



Controlling flood displacement fronts using a parallel analytical streamline simulator



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ABSTRACT

The Analytical Element Method (AEM), originally developed for mathematical modeling of groundwater flow, is here applied in closed-loop waterflood simulations. The Parallel Analytical Streamline Simulator (PASS), based on AEM, enables fast time-of-flight (TOF) calculations and visualizations of sweep efficiency in homogeneous, heterogeneous and fractured reservoirs. Simulations with PASS can test the sweep efficiency for a wide range of well patterns even before field development. We assume a simple direct-line drive and various initial reservoir attributes: a homogenous base case and further explore the effects on the flood advance of zones with heterogeneous permeability and an impervious fault. For all cases, analytical streamline patterns and time-of-flight contours for the flood front (obtained with PASS) are compared to those generated via an independent method based on numerical discretization by a commercial reservoir simulator. The results are convergent and confirm that PASS can be used to determine in closed-loop simulations the well rates that will avoid the occurrence of premature water breakthrough in the production wells. Early breakthrough in the homogenous reservoir occurs for the central producers and occurs later for the peripheral producers. Real-time adjustments of the water injection rates based on closed-loop surveillance of the pressures in producer wells can redirect and control the reservoir flow such that the floodfront arrives simultaneously at all producers. For the heterogeneous reservoir, smart-field well-control for improved sweep efficiency is also visualized. However, when an impervious fault zone blocks the flow path between injector and producer wells the occurrence of premature arrival of injection water in some producers cannot be avoided.

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1. Introduction

Effective waterflood management begins with optimization of the well architecture design to establish the most effective well constellation to achieve the largest net cash flow from a certain field. Integrated over time, the maximum net cash flow generates a corresponding maximum net present value over the lifecycle of the field. Reservoir models in early field life are commonly based on few subsurface data and become more accurate when more data on field performance accumulate over time. Determining the optimum well patterns, borehole orientation and locations, as well as the actual number of wells will result in a higher NPV (e.g., refs. in Zandvliet, 2008). Testing multiple scenarios for a range of well architectures under geological uncertainty is possible with our Parallel Analytical Streamline Simulator (PASS). The present proof-of-concept study focuses on a simple dynamic optimization for a

given well pattern and assumes a number of synthetic reservoir attributes to benchmark results and to demonstrate how well-rate adjustments can control and redirect the flood front.

The simulator developed by us is based on the Analytical Element Method (AEM), previously used in groundwater flow studies (Strack, 1989; Haitjema, 1995). The basic philosophy of AEM makes use of the analytical elements described by complex potentials. This study uses a subset of such analytical elements and demonstrates the potential merit for closed-loop reservoir modeling and flow visualizations. All integrals in the AEM are based on linear partial-differential equations which are analytically obtained. Many of these equations cannot be solved practically without the aid of modern computing power. The AEM differs from the finite difference and finite element methods in that the former does not rely upon discretization of volumes or areas in the modeled system; only internal and external boundaries are discretized. The strength of the AEM is its foundation in analytical descriptions that require only few input parameters to model a broad range of flow scenarios. The acquisition of detailed reservoir data by geological

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and geophysical methods is costly, which is why reservoir response studies based on fast streamline simulations with PASS can help guide the selective acquisition of subsurface data to improve field performance even before drilling the actual wells.

Early reservoir descriptions based on complex potentials have simplified spatial variations in reservoir properties. For example, Muskat (1949 a,b) extended his line integral method to account for reservoir heterogeneity by assuming that varying the layer thickness is equivalent to specifying a spatial permeability gradient. A more advanced approach makes use of integrated line sources and sinks (line dipoles and line doublets), which can be collated to delineate reservoir sub-domains of different permeability using analytical elements to create closed boundaries (Strack, 1989). The AEM approach was more recently applied to model reservoir flow patterns and pressures in synthetic well models (Fokker et al., 2005; Fokker and Verga, 2008). However, the latter models did not consider any closed-loop response simulations. The application in our study advances the AEM in that direction.

Certain analytical tools used in AEM have previously been applied to model particular aspects of hydrocarbon flow in the early days of automated computing power development. However, processing speed was limited and processor cost so high that computer-aided streamline solutions using linear partial-differential equations based on complex potentials could only be afforded by a limited number of corporate developers. For example, Doyle and Wurl (1971) used a \$2 million UNIVAC11008 developed by Sperry Rand Corporation to model analytically with potential functions the waterflood performance of an oil field in northeast Texas. The field, bounded by faults on all sides, was modeled using the method of image wells to ensure that streamlines conformed to the fault boundaries. Similarly, Higgins and Leighton (1974) used a \$7 million CDC6600 mainframe computer developed by Control Data Corporation (with just enough memory when it became available in the 1960s) to compute the line integrals for flow in sub-domain layers of their reservoir model. The costly method was merited at the time because field performance and reservoir models could be compared in order to improve waterflood performance. History matching was applied to improve the model parameterization and enhance the accuracy of the production forecast for the second half of the field life-cycle.

