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# Numerical modeling on air injection in a light oil reservoir: Recovery mechanism and scheme optimization

Hu Jia *, James J. Sheng

*State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, China*
*Bob L. Herd Department of Petroleum Engineering, Texas Tech University, Lubbock, TX 79409, USA*

## HIGHLIGHTS

- EOR mechanism of air injection is investigated through numerical modeling approach.
- How thermal effects affecting production performance is revealed.
- We proved the "bulldozing effect (or pore blocking)" for air injection in light oil reservoirs.
- Activation energy shows different effect on production performance.

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## ABSTRACT

Air injection in light oil reservoirs is a promising enhanced oil recovery (EOR) method because of its wide availability, low cost, and ability to stimulate subterranean oil combustion. However, oil recovery mechanisms and physical processes for air injection in conventional light oil reservoirs are still not well understood. An improved understanding of air injection mechanism in conventional light oil reservoirs is provided in this paper. We use the reservoir simulation approach to study air injection in a light oil reservoir. Effects of $O_2$ mole concentration, activation energy, intake air temperature, geological structure and development scheme on the well performance of air injection are examined. The driving mechanism of thermal effect is revealed through the observation of oil rate fluctuating and dynamic temperature distribution. We present the evidence of the "bulldozing effect (or pore blocking)" for air injection in a light oil reservoir which shows the sudden decrease of gas relative permeability. The effect has the potential of re-directing gas flow to improve sweep efficiency. Analysis of influence factors from this work indicates that the oil recovery factor is sensitive to $O_2$ content in air and geological structure of the reservoir. The performance with gas injected updip is better than that downdip. It is insensitive to intake air temperature or activation energy in the reaction scheme favoring a generation of more $H_2O$, insoluble CO and $CH_4$.


## 1. Introduction

Historically, successful light oil air injection projects mainly include Buffalo, Medicine Pole Hills Unit (MPHU), Horse Creek, Coral Creek and Hackberry fields [1–5]. Field experiences and project design that indicate spontaneous low temperature oxidation (LTO) can lead to in-situ combustion, which may occur in fields with relatively high reservoir temperature 194–248 °F (90–120 °C) and pressures [6–8]. The preexisting evidence from the Buffalo Red River Unit (BRRU) and South Buffalo Red River Unit (SBRRU) in the Buffalo field indicates that oil is actually burning and suggests that the combustion front has a favorable impact on the production performance of the oil field [9]. A stable propagation of combustion front can provide more benefits of the thermal recovery process for air injection both in light oil and heavy oil reservoirs [10,11]. Heavy oil is known to be rich in heavier unsaturates such as resins and asphaltenes [12]. These components mainly dominate oxygen addition reaction in LTO to generate various oxygenated hydrocarbons, such as alcohols, aldehydes, hydroperoxides, ketones, carboxylic acids and water [13,14]. Application of in-situ combustion in heavy oil reservoirs sometimes requires an ignition operation to initiate it and create the heat wave, while air injection in light oil does not [15]. The reported main recovery mechanisms of air injection in light oil are summarized as: (1) improvement of sweep efficiency due to flue-gas sweep; (2) rapid re-pressurization of reservoirs; (3) light components extracting for subsequent liquid nature gas flooding; (4) oil

* Corresponding author.
*E-mail addresses:* hu.jia@ttu.edu, jiahuswpu@swpu.edu.cn (H. Jia).

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**Nomenclature**

*Acronyms and units*

| | |
|---|---|
| EOR | enhanced oil recovery |
| LTO | low temperature oxidation |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| $O_2$ | oxygen |
| $N_2$ | nitrogen |
| $H_2O$ | water |
| $CH_4$ | methane |
| MSCF | $10^3$ standard cubic feet |
| STB | stock tank barrels |
| GOR | gas oil ratio |

°API 141.5/(131.5+°API) = g/cm$^3$
bbl × 1.589873 E−01 = m$^3$
1bm × 4.535924 E−01 = kg
Btu × 1.055056 E+00 = kJ
°F (°F-32)/1.8 = °C
psi × 6.894757 E+00 = kPa
ft × 3.048 E−01 = m
cp × 1.0 E−03 = Pa s
mD × 9.869233 E−04 = μm$^2$

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 [16–22].

