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Original article

Development of a Laboratory Methodology for Core Flooding Experiments to Evaluate Gravity Segregation in Oil–Water Saturated Porous Media

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ABSTRACT
Background: High water cut increases operating costs and reduces oil recovery. Gravity-driven redistribution of oil and water during well shut-in periods has been proposed for reducing water cut; however, laboratory methodologies for investigating this phenomenon in core samples remain limited.
Aim: To develop a laboratory methodology for evaluating gravity segregation in oil–water saturated cores under controlled conditions.
Materials and methods: The methodology is based on epoxy-sealed cores fixed inside a sleeve, providing a practical and cost-effective core holder capable of accommodating pressure ports. Two experimental scenarios are considered: early water breakthrough caused by an unfavorable mobility ratio, and breakthrough induced by a high-permeability channel. After water breakthrough, flooding is suspended, the core is aged in a vertical position, and water injection is subsequently resumed. Effluent analysis is performed using a gravimetric oil–water separation technique based on the adhesion of oil to polyethylene. The methodology enables qualitative and quantitative assessment of fluid redistribution caused by gravity.
Results: Fractional flow analysis demonstrates that, when viscous oils are used, a significant fraction of mobile oil remains in the core after water breakthrough, whereas artificial high-permeability channels can be used to preserve low-viscosity mobile oil within the matrix for subsequent redistribution by gravity segregation.
Conclusion: The developed methodology provides a reliable and inexpensive platform for investigating gravity segregation in cores and may support the development of field technologies aimed at reducing water cut and improving oil recovery.
Keywords: *gravity segregation; water cut; flow rate; core sample; core holder.*

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Оригинальное исследование

Методика проведения фильтрационных экспериментов на кернах для оценки гравитационного разделения воды и нефти в пористой среде

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АННОТАЦИЯ

Обоснование. Высокая обводнённость скважин приводит к повышенным затратам и снижению добычи нефти. Гравитационное разделение воды и нефти в пласте после временной остановки скважины рассматривается как один из методов снижения обводнённости. Для оценки эффективности данного метода в первую очередь необходимо разработать методику лабораторных экспериментов на керновом материале.

Цель. Разработка методики проведения фильтрационных экспериментов на кернах для изучения процессов гравитационного разделения воды и нефти в пористой среде.

Материалы и методы. В данной работе используется практичный и простой в изготовлении эпоксидный кернодержатель с промежуточными датчиками давления. Рассматриваются два сценария: ранний прорыв воды, вызванный высоким коэффициентом подвижности, и прорыв воды через высокопроницаемый канал. После прорыва воды фильтрация останавливается, керн выдерживается в вертикальном положении, затем закачка воды возобновляется. Анализ фильтрата осуществляется с использованием гравиметрического метода разделения нефти и воды, основанного на адгезии нефти к поверхности полиэтилена. Методика позволяет оценивать влияние выдержки керна в вертикальном положении на динамику обводнённости, обусловленную перераспределением нефти и воды в порах керна под действием силы тяжести.

Результаты. Расчёты показывают, что в экспериментах с вязкими нефтями значительная доля подвижной нефти остаётся в керне после прорыва воды, тогда как при использовании маловязких нефтей необходимы искусственные высокопроницаемые каналы, т.к. они способствуют сохранению подвижной нефти в матрице для дальнейшего распределения за счёт силы тяжести.

Заключение. Разработанная методика представляет собой надёжный способ для исследования гравитационной сегрегации в кернах и может служить основой для создания промысловых технологий, направленных на снижение обводнённости и повышение добычи нефти.

Ключевые слова: *гравитационная сегрегация, обводнённость, расход фильтрации, образец керна, кернодержатель.*

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Түпнұсқа зерттеу

Кеуекті ортадағы су мен мұнайдың гравитациялық бөлінуін бағалау үшін керн үлгілерінде сүзгілеу (фильтрациялық) эксперименттерін жүргізу әдістемесі

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АҢДАТПА
Негіздеу. Ұңғымалардың жоғары сулануы шығындардың жоғарылауына және мұнай өндірудің төмендеуіне әкеледі. Ұңғыманы уақытша тоқтатқаннан кейін қабаттағы су мен мұнайдың гравитациялық бөлінуі сулануды азайту әдістерінің бірі ретінде қарастырылады. Бұл әдістің тиімділігін бағалау үшін ең алдымен негізгі керн материалында зертханалық эксперименттер әдісін жасау қажет.
Мақсаты. Кеуекті ортадағы су мен мұнайдың гравитациялық бөліну процестерін зерттеу үшін керн үлгілерінде сүзгілеу (фильтрациялық) эксперименттерін жүргізу әдістемесін әзірлеу.
Материалдар мен әдістер. Бұл жұмыста аралық қысым датчиктері бар практикалық және қарапайым эпоксидті керн ұстағыш қолданылады. Екі сценарий қарастырылады: жоғары қозғалғыштық коэффициентінен туындаған судың ерте жарылуы және жоғары өткізгіш канал арқылы судың жарылуы. Су жарылғаннан кейін сүзу тоқтатылады, керн тік күйде ұсталады, содан кейін су айдау қайта жалғасады. Фильтратты талдау мұнайдың полиэтилен бетіне адгезиясына негізделген мұнай мен суды бөлудің гравиметриялық әдісін қолдану арқылы жүзеге асырылады. Бұл әдістеме ауырлық күші әсерінен керн кеуектеріндегі мұнай мен судың қайта бөлінуінен туындайтын сулану динамикасына кернді тік қалыпта ұстап тұрудың әсерін бағалауға мүмкіндік береді.
Нәтижелері. Есептеулер көрсеткендей, тұтқыр мұнай тәжірибелерінде жылжымалы мұнайдың едәуір бөлігі судың бұзылуынан кейін өзекте қалады, ал тұтқырлығы төмен мұнайды пайдаланған кезде жасанды жоғары өткізгіш арналар қажет, өйткені олар ауырлық күші арқылы әрі қарай тарату үшін матрицадағы жылжымалы мұнайдың сақталуына ықпал етеді.
Қорытынды. Әзірленген әдістеме керндердегі гравитациялық сегрегацияны зерттеудің сенімді құралы болып табылады және сулануды төмендетуге әрі мұнай өндіруді арттыруға бағытталған кәсіпшілік технологияларды әзірлеуге негіз бола алады.
Негізгі сөздер: *гравитациялық сегрегация, сулану, сүзу шығыны, керн үлгісі, кернұстағыш.*

