



# Fully implicit compositional simulator for modeling of asphaltene deposition during natural depletion



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## ABSTRACT

This paper describes development of a fully implicit compositional simulator for modeling of asphaltene deposition during natural depletion. In this paper, a new approach for multiphase flash calculation has been developed. This approach provides a more detailed description of the kinetic part of asphaltene deposition which needs to be explained more clearly. Due to a large number of unknowns, there are many ways to solve such a system by choosing different sets of independent variables. A new set of independent variables in a fully implicit model is considered for asphaltene deposition modeling. By incorporating an asphaltene precipitation model into a compositional simulator where the phase equilibrium equations, the volumetric constraint equation, the component transport equations, the multiphase flash equations and the deposition equation are solved simultaneously; a simulator for asphaltene deposition was developed with respect to natural depletion. The pure solid model is used to model asphaltene precipitation. The solid particles are considered to be separated into three parts: precipitated, flocculated and deposited solid. A first-order chemical reaction is used which models forward and reverse rates for the conversion of precipitated asphaltene to flocculated asphaltene. Also, a deposition model including adsorption, pore throat plugging, and re-entrainment was used. The simulator can also predict formation damage including porosity and permeability reduction in each block.

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## 1. Introduction

Asphaltene deposition phenomena in the oil reservoir during natural depletion is a complex and destructive problem which the most of the oil field reservoir, production and/or process facilities is encountered with. Wettability alterations, relative permeability reduction, blockage of the flow with additional pressure drop in wellbore tubing, upstream process facilities and surface pipelines are the common problems which are created from asphaltene deposition [1]. By having a good prediction of location and amount of asphaltene precipitation and deposition, oil field operators will be able to design an efficient operation process to avoid the risks associated with asphaltene deposition [2].

Various thermodynamic models have been presented to model the phase behavior of asphaltene precipitation. The liquid solubility models, the pure solid models, the colloidal solution models and a thermodynamic micellization model are the four main groups of thermodynamic models which are available in the literature.

The liquid solubility models are based on polymer solution theories by Flory–Huggins [3]. The first of such a model was developed by Hirshberg et al. [4]. According to this model, asphaltene stability is described in terms of reversible solution equilibrium.

In the solid models, EOS is applied to solid oil and gas phases and asphaltene is considered as a single dense phase. Nghiem et al. [5] and Chung [6] applied the solid model approach to simulate phase behavior of asphaltene precipitation.

In 1987, Leontaritis and Mansoori [7] established a thermodynamic colloidal model to simulate phase behavior of asphaltene precipitation. This method assumes that asphaltene can be found in the oil as colloidal particles peptized by resins.

The thermodynamic micellization model was initially developed by Pan and Firoozabadi [8,9]. It assumes that asphaltene micelle is stabilized by resin molecules. Minimization of the total Gibbs energy is the basis of this approach to determine the structure and concentration of the micelle [10].

Even though none of these models satisfactorily match the experimental data, some are simple and fast and have been implemented in reservoir simulators [11,12]. The solid models have been widely used in the reservoir simulators due to the flexibility and simple application [13]. In addition, the main aim of this research is to develop an EOS compositional simulator. Thus, a

