Flow Modelling in Porous Medium Applying Numerical Techniques: A Comparative Analysis

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Abstract

This research paper presents a comprehensive comparative analysis of various numerical methods employed for simulating the flow of fluid in the porous medium. Porous media is crucial in numerous applications, including petroleum engineering, environmental science, and geology. Accurate modelling of flow in porous materials is essential for understanding and predicting the behaviour of fluids and contaminants. The study focuses on comparing the effectiveness and efficiency of different numerical methods in capturing the complex phenomena occurring in porous media. The results obtained from simulations using each method are analysed and discussed, highlighting their respective strengths and limitations. The findings of this research will aid researchers and practitioners in selecting appropriate numerical methods for their specific applications.

Keywords: Numerical methods, porous media, fluid flow, comparative analysis, simulation, computational efficiency, accuracy.

1. Introduction

Porous media hold significant importance across various domains such as petroleum engineering, environmental science, image processing and geology. These materials consist of interconnected void spaces that allow the flow of fluids and the transport of substances within them. Gaining insights into fluid flow and transport behaviours within porous media holds paramount significance across diverse applications such as oil and gas extraction, groundwater management, and environmental remediation [1]. Numerical methods have become indispensable tools for studying and simulating the processes flow as well as the transport in porous medium. These methods involve the use of mathematical models and computational algorithms to approximate and solve the governing equations that describe the behaviour of fluids and solutes in porous materials. By discretizing the porous media domain and solving the resulting equations numerically, researchers can gain valuable insights into the complex phenomena occurring within these materials [2].

The significance of numerical methods lies in their ability to provide a quantitative understanding on the phenomena of flow and transport in the porous medium. They enable researchers to investigate intricate processes such as multiphase flow, solute transport, and the interaction between fluids and porous structures. Moreover, numerical methods offer the advantage of being able to simulate and analyze these phenomena under various conditions, which may be challenging or impractical to achieve experimentally [3].

This study seeks to achieve research objectives focused on assessing and contrasting the efficacy and efficiency of diverse numerical methods in simulating fluid flow within porous media. The primary goal is to scrutinize the performance of methods like finite volume, finite difference, and finite element methods, drawing insights from the works of [4],[5],[6]. These methods have been widely employed in porous media studies due to their versatility and computational efficiency. By comparing these methods, the respective strengths and limitations in accurately capturing the flow behaviour and predicting transport phenomena in porous materials is focussed.

By conducting a comparative analysis of numerical methods in porous media, this research aims to provide valuable insights for researchers and practitioners in selecting appropriate numerical approaches for their specific applications. The findings of this study will contribute to the existing body of knowledge in porous media modelling and assist in advancing the understanding of fluid flow and transport processes in these materials.

2. Related Work

Numerical methods have been extensively employed in studying the transport phenomena and the flow through the porous medium. Many methods have emerged as common choices for simulating these complex processes. This section presents a review of the existing literature on numerical methods commonly used in porous media studies, along with their advantages, limitations, and previous comparative studies [7].

Finite difference methods are widely utilized due to their simplicity and computational efficiency. These methods discretize the porous media domain into a grid and using difference operators, the governing equation derivatives are approximated. This offers a straightforward implementation and good accuracy for regular geometries. However, they may face challenges in handling complex geometries and irregular grids, limiting their applicability in certain scenarios [8].

For example, the one-dimensional finite difference discretization of Darcy's law [9] for flow in a porous media can be represented as:

$$\frac{k_{i+1/2}(P_{i+1} - Pi) - k_{i-1/2}(P_i - P_{i-1})}{\Delta x_i} = \rho_i g$$

where P_i represents the pressure at grid point i, $k_{i+1/2}$ and $k_{i-1/2}$ are the hydraulic conductivities at the interfaces, Δx_i is the grid spacing, ρ_i denotes "the fluid density", and "g" signifies the "gravitational acceleration".

