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Simulation study of huff-n-puff air injection for enhanced oil recovery in shale oil reservoirs

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ABSTRACT

This paper is the first attempt to evaluate huff-n-puff air injection in a shale oil reservoir using a simulation approach. Recovery mechanisms and physical processes of huff-n-puff air injection in a shale oil reservoir are investigated through investigating production performance, thermal behavior, reservoir pressure and fluid saturation features. Air flooding is used as the basic case for a comparative study. The simulation study suggests that thermal drive is the main recovery mechanism for huff-n-puff air injection in the shale oil reservoir, but not for simple air flooding. The synergic recovery mechanism of air flooding in conventional light oil reservoirs can be replicated in shale oil reservoirs by using air huff-n-puff injection strategy. Reducing huff-n-puff time is better for performing the synergic recovery mechanism of air injection. O_2 diffusion plays an important role in huff-n-puff air injection in shale oil reservoirs. Pressure transmissibility as well as reservoir pressure maintenance ability in huff-n-puff air injection is more pronounced than the simple air flooding after primary depletion stage. No obvious gas override is exhibited in both air flooding and air huff-n-puff injection scenarios in shale reservoirs. Huff-n-puff air injection has great potential to develop shale oil reservoirs. The results from this work may stimulate further investigations.

1. Introduction

Various enhanced oil recovery (EOR) methods have been investigated for shale oil exploitation in recent years. Among them, gas injection is a good option for recovering hydrocarbon from a shale oil reservoir. Either immiscible or miscible gas flooding, including carbon dioxide (CO_2), nitrogen (N_2), natural gas, or the mixture of them could be an effective way to enhance oil recovery in shale oil reservoirs [1–8]. Among these gases, CO_2 injection as a huff-n-puff process has received more attention for enhanced oil recovery in tight formations [9–14]. Both lab studies and simulation results support CO_2 as a promising EOR agent for unconventional liquid reservoirs [. However, the current enhanced oil recovery methods in tight oil reservoirs have some limitations both practically and economically. CO_2 is currently unavailable in many cases [1]. One important advantage of air injection over CO2 injection is thermal effect. Although hydrocarbon gases are available in most oil fields, they are rarely used as injectants because they are marketable [1,15,16]. Besides, almost all gas flooding techniques often suffer from channeling problems.

Air injection in light oil reservoirs could be a good synergetic EOR method because of the availability and low cost of air. Crude oil oxidation reactions results in flue-gas sweep and thermal drive, and in-situ generated CO_2 has the potential for IFT reduction. In addition we have proved the evidence of the “bulldozing effect (or pore blocking)” for air injection in light oil reservoirs, which has the potential of re-directing gas flow to improve sweep efficiency [17]. Air injection in light oil reservoirs has received considerable attention as an effective, improved oil recovery process, based primarily on the success of several projects within the Williston

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Basin in the United States. The main air injection recovery mechanisms are summarized as: 1) improving sweep efficiency due to flue-gas sweep; 2) rapid re-pressurization of the reservoir; 3) light components extracting for subsequent NGL recovery; 4) oil swelling by flue-gas dissolution; 5) the potential of miscible flooding; 6) the creation of thermally generated microfractures in the reservoir; and 7) crude oil viscosity reduction by thermal effects [15,16,18–21].

Due to the ultra-low matrix permeability in shale reservoirs, air injectivity will not be good compared to conventional reservoirs, because shale formations are not highly permeable. However, air huff-n-puff injection could be a good option, as the huff-n-puff mode may not require as high permeability as the flooding mode [3]. In this paper, we use numerical reservoir simulation to model air huff-n-puff injection in shale oil reservoirs. The paper aims at a better understanding of the physical processes and the recovery mechanisms of air huff-n-puff injection in shale oil reservoirs. This study provides a framework to further evaluate the potential of air huff-n-puff injection in shale oil reservoirs in North America.

2. Reservoir simulation model

A 3-D Cartesian grid of 22 × 55 × 7 with 8470 active blocks is used to simulate one section of stimulated reservoir volume (SRV) as shown in Fig. 1. The local grid refinement (LGR) with logarithmic cell spacing method is employed to reduce the numerical dispersion effect, especially for capturing accurate temperature distribution in air injection. The LGR is also used to accurately capture flow to/into fracture [22–24]. Two half-vertical wells connected with two half fractures, respectively. Each fracture is 1-ft wide and has a conductivity of 46.65 md-ft following the Rubin's approach [25]. We use a simple model to simulate the flow between the two lateral hydraulic fractures of a horizontal well. Assuming the flow between any two lateral fractures is the same, then such a small model can represent the flow through a part of a horizontal well. In a previous study, the same model has been used to evaluate the EOR potential of gas and water injection in shale oil reservoirs 3). Reservoir properties based on the actual data in the Eagle Ford shale reservoir are summarized in Table 1. The relative permeability curves, such as water–oil relative permeability and liquid–gas relative permeability (Fig. 2) are from the previous work [3,26]. The reservoir simulator CMG-STARS (version 2014) [27] is used in this work. Non-Darcy flow that may occurs in shale reservoirs is not considered in the CMG-STARS. Because this model is the same as the previous work [3] and has been validated in Wan's thesis [26], our reservoir model is assumed to be validated. The validation has been performed in Chen's thesis [28], and it is not repeated here. However, we further run a case with 13 blocks in the Z direction to check the grid sensitivity. The oil recovery vs. time for this finer model is shown in Fig. 3. It can be seen that the result almost

Table 1
Reservoir properties of Eagle Ford formation used in the base model (Sheng and Chen, 2014).

