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Introducing a novel model and tool for design and performance forecasting of waterflood projects

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ABSTRACT

Although the waterflood process as an improved oil recovery method for increasing production and pressure maintanence has been around and widely used for more than six decades, it still holds a significant portion of world oil production. In some giant international companies, e.x. BP, about half of their production is by waterflooding. On the other hand, forecasting the performance of waterflooding projects plays an important role in successful study, design and selection of the best candidates from company reservoir asset. A model which is fast, robus, easy to use and reasonably accurate with a few input data required is of great desire. In this paper we address this deficiency by presenting a novel analytical-base forecasting model/tool that does not rely on conventional numerical simulation.

Using the concepts of material balance, momentum balance, segregated flow and fractional flux (F-C or F-Phi) we achieve an analytical approach for modeling waterflooding behavior in reservoir. We used a Koval flow-storage capacity (F-C) model in the current research because of its strength and wide applicability for both homogenous and heterogeneous permeable media. The validity of the forecasting model was investigated by matching numerous actual field, single well and also simulation results.

History matching showed good agreement between field data and forecasting results. The forecasting model demonstrates a strong ability to forecast the oil saturation, recovery efficiency, cumulative oil recovery, oil cut and oil rate changes with time. In addition, predicting the recovery efficiency enables us to generate the volumetric efficiency change with time which is of great importance for studying and evaluating waterflood process. These valuable results are produced using a few input data required.

1. Introduction

Waterflooding, as a secondary recovery process, is one of the key methods to improve oil recovery and meet the increasing demand of required world energy. Therefore, performance prediction of waterflood projects and evaluating the incremental recovery potentials is a key step in selecting the best candidates and implementation of a successful project.

It is not always possible neither convenient to use numerical simulation for history matching or predicting (forecasting) the reservoir performance under an improved recovery process. For example, in screening/feasibility studies for an asset of reservoirs it could be too difficult or even impossible to use numerical simulation for predicting the performance of all of the reservoirs in the asset. Lack of necessary reservoir data and too much required time and resources can be barriers for history matching and/or predicting waterflood performance even for one reservoir in a timely manner. Therefore, using fast and robust analytical techniques (forecasting or predictive models), for screening or as an alternative to very costly and time consuming numerical simulation, are of great importance to fulfill a thorough study and achieve successful design.

Predictive models have been used in literature as a fast way to forecast different improved recovery processes including waterflooding [3,6,24,22,13,11,5,21]. Each method attempts to model the process analytically including different features of the process, e.x. estimating oil production volumes as a function of cumulative water injection. CRM (capacitance-resistance model [22], utilizes injection/production rate and bottomhole pressure data for history matching, optimization and evaluating reservoir uncertainty for water/CO_2 floods. Many authors tried to develop analytical models to forecast the performance of waterflood such as recovery and sweep efficiency, production rates and economic evaluation to identify the potentials of the reservoirs. Buckley and Leverett [3] to describe the performance of two-phase immiscible displacement was the pioneer of the models used for waterflooding. It is linear (single layer) and lacks the heterogeneity of the reservoir. Stiles [21] presented a method for estimating the performance of waterflood based on piston-like displacement assumption and stratified layers (multilayer) with different heterogeneity and the rate of the advance of the front in each layer were proportional to the permeability of the layer. Dykstra and Parsons [10] presented a model which is a bit more sophisticated and in addition to incorporating multilayer and heterogeneity (in form of permeability variations), considers different fluid

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Nomenclature

C	Storage capacity, fraction
E_D	Displacement efficiency, fraction
E_V	Volumetric sweep efficiency, fraction
E_R	Ultimate recovery efficiency, fraction
F	Flow Capacity, dimensionless
f_o	oil cut, dimensionless
H	Total thickness, ft
H	Layer thickness, ft
K	Koval factor, dimensionless
K	permeability, md
M^o	End point mobility ratio, dimensionless
N_p	Oil production, STB
OOIP	Original oil in place, STB
P	Pressure, psia
R^2	Correlation Coefficient, dimensionless
S_{or}	Residual oil saturation after waterflood, fraction
S_{oR}	Average remaining oil saturation at start of Waterflood, fraction
t_D	Dimensionless time, dimensionless
V_{DP}	Dykstra-Parsons coefficient dimensionless
V_p	Pore volume, dimensionless
V	Specific velocity, dimensionless
x_D	Dimensionless distance, dimensionless

