Fuel 226 (2018) 698–708

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Feasibility of spontaneous ignition during air injection in light oil reservoirs

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ARTICLE INFO

Keywords:
Air injection
Low temperature oxidation
Spontaneous ignition
Enhanced oil recovery

ABSTRACT

Air injection in light oil reservoirs is a complicated EOR (enhanced oil recovery) technique. Till now, the mechanisms of HPAI (high pressure air injection) are still under controversy. Some researchers state that the heat generation is not important for the recovery of light oil during HPAI, and consider the LTO (low temperature oxidation) is only to remove the oxygen but not to establish the combustion front, while others claim that the spontaneous ignition and sustainable combustion front are the key aspects for a success HPAI project. The experimental trials on spontaneous ignition of HPAI to light oil are reviewed and discussed in this paper. This paper also investigates the spontaneous ignition feasibility through both analytical method and numerical method. The review shows that the combustion tube test is used to study combustion sustainability but not suitable to study the spontaneous ignition, and the thermal experiments can only be applied as screening tool to select favorable oil for HPAI in terms of feasibility of spontaneous ignition while further core flooding tests are still required. This paper also proposes an approach which associates thermal experiments with numerical simulation method to investigate the spontaneous ignition of a light oil. A case study is performed with a Wolfcamp light oil, the simulation study shows that the LTO of this light oil cannot induce spontaneous ignition during air injection in both core flooding experiment and field application. The analytical approach is very sensitive to the kinetic data which is used to estimate the ignition delay time. As a result, the analytical method may be misleading in terms of the feasibility of spontaneous ignition, if inappropriate data are selected.

1. Introduction

The thermal enhanced oil recovery method has been developed to recover heavy and viscous crude oil. Thermal recovery mainly involves cyclic steam injection, steam flooding, steam-assisted gravity drainage, hot water flooding and air injection. It has been reported that more than 90% of heavy oil is produced by thermal recovery methods in China [1]. Among all kinds of thermal recovery methods, air injection is the only technique that is capable of generating and accumulating thermal energy in-situ to recover extra crude oil from the reservoir. During the last decades, the AIP has been applied not only to the heavy oil reservoirs but also to the light oil reservoirs since air has immerse availability and free resources. The AIP can be further divided into two categories of ISC (in-situ combustion) technique and HPAI (high pressure air injection) technique. The ISC technique is usually applied when developing a heavy oil reservoir, and for a light oil reservoir, the HPAI technique is often used. For an ISC project, high temperature combustion reactions are usually achieved by means of artificial ignition. The HPAI process to light oil reservoirs is quite different from that of the ISC as most of the HPAI projects are designed to meet self-ignition criteria which depends mainly on the crude oil and rock properties as well as the operational conditions. Theoretically, the combustion of oil can be initiated whenever oxygen comes in contact with fuel if a high temperature can be reached. However, temperature, fuel composition, oxygen supply and reaction mode dictate the nature of combustion reaction.

It was claimed that the success of HPAI technique in Williston Basin, U.S was attributed to the thermal effect from the combustion process, where the flat GOR curve indicates the combustion occurrence [2,3]. In addition, field experiences implied that LTO (low temperature oxidation) reactions at initial reservoir condition could lead spontaneous ignition, where the reservoir has relatively high temperatures (90–120 °C) and high pressures. However, this process requires continuous adiabatic exothermicity of the crude oil to maintain the temperature greater than 300 °C [4–6]. Montes et al. [7] performed combustion tube tests to study the thermal effects of HPAI. The experimental results indicate that extra oil can be produced by the combustion front displacement, where the combustion front acts like a bulldozer. However, the combustion tube test is not designed to study the spontaneous ignition feasibility, but to study the combustion

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https://doi.org/10.1016/j.fuel.2018.04.052
Received 5 December 2017; Received in revised form 9 April 2018; Accepted 10 April 2018
Available online 24 April 2018
0016-2361/ Published by Elsevier Ltd.

Nomenclature

EOR	enhanced oil recovery
HPAI	high pressure air injection
LTO	low temperature oxidation
ISC	in situ combustion
DSC	differential scanning calorimetry
DTA	differential thermal analysis
ARC	accelerating rate calorimetry
TGA	thermogravimetry analysis
EGA	evolved gas analysis
PDSC	pressurized differential scanning calorimetry
HTO	high temperature oxidation
NTC	negative temperature coefficient
HP	hydro-peroxide

sustainability since the combustion tube test starts with a high initial temperature that was established by the heater. Till now, the contribution of combustion process to HPAI is still remained controversial to researchers, which directly influence how researchers understand and interpret the HPAI technique. Some researchers state that the heat generation is not the important mechanism for the recovery of light oil during HPAI, and consider the LTO is only to remove the oxygen but not to establish the combustion front [8–11]. However, others claim that the spontaneous ignition and sustainable combustion front are the key to the success of a HPAI project [2,7,12]. Therefore, in order to better design an air injection project and to properly interpret field observations, it is important to understand the spontaneous ignition feasibility of crude oil during air injection. This paper aims to review the experimental trials on spontaneous ignition of HPAI to light oil, and investigate the spontaneous ignition potential by both analytical method and numerical method. In this study, a previously developed kinetic model was utilized in a lab scale model and a field model to evaluate the feasibility of spontaneous ignition under both lab scale and field scale. The data and analysis presented in this paper will bring researchers insights to better understand and further investigate the HPAI technique in light oil reservoirs.

