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Three-dimensional streamline-based simulation of non-isothermal two-phase flow in heterogeneous porous media

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ABSTRACT

Streamline-based simulation is extended to simulate non-isothermal two-phase flow of hot water injection in three-dimensional (3D) realistic field-scale reservoirs containing heavy oil. First the pressure equation is solved on the 3D Eulerian grid for a global time-step and the total velocity is calculated at cell faces. Then the streamlines are traced from injector wells to producers, implementing a semi-analytical method and the time-of-flight (TOF) is computed over the streamlines. The mass and energy transport equations are mapped onto streamlines using the TOF as the distance variable. The advective part of the transport equations are solved along the streamlines. The saturation and temperature are calculated in the TOF domain until the end of the global time-step and then mapped back to the 3D grid. The effects of gravity and heat conduction are included by an operator splitting technique, at the end of each global time-step.

A 2D petroleum reservoir model without gravity is tested to show the feasibility of the method. To further test the approach, a 3D heterogeneous model with a fine grid and multiple wells is simulated, and the results are compared with those of a commercial grid-based thermal simulator. The predicted saturation distribution, temperature and oil production at the wells are in good agreement with the commercial code; furthermore the streamline technique is significantly faster while generating results similar to those obtained using a conventional method that has a finer grid. We conclude that the streamline method can simulate non-isothermal two-phase flow of water–oil in heterogeneous porous media accurately with lower cost and better performance than grid-based approaches.

1. Introduction

Modeling of multiphase flow in porous media is crucial to solve many engineering problems such as petroleum reservoir simulation to access and manage energy resources [1–3], maintaining secure clean water supplies, CO_2 sequestration to alleviate global warming [4,5] and designing fuel cells [6].

Petroleum reservoir simulation is an essential tool to be employed for enhanced oil recovery (EOR) projects that increase the amount of oil that can be extracted from a hydrocarbon reservoir. Thermal EOR techniques have been extensively used for displacement of heavy oil in petroleum reservoirs. Among different EOR approaches, thermal methods are often effective and offer a successful process for about 70% of the world's tertiary production [7]. Hot waterflooding, steamflooding, in-situ combustion and wet combustion are the different thermal EOR techniques and between them, waterflooding and steamflooding approaches have received the most attention. Injection of hot fluid reduces the oil viscosity and causes an increase in the mobility of oil that improves the reservoir recovery [7].

The governing fluid and heat transport equations used to model thermal recovery processes are highly nonlinear. As fluid properties are defined as a function of temperature and pressure, there is a strong coupling between the mass balance and energy balance equations. Traditionally, a fully implicit numerical method is used for non-isothermal recovery processes [8]. This method is stable and can use larger time-steps in comparison with an explicit IMPES method. However, a large non-linear system of energy and mass

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conservation equations has to be solved for each time-step, using an iterative procedure. The computational cost can be excessively high or even impossible for the simulation of realistic field-scale models with a fine geological grid, combined with sensitivity analysis, optimization or history matching [9].

Batycky et al. [10] proposed a streamline-based simulation technique, in which a 3D fluid flow problem is decoupled into multiple 1D problems along streamlines. This numerical method is compatible with the physics of fluid flow, as fluids move along streamlines, in contrast of common numerical methods, in which fluids move between discrete grid-blocks. Streamline-based simulation can be far faster than common numerical methods for advection-dominated displacements [10,11]; moreover it can reduce the memory requirements. Computation of new valuable engineering data, flow visualization [12], rapid full field modeling on fine-scale geological models [10] and easy parallel processing potential [13] are some of its advantages over conventional grid-based techniques.

The streamline method has many applications in the petroleum industry. It is an appropriate tool for problems that require many simulations and has been used successfully in history matching and optimization [14–18]. This method can also be used for models with curvilinear, structured and unstructured girds [19–21]. Compositional displacement can also be simulated [22,23] including compressibility [24]. Other applications include polymer flooding [25], fractured reservoirs [26–30], API tracking for compressible flow with changes in oil composition [31], and carbon dioxide storage [4,32,33].

Recently a thermal streamline simulator for hot waterflooding has been developed and tested in 2D to model a simple ¼ five-spot model with one injector and one producing well [34]. Fluid flow in real, field-scale reservoirs with complicated heterogeneity distribution in different layers and multiple wells are far more complex than simple 2D models. In this study we use an in-house 3D streamline-based code described in [10,31,33], with the same formulation proposed in [34], and extend it to be used for simulation of thermal EOR in realistic field-scale geological models. Furthermore, we test it more extensively in 2D and 3D heterogeneous models with multiple wells, accounting for the effects of heat conduction and cross-flow due to gravity.

