نهمین همایش بین‌المللی
توسعه فناوری در نفت، گاز، پالایش و پتروشیمی
9th International Conference on
Technology Development in Oil, Gas, Refining and Petrochemicals
www.oil.bcnf.ir

Methanol Tracer Application for Pre-EOR Water Flow Evaluation in a Simulated Reservoir

Javan, Nazanin [1]; Porbar, Amir Javad [1]; Afarideh, Hossein [1,*]; Rashidi, Fariborz[2]
[1]Amirkabir University of Technology, Department of Physics and Energy Engineering, Nuclear Engineering
[2]Amirkabir University of Technology, Department of Chemical Engineering, Chemical Engineering

ABSTRACT

Understanding water movement in petroleum reservoirs is critical for the effective design of enhanced oil recovery (EOR) strategies. In this study, methanol was employed as a conservative aqueous-phase tracer to investigate pre-EOR water flow behavior in a simulated reservoir. Numerical modeling was conducted using ECLIPSE, and four production wells were monitored to evaluate tracer recovery, breakthrough time, mean residence time, water velocity, and swept pore volume. The results revealed notable spatial variation in flow characteristics across the reservoir. Tracer recovery ranged from 20% to 29%, while water velocity varied between 0.35 and 0.41 m/d. The estimated swept pore volume extended from $5{,}01 \times 10^6$ to $7{,}97 \times 10^6$ m^3. Mean residence times were between 3900 and 4810 days, and breakthrough times ranged from 3092 to 4247 days. Among the monitored wells, Production Well-2 demonstrated the highest tracer recovery and swept pore volume, along with favorable flow characteristics, indicating a stronger hydraulic connection with the injection well. This makes it a promising candidate for targeted EOR operations. The insights gained from tracer-based diagnostics are instrumental in identifying preferential flow paths and unswept zones, thereby enhancing the efficiency of subsequent EOR implementation and reservoir management.

Keywords: Methanol tracer, Mean Residence Time, Reservoir simulation, Tracer recovery, Swept pore volume

1. INTRODUCTION

Most oil reserves worldwide are approaching the end of their primary production phase, presenting a considerable challenge to the petroleum industry. This situation has prompted the development of innovative strategies and technologies aimed at reducing production costs [1]. In response, there has been increasing interest in enhanced oil recovery (EOR) methods, which seek to improve recovery factors in existing reservoirs. EOR encompasses a range of advanced processes and technologies designed to extract additional hydrocarbons from reservoirs that have already undergone primary and secondary production.

The success of EOR projects is highly contingent upon a comprehensive understanding of flow dynamics and pore volume distribution within the reservoir. Prior to field-scale implementation, it is essential to thoroughly evaluate the reservoir's structural and petrophysical characteristics. Various methods are employed to achieve this objective, including time-lapse seismic interpretation, advanced reservoir simulation, production log analysis, pressure fall-off testing, and tracer-based diagnostics [2].

Generally, EOR methods refer to techniques used to recover additional oil following primary and secondary recovery phases. The selection of the injection fluid is significantly influenced by geological factors, reservoir fluid composition, cost, and availability of the injected fluid [1].

[1] hafarideh@aut.ac.ir
hafarideh@yahoo.com

The importance of tracer testing is widely acknowledged in both hydrological studies and the petroleum industry, particularly in the assessment of reservoir performance and inter-well connectivity. Tracers serve as effective diagnostic tools for characterizing subsurface flow paths, identifying preferential flow channels, and quantifying fluid migration patterns. In the context of hydrocarbon exploration and production, tracer techniques contribute significantly to reducing geological uncertainties and improving reservoir management strategies. Accurate delineation of subsurface reservoir structures is essential for optimizing production and enhancing recovery efficiency, making it a critical component of comprehensive petroleum system analysis.

Tracer testing is among the few diagnostic techniques in the oil and gas (O&G) industry capable of addressing the complex demands of reservoir characterization. It is effectively utilized for the quantitative identification and analysis of structural and stratigraphic heterogeneities at sub-seismic scales. Additionally, tracer testing plays a key role in evaluating the lateral continuity of reservoir properties and understanding inter-well connectivity in the subsurface. In practice, two primary types of tracers—chemical and radioactive—are commonly employed in the petroleum industry to monitor gas and fluid flow behavior, optimize waterflooding processes, and enhance reservoir management strategies [4].