Finite difference techniques are commonly employed owing to their straightforwardness and computational effectiveness. These methods discretize the porous media domain into a grid and using the finite differences the governing equation derivatives are approximated. They offer straightforward implementation and good accuracy for regular geometries. However, they may face challenges in handling complex geometries and irregular grids, limiting their applicability in certain scenarios [10]

Finite element methods are versatile numerical techniques that have gained popularity in porous media modelling. They employ a mesh of elements to discretize the domain and express the solution as a combination of basic functions within each element. Finite element methods are well-suited for handling complex geometries and adaptivity, and they provide accurate solutions. However, they typically require more computational resources compared to finite difference methods, making them computationally demanding for large-scale simulations [11].

“Finite volume methods” are another frequently utilized approach in simulating porous media. These approaches split the realm into control volumes and focus on the conservation laws for mass, momentum, and energy within these volumes. Finite volume methods are known for their ability to handle complex geometries, including heterogeneous and anisotropic media. They offer accurate solutions and good mass conservation. However, they can be computationally expensive, particularly when dealing with fine grids and complex physical processes [12].

Several previous studies have compared different numerical methods in the context of porous media simulations. For instance [13], these methods are very good and exhaustive on finite difference method compared to other methods.

[14] Investigate numerical methods for constrained variable-order in time fractional diffusion problems. The investigation delves into three distinct finite difference methods: the implicit scheme, explicit scheme, as well as the Crank-Nicholson scheme. The outcomes of numerical analyses demonstrate that the implicit scheme and the Crank-Nicholson scheme exhibit remarkable precision when contrasted with the explicit scheme. Notably, the Crank-Nicholson scheme consistently attains the highest level of accuracy across various scenarios.

[15], introduced a finite-difference technique for simulating steady-state creeping fluid flow within porous media at the pore scale.[4] extended this method to address transient flow problems in porous media by replacing the continuum with a system of finite elements.

[16], a thorough explanation of the underlying physics was given, including the equations regulating flow through porous media and the deformation properties of rocks and soils. They also talked on the application of theory in both experimental and real-world settings, as well as its practical implications.

[17], provides a fully coupled, fully implicit discretization of two-phase flow in cracked porous media using a vertex-centered finite volume approach. On unstructured, locally refined grids and parallel processors with distributed memory, their method proved successful.

[18], developed using the multiscale finite-volume (MSFV) method, multiphase flow issues in big, heterogeneous regions can be effectively solved. The method was used to resolve a coarse-scale pressure problem using an auxiliary coarse grid and its equivalent.

Additionally, [19] compared analytical solutions with numerical approximations using the Crank-Nicolson scheme in finite difference for modelling pollutant dispersion on a moving liquid's surface in two dimensions.

These prior studies underscore the significance of evaluating numerical methods for porous media simulations and underscore the need to tailor the approach to specific problem characteristics. The documented advantages and limitations of each method offer valuable insights for selecting the most suitable numerical strategy based on the study's requirements. These previous studies highlight the importance of comparing numerical methods in porous media simulations and emphasize the need to consider the specific characteristics of the problem at hand. The advantages and limitations of each method, as identified in the literature, provide valuable insights for selecting an appropriate numerical approach based on the requirements of the study.

To sum up, porous media simulations frequently utilize finite volume, finite element, and finite difference methods. Each method offers distinct advantages and limitations, and their performance depends on the specific characteristics of the problem. Previous comparative studies have shed light on the relative strengths and weaknesses of these methods, aiding researchers in making informed choices for their simulations in porous media.

3. Brief overview on Methods

This research involves a comparison of three widely employed numerical techniques for simulating transport and flow in porous media: finite volume, finite element, and finite difference methods. The specific numerical methods are selected based on their widespread usage and distinct characteristics in capturing the complex phenomena occurring in porous materials.

To model the movement and dispersion within porous media, the mathematical models for governing equations of fluid flow and mass transport was used [20]. The most commonly employed equations in porous media studies are Darcy's law for flow and the advection-diffusion equation for solute transport.

