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Comprehensive modeling of radioactive gas tracer behavior for enhanced oil recovery optimization using a simulator

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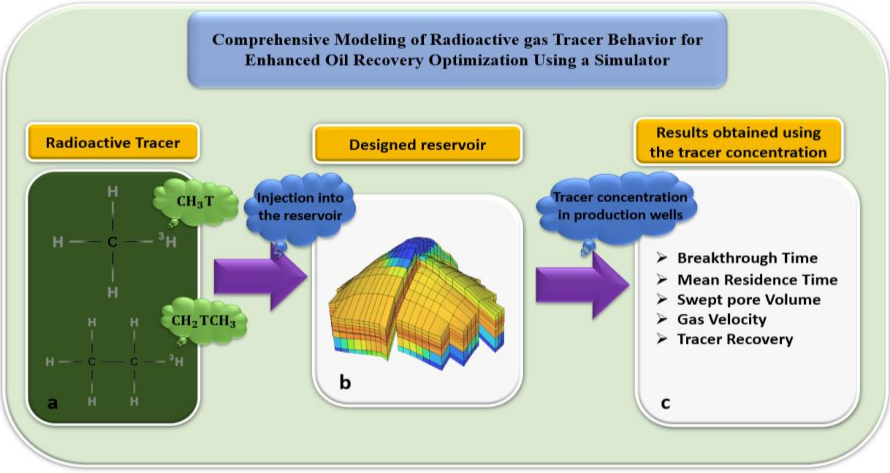
Abstract

In the oil and gas industry, radioactive tracers serve as effective tools for analyzing fluid flow and evaluating hydrocarbon reservoir behavior. These methods provide critical insights into fluid transport, swept pore volume, and hydrodynamic connectivity between injection and production wells, which are essential for optimizing reservoir management and designing enhanced oil recovery (EOR) projects. In this study, the behavior of radioactive gas tracers was simulated and analyzed in two distinct oil reservoirs, R1 and R2. In reservoir R1, the gas tracer CH_3T was injected through injection well I, while in reservoir R2, the gas tracer CH_2TCH_3 was utilized. The tracer responses were monitored in two production wells (P1 and P2) for each reservoir. By analyzing the tracer concentration curves over time, parameters such as swept pore volume in the gas phase, gas flow velocity, and hydrodynamic connectivity were determined for both reservoirs. The results revealed that in reservoir R1, production well P1 demonstrated the highest swept pore volume and tracer recovery, indicating a strong and direct connection with injection well I. Similarly, in reservoir R2, production well P1 exhibited superior connectivity and tracer recovery compared to P2. The comparison of these reservoirs highlights differences in gas transport dynamics and fluid flow behavior, which are influenced by reservoir-specific characteristics. These findings offer valuable insights into the design of enhanced oil recovery projects, emphasizing the importance of tailored reservoir management strategies based on tracer behavior.