The effectiveness of chemical tracers has been demonstrated in petroleum exploration due to their rapid and cost-effective characteristics. This technique has been successfully used to monitor fluid flow pathways and gradients in complex subsurface conditions [3]. Chemical tracers measure the concentration of a chemical substance in a fluid, whereas physical tracers are used to measure temperature. Generally, two types of tracer tests are commonly applied: (i) inter-well tracer test (IWTT) and (ii) single-well tracer test (SWTT) [4].

The information obtained from tracer tests is unique and relatively inexpensive. It supplements general field production data and helps reduce uncertainties in reservoir modeling. Tracer tests yield tracer-response curves, which can be analyzed further to extract valuable insights. Primarily, useful data is gathered by observing breakthrough times and inter-well communication. Even simple hand calculations and well-presented data can enhance our understanding of reservoir flow behavior. More detailed information can be acquired by fitting numerical simulation results to observed response curves. Analytical methods based on simplified reservoir models can also provide additional insights [10].

METHODOLOGY

2.1. Theoretical Background

The use of chemical tracers in enhanced oil recovery (EOR) has gained significant traction due to their cost-effectiveness, high sensitivity, and ability to provide valuable insights into reservoir flow dynamics. Among chemical tracers, methanol has been widely applied for its simplicity, stability, and rapid analytical detectability under a variety of reservoir conditions. Methanol tracers have proven particularly effective in identifying fluid flow pathways, evaluating inter-well connectivity and delineating subsurface heterogeneities at scales beyond the resolution of seismic techniques.

Previous studies have demonstrated that chemical tracer testing offers a reliable means of characterizing reservoir heterogeneity and monitoring fluid displacement efficiency. **Fig.1** presents a detailed classification of field tracers utilized in the oil and gas industry. This classification highlights the diversity, applications, and functional capabilities of these tracers, offering a robust framework for selecting the most appropriate tracer types. In addition to their well-established role in EOR operations, both radioactive and chemical tracers have been extensively utilized to evaluate the efficiency of secondary and tertiary recovery processes. These tracers help visualize fluid migration routes, reveal the influence of natural or induced fractures, and provide critical insights into multiphase flow behavior within complex reservoir settings. Such diagnostic capabilities significantly improve the quality of reservoir models and lead to more accurate assessments of recovery factors.

The effectiveness of methanol as a chemical tracer has been demonstrated in numerous field-scale studies, where it has provided timely and interpretable response curves. Compared to radioactive tracers, methanol offers several operational advantages, including safer handling, environmental compatibility, and the elimination of radiological risk. These properties make methanol particularly suitable for field implementations involving frequent monitoring and integration with production history. A successful tracer study depends heavily on a well-structured design and execution plan. Careful planning ensures the optimal use of resources, minimizes operational risks, and enhances the reliability of the resulting data. One of the most crucial aspects in this context is the careful selection and accurate dosing of the tracer. This decision is influenced by a wide

range of factors, including reservoir temperature and pressure, fluid composition, flow regime, and the intended diagnostic objectives of the test. Tracer selection thus requires a multidisciplinary approach that combines reservoir engineering, geochemistry, and fluid mechanics. To maximize the effectiveness of tracer studies, it is essential to tailor the tracer formulation and injection strategy to the specific characteristics of the reservoir. The quantity of tracer must be calculated to ensure sufficient coverage and detectability across the target zone, without incurring excessive costs or introducing environmental risks. When appropriately implemented, tracer tests provide not only a clearer picture of flow connectivity but also serve as a valuable tool for reducing uncertainty in reservoir simulation models.

Recent studies [4] highlight the growing significance of chemical tracers in enhancing reservoir characterization, particularly in mature or naturally fractured reservoirs where conventional data acquisition methods often fall short. Tracer-response curves obtained from inter-well and single-well tracer tests (IWTT and SWTT) serve as valuable diagnostic tools for interpreting subsurface flow behavior. These curves can be analyzed to estimate critical reservoir parameters such as porosity distribution, permeability trends, and sweep efficiency factors that play a decisive role in guiding field development strategies and improving reservoir management.

Ultimately, integrating methanol-based tracer testing into EOR workflows facilitates a deeper understanding of subsurface processes, enabling operators to make more informed, data-driven decisions that enhance overall recovery efficiency.

