

Foreword

“Mathematical simulation of reservoir behavior may be used to help understand reservoir processes and predict reservoir behavior... in addition simulation can be used as a tool for reservoir description to learn more about the physical nature of the reservoir... this use is essential in most reservoir studies and represents one of the more significant applications of simulation.”

This comment was from an article nearly 40 years ago (Peery and Herron 1969) in which the authors described development of an “accurate, efficient, and economical prediction of the reservoir flow of three phases in two-dimensional geometry.” Their large (800-block) model ran 100 timesteps in 100 minutes on an IBM 360.

Since that article over 40 years ago, reservoir simulation has become a big business and is a tool used by thousands of reservoir engineers worldwide to assist in reservoir management decisions. Therefore, in our view, reservoir simulation has proven to lead to more “accurate, efficient, and economical” reservoir development when properly applied. We intend this book to be a readable and clear introduction to the areas of history matching and reservoir forecasting for those that interact with the reservoir engineer (e.g., geoscientists, production engineers, managers) and need to interpret or use the results of flow simulation in their work. We do not intend for this primer to read like a textbook nor to be used as a reference book as there are many good references already available (Aziz and Settari 1979; Ertekin et al. 2001).

Reservoir simulation remains in development and has seen new branches emerge and old ones die over the past 40 years. The hope is that this primer will crystallize the current state of the technology by underlining its tremendous potential when used properly but also expose inherent difficulties and potential missteps that await the uninitiated practitioner.

Although there are many pitfalls in the technology, flow simulation combined with modern reservoir characterization has proven to be a very effective means for managing the development of reservoirs. The word “modern” should be emphasized here: it has been the ability to construct geo-images of reservoirs that honor all known static geological, geophysical, and petrophysical constraints that has allowed a major shift in how we do flow simulation and history matching today (Suzuki and Caers 2006). Chapter 2 will address this further.

While flow simulators do not include *all* the detailed flow physics, many years of development and experience have clearly demonstrated that well-thought-out simulation studies combined with proper geological-reservoir characterization is one of the best ways to manage reservoir development. The basic tool has evolved tremendously but is still based on a few simple concepts like Darcy’s law and its extension to multiphase flow

by means of empirical relative permeability relations. How far we take the tool depends not just on the formulation and coding efficiency, but it requires lots of careful guidance from the practitioners.

Following an introductory section, the book is organized according to the major steps for undertaking a simulation study for history matching and forecasting purposes. The steps—usually not undertaken in a simple linear fashion—include

1. Building the initial geological reservoir and fluid models
2. Choosing the reservoir simulator(s)
3. Improving and validating the reservoir model through history matching
4. Forecasting and managing/quantifying uncertainties associated with proposed development plans

A final chapter will discuss possible future trends in the areas of reservoir flow simulation and history matching. An example history-matching exercise is provided in the Appendices to illustrate the power of modern assisted history-matching methods. The data set is available from the authors.

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Chapter 1

Introduction to Simulation and History Matching

Simulation development has moved away from much of the mainstream technology within the midsize oil companies making simulation development and use a commodity. This might suggest that there is little strategic value in developing in-house technology. However, Rex Tillerson, chairman and CEO of ExxonMobil Corp., illustrated the importance of simulation as part of their technology development. He stated, “Nearly fifty years ago, Exxon engineers applied a new mathematical technique for solving multiphase flow equations using the latest computer technology to simulate reservoir behavior ... that revolutionary technology has been built upon, capitalizing on new modeling techniques and computing advances to better understand the full physics of multiphase fluid flow. It has been an evolutionary process in which ExxonMobil has dedicated more than 900 work years over the past 30 years” (New Era of Innovation 2012).

After the merger between Exxon and Mobil, it is reported that ExxonMobil invested “more than USD 60 million” in the development of a new simulator (Duvall 2006).

From another news release in 2000, it is reported that “Chevron Corp. and Schlumberger Oilfield Services announced today they have launched a multiyear research project aimed at developing improved reservoir optimization software. The two companies will jointly own developed software and intellectual property resulting from this initiative” (Chevron Corp. 2012).

In 1997, Saudi Aramco announced the release of their simulator named Parallel Oil, Water and Gas Enhanced Reservoir Simulator (POWERS). Their brochure states, “POWERS is a three-dimensional, three-phase simulator which incorporates Saudi Aramco’s specific well-management rules and can be linked to the surface production/injection pipe network. Most importantly, POWERS can run multimillion-cell simulation models with great speed and accuracy” (Saudi Aramco Unveils Giant POWERS Simulator 1998).

