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# A novel insight of laboratory investigation and simulation for high pressure air injection in light oil reservoir

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ABSTRACT

Due to the precipitous dropping oil price, air injection becomes advantageous to other gas flooding techniques as a result of the low cost. Therefore, this work targeted a light oil reservoir and comprehensively investigated the potential of air injection in this reservoir using experimental and numerical simulation, from which some new insights into high pressure air injection were recognized. Oxidation kinetics of the crude oil were first established using Thermal Gravity Analysis (TG)/Differential Thermal Gravity (DTG), and further validated through a set of history matching. The results indicate that the intense oxidation reaction consumed a great volume of oxygen forming only $CO_2$. Temperature peak occurred after reacting 23 h, revealing that the oxidation reaction is an exothermic process under reservoir conditions and spontaneous combustion might take place. Reservoir dip angle is a crucial parameter governing the oil production and updip injection is generally suggested. Earlier air injection leads to more noticeable incremental temperature effect and also higher ultimate recovery. Air injection seems notably appropriate for rhythm reservoirs. Given a mature reservoir, high-permeability zone would cause gas breakthrough and thus considerably detract the air injection performance. Temperature-resistant polymer gel or foam is suggested to plug thief zones promoting oxidation reactions and air sweep efficiency.



## 1. Introduction

Gas flooding has been successfully applied in many fields all over the word (Watts et al., 1997; Clara et al., 1998; Gutierrez et al., 2009a,b). However, in China, traditional gas flooding techniques such as $CO_2$, natural gas and $N_2$ flooding are not applicable due to the limitations of gas sources and current oil price (Sheng, 2015; Seyyedsar et al., 2016). Given this issue, air injection is expected to be a promising method because of the vast sources and low cost. High pressure air injection (HPAI) can not only improve or maintain reservoir pressure but react with crude oil in place producing flue gas (a mixture of $N_2$, CO, $CO_2$ and light hydrocarbon) and heat (Fassihi et al., 2015; Hughes and Sarma, 2006; Moore et al., 2002). The mechanisms responsible for oil displacement by air injection include sweeping, field re-pressurization, stripping off light components and thermal effects (Jia et al., 2012).

Since 1990, numerous research efforts have been made towards using air to produce oil. For example, Sakthikumar et al. assessed the feasibility of air injection in a water flooded light oil reservoir through immiscible nitrogen flooding to simulate air injection. It was confirmed that air injection process in a water flooded reservoir was promising and economic (Sakthikumar et al., 1995). Fraim et al. evaluated the improved oil recovery performance of high-pressure air injection as an economic alternative to other unavailable or costly gases in a light oil reservoir. High pressure air injection was modeled as a miscible flue gas process. Their results showed that oil recovery factor was increased by 4.5–6.6% (Fraim et al., 1997). Furthermore, Fassihi et al. studied the economics of air injection as flue gas flooding for Medicine Pole Hills Unit oilfield in North Dakota and Buffalo Red River Unit oilfield (BRRU) in South Dakota. For both of the oilfields, the enhanced oil recovery factors were from 14 to 16% (Fassihi et al., 1996, 1997). Glandt et al. examined the technical viability of tertiary HPAI, equation-of-state model was employed and an 8-component lumped model was extracted for reservoir simulation. High pressure air injection was modeled as an isothermal flue gas process. The data verified that air injection could double waterflood reserves and greatly improved

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daily oil production (Glandt et al., 1999). Kuhlman et al. conducted a series of simulations of light oil air injection in a viscous-dominated ¼ five spot model, and a dipping gravity-dominated Gulf Coast salt-dome reservoir was used to assess the performance of light oil air injection in Equation of State (EOS), black-oil and thermal simulators (Kuhlman, 2000). They found that the isothermal fuel gas model should be used in light oil reservoirs while thermal model should be used in heavy reservoirs. The following works found that if air injection was treated as a non-miscible nitrogen flooding or flue gas flooding, it could not accurately simulate the mechanisms of air injection (Sakthikumar et al., 1995; Glandt et al., 1999). The original models proposed by Gutierrez et al. did not consider the "bulldozing effect" (Gutierrez et al., 2009a,b), and thus these models are not able to predict the thermal effect in air injection process (Montes et al., 2010). The results of numerical simulation in West Heidelberg oilfield suggested that despite HPAI was proposed for pressure maintenance as a secondary oil recovery technology in the beginning, more than 50% of oil was devoted by thermal effects (Gutierrez et al., 2008). Jia and Zhao established a new multi-reaction model for HPAI process. High peak temperature and long term stable combustion front were detected when air injection rate was high (Jia et al., 2014).

