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Sensitivity analysis of water-alternating-CO_2 flooding for enhanced oil recovery in high water cut oil reservoirs

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ABSTRACT

The objective of this work is to investigate the effect of operational schemes, reservoir types and development parameters on both the amount of incremental oil produced and CO_2 stored in high water cut oil reservoirs during CO_2 water-alternating-gas (WAG) flooding by running compositional numerical simulator.

The method used is the orthogonal experimental design method to optimize operation parameters, including CO_2 slug size, ratio of CO_2 slug size to water slug size (WAG ratio), CO_2 injection rate, and voidage replacement ratio. The Net Present Value (NPV) was used as an objective function for economic analysis. Various 3-D heterogeneous reservoir models were built to investigate the impact of reservoir types and development parameters on CO_2 flooding efficiency and storage capacity.

The results indicate that as compared to inverted nine-spot pattern and inverted seven-spot pattern, five-spot pattern is more suitable for CO_2 WAG flooding. The earlier water injection is switched to CO_2, the more benefit can be obtained. Compared with CO_2 injection cost and tax credit per ton of CO_2 stored, oil price is considered as the most influential economic parameter on CO_2 WAG flooding.

1. Introduction

Carbon dioxide flooding has been recognized as one of the most effective options for oil recovery enhancement in depleted or mature oil reservoirs [1–3]. The benefits of injecting CO_2 include the expansion of oil volume and the reduction of oil viscosity [4,5]. CO_2 is able to displace the residual oil that is immobilized by water flooding and therefore improve the microscopic displacement efficiency [6]. The CO_2 EOR projects in Weyburn and the North Sea have also proved the great potentials of both oil production increment and CO_2 sequestration [7,8].

However, if the gas source is located far from a target oil reservoir, considering the cost of CO_2 capture, transportation, compression and injection, CO_2 EOR projects may not be profitable without economic incentives from the government. Ghomian et al. [9] established the amounts and types of economic incentives for different reservoir types. They found that sandstone reservoirs had higher probability of need for economic incentives than carbonate reservoirs. Using the methodology of NPV, Jahangiri and Zhang [10] determined that a minimum of $40/ton of carbon tax credit is required for immiscible CO_2 flooding so as to obtain the same NPV as water flooding, while miscible CO_2 flooding is more profitable than water flooding even without any economic incentives.

Regarding the optimization of operational scheme, a number of studies have been conducted. Yang et al. [11] developed an integrated model to optimize the production-injection operation systems (PIOS). Taking the NPV as an objective function, the optimum production and injection parameters were achieved in a WAG miscible flooding reservoir. Kovscek and Cakici [12] defined an objective function that combines the ultimate oil recovery and the fraction of reservoir volume filled with CO_2. The most effective injection and production scheme was determined which could co-optimize oil recovery and simultaneous CO_2 sequestration. Chen et al. [13] developed a hybrid method that integrates orthogonal array and Tabu technique into a genetic algorithm. When conducting a sensitivity analysis on oil recovery and NPV, controlling variables were selected including injection rate, WAG ratio, injection time and bottomhole pressure for the producers. Studies revealed that WAG flooding recovers more oil than continuous injection flooding. That is because WAG flooding can reduce CO_2 viscous fingering and provide better vertical sweep efficiency [14,15]. Additionally, the horizontal well impacts CO_2 flooding greatly for the

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reason that the displacement provides better sweep efficiency based on both reservoir simulations and laboratory studies [16–18].

Despite the potentials of CO_2 EOR, this technology is not suitable for all types of hydrocarbon reservoirs [19,20]. Based on both field results and oil recovery mechanism study, Taber et al. [21] proposed the screening criteria for CO_2 miscible and immiscible flooding, respectively. Shaw and Bachu [22] presented a method for the screening and ranking of oil reservoirs suitable for CO_2 EOR. Oil gravity, reservoir temperature and pressure, minimum miscibility pressure and remaining oil saturation were selected as variables. However, most of studies on CO_2 flooding described above have been conducted on undeveloped oil reservoirs, and very few results from high water cut oil reservoirs are seen in the literature.

The main objective of this study is to investigate the effect of operational schemes, reservoir types and development parameters on WAG flooding in high water cut oil reservoirs by running compositional simulations. By applying orthogonal experimental design, the most effective operational scheme was determined which could maximize the incremental oil produced by WAG flooding. Afterwards, various geological models were constructed by employing different reservoir parameters and development parameters. A technical analysis of five reservoir parameters and two development parameters was conducted. The NPV model was built for economic analysis. The effect of oil price, CO_2 injection cost and tax credit on the NPV was investigated in the study.