Graphical Abstract



1. Introduction

Tracer testing is a critical method for characterizing oil and natural gas reservoirs, providing essential insights into subsurface conditions and properties, such as water and gas flow directions, flow velocities, and material-specific dispersion and diffusion coefficients [1]. In modern reservoir studies, tracer technology has become indispensable for tracking groundwater movement and determining formation fluid characteristics on a field scale. The spatial and temporal variations in tracer concentrations are invaluable for evaluating hydrocarbon reservoirs in terms of the quality and quantity of produced natural gas. The objective of this research is to examine the migration of formation fluids and to determine the medium properties in a gas reservoir through the analysis of the tracer breakthrough curves, providing the change in tracer concentration as a function of time. Diminishing oil field production coupled with growing difficulty linked with economic extraction of hydrocarbon resources has highlighted the key significance of enhanced oil recovery (EOR) techniques. These enhanced techniques are accountable for addressing the world's demand for a continuous supply of oil while mitigating the natural decline in the rates of production. By significantly improving recovery factors, EOR techniques enable the extraction of residual oil that would otherwise remain untapped. EOR processes employ a wide range of chemical and physical approaches, each meticulously designed to optimize injection and production efficiency. Traditional methods such as the injection of alkaline solutions, polymers, surfactants, and their combinations have demonstrated considerable success in improving sweep efficiency, enhancing reservoir performance, and maximizing hydrocarbon recovery [2]. Beyond these established techniques, recent advancements in EOR have introduced more innovative strategies. These include engineered water or gas injection, foam-assisted fluid displacement to improve volumetric sweep efficiency, and the application of nanoparticles to block macropores and enhance oil recovery from low-permeability formations. These assessments are pivotal for optimizing recovery processes and are commonly conducted through pilot-scale field experiments integrated with high-resolution numerical simulations. These tests not only help in understanding the mechanics of recovery but also offer practical guidelines to enhance the economic feasibility of Enhanced Oil Recovery (EOR) operations [3]. Design and development of sophisticated methodologies are key for the optimization of EOR strategies, especially for reservoirs with complex flow physics and heterogeneity. Of these techniques, gas tracer technology has emerged as a strong diagnostic tool, providing unmatched precision in the interpretation of fluid flow patterns, establishing inter-well connectivity, and measuring displacement efficiency in subsurface reservoirs. Tracer technology provides critical insights essential for designing and refining EOR operations. This technique is extensively applied during secondary and tertiary recovery phases, with inter-well tracer tests (IWTTs) serving as one of its most prominent applications. These tests facilitate the monitoring of injected fluids, such as water or gas, as they propagate through reservoir formations, thereby delineating flow pathways, quantifying swept volumes, and assessing inter-well connectivity between injection and production wells [4]. The tracers employed in such applications are specifically engineered to be chemically inert, phase-compatible, and non-reactive, ensuring the accuracy of flow monitoring without altering the intrinsic properties of the reservoir fluids. Additionally, by achieving optimal dilution prior to injection, tracers can be reliably detected at trace concentrations in production wells, facilitating high-resolution analyses of reservoir dynamics. Through the use of tracer technology, it is possible to estimate swept pore volumes, identify high-permeability channels and detect geological barriers that hinder fluid movement. These capabilities make tracer-based diagnostics indispensable for evaluating the efficacy of EOR processes and developing targeted recovery strategies. The accuracy, reliability, and ability to provide detailed characterizations of reservoir conditions underscore the critical role of tracers in enhancing hydrocarbon recovery from complex and heterogeneous reservoirs [5].

2. Materials and Methods

2.1. Theoretical Background

Radioactive gas tracers have long been recognized as indispensable tools in advanced research, particularly within the domains of subsurface and reservoir engineering. Their unmatched capability in providing accurate and dependable information has made them indispensable in deciphering reservoir process complexities, enhancing the knowledge of fluid flow mechanisms, and assisting in the formulation of enhanced oil recovery (EOR) methods. Among the most significant applications of radioactive tracers is the tagging of chemical compounds with isotopes. This method not only provides exceptional sensitivity and selectivity but also enables researchers to trace minute quantities of materials under challenging reservoir conditions. Such attributes are critical for achieving accurate measurements in highly specialized analyses of hydrocarbon reservoirs [6]. The performance and utility of radioactive gas tracers are intrinsically tied to their chemical composition, which governs their reactivity, compatibility with reservoir fluids, and detectability across various phases. These fundamental properties enhance their capability to investigate critical reservoir characteristics, such as porosity, permeability, and fluid saturation. Additionally, the high analytical precision of radioactive gas tracers plays a crucial role in optimizing field operations by identifying bypassed hydrocarbons, evaluating sweep efficiency, and assessing inter-well connectivity [7]. In addition to their well-established applications, radioactive and chemical gas tracers play a pivotal role in characterizing reservoir heterogeneities and evaluating the efficiency of secondary and tertiary recovery processes. These tracers facilitate the analysis of fluid migration pathways, provide critical insights into the influence of reservoir fractures, and enhance the understanding of the distribution and interaction of multiphase fluids under reservoir conditions. Such capabilities are particularly valuable for improving reservoir characterization and achieving more accurate estimations of recovery factors. **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. By accounting for specific reservoir conditions, including temperature, pressure, and fluid composition, engineers can optimize the accuracy and reliability of tracer-based analyses. This systematic approach ensures the seamless integration of tracers into reservoir management strategies, thereby enabling more informed decision-making in petroleum exploration and production [6].