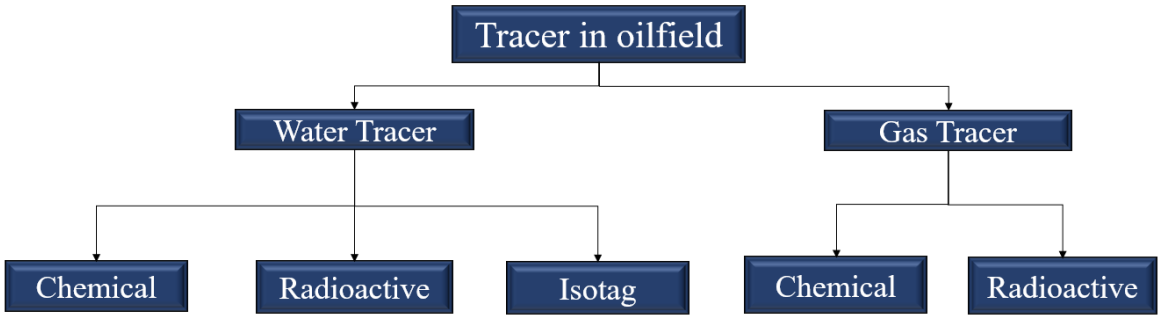


Fig. 1. Classification of tracer types in oil field

2.2. Method of Moments

The Method of Moments (MOM) is a robust analytical approach used to extract temporal moments from tracer response curves, providing quantitative insight into subsurface transport mechanisms. Initially developed for application in closed reactor systems within the chemical process industry, MOM has been effectively adapted to a variety of geoscientific contexts, including systems with open boundaries, fractured media subjected to continuous tracer reinjection, and complex flow geometries [9]. Grounded in a rigorous mathematical framework, the method offers valuable diagnostic capabilities for characterizing flow behavior and transport heterogeneities.

MOM can be employed independently or integrated as a constraint within numerical reservoir simulations, where it facilitates the estimation of inter-well pore volume and geometric flow configurations. Central to the method is the analysis of the residence time distribution (RTD) of tracer particles, which quantifies the temporal dispersion associated with fluid migration from injection to production points. As tracer particles traverse distinct flow paths, they experience varying residence times, collectively represented by the exit age distribution, denoted as $E(t)$ [5].

While modern reservoir simulators may incorporate complex tracer phenomena such as adsorption and phase partitioning, the classical formulation of MOM does not account for these effects. Nevertheless, integrating such processes into numerical models enhances the precision of history matching and improves the

interpretability of tracer response data. Accordingly, MOM remains a powerful and complementary tool in reservoir characterization and tracer-based diagnostics.

$$E(t) = \frac{C(t)Q_P(t)}{M} \quad (1)$$

With C(t) being the produced tracer concentration reported as mass per unit volume, $Q_P(t)$ being the production rate and M being the total mass of tracer injected. If the system has multiple producers j with production rate Q_j, the residence time distributions can be defined between each injector and producer pair j as:

$$E_j(t) = \frac{C_j(t)Q_{Pj}(t)}{M} \quad (2)$$

In a closed system (100% tracer recovery), the normalization by total injected tracer mass ensures that:

$$\sum_j \int_{-\infty}^{+\infty} E_j(t), dt = 1 \quad (3)$$

Three temporal moments exists that can be derived:

The zero order moment:

$$m_{0.j} = \int_{-\infty}^{+\infty} E_j(t), dt \quad (4)$$

This is equal to:

$$m_{0.j} = \int_{-\infty}^{+\infty} E_j(t), dt = \int_{-\infty}^{+\infty} \frac{C_j(t)Q_{Pj}(t)}{M}, dt = \frac{1}{M}\int_{-\infty}^{+\infty} C_j(t)Q_{Pj}(t), dt = \frac{m}{M} \quad (5)$$

With $m_{0.j}$ being the total mass recovered from the producer j at infinite time. This ratio can be used as a weighting factor to allocate the ratio of injected water that is flowing between the injector and the producer j.

$$m_{1.j} = \int_{-\infty}^{+\infty} t, E_j(t), dt \quad (6)$$

$$m_{2.j} = \int_{-\infty}^{+\infty} t^2, E_j(t), dt \quad (7)$$

The first moment represents the average residence time for tracers between the injections well and producer j and it is referred to as the mean residence time. Although this quantity is not of big importance in itself, it is directly related to the mean pore volume which will be discussed later in this chapter. The second order moment is related to the dispersion of the tracer and can be related to the Péclet number.

