therefore, the effects of CO_2 EOR are studied in this work. Miscibility evaluation is very important for evaluating the oil displacement efficiency for CO_2 flooding.

Under high pressures, CO_2 may become “enriched” by the extraction of components from the oil, which can cause the gas displacement front to be miscible (Holm, 1986). Under this condition, the interface between oil and gas vanishes. In other words, the gas–oil interfacial tension (IFT) becomes zero. When the gas displacement front is immiscible, the gas–oil IFT is greater than 0.1 mN/m, and hence, owing to capillary forces, residual oil may be left in the reservoir. Therefore, a smaller gas–oil IFT value implies that a higher oil displacement efficiency is possible.

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A key parameter in CO_2 EOR is the minimum miscibility pressure (MMP) of the injected CO_2 and oil. Experimental, correlation, and simulation methods can be used to determine the MMP. The most reliable method is the experimental method called the slim tube test (Belhaj et al., 2012a; Ekundayo and Ghedan, 2013; Elsharkawy et al., 1992; Randall and Bennion, 1988; 1989; Wu and Batycky, 1990). In this test, 1.2 pore volume (PV) CO_2 is injected at a series of pressures; then, the curve of pressure and recovery is plotted. The pressure at the inflection point is the MMP. Vanishing interfacial tension (VIT) experiments, including the pendant drop method and capillary rise method, have also been adopted to determine the MMP. In these experiments, the IFT is measured at a series of pressures; then, the MMP is obtained by extrapolating the measured data to the point of zero IFT. However, the VIT tests often overestimate the MMP as compared to the slim tube experiment results (Ghorbani et al., 2014; Ayirala et al., 2003; Christiansen and Haines, 2008).

Correlations are convenient approaches to evaluate the MMP because they are less time-consuming and less expensive. The variables considered in correlation methods include C1, C2-C6 (or C2-C5), C6+ (or C7+), temperature, API, and asphaltene–wax (Ayirala and Rao, 2006; Hossein et al., 2014; Shokrollahi et al., 2013). In addition, for cases in which CO_2 is mixed with another type of gas, the MMP of the impure gas and oil were tested by many researchers (Li et al., 2012; Shokir, 2007; Metcalfe, 1982; Sebastian et al., 1985). Empirically, C1, C7+ (heavy content), and temperature have positive relationships with the MMP, while C2-C6 have negative relationships. However, the correlations often only fit a specific reservoir and with insufficient accuracy.

In this research, to ensure accuracy and efficiency, three simulation methods were used to determine MMP. These methods are the tie line method (Iranshahr et al., 2010; Rannou et al., 2013; Yan et al., 2013, 2014; John and Orr, 1996), cell-to-cell method (Rezaveisi et al., 2015; Pederson et al., 1986; Metcalfe et al., 1973), and one-dimensional slim tube simulation method (Belhaj et al., 2012b). Furthermore, few numerical models were developed to capture the features of coupled flow regimes and reservoir dynamics subject to acid gas injection (Zhang, 2013) and CO_2 EOR (Zhang et al., 2016a). In addition to the traditional reservoir simulators, few THMC numerical simulation studies were conducted recently to solve the coupled flow and geomechanics. Zhang et al. (2016b) proposed a novel fully coupled numerical simulation framework for CO_2 geosequestration; it provides the mathematical framework to consider the chemical impact on the geomechanical modulus. The numerical model can be easily applied to the other THMC processes owing to its flexibility and tight coupling between the chemical and mechanical processes.

In this work, we investigated the reservoir dynamics of H-26 reservoir subjected to CO_2 injection. The H-26 reservoir, which is located in the Liaohe oilfield, has a development history of more than 25 years. The characteristics of the reservoir pose a challenge because the development involves water flooding, which includes conditions of low permeability, strong heterogeneity, and a high water cut. Because of water flooding, the current average recovery factor is only 17.7%. To overcome these difficulties, gas injection may be worth trying.

For the H-26 reservoir, the MMP of oil and CO_2 are not constants. The oil component changes with the period of water flooding, resulting in changes in the MMP. This phenomenon, however, has been often ignored in research, causing errors in the evaluation of CO_2 EOR effects. In this paper, the changes in the MMP caused by water flooding at different development stages will be explained.

2. Phase behavior simulation

To determine the potential of CO_2 injection into H-26 reservoir, the gas–liquid phase behavior and gas–oil MMP should be clearly tested. In this work, the simulation of the MMP was accomplished by the phase behavior package WINPROP, a CMG software package. Parameters of the equation of state (EoS) were constructed using the oil PVT regression. The P-R equation of state (Peng and Robinson, 1978) was selected to simulate the PVT properties.

More accurate EoS parameters can be determined by simulating more components. The simulation speed of the phase simulation process in WINPROP is high. However, the speed of the numerical simulation in GEM, a compositional simulator using the EoS parameters generated in WINPROR in the CMG package, is severely influenced by the number of components. Therefore, 15-component EoS parameters (EoS-5) were constructed to predict the MMP in WINPROP, and 5-component EoS parameters (EoS-5) were constructed to simulate the reservoir development.

2.1. Component characterization

Component characterization of H-26 crude oil is necessary before simulating the phase behavior. Initial bottom-hole sample data are listed in Table 1. Component characterization, including the lumping and splitting theory and method, has been investigated in previous studies (Lee and Kesler, 1975; Riazi and Daubert, 1980; Twu, 1984; Nagarajan et al, 2007; Sancet, 2007). Two sets of parameters of the EoS with 15 pseudo-components (EoS-15) and five pseudo-components (EoS-5) are calculated to be used in the regression of the PVT properties.

EoS-15 and EoS-5 are used to predict the MMP and reservoir simulation, respectively, as described in the following parts. The component characterization principles are shown in Fig. 1.

2.2. Regression of the EoS parameters

The existing experimental crude oil PVT data includes the saturation pressure, initial gas–oil ratio, volume factor, viscosity of the formation oil, density of the formation oil, viscosity of the stock tank oil, and density of the stock tank oil. In order to ensure the highest possible accuracy of the EoS-5 and EoS-15 parameters, the deviation of the regression is controlled within 5%. As expected, the regression of EoS-15 matches the target more closely (Table 2). The two sets of EoS parameters are listed in Table 3. Using these parameters, the two-phase P-T diagram can be plotted (Fig. 2).

Oil swelling can mobilize the residual oil to be recovered, in turn increasing the oil saturation and oil relative permeability (Yang and Gu, 2003). The measurement of the oil swelling factor provides a better understanding of the oil recovery mechanisms of CO_2

Table 1
Bottom-hole samples.

COMP	Mol,%
CO_2	0.287
N_2	0.928
C_1	40.203
C_2	3.822
C_3	2.591
iC_4	2.066
nC_4	2.217
iC_5	1.686
nC_5	2.879
C_6	6.337
C_7^+	36.984