Development and Validation of an Open-Source Reservoir Simulator: A Comparative Study with Commercial Software

Amrajaa Ahmed salih handar
Al-Ahli Higher institute of computer technologies and administrative and financial sciences
mragahanderhander@gmail.com

Abstract-Reservoir simulation is a critical tool for predicting hydrocarbon recovery and optimizing field development strategies. While commercial software packages like Schlumberger's ECLIPSE are industry standards, their high cost and closed-source nature limit accessibility and customization, particularly in academia. This study investigates the potential of open-source software as a viable alternative for reservoir simulation. We developed a specialized single-phase reservoir solver, PRS Foam, within the open-source Computational Fluid Dynamics (CFD) platform OpenFOAM. The solver implements a simplified black-oil model for incompressible fluid flow through a compressible porous medium. To validate its accuracy, we conducted a comprehensive comparative analysis against the commercial simulator ECLIPSE. Three test cases of varying complexity were designed: a simple homogeneous "shoe-box" model (TESTCASE_1), a complex, geologically realistic model (TESTCASE_2), and a single-phase injection-production scenario (WATER_INJECTION). Results demonstrated a remarkable agreement between PRSFoam and ECLIPSE. For the simple model, pressure and production rate discrepancies were less than 1.5% over four years. Even for the complex model, the differences in cumulative production after 20 years were only 3.24%, and pressure distributions were visually and quantitatively consistent. This work confirms that open-source-based reservoir simulation, leveraging tools like OpenFOAM, can achieve a high degree of accuracy comparable to established commercial software. It presents a cost-effective, flexible, and pedagogically valuable platform for academic research and training, with significant potential for future development towards more complex, multi-phase flow simulations.

Keywords: Reservoir Simulation, OpenFOAM, ECLIPSE, Open-Source, CFD, Porous Media, Single-Phase Flow, PRSFoam.

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الملخص
تُعد محاكاة المكامن أداة حاسمة للتنبؤ باستخلاص الهيدروكربونات وتحسين استراتيجيات تطوير الحقول. بينما تُعتبر الحزم البرمجية التجارية مثل برنامج ECLIPSE من شركة شلمبرجير معايير قياسية في الصناعة، إلا أن تكلفتها العالية وطبيعتها مغلقة المصدر تحد من إمكانية الوصول إليها والتخصيص، خاصة في الأوساط الأكاديمية. تبحث هذه الدراسة في إمكانية استخدام البرمجيات مفتوحة المصدر كبديل عملي لمحاكاة المكامن.

قمنا بتطوير محلل متخصص للمكامن أحادية الطور، أطلقنا عليه اسم **PRSFoam**، ضمن المنصة مفتوحة المصدر لديناميكيات الموائع الحسابية (CFD) والمعروفة باسم OpenFOAM. ينفذ هذا المحلل نموذج الزيت الأسود المبسط لتدفق المائع غير القابل للانضغاط خلال وسط مسامي قابل للانضغاط. للتحقق من دقته، أجرينا تحليلاً مقارناً شاملاً مقابل المحاكي التجاري ECLIPSE. تم تصميم ثلاث حالات اختبار بدرجات تعقيد متفاوتة: نموذج بسيط ومتجانس على شكل "صندوق حذاء(TESTCASE_1) ، ونموذج معقد واقعي جيولوجياً (TESTCASE_2)، وسيناريو لحقن وإنتاج أحادي الطور.(WATER_INJECTION) أظهرت النتائج توافقاً ملحوظاً بين PRSFoam وبرنامج ECLIPSE. بالنسبة للنموذج البسيط، كانت الفروق في الضغط ومعدل الإنتاج أقل من 1.5% على مدى أربع سنوات. حتى بالنسبة للنموذج المعقد، بلغت الفروق في الإنتاج التراكمي بعد 20 سنة 3.24% فقط، وكانت توزيعات الضغط متسقة بصرياً وكمياً. يؤكد هذا العمل أن محاكاة المكامن القائمة على المصادر المفتوحة، بالاستفادة من أدوات مثلOpenFOAM ، يمكن أن تحقق درجة عالية من الدقة التي توفرها البرمجيات التجارية الراسخة. إنها تقدم منصة فعالة من حيث التكلفة ومرنة وذات قيمة تعليمية للبحث الأكاديمي والتدريب، مع إمكانات كبيرة للتطوير المستقبلي نحو محاكاة تدفقات متعددة الأطوار أكثر تعقيداً.