2.3. Residence Time Distribution (RTD) Method for Tracer Analysis

The residence time distribution (RTD) method analyzes tracer response curves by extracting key time points, helping to characterize porous media during tracer injection and to estimate flow patterns [4]. This approach relies on studying how long tracer particles stay within the system, using the method of moments. Because tracer particles move along different flow paths, they reach the production well at different times, resulting in a distribution known as the residence time distribution. By applying the method of moments along with proper

boundary conditions, it's possible to accurately estimate the swept pore volume [5–8]. Asakawa developed partial differential equations to describe tracer flow in three-dimensional, heterogeneous reservoirs and across different phases. He demonstrated how these solutions could be used to calculate the swept pore volume over time [6-8].

$$m_{ij} = \int_0^\infty q_j C_{ij}\, , dt \tag{8}$$

$$t^* = \frac{\int_0^\infty q_j C_{ij} t, dt}{\int_0^\infty q_j C_{ij}\, , dt} \tag{9}$$

$$V_{Sij} = q_i \frac{m_{ij}}{M_K} t^* \tag{10}$$

In Eq.(8), m_{ij} represents the total amount of chemical tracer injected into well i and detected at production well j, while M_K denotes the total injected tracer mass into the reservoir. Additionally, q_i and q_j refer to the injection and production rates, respectively. Generally, a tracer injected into well i migrates toward multiple production wells j, and the residence time of the tracer at a given production well can be calculated using Eq.(9). Eq.(9) generalizes the basic concepts of residence time, accounting for production rates, injection rates, and the relative tracer recovery. Since a single injected tracer can be produced from multiple wells, Eq.(10) provides the method for estimating the swept pore volume between a specific injection well i and a production well j where the tracer is detected. The water velocity in the reservoir, an important parameter for tracer transport analysis, can be calculated by dividing the distance between the injection and production wells L by the tracer residence time t^*, as shown below:

$$v = \frac{L}{t^*} \tag{11}$$

The inclusion of this parameter within tracer transport models leads to enhanced precision in reservoir flow analysis and facilitates a deeper exploration of the governing transport phenomena.

2.4. Simulation Methodology

In this study, a realistic reservoir model was meticulously constructed using advanced Petrel software and subsequently simulated with the ECLIPSE100 numerical simulator to comprehensively model the injection and transport of a methanol tracer (**Fig.2**). This integrated approach enabled an in-depth investigation of subsurface water flow behavior and enhanced the reliability of the simulation results. The primary objective of this research was to assess the performance of methanol as a conservative aqueous-phase tracer injected prior to enhanced oil recovery (EOR) operations, and to analyze its migration and distribution toward four production wells under varying reservoir conditions.

In the simulation, methanol tracer was injected with water through injection well I, before any EOR processes were initiated. The transport dynamics and breakthrough of the tracer were monitored and analyzed at four production wells (Production Well-1 to Production Well-4). This modeling strategy provided valuable insights into pre-EOR water movement patterns within the reservoir and enabled the evaluation of key flow characteristics such as tracer recovery, breakthrough time, mean residence time, and swept pore volume at each production location.

The general characteristics of the designed reservoir, which served as the foundation for the simulation, are summarized in Tables 1 and 2. These include essential reservoir properties such as porosity, permeability, pressure, and temperature, ensuring that the model accurately reflects field conditions. The simulation results highlighted significant spatial variations in water flow and tracer distribution, revealing the influence of

reservoir heterogeneities and inter-well connectivity. Among the four production wells, Production Well-2 exhibited the highest tracer recovery and swept volume, indicating a stronger hydraulic connection with the injection well and suggesting its suitability for future EOR targeting.