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### Nomenclature

$A$	Gridblock cross-sectional area (ft <sup>2</sup> )
$C_{s_1o}$	Concentration of suspended solid $s_1$ in oil phase (lb mole/ft <sup>3</sup> )
$C_{s_2o}$	Concentration of suspended solid $s_2$ in oil phase (lb mole/ft <sup>3</sup> )
$C_{s_2}^f$	Volumetric concentration of flowing solid $s_2$ per volume of oil
$f_{ig}$	Fugacity of component $i$ in gas phase (psi)
$f_{io}$	Fugacity of component $i$ in oil phase (psi)
$f_{n_{c,o}}$	Fugacity of asphaltene component in oil phase (psi)
$f_{s_1}^*$	Reference solid fugacity (psi)
$f_{s_1}$	Fugacity of solid $s_1$ (psi)
$K_i$	Equilibrium ratio of component $i$
$K_{ig}$	Gas–oil equilibrium ratio of component $i$
$K_{rk}$	Relative permeability of phase $k$
$K_{n_c}$	Solid–oil equilibrium ratio for component $n_c$
$K_0$	Original permeability before asphaltene precipitation (md)
$K$	Absolute or instantaneous permeability (md)
$K_{12}$	Forward rate of formation of solid $S_2$ from solid $S_1$ (1/day)
$K_{21}$	Reverse rate of formation of solid $S_1$ from solid $S_2$ (1/day)
$L_g$	Mole fraction of gas phase
$L_s$	Mole fraction of solid phase
$n_b$	Total number of gridcells
$n_c$	Number of hydrocarbon components
$N_i$	Moles of component $i$ per pore volume (lb mole/ft <sup>3</sup> )
$N_T$	Total number of moles per pore volume (lb mole/ft <sup>3</sup> )
$N_T^*$	Total number of moles without flocculated solid and deposited solid per pore volume (lb mole/ft <sup>3</sup> )
$N_{s_1}$	Moles of solid $s_1$ per pore volume (lb mole/ft <sup>3</sup> )
$N_{s_2}$	Moles of solid $s_2$ per pore volume (lb mole/ft <sup>3</sup> )
$N_{s_3}$	Moles of deposited solid per pore volume (lb mole/ft <sup>3</sup> )
$s_1$	Solid phase which is in equilibrium with oil and gas phases
$s_2$	Solid phase created from solid $s_1$ via a chemical reaction
$s_3$	Solid phase created from solid $s_2$ via a deposition equation
$T_k$	Transmissibility of phase $k$ ( $k = o, g$ )
$u_o$	Oil phase Darcy velocity (ft/day)
$v_o$	Oil phase interstitial velocity (ft/day)
$v_s$	Solid molar volume (ft <sup>3</sup> /lb mole)
$V$	Gridblock volume (ft <sup>3</sup> )
$V_{cr,o}$	Critical oil phase interstitial velocity (ft/day)
$V_{s_2}^d$	Volume of deposited solid $s_2$ per gridblock volume
$W_{exp}$	Experimental results of weight percent of precipitated asphaltene
$W_{model}$	Calculated results of weight percent of precipitated asphaltene
$y_{ik}$	Mole fraction of component $i$ in phase $k$ ( $k = o, g$ )
$y_{sj}$	Mole fraction of suspended solid in oil phase ( $j = 1, 2$ )
$z_i$	Global mole fraction of component $i$ in feed
$\varphi_{ij}$	Fugacity coefficient of component $i$ in phase $j$
$\alpha$	Surface deposition rate coefficient (day <sup>-1</sup> )
$\beta$	Entrainment rate coefficient (ft <sup>-1</sup> )
$\gamma$	Pore throat plugging rate coefficient (ft <sup>-1</sup> )
$\xi_k$	Molar density of phase $k$ ( $k = o, g$ ) (lb mole/ft <sup>3</sup> )
$\mu_k$	Viscosity of phase $k$ ( $k = o, g$ ) (cP)
$\gamma_k$	Gradient of phase $k$ ( $k = o, g$ )
$\Delta l$	Gridblock distance (ft)

thermodynamic model must be used to be compatible with flash calculation in an EOS simulator. Considering these reasons, the solid model is used for the modeling of asphaltene precipitation.

The pure solid model has been enhanced by allowing the precipitated asphaltene to be converted to larger flocculated particles according to a simple chemical reaction. The use of forward and backward reaction rates allows this conversion to be specified as fully irreversible, fully reversible or partially reversible [14].

A few models have been proposed to describe asphaltene deposition. Leontaritis [15] presented the first model to predict asphaltene deposition in the near wellbore region with the assumption of constant production rate. It was assumed that asphaltene deposition occurs only around the wellbore vicinity and the area of formation damage caused by asphaltene deposition was constant [16]. Nghiem et al.'s model [17] assumes that the asphaltene deposition is a pure adsorption process. The surface deposition, pore throat plugging and deposit entrainment were observed in asphaltene deposition rather than adsorption [18]. Nghiem's model was criticized for ignoring deposition in the pore space which was considered to be an important factor. The surface deposition, pore throat plugging and entrainment were presented in Wang's deposition model [19]. It was assumed that asphaltene can deposit everywhere rather than the near wellbore region.

In this work pure solid model is used to model asphaltene precipitation [20,21]. A first-order chemical reaction was employed to model forward and reverse rates for the conversion of precipitated asphaltene to flocculated asphaltene. Also, a deposition model including adsorption, pore throat plugging, and re-entrainment is used. The reduction in the rock porosity and permeability are also included in the asphaltene model [22].

This paper talks about developing new method to calculate asphaltene precipitation through thermodynamics point of view. Also, the details of dynamic aspect of asphaltene precipitation which needs to be explained more clearly are described. The implementation of an asphaltene thermodynamic model into a fully implicit, multiphase, compositional simulator was the challenging part of this research. A new set of independent unknowns in a fully implicit scheme was presented for asphaltene deposition modeling. In order to find the solution of these variables, the same number of equations was also presented. The mathematical formulation for the derivatives of the governing equations for building the Jacobian matrix and the residuals of the governing equations are described. In addition, the techniques used to implement formulations in Matlab code are described. The asphaltene precipitation model in Matlab code was compared to CMG's compositional simulator, called GEM.

## 2. Asphaltene precipitation model

The asphaltene precipitation, flocculation and deposition models used in the simulator are discussed in detail in this paper.  $S_1$ ,  $S_2$  and  $S_3$  represent asphaltene precipitation, flocculation and deposition, respectively. Kohse and Nghiem proposed a model which assumes the heaviest component of oil can be splitted into a non-precipitating and precipitating component [14]. The precipitated solid is divided into solid 1 which is in equilibrium with the heaviest component in the oil phase and solid 2 that is created from solid 1 via first order chemical reaction. Solid 2 can be used to represent the flocculation of smaller precipitated asphaltene particles into larger aggregates. This process is modeled by a set of two kinetic reactions to allow reversibility between aggregation of the fines into flocs and dissociation of the flocs into fines. Once the asphaltene component becomes flocs they are available to deposit onto the rock. Solid 1 flows as suspended particles in the oil phase, while solid 2 may flow with the oil or deposit in the rock

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