In this paper, two-phase non-isothermal flow of water and oil are simulated. Viscosity is defined as a function of temperature, while density is a function of both temperature and pressure. The pressure equation is solved on a 3D Eulerian grid by fixing the temperature and saturation over a global time-step. Then, the pressure is assumed to be constant over the global time-step and the saturation and energy conservation equations are solved simultaneously along streamlines, using an explicit method with local time-steps up to the end of the global time-step. Gravity and heat conduction effects are calculated separately at the end of each global time-step using operator splitting [35]. The simulator is tested to simulate hot waterflooding in the SPE-10 model [36] and the results are compared with a commercial grid-based thermal simulator, CMG-STARS [37].

In the following, first the governing equations are introduced for two-phase non-isothermal immiscible flow. Subsequently, the thermal streamline technique is explained. In Section 4, fluid properties and the reservoir model are presented. In Section 5, the method is used to simulate a 2D model and results are validated through comparison with the grid-based simulator. Then an upscaled model of the 3D SPE-10 model is employed and the simulator is tested to account for gravity effects. Finally the simulator is tested in a fine-grid SPE-10 model to investigate the effect of different parameters of streamline method on the accuracy and speed of simulator.

2. Governing equations

In this study, non-isothermal two-phase flow of oil–water is investigated and it is assumed that the phase pressures of water and oil are always higher than the bubble point pressure. In addition, it is assumed that water and oil are immiscible and their components are present just in their own phases. The capillarity effect is neglected for simplicity; hence the mass balance equation for water and oil phases can be presented as follows:

$$\frac{\partial(\phi\rho_w S_w)}{\partial t} + \nabla\cdot(\rho_w \mathbf{u}_w) = \dot{m}_w \tag{1}$$

$$\frac{\partial(\phi\rho_o S_o)}{\partial t} + \nabla\cdot(\rho_o \mathbf{u}_o) = \dot{m}_o \tag{2}$$

ϕ is the porosity and ρ_j, S_j and $\dot{m}_j$ represent the density, the saturation and the mass flow rate of phase j, respectively. $\mathbf{u}_j$ is the Darcy velocity of phase j defined as follows:

$$\mathbf{u}_j = -\mathbf{k}\frac{k_{rj}}{\mu_j}\cdot(\nabla P_j + \rho_j g \nabla D) \tag{3}$$

In Eq. (3), P_j is phase pressure, μ_j is viscosity of phase j, $\mathbf{k}$ is absolute permeability, k_{rj} is relative permeability of phase j and D is depth.

The porous medium is saturated with fluid and so:

$$S_w + S_o = 1 \tag{4}$$

Assuming that all fluid phases and rock are in thermal equilibrium and the kinetic energy is negligible, then the energy conservation equation to compute temperature is [8,38]:

$$\frac{\partial}{\partial t}\left(\phi\sum_{j=w,o}\rho_j S_j U_j + (1-\phi)\rho_r C_r T\right) + \nabla\cdot\left(\sum_{j=w,o}\rho_j \mathbf{u}_j H_j\right) - \nabla\cdot(k_T\nabla T) = q_H \tag{5}$$

U_j and H_j are specific internal energy and enthalpy per unit mass of phase j respectively; these are functions of the temperature. C_r and ρ_r are the specific heat capacity and density of rock respectively. k_T is total thermal conductivity, T is absolute temperature and q_H is heat source or sink.

Substituting the Darcy velocity (3) into the mass balance Eqs. (1) and (2), and then summing mass conservation equations of all phases, gives the following equation for pressure (see the Appendix).

$$\phi c_t\frac{\partial P}{\partial t} - \phi\alpha_t\frac{\partial T}{\partial t} - \frac{1}{\rho_w}\nabla\cdot(\rho_w\mathbf{u}_w) - \frac{1}{\rho_o}\nabla\cdot(\rho_o\mathbf{u}_o) = q_T \tag{6}$$

The total compressibility is defined by $c_t = c_w S_w + c_o S_o$ and the total thermal expansion coefficient is $\alpha_t = \alpha_w S_w + \alpha_o S_o$, where c_j and α_j are compressibility and thermal expansion coefficient of phase j respectively. It is assumed that rock is incompressible.

3. Streamline simulation

3.1. Streamline simulation framework

The principles of the streamline simulation can be described by representing the phase velocity of phase j in terms of the total velocity ($\mathbf{u}_t$) [38,39]:

$$\mathbf{u}_j = f_j\mathbf{u}_t + \mathbf{u}_{j,grav} + \mathbf{u}_{j,cap} \tag{7}$$

where f_j is the fractional flow of phase j, defined as $f_j = \lambda_j/\lambda_t$. $\mathbf{u}_{j,grav}$ and $\mathbf{u}_{j,cap}$ are velocity components due to gravity segregation and capillary effects, respectively. As depicted in Fig. 1, the phase velocity is composed of three components. The first term in Eq. (7) represents the advective contribution of flow that is computed along streamlines. The second term is the flow caused by gravity segregation and is accounted by solving conservation equations in direction