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Discussion of thermal experiments' capability to screen the feasibility of air injection

Siyuan Huang [a], James J. Sheng [a,b,*]

[a] Texas Tech University, United States
[b] Southwest Petroleum University, China

HIGHLIGHTS

- Discuss the roles of thermal experiments (mainly TGA and DSC).
- Collect kinetic data from thermal experiments.
- Present workflow to use thermal experiments.
- Present application of kinetic data.

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ABSTRACT

Thermal experiments such as thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), accelerating rate calorimetry (ARC), and small batch reactor (SBR) are typically used to screen the feasibility of air injection in a reservoir. In this paper, the capability of these tools were studied. The screening criteria for air injection process (AIP) based on the thermal experiments were summarized. A practical workflow to use the thermal experiments to build a base simulation model for AIP it was proposed. In an AIP simulation model, there are about 12 variables to govern the process. Generally, researchers consider kinetic data as adjustable variables to match experimental or field data. How to properly adjust the kinetic data and understand the effect of the kinetic data on the production performance of a reservoir are not well established. In this paper, the reaction temperature ranges and the exothermic peak temperatures for the low temperature oxidation (LTO) stage and high temperature oxidation (HTO) stage were summarized from the experiments using 19 crude oils. The measured kinetic data of 22 different crude oils, and the kinetic data of 25 sets of crude oils with the presence of additives were also summarized. From these data, the ranges of activation energy and frequency factor were defined as the reference for future studies, if such data are readily available. A simulation study has been conducted to study the significance of the kinetic data on production performance. It is observed that the variation of the activation energy significantly influence the recovery performance while the variation of the frequency factor does not.

1. Introduction

AIP (air injection process) is one of EOR methods. For a heavy oil reservoir, the ISC (in-situ combustion) is usually considered, and for a light oil reservoir, the HPAI (high pressure air injection) is usually considered. The differences between conventional reservoir engineering and combustion reservoir engineering has been discussed by Gutierrez et al. [1]. One reason for the differences is the complicated reaction mechanisms among crude oil, rock, and air.

Similar to other EOR techniques, feasibility tests including both numerical simulation studies and laboratory studies have to be considered before conducting a field test. In order to reliably predict the field performance through the numerical simulation, both a well understood kinetic model and a fluid model are required. A well-established kinetic model contains a series of relevant reactions of the oil, rock, and air, and this is also why the chemical reactions between air and oil-rock system are so important for an AIP project. In order to create a kinetic model for the AIP, the thermal-oxidative feature of the oil and rock system of a specific

* Corresponding author at: Texas Tech University, United States.
E-mail address: james.sheng@ttu.edu (J.J. Sheng).

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Nomenclature

AIP	air injection process	DTA	differential thermal analyzer
EOR	enhanced oil recovery	FD	fuel deposition
LTO	low temperature oxidation	PDSC	pressurized differential scanning calorimetry
HTO	high temperature oxidation	Ea	activation energy, kJ mol^{-1}
TGA	thermogravimetric analysis	Ar	frequency factor, s^{-1}
DSC	differential scanning calorimetry	R	universal gas constant, J mol^{-1} K^{-1}
ARC	accelerating rate calorimetry	K(T)	reaction rate, s^{-1}
SBR	small batch reactor		
ISC	in-situ combustion		

reservoir need to be understood. To do that, different experimental techniques have been utilized during the last few decades. There are two categories of experimental studies for the AIP: qualitative studies and quantitative studies. The quantitative study is known as the combustion tube test, which is not the focus of this paper. Thins study mainly talks about the role of the qualitative study, which is also called the "Screening" or "Fingerprinting" study. Thermal experiments such as TGA (thermogravimetric analysis), DSC (differential scanning calorimetry), DTA (differential thermal analyzer), ARC (accelerating rate calorimetry), SBR (small batch reactor) etc., belong to qualitative studies.

The intention of these screening studies was to evaluate the potential of the reservoir for AIP implementation. However, it has been found that the established screening criteria may have to use the reservoir properties and production history to evaluate the reservoir [2,3]. Questions such as "How do we use the thermal experiments to guide the selection of candidate reservoir for the AIP" and "What is the role of the thermal experiments in an AIP" are not well answered. Therefore, it is necessary to study the role of those screening techniques to guide the design of an AIP project.