Over the past 5 decades, the cost of computation time has come down at least three orders of magnitude. Most modern desktop computers have now enough processing power to run flow simulations based on complex potentials. Previous limitations of the complex potential method itself have also been overcome. For example, extensions of analytical to semi-analytical streamline solutions have been documented in numerous studies (Sato and Horne, 1993a,b; Sato and Watanabe, 2004; Hazlett et al., 2007; Sato, 2015). Such extensions allow for streamline simulations accounting for, *a.o.*, finite reservoir boundaries, internal heterogeneity and anisotropy. In spite of these developments, commercial reservoir modeling tools based on finite difference techniques remain the principal tool used by industry in the optimization of production output and net present value (NPV) for at least a certain type of assets (see Section 2.1). The present study advocates that the expanding range of reservoir modeling tools all have their specific merits. For example, analytical models can be employed for generating conceptual insight and for instructional purposes, as well as in practical applications because of their transparency, speed and versatility.

This article is organized as follows. Section 2 places streamline-based reservoir models in a broader context and outlines the analytical element method and key algorithms used to develop our streamline simulator (tailor-made in this study for 2D waterflooding applications). Section 3 details the basic assumptions. Section 4 applies the simulator to synthetic examples and

benchmarks the results against streamline simulations rendered with a numerical simulator (combining ECLIPSE, DESTINY and Petrel data). A discussion and conclusions are given respectively in Sections 5 and 6.

2. Tools and methods

2.1. Streamline simulation merits

The petroleum industry strives to develop the most sophisticated tools to validate field development decisions. Appropriate estimations of the hydrocarbon reserves categories are at the foundation of investment decisions, which is why a range of tools and methods is available for estimating hydrocarbon reserves (Fig. 1). The proved reserves are based on a proven recovery technology and the resource recovery profile is determined using a field development concept. Investments must meet the threshold of economic returns using certain commodity price scenarios applied to an estimation of the reserve volumes. Integrated production models are the ultimate state-of-the-art (Fig. 1, top), and other reservoir modeling tools carry the risk of compromising technical rigor (which reviewers of our paper frequently reminded us). Streamline-based methods, like any model tool, indeed have limiting assumptions but these need not compromise technical rigor when the proper tool (or a combination of tools) is applied to the proper asset. Streamline-based history matching and well simulations are part of the larger tool box currently available for modeling hydrocarbon recovery optimization. The hierarchy of modeling tools to evaluate the reserve volumes in a particular hydrocarbon reservoir can be summarized as follows (Fig. 1):

1. *Analogy methods* are mostly used for estimation of prospect size before drilling and for proved undeveloped reserves in outstep and infill drilling locations observing the limiting spacing units.
2. *Volumetric methods* are used in early field life when no or only limited production data are available. Oil and gas in place are estimated using 3D reservoir characterization based on detailed geological, petrophysical (logs) and geophysical data (seismic).
3. *Material balance methods* use early production data to obtain reserve estimations by assuming production is maintained by a linear pressure decline until the economic limit is reached.
4. *Decline curve analysis* prevails as the principal tool [based on the early work of Arps, 1945] for estimating the productivity of single and multiple wells of unconventional reservoir rocks as a basis for estimations of the natural gas and liquids reserves. History matching is used to continually update the production

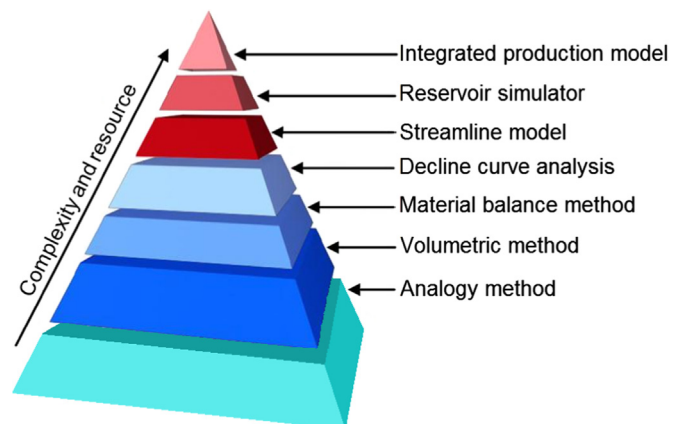


Fig. 1. Hierarchy of common methods employed for hydrocarbon reserves estimation. Adapted from Browning et al. (2012), after Pande (2005).

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