The above mechanisms are mainly drawn from theoretical hypothesis, lab experiments, and field performance. Over the years, air injection in light oil has been simply modeled as gas flood, giving little credit to combustion as a drive mechanism [8,23–25]. Jia et al. [26] derived a mathematical model to investigate how thermal effects influence production performance by qualitative analysis. They concluded that such methods as reducing well spacing and extending air injection cycle should be taken into consideration to achieve a high oil recovery factor contributed by thermal effects. Besides, field experience and laboratory testing also concluded that air injection in a light oil reservoir is beneficial both from primary gas flooding effects and secondary thermal driving after a certain pore volume of air is injected [27]. Additionally, the "bulldozing effect" (or pore blocking) feature is assumed to occur in light oil air injection based on several hypotheses [28]. However, the terminology is mainly used for air injection in heavy oil reservoirs for in-situ combustion [29]. Hence, further investigation is needed to prove whether "bulldozing effects" (or pore blocking) really exists during air injection for light oil. Ref. [28] proposed that the "bulldozing effect" is treated as the drive mechanism of thermal effects for air injection in light oil reservoirs, and people start to recognize that the thermal effects drive should be a main recovery mechanism for air injection, but no simulation work to visualize this process and how it works has been done.

To the best of our knowledge, the comprehensive study on the recovery mechanisms of air injection in light oil works is poor, especially for the thermal effects drive from the aspect of reservoir simulation interpretation. Misunderstanding of air injection mechanism would seriously lead to the failure of project design. The numerical modeling of the field performance of air injection projects still face challenges due to the sufficiently complexity of oxidation reactions [28]. But we have no alternative except for this tool for predicting the field performance of air injection. No matter how strong the numerical simulators are, human experience is vital for designing a reasonable reaction scheme as well as operating the process based on laboratory testing results. Hence, we can interpret the recovery mechanism of air injection from simulation results in a reasonable way for better guiding field design.

The aim of this work is to visualize the main recovery mechanisms of air injection in light oil reservoir as well as to prove the thermal effect and pore blocking phenomenon hypothesis by a numerical simulation approach. The basic model is first calibrated from the simulation results of air injection in a North Sea light oil field [30,31]. It must be pointed out that the calibrated model was well upscaled from combustion tube experiments, while some important findings were still not revealed due to the limited knowledge of recognizing air injection mechanisms at that time as well as serious numerical instability of the old version of the simulator. The rest of this paper is organized as follows. Section 2 describes reservoir simulation model set-up and methodologies. Section 3 introduces fluid properties and reaction schemes. Section 4 initiates theoretical analysis on air injection mechanism and scheme optimization. Some highlights are summarized in Section 5. This work can provide a better understanding of the air injection mechanism in light oil reservoirs with the aid of numerical simulation, which can be extended to evaluate air injection in tight oil reservoirs in North America such as Eagle Ford shale of West Texas, Bakken shale of North Dakota, and Marcellus shale of Pennsylvania with high reservoir temperatures between 168 and 255 °F and API gravities greater than 40° [32–34].

## 2. Reservoir simulation model

A 3-D Cartesian grid of 22 × 9 × 5 with 990 active blocks is used in this field scale model as show in Fig. 1. The total grid block size is set to 2742 ft × 865 ft × 175 ft in *x*, *y*, *z* directions, respectively. Reservoir properties are based on the actual data in the North Sea oil field [31]. The initial reservoir pressure of 6440 psi and temperature of 210 °F are used. The reservoir top depth TVD is 8205 ft with a dip angle of around 15°. The calculation of the geological structure is based on the variation of the top depths in the grid columns. In this model, the depth to the top of each grid column is set from maximum 8620 ft to minimum 8200 ft with 20 ft gradient. The reservoir permeability is 1100 md and 1300 md, respectively, for the upper three layers and the bottom two layers. The porosity is 0.19 for all the layers. The perforated horizontal injection well (Well 2) and production well (Well 1) are located in the updip and downdip, respectively, in the base case.

The software used for numerical simulations was CMG-STARS (version 2014) with the non-isothermal module. A typical thermal simulator solves mass and heat balance equations below [13,35,36].

The conservation equation of flowing component *i* is

$$\frac{\partial}{\partial x}\left[V_f\left(\rho_w S_w w_i + \rho_o S_o x_i + \rho_g S_g y_i\right)\right]$$
$$= \sum_{k=1}^{n_f}\left[T_w \rho_w w_i \Delta\phi_w + T_o \rho_o x_i \Delta\phi_o + T_g \rho_g y_i \Delta\phi_g\right]$$
$$+ V\sum_{k=1}^{n_r}(s'_{ki} - s_{ki})r_k + \sigma_{iw}\sum_{k=1}^{n_f}\rho_w qaq_{wk} + \rho_w q_w w_i + \rho_o q_o x_i$$
$$+ \rho_g q_g y_i[\text{well layer } k] \quad (1)$$

where $V_f$ is volume of fluid phases added together, $V$ is total region volume. $\rho$ is phase density, $S$ is phase saturation, $T$ is phase temperature and $\Delta\phi$ is potential gradient of phase. $qaq_{wk}$ is a volumetric