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# Numerical study of air assisted cyclic steam stimulation process for heavy oil reservoirs: Recovery performance and energy efficiency analysis

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ABSTRACT

Cyclic steam stimulation (CSS) has been widely applied as an effective technique for heavy oil reservoirs, but it is increasingly concerned in recent years for its limited oil recovery performance, low energy efficiency, high water consumption and great environmental footprints due to greenhouse gas emissions. The hybrid injection of air and steam in terms of low temperature oxidation (LTO) is an innovative technique for the development of heavy oil reservoirs, which can be operated based on the conventional well configuration and was firstly proposed as an enhanced oil recovery (EOR) process for mature heavy oil reservoirs encountered with low reservoir pressure, poor steam sweep efficiency and high water cut. In this study, numerical simulation study is conducted to evaluate the potentials of air assisted cyclic steam stimulation (AACSS) process as an alternative to CSS technique for heavy oil reservoirs. Effects of oil viscosity, LTO reaction and operated air to steam ratio on the well performance are examined for typical heavy oils. The results indicate that AACSS process can effectively improve oil recovery, enhance the energy efficiency and reduce $CO_2$ emissions in comparison with CSS alone, which can be attributed to the thermal effect due to oil oxidation, reservoir repressurization and gas driving offered by air injection, and the AACSS process can be more economically and environmentally attractive than CSS alone. The production performance of AACSS process for ultra heavy oil reservoirs can be more pronounced in comparison with that of ordinary heavy oils, and the LTO characteristics of different oils and the feasible air to steam ratio are reservoir specific for field operation.

## 1. Introduction

With the declining conventional light oil production and escalating oil demand, the attention of the petroleum industry has been shifted to the development of unconventional oil resources to ensure the oil security. Heavy oil and bitumen are considered as promising succeeding resources for conventional light oils on account of their abundant reserves and wide distribution [1], which can have higher recovery factor in comparison with other unconventional oil resources (e.g. tight oil and shale oil) from the technical point of view [2]. High oil viscosity at original reservoir conditions can pose great viscous force and thus impede oil flowing to production wells, which is the greatest challenge for unlocking heavy oil and bitumen. However, oil viscosity is extremely sensitive to temperature, which can be reduced by several orders of magnitudes when the reservoir temperature is raised to 200 °C or higher [3]. Therefore, thermal recovery techniques, especially steam injection based processes, including cyclic steam stimulation (CSS), steam flooding and steam assisted gravity drainage (SAGD), have been the prevailing methods to produce heavy oil and bitumen and have achieved great success in the past several decades [4]. However, there are still various problems encountered for heavy oil reservoirs in some steam injection based processes, such as low reservoir pressure, poor steam sweep efficiency and high water cut, which can restrict the final oil recovery performance and increase the production cost. Steam injection usually needs huge energy input for each barrel of oil produced and consumes a large quantity of water and other fossil fuels (for steam generation), which can result in expensive post production water treatment and considerable greenhouse gas (mainly carbon dioxide) emissions [5]. It is estimated that up to 15.3% of total greenhouse gas emissions in Alberta (Canada) can be accounted for 19 in situ oil sands facilities in 2010 [6]. Therefore, it is of fundamental and practical significance to improve the current steam injection techniques or find novel techniques which can not only improve heavy oil recovery but also be less energy intensive and more environmentally friendly.

In recent years, a lot of techniques have been proposed and investigated in both laboratory and field scale for enhanced heavy oil recovery as well as reducing greenhouse gas emissions. For instance, solar generated steam injection technology [7–8] has attracted a great

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| AACSS | air assisted cyclic steam stimulation |
| AIP | air injection process |
| CAGD | combustion assisted gravity drainage |
| cCOR | cumulative carbon dioxide to oil ratio |
| cEOR | cumulative energy to oil ratio |
| cSOR | cumulative steam to oil ratio |
| CSS | cyclic steam stimulation |
| CWE | cold water equivalent |
| EOR | enhanced oil recovery |
| HTO | high temperature oxidation |
| IFT | interfacial tension |
| IOR | improved oil recovery |
| ISC | in situ combustion |
| IUP | in situ upgrading process |
| LHV | lower heating value |
| LTO | low temperature oxidation |
| OTSG | once-through steam generator |
| SAGD | steam assisted gravity drainage |
| SARA | saturates aromatics resins and asphaltenes |
| SBR | small batch reactor |
| THAI | toe to heel air injection |