This paper first reviews the attempts using screening tools for a feasibility study and summarize the screening criteria for the AIP base on the implementation of the thermal experiments. Then a practical workflow which uses the thermal experiments to build the base model for the further AIP simulation study was proposed. After that, the kinetic data of 22 crude oils and 25 crude oils with the presence of additives were summarized, and a general range of the kinetic data for researchers to tune their model or to set up their model were provided. Finally, a simulation study was conducted, and the effect of the kinetic data on reservoir recovery performance is analyzed.

2. Overview of thermal experiments' functions

Over the last decades, thermal experiments have been applied to investigate the combustion reactions during the AIP. As mentioned previously, despite of the convention combustion tube tests, various thermal experiments were conducted to study the air injection process. This section briefly introduces the functions of the thermal experiments in the air injection study.

DTA and DSC are used to measure the thermal behavior of the crude oil through the experiment. During the experiment, the crude oil is heated at a constant heating rate with the presence of the continuous air flow. From the thermograms, information such as temperature intervals of different oxidation reaction stages and exothermic peaks are extracted and interpreted. Generally, there will be two exothermic peaks shown in the thermograms, which are signaled by the onset of LTO (low temperature oxidation) and HTO (high temperature oxidation), respectively. Identifying the exothermic peaks actually tells us at what temperature the oxidation reactions can be triggered, which helps determine the ignition condition. On the other hand, the relevant kinetic data such as frequency factor and activation energy can be obtained through analyzing the thermograms. TGA is used to measure the mass change of the crude oil through the experiment. Similar to the DTA and the DSC, during the TGA experiment, a sample is heated at a constant heating rate with the presence of the continuous air flow. In most of the cases, there will be two sudden mass losses of the crude oil present in the TGA thermograms. These losses indicate the LTO and the HTO. Between the LTO and HTO, there is a stage where the mass loss rate stays relatively unchanged, which indicates the FD (fuel deposition) stage. The relevant kinetic data such as activation energy and frequency factor can also be estimated through analyzing the thermograms of the TGA. ARC is used to detect the self-heat rate of the crude oil, and it can maintain nearly perfect adiabatic conditions through the test. During the test, once the self-heat rate is detected, the time, temperature, and pressure data are recorded. Then, the thermal data and kinetic data can be derived. The advantage of the ARC is that it can be applied at a very high pressure condition (till 6000 psi). A SBR has two sample holders, one is the reactor and the other is served as the reference cell. The reactor is subjected to a heating schedule while air is flown through. The heating is continued at the desired rate until the termination is reached and then held at that temperature during the test of the test. During the test, the temperature profiles of both reactor and reference cell are measured. By comparing these two profiles, the temperature intervals of the exothermic and the endothermic process can be identified. Relevant kinetic data can also be estimated through analyzing SBR data.

3. Attempts to use thermal experiments in the feasibility study

Constant attempts were made by researchers to conduct an AIP feasibility study using thermal experiments. The objective of these attempts was to screen better reservoir candidates for field AIP implementation. The traditional experiment used for this purpose is known as the combustion tube test; however, this test cannot provide any kinetic data for the combustion reactions. Also, when compared to screening tools, the cost and time spent in conducting a combustion tube test is much higher. Tadema [4] first proposed that instead of using conventional combustion tube tests to evaluate the combustion reactions, we might use quicker and more cost-effective DTA and TGA (thermogravimetric analysis) tools. Later, Bae [5] used the DTA to study various crude oils, with gravity ranging from 6° to 38° API. The result shows that the API gravity of the oils have no obvious relation to their thermo-oxidative behaviors. Bae mentioned that when the pressure was at 1000 psig, the oil which could generate more heat in the LTO than the HTO stage from the DTA experiments could be considered as a good candidate for AIP. This is because when the crude oil shows highly reactive behavior in the LTO stage, more heat could be used to sustain the combustion front. Although he did not systematically discuss