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Ensemble-based optimization of interwell connectivity in heterogeneous waterflooding reservoirs

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ABSTRACT

Estimation of interwell connectivity is of great importance to optimization of injection-production scheme and decision-making of potential-tapping strategies during the later stage of waterflooding. However, the traditional reservoir simulation requires detailed information of various reservoir/fluid parameters, which is time-consuming and difficult to obtain the reliable estimates due to large uncertainties. The capacitance-resistance model inferred from field injection and production data provides an attractive alternative to understanding the interwell connectivity relationship and close-loop reservoir management. For this study, the producer-based and injector-producer pair-based capacitance resistance model, CRMP and CRMIP, are employed to compute liquid production rate of each producer, respectively, followed by description of observed water cut data using the Koval fractional-flow equation. Then, this paper proposes a novel framework that enables the newly developed Stochastic Simplex Appropximate Gradient (StoSAG) algorithm to optimize interwell connectivity in waterflooding reservoirs by preconditioning the hybrid nonlinear constraints, which is further validated by a heterogeneous synthetic case. The results show that, compared to the projected-gradient (PG) and EnKF methods, the StoSAG optimization technique can handle the sequential data assimilation in large-scale nonlinear dynamics more robustly; due to more degrees of freedom, the CRMIP representation captures the reservoir's dynamic behavior better than CRMP, resulting in a more satisfactory estimation of geological parameters relative to each reservoir control volume; The Koval fractional-flow equation are effective to represent the water-producing characteristics from small-to-large water cut period, but a great deviation will be caused during the extra-high water cut stage (f_w>90%) because of its inherent drawbacks.

1. Introduction

Estimation of interwell connectivity is essential to field development project design, which is also of great importance to optimization of injection-production scheme, analysis of remaining oil distribution and decision-making of potential-tapping strategies. However, the traditional reservoir simulation is usually based on the finite difference method, which requires detailed information of various reservoir/fluid parameters, such as porosity, permeability, relative permeability and saturation in grid blocks. Since information about those parameters is also limited by measuring techniques, vast majority of those parameters are mainly determined by interpolation from that of well points, usually leading to a great deviation. Furthermore, uncertainties of the reservoir/fluid parameters used for history matching field production data are further intensified by the inherent drawbacks of the existing measuring techniques, which cannot meet the requirement of good physical understanding to reservoir (Jin et al., 2004; Kang et al., 2012; Zhao et al., 2015a). Using historical data of injection and production rates has proven to be an attractive alternative to

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accurate estimation of interwell connectivity in water flooded reservoirs. The simplified reservoir models proposed mainly consist of the linear multivariate regression model (Gentil, 2005), the capacitance-resistance model (CRM) (Yousef et al., 2006a, 2006b; Sayarpour et al., 2007; Moreno, 2013; Mamghaderi and Pourafshary, 2013; Zhang et al., 2015; Holanda et al., 2015), the multiwell productivity index (Kaviani et al., 2010), the flow-network model (Lerlertpakdee et al., 2014) and the interwell numerical simulation model (Zhao et al., 2015b, 2016). As an alternative to reservoir simulation, the CRM representation is generally based on signal-processing techniques and a total mass balance equation with compressibility, in which injection rate are assumed as input signals and production rates are treated as output signals of the integrated dynamic system, respectively, and characterizes a flooded reservoir by rapid estimating connectivity coefficients, time constants and productivity indices using only the producers' bottom-hole pressure if necessary and production/injection rate for history matching. Due to its high computational efficiency and capability for reservoir performance prediction, the CRM has gained substantial popularity to close-loop reservoir management and production optimization, especially in areas of primary recovery (Nguyen, 2012), waterflooding (Lee et al., 2011; Tafti et al., 2013), gas flooding (Nguyen, 2012; Sakazar-Bustamante et al., 2012) and CO_2 geological sequestration (Tao and Bryant, 2015).

