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IMPROVEMENT OF PREDICTION OF OIL DISPLACEMENT EFFICIENCY DURING WATERFLOODING DUE TO DETAILING OF LITHOLOGICAL DISTRIBUTION

The object of research is the process of oil displacement during waterflooding. The research aims to develop and substantiate a methodology that improves the reliability of predicting oil displacement efficiency during waterflooding. For this purpose, the classical Buckley-Leverett method and the State Standard of Ukraine method for calculating the oil displacement efficiency during waterflooding were extended by integrating lithological data, which allows considering the influence of geological characteristics on the process of oil displacement by water.

The developed methodology for improving the reliability of oil displacement efficiency prediction encompasses the identification of lithofacies and the determination of core and fluid sample properties. Subsequently, the representative elementary volume (REV) is ascertained for each facies. Based on this, the irreducible water saturation and irreducible oil saturation are calculated. Relative permeability curves are then constructed for each facies. The Buckley-Leverett equation is applied, and fractional flow curves are generated. The data is integrated into a three-dimensional reservoir model, with facies volumes determined using the kriging method. Finally, the averaged oil displacement efficiency is calculated.

A comparative analysis of the reliability of methods, with and without lithological subdivision, was conducted by constructing an experimental histogram and a normal distribution plot, considering or disregarding lithological distribution, respectively. For the comparative analysis, this research generates one hundred reservoir realizations, both with and without lithological subdivision, using the Sequential Indicator Simulation tool.

It was established that the use of lithological data in the calculations of the Buckley-Leverett method, with consideration of the lithological factor, allows a reduction in the scatter of predicted values by 11% in comparison with a similar method without consideration of the lithological factor.

The originality of the research lies in integrating lithological distribution into the Buckley-Leverett method and the State Standard of Ukraine method of calculating the oil displacement efficiency during waterflooding, which significantly improves the predictive results. The proposed approach allows considering the lithological factor at the level of analytical formulas when calculating the two methods.

Keywords: *oil displacement efficiency, waterflooding, Buckley-Leverett method, lithological distribution, relative permeabilities.*

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1. Introduction

In practice, discrepancies exist between the predicted and actual indicators of the oil recovery coefficient (ORC) during flooding. The most important task facing the oil production industry is to optimize the development of hydrocarbon deposits to achieve maximum oil recovery. The reliability of the ORC assessment, and particularly its component – the oil displacement coefficient (ODC), becomes a basic factor in making decisions on methods, technologies, and monitoring of oil field development. The ORC value is estimated at the stage of drawing up and adopting the design document, which becomes the most important uncertainty in drawing up subsequent design documents, in which only the option that allows obtaining the previously approved ORC value will be accepted. For new fields characterized by incomplete and inaccurate information, the adopted ORC value may be either underestimated or overestimated. For deposits with a low degree of reserve production and high-water content of the product, an explanation in the form of "adverse geological and physical conditions" is often found.

The problem addressed in this research is the need to enhance the reliability of predicting the oil displacement coefficient (ODC) during flooding. The existing classical Buckley-Leverett method for calculating the oil displacement coefficient during flooding does not account for the complexity of geological conditions, particularly lithological dismemberment. The method of the State Standard of Ukraine GSTU 41-00032626-00-022-2000 adopted in 2000, in addition to the complexity of geological conditions, does not consider the effective and relative permeability. The method for determining ORC (and ODC as its component) according to the Ukrainian standard involves the use of only absolute permeability. This decision was made due to the laboratory capabilities available at the time.

Using only absolute permeability when calculating ODC (and ORC) according to the State Standard of Ukraine leads to significant errors in forecasting oil production volumes. The insufficient accuracy of existing methods for calculating ORC leads to incorrect decisions regarding the water injection volumes of wells, resulting in significant volumes of oil remaining in the formation and inefficient use of investments and natural resources.

The State Standard of Ukraine GSTU 41-00032626-00-022-2000 "Determination of oil recovery coefficients for geological and economic assessment of resources and reserves of predicted and discovered deposits" was developed in 2000 by the Ukrainian Oil and Gas Academy and the Ukrainian State Geological Exploration Institute. This standard, approved by the Ministry of Ecology and Natural Resources of Ukraine, establishes a methodology for determining the oil recovery coefficient necessary for assessing the potential of oil fields.