2. Review of experimental studies on spontaneous ignition during air injection

As mentioned previously, theoretically, the combustion of oil can be established whenever oxygen comes in contact with fuel if a high temperature can be reached. However, in reality, the combustion is restricted by a lot of factors (oil property, formation property and operation property) during the air injection process. It was claimed that the spontaneous ignition is usually identified by two signals: a sharp temperature rise in the sand-face (150–300 °C) and an oxygen concentration decrease in the produced gas [12]. However, some recent studies indicate that the oxygen consumption as well as the carbon dioxide generation could also be caused by the LTO reactions [11,13,10]. Therefore, the sharp in-situ temperature rise should be used as the only reliable indicator to spontaneous ignition. During the last decades, constant attempts were made by researchers to study the spontaneous ignition potential during air injection process. The main objective of these studies was to screen preferable candidate oil reservoir for implementing HPAI. The traditional experiment designed to study air injection is known as the combustion tube experiment; however, the combustion tube test is not designed to study the ignition potential but to investigate the combustion front sustainability as it uses heaters to build high temperature before introducing air flow. Therefore, thermal experiments are utilized to study the exothermic behavior of crude oil during air injection as DSC (differential scanning calorimetry), DTA (differential thermal analysis) and ARC (accelerating rate calorimetry).

The function of DTA and DSC experiments are similar. During a DSC or a DTA test, the sample is heated at a constant heating rate with the presence of the continuous air flow. From the experimental results, information such as temperature intervals of different oxidation reaction stages and exothermic peaks are obtained and interpreted. In addition, the heat flow (positive for exothermic and negative for endothermic) will be plotted versus the temperature, where the area of the exothermic peak represents the enthalpy value of a stage. Razaghi et al. [14,15] proposed a method to use TGA (thermogravimetry analysis) /DSC and EGA (evolved gas analysis) techniques to evaluate the spontaneous ignition feasibility. It was stated that as long as the exothermicity of the LTO is greater than the heat loss to the surrounding strata, as a consequence, the temperature in the region will rise and eventually initiate the combustion. However, in their study, the DSC experiments were performed to observe the exothermic intensity, while the spontaneous ignition was determined based on the effluent gas. Therefore, their method cannot be used to quantitatively evaluate the spontaneous ignition of a crude oil during air injection. Fan et al. [16] performed a series of PDSC (pressurized differential scanning calorimetry) experiments to study the pressure effect to the exothermic of a devolatilized heavy oil. The results indicate that the pressure has a linear relation to the net heat produced in the low temperature stage. Also, it was observed that more heat was generated in the low temperature stage than in the high temperature stage under high pressure condition (3 MPa). The reason caused this phenomenon is still unclear, possible reasons could be high pressure condition changes the oxidation reactions occurred in the low temperature stage or high pressure condition causes HTO (high temperature oxidation) reactions occur at a lower temperature stage. We tend to believe the latter explanation because in the Arrhenius equation, the pressure shows a proportional relation to the reaction rate, which indicates the heat can be generated and accumulated much faster in the low temperature stage under a high pressure condition. However, more studies need to be done to fully understand this phenomenon. Despite of the pressure effect, Huang and Sheng [17] proposed a method to develop a comprehensive kinetic model for a light oil during AIP, where the enthalpy value of a temperature stage is obtained from the DSC experiments. In addition, a lot of DSC experiments have been performed and showed that for a light oil, considerable heat is available in the LTO stage which implies the feasibility of LTO induced spontaneous ignition [18–22].

The ARC technique was developed to study the oxidation reaction kinetics under adiabatic condition. Comparing with DTA and DSC, the advantage of ARC is that the ARC can operate up to 41.4 MPa. Moreover, one shortcoming of the DTA and DSC experiment is that the applied heating rate is high (1–10 °C/min), which limits the observation to the continuity of the transition from the LTO to the HTO reaction. While the ARC follows a method known as "heat-wait-search" method, which can detect very small exothermic initiation at 0.025 °C/min without adding a constant base heating rate. The experimental result of ARC is presented as rate of exothermic heat release versus temperature. Since the system can provide perfect adiabatic environment, the presence of a heat flow trace in a temperature interval stands for an exothermic reaction interval [23]. Yannimaras and Tiffin [5] studied the spontaneous ignition of crude oil by a series of ARC experiments and further validated the ignition performance with corresponding combustion tube tests. According to the experimental results, the ignition of two light crude oil samples were observed at around 115 °C and 121 °C, respectively, where the ignition was identified when the self-generated heating rate is higher than 0.025 °C/min. In addition, the authors discussed that in order to screen out the favorable crude oil for HPAI, one of the key behaviors is the continuous exothermic activity from LTO to