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Investigation of the combustion characteristics of Bati Raman oil with sand

Melek Deniz-Paker, Murat Cinar *

Istanbul Technical University, Turkey

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ABSTRACT

In situ combustion (ISC) is one of the thermal oil recovery processes that has been applied in a variety of reservoirs. The energy is generated within the reservoir by a series of multi-step reactions that provide energy to heat the reservoir and reduce oil viscosity. Also, the oil is upgraded in situ by burning heaviest fractions.

In this study, combustion characteristics of Bati Raman crude are investigated. The Bati Raman oil field is the largest known oil field in Turkey. Ramped temperature oxidation (RTO) experiments with effluent gas analysis (EGA) are performed with oil-sand mixtures having different sand particle size. The results are analyzed using isoconversional kinetic approach, which is a model-free method, based on effluent gas analysis and temperature measurements. Effective activation energy values are estimated for the sample with two different sand particle size. Besides, for the same samples, laboratory combustion tube experiments are conducted to evaluate ignition and combustion front propagation characteristics. Asphaltene content and API gravity of the oil sample prior to experiments and produced oil are measured and compared. Results indicate that the oil is upgraded through a reduction in asphaltene content.

A complete set of kinetics and combustion experiments are provided for Bati Raman oil. There are only limited number of studies in the literature to link kinetic experiments to proposed reaction models of ISC. This work presents a way to link a reaction model to isoconversional fingerprint obtained through kinetic experiments. In addition, it is shown that Bati Raman oil exhibits good combustion characteristics and it is associated with its isoconversional fingerprint.

1. Introduction

Heavy oils, are classified by World Petroleum Congress as oils having API gravity between 10 and 22.3, exhibit high viscosity and density. Despite having adverse characteristics of production, heavy oil resources constitute a substantial amount of world's hydrocarbon resources. Based on statistical techniques, Meyer et al. (2007) estimated that approximately 3500 billion barrels of heavy oil reside in the earth crust. Primary and secondary production of heavy oil reservoirs are strictly limited due to its unfavorable characteristics. Application of enhanced oil recovery (EOR) methods and surface mining for shallow reservoir are common for the production of such reservoirs. Among EOR techniques, thermal recovery methods are the most widely applied methods for heavy oil recovery. The primary aim of thermal methods is to add energy into the system in forms of heat to reduce oil viscosity that would result in easier displacement oil to production wells.

In situ combustion (ISC) is one of the thermal recovery processes that is applicable over a wide range of reservoirs with different geological settings, and characteristics (Karimi and Samimi, 2010; Sarathi, 1999; Taber et al., 1997a, b). ISC is based on the injection of air or oxygen enriched air into a reservoir, and as a result of multi-step reactions between the gas and the fuel, heat is generated (Islam and Ali, 1989; Green and Willhite, 1998; Sarathi, 1999; Butler, 1991). The fuel for combustion is referred to as coke, which is a residue produced by cracking, pyrolysis, and vis-breaking processes that takes place downstream of the combustion front (Green and Willhite, 1998). The mechanism of ISC process varies depending on the direction of the combustion front propagation concerning the air flow (Sarathi, 1999; Turta, 2013). Forward dry combustion (FRY) is one of the combustion processes that the ignition occurs near the injection well and the combustion front propagates from the injection to the producing wells (Chu, 1977; Islam and Ali, 1989) with the same direction as injected gas. Due to the generation of energy within the reservoir, in situ combustion is more energy efficient than steam injection or hot water flooding. Also, ISC process consumes the heaviest fractions of crude oil, and as a result of this phenomenon, produced oil is upgraded (Castainer and Brigham, 2003).

Designing and monitoring ISC processes at field scale require an understanding of a variety of different physical processes such as heat and

* Corresponding author.
E-mail address: cinarmura@itu.edu.tr (M. Cinar).

