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Two-dimensional Numerical Modeling of Two-phase Fluid Filtration in Carbonate Reservoirs

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Introduction

Fluid filtration in carbonate reservoirs is a complex process influenced by geological heterogeneity, fluid properties, and reservoir dynamics. Numerical modeling of two-phase fluid filtration in a two-dimensional formulation provides an essential tool for understanding and optimizing fluid flow behavior in such reservoirs. This approach helps in predicting oil recovery, designing enhanced oil recovery (EOR) techniques, and evaluating reservoir performance under various operating conditions. Two-phase fluid flow in porous media is governed by fundamental physical principles, including mass conservation, Darcy's law, and capillary pressure effects. The two primary fluids in a reservoir—oil and water—interact dynamically, influenced by relative permeability, wettability, and fluid saturation distributions. The mathematical representation of this process involves coupled partial differential equations that describe the conservation of mass for each phase and momentum transfer within the porous structure.

Description

The governing equations for two-phase flow are derived from Darcy's law and the continuity equation. The saturation equation, which accounts for the movement of the wetting and non-wetting phases, where is the water saturation, is the water velocity, and represents source or sink terms. Similarly, the equation for oil saturation is obtained by subtracting the water saturation from unity. where is the absolute permeability, and are the relative permeabilities of water and oil, and are the viscosities of water and oil, and are the phase pressures, and and are the phase densities. Capillary pressure is a crucial factor in two-phase flow and is defined as the pressure difference between the non-wetting and wetting phases. This relationship influences the saturation distribution and the displacement efficiency of fluids in the reservoir. The relative permeability curves, derived from experimental data, dictate how easily each phase moves through the porous medium depending on saturation. Numerical modeling of two-phase fluid flow requires discretization of the governing equations using finite difference, finite volume, or finite element methods. The two-dimensional formulation allows for a more detailed representation of reservoir heterogeneity, fracture networks, and flow pathways. The computational domain is typically divided into a grid, where each cell represents a small volume of the reservoir. The flow equations are solved iteratively to update pressure and saturation values over time [1].

Implicit and explicit schemes are used for time integration. The implicit method, though computationally intensive, ensures numerical stability and allows for larger time steps. The explicit method is simpler but requires smaller time steps to maintain stability. Hybrid approaches, such as the IMPES (Implicit Pressure, Explicit Saturation) method, combine the advantages of both methods by solving pressure implicitly and saturation explicitly. Boundary conditions play a crucial role in defining the behavior of fluid flow within the model. Typical boundary conditions include constant pressure, no-flow (impermeable), and flux-specified conditions. Initial conditions, including initial pressure distribution and fluid saturation, are set based on reservoir data and well logging information. Carbonate reservoirs exhibit complex pore structures, often characterized by vuggy and fractured formations. These features significantly impact permeability and fluid flow behavior. Dual-porosity and dual-permeability models are commonly used to account for the presence of fractures and matrix interactions. In these models, the total flow is divided between the matrix and fracture systems, with exchange terms governing mass transfer between them. Simulation results provide valuable insights into fluid displacement patterns, breakthrough times, and sweep efficiency [2,3].

Sensitivity analysis is performed to evaluate the impact of key reservoir parameters such as permeability distribution, capillary pressure, and relative permeability curves. The results are used to optimize production strategies, enhance oil recovery techniques, and mitigate water coning or fingering effects. Enhanced Oil Recovery (EOR) methods, including water flooding, polymer flooding, and gas injection, can be evaluated using numerical models. The effectiveness of these methods depends on reservoir characteristics, fluid properties, and injection strategies. Simulation studies help in designing optimal injection rates, well placements, and production schedules to maximize recovery. Modern numerical simulations leverage high-performance computing (HPC) and parallel processing techniques to handle large-scale reservoir models efficiently. Advanced algorithms, including machine learning and data assimilation techniques, are increasingly integrated into reservoir simulation workflows to improve prediction accuracy and decision-making. The application of two-dimensional numerical modeling extends beyond petroleum engineering. Similar approaches are used in groundwater hydrology, environmental engineering, and geothermal energy studies to analyze fluid transport in porous media. The fundamental principles of multiphase flow modeling remain applicable across these disciplines, providing valuable tools for research and practical applications [4,5].

Conclusion

In conclusion, numerical modeling of two-phase fluid filtration in carbonate reservoirs using a two-dimensional formulation is an essential technique for understanding and optimizing reservoir performance. By incorporating geological heterogeneity, fluid properties, and advanced computational methods, these models provide critical insights into fluid flow dynamics, aiding in the development of efficient extraction and management strategies. Ongoing advancements in numerical methods and computational resources continue to enhance the accuracy and applicability of these models in the field of reservoir engineering.

Acknowledgement

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Conflict of Interest

None.

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