Latin Symbols

φ	Porosity, fraction
λ	Geostatistical dimensionless correlation length, dimensionless
μ	Viscosity, cp

Subscripts and Superscripts

B	Oil bank
BT	Break through
F	Final
f =	front
I	Initial
I	original
J	Injection
O	Oil
SW	Sweep-out
W	Water

mobilies. Craig-Geffen-Morse [6] developed a method for performance prediction of waterflood based on a five spot pattern. Dake [8] presented an analytical approach by Dietz [9] to evaluate the recovery efficiency of unstable immiscible displacement with the effect of gravity. The model is based on segregated flow condition that assumes there is no mobile oil behind the front.

There are several steps in evaluating waterflood for field applications such as: binary screening, forecasting (analytical evaluating), laboratory studies and numerical simulation, pilot and/or field deployment.

Binary screening guides in which reservoirs are selected on the basis of reservoir average rock and fluid properties are found to be more consulted for initial determination of applicability. However, quick quantitative comparisons and performance predictions of waterflood that are performed in forecasting step studies are more important and complicated than initial screening.

In forecasting, we look for ways to get quick and robust quantitative results of the performance of the improved recovery process before detailed numerical simulations of the reservoirs under study. This is necessary in screening the potential reservoirs for waterflood because it is neither possible nor logical to do a detailed engineering study on all candidate reservoirs. To reach to these goals we need fast forecasting of the waterflood performance using analytical models that include the relevant aspects of the process and also show the relative advantages of various design scenarios, yet be simple and fast to allow multiple executions of the model.

We describe the development of the model as follow: first, the fundamental and mathematical formulation of the model is presented. Then, we continue with history matching of the pilot and field waterflood data to validate the model. Finally, development of the model for forecasting and predicting of waterflood results is done using systematic numerical simulation based on experimental design and response surface modeling techniques.

2. Development of the waterflood forecasting model

2.1. Model assumptions

The forecasting model is based on the assumption that displacements are locally segregated. "Locally" in this context means on the scale of a laboratory experiment. Standard theories of displacement (like fractional flow based theories; [3]) on this scale do not, in general, predict locally segregated. However, in practice local segregation is by far the most common displacement type so we assume it to be true from the start. Any deviations from this as accounted for in the Koval [14] approach described below. The advantage of this approach is that local segregation renders it unnecessary to know relative permeability data over the complete saturation range. All that is needed are the endpoint relative permeabilities and perhaps a single point on a fractional flow curve. See Lake [15] for a discussion of the behavior of the local displacements.

In segregated flow, the oil saturation behind the displacing front is reduced to a final oil saturation (S_{oF}) while the oil saturation in the unswept zone is S_{oR}, which is the oil saturations at the start of the waterflooding process. We will show that these simplifying assumptions lead to results that agree well with field results and numerical simulation. Fig. 1 shows a schematic of a segregated flow displacement when injected fluid displaces the oil.

We assume that isothermal and steady state conditions prevail and there is no reaction.

2.2. Mathematical formulation

The key simplification from the Koval-based approach (1963) is the replacement of a physical dimension, thickness, with a storage capacity. Later we show how the flow-storage capacity curve is parameterized with the Koval factor. Fig. 2 shows the typical storage capacity profile (defined in Appendix A-1). S_{oF} is the final average oil saturation

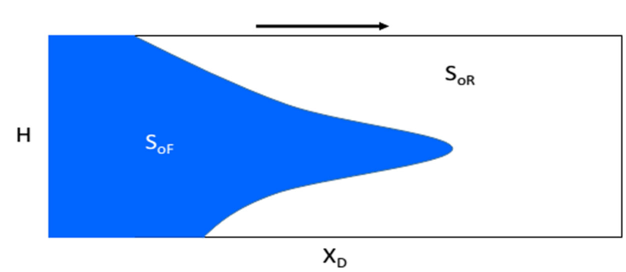

Fig. 1. Schematic of segregated flow.