The sixth section of the standard provides detailed instructions for calculating oil recovery coefficients for various reservoir regimes. The section offers a formula for calculating the oil recovery coefficient for the water-pressure regime, as well as describes methods for determining the components of this formula. This method involves calculating the oil recovery coefficient as the product of several coefficients: the oil displacement coefficient (ODC), the coefficient of reservoir coverage by the displacement process, and the coefficient of reservoir coverage by the flooding process [1].

In the following, the research will consider the oil displacement coefficient by water, as described in the State Standard of Ukraine, which outlines the process of fluid mass transfer through a porous medium.

The approach to determining the oil recovery coefficient during flooding, in the classical literature on field development [2], is based on the decomposition of the total oil recovery coefficient into three components: the displacement coefficient, the areal coverage coefficient, and the vertical coverage coefficient.

As shown earlier, in terms of their physical content, all the coefficients present in the two different approaches – the classical and the Ukrainian – are identical. This means that the content of the oil displacement coefficient during water flooding using the Ukrainian method is similar to that of the classical method. However, further research reveals discrepancies in the analytical approaches used to determine the oil displacement coefficients during flooding with different methods.

Several methods for calculating the oil displacement coefficient during flooding are described in the scientific and technical literature, including the Buckley-Leverett method [3], the material balance method [4], the simulation method based on hydrodynamic equations [5], and the sorption kinetics method [6]. The Buckley-Leverett method is the closest in content to the Ukrainian method, as it also does not require existing production data, data on sorption parameters, or the creation of a hydrodynamic model.

The task is to determine how flexible the studied methods are in considering different aspects of the deposit, such as the case when the layers have an inclination angle, which indicates the action of gravitational forces. The results of the influence of gravitational forces on the flooding processes are described in detail in the works [7, 8]. The authors of the studies demonstrate that gravity and capillary pressure have a significant impact on the change in saturation profiles at low displacement rates, and the rate of fluid stratification can be substantial under the influence of these forces.

Additionally, the task of this research is to examine the lithological distribution factor at the analytical level for the two methods under consideration: the state standard of Ukraine and the Buckley-Leverett method. The lithological factor is actively utilized in various studies and has consistently demonstrated its effectiveness in enhancing the reliability of various methods and forecasts. Numerical results confirm the increase in forecast reliability. This is achieved by considering lithological structures. Estimates of the distribution of reservoir properties become more reliable [9]. The reliability of the forecast of the lithological section of the future well also increases when detailing the data of lithological structures in existing wells [10–12].

Thus, it is relevant to enhance the reliability of determining the oil displacement coefficient during flooding by utilising the lithological distribution of the reservoir's permeable part.

The aim of research is to enhance the reliability of predicting the oil displacement coefficient (ODC) during flooding by refining and substantiating a methodology that takes into account the detailed lithological heterogeneity of the reservoir.

2. Materials and Methods

The object of research in the work is the process of oil displacement during flooding.

The oil displacement coefficient, as specified in the State Standard of Ukraine, is calculated using formula (1).

$$K_{displ} = \frac{1 - K_w - K_{os}}{1 - K_w}, \quad (1)$$

where K_{displ} – oil displacement coefficient; K_w – collector water saturation; K_{os} – irreducible (after washing) oil saturation.

The oil displacement coefficient during flooding using the Buckley-Leverett method can be determined using formula (2).

$$E_D = \frac{\overline{S}_w - S_{wi}}{1 - S_{wi}}, \quad (2)$$

where E_D – displacement efficiency; S_{wi} – initial water saturation at the start of the flood; $\overline{S}_w$ – average water saturation in the swept area.

The oil displacement coefficients at the plant of the Ukrainian method (1) and the Buckley-Leverett method (2) are somewhat different and have specific differences in analytical approaches, although they try to use the same data for calculations.

Analysis of the formula according to the method of the State Standard of Ukraine (GSTU) and the Buckley-Leverett method revealed differences in approaches to accounting for physical factors.

