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An optimization methodology of alkaline–surfactant–polymer flooding processes using field scale numerical simulation and multiple surrogates

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Abstract

After conventional waterflood processes the residual oil in the reservoir remains as a discontinuous phase in the form of oil drops trapped by capillary forces and is likely to be around 70% of the original oil in place (OOIP). The EOR method so-called alkaline–surfactant–polymer (ASP) flooding has proved to be effective in reducing the oil residual saturation in laboratory experiments and field projects through the reduction of interfacial tension and mobility ratio between oil and water phases.

A critical step to make ASP floodings more effective is to find the optimal values of design variables that will maximize a given performance measure (e.g., net present value, cumulative oil recovery) considering a heterogeneous and multiphase petroleum reservoir. Previously reported works using reservoir numerical simulation have been limited to sensitivity analyses at core and field scale levels because the formal optimization problem includes computationally expensive objective function evaluations (field scale numerical simulations). This work presents a surrogate-based optimization methodology to overcome this shortcoming.

The proposed approach estimates the optimal values for a set of design variables (e.g., slug size and concentration of the chemical agents) to maximize the cumulative oil recovery from a heterogeneous and multiphase petroleum reservoir subject to an ASP flooding. The surrogate-based optimization approach has been shown to be useful in the optimization of computationally expensive simulation-based models in the aerospace, automotive, and oil industries. In this work, we improve upon this approach along two directions: (i) using multiple surrogates for optimization, and (ii) incorporating an adaptive weighted average model of the individual surrogates.

The cited approach involves the coupled execution of a global optimization algorithm and fast surrogates (i.e., based on Polynomial Regression, Kriging, Radial Basis Functions and a Weighted Average Model) constructed from field scale

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numerical simulation data. The global optimization program implements the DIRECT algorithm and the reservoir numerical simulations are conducted using the UTCHEM program from the University of Texas at Austin.

The effectiveness and efficiency of the proposed methodology is demonstrated using a field scale case study.

Keywords: Enhanced oil recovery; Chemical flooding; ASP flooding; Global optimization; Surrogate modeling; Surrogate-based optimization

1. Introduction

After conventional waterflood processes the residual oil in the reservoir remains as a discontinuous phase in the form of oil drops trapped by capillary forces and is likely to be around 70% of the original oil in place (OOIP) (Dosher and Wise, 1976). The EOR method so-called alkaline–surfactant–polymer (ASP) flooding has proved to be effective in reducing the oil residual saturation in laboratory experiments and field projects through the reduction of interfacial tension and mobility ratio between oil and water phases. Some ASP pilot tests reported in the literature have reached an oil recovery over 60% OOIP (Clark et al., 1988; Meyers et al., 1992; Vargo et al., 1999; Demin et al., 1999).

In ASP floodings the surfactant is responsible for reducing the interfacial tension between oil and water phases to a level that promotes the mobilization of trapped oil drops. The alkaline agent is intended to react with the acids to generate in situ surfactant (Rivas et al., 1997) to overcome the surfactant depletion in the liquid phases due to retention. The role of the polymer is to increase the viscosity, reducing the mobility ratio and hence allowing a greater volumetric swept efficiency. Details of the physical processes taking place can be found in, for example, Shah and Schechter (1977).

The design of an ASP flooding process must achieve three main objectives: propagation of the chemicals in an active mode, the injection of enough chemicals accounting for the retention, and a complete swept of the area of interest (Lake, 1989). Achieving these objectives is significantly affected by the selection of the chemicals, the concentration of the ASP solution and the slug size, among other factors.

Previous works toward the optimization of ASP processes have concentrated mainly around identifying formulations that will achieve minimum interfacial tension using laboratory experiments and empirical correlations (Salager et al., 1979a,b; Bourrel et al., 1980; Salager, 1996), and sensitivity analyses using numerical simulation at core and field scale levels (Wei-Ju, 1996; Zhijian et al., 1998; Manrique et al., 2000; Qi et al., 2000; Hernández et al., 2001). Table 1 presents a summary of these works and shows that the formal optimization of ASP flooding has not been addressed. The latter is a critical step to find the optimal parameters that will maximize a given performance measure (e.g., net present value, cumulative oil recovery) considering a heterogeneous and multiphase petroleum reservoir.

The cited formal optimization has been limited due to the high computational cost exhibited by the numerical simulations at the reservoir level, which makes impractical the coupled execution of the simulator and optimization algorithms. The surrogate-based optimization approach has been shown to be useful in the optimization of computationally expensive simulation-based models in the aerospace (Giunta et al., 1997; Balabanov et al., 1998), automotive (Craig et al., 2002; Kurtaran et al., 2002), and oil industries (Queipo et al., 2002a,b). Surrogate-based design makes reference to the idea of constructing an alternative fast model (surrogate) from numerical simulation data and using it for optimization purposes. In this work, we improve upon this approach along two directions: (i) using multiple surrogates for optimization, and (ii) incorporating an adaptive weighted average model of the individual surrogates. The rationality of these improvements is described in later sections of the paper.

The proposed methodology estimates the optimal parameters (slug size and concentration of the chemical agents) to maximize the cumulative oil recovery from a heterogeneous and multiphase petroleum reservoir subject to an ASP flooding. The methodology involves the coupled execution of a global optimization algorithm and surrogates (based on Polynomial Regression, Kriging, Radial Basis Functions and a Weighted