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Numerical Modeling of Permeability in Porous Media: Integrating Experimental and Computational Approaches for Enhanced Fluid Flow Prediction in Petroleum Reservoirs

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Abstract**—*Permeability analysis considers both symmetric and asymmetric flow patterns. The study focuses on theoretical research into the permeability of porous media, which entails a thorough examination of the fundamental concepts and mathematical models that regulate fluid flow through porous media. After researching and assessing existing theoretical frameworks and models for permeability in porous media, including ideas like Darcy's law, which characterizes fluid flow through porous medium using pressure differentials and hydraulic conductivity. We used mathematical models to investigate how different factors and situations influence the permeability of porous media. This study advances our understanding of fluid flow in porous media by utilizing numerical simulation approaches, as well as providing insights into the complicated mechanisms determining permeability. This work has practical applications in fields such as groundwater hydrology, geotechnical engineering, petroleum reservoir characterization, and environmental remediation.*

Keywords**—*Porous media, Permeability, Numerical simulation, Asymmetric structure, uniform distribution.*

I. INTRODUCTION

The recovery of oil and gas from underground reservoirs is a complex process that requires a deep understanding of fluid dynamics in porous media, particularly permeability [1–4]. Traditional empirical models, such as the Kozeny-Carman equation [5], struggle to accurately model and predict permeability due to the complexity of pore structures and fluid properties. Therefore, numerical simulations, which integrate experimental data with advanced computational techniques like Computational Fluid Dynamics (CFD) [6,7] and the Lattice Boltzmann Method (LBM) [7,8], have become increasingly important. These methods offer improved predictive accuracy and provide deeper insights into permeability evolution in cracked porous media, which is critical for addressing fluid flow concerns across various engineering fields. Understanding the hydraulic conductivity (K) [9,10] of porous sediments is also vital for simulating water flow in saturated zones. Empirical formulas for estimating K often limit the use of field techniques, highlighting the importance of fluid analysis in optimizing operational efficiency, minimizing energy consumption, and preventing costly disruptions in macro piping systems [11,12]. The microscopic flow of gases within rocks and soils holds significant implications for geoscience, environmental engineering, and energy management [13,14]. Exploring these dynamics is crucial for enhancing oil recovery, improving groundwater contamination predictions, and developing innovative solutions for subsurface resource exploration and production. This research adopts a comprehensive, multidisciplinary approach that combines experimental methods, advanced computational models, and real-world field observations.

In the present work, we hope to bridge the gap between classic empirical models and modern computational techniques for estimating permeability in porous media. We improve our understanding of fluid flow in complicated pore structures by combining experimental data, CFD, and the LBM. This holistic approach not only refines existing models but also opens up new paths for improving oil recovery processes, resulting in more efficient and sustainable extraction methods in petroleum engineering.

II. MATERIALS AND METHOD

We used MATLAB for numerical simulation, and according to the obtained results, we then arranged the vessel geometry as displayed in Fig. 1.

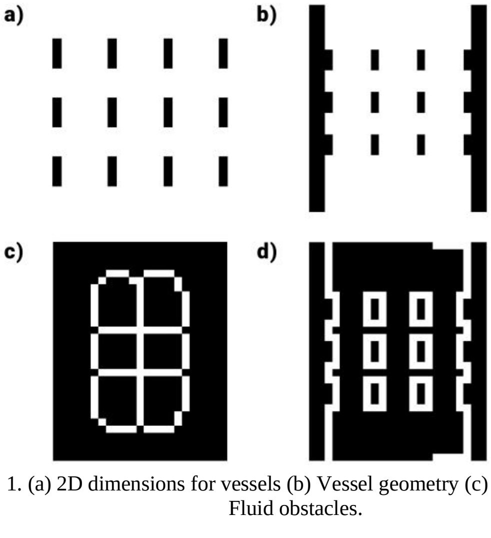

Fig. 1. (a) 2D dimensions for vessels (b) Vessel geometry (c) Medial axis (d) Fluid obstacles.

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The analysis of pipe systems involves macroscopic and microscopic flow of hot fluid. Macroscopic methods focus on the uniform distribution of fluid throughout the system, using angles, symmetry, inlet velocity, and pressure. In contrast, microscopic methods use fractal models and numerical simulations like MATLAB, ANSYS, and FLUENT. The macro and micro piping system model which we used is shown in Fig. 2.