Additional determination of the oil displacement coefficient, as specified in the Ukrainian standard (formula (1)), enables the calculation of the irreducible oil saturation coefficient. If such information is not available in the industry standard, the specified formula for determining the oil displacement coefficient is

$$K_{os} = K_i \cdot K_{ios}(\mu_o) \cdot \left[1 + \Delta K_{os}(K_p)\right], \quad (3)$$

where K_{ios} – irreducible oil saturation coefficient; K_i – average coefficient of initial oil saturation of the reservoir; $K_{ios}(\mu_0)$ – irreducible oil saturation coefficient for a specific reservoir oil viscosity value; $\Delta K_{os}(K_p)$ – correction factor for the average permeability of the reservoir to irreducible oil saturation.

In formula (3), the coefficient of irreducible oil saturation is used for a specific viscosity value of the reservoir oil. A correction factor for the average permeability of the reservoir is also used. These coefficients are determined according to the graph from the industry standard.

The average value of the absolute permeabilities of the rock samples of the studied reservoir determines the correction for the average permeability of the reservoir. Absolute permeability characterizes the rock's ability to pass a homogeneous fluid (for example, clean water or gas) through itself in the absence of other fluids. It represents the potential maximum permeability of the rock. Thus, absolute permeability reflects the permeability of one phase in the pore space, considering the action of capillary forces within the rock and the wettability of that phase.

For a more accurate description of filtration processes and mass transfer in a multiphase system, the concepts of effective and relative permeability were introduced. Effective permeability is the ability of a rock to allow a fluid (such as oil, gas, or water) to pass through in the

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presence of other fluids. The effective permeability of a certain fluid is measured for different percentages of another fluid. For example, the effective permeability of oil will vary in the presence of different proportions of water in the reservoir rock. Relative permeability is calculated as the ratio of the effective permeability of a certain fluid to the absolute permeability of the rock and is depicted in the form of curves. The relative permeability curve of oil is a measure of the movement of oil at different fractions of water and oil saturation in a porous medium. Thus, the relative permeability curves reflect the influence of liquids on each other, taking into account capillary forces at the interface of two liquids in the pore space and the wettability of the rock in the presence of two liquids.

The Buckley-Leverett method for calculating the oil displacement coefficient (formula (2)) utilizes relative permeability curves and a fractional flow curve.

Relative permeability curves are determined in the laboratory. If laboratory data are not available, correction factors n and m are used for oil and water, respectively. The factors n and m determine the nature of the curvature of the relative permeability and depend on the wetting angle of the rock at the contact of the two phases and the rock [2, 13].

The following formula can determine the fractional flow curve

$$f_w = \frac{1 \pm \left[\frac{0.001127 \cdot 0.433 \cdot kk_{ro} A(\rho_w - \rho_o)}{\mu_o} \cdot \frac{\sin(\alpha)}{i_w} \right]}{1 - \frac{k_{ro}}{k_{rw}} \frac{\mu_w}{\mu_o}}, \quad (4)$$

where f_w – fractional flow; k – permeability; k_{ro}, k_{rw} – relative permeabilities for oil and water; A – cross-sectional area of the reservoir; ρ_o, ρ_w – densities of oil and water; $\sin(\alpha)$ – angle of inclination of the formation; μ_o, μ_w – viscosity of oil and water; i_w – pumped water flow rate.

Analysis of formula (4) allows to conclude that the gravitational effect is considered through $\sin(\alpha)$, which will be positive or negative according to the conditions of the well location in relation to the slope of the formation.

It should also be noted that the Buckley-Leverett method can be expanded using the Welge method, which in turn calculates the average water saturation of the flow as it passes. This helps determine several parameters, such as the oil production rate over a certain time period, the accumulated production after the breakthrough, and others [14].

In this research, the aim of increasing the reliability of the ODC estimate when flooding both methods with the lithological segmentation factor was to construct an experimental histogram and a normal distribution graph for one hundred cases with and without considering the lithological distribution.

3. Results and Discussion

The results of the comparative analysis of the Ukrainian method and the Buckley-Leverett method are presented in Table 1.