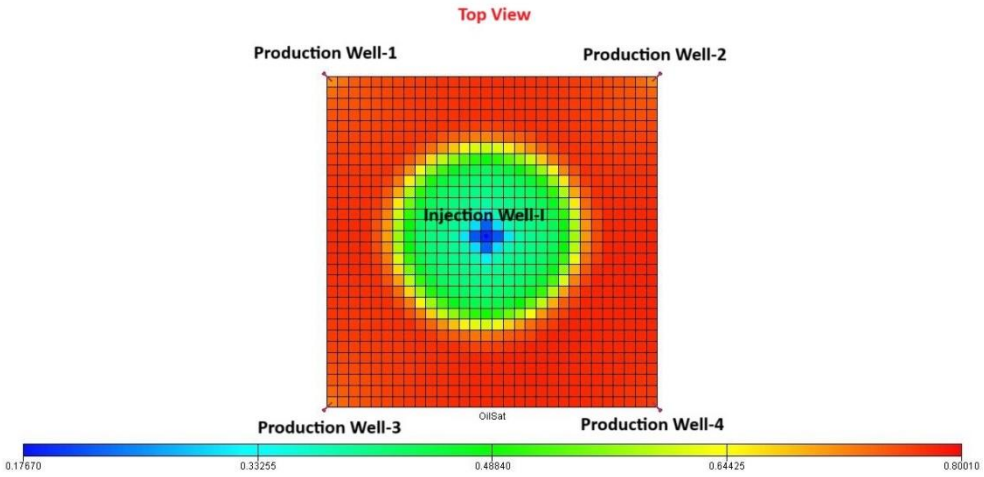
Overall, the insights obtained through numerical tracer simulation offer a robust diagnostic tool for understanding subsurface water flow, optimizing injection planning, and improving the effectiveness of subsequent EOR implementation. This study demonstrates the practical utility of methanol tracers in advanced reservoir management and pre-EOR performance assessment.

Table 1. Characteristics of the Designed Reservoir

Permeability (mD)	Porosity	Oil Saturation
30	0.18	0.55

Table 2. Distance and Flow Rate of Targeted Wells in the Experiment

Well No	Flow Rate (stb/day)	Distance (ft)
Production Well-1	1.50E+04	5.30E+04
Production Well-2	1.50E+04	5.30E+04
Production Well-3	1.50E+04	5.30E+04
Production Well-4	1.50E+04	5.30E+04



