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State-of-the-art adaptive mesh generator implementation for dynamic asphaltene deposition in four-phase flow simulator in near well-bore region

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ABSTRACT

Asphaltene deposition leads to rigorous problems in petroleum industry such as relative permeability reduction, wettability alterations, and blockage of the flow with additional pressure drop in wellbore tubing, *etc*. Many attempts have been undertaken to develop reliable and accurate models to predict phase behavior of asphaltene. However, previously published models cannot couple static and dynamic behaviors of reservoir and its fluids. In this communication, a novel four-phase flow simulator has been developed considering asphaltene deposition as one of the phases, using finite volume formulation. A novel adaptive unstructured mesh generator technique has been introduced in which dynamic properties of reservoir are combined with static field parameters. The results of this study illustrated that the proposed methodology can accurately predict the oil sample properties, and the amount of asphaltene precipitation. Moreover, it was found that the proposed approach is faster and computationally less expensive compared to fine structured model. The proposed strategy can be applied in any reservoir simulator and provides asphaltene phase behavior and reservoir properties with high degree of accuracy.

1. Introduction

Crude oil is a mixture of hydrocarbons, organic compounds of nitrogen, sulfur, and oxygen as well as compounds containing metallic elements. From a physicochemical point of view, crude oil is categorized into four main fractions, namely saturates, aromatics, resins, and asphaltene. Among these fractions, asphaltene is known as the most sophisticated one which alone contains around 100,000 different molecules. It is insoluble in normal alkanes such as heptanes and pentane, while it is soluble in some aromatic solvents, for instance, toluene and benzene. Variations in pressure, temperature, and composition of the crude oil may cause asphaltene to precipitate out of the solution [1–3]. Amount of precipitated asphaltene may deposit on porous media due of electrostatic forces existing between rock and fluid. Asphaltene deposition is one of the most significant problems affecting well bore region and causes relative permeability reduction, wettability alteration, and blockage of the flow with additional pressure drop in surface pipelines and upstream process. Owning to the aforementioned problems associated with the asphaltene deposition, accurate prediction of asphaltene precipitation and deposition has been the subject of many experimental and theoretical studies [4,5].

Bolouri and Ghoodjani [3] studied permeability alteration during asphaltene deposition and obtained entrainment and deposition coefficients in square mass model. In previous studies, a linear behavior for asphaltene deposition was reported. However, this approach leads to more flexible behavior for predicting asphaltene prediction. They also investigated the experimental results of CO_2 injection tests including the three mechanisms of adsorption, entrainment and mechanical sweeping and studied on the effects of these parameters on permeability reduction. Recently, Kamari et al. [6,7] represented a new approach to predict the minimum miscibility pressure in both pure and impure CO_2–oil as well as the onset of the asphaltene precipitation and saturation pressure

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Nomenclature

∇p	pressure gradient
ρ_α	density of the component α
μ_α	viscosity
u_α	volumetric velocity
B_α	formation volume factor
$k_{r\alpha}$	relative permeability of phase α
P_{COW}	capillary pressure of oil and water
$Q_{w,k}$	volumetric flow rate
ϕ_0	initial porosity
λ	mobility for each phase
ϕ	system porosity
β	non-Darcy flow coefficient (Eq. (10))
α	surface deposition rate constant
β	entrainment of deposits constant
γ	pore throat plugging rate constant
u	velocity
C_A	volume fraction of the precipitated asphaltene
D	depth function
E_A	volume fraction of deposited asphaltene
e_{ij}	boundary
F	non-Darcy flow parameter
P	pressure
$P_b$bubble point pressure	bubble point pressure
P_{bh}bottom hole pressure	bottom hole pressure
S_a	applied element size map (Eq. (9))
S_d	desired element size map (Eq. (9))
S_α	saturation of the phase α
WI	well index
x_e	exit coordinate system positions in x direction
x_i	inlet coordinate system positions in x direction
x_o	local coordinate system positions in x direction
v_{cr}	critical value of oil interstitial velocity
v_l	interstitial velocity of oil

in live oil systems. He also developed the least square modification of support vector machine (LSSVM) methodology to evaluate unloading gradient pressure in gas-lift systems [8]. It is worthwhile to mention that the proposed approach is applicable to determine the air specific heat ratios at elevated pressures [8].