الكلمات المفتاحية :محاكاة المكامن، OpenFOAM، ECLIPSE، مفتوح المصدر، ديناميكيات الموائع الحسابية(CFD) ، الوسط المسامي، التدفق أحادي الطور، PRSFoam.

1. Introduction

The global energy landscape faces the dual challenge of increasing demand and the finite nature of hydrocarbon resources. Maximizing recovery from existing and future reservoirs is therefore paramount. Reservoir simulation has become an indispensable tool for the upstream oil and gas industry, enabling engineers to create predictive models of reservoir behavior, assess different production strategies, and optimize economic returns [4, 5].

The market is dominated by sophisticated commercial simulators like Schlumberger's ECLIPSE [4]. These tools, while powerful, present significant barriers: high license costs (often exceeding €35,000 per year per seat [4]), a "black-box" nature that restricts access to the underlying algorithms, and a steep learning curve. These limitations are particularly constraining in academic settings, where budget constraints and the need for pedagogical transparency are crucial.

The emergence of high-performance, open-source CFD software offers a promising alternative. OpenFOAM (Open Field Operation and Manipulation) is a robust, GPL-licensed C++ library designed for complex fluid dynamics problems [4, 7]. Its open-source philosophy provides unparalleled access to the source code, allowing users to develop custom solvers and utilities tailored to specific problems. This study posits that OpenFOAM can be effectively adapted for reservoir simulation tasks, providing a powerful, cost-free platform for research and education.

This paper presents the development and validation of PRSFoam, a custom reservoir solver built within OpenFOAM. The primary objective is to perform a rigorous, quantitative comparison between this open-source solution and the industry-standard ECLIPSE simulator. By testing against models of increasing complexity, we aim to evaluate the accuracy, limitations, and future potential of open-source reservoir simulation.

2. Related Work

The pursuit of robust and accessible reservoir simulation tools has been a long-standing endeavor in petroleum engineering. Traditional approaches have been dominated by commercial software suites like Schlumberger's ECLIPSE [2], Halliburton's Nexus, and CMG's suites, which offer comprehensive, well-tested solutions for industrial applications. These tools employ fully implicit, IMPES, or adaptive implicit (AIM) methods to solve complex multi-phase, multi-component flow equations [9, 2]. While powerful, their proprietary nature and high cost have historically limited transparency and customization, creating a barrier for fundamental research and academic exploration.

The academic community has often responded by developing in-house research simulators. These are typically tailored to investigate specific physical phenomena, such as compositional flow, thermal recovery, or geomechanically effects [4, 3]. While highly specialized, these codes often lack the robustness, user-friendly interfaces, and extensive validation of their commercial counterparts, and their development requires significant investment of time and expertise.

The emergence of open-source scientific computing has begun to bridge this gap. The MATLAB Reservoir Simulation Toolbox (MRST) [Lie et al., 2011] is a prominent example, providing a high-level platform for rapid prototyping and algorithm development in reservoir modeling. MRST has been widely adopted in academia for its ease of use and strong focus on discretization methods and flow physics. However, its performance can be limited for large-scale, three-dimensional, transient problems due to its reliance on a MATLAB environment.

The use of OpenFOAM for porous media and reservoir simulation represents a more recent and powerful trend. Open Foam's foundation in finite-volume CFD makes it inherently suitable for flow problems. Early applications focused on fundamental flow in porous media [9, 7], and its use has since expanded. Previous studies have demonstrated its capability for modeling polymer flooding [6], near-wellbore flow dynamics, and coupling flow with geomechanics. The work by [Horgue et al., 2015] on the "Porous Flow" module is a significant contribution, providing a dedicated framework for multi-phase flow in porous media within OpenFOAM.