Thus, from the point of view of some of the world’s largest energy companies, there is strategic value in reservoir simulation. Developing and applying the latest simulation technology provides a competitive advantage. So what is the difference between a shareware program from the US Department of Energy or a USD 60 million simulator developed by ExxonMobil? We will attempt to highlight some of the complexities and

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limitations in simulation and why they are such an integral part of a reservoir engineer's tool kit.

Reservoir simulation is a widely used tool in modern reservoir management. Major reservoir development decisions by major oil companies and larger independents are often based on some form of flow simulation. Also, because of the low cost of hardware, we are seeing simple reservoir simulators tied to many of today's basic reservoir-engineering software packages, such as well-testing and material-balance calculations. However, many reservoir-engineering decisions are still made without the use of reservoir simulators.

Certainly, the complexity and nonlinearity of the discipline has something to do with the limited application of simulation within smaller companies. It takes years of dedicated studies and many more years of hands-on practical experience to mature an effective reservoir engineer that can put the available tools to good use. Perhaps, however, the expert users of this technology have partially failed to clearly demonstrate its value in making business decisions. Rarely, if ever, are players and tools in our industry debriefed at the end of a project, so its value is not easily proven. Even worse, how often has misuse or lack of understanding of the limitations of the technology resulted in poor decisions? We intend to demonstrate that reservoir simulation is a complex endeavor that requires careful calibration. There are many valid reasons for not applying simulation as listed here:

- Limited reservoir description and lack of data for validation leading to poor forecasts
- Availability of alternative/simpler ways to make decisions
- Cost is perceived as too high and lead times as too long
- Lack of technical expertise
- Limitations of simulators (grid size, simplified geometry, simplified equations)
- Answers that strongly depend on assumptions made and the methodologies that were applied
- Nonuniqueness of history matching and uncertainty of predicted outcomes
- Poor experience with previous studies

We will not address all of these issues in this text, but we hope to convince the reader that reservoir simulation does indeed have a bright future, and continuing investment in this technology will lead to long-term rewards for the industry. We contend that reservoir simulation should be one of the basic tools applied by all reservoir engineers.

1.1 What Is a Reservoir Simulator? A Reservoir Model?

A reservoir simulator is a computer program that solves a set of equations that mathematically describe dynamic processes governing fluid flow in porous media in three physical dimensions and time. The flow equations used to describe flow in porous materials are based on mass, momentum, and energy conservation equations, plus constitutive relations for the fluids and the porous material involved. Through the proper choice of input data (e.g., reservoir rock and fluid properties) and the proper solution of the mathematical equations, the performance of petroleum reservoirs—both past and future performance—can be mimicked (simulated). In other words, it is possible to build a virtual reservoir that can be drilled, produced, and managed within the confines of a computer. How good this virtual world really is depends on many factors, including the accuracy of the mathematical description of recovery processes, the numerical methods

used to solve the equations, the reliability of the input data, and the validity of the simplifying assumptions applied by the program developer or users.

The computer program that solves the linearized set of equations (to be explained later) is normally referred to as a “simulator,” while the set of input and output data for a particular application is the “model.” Reservoir modeling is, therefore, the process of incorporating data evaluations and interpretations into a numerical simulator and using the results for reservoir engineering and reservoir management purposes.

A mathematical description of the physics (as well as the chemistry for some processes) of fluid flow in porous media entails solving complex sets of coupled nonlinear partial differential equations and auxiliary relations. It is important to understand that certain simplifications are always required. For example, isothermal (constant, but not necessarily uniform temperature) conditions are often assumed, so that the energy conservation equations can be ignored; also, geomechanical aspects may be based on simple pore pressure relations (e.g., permeability reduction as a function of pore pressure decline). Physics at the pore scale is rarely modeled explicitly but rather captured through empirically based relations like relative permeability and capillary pressure functions that are assumed to be valid on a representative element volume (Lake 1989). There is no simulator that does not simplify; the challenge for the practicing reservoir engineer is to understand what physics have a first-order impact on the output vs. second- and third-order effects. This argument gains in significance if it is additionally considered that all input data associated with a reservoir model is uncertain. It is imperative, therefore, to have a reservoir simulator that is, in Einstein’s words, “as simple as possible but not simpler.” Once the partial differential equations have been defined, they can be solved either analytically or numerically. Analytic methods exactly solve the flow equations under a simplified set of conditions (e.g., pressure-transient solutions for homogeneous reservoir properties), while numerical methods provide an approximate solution to a more complex set of relations. Most reservoir simulators employ numerical methods because of their broad applicability. For example, analytical methods cannot generally cope with heterogeneous domains, and it is, therefore, not possible to impose a complex permeability/porosity distribution.