However, all the above-mentioned simplified reservoir models are single-phase flow model merely history matching and predicting the liquid production rate, and not capable of separating the oil production from the total production adaptively, which bring about plenty of difficulties for decision-making of potential-tapping strategies during the later stage of waterflooding. To tackle the deficiencies, Gentil et al. (Gentil, 2005) present an empirical linear relationship between the natural logs of instantaneous water-oil ratio and cumulative water injection, which is usually valid in mature water floods. For the same reason, it provides often a good approximation at the late life of a waterflood when water cut is large. Zhao et al. (2015a; 2015b; 2016) assume that the rock and fluid are incompressible during the tracking process of water cut data. Instead of solving the saturation distribution along each one-dimensional space, the Buckley-Leverett waterflood front equation is applied to compute water cut at the downstream well of each well pair, which keeps a fast computation speed. Nevertheless, the Buckley-Leverett model has many assumptions such as homogenous media, one dimension flow, incompressible system, negligible gravity and capillarity, all of which should be carefully understood prior to application. Cao et al. (2014, 2015) provide a water fractional flow equation inferred from field production data using the Koval theory. By history matching field water cut data, two model parameter, Koval factor and drained pore volume, will be estimated. The Koval fractional-flow equation is far more general and flexible because there is no specific assumption regarding the immiscible displacement, which has the advantage to address the issue of viscous fingering in a miscible displacement. Furthermore, due to the high complexity of flooded reservoirs and urgent requirement of real-time production optimization, the gradient-based methods (e.g., the steepest-descent method, the projected-gradient method, and so on) commonly used to solve optimization problems where the direction of search for a local minimum is obtained by computing the gradient of objective function with respect to the geological parameters such as connectivity coefficients, time constants and productivity indices, will not be suitable in many cases, particularly, the large-scale heterogeneous waterflood reservoirs with hybrid nonlinear constraints. Nowadays, the derivative-free optimization techniques have garnered attentions in the computational mathematics literature. Whereby, the ensemble-based methods have proven to be one of the most popular derivative-free optimization techniques for many applications due to its versatility and simplicity, involving in close-loop reservoir management (Chen et al., 2009, 2012; Do and Reynolds, 2013; Zhao et al., 2013), estimation of optimal well controls (Su and Oliver, 2010; Oliveira and Reynolds, 2014; Fonseca et al., 2014), and EOR screening (Odi et al., 2010; Katterbauer, 2015; Chen and Reynolds, 2016). However, there are few proposals for interwell connectivity estimation with the ensemble-based optimization techniques (Zhang et al., 2015; Jafroodi and Zhang, 2011).

Here, we develop a novel framework that enables the newly developed Stochastic Simplex Appropximate Gradient (StoSAG) algorithm to optimize interwell connectivity in heterogeneous waterflooding reservoirs by preconditioning the hybrid nonlinear constraints. This paper is organized as follows: First, we provide the formulation and architecture of different capacitance-resistance models and Koval fractional flow equation, respectively, followed by a brief description of the ensemble-based optimization process for solving hybrid nonlinear constrained problems. Thereafter, with respect to a heterogeneous synthetic case, the proposed technique is performed to history match the observed production data adaptively, and thus determine the interwell geological parameters such as connectivity coefficients, time constants, and drained pore volumes. Finally, we summarize the results and present the conclusions of this work.

2. Methodology

In this section, the producer-based and injector-producer pair-based capacitance resistance models (Sayarpour et al., 2007), CRMP and CRMIP, are respectively introduced to compute liquid production rate of each producer within a specific reservoir control volume in terms of considering the impact of interwell connectivity, time lag and reservoir/fluid compressibility. Moreover, the Koval water fractional-flow equation developed by Cao et al. (2014, 2015) is applied to separate the oil production from total production. Thereafter, a novel ensemble-based optimization framework preconditioning hybrid nonlinear constraints is then provided to minimize the squared difference between the predicted and observed production data, so that the interwell geological parameters such as connectivity coefficients, time constants, and drained pore volumes will be eventually estimated.

2.1. Capacitance-resistance model

(1) Producer-based representation-CRMP

As shown in Fig. 1, the producer-based representation (CRMP) divides the reservoir into a series of control volumes based each producer and includes all the injectors that influence their production rates, which may be all injectors, unless some extra

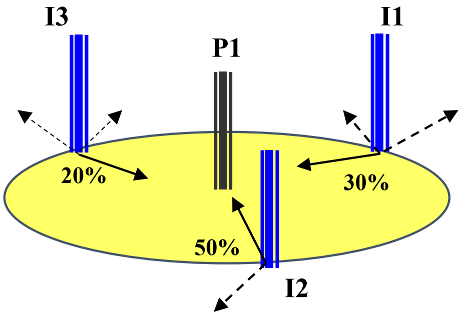

Fig. 1. Schematic of reservoir control volume in the CRMP representation.