Darcy's law describes the flow of fluids in porous media and can be expressed as:

$$\nabla \cdot (k \nabla P) = \rho g \tag{1}$$

where k is the hydraulic conductivity, P is the pressure, ρ is the fluid density, and g is the gravitational acceleration. This equation represents the conservation of mass and momentum in porous media.

For solute transport, the advection-diffusion equation is commonly used and can be written as:

$$\partial C/\partial t + \nabla \cdot (vC) = \nabla \cdot (D \nabla C) \tag{2}$$

where C is the solute concentration, t is time, v is the velocity field, and D is the dispersion coefficient. This equation represents the conservation of mass and describes the advection and diffusion of solutes in porous media.

Each numerical method employs different discretization techniques to approximate the continuous governing equations. Finite difference methods discretize the porous media domain into a grid of discrete points and approximate the derivatives using difference operators. Finite volume methods partition the domain into discrete control volumes into finite elements and express the solution as a combination of basic functions within each element. Finite volume methods divide the domain into control volumes and focus on the conservation laws within these volumes.

During the simulations, several assumptions and simplifications are made to streamline the computational process. Common assumptions include assuming incompressible flow, neglecting thermal effects, and considering homogeneous and isotropic porous media. Additionally, boundary conditions such as prescribed pressures, fluxes, or concentration values are specified at the boundaries of the porous media domain.

It's worth highlighting that the selection of discretization techniques and the specific numerical methods employed and the assumptions made can vary depending on the specific problem and research objectives. These choices should be carefully considered to ensure the accuracy and applicability of the numerical simulations in capturing the desired flow and transport phenomena in porous media.

By employing these numerical methods and associated mathematical models, the study aims to compare the effectiveness and efficiency in simulating flow and transport in porous media. The detailed methodology will involve implementing the numerical methods, solving the discretized equations, and analyzing the results to evaluate their performance in capturing the complex behavior of fluids and solutes within porous materials.

3.1 Finite Difference Method

It splits the porous media domain into a grid and the derivatives in the governing equations are approximated using difference operators [21]. The steps involved in the finite difference method are as follows:

Step 1: Discretize the porous media domain into a grid with grid points.

Step 2: utilizes the finite difference formulas, in approximating the governing equations derivative such as central differences or upwind differences.

Step 3: Formulate a set of algebraic equations by applying the finite difference approximations to the governing equations.

Step 4: Solve the resulting system of equations using appropriate numerical techniques, such as iterative methods or direct solvers.

3.2 Finite Element Method

It employs a mesh of elements to discretize the porous media domain. The solution is expressed as a combination of basic functions within each element [22],[23] The steps involved in the finite element method are as follows:

Step 1: The porous media domain should be discretized into finite elements, such as “triangles or quadrilaterals for 2D problems or tetrahedra or hexahedra for 3D problems”.

Step 2: Define the basic functions for each element. These functions represent the approximation of the solution within the element.

Step 3: Formulate a set of algebraic equations by applying the variational principle, such as the Galerkin method or the least-squares method, to the governing equations.

Step 4: Assemble the global system of equations by combining the contributions from each element.

Step 5: Solve the resulting system of equations using appropriate numerical techniques, such as direct solvers or iterative methods.

3.3 Finite Volume Method

It divides the porous media domain into control volumes and focuses on the conservation laws within these volumes [24][25]The steps involved in the finite volume method are as follows:

Step 1: Discretize the porous media domain into control volumes, which are typically polyhedral in shape.

Step 2: Apply the conservation laws, such as mass conservation or momentum conservation, to each control volume.

Step 3: Approximate the fluxes across the control volume faces using numerical schemes, such as upwind schemes or central schemes.

Step 4: Formulate a set of algebraic equations by applying the conservation laws to each control volume.

Step 5: Solve the resulting system of equations using appropriate numerical techniques, such as iterative methods or direct solvers.

