Fuel 195 (2017) 299–313

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Scaling analysis of the In-Situ Upgrading of heavy oil and oil shale

Julien Maes [a,*], Ann H. Muggeridge [b], Matthew D. Jackson [b], Michel Quintard [c], Alexandre Lapene [d]

[a] Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom
[b] Department of Earth Sciences and Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom
[c] Université de Toulouse, INPT, UPS, Institut de Mécanique des Fluides de Toulouse, Allée Camille Soula, F-31400 Toulouse, France
[d] TOTAL E&P USA, 705 Forest avenue, Palo Alto, CA 94301, USA

ARTICLE INFO

Article history:
Received 23 November 2015
Received in revised form 17 January 2017
Accepted 19 January 2017
Available online 31 January 2017

Keywords:
In-Situ Upgrading
Heavy oil
Oil shale
Dimensionless numbers

ABSTRACT

The In-Situ Upgrading (ISU) of heavy oil and oil shale is investigated. We develop a mathematical model for the process and identify the full set of dimensionless numbers describing the model. We demonstrate that for a model with n_f fluid components (gas and oil), n_s solid components and k chemical reactions, the model was represented by $9 + k \times (3 + n_f + n_s - 2) + 8n_f + 2n_s$ dimensionless numbers. We calculated a range of values for each dimensionless numbers from a literature study. Then, we perform a sensitivity analysis using Design of Experiments (DOE) and Response Surface Methodology (RSM) to identify the primary parameters controlling the production time and energy efficiency of the process. The Damköhler numbers, quantifying the ratio of chemical reaction rate to heat conduction rate for each reaction, are found to be the most important parameters of the study. They depend mostly on the activation energy of the reactions and of the heaters temperature. The reduced reaction enthalpies are also important parameters and should be evaluated accurately. We show that for the two test cases considered in this paper, the Damköhler numbers needed to be at least 10 for the process to be efficient. We demonstrate the existence of an optimal heater temperature for the process and obtain a correlation that can be used to estimate it using the minimum of the Damköhler numbers of all reactions.

1. Introduction

Heavy oil and oil sands are important hydrocarbon resources that account for over 10 trillion barrels [1], nearly three times the volume of conventional oil in place in the world. Thermal EOR (Enhanced Oil Recovery) techniques are generally applied to very viscous heavy oil. In the Steam Assisted Gravity Drainage (SAGD) process, steam is injected from a well and forms a saturated zone. The steam flows to the perimeter of this vapour chamber from the wells and condenses. The heat is transferred by thermal conduction to the surrounding reservoir, the viscosity of the oil is reduced and so it flows, driven by gravity, to a horizontal production well below. SAGD was first introduced in the early 1980's by Butler and co-workers [2] and has been described and used in several pilots and commercial projects [3,4]. However, such a process comes with two main drawbacks; firstly, it require tremendous quantities of water, and secondly, the resulting hydrocarbons are still extra heavy oil/bitumen. Pipe transport of such viscous oil is challenging and refining on site is often required.

As an alternative, the process of In-Situ Upgrading (ISU) by subsurface pyrolysis has been applied in various pilot projects and laboratory experiments [5,6]. The idea behind ISU is to use subsurface electrical heaters to bring the formation to a high temperature of about 350 °C. At this temperature, the long chain hydrocarbon structures that mostly compose bitumen decompose through a series of chemical reactions of pyrolysis and cracking. Initially, this will occur in a zone near the heat source. As the heat propagates through the formation, initially by thermal conduction, a reaction zone propagates following the heat front. The pressure in the heated domain increases due to thermal expansion and creation of lighter products and the fluids flow toward the production well. This fluid transport also enables further heat transfer via convection. As the heat continue to propagate in the domain, more bitumen is converted and more hydrocarbons are produced.

During an ISU process, the undesirable products of the pyrolysis such as coke are left in the rock formation because the upgrading takes place in the reservoir. The main product of the upgrading is formed of molecules of lower molecular weight (typically lower than C30) that become volatile at modest temperatures. In addition, the viscosity of the oil phase is reduced by both the temperature and the conversion, unlike simple temperature-led

* Corresponding author.
E-mail address: julien.maes@pet.hw.ac.uk (J. Maes).