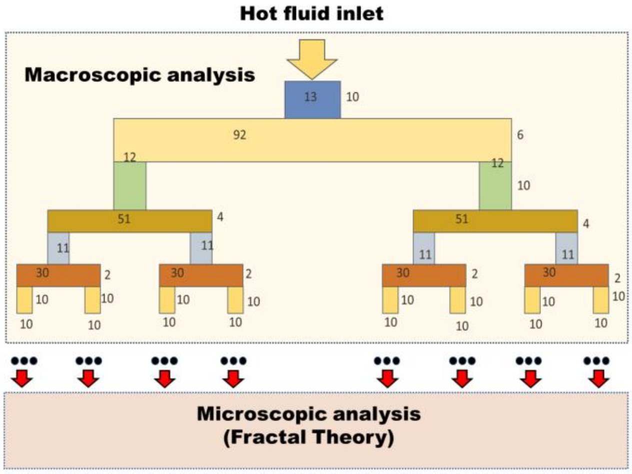

Fig. 2. Schematic illustration of Macroscopic and Microscopic fluent flow analysis.

Fluent Analytics is a tool that allows researchers and engineers to study fluid behavior in pipelines, enabling detailed simulation and predictive modeling of flow patterns, pressure gradients, and turbulence. This approach helps optimize pipeline design, operational strategies, and maintenance protocols while reducing operational risk by evaluating performance metrics and identifying potential bottlenecks in a virtual environment.

III. RESULTS AND DISCUSSION

The graphs below represent the convergence path of a numerical solution Fig. 3(a), a crucial aspect in computational simulations to ensure the model accurately reflects the physical system. The analytical solution Fig. 3(b), derived from mathematical equations, is displayed to verify the simulation's accuracy. The flow profile Fig. 3(c) in a channel illustrates fluid movement, allowing for optimization of channel design and minimizing energy losses. The fluid velocity profile Fig. 3(d) shows the distribution of fluid velocity across the channel, enabling analysis of fluid dynamics and its changes with position. Understanding these graphs is essential for optimizing flow conditions and ensuring uniform distribution, which can affect system efficiency.

Several factors were considered while calculating the initial edge value (IEV) for geometric models of porous media. The IEV for a porous medium model was determined based on its geometric features, mesh quality, physical properties, boundary conditions, solver requirements, and convergence and stability. The mesh resolution and refinement were crucial for accurately capturing flow behavior within the porous medium. The boundary conditions, such as porosity, permeability, and tortuosity, were also considered. Different solvers were used to ensure optimal convergence and accuracy. The IEV was chosen to achieve convergence and stability within a reasonable computational time, with adjustments made based on preliminary simulations and sensitivity analyses to ensure robust and reliable results.

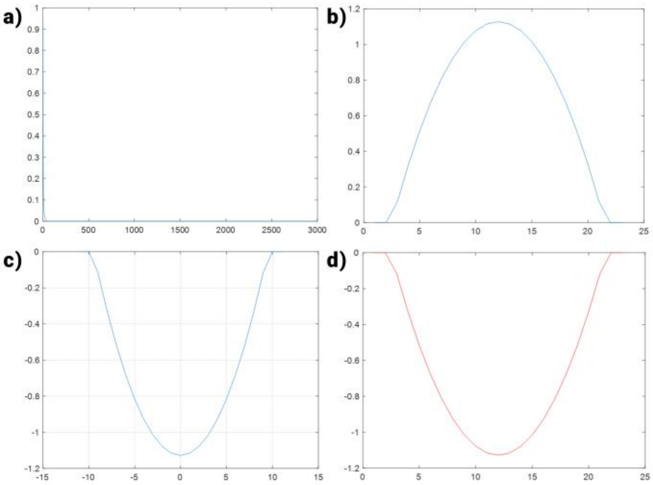

Fig. 3. (a) Convergence path. (b) Analytical solution. (c) Flow profile in the channel. (d) Fluid Velocity Profile.