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mass transfer, phase change, and reaction kinetics (Cinar, 2011). ISC tube tests are useful for the understanding of these mechanisms and obtaining significant information for a field test such as hydrogen-carbon ratio (H/C), air requirement, fuel deposition, front velocity, front temperature (Farouq Ali, 1972; Sarathi, 1999). Penberthy and Ramey (1966) stated that the laboratory combustion tube experiments could be operated far more rapidly and cheaply than field tests, but subject to scaling and interpretation problems.

In 1980's, studies on reaction kinetics were conducted at both isothermal and non-isothermal conditions (variable temperature), known as ramped temperature oxidation (RTO). Fassihi and Brigham (1982); Fassihi et al. (1984a,b) stated that multiple reaction models should be used for defining the reaction model because reacting carbon and hydrogen varies with temperature level. Later, Mamora et al. (1993) developed a new oxidation reaction model, which determines the effect of surface area and assumes the kinetic model as a priori. In another study, Belgrave et al. (1993) proposed a reaction model for simulation applications of ISC process. The model integrates thermal cracking, LTO, and HTO reactions together. All these studies are based on the effluent gas analysis and a reaction model is assumed for the interpretation of kinetic data. The kinetic parameters such as frequency factor and activation energy can be found by fitting the RTO test data to a kinetic model. However, the estimated parameters may contain some errors due to the inconsistencies between the hypothetical and the real kinetic model. Assuming a reaction model obtained through experiments at single heating rate may result in unreliable kinetic parameters (Burnham and Dinh, 2007).

An alternative method, isoconversional approach, states that the reaction rate is only a function of temperature at a constant extent of conversion (Friedman, 1964). This method provides effective activation energy values without assuming any reaction model. Thus, it is generally referred to as "model free" method (Vyazovkin, 2006; Cinar et al., 2008, 2009). Cinar et al. (2008, 2009, 2011) were to first to apply the isoconversional method to the analysis of RTO kinetic data of crude oil combustion and showed that activation energy values for ISC could be estimated without assuming any reaction model.

The Bati Raman Field was discovered in 1961 and the original oil in place is 1.85 billion barrels which makes the field the largest in Turkey (Babadagli et al., 2008). Sahin et al. s' (2014) study indicates that by using primary techniques approximately 2% recovery was achieved due to the poor quality of oil and adverse reservoir characteristics, even after 30 years of immiscible CO_2 flooding only 6–8% of the oil was recovered. Low recovery to date attract many researchers' attention for the application of EOR techniques (Issever et al., 1993; Kok and Ocalan, 1995; Akõn et al., 2000; Bagci, 2006; Babadagli et al., 2008, 2009; Hascakir et al., 2010; Sahin et al., 2014). In this study, reaction kinetics and combustion properties of Bati Raman oil samples are investigated experimentally. Both kinetic and combustion tube experiments were conducted with Bati Raman crude oil with 60 and 45-mesh (250 and 500 μm) sand. Bati Raman field is composed of naturally fractured carbonates. In this study, sand is used instead of carbonates to reduce the complexity. Combustion in carbonates is complicated by the fact that carbonates contribute to reactions. In our approach, the first target to model such a complex system is to understand the reaction mechanism of oxidation reactions alone first. The next step would be introducing carbonates and repeat the experiments with carbonates.