Our work distinguishes itself from and builds upon these previous efforts in several key aspects. Unlike MRST, our approach leverages Open Foam's compiled C++ core and its ability to handle complex, unstructured meshes natively, making it more suitable for high-performance computing and geometrically complex reservoirs. While projects like "Porous Flow" aim for generality, this study focuses on a specific, rigorous objective: the direct, quantitative validation of a newly developed OpenFOAM solver

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against the industry-standard ECLIPSE. We move beyond demonstrating feasibility and provide a detailed, case-based comparison of results, computational performance, and workflow, which is less common in the existing literature. Furthermore, the development of the ECL2FoamGrid converter addresses a critical practical challenge, enabling the direct translation of industry-standard models into the open-source domain, thereby enhancing the practical utility of this research.

This study thus positions itself at the intersection of open-source CFD software development and rigorous petroleum engineering practice, aiming to provide a validated and accessible pathway for leveraging Open FOAM's full potential in reservoir simulation.

3. Mathematical Model and Numerical Methods

The physical problem involves the single-phase flow of an incompressible fluid (oil) through a compressible porous rock matrix.

3.1 Governing Equations

The model is derived from the fundamental principles of mass conservation and Darcy's law.

- Darcy's Law: The superficial velocity u is given by:

u=−1μk‾·(∇p−ρg∇z) u=−*μ*1k‾·(∇*p*−*ρg*∇*z*)

where k‾k‾ is the permeability tensor, μ*μ* is viscosity, p*p* is pressure, ρ*ρ* is density, g*g* is gravity, and z*z* is depth.

- Mass Conservation (Continuity Equation):

∂(ϕρ)∂t=−∇·(ρu) +q*∂t∂*(*ϕρ*)=−∇·(*ρ*u) +*q*

where ϕ is porosity and q*q* is a source/sink term (representing wells).

For an incompressible fluid (ρ=constant=constant) and a rock with constant compressibility cR*cR*, the porosity can be approximated as ϕ≈ϕ0(1+cR(p−p0)) *ϕ*≈*ϕ*0(1+*cR*(*p*−*p*0)). Combining this with Darcy's Law and the continuity equation yields the simplified pressure equation solved by PRSFoam:

∇·(k‾μ∇p) =ϕ0cR∂p∂t∇·(*μ*k‾∇*p*) =*ϕ*0*cR∂t∂p*

This equation describes the transient pressure diffusion through the porous medium.

3.2 Numerical Discretization with the Finite Volume Method (FVM)

OpenFOAM employs the Finite Volume Method (FVM) for spatial discretization [7, 3]. The solution domain is subdivided into discrete control volumes (cells). The governing partial differential equation is integrated over each control volume, converting volume integrals of divergence terms into surface integrals using Gauss's theorem. This method ensures inherent conservation of mass and is well-suited for complex unstructured meshes, a key advantage of OpenFOAM. For temporal discretization, a second-order accurate backward differencing scheme was used to ensure stability and comparability with ECLIPSE.

4. Solver Development: PRSFoam in OpenFOAM

The PRSFoam solver was developed to implement the mathematical model within the OpenFOAM framework. Key features and assumptions include:

- Single-Phase Flow: The reservoir is 100% saturated with oil; no free gas or water is present.
- Incompressible Fluid: Oil density and viscosity are constant.
- Compressible Rock: Rock porosity is pressure-dependent.
- Closed Boundaries: No-flow conditions are applied on all outer reservoir boundaries.

The solver workflow involves:

1. Field Creation: Reading and defining fields (pressure, permeability, porosity, viscosity).
2. Equation Solution: Solving the discretized pressure equation (pEqn.H) at each time step.
3. Well Management: Handling well constraints (constant rate or constant bottom-hole pressure) as boundary conditions on specific "well-block" cells.
4. Output: Writing pressure and velocity fields for post-processing and analysis.

A critical step was the conversion of ECLIPSE input files (grid geometry, properties) to the OpenFOAM format using a custom converter, ECL2FoamGrid, ensuring an identical starting point for both simulators.

