Journal of Petroleum Science and Engineering 106 (2013) 46–61

Contents lists available at SciVerse ScienceDirect

Journal of Petroleum Science and Engineering

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

Numerical analysis of a one-dimensional multicomponent model of the in-situ combustion process

I.A. Nesterov [a,*], A.A. Shapiro [a], E.H. Stenby [b]

[a] CERE—Center for Energy Resources Engineering, Department of Chemical and Biochemical Engineering, Technical University of Denmark, DTU Building 229, 2800 Kgs. Lyngby, Denmark

[b] CERE—Center for Energy Resources Engineering, Department of Chemistry, Technical University of Denmark, DTU Building 206, 2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 27 April 2012
Accepted 19 March 2013
Available online 9 April 2013

Keywords:
in-situ combustion
numerical model
heavy oil
multicomponent mixture
oxidation reactions

ABSTRACT

An advanced numerical model for the in-situ combustion process is developed and studied in detail. The model is based on further extension and modification of the virtual kinetic cell (VKC) and virtual combustion tube (VCT) developed by Kristensen et al. (2007) and Kristensen (2008). Moreover, the model is based on SARA representation of a petroleum mixture (saturates–aromatics–resins–asphaltenes), which may react differently with oxygen and produce other components (for example, light oils and coke). In total, the model contains 14 components, which may undergo 15 chemical reactions. The set of reactions in the original model of M.R. Kristensen has been modified in order to account for secondary combustion of the light oil fraction. The results of the model implementation are applied to the four heavy oil systems and qualitatively compared to the results of previous experimental studies. A new parameter, the critical ignition saturation, is introduced, in order to describe the easiness of oil ignition. Its dependence on the different parameters of the oil mixture and injection gas is studied. The conclusions on the processes governing the ignition of oil in the presence of water are made. A parameter which affects most the possibility of ignition is the activation energy of the light fraction of the oil.

1. Introduction

In-situ combustion (ISC) is an enhanced oil recovery technique in which oxygen-containing gas mixture is injected into the reservoir in order to start the combustion process (Green and Willhite, 1998). High temperatures at the combustion front zone make oil less viscous, decomposition (cracking) of the heavy oil molecules may be observed, and its displacement may be forced by the combustion gases. The ISC process is known from the beginning of the 20th century with the first field pilots built at the early 30th pilot (Turta et al., 2007). ISC can be applied to a wide range of petroleum mixtures, especially, very heavy and viscous (9° API and over 5000 cP, as reported by Hincapie et al., 2011).

In view of the complexity of the ISC process, its study is still ongoing, in spite of a large history of application. The different mechanisms behind ISC are studied in order to be able to verify the applicability of the method under different conditions. A number of experimental works have been published in recent years studying various aspects of in-situ combustion like behavior of the system at various gas and water saturations (Hasçakir et al., 2011), kinetic studies (Cinar et al., 2008; Glatz et al., 2011; Mamora, 1995), the effect of the system geometry (Alamatsaz et al., 2011) and other (Bazargan et al., 2011; Castanier and Bringham, 2003).

The current study is based on the models developed in the works of M.R. Kristensen with co-authors: The virtual kinetic cell (VKC) and the virtual combustion tube (VCT). The numerical simulators have been described by M.R. Kristensen in his Ph.D. thesis (2008) (see also Kristensen et al., 2007). The VKC is, essentially, a zero-dimensional reaction cell where, under the conditions of ideal mixing, simultaneous multiple reactions occur in three phases: water, oil, and gas. The cell exchanges heat and substance with the environment. A one-dimensional chain of virtual combustion cells forms a virtual combustion tube. The mass transfer functions between the cells in the VCT are proportional to three-phase relative permeabilities, so that the whole VCT represents a numerical discretization scheme for a model of the one-dimensional multicomponent multiphase reactive flow in a porous medium. This scheme (a variation of the method of lines) is relatively simple, numerically efficient and makes it possible to model a large number of reactions and phase equilibria in a relatively short time.

In the present work the original VCT model by M.R. Kristensen was modified in the following ways. The set of reactions was

* Corresponding author. Tel.: +45 452 52864.
E-mail addresses: igne@kt.dtu.dk (I.A. Nesterov), ash@kt.dtu.dk (A.A. Shapiro), ehs@kt.dtu.dk (E.H. Stenby).

0920-4105/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.petrol.2013.03.022

extended in order to account for the combustion of the secondary light oil fraction. A more advanced model for three-phase permeabilities (Delshad and Pope, 1989) was applied, after testing several other models. This made it possible to make a model more physically consistent and to study in detail its physical and practical implications. In particular, it has been found that our model reproduces qualitatively most of the experimentally observed phenomena.