Table 1

Comparative analysis of the Ukrainian method and the Buckley-Leverett method

Factor	State Standard of Ukraine	Buckley-Leverett method
Wettability, Capillary Forces and Viscosity	It is taken into account due to absolute permeability	It is taken into account through relative permeability
Gravitational forces	Not taken into account	Can be taken into account
Calculation of production over time	No analytical solution	Solved using the Welge method
Lithological dissection	Not considered	Not considered

From Table 1, it can be concluded that the Buckley-Leverett method can be improved by considering the lithological segmentation factor. To introduce this factor into the calculation, it is necessary to determine the facial segmentation of the reservoir being studied. Next, using the Buckley-Leverett method and formula (2), the oil displacement coefficients are calculated for each facies separately. It is also necessary to determine the percentage of the volume of each facies in the reservoir. The results obtained for each facies must be substituted into formula (5), which is the weighted average oil displacement coefficient for the studied reservoir.

$$\overline{E}_D = \frac{\sum_{i=1}^{n} E_{Di} \cdot v_i}{\sum_{i=1}^{n} v_i}, \quad (5)$$

where $\overline{E}_D$ – weighted average oil displacement factor taking into account the facies distribution; v_i – the volume fraction of a facies in the layer where i corresponds to certain facies; E_{Di} – oil displacement coefficient for i facies;

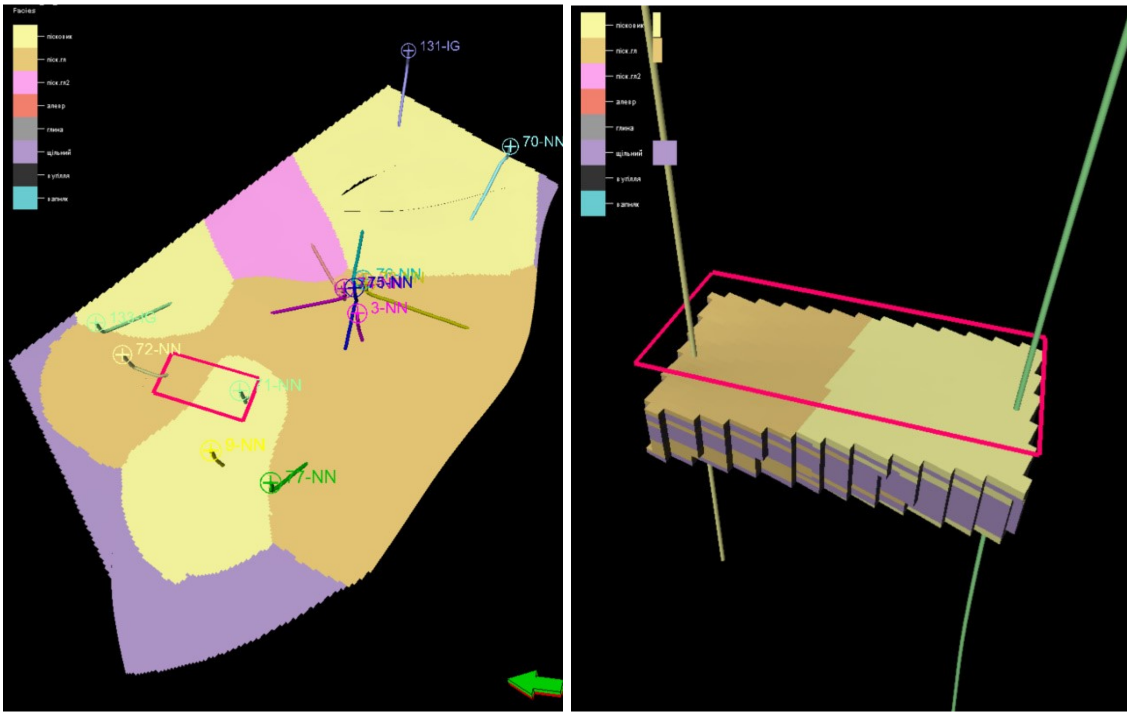
Determining the volume fraction of a facies in a reservoir can be accomplished by using three-dimensional reservoir modeling and applying the Kriging method to distribute facies between wells as shown in Fig. 1.

To build a three-dimensional model, a synthetic deposit was used, representing a generalized model of a terrigenous reservoir formed based on systematized literary and experimental data from real Ukrainian deposits [15, 16]. The geological structure of the synthetic deposit includes a typical set of facies characteristic of terrigenous deposits, which corresponds to the conditions for the formation of reservoirs within the Dnipro-Donets Basin and the Precarpathian Foredeep [17, 18].

