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Combustion assisted gravity drainage – Experimental and simulation results of a promising in-situ combustion technology to recover extra-heavy oil

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ABSTRACT

Combustion Assisted Gravity Drainage (CAGD) is a novel in-situ combustion process that utilizes a horizontal injector at the top of the reservoir with a horizontal producer located parallel to and near the bottom of the reservoir. Air is injected, and combustion is initiated with the aid of an electric heater. The heated oil begins to flow downward to the underlying horizontal producer by gravity drainage. The combustion front then develops towards the heel-end of the injector and extends laterally. Direct oil production and short distance traveled by the injected air lead to preserving thermal upgrading and efficient oxygen consumption.

This paper presents experimental and numerical simulation studies of the CAGD process. In-situ combustion experiments have been carried out using a rectangular 3D combustion cell with dimensions of 0.62 m, 0.41 m, and 0.15 m. The sand mix consists of 8.2°API Athabasca bitumen, water, and 100 mesh sand and is packed into the cell. Combustion was initiated with air injection, however, to sustain combustion enriched air (50 mol% Oxygen, 50 mol% Nitrogen) was later injected. Experimental and simulation results show that oil displacement occurs mainly by gravity drainage. Vigorous combustion was observed at the early stages near the heel of the injection well, where a peak temperature of 560 °C was recorded. Final bitumen recovery was 72% of OOIP, with produced bitumen being upgraded by more than 2°API. In addition, a thermal simulator (CMG STARS™) was used to history match the laboratory data and to capture the main combustion characteristics and drive mechanisms. Simulation results are in good agreement with experimental data in terms of fluid production rate and recovery, combustion temperature profile and produced the gas composition.

1. Introduction

In-situ combustion (ISC) has been recognized for many years as a feasible thermal process for recovery of heavy oil and bitumen deposits. This process has been extensively investigated in both laboratory and field tests. Several pilot projects have been tested since 1933 (Adabala et al., 2007; Roychaudhury et al., 1997; Gutierrez et al., 2012; Hascakir et al., 2008; Moss et al., 1959). Technically, ISC is a gas injection process which leads to propagation of heat wave (combustion front) inside the formation. The combustion front is sustained by continuous air injection (Turta et al., 2005; Hasçakir et al., 2011). Despite extensive laboratory investigation and the promises of this technique in challenging reservoirs, there were many failures in the field application. These difficulties are generally associated with unfavorable gas gravity segregation, low sweep efficiency and poor directional control of combustion front movement (Bhattacharya and Chattopadhyay, 2007; Gates and Sklar, 1971; Showalter and Maclean, 1974; Terwilliger et al., 1975; Rahnema et al., 2013, 2016; You et al., 2016).

In conventional ISC process, air is typically injected through a central vertical well surrounded by a number of production wells. Combustion initiated at the injector well then sweeps the pattern volume toward the producer. Due to gravity override of the injected gasses, the combustion front may not advance uniformly in the vertical direction, and the total sweep efficiency may be reduced by the preferential flow of the gasses to one or more wells of the pattern. Another problem frequently encountered in conventional ISC is the presence of a cold oil bank in front of the mobilized oil. Well configuration of conventional ISC process requires that the mobilized oil flows ahead of the combustion front into the colder immobile oil.

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This can cause other problems such as mobility reduction and lower injectivity (Coates et al., 1995).

Most laboratory ISC studies have been conducted using 1D combustion tubes. Combustion tube experiments measure gross combustion parameters such as combustion front temperature, oil recovery factor, fuel concentration, air-fuel ratio, apparent HC ratio and etc. These parameters are essential in the engineering design of field ISC projects. However, they cannot provide information on either areal or vertical sweep efficiencies (Akin et al., 2000; Garon et al., 1986).

Garon et al. Garon et al. (1986) conducted ISC experiments using a 3D scaled laboratory model with a vertical injector and a vertical producer. They investigated the sweep efficiency of dry and wet combustion. Their experiments demonstrated the application of 3D laboratory models for better understanding the basics of combustion and the effect of various injection and production parameters. Akin et al., (2000, 2002) presented an in-situ combustion experiment conducted on a 3D semi-scaled physical model and concluded that a vertical injector and horizontal producers performed better than the other well configurations.

Toe-to-Heel Air Injection (THAI) is a modification of conventional ISC process that uses a horizontal well producer. This technique is based on short-distance displacement and direct production of mobilized oil (Greaves and Al-Honi, 2000; Greaves et al., 2001, 1993). THAI process field pilot tested in McMurray formation of the Athabasca oil sands (Ayasse et al., 2005; Greaves et al., 2005). The project terminated in 2011 after numerous technical problems and economic underperformance (Tait, 2013; Findlay, 2016; Petrobank Reports Year-End, Financial and Operating Results, 2011, 2011).