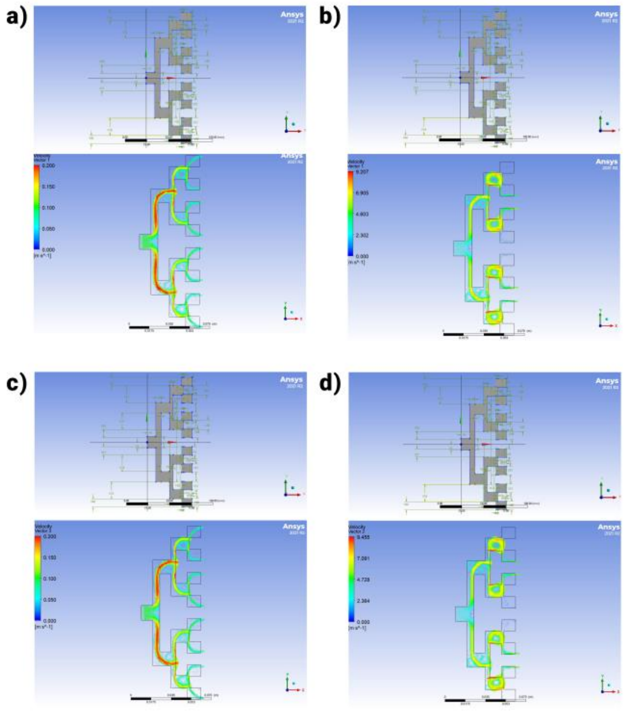

Fig. 4. Geometrical and CFD results; inlet velocity and inlet pressure of fluid flow expansion. (a) Velocity: 0.1 m/s, Pressure: 1e5pa, Angle: 90, 90, 90 (b) Velocity: 3 m/s, Pressure: 1e5pa, Angle: 90, 90, 90 (c) Velocity: 0.1 m/s, Pressure: 1e5pa, Angle: 90, 90, 90, Alpha: 1.01 (d) Velocity: 3 m/s, Pressure: 2e5pa, Angle: 90, 90, 90.

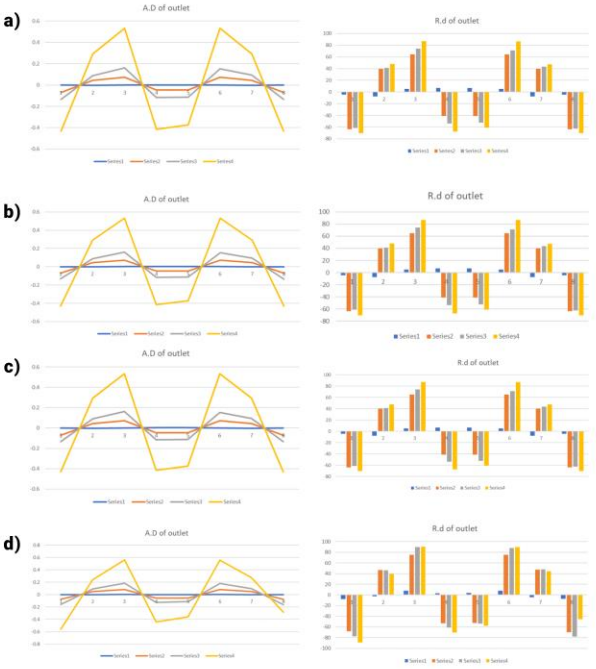

Fig. 5. Inlet velocity and inlet pressure of fluid flow expansion (a) Velocity = 0.1 m/s, 0.5 m/s, 1 m/s, and 3 m/s; Pressure = 1e5pa, Angle = 90º:90º:90º (b) Velocity = 0.1 m/s, 0.5 m/s, 1 m/s, and 3 m/s; Pressure = 1e5pa; Angle = 90º:90º:90º; α = 1.01 (c) Velocity = 0.1 m/s, 0.5 m/s, 1 m/s, and 3 m/s; Pressure = 1e5pa, Angle = 90º:90º:90º (d) Velocity = 0.1 m/s, 0.5 m/s, 1 m/s, and 3 m/s; Pressure = 2e5pa; Angle = 90º:90º:90º; α = 1.01.

IV. CONCLUSION

In this research, 17 angles of experiments were conducted with two types of pressure and four types of inlet velocities. The results showed that the blue trend (0.1 m/s) was consistent throughout all experiments, while the purple trend (1 m/s) initially ascended and then declined. The yellow trend (3 m/s) begins below the baseline and ascends until the third outlet. The study also examined the impact of changing a symmetric structure to an asymmetric one on outlet distribution, particularly focusing on different alpha values (1.01, 1.05, and 1.1). The results showed that using an inlet velocity of 0.1 m/s consistently produced the best outcomes across all experiments, ensuring normal flow in all outlets and reducing the number of vertices in the streamlined images.

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