Several laboratory studies were conducted, which included facies identification, determination of representative elementary volume (REV) [19], for the number of samples reflecting each facies, calculation of irreducible water saturation, calculation of irreducible oil saturation, calculation of relative permeability curves, construction of fractional flow curves according to the Buckley-Leverett equation, calculation of the oil displacement coefficient for each facies, calculation of the average oil displacement coefficient according to formula (5). The resulting weighted average oil displacement coefficient is 0.537. A detailed, step-by-step description of the laboratory studies, including the determination of all indicators, is provided in the study [20].

In comparing the Buckley-Leverett method with lithological distribution, calculations were also performed where the lithological distribution was neglected. In this case, the lithology in the well and the formation were divided into permeable and impermeable zones. The oil displacement coefficient was determined by formula (2). The obtained oil displacement coefficient without lithological dismemberment is 0.547.

To test this theory, considering the lithological distribution leads to more reliable results of calculating the oil displacement coefficient, a methodology was developed, which was called "Methodology of modelling random lithological distribution with and without facial dismemberment". The methodology involves creating a three-dimensional reservoir model and generating one hundred cases of lithological distribution between wells using the Truncated Gaussian Simulation method with and without facial distribution. Based on the generated one hundred cases of lithological distribution, oil displacement coefficients during flooding were calculated using formula (5) for cases that account for facial dismemberment and using formula (2) for cases without facial dismemberment. A detailed description of the methodology is presented in the study [21].



a *b*

Fig. 1. Layer with lithological division:
a – three-dimensional model using the Kriging method; *b* – fragment of this formation with injection and production wells

Theoretical normal distribution graphs were constructed using the obtained oil displacement coefficients using the Buckley-Leverett method with and without facial dismemberment (Fig. 2). The results of this research show that the oil displacement coefficients in one hundred cases with facial dismemberment have a smaller spread by 11% compared to one hundred cases where facial dismemberment was ignored.

A similar study was conducted using the state standard of Ukraine, similar to the Buckley-Leverett method. The particle volumes obtained in one hundred cases with and without facial dismemberment were applied to formulas (5) and (1), respectively. The method for determining the displacement coefficient during flooding according to the state standard of Ukraine, unfortunately, did not show the desired result and did not even repeat its results with and without facial distribution (Fig. 2). Such results are due to the use of absolute permeability in calculations, which considers the permeability of one phase in the pore space. This highlights the importance of using relative permeabilities in the analytical method for calculating the oil displacement coefficient, as relative permeabilities more accurately describe filtration processes in a multiphase system where two fluids are present.

These results indicate that the oil displacement coefficient during flooding, taking into account lithological heterogeneity, has a smaller uncertainty spread compared to a similar coefficient that does not consider lithological heterogeneity (Fig. 3).

Fig. 3 schematically illustrates how the uncertainty (width of the range of possible values) of the oil displacement coefficient is reduced during the exploration and development of the field through the acquisition of new data and the use of more accurate methods. It is shown that implementing a process that considers facies distribution (BL with Facies) allows for significantly reducing the uncertainty of the forecast already at the planning and production stages compared to the classical Buckley-Leverett method (BL). This emphasizes the practical value of detailing the geological model to make more informed decisions at different stages of the field life.

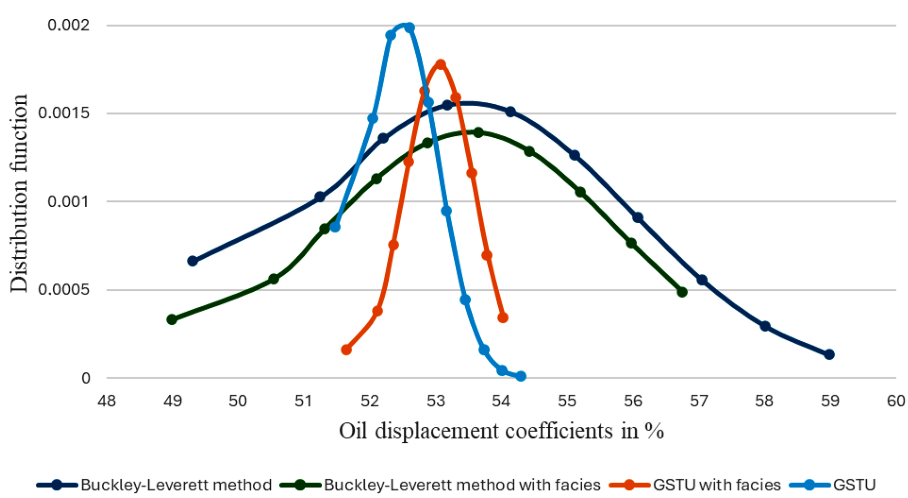


Fig. 2. Theoretical graphs of the normal distribution of oil displacement coefficients according to the Ukrainian method, the Buckley-Leverett method with and without considering the facial distribution

