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Uncertainty assessment of Vapex performance in heterogeneous reservoirs using a semi-analytical proxy model

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ABSTRACT

While compositional simulators are available for modeling the recovery performance of Vapex process, computational constraints often preclude detailed numerical solution of the flow and transport differential equations, as implemented in traditional flow simulators, using an entire suite of geostatistical realizations that represent the uncertainty due to reservoir heterogeneity occurring at different scales. Proxy models that are based on analytical formulations provide efficient alternatives to expensive detailed flow simulations.

A novel semi-analytical proxy has been developed to model solvent transport in Vapex at isothermal conditions. Detailed analytical formulations were derived and implemented in a calculation procedure to advance the solvent–oil interface and estimate producing oil rate with time. A mass penetration parameter was formulated, and its change with time was tracked. Results obtained from the proxy were validated against experimental data available in the literatures as well as detailed compositional simulation studies (Shi and Leung, 2014a, 2014b). Later, a suite of geostatistical realizations are ranked based on their cumulative oil production using this proxy, and the results demonstrate good agreement with those based on detailed compositional simulations but with significant savings in computational costs. Finally, this proxy is employed to assess impacts of uncertainty in subscale heterogeneity.

An important contribution from this work is that process physics are built directly into this proxy; it represents an advantage over other alternative modeling approaches (i.e., regression) that are driven only by data. This proposed proxy can be easily integrated in existing reservoir management workflows to optimize production scenarios in a quick and robust manner. It can be applied to rank numerous geostatistical realizations and quickly identify a smaller, more manageable subset of realizations for further simulation analysis. It presents an important tool for assessing the uncertainty in reservoir properties on effective mass transfer and the ensuing recovery performance, as well as assisting decisions-making for future pilot and field development planning.

1. Introduction

Vapex (vapor extraction) is an in-situ non-thermal bitumen recovery process, which is analogous to the commonly adopted Steam-Assisted Gravity Drainage (SAGD) method (Butler and Mokrys, 1989). Vaporized hydrocarbon solvent is injected into the reservoir via a horizontal injection well, and the diluted low-viscosity oil is drained to the bottom production well by gravity. The key recovery mechanism is molecular diffusion enhanced by various spreading mechanisms such as velocity variations known as dispersion (Das and Butler, 1998; Boustani, 2001; Das, 2005). It has been widely established that dispersion is a strong function of heterogeneities occurring at various scales (Lake, 1989) including those randomly distributed, discontinuous, thin shale lenses commonly found in oil sands deposits (Das, 1998; Chen et al., 2008).

After the initial physical model of the Vapex process was developed by Butler and Mokrys (1989) in a series of Hele-Shaw cell experiments, subsequent improvement to this process has been proposed in many studies over the years (Das and Butler, 1994; Yazdani and Maini, 2005, 2008). Most of these works focus on estimating recovery performance at the laboratory scale. This understanding, however, is not sufficient to describe the recovery mechanisms at the reservoir scale, where geology is sufficiently complex that there is significant uncertainty due to the heterogeneous reservoir properties. A number of published works over recent years have attempted to quantify the effects of heterogeneity and distribution of shale barriers on SAGD performance.

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Nomenclature

g	gravitational constant, ft/d^2
h	vertical drainage height, ft
k	absolute permeability of reservoir, mD
k_o	effective oil permeability, mD
k_v	vertical permeability, mD
k_h	horizontal permeability, mD
q	cell flow rate for a certain grid block, bbl/d
t	time, days
C_s	solvent concentration (volume fraction) at a distance ξ from interface
C_{sc}	solvent concentration in the edge of solvent chamber
C_{sr}	the solvent concentration in the reservoir
D_s	intrinsic diffusion coefficient of solvent, ft^2/d
L_i	length along interface between two neighboring nodes around node i, ft
N_s	dimensionless integral
Q	total oil drainage rate per unit length of well ft^3/d ft
S_o	oil saturation, %
S_{wi}	irreducible water saturation, %
S_{or}	residual oil saturation, %
ΔS_o	oil saturation difference between initial and residual, %
U	frontal advancing velocity of interface, ft/d
V	average drainage velocity due to gravity, ft/d

