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Maximizing volumetric sweep efficiency in waterfloods with hydrocarbon F–Φ curves

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ABSTRACT

Waterflooding is by far the most commonly used method to improve oil recovery. Success of a waterflood depends on its ability to sweep mobile oil efficiently. Incorrect or insufficient design may lead to increases in cost associated with water cycling and poor sweep. Most waterflood management is restricted to classical methods (e.g., surveillance or pattern balancing) or sensitivity studies centered on finite difference simulation. Most of the time, conventional methods fail to account for subsurface heterogeneity. Optimizing sweep via numerical modeling is time consuming in waterfloods with large number of wells or a relatively high-resolution numerical grid.

We propose a practical and efficient approach for rapid and full-field optimization of waterfloods. Our method focuses on optimizing volumetric sweep efficiency using streamlines. We introduce two new concepts: the hydrocarbon F–Φ curve and Hydrocarbon Lorenz Coefficient ($L_{C\text{-}HC}$). We show that these concepts can be easily derived from streamline simulation and can be used for optimum waterflood management. $L_{C\text{-}HC}$ serves as a unique measure of the flow – or dynamic – heterogeneity. We show that minimizing $L_{C\text{-}HC}$ results in maximum volumetric sweep efficiency. The method is straightforward: we evaluate the sensitivity of $L_{C\text{-}HC}$ to variations in operating conditions in a design of experiment (DoE) study, describe the $L_{C\text{-}HC}$ as a function of those operating conditions using response surface methods, then select the operating conditions that minimize $L_{C\text{-}HC}$ (maximize sweep efficiency). The main advantages of our method are its speed, flexibility to start optimizing at any arbitrary time regardless of the history, and ability to handle large problems. The new approach requires running a streamline simulator only a few time steps, so multi-million cell models are simulated in minutes.

We verified our approach with several synthetic examples. An example shows that a 100,000 cell, complex reservoir with 13 wells, and 29 completions can be optimized in less than 4 h, leading to significant increase in recovery efficiency and reduced water cycling. We then apply the method to a model of the Brugge field, the SPE comparative problem on recovery optimization. Improved production response illustrates the power of the new method.

1. Introduction

Billions of barrels of proven resources have been converted to reserves through waterflooding, easily the most commonly used secondary recovery method. Despite its long and historied use, reservoir heterogeneity may have a significant impact on the efficiency, hence life, of a waterflood. In most cases areas of water cycling and poor sweep develop as the flood matures.

Implementing a methodical approach to understand where the opportunities exist is a first step to a better waterflood project. Surveillance and monitoring techniques have been discussed in the literature widely (e.g., Terrado et al., 2007). One of the key lessons the industry learned is the importance of reservoir characterization and accurate quantification of reservoir heterogeneity. Most times, heterogeneity is defined simply as “the contrast in reservoir properties”. But what really controls the efficiency of a flood is how this heterogeneity is connected. This can be called connectivity or “dynamic heterogeneity.” In waterfloods, heterogeneity causes premature breakthrough of injected fluids. Interwell connectivity, in waterfloods, has been determined qualitatively using natural tracers and other geochemical fingerprinting. Some of the useful studies that appear in the literature in this context are presented by Smalley et al. (1994), Westrich et al. (1999), and Kaufman et al. (2000, 2002), among others. Recently capacitance-resistance models (CRMs) were introduced to map the interwell connectivity between producers and injectors (Izgec and Kabir, 2009; Sayarpour et al., 2009; Yousef et al., 2006).

A key element to a successful waterflood is high volumetric sweep efficiency. A generalized definition of sweep efficiency is the ratio of the reservoir pore volume contacted at time t to total pore volume. Improved sweep efficiency means improved oil recovery and reduced

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water cycling. While defining sweep efficiency is straightforward, it is difficult to optimize because of the complex interactions between wells. There is no formal procedure that can be followed which ensures improved sweep efficiency.

Actions that can be taken to improve the waterflood sweep efficiency can be summarized as: rate allocation, conformance control (vertical and/or areal by mechanical and/or chemical means), infill drilling, well conversion and pattern realignment. By allocating the rate, reservoir engineers can partially improve the areal sweep efficiency. For instance in an inverted 5 spot pattern if a high permeability streak is identified, the rate of a given injector can be reduced and water can be reallocated to other quadrants in the pattern. This may delay the breakthrough or reduce field watercut. But, this may reduce the daily production rate of the other producers in the pattern and ultimately lead to poor sweep for a given time. A systematic approach that resolves the complex interactions of the wells and finds the optimum operating conditions is needed. These methods, historically, are called optimum rate control methods.