2. Description of the base reservoir model

This study was conducted based on a reservoir on Guan 104 fault block in Dagang Oilfield in China [23–28]. For the particular interested area of 3.5 km^2, the reservoir depth is from 2,650 m to 2,750 m; the formation net thickness varies from 9.7 m to 41.4 m; the average horizontal permeability varies from 254.7 md to 425.7 md; the range of porosity is from 18% to 22% and the average porosity is 19.04%. The permeability variation coefficient varies from 0.45 to 0.8. The sand body rhythms include normal, reverse, compound normal and compound reverse. Five-spot patterns were initially applied and are still used in this reservoir. This is a water-wet reservoir. The relative permeability end points are the critical water saturation of 0.478, the residual oil saturation of 0.227 for water–oil system, the connate gas saturation of 0, and the maximum gas saturation of 0.522 for gas–liquid system. The relative permeability curves for water–oil system were depicted in Fig. 1(a), while the relative permeability curves for gas–liquid system were shown in Fig. 1(b). The same set of relative permeability curves was utilized in the simulations during water flooding and CO_2 WAG flooding.

In order to investigate the impact of operational schemes on CO_2 flooding, a base reservoir model with impermeable boundary was built based on the range of main parameters of that particular reservoir. The base reservoir model is 925 m, 925 m and 10 m in the *x*, *y* and *z* dimensions, respectively. It consists of nine five-spot patterns with a well spacing (i.e., the distance between two adjacent producers) of 300 m; the locations of the 9 injectors and 16 producers were shown in Fig. 2. These wells perforated in all four layers of the formation. The sand body is normal rhythmic, which means the formation permeability increases downward. The base reservoir is water-wet, and the initial oil saturation is 0.522. Other parameters in the base reservoir model were summarized in Table 1.

Slim-tube experiments were conducted to determine the minimum miscibility pressure (MMP) between the reservoir oil and CO_2. The experiments were conducted under the temperature of 108 °C. A slim tube with a length of 18 m and an inner radius of

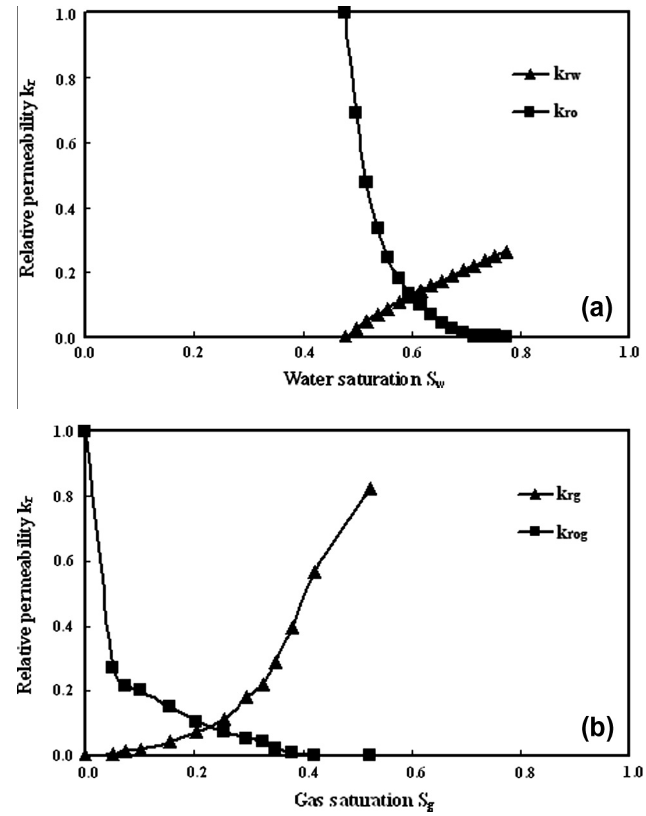

Fig. 1. Typical relative permeability curves for the target oil reservoir. (a) Relative permeability curves for water–oil system. (b) Relative permeability curves for gas–liquid system.

3.175 mm was packed with sand of 200 mesh size. The pore volume of the slim tube is 255.7 cm^3. The slim tube was saturated by reconstituted oil that contains $C_1 + N_2$ (14.0 mol%), $CO_2 + C_2 \sim C_{10}$ (27.9 mol%) and C_{11+} (58.1 mol%). During the experiments, 1.2 PV CO_2 was injected at the rate of 0.167 cm^3/min at six different displacement pressures. The color change and phase behavior of the effluent were observed through the inspection window. The effluent was flashed in the separator connected with a flow meter to measure gas flow. The oil was collected in a conical flask and the density was measured using a densitometer. The cumulative oil recovery was recorded and the MMP was defined as the break in slope from the plot of oil recovery against displacement pressure [29]. As Fig. 3 depicts, the MMP was determined to be 322.8 bars. The initial formation pressure is 272.1 bars that are lower than the MMP, which means CO_2 immiscible flooding. Using the PVTi module in Eclipse software, the pseudo-components of crude oil were obtained as shown in Table 2. The light components ($C_2 \sim C_6$) just account for 10.1 mol%, and a large amount of heavy components leads to a high MMP between reservoir oil and CO_2.

Eclipse Compositional Simulator was used. Initially, the reservoir was water flooded; then RESTART function was used to conduct WAG flooding. During WAG flooding, mass transfer between CO_2 and oil was automatically considered in the compositional simulator.

3. Methodologies

3.1. Determination of operational scheme

In CO_2 WAG flooding, the CO_2 slug size, WAG ratio, CO_2 injection rate and voidage replacement ratio impact WAG flooding significantly [13,30]. A big CO_2 slug size results in early gas