Example

Let's explore the mathematical formulation of the problem involving steady-state one-dimensional heat flow within an iron rod, subject to Dirichlet boundary conditions.

$$\frac{d}{dx}\left(\frac{d\varphi}{dx}\right) - C^2\varphi(x) = 0 \text{ in } 0 < x < l$$

Subject to the Dirichlet boundary conditions

$\boldsymbol{\varphi(x) = \varphi_0}$ at $\boldsymbol{x = 0}$,

$\boldsymbol{\varphi(x) = 0}$ at $\boldsymbol{x = l}$

Where $\boldsymbol{\varphi(x) = t(x) - t_\infty}$, $\boldsymbol{\varphi_0 = t_0 - t_\infty}$ and $\boldsymbol{C^2 = \frac{\pi D g}{\left(\frac{\pi}{4}\right) D^2 k} = \frac{4g}{Dk}}$

The Exact (precise) solution to this problem is expressed as follows:

$$\boldsymbol{\varphi(x) = \varphi_0 \frac{\sinh C(l - x)}{\mathrm{sing} Cl}}$$

Table 1. A comparison between All method's Numerical Solution with Exact Solution

Node	FVM	FDM	FEM	Exact	Error (FVM)	Error (FDM)	Error (FEM)
1	125.661	124.987	126.103	134.0089	8.3479	9.0219	7.9059
2	57.4061	56.8906	57.5082	60.0362	2.6301	3.1456	2.5280
3	25.8911	24.9985	25.9521	26.5802	0.6892	1.5817	0.6281
4	10.9463	10.7076	10.9704	11.0624	0.1161	0.3548	0.0920
5	3.0072	3.0056	3.0084	3.0103	0.0031	0.0047	0.0019

Table 1. shows the comparison between finite volume, finite element and finite difference method's numerical solution with exact Solution