http://dx.doi.org/10.1016/j.fuel.2017.01.072
0016-2361/

Nomenclature

Variables

A	pre-exponential factor (s^{-1})
a	mass stoechiometric coefficient (no unit)
A_c	acentric factor (no unit)
C	mole concentration (mol/m^3)
c	compressibility (1/Pa)
D	depth (no unit)
E_a	activation energy (J/mol)
e	thermal expansion (1/K)
g	gravity constant (9.81 m/s^2)
h	specific enthalpy (J/kg)
K	absolute permeability (m^2)
L	domain length (m)
m_w	molecular weight (kg/mol)
P	pressure (Pa)
P_c	critical pressure (Pa)
R	universal gas constant (8.314 J/mol/K)
r	reaction rate ($kg/m^3/s$)
S	saturation (no unit)
T	temperature (K)
t	time (s)
T_c	critical temperature (K)
T_H	heater temperature (K)
u	specific energy (J/kg)
v	velocity (m/s)
α	permeability function parameter
Δh_r	reaction enthalpy (J/kg)
γ	specific heat capacity (J/kg/K)
κ	thermal conductivity (W/m/K)
μ	viscosity (Pa s)
ω	mass fraction (no unit)
ϕ	rock porosity (no unit)
ρ	mass density (kg/m^3)
τ	time scale of heat conduction in domain (s)

Subscript

0	initial value
g	gas phase
o	oil phase
r	inert rock
s	solid phase

viscosity reduction observed in standard SAGD processes [7]. As a result, the efficiency of the process, estimated by the Energy Return Over Investment (EROI) ratio, is potentially large compared to SAGD. Moreover, no water is used at the recovery stage, so using ISU can reduce costs by reducing the amount of infrastructure required on site for separation and treatment of the produced oil prior to transportation.

ISU can also be applied to oil shale reservoirs. Kerogen, the organic matter contained in oil shales is similar to the organic matter of source rocks that transform to petroleum fluids through geological time [8]. In oil shales, the natural maturation process, which would eventually lead to oil and gas, is at a very early stage and may still require millions of years and deeper burial. This process can be accelerated through ISU [9]. The initial decomposition of kerogen gives an asphaltene-rich heavy oil which then pyrolyses further in a manner very similar to heavy oil upgrading. The main differences between heavy oil and oil shale upgrading are that (1) the primary reactant for oil shales is solid rather than very viscous liquid and (2) unlike oil sands, oil shales initially have a very low permeability. During the initial stages of pyrolysis the reaction products are trapped in pores within the solid, resulting in an increase of pressure in the heated domain. However, as more of the solid decomposes, these pores become interconnected and the liquid and/or gas can flow away from the reaction zone and to the producer well.

The ISU process generally uses horizontal [10] or tightly spaced vertical electrical heaters [5] to slowly and uniformly heat the formation by thermal conduction to the conversion temperature. Fig. 1 shows the well pattern for the Mahogany Field Experiment, which is a part of Shell's Colorado field pilot [5]. For these experiments, the distance between two wells varied from 2 ft ($\simeq$ 0.6 m) to 30 ft ($\simeq$ 9 m).

Thermal cracking of extra-heavy oil and oil shale can be described by a compositional kinetic model. One such model for oil shale pyrolysis was developed by Braun and Burnham [11] for oil shale pyrolysis. It contains 83 species and 100 reactions. Fan et al. [12] present an adapted kinetic model that includes three hydrocarbon components and five chemical reactions. For this, they modified the previous model to eliminate water and prechar, and they performed a component-lumping process to map the hydrocarbon species to three lumped pseudo-components. For

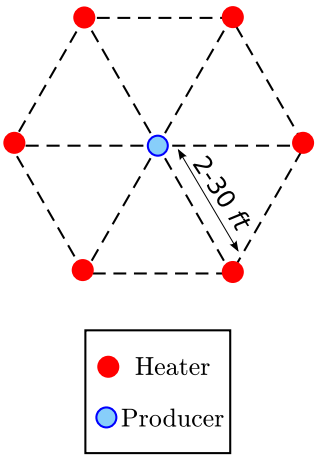

Fig. 1. Top view of well pattern for the in situ upgrading process, Mahogany field experiment (figure from [5]).

bitumen pyrolysis, Behar et al. [13] developed a kinetic model that contains 11 lumped chemical classes and 32 reactions.

The outcome of the ISU process depends on a large number of physical parameters, the values of which are usually uncertain. For example, the calibration of kinetic models from laboratory to reservoir condition is often challenging [13]. Scaling using dimensionless numbers can provide useful insight into the relative importance of different parameters and physical processes. Design of Experiment (DOE) [14] allows quantification of the impact of the dimensionless parameters with a minimal amount of computation. Dimensionless numbers are often used to scale laboratory results to the application length scale and conditions, and may be developed using techniques such as Dimensional Analysis (DA) [15] and Inspectional Analysis (IA) [16]. Ranking the different parameters controlling a given thermal decomposition application enables experimental programs to be focused on acquiring the relevant data with the appropriate accuracy.

This paper has four objectives: (1) to present a set of dimensionless numbers that describes the ISU process, (2) to demonstrate the importance of using accurate activation energies, (3) to