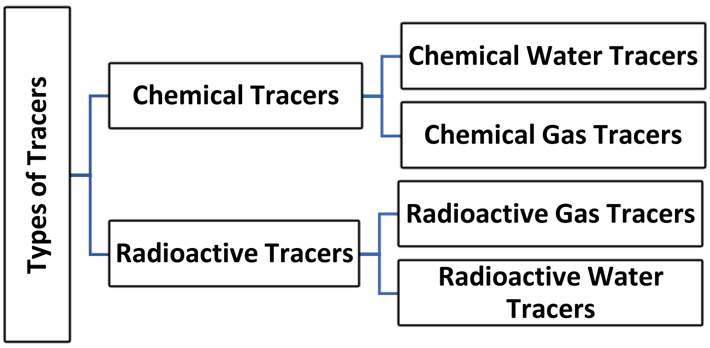


Fig. 1. Classification of tracer types.

Effective and actionable planning is an essential element in the success of any field project, especially in complicated subsurface operations like tracer tests. Effective planning ensures that resources are optimized, reduces operational risks, and improves the quality of data acquired. One of the most important considerations in the design and implementation of tracer studies in field applications is the proper identification of the type and amount of tracer to be utilized. The selection of a tracer is governed by a list of considerations that include reservoir characteristics, fluid characteristics, and the particular goals of the study. The selection of a tracer is therefore a multidisciplinary undertaking, demanding a broad-based knowledge of reservoir conditions like temperature, pressure, fluid composition, and flow regime. In petroleum reservoirs, these parameters play a critical role in determining the dynamics of interaction between the tracer and the reservoir fluids, in addition to influencing the detectability and stability of the tracer when exposed to severe subsurface conditions. Additionally, the quantity of tracer required must be calculated meticulously to ensure sufficient coverage and detectability throughout the intended area of study, while avoiding unnecessary costs and potential environmental impacts [8]. In this study, the focus is on the application of a radioactive gas tracer, a category of tracers known for their exceptional sensitivity and suitability for high-resolution analyses in complex reservoir systems. Radioactive gas tracers offer unique advantages, including the ability to trace minute quantities of materials over long distances and through heterogeneous formations. To accurately determine the required tracer amount for oil reservoirs, a rigorous calculation framework is employed, incorporating the principles of mass balance and flow dynamics. These calculations are performed using **Eq. (1)** and **Eq. (2)**, which are derived from established reservoir engineering principles and tracer physics [8].

$$V_p = \pi \times x^2 \times h \times \phi \times S_g, \quad (1)$$

$$A_0 = e \times DL \times V_p. \quad (2)$$

V_p = volume of the porous medium	DL = detection limit	A_0 = activity of the injected source
S_g = gas saturation	ϕ = porosity	x = distance between the injection and the production well
e = The tuning factor is between 10 and 100	h = thickness	

The tracers CH_3T and CH_2TCH_3 are advanced chemical gas tracers, each labeled with the radioactive isotope tritium (**Table 1**). These tracers are characterized by exceptional properties, including high sensitivity, stability under reservoir conditions, and precise detectability, making them invaluable tools in reservoir engineering and enhanced oil recovery (EOR) research. In the R1 reservoir, the radioactive gas tracer CH_3T, accompanied by a gaseous reference phase, is injected through a dedicated gas-phase injection well. Similarly, in the R2 reservoir, the radioactive gas tracer CH_2TCH_3 is deployed using the same gaseous reference phase and injected via a gas-phase injection system. These tracers are meticulously engineered to achieve uniform distribution across the reservoirs, enabling high-resolution monitoring and comprehensive analysis of fluid dynamics and reservoir behavior under subsurface conditions. Following injection, sampling is performed at production wells surrounding the reservoirs, with the collected data undergoing rigorous analysis through advanced laboratory techniques. The utilization of radioactive tracers CH_3T and CH_2TCH_3 not only facilitates the acquisition of highly accurate data but also supports comprehensive studies that are essential for the optimization of production strategies and reservoir management in both reservoirs.