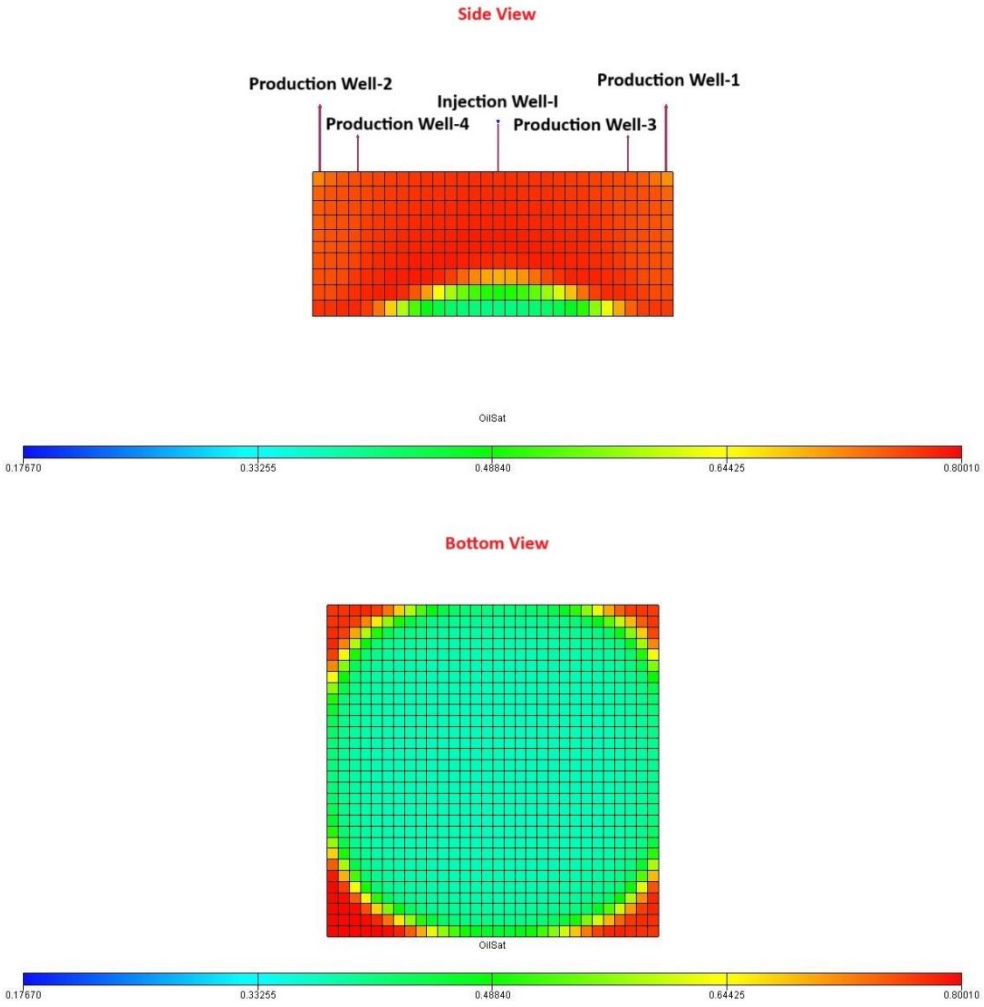


Fig. 2. Different Views of the Designed Reservoir Model

3. RESULTS

The concentration-time curve of the methanol tracer (**Fig.3**) was utilized to calculate the swept pore volume, tracer residence time, and water phase velocity within the reservoir. The results of these calculations are summarized in Table 3.

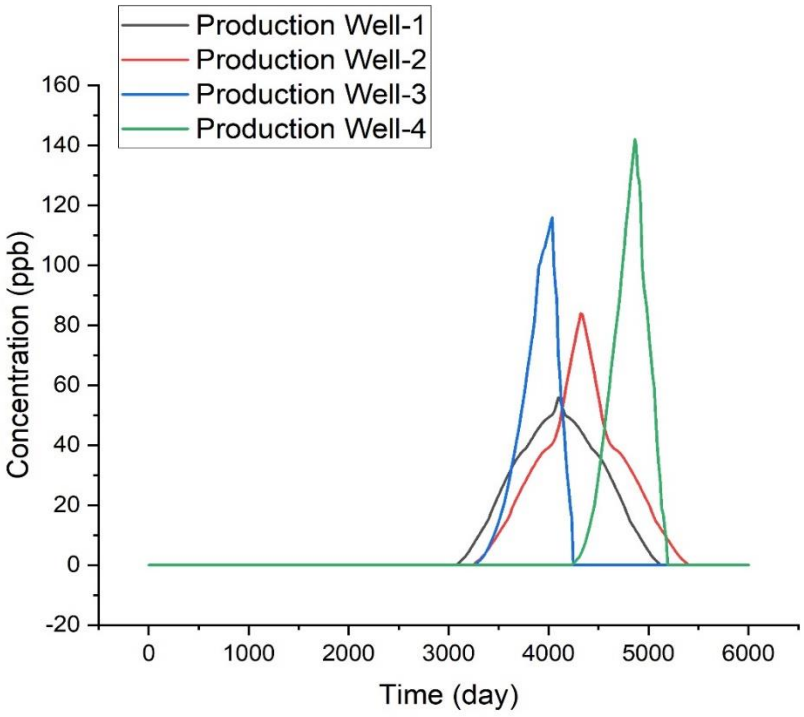


Fig. 3. The concentration–time curves of the chemical water tracer are presented for the four production wells in the designed reservoir.

Table 3. Analytical Results of Sweep Volume and Water Dynamics

Well No	Breakthrough Time (day)	Mean Residence Time (day)	Swept pore Volume (m^3)	Water Velocity (m/d)	Tracer Recovery (%)
Production Well-1	3092	4100	6.43E+06	0.39	25
Production Well-2	3257	4330	7.97E+06	0.37	29
Production Well-3	3272	3900	5.01E+06	0.41	20
Production Well-4	4247	4810	7.34E+06	0.35	24

4. CONCLUSION

This study investigated the behavior of methanol as a conservative aqueous-phase tracer in a simulated reservoir environment using the ECLIPSE100 simulator. The results demonstrated that pre-EOR methanol tracer injection provides valuable insights into water flow distribution and the estimation of swept pore volume within the reservoir. Among the four monitored production wells, Well-2 exhibited the highest tracer recovery (29%) and swept pore volume (7.97×10^6 m³), indicating a stronger hydraulic connection with the injection well and suggesting it as the most favorable candidate for subsequent enhanced oil recovery operations. In contrast, Well-3 showed the lowest tracer recovery (20%) and the smallest swept pore volume (5.01×10^6 m³), pointing to weaker connectivity and possible heterogeneities that hinder water movement.

Additionally, the mean residence times and breakthrough times varied considerably across the wells, with Well-4 displaying the longest breakthrough and residence times, which may reflect extended flow paths or lower permeability zones. These differences emphasize the role of reservoir heterogeneity and inter-well connectivity in controlling flow dynamics. Overall, the application of methanol tracer diagnostics proves to be

a reliable approach for pre-EOR flow characterization, enabling more informed reservoir management and improved planning for efficient recovery strategies.

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