Most of previous studies in the interest of air injection in light oil reservoirs treated this process as immiscible nitrogen flooding, miscible flue gas process or isothermal flue gas process etc. (Greaves et al., 1999, 2000). Limited works investigated the contribution of thermal effect during air displacing the oil in place. Moreover, the establishment of appropriate oxidation reaction modes using logical oxidation kinetics parameters is of particular importance to the numerical model of air injection. However, the reported methods to acquire and adjust oxidation kinetics parameters on the of a single type of experiment are unreliable. Furthermore, factors (*e.g.* injection opportunity, reservoir sedimentary type and existence of high-permeability zone etc.) which are associated with the success of air injection are still not yet well understood. Given the above issues, this paper first conducted a set of oxidation experiments under reservoir conditions to investigate the reaction characteristics (thermal effect, air displacement efficiency, pressure change and gas component). Based on the results, simplified oxidation reaction modes were established. Afterwards, the oxidation kinetics parameters were obtained using TG/DTG and validated through history matching. In the end, air injection was numerically modeled in the targeted light oil reservoir to understand the effects of the reservoir condition on the success of air injection. The new methods and new insight derived from our study can provide some necessary clues for pilot tests of air injection in this light oilfield and also other oilfields having similar conditions.

## 2. Materials and experimental methodolgy

Laboratory experiment was performed to investigate the oxidation characteristics of the crude oil. The oxidation reaction carried out in tube experiments was to establish the oxidation reaction modes. The thermal effect of oxidation reaction was studied in thermal monitoring experiments. Air displacement tests were conducted and then history-matched using numerical simulation model to correct the oxidation kinetics parameters.

### 2.1. Materials

The crude oil used in this work was sampled from the targeted reservoir, which is a high-pressure and temperature light oil reservoir having temperature of 95 °C and current pressure of about 13.5 MPa. The composition analysis and properties of the light oil can be seen in Table 1 and Fig. 1 (Liu et al., 2015). Cutting

**Table 1**
Properties of the crude oil.

| $C_{4\text{-}6}$ (mol %) | $C_{7\text{-}15}$ (mol %) | $C_{16+}$ (mol %) | Asphatene (mol %) | Paraffin (mol %) | Resin (mol %) | Viscosity at reservoir temperature (mPa·s) | API (°) |
|---|---|---|---|---|---|---|---|
| 1.65 | 41.64 | 56.71 | 0.18 | 9.94 | 29 | 2.63 | 33.96 |

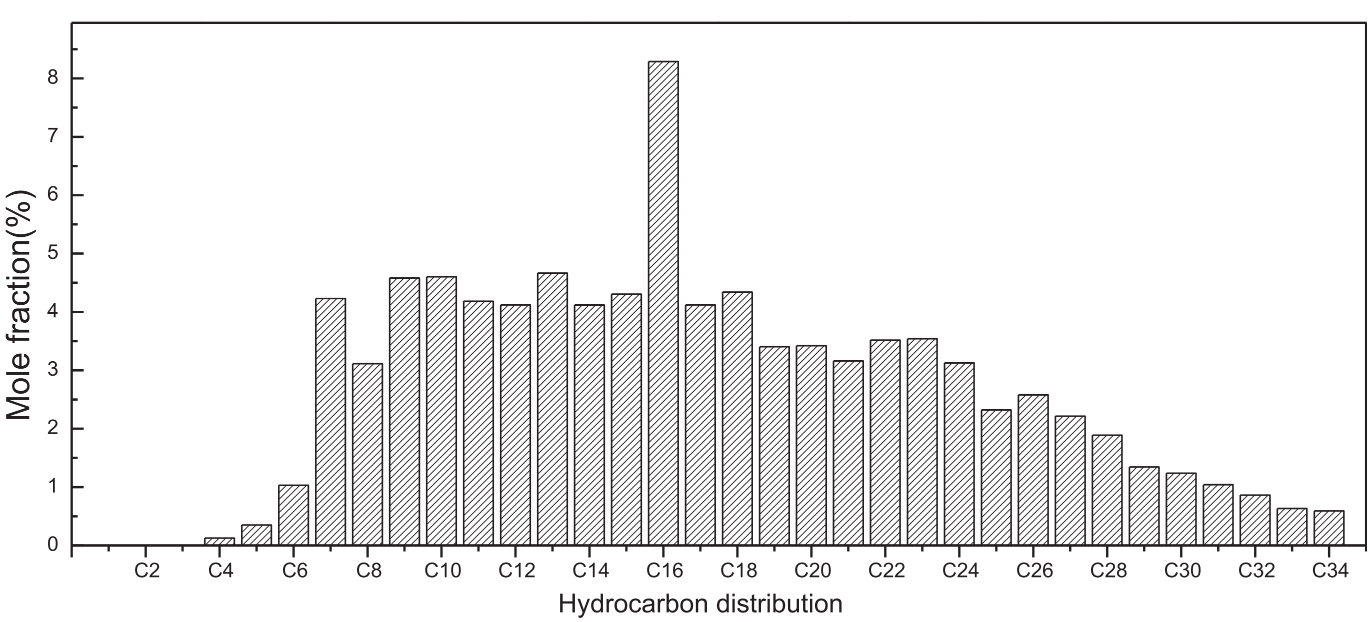


**Fig. 1.** Hydrocarbon distribution of the crude oil (Liu et al., 2015).