Garrouch and Al-Ruhaimani [9] developed a relationship for asphaltene deposition during primary steps of the process. This model was developed based on mass balance equation and applied for predicting the permeability alteration in all types of reservoirs. The developed model, accounts for position and time in the porous media. This model is applicable for homogenous and heterogeneous reservoirs; however, it is just limited to one-dimensional and one-phase flow. Nghiem et al. [10] developed a compositional simulator using thermodynamic model of Nghiem et al. [11]. In this approach, the heaviest component was divided into precipitating and non-precipitating components. This method was able to make predictions for the experimental as well as industrial data. However, application of the adjustable parameters limited the applicability of the proposed model. He also developed an algorithm for three-phase flash calculations. Qin et al. [12] also applied the stated thermodynamic model in compositional simulator of University of Texas to correlate the medium permeability with its porosity by means of scaling laws [13]. He effectively combined the developed precipitation model to flow equations. The proposed algorithm for asphaltene precipitation was in good agreement with other simulators with significant reduction in computational time. Recently, Soulgani [14] combined thermodynamic and hydrodynamic models through the well column for prediction of asphaltene precipitation. The proposed model was applied in predicting the amount of asphaltene precipitation in the well bore. Monteagudo [15] combined network and macroscopic models for the first time in order to predict changes in fluid flow due to asphaltene deposition. Jamialahmadi [16] focused on asphaltene precipitation and deposition on production facilities. Kord et al. [17] considered the surface deposition mechanisms of asphaltene using a modified analytical model. Ju et al. [18] survived the effect of this phenomenon on enhanced oil recovery. Using all of the above mentioned methods lead to progress in asphaltene deposition studies; however, these conventional approaches are mostly developed in finite difference approach in which there is no flexibility in mesh structure. This means losing the advantage of detailed studying of fractured reservoirs and near well bore region as well as the criteria for high flow region in the reservoir. Using unstructured mesh based on finite element or finite volume discretization techniques introduces flexibility in computation process as well as some additional efforts due to management of the mesh quality and computational overheads.

In this study, firstly, deterministic parameters for the reservoir, such as permeability distribution, location of active wells, and flow trajectory, are introduced. Afterward, these parameters are applied for generating background grid, which subsequently leads to eliminating the computational complications of solving the flow equations. This method involves precisely studying static and dynamic characteristics of the reservoir. Static properties of the reservoir include permeability distribution and location of active wells which are important parameters in detailed characterization of the reservoir [19,20]. Coupling the parameters of well locus and permeability distribution as static features and flow trajectory in the reservoir with updating during simulation time generated a reliable background grid. Then, Green and Sibson algorithm was applied to develop a robust algorithm for creating a mesh for dynamic reservoir simulation. The developed mesh was applied in four-phase flow modeling. Thermodynamic and precipitation models were combined in order to compute the deposited amount of asphaltene in black-oil simulator. Asphaltene deposition in near well bore region was modeled using Almehaideb [21] method, while Wang and Civan model was applied for modeling asphaltene deposition in other parts of the reservoir.

2. Model development

2.1. Developing PVT package

The measured pressure–volume–temperature (PVT) data of Dorud field including crude oil composition, differential liberation (DL), and constant composition expansion (CCE) test results are summarized in Tables 1–4. In the developed PVT package, there is no limitation on the number of regression variables, while most of PVT simulators such as PVTsim are limited to maximum 15 regression variables for tuning the plus fraction characteristics. The following parameters were tuned to obtain the most reliable results:

- Binary interaction parameters between CO_2 and hydrocarbons
- Volume shift parameters for all components and pseudo-components
- Molecular weights of pseudo-components