deal of attention recently due to its positive impacts on reducing natural gas consumption and greenhouse gas emissions, while it may be restricted by the large land area intensity and the geological location resulting from the variation of annual irradiance on the earth's surface [9]. In situ combustion (ISC) process, such as toe to heel air injection (THAI) technique [10] and combustion assisted gravity drainage (CAGD) technique [11], has been investigated and proven as an effective technique for heavy oil reservoirs featured with high oil recovery and enhanced energy efficiency. The produced oil is usually upgraded to some extent as a result of the cracking reactions and high temperature oxidation (HTO) reactions occurring underground. The produced flue gas during ISC process can be re-injected into nearby light or heavy oil reservoirs for both enhanced oil recovery (EOR) and geological storage. Furthermore, in situ upgrading process (IUP) has been proposed to upgrade heavy oil through subsurface pyrolysis and cracking with the oil layer being heated to about 350 °C via a wellbore based electric heater instead of steam injection [12], which has been applied in several pilot projects. The energy efficiency of IUP can be larger than that of steam injection based processes (e.g. SAGD), and no water will be used during the recovery process, while further studies are still needed for its commercial field scale application. Non-condensable gases and solvents assisted steam injection processes [13–17] have been proved as effective methods to improve oil recovery performance compared with steam injection alone, which can also reduce the steam injection volume, accelerate oil production rate and decrease greenhouse gas emissions, whereas the gas source and solvents' retention in the reservoir may be the restrictions to their large-scale field application.

Air injection process (AIP) has been widely applied in both light and heavy oil reservoirs as a secondary or tertiary oil recovery technique, including high pressure air injection (HPAI) process for light oil reservoirs [18–27], ISC and THAI processes for heavy oil reservoirs [10,11,28]. Air assisted steam injection process in terms of low temperature oxidation (LTO) reaction is an innovative technique for heavy oil reservoirs, which is proposed as an alternative technique to other non-condensable gas injection processes as a result of the large quantity and free availability of air [29–31]. During air assisted steam injection process, the temperature in the steam swept region can reach over 200 °C, and thus LTO reaction between heavy oil components and oxygen in the injected air will be the prevailing reaction. The successful field pilot tests of air assisted steam injection process in D-80 block [29,30] and Qi-40 block [31], Liaohe oilfield, Northeast China, have proven its great potentials from both EOR and economic perspectives.

The main objective of this study is to evaluate the potentials of air assisted cyclic steam stimulation (AACSS) technique as a novel alternative to conventional CSS for the exploitation of heavy oil reservoirs. Numerical simulation study is conducted to investigate the performance of this technique associated with various evaluation criteria including oil recovery performance, energy efficiency and $CO_2$ emissions. Meanwhile, the impacts of oil viscosity, LTO reaction, and operated air to steam ratio on the well performance are investigated and analyzed. This work is of benefit to understanding the effectiveness of AACSS process for heavy oil reservoirs and is expected to provide some guidance for its further field application.

## 2. Air injection assisted cyclic steam stimulation process

### 2.1. LTO characteristics of heavy oils

Low temperature oxidation of oil components (LTO reactions) can prevail in the AACSS process, which distinguishes air injection from other gas injection processes, and is very crucial not only to enhance oil production performance but also to ensure safe production without explosion via oxygen consumption. The original reservoir temperature of heavy oils is usually much lower than that of deep and light oil reservoirs due to their relatively shallow buried depth, and air injection process for heavy oils in terms of LTO is usually conducted based on steam injection, i.e. the so-called air assisted steam injection process, in which air is injected after or along with steam injection. Air injection alone (without high temperature oxidation reaction or in situ combustion) cannot effectively reduce the oil viscosity and its production performance for heavy oils will be very poor. However, air injection can effectively improve light oil recovery, such as the HPAI process [19,20,22,23,26]. Some laboratory experiments have been conducted to study the LTO characteristics and reaction schemes in terms of different oil components and SARA (saturates, aromatics, resins and asphaltenes) fractions, and the results indicate that the oxidation reactivity of heavy oils at lower temperatures can be higher than that of light oils, which may be induced by a relatively lower activation energy of heavier components at lower temperatures [21,32]. Table 1 shows the activation energies of different oil components. It can be observed that the activation energy of wax compound (heavy saturates) is less than that of n-hexadecane (light saturate), and the activation energy of asphaltene is of 50.5 kJ/mol, which is far less than that of simple anthracene (aromatic). In the LTO reactions of both light and heavy oils, a lot of $CO_2$ generation has been observed [18,21], and it is also speculated that saturated oil components can be oxidized to oxygenated hydrocarbons, and complex aromatic hydrocarbons can be converted into resin and/or further oxidized into asphaltenes, and asphaltene can be oxidized to form coke like substance[33–35].

To facilitate reservoir simulation study, the LTO reaction is usually simplified into a simple reaction scheme, including oxidation and decarboxylation reactions [22], shown as follows,

$$C_xH_y + 1.5O_2 \rightarrow \lambda C_xH_y + \gamma CO_2 + H_2O - \Delta H \quad (1)$$

**Table 1**
Activation energies of LTO reaction for different oil components (70–110 °C) [32].

| Component | Anthracene | n-Hexadecane | Wax | Asphaltene |
|---|---|---|---|---|
| Activation energy (kJ/mol) | 124.1 | 119.0 | 94.3 | 50.5 |