Bati Raman field is favorable for thermal EOR methods due to the high viscosity of the oil. Many researchers have studied the field to increase low oil recovery factor. Kok and Okandan (1994) investigated lignite/oil mixture's thermal characteristics by using differential scanning calorimetry (DSC). Kok and Ocalan (1995) developed one-dimensional in situ combustion model for three oil fields including Bati Raman to investigate the economic analysis of dry and wet in situ combustion. Akõn et al. (2000) conducted 3D in situ combustion tests, saturate, aromatic, resin, and asphaltene (SARA) fraction analysis by using thermogravimetric (TGA) and differential thermal analysis (DTA). They used a commercial thermal simulator to develop 3-D combustion model with experimental data to make a field-scale combustion model. Later, Bagci (2005) estimated kinetic parameters of Bati Raman oil/crushed limestone mixture with different clay contents by using a reaction cell, and he stated that increasing surface area increased the fuel deposited on the matrix and decreased Arrhenius constants and activation energies for combustion of oil. In his study, Bagci (2006) used a reaction cell to observe pressure effect on reaction kinetic parameters with oil/crushed limestone media. He concluded that increasing pressure cause activation energies to increase. Anto-Darkwah and Cinar (2016) studied the pressure effect on reaction kinetics of oil/sand mixture by using the isoconversional method, and they stated that activation energies with increasing pressure on LTO region are almost constant whereas increasing at HTO region.

There are several researchers who studied the effect of different clays on combustion characteristics (Vossoughi et al., 1985; Fassihi et al., 1984a,b; Drici and Vossoughi, 1985; Bagci, 2005; Kok and Gundogar, 2013; Glatz et al., 2011; Kok, 2012; Hascakir et al., 2013; Kozlowski et al., 2015). Researchers stated that clay materials are fine and have a larger surface area which provides more fuel deposition on the surface of the matrix. Bousaid and Ramey (1968) conducted several isothermal oxidation experiments with pre-coked unconsolidated sand, and sand/clay mixtures to investigate the reactions at various temperature level and their results showed that the amount of fuel deposited on the solid matrix at a given temperature increased with clay existence in the system. Vossoughi et al. (1982) developed kinetic models to estimate the amount of fuel deposited and reaction rate by using DSC and TGA. They determined a minimum weight of crude oil/sand ratio to sustain combustion front with respect to the surface area of the rock. In their study, Fassihi and Brigham (1982) used effluent gas analysis at both isothermal and linearly increasing temperature conditions. They indicated that natural cores contain clays adsorbed more fuel and metallic additive promoted the reactions. Drici and Vossoughi (1985) studied the effect of surface area on combustion by using DSC and TGA. They investigated this effect by using a variety of material such clays, silica, alumina as a porous media that their specific surface area changes between 24.3 and 30 cm^2/g. Their results showed that decreasing crude oil/surface area ratio promoted LTO reactions and increasing surface area cause a positive influence of heat generation which makes HTO shifted LTO. Besides, the samples with lower crude oil/surface area ratio have lower activation energies, which means that higher surface area enhanced the oxidation reactions. In their study, Vossoughi et al. (1985) also conducted in situ combustion tube tests in addition to DSC/TG analysis with grain sizes 210, 105, and 7.3-μm silica. They indicated that a minimum specific surface area should be determined for self-sustained combustion front propagation and combustion front could not self-sustained for 210-μm sand grain size. Abu-Khamsin et al. (1988) conducted several experiments with clay/oil mixtures under nitrogen flow at linearly increasing temperature by a reactor cell. Clay minerals promote the reactions, and the asphaltene fraction of crude oil was found to correlate with the fuel content of that oil. Mamora et al. (1993) used six types of analyses in addition to kinetic and combustion tube experiments and by using experimental data. From their results, they concluded that the existence of clays or fine sands increases surface area, and coke deposition on the solid matrix which may have resulted in higher residual oil saturation for HTO reactions. Kok et al. (1997) used high-pressure thermo-gravimetric analysis (HPTG) to investigate the oxidation of oil limestone mixtures under pressurized conditions for the simulation of ISC. They emphasized that LTO reaction rate is proportional to the specific surface area of the rock and during middle-temperature oxidation reaction, the coke is deposited as fuel. Later, Glatz et al. (2011) conducted both kinetic analysis with a reactor cell and combustion tube tests with 1190, 250, and 74-μm sand. They observed a barrier at LTO region due to the low surface area and increasing activation energies at HTO region which emphases that 1190-μm grain size was less favorable grain size for combustion. Pu et al. (2015) evaluated the effect of clays on combustion