Greek symbols

ξ	distance from interface, ft
μ_b	dynamic viscosity of bitumen in solution, cP
θ	the angle of interface from horizontal, deg
ϕ	porosity, %
γ_m	mass penetration, ft
γ (h)	variogram at a lag distance of h
$\Delta\rho$	density difference between solvent and oil, kg/ft^3

Subscripts

i	grid block index
max	maximum

Superscripts

n	time level

For example, Yang and Butler (1992) constructed a 2-D experimental model to simulate SAGD performance in two different types of heterogeneous reservoir settings: one with thin shale layers and another one containing horizontal layers of varying permeabilities. They concluded that a horizontal barrier with limited areal extent does not have significant impact on the cumulative production; the chamber is distorted only slightly near these shale barriers.

Detailed compositional simulators have been employed widely for modeling Vapex performance (Nghiem et al., 2001). However, complexities of its recovery mechanisms render numerical modeling of such process in heterogeneous reservoirs is highly cumbersome and expensive. Efficient alternatives, like semi-analytical proxy models, can overcome such computational challenges by providing an approximate solution without solving all the detailed equations. A number of these proxy models have been proposed for assessment of SAGD and solvent-assisted processes in the past (Vanegas et al., 2008, 2009; Gupta and Gittins, 2011; Azom and Srinivasan, 2013), but its application for modeling Vapex process is lacking. In addition, all these semi-analytical methods predict only drainage rate and cumulative steam oil ratio, but not chamber advancement, in homogeneous reservoirs.

Computational requirement is further intensified because heterogeneity informed by insufficient information leads to uncertainty in reservoir models. Descriptions of heterogeneity are incomplete because data is typically noisy and sparse (Leung and Srinivasan, 2012), rendering uncertainty an intrinsic characteristic of any reservoir geological modeling effort (Forster, 2008; Yang et al., 2011; Leung, 2012). Therefore, accounting for the uncertainty that exists in heterogeneous reservoir, in terms of rock properties (i.e., lithofacies, porosity and permeability) in the modeling or simulation workflow, is critical for improved oil recovery and reservoir management (Deutsch and Srinivasan, 1996).

Several optimization studies of SAGD projects were conducted in the past considering reservoir heterogeneities: Li et al. (2011) conducted a simulation study to investigate the impact of shale barriers on SAGD performance and proposed optimization injection strategies including solvent co-injection and/or placement of additional steam injectors above the shale barrier. They stated that solvent coinjection with mixtures of C_7 and C_{12} can reduce the flow resistance at the end of a shale barrier and deliver higher recovery factor as well as a lower cumulative energy/oil ratio; Kumar et al. (2010) investigated the influence of heterogeneity (i.e. low permeability regions) on SAGD wellbore design by optimizing the length and positioning of tubular strings, as well as the allocation of injected steam among tubing strings; Al-Gosayir et al. (2012) proposed a hybrid genetic algorithm to optimize cumulative steam–oil ratio (cSOR) and recovery factor in two synthetic heterogeneous reservoir models exhibiting different shale distributions. In these studies, only a couple of realizations were randomly selected and utilized in the optimization procedure, which may ignore the uncertainty of reservoirs and deviate significantly from the actual solution. To capture reservoir uncertainties, a large number of realizations honoring geological properties (i.e. porosity and permeability) are often needed. In an optimization procedure described by Yang et al. (2011), preliminary screening using detailed flow simulation was performed using a large number of realizations, and a reduced subset is selected for subsequent detailed optimization of well placement and operating strategy including bottom-hole pressure and steam injection rate. However, only a few works have alluded to the uncertainty assessment of Vapex performance due to variability in reservoir heterogeneities (Forster, 2008; Leung, 2012).

In most practical scenarios, a large number (hundreds) of equally probable realizations of reservoir properties (i.e., facies, porosity, and permeability) are constructed (Kelkar and Perez, 2002); however, it is typically impractical to subject all the realizations to flow simulation. Some researchers have proposed various ranking schemes for selecting a subset of these realizations that would capture the response uncertainty exhibited by those multiple realizations prior to optimization. For example, realizations are ranked based on particular recovery indicators such as average oil production rate, cumulative oil production, and cumulative steam–oil ratio for characterizing SAGD performance (Pooladi-Darvish and Mattar, 2002; Fenik et al., 2009; Vanegas et al., 2009). McLennan and Deutsch (2005) implemented a number