Kisman and Lau (1994) came up with a novel well arrangement for ISC. They proposed to use lateral wells to vent flow gasses out of the reservoir. This so-called COSH process (Combustion Override Split Production Horizontal Well) uses a horizontal well as a producer. Gravity drainage stabilizes the combustion front development along the production well. They showed that horizontal wells provide certain advantages in in-situ combustion operations. Horizontal wells provide a larger contact area between the formation and the combustion front. Oskouei et al. (2010, 2011) confirmed the feasibility of starting the combustion process in mature SAGD chambers using dual horizontal wells. In 2012, Rahnema et al. (2011) used a semi-scaled physical cell to show the performance of air injection using SAGD paired wells. Their experimental observations show that, while the combustion front does not advance beyond the SAGD chamber, it creates a continues hard coke shell around the SAGD chamber which can minimize steam leakage from adjacent steam chambers.

Using numerical tools, Rahnema and Mamora (2010); De Almeida et al. (2017) showed that CAGD (Combustion Assisted Gravity Drainage) process has a lower cumulative energy to oil ratio and its oil production rate is comparable to SAGD. Their results identified CAGD as a potential alternative to ISC method. CAGD is a form of in-situ combustion process that utilizes a horizontal injector at the top of the formation with a horizontal producer located near the bottom of the reservoir. Air is injected, and combustion is initiated along the length of the injector. The heated oil begins to flow downward towards the underlying horizontal producer by gravity drainage. The combustion front then develops towards the heel-end of the injector and extends laterally. Direct oil production and short distance traveled by the injected air lead to preserving thermal upgrading and efficient oxygen consumption.

This paper presents the results of an integrated laboratory and numerical modeling study on CAGD process. A 3D laboratory model is used to investigate the combustion process using dual horizontal wells for Athabasca crude oil sample. Also, a commercial thermal simulator (CMG STARS™) was used for history matching the experimental results. Both experimental and simulation results indicate that CAGD may be a promising thermal recovery method.

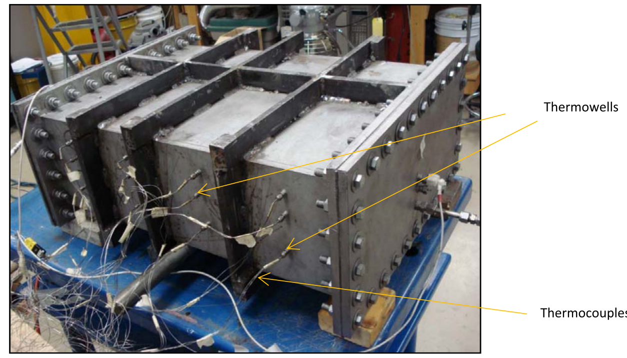

Fig. 1. Photograph of CAGD cell. The ends of the cell may be removed to introduce sand mix or to clean out burnt sand after an experiment. A total of 48 thermocouples are placed inside the thermowell that are installed on two sides of the cell.

2. Materials and methods

The experimental equipment includes five main parts; injection pressure panel, CAGD cell, temperature monitoring board, gas chromatograph and data recording system. Combustion physical model consists of a box made of stainless steel with a dimension of 0.62 m length, 0.41 m width, and 0.15 m height. A detailed description of the experimental setup is presented by Rahnema et al. (2012). A horizontal injection well is placed at the top portion of the model with a horizontal producer at the bottom of the cell. A total of twelve 0.3175 cm (1/8 in) tubing (thermowell) are installed on the side of the cell, and four thermocouples are introduced into each thermowell (Fig. 1). The tips of the thermocouples are uniformly located in the cell to give a total of 48 thermocouple measurement points. Temperature profile inside the model is carefully monitored and recorded using a LabVIEW™ program. Inner insulation (waterproof ceramic fiber) is placed inside the model to minimize heat conduction through the stainless steel body. The concept of CAGD process is explained in Fig. 2 and schematic diagrams of the experimental setup and is shown in Fig. 3. To determine how much experimental error will be introduced by using inner insulation slab for boundary effects, Cumulative heat loss was calculated and then compared for both field condition and laboratory model. Heat loss calculation was based on earlier work by Stegemeier et al. (1980). Based on these calculations, it is estimated that inner insulation of the experimental model results in 11% more heat loss compare to the field case.

An Agilent 34970A data logger is used to record and monitor the following parameters: time, fluid injection temperature, injection pressure, production pressure, gas production rate, and produced gas composition. These parameters were recorded at 30-sec intervals. Temperature measurements within the sand pack were obtained using an array of thermocouples inserted throughout the porous media. Initially, the 3D laboratory cell is packed with a mixture of Athabasca bitumen and 100 US mesh size crushed sandstone. Sand pack permeability was estimated to be between 40 and 60 Darcy using Berg (1970) correlation. High-temperature graphite sealant is used to seal both end-caps of the cell. Outer insulation is wrapped around the cell after

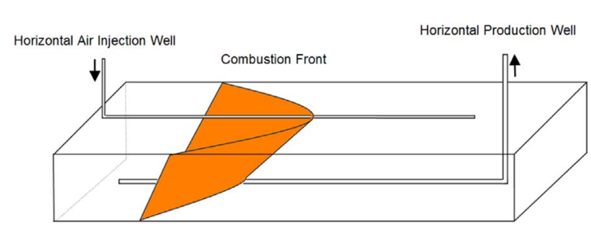

Fig. 2. The combustion front is initiated near the heel of the injection well and follows the path of the injector. Mobilized oil is drained to the lower horizontal producer by gravity drainage.