In recent years some methods of optimum rate control were introduced (Alhuthali et al., 2007; Asheim, 1998; Brouwer and Jensen, 2004; Brouwer et al., 2001; Grinestaff, 1999; Grinestaff and Cafferey, 2000; Sudaryanto and Yortsos, 2001). Brouwer et al. (2001) studied the static optimization of waterflooding. In their method the flow rates of the inflow control valves (ICVs) along the well were kept constant during water flooding. Brouwer and Jensen (2004) extended the same concept by allowing dynamic control of the ICVs. Both rate- and bottomhole pressure-constrained cases were studied in their work. Several authors used streamlines for waterflood optimization (Grinestaff, 1999; Grinestaff and Cafferey, 2000). In early streamline-based optimization studies, streamlines were solely used for flow visualization and allocation factor calculation. The first study which combines formal optimization with streamlines was from Thiele and Batycky (2006). Their method uses the unique ability of streamlines to define dynamic well allocation factors (WAFs) between injection and production wells. Furthermore, streamlines allow well allocation factors to be broken down additionally into phase rates. They used this information to define injection efficiency for each injector/producer pair in a simulation model.

Alhuthali et al. (2007) presented a streamline-based method for optimum rate control. The underlying principle behind their optimization scheme is to equalize the arrival time of the waterflood front at all producers within selected sub-regions of a waterflood. They also incorporated an analytical method to calculate sensitivities of water arrival times to well controls. In a later publication (Alhuthali et al., 2008) they extended their study to optimize a waterflood under geological uncertainty. Chen and Oliver (2010) used Ensemble-based closed-loop optimization methods in the Brugge field comparative study. Because of the complexity of the Brugge field, they incorporate some advanced techniques to improve their results, such as saturation normalization to account for different rock types and localization to alleviate the effect of spurious correlations.

The fundamental idea behind rate (and/or flowing bottomhole pressure) control is manipulating the pressure field via well controls, thus redistributing the fluid. In this study we present an approach and a novel integration of concepts for improved sweep efficiency through well control. We develop a formal procedure for sweep optimization that has a rigorous mathematical basis. Next we illustrate the procedure using a synthetic 5-spot pattern flood example, and then show the results of the optimization study applied to the SPE Brugge field. The SPE Brugge field comparative study is a unique benchmark project to test the use of history matching and flooding optimization methods (Peters et al., 2009). Finally we discuss the relevant issues regarding to proposed approach.

2. Approach

In waterfloods, engineers have the ability to manipulate individual well controls (e.g., bottomhole pressures, injection rates, etc.) to delay water breakthrough and to enhance recovery efficiency. Identifying the appropriate well controls is difficult because changing a given bottomhole pressure, for example, can affect the distribution of water from one or more injection wells. The conventional method for optimizing sweep efficiency in waterfloods is through the use of a finite difference field model. This can be especially cumbersome and time-consuming when the reservoir model is large, and/or there are many wells. Our method combines several tools in a manner that makes an optimization study extremely rapid. An important contribution of the new method is that it provides a mathematical foundation for optimizing sweep efficiency; therefore a formal procedure can be developed. We show a rigorous procedure for maximization of volumetric sweep efficiency at any arbitrary time during a waterflood. Below, we discuss the elements of our integrated approach. The method presented here introduces two new concepts: hydrocarbon F–Φ curve and hydrocarbon Lorenz Coefficient ($L_{C\text{-}HC}$). Like all simulation-based approaches, the method requires a history matched model.

2.1. Streamline simulation

Streamline-based flow simulation has emerged in the past 15 years as a powerful tool, complementary to traditional finite difference simulation. One distinguishing feature of current streamline simulation is that the streamlines are truly 3D, rather than 2D as in the streamtube methods of the 70's and 80's (Datta-Gupta and King, 2007). Transport calculations are done for each streamline using a 1D IMPES-type formulation, which makes this method fast compared to finite difference simulation. The interested reader is referred to the literature for an extensive discussion of streamline modeling (Datta-Gupta, 2000; Datta-Gupta and King, 2007; Thiele et al., 2010). In addition to the given speed advantage of streamline simulation, our new approach requires running a streamline simulator only a few time steps, which makes the optimization extremely fast. This is one of the most important features of our method. The output data that is used in this method from streamline models is time of flight (TOF) of the streamlines, τ_i, and their volumetric hydrocarbon flow rate, q_o. Our method requires running a streamline simulator a few times steps to attenuate pressure transients, and then output TOF and q_o distributions. Because we take only a few time steps with the streamline simulator, we are thus able to optimize multi-million cell models extremely fast. The optimization can be repeated as needed (workovers, well shut-in, infill drilling, pattern realignment and non-unit mobility ratio cases). We discuss the update criteria for optimization later in the text.

2.2. Conventional F–C and streamline-derived F–Φ curves

Flow capacity–storage capacity diagrams have appeared in reservoir engineering literature for decades (Lake, 1989; Schmalz and Rahme, 1950). Also known as F–C curves, they were originally derived for 2-D, vertical cross section, non-communicating, layered reservoirs. Under those conditions, Flow Capacity, F, and Storage Capacity, C are readily calculated. Imagine a collection of N permeable medium layers, each having a different permeability, k, porosity, Ø, and thickness, h. If there is no communication between these layers, we can uniquely describe the flow capacity and storage capacity of the individual layers. Writing Darcy's law for each layer and canceling like terms (recall that cross sectional area and length is equal for all N layers) gives

$$f_i = \frac{q_i}{\sum_{i=1}^{N} q_i} = \frac{(kh)_i}{\sum_{i=1}^{N} (kh)_i}. \quad (1)$$