Table 1. Characteristics of radioactive gas tracers.

Gas Tracer Compound	Main Radiation Charcteristics (*KeV*)	Half-Life (*year*)
CH_3T	$\beta^{-}(18.5)$	12.32
CH_2TCH_3	$\beta^{-}(18.5)$	12.32

2.2. Method of Moments

The Method of Moments (MOM) involves deriving the temporal moments from the tracer response curve. Initially developed for closed reactor vessels in the chemical process industry, this technique has since been adapted to more general conditions, including open boundary systems, fractured media under continuous tracer reinjection, and flow geometry estimation [9]. MOM is grounded in a rigorous mathematical framework and provides valuable additional insights into subsurface dynamics. While it can be used independently, it is also an effective tool for constraining numerical models by defining inter-well volume and flow geometry. The Method of Moments and its applications are primarily based on the analysis of tracer residence time distribution. Tracer particles follow distinct paths through the system, requiring varying amounts of time to travel from the inlet to the outlet. The distribution of these time periods is referred to as the exit age distribution, or residence time distribution (RTD) of the tracer in the system [9]. Notably, some modern simulators are capable of modeling tracer adsorption and partitioning. However, the current formulation of the Method of Moments does not account for these factors. Incorporating these properties into numerical simulations can significantly enhance the accuracy of history matching and tracer curve interpolation. The residence time distribution is referred to as *E(t),* and it is defined as:

$$E(t) = \frac{C(t)Q_P(t)}{M}, \tag{3}$$

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:

$$E_j(t) = \frac{C_j(t)Q_{Pj}(t)}{M}. \tag{4}$$

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

$$\sum_j \int_{-\infty}^{+\infty} E_j(t).dt = 1. \tag{5}$$

Three temporal moments exist that can be derived:

The zero-order moment:

$$m_{0,j} = \int_{-\infty}^{+\infty} E_j(t).dt. \tag{6}$$

This is equal to:

$$m_{0,j} = \int_{-\infty}^{+\infty} E_j(t).dt = \int_{-\infty}^{+\infty} \frac{C_j(t)Q_{Pj}(t)}{M}.dt = \frac{1}{M}\int_{-\infty}^{+\infty} C_j(t)Q_{Pj}(t).dt = \frac{m}{M}, \tag{7}$$

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 gas that is flowing between the injector and the producer *j*.

$$m_{1,j} = \int_{-\infty}^{+\infty} t.E_j(t).dt, \tag{8}$$

$$m_{2,j} = \int_{-\infty}^{+\infty} t^2.E_j(t).dt. \tag{9}$$

The first moment represents the average residence time for tracers between the injection well and producer *j,* and it is referred to as the mean residence time. Although this quantity is not of great 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) analysis method involves extracting time points from the tracer response curve, aiding in the characterization of porous media during tracer injection and the estimation of flow geometry [7]. The application of moments is fundamentally based on the analysis of the tracer residence time distribution (RTD). Tracer particles follow distinct pathways, resulting in varying transit times between the injection and production wells. The distribution of these transit times is referred to as the tracer residence time distribution within the system. By utilizing the method of moments and adhering to appropriate boundary conditions, an accurate estimation of the swept pore volume can be achieved [9-12]. Asakawa derived partial differential equations describing tracer flow in a three-dimensional heterogeneous reservoir and across phases [13]. He demonstrated how these solutions can be applied to calculate the swept pore volume as a function of time [10-12].

$$A = \int_0^\infty q_j A_{ij}\,.dt, \tag{10}$$

$$t^* = \frac{\int_0^\infty q_j A_{ij} t.dt}{\int_0^\infty q_j A_{ij}\,.dt}, \tag{11}$$

$$V_{Sij} = q_i \frac{A}{A_0} t^*. \tag{12}$$

In **Eq. (10**), A represents the total recovery of the tracer injected into well i and observed in production well j, while A_0 activity of the injected source into the reservoir. Additionally, q_i and q_j are the injection and production rates, respectively. Generally, a tracer injected into well i flows to more than one production well j, and the residence time of each tracer in a given production well can be calculated using **Eq. (11)**. **Eq. (11)**, generalizes the fundamental concepts of residence time, incorporating production rates, injection rates, and relative tracer recovery. Since a specific injected tracer is typically produced in multiple wells, **Eq. (12)** describes the swept pore volume between a specific injection well i and a production well j where the tracer is detected. The gas velocity in the reservoir, a crucial parameter for analyzing tracer movement, can be calculated by dividing the distance between the injection and production wells L by the tracer residence time t^* as follows:

$$v = \frac{L}{t^*}. \tag{13}$$

Incorporating this parameter into tracer flow equations enhances the precision of reservoir flow analysis and provides deeper insights into transport processes.

2.4. Simulation Methodology

In this study, two reservoir models, R1 and R2, were meticulously designed using advanced software and subsequently simulated to comprehensively model the tracer injection and transport processes. In these models, two radioactive gas tracers, including CH_3T and CH_2TCH_3, were injected into the reservoirs (**Fig. 1**). This integrated approach enabled a detailed investigation of subsurface fluid behavior in both reservoirs, enhancing the accuracy of the simulated results. The primary objective of this research was to examine the behavior of these two radioactive gas tracers and analyze their distribution and migration toward the production wells under varying reservoir conditions. In the simulation, a radioactive gas tracer with an

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activity level of 50 curies CH_3T was injected into the R1 reservoir, while in the R2 reservoir, a tracer with an activity level of 5 curies CH_2TCH_3 was used. Both tracers were injected along with gas through injection well I. The transport dynamics of these tracers and their breakthrough at production wells P1 and P2 were carefully monitored and analyzed. This modeling strategy provided valuable insights into the flow behavior of gas within both reservoirs and its interaction with the tracers. It also offered a detailed evaluation of critical parameters influencing injection efficiency, sweep profiles, and production performance in both reservoirs. The general characteristics of the designed reservoirs, which formed the foundation for the simulation, are presented in **Tables 2-3**. These include key reservoir properties such as porosity, permeability, pressure, and temperature, ensuring that the model accurately represents field conditions. The modeling results yielded significant findings related to tracer distribution, flow pathways, and the influence of reservoir heterogeneities on gas movement. By leveraging numerical simulations, this study provides a robust framework for understanding fluid behavior in subsurface reservoirs. The insights derived not only contribute to optimizing injection and production processes but also facilitate more effective planning and execution of enhanced recovery projects. The findings serve as a critical reference for the behavior of gas tracers in reservoir environments, providing a deeper understanding of their application in advanced reservoir management and field development strategies.

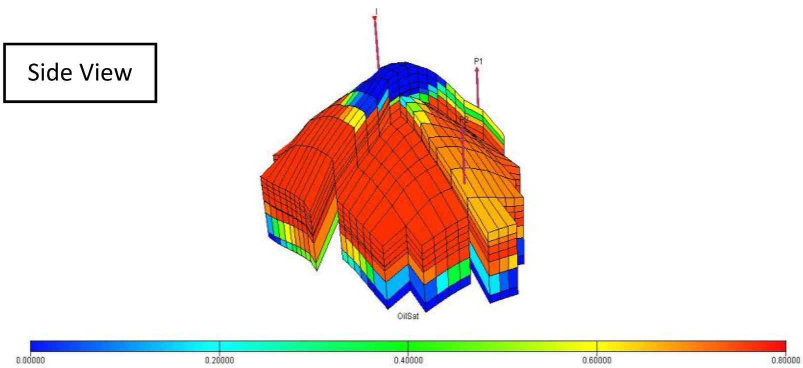
Table 2. Characteristics of the designed reservoir.

Reservoir models	Permeability (*mD*)	Porosity	Gas Saturation
R1	20	0.2	0.1
R2	15	0.18	0.1

Table 3. Distance and flow rate of targeted wells in the experiment.

Well No	Flow Rate for R1 (*stb/day*)	Flow Rate for R2 (*stb/day*)	Distance (*m*)
P1	25000	25000	2500
P2	25000	21000	3000

A liquid scintillation detector was used for data collection. Given the low energy of beta radiation emitted by tritium, this detector is considered an ideal choice due to its high sensitivity. Since the tracer used is in gaseous form, the gas is first dissolved in a liquid solution to enable precise analyses. This process not only enhances the ability to detect weak beta signals but also ensures the accuracy and reliability of the results.