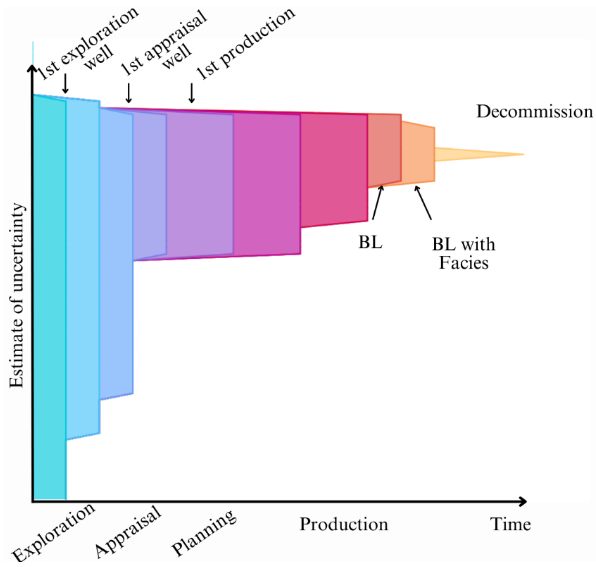


Fig. 3. Schematic uncertainty plot

Practical significance. The improved method of forecasting the oil displacement coefficient considering lithology provides more reliable estimates of the displacement potential, which improves the validity of design decisions (development systems, investments). At the operational stage, it helps identify unextracted reserves, which, considering the demonstrated 11% reduction in the spread of forecast values, leads to more efficient resource use.

Limitations of research. The validation of the method is limited to a synthetic model based on generalized data from Ukrainian deposits; therefore, further studies are needed on existing facilities to confirm its universality. Reliability depends on the quality of geological and laboratory data (especially facies-specific relative phase permeabilities). The use of the Buckley-Leverett analytical method also imposes certain limitations (one-dimensional flow and neglect of capillary forces in the basic version).

Prospects for further research. It is promising to compare the results with full-scale hydrodynamic modeling to assess the impact of analytical simplifications. It is essential to investigate the method's sensitivity to input data uncertainty. Extending the consideration to capillary forces and adaptation to other flooding methods (e. g., polymer) are relevant directions.

4. Conclusions

A comparative analysis of the state standard of Ukraine and the Buckley-Leverett method for calculating the oil displacement coefficient during flooding revealed a difference in the use of data in analytical calculations. In particular, the oil displacement coefficient used in the flooding of the state standard of Ukraine utilizes absolute permeability data, whereas the Buckley-Leverett method employs relative permeability data. This main difference introduces uncertainty into the calculations during the flooding process, as it is caused by the movement of two or more fluids in the pore space. Additionally, the Ukrainian method does not account for the gravity factor in angled formations. The Buckley-Leverett method can be expanded using the Welge method, which enables the calculation of oil flow rates over time.

The research confirmed the feasibility of integrating lithological data to increase the reliability of oil displacement coefficient calculations using the Buckley-Leverett method. The expansion of the classical approach through detailed facies modeling significantly improves the results of oil displacement prediction. A comparative analysis of the construction of a theoretical normal distribution graph revealed that the use of lithological disaggregation in calculations reduces the spread of oil displacement coefficient values by 11% compared to the classical Buckley-Leverett method.

However, the integration of lithological data into the Ukrainian industry standard for determining the oil displacement coefficient during flooding did not yield a positive result in increasing the reliability of this coefficient. The results of the Ukrainian method, when considering facies disaggregation, differ significantly from those where facies disaggregation is absent. The obtained data indicate the importance of using relative permeabilities in calculations of complex filtration processes in the reservoir, particularly oil displacement during flooding.

Conflicts of interest

The authors declare that they have no conflicts of interest related to the current research, including financial, personal, authorship, or any other interests that could influence the research or the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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