ISC is a complex process, behavior of which is determined by many governing parameters. For engineering purposes, it is desirable to introduce a single parameter characterizing the possibility of ignition and subsequent combustion. This parameter should to some extent be similar to the minimum miscibility pressure (MMP) or maximum miscibility enhancement used for characterization of the miscible gas injection (Green and Willhite, 1998). In this work, we propose to use the critical ignition saturation as such a parameter: the maximum water saturation, for which ignition is possible. Roughly speaking, we determine "the minimum amount of water needed to extinguish the fire". This parameter turns out to be rather sensitive to the combustion behavior of a particular mixture. Its study makes it possible to analyze the roles of activation energies and mixture composition in the ignition process, where a component with the lowest activation energy turns out to play the most important role. It is also found that products of low-temperature oxidation affect the ignition process. The influence of other parameters (like temperature or enrichment of the injected air) is also studied.

The study is carried out on the basis of four oil mixtures, which composition is reported in the literature. The study makes it possible to select the most important and influential parameters for evaluation of ISC applicability under particular reservoir conditions.

2. Virtual combustion tube

2.1. General model

The virtual combustion tube (VCT), in-situ combustion simulator, was developed by Kristensen (2008). The aim of this approach is to simulate the behavior of the system containing three mobile phases — oil, water and gas — and one immobile solid phase which represents the solid combustion products within the tube of chemically inert porous medium (rock). This model includes a description of reactions taking place during the combustion process, and the mass and heat transfer through the tube. To model these processes the whole system is divided into a set of consecutive cells, so that a description of chemical reactions and phase transitions within each cell and of the intercell fluid transport is available.

The following set of assumptions was adopted for the modeling (Kristensen, 2008):

1. The VCT is represented by a one-dimensional Cartesian grid of 100 cells of uniform volume (as proposed by Kristensen, 2008).
2. The tube is placed horizontally. No gravity contribution assumed.
3. Temperature, pressure and chemical composition are assumed to be uniform at every cell at each time step.
4. Oil, water and gas phases in every cell are in equilibrium conditions.
5. Oil and water are immiscible.
6. Porous medium is not affected by deposition of solids.
7. Gas mixture is injected through a single injection well ("injection side" of the tube); the injected gas composition and the injection flow rate are uniform throughout the simulation.
8. System components are produced through a single production well ("production side" of the tube).

The VKT represents a discretization scheme for the system of 1D balance equations:

1. Component balance:

$$\frac{\partial C_i}{\partial t}+\frac{\partial q_{m,i}}{\partial x}=Q_i^{m,reac}\ \ (i=1,\ldots,n),$$

where C_i is the total concentration of component i;q_i^m the mass flux, and$Q_i^{m,\,reac}$ the mass source density due to chemical reactions.

2. Energy conservation equation:

$$\frac{\partial U}{\partial t}+\frac{\partial}{\partial x}(q^{h,adv}+q^{h,cond})=Q^{h,reac},$$

where U is the total internal energy of the system, $\mathbf{q}^{h,adv}$and $\mathbf{q}^{h,cond}$ are the heat transport due to advection and conduction, respectively, and $Q^{h,\,reac}$ is the heat source density due to chemical reactions.

The boundary conditions for this system are given initial concentrations and injection flow rates for each component at the injection boundary of the VCT.

Discretization of the system corresponding to representation of the VCT as a system of virtual kinetic cells exchanging the matter and energy according to the transfer functions is connected with relative permeabilities. The system of differential equations is solved by the fully coupled implicit method. The reader is referred to the work of Kristensen (2008) for details.

The closing relations for the system depend on phase equilibria, reaction and mass transfer models. They are described in the following.

2.2. Phase equilibria

In the current study an approach is adopted which is based upon the K-values of all the oil pseudocomponents tabulated by pressure and temperature from the negative flash routine using the PR equation of state (see Kristensen, 2008).

For non-hyrocarbon components the following equation was used:

$$K_i=\frac{K_{v1}}{P}e^{K_{v4}/T-K_{v5}}$$

with constantsK_{v1},K_{v4}, K_{v5} to calculate the value of K_i at given temperature (T) and pressure (P).

K-values for hydrocarbon compounds are calculated using Wilson's correlation and component constants as critical pressure(P_{c_i}), temperature (T_{c_i}) and acentric factor (ω_i). All these parameters are presented in Table 1:

$$K_i=exp\left(ln\left(\frac{P_{c_i}}{P}\right)+5.373(1+\omega_i)\left(1-\frac{T_{c_i}}{T}\right)\right)$$

2.3. Reaction model

The SARA-based reaction model for oil combustion is chosen for the simulations. The following set of (pseudo) components and reactions is used in the current work:

Components:

1. Inorganic substances: water (H_2O), oxygen (O_2), nitrogen (N_2), carbon dioxide (CO_2).
2. Oil SARA fractions: saturates (Sat), aromatics (Arom), resins (Resins), asphaltenes (Asph).
3. Additional oil fractions: inert oil (InertOil), light ends (Lites).
4. Products of low-temperature oxidation of oil fractions: saturates' oxidation products (OxdSat), oxidized resins and aromatics (OxdResAr), oxidized asphaltenes (OxdAsph).