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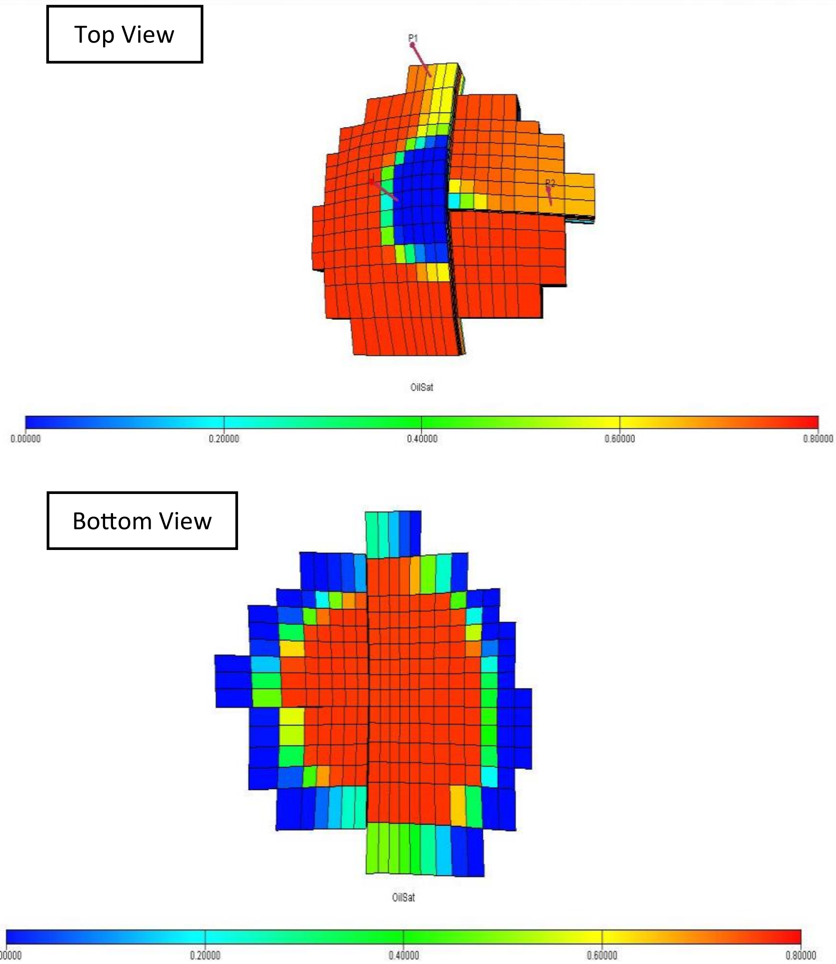

Fig. 1. Different Views of the Designed Reservoir Model.

3. Results and Discussion

The numerical simulations conducted on the two reservoirs, R1 and R2, revealed several key findings related to the tracer distribution and fluid flow behavior. In reservoir R1, where the CH_3T tracer was injected at a concentration of 50 curies (**Fig. 2a**), the tracer showed a rapid breakthrough at the production well, P1, occurring at approximately day 352 (**Table 4**). This early breakthrough suggests efficient flow pathways between the injection and production wells. Similarly, in reservoir R2, where the CH_2TCH_3 tracer was injected with an activity level of 5 curies (**Fig. 2b**), the breakthrough at production well P1 was observed at day 452 (**Table 5**), indicating a slower migration of the tracer compared to R1. The simulation results also showed that the sweep efficiency in R1 was relatively higher due to a more homogeneous permeability distribution, whereas R2 exhibited more heterogeneity, leading to a relatively lower sweep efficiency. The comparison of tracer behavior across both reservoirs provided valuable insights into the influence of reservoir heterogeneities on tracer migration and fluid flow dynamics. In addition, the model's sensitivity analysis revealed that varying injection rates and tracer concentrations significantly impacted the tracer breakthrough times and the overall flow efficiency. The observed differences in tracer breakthrough times between the two reservoirs underscore the importance of considering reservoir-specific characteristics when designing enhanced oil recovery (EOR) strategies.