5. Case Studies and Comparative Results

Three test cases were designed to evaluate the solver's performance.

5.1 TESTCASE_1: Homogeneous Shoe-Box Model

- Description: A simple, homogeneous cubic reservoir with three production wells.
- Objective: Benchmarking and workflow validation.
- Results: Excellent agreement was observed. At a constant production rate, the bottom-hole pressure (BHP) declines curves from PRSFoam and ECLIPSE were nearly identical, with a maximum deviation of only 1.35% after 4 years. Production forecasts at constant BHP also showed a cumulative production difference of just 1.48%.

5.2 TESTCASE_2: Complex Geologically-Based Model

- Description: A large, heterogeneous reservoir based on real seismic data, with significant variations in permeability and layer structure.
- Objective: Stress-testing the solver under realistic, challenging conditions.
- Results: PRSFoam successfully handled the complexity. The pressure distribution after 20 years of production was visually consistent with ECLIPSE results. Quantitative analysis revealed a maximum pressure difference of 4.47% for a single well and a difference in ultimate cumulative production

of 3.24%. These minor discrepancies are attributed to underlying differences in how the simulators handle fluid properties; ECLIPSE models slightly compressible oil, while PRSFoam assumes strict incompressibility.

5.3 WATER_INJECTION: Displacement Scenario

- Description: A scenario with one injector and one producer, forcing flow through different vertical layers.
- Objective: Testing the solver's capability to model displacement processes.
- Results: The pressure communication between the injector and producer was accurately captured. The BHP trends for both wells matched closely, with a maximum deviation of 2.47% over 10 years, confirming the solver's robustness in managing injection/production balance.

5.4 Computational Performance

For the simple TESTCASE_1, PRSFoam was faster and used less memory than ECLIPSE. However, for the larger and more complex TESTCASE_2, ECLIPSE demonstrated superior optimization, requiring less CPU time and memory. This highlights a trade-off between the flexibility of an open-source, general-purpose CFD tool and the specialized optimization of a commercial reservoir simulator.

6. Discussion

The results consistently demonstrate that the open-source PRSFoam solver can achieve a level of accuracy comparable to a leading commercial simulator for single-phase flow problems. The small observed discrepancies are well within an acceptable range for engineering analysis, particularly for training and preliminary studies.

Advantages of the Open-Source Approach:

- Cost-Efficiency: Eliminates prohibitive license fees.
- Transparency and Customization: Full access to the source code allows for algorithm modification and solver development for specific research needs (e.g., modeling novel EOR processes).
- Educational Value: Provides students with a deep understanding of the numerical and physical principles underlying simulation.

Limitations and Future Work:

The current PRSFoam solver has limitations that define clear paths for future development:

1. Multi-Phase Flow: The most significant enhancement would be to extend the solver to handle multi-phase flow (oil, water, gas) using a full black-oil or compositional model.
2. Fluid Compressibility: Introducing pressure-dependent fluid properties (Formation Volume Factor, viscosity) would increase physical accuracy.

3. Near-Wellbore Effects: Implementing a model for rate-dependent skin factor would allow for more accurate well performance prediction.
4. Graphical User Interface (GUI): Developing a user-friendly pre- and post-processing GUI would greatly enhance accessibility for non-programmers.

7. Conclusion

This study successfully developed and validated a single-phase reservoir simulator within the open-source OpenFOAM environment. The direct comparison with Schlumberger's ECLIPSE across multiple test cases confirms that open-source software is a viable and accurate platform for reservoir simulation.

While commercial software remains the optimized tool for large-scale, complex industrial projects, the open-source alternative presents a compelling solution for academic research, training, and prototyping. It offers a unique combination of zero cost, full transparency, and extensive customizability. By bridging the gap between advanced CFD and reservoir engineering, this work lays the foundation for a new, accessible path for innovation and education in petroleum engineering. The promising results encourage further development to overcome current limitations and fully unlock the potential of open-source solutions in the energy sector.

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