There are two general types of numerical methods: gridded (discretized) methods and nongridded methods. The most common numerical methods are finite-difference (FD) and finite-element methods (FEMs) in which the domain (reservoir) is completely gridded (divided into a number of small elements). Analytic element methods and the boundary integral (or boundary element) methods are discretized at boundaries or along flow elements (e.g., line sinks, area sources), with the inner element domain being mesh free. We will not address these later methods because they are not widely employed for reservoir simulation.

Gridded methods like FD and FEMs solve the flow equations by dividing the domain into many small geometric elements, which are referred to as nodes, cells, or gridblocks. (Nodes would generally refer to a point location, while cells or gridblocks would refer to a volume). In other industries/applications that require solutions to be at nodes, the layout is called “the mesh,” and the process is known as “mesh generation.” Gridding is required for two primary aspects: (1) to solve the pressure and saturation values, and (2) to account for variations in static reservoir properties. The flow equations are solved for each element (all material properties are assumed constant or possibly linearly variable within an element). The elements are linked together using conservation of mass and

momentum across the boundaries between the elements; for example, the mass going out of a block should equal the total mass entering its neighbors. There are many differences between finite-element and FD formulations, each having advantages and disadvantages. FD methods have been significantly more popular in the petroleum industry, and most all commercially available reservoir simulators use FDs.

This subdivision of the reservoir into nodes or cells is called spatial discretization. Time is also discretized into timesteps; therefore, the equations are solved only at the nodes or cells and at the ends of timesteps. Among the available options, FD methods are the simplest to understand and implement. They are a way of representing continuous differential operators using discrete intervals (Δx a distance difference and Δt a time difference). For example, pressure is a continuous variable over the reservoir volume, and a pressure change caused by the introduction of production wells leads to fluid movement. The change in pressure with time is a reflection of fluid movement and withdrawal from the system. In FD formulations, the first-order time derivative (i.e., pressure change at a specific location with respect to time) is often approximated using a backward FD, in which the superscripts indicate a discrete time value:

$$\frac{\partial p}{\partial t} = p'(t^n) \approx \frac{p^n - p^{n-1}}{t^n - t^{n-1}} = \frac{\Delta p^n}{\Delta t} \dots\dots\dots (1.1)$$

The FD grids can be formulated using point-centered grids in which the formulation is centered on gridded points (mesh nodes) or centered on the center of the blocks (block centered). A special case of block-centered gridding is the corner-point geometry that is widely used in commercial simulators (see Advanced Reading Box).

In FEMs, the solution of the flow equations relies on interpolation functions. The nodal values are solved in a manner to minimize the numerical error associated with the approximation of the partial differential equations on the average, over the domain. There are many methods available for approximating the complex flow functions for finite elements. Also, the domain for finite elements can be discretized in a variety of ways, ranging from 1D line elements to triangles and prisms.

The advantage of the finite-element formulation is its ability to mimic complex geometry because of the variety of ways in which a domain can be discretized. This feature makes finite elements well suited to problems involving moving boundaries, such as geomechanical deformation. However, FD has the advantage of computational efficiency and of ensuring continuous fluid flux continuity between cells. In other words, the sum of fluxes out of a cell equals the sum of flux into other cells or to wells. In the finite-element formulation, unless the material is uniform, the fluxes may not necessarily be continuous and can lead to material-balance errors. However, methods can be employed to address these limitations. The advantages discussed above are the reason that many commercial simulators to date have relied on FD approaches.

Finite volume and control-volume-finite-element (CVFE) are two other gridding options. Finite volume is a method in which the governing equations for flow are integrated around the boundary of each gridded volume or element. Flows in/out of the elements are evaluated by summing the flows in/out from each contributing subarea. The CVFE method can be considered a combination of the finite-element and finite-volume methods. It has the flexibility of domain discretization of the FEM, and the capability of conserving physical quantities of the finite volume method. There is much interest today in the application of CVFE methods to handle complex geometries and flow behavior.