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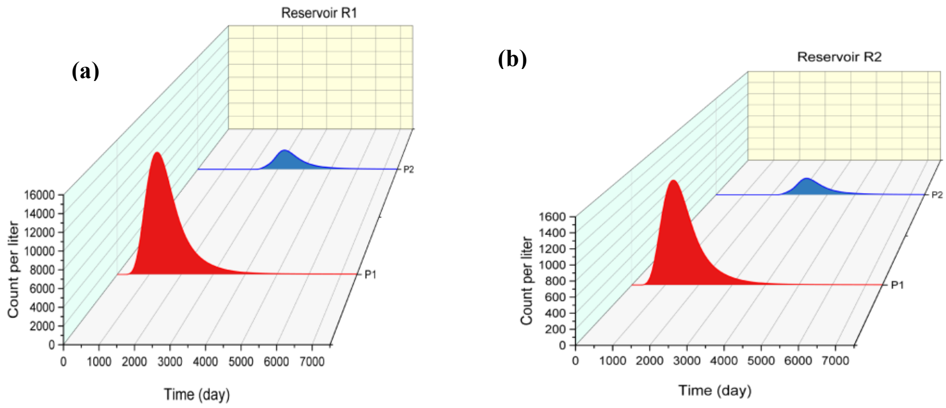

Fig. 2. (a) The concentration-time curve of the radioactive tracer (a) CH_3T (50 Ci) is presented for production wells P1 and P2 in reservoir R1, and (b) CH_2TCH_3 (5 Ci) is presented for production wells P1 and P2 in reservoir R2.

Table 4. Evaluation of gas flow dynamics and reservoir sweep in R1 using tracer simulation data.

Well No.	Breakthrough time (*day*)	Mean residence time (*day*)	Swept pore volume (m^3)	Gas velocity (*m/s*)	Tracer recovery (%)
P1	352	1611	2170000	1.50	85
P2	2252	3658	968000	0.82	15

Table 5. Evaluation of gas flow dynamics and reservoir sweep in R2 using tracer simulation data.

Well No.	Breakthrough time (*day*)	Mean residence time (*day*)	Swept pore volume (m^3)	Gas velocity (*m/s*)	Tracer recovery (%)
P1	452	1600	2150000	1.56	84
P2	2452	3651	966000	0.81	16

Additionally, the results indicated that a 5 curies source was sufficient for both reservoirs, and there was no need for a 50 curies source in reservoir R1. This amount of tracer provided accurate and reliable data regarding the tracer behavior and gas flow dynamics in both reservoirs.

4. Conclusion

In this study, the behavior of two radioactive gas tracers, CH_3T and CH_2TCH_3, was investigated in two separate reservoirs, R1 and R2, using a simulator. The results for reservoir R1 demonstrated that the injected tracers, along with the gas, provided valuable insights into gas flow distribution and the swept pore volume within the reservoir. The tracer recovery fraction in production well P1 of R1 was 85%, which was considerably higher than the 15% observed in production well P2. This indicated a dominant gas flow towards P1, highlighting its more effective role in production. Additionally, the shorter mean residence time and greater swept pore volume in P1 confirmed its higher efficiency in production. For reservoir R2, the tracer recovery fraction in P1 was also higher (84%) compared to P2 (16%), with similar trends observed in terms of gas flow dynamics. However, the residence time of the tracers in P2 was longer, which, combined with the lower recovery fraction, suggested potential challenges in gas flow to this well. These challenges could be attributed to factors such as lower permeability or longer flow paths within R2. The comparison of tracer behavior across both reservoirs provided insights into the influence of reservoir heterogeneities on gas flow dynamics, further highlighting the differences in flow efficiency between the two reservoirs. Overall, the use of both CH_3T and CH_2TCH_3 tracers in these two reservoirs provided a powerful tool for evaluating fluid behavior in subsurface reservoirs and optimizing injection and production processes. The findings from this study can serve as a foundation for better reservoir management and the design of enhanced recovery projects in the future.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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