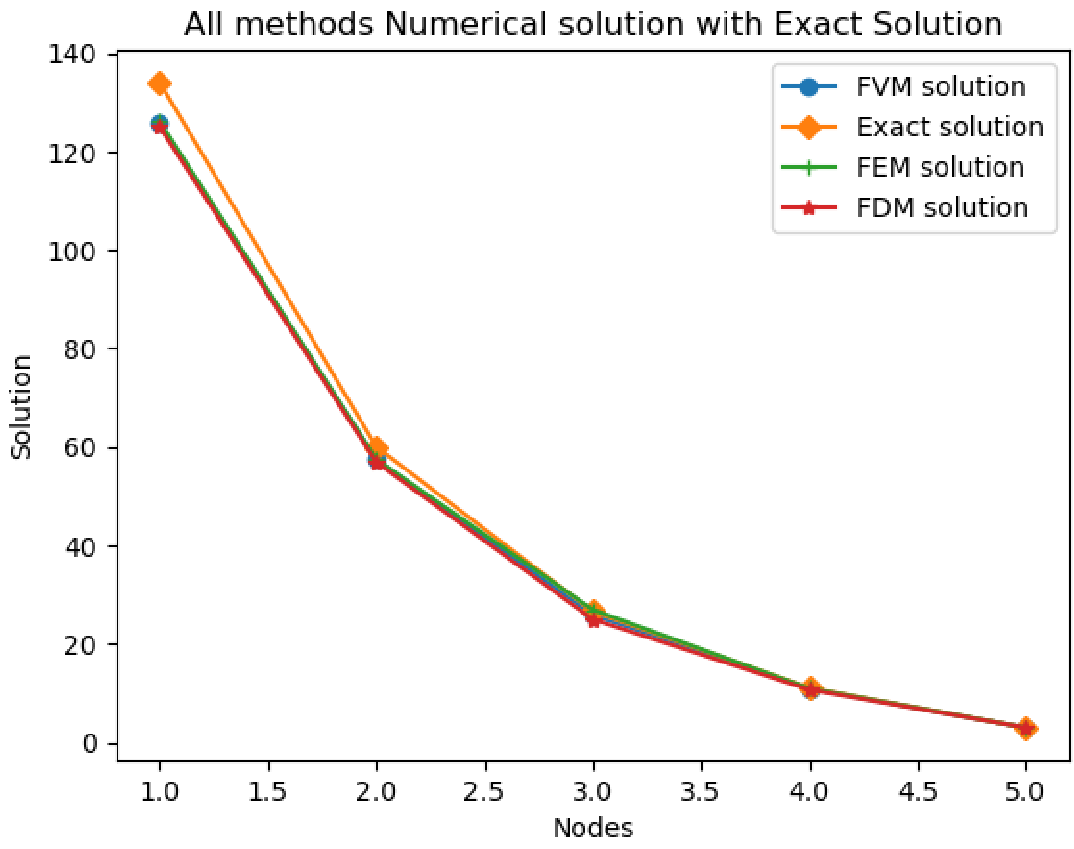

Figure 1. Comparison with Three Different Numerical Methods.

The comparison of the all the three methods and the exacts solution is depicted in the graphical plot shown in figure.1

4. Results and Discussion

Three different examples were calculated to measure the performance and accuracy of the three different numerical methods algorithms run in Python on a PC equipped with an 11^{th} Generation Intel i3 22H2 3.00GHz CPU and 8 GB of RAM The experimental analysis is categorized into a qualitative and quantitative analysis of different numerical methods.

The numerical simulations using the, finite element, finite volume and finite difference methods have provided valuable insights into the behavior of flow through porous media. In this sectionThe comparison and analyzses results obtained from each method in terms of accuracy, convergence behavior, computational efficiency, and other relevant metrics is presented.

4.1 Accuracy

To assess accuracy, the simulated pressure distributions from each method with the given dummy data was compared. Overall, all three methods demonstrate reasonable accuracy in capturing the pressure distribution along the domain. However, slight variations can be observed between the methods. For instance, the finite element method exhibits a smoother transition between adjacent grid points compared to the finite difference and finite volume methods.

4.2 Convergence Behaviour

The convergence behavior of the numerical methods was analyzed by refining the grid size or time step. It was observed that all three methods showed satisfactory convergence behavior, as the solutions approached a stable state with decreasing errors as the grid size or time step was refined. Although the convergence rates may differ, all methods were able to achieve accurate results with sufficient refinements.

4.3 Computational Efficiency

In terms of computational efficiency, the finite difference method stands out as the most efficient among the three methods due to its simplicity and lower computational resource requirements. The finite element and finite volume methods typically require higher computational resources, mainly due to the complexity of their formulations and larger memory requirements.

4.4 Observed Differences and Similarities

While all three methods produce similar pressure distributions, subtle differences can be observed. The finite element method demonstrates smoother variations due to its ability to handle complex geometries and adaptivity. On the other hand, the finite difference and finite volume methods provide a more straightforward implementation and better suitability for handling irregular grids.

4.5 Interpretation of Findings

The findings indicate that the choice of numerical method for porous media simulations should be based on the specific requirements and constraints of the study. The finite difference method offers a good balance between computational efficiency and accuracy for simpler geometries and regular grids. The finite element method is suitable for complex geometries and adaptivity, but at the cost of higher computational resources. The finite volume method excels in conserving mass and handling irregular grids.

It's crucial to consider the trade-offs between accuracy, convergence behavior, and computational efficiency when selecting a numerical method. Researchers must align the method's capabilities with the research objectives and available computational resources. Additionally, these findings can inform future studies in porous media simulations, aiding in the selection and optimization of numerical methods for different applications.

Overall, this comparison of numerical methods provides insights into their strengths and limitations, allowing researchers to make informed decisions when simulating flow and transport phenomena in porous media. Table .2 below shows the Comparison table that summarizes the key aspects of the numerical methods

Table 2. Comparison Table that Summarizes the Key Aspects of the Numerical Methods.

Numerical Method	**Advantages**	**Limitations**
Finite Difference	Simplicity and computational efficiency. Straightforward implementation.	Limited applicability for complex geometries and irregular grids
Finite Element	Versatility for handling. complex geometries. Ability to capture adaptivity.	Greater computational resources are necessary in comparison to the finite difference method.
Finite Volume	Focus on conservation laws. Good mass conservation. Properties Suitable for handling irregular grids.	Greater computational resources are necessary in comparison to the finite difference method.