Parameter	value	unit
Initial reservoir pressure	6400 (4.41×10^7)	psi (Pa)
Reservoir temperature	237(114)	°F (°C)
Matrix permeability	0.0001(9.87×10^{-20})	mD (m^2)
Matrix porosity	0.06	Value
Initial water saturation	0.3	Value
Compressibility of shale	5×10^{-6} (7.25×10^{-10})	Psi^{-1}(Pa^{-1})
Reservoir thickness	200 (60.96)	ft (m)

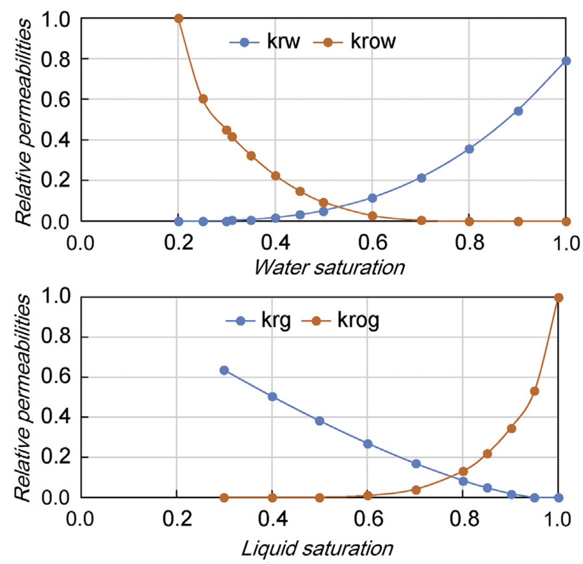

Fig. 2. Relative permeability curves used in this work (Wan, 2013; Sheng and Chen, 2014).

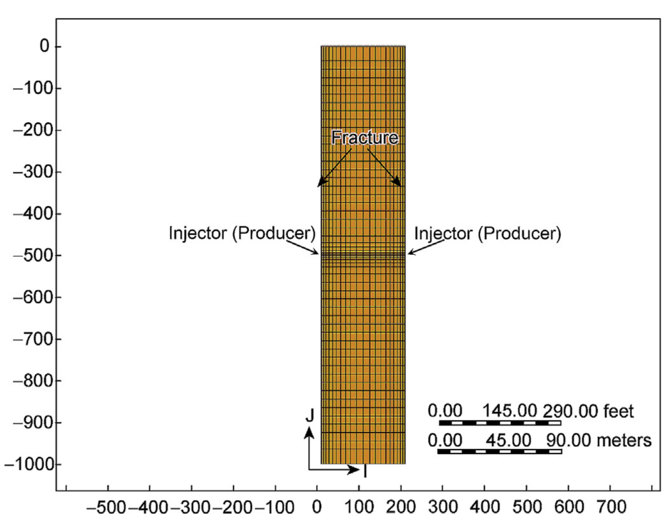

Fig. 1. Reservoir simulation model (2D cross section).

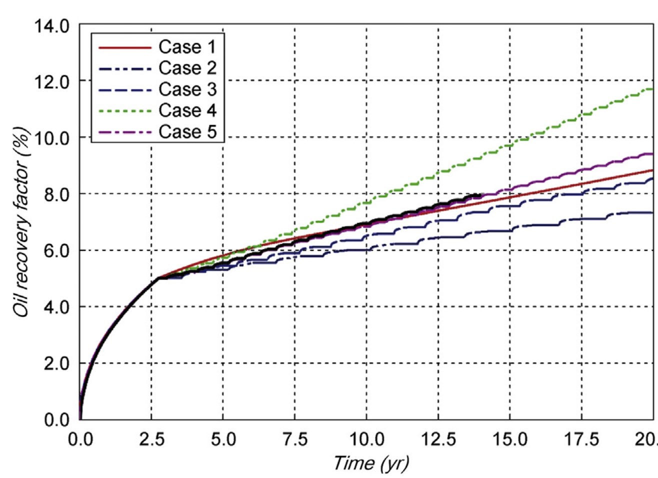

Fig. 3. Comparison of oil recovery factor for different injection scenarios. The black curve is the case similar to Case 5 but using 13 blocks in the Z direction.

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