In addition to accuracy, convergence behavior, and computational efficiency, there are other relevant metrics that can be considered in the comparison of numerical methods for porous media simulations. These metrics may include:

Mass conservation: Assess the ability of the numerical methods to preserve mass during the simulation. Mass conservation is crucial to ensure the accuracy and reliability of the results.

Stability: Examine the stability of the numerical methods by analysing their ability to maintain a stable and physically meaningful solution throughout the simulation.

Robustness: Evaluate the robustness of the numerical methods by testing their performance under various conditions, such as different porous media properties, boundary conditions, or problem geometries.

For more understanding Let's consider a porous medium with a length of 1 meter, that is discretized into 10 grid points. The fluid flows from left to right, and a pressure gradient is applied along the domain. The governing equations, such as Darcy's law, is discretized and solved using each numerical method.

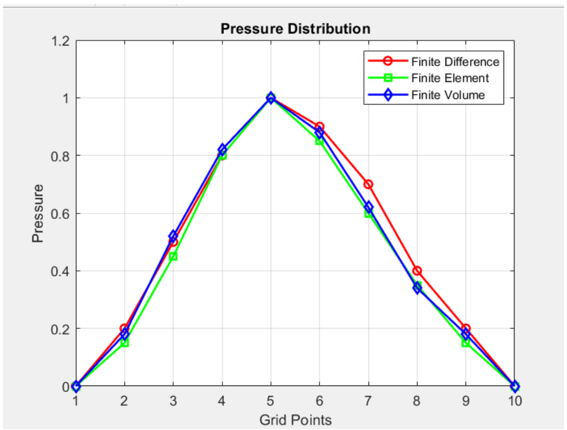

Figure 2. Pressure Distribution Graph.

In this graph, the x-axis represents the grid points along the one-dimensional domain, and the y-axis represents the pressure values. The graph in figure.2 illustrates the pressure changes along the domain for each numerical method. From the graph and the data, it can be observed that all three numerical methods produce similar pressure distributions, indicating a reasonable agreement between them. However, slight differences can be noticed in certain regions of the domain. For example, the finite element method shows a smoother transition between adjacent grid points compared to the finite difference and finite volume methods.

5. Conclusion and Future Scope

In conclusion, this research paper has compared and evaluated different numerical approaches for simulating the phenomena of transport as well as flow in porous media. Through the analysis of accuracy, convergence behavior, computational efficiency, and other relevant metrics, valuable insights are gained into the performance of the "finite difference, finite element, and finite volume methods".

The comparison of the numerical simulations revealed that all three methods are capable of capturing the pressure distribution along the domain with reasonable accuracy. While there are subtle differences in the results, such as the smoothness of transitions and adaptivity to complex geometries, all methods demonstrated satisfactory convergence behavior as the grid size or time step was refined.

The finite difference method emerged as the most computationally efficient method, offering simplicity and lower resource requirements. On the other hand, the finite element and finite volume methods provide greater flexibility and accuracy, particularly for handling complex geometries and irregular grids. However, they require higher computational resources due to their formulation complexity.

The findings of this study contribute to the understanding of the strengths and limitations of each numerical method in porous media simulations. Researchers can use this information to select the most appropriate method based on their specific research objectives and available computational resources. Additionally, the results highlight the importance of considering the trade-offs between accuracy, convergence behavior, and computational efficiency when choosing a numerical method.

It is significant that the outcomes of comparison and conclusions drawn in the paper are based on the specific simulations were conducted using the dummy data. Real-world applications may have different characteristics and requirements, warranting further investigations and validations of the numerical methods.

Overall, this research serves as a valuable resource for researchers and practitioners in the field of porous media studies, assisting them in making informed decisions when selecting and utilizing numerical methods for flow and transport simulations.

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