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Introduction

The low oil recovery and high water cut in the petroleum industry presents a significant challenge, impacting both operational efficiency and economic viability [1]. Many studies have explored various aspects of this problem and potential mitigation approaches [2–4].

The high water cut observed in production wells is primarily attributed to a combination of geological and operational factors. One significant geological factor is the presence of complex reservoir structures, such as fractures and vugs, which facilitate water ingress and contribute to increased water production. For example, Zhao M., et al., highlighted that in fracture-vuggy carbonate reservoirs, the mechanisms leading to high water cut include the connectivity of fractures and vugs, which enables water to bypass oil zones and consequently increases water production levels [5].

Polymer gels are among the most well-known technologies widely applied for fracture plugging and water cut reduction [6–8]. However, this technology has several significant disadvantages, including thermal and salinity degradation, possible formation damage, high chemical cost, and environmental concerns [9–11].

At the same time, the literature has reported that in cases where aggressive production rates cause severe water or gas coning, temporarily shutting in the well or reducing the production rate may help stabilize fluid contacts [12]. This stabilization process is expected to involve the effect of gravity on the redistribution of oil and water saturations within porous media.

Gravity segregation is commonly considered during gas injection processes. For instance, in-situ visualization studies of CO_2 flooding revealed pronounced gravity segregation and viscous fingering caused by the significant differences in density and viscosity between CO_2 and oil [13]. However, a similar phenomenon also occurs between water and oil phases in porous media, despite the much smaller density difference between these fluids. For example, the authors of [14] demonstrated that the balance between viscous forces and gravitational segregation strongly affects the vertical sweep efficiency during water flooding (Fig. 1). In low-permeability models (e.g., 500 mD), higher viscous resistance suppresses gravity segregation, allowing the injected water to more effectively sweep oil from the upper parts of the reservoir and resulting in lower residual oil saturation. In contrast, in high-permeability models (e.g., 2800 mD), reduced viscous resistance enhances gravity segregation, causing injected water to preferentially flow through the lower part of the model while leaving a significant amount of unswept oil in the upper zones near the production well [14].

If this phenomenon occurs in porous media, as demonstrated by the above-mentioned laboratory studies and the previous work by the authors [15],

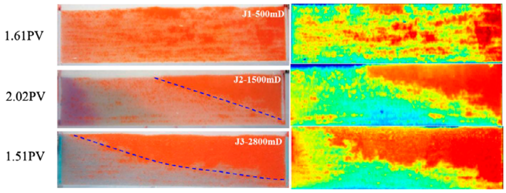

Figure 1. Visualization of the effect of gravity on the distribution of water and oil in 2D laboratory models with varying permeability (500–2800 mD) [14]

it may theoretically be exploited to achieve oil–water segregation in the vicinity of a production well during temporary shut-in periods. Such shut-ins may promote restoration of the pressure profile and redistribution of fluid saturations near the wellbore due to gravitational forces. However, before practical application, comprehensive core flooding experiments must be conducted to demonstrate the effect of gravity-driven oil–water segregation in core samples of varying length and permeability.

This article presents a methodology for constructing cost-effective epoxy core holders and describes a core flooding experimental methodology using both low- and high-viscosity oils.

Materials and methods

Preparation of core samples

Both sandstone and limestone core samples can be used. The cores may be either cut along the axis to simulate a fracture or drilled internally to a certain depth to represent a high-permeability anomaly. At this stage, an important factor to consider during core preparation is that, when using cores from real reservoirs (as opposed to outcrop cores such as Berea sandstone or artificial cores), drilling perpendicular to the bedding planes is strongly recommended (Fig. 2). This approach is more relevant to the objectives of the study, particularly for investigating vertical gravity segregation of fluids in porous media.

Figure 2. Drilling the core plug perpendicular to the bedding

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After drilling, the sides of the core should be machined to be flat and parallel to each other using a standard stone cutting saw or a lathe (Fig. 3).

Figure 3. Sandstone core plugs after being machined using a standard lathe

Before placing the core sample inside a metal sleeve for casting with an epoxy–clay material, the samples must be coated with a 4-minute epoxy adhesive to encapsulate the core and prevent the casting material from penetrating into the porous medium. Fig. 4 shows the composite core sample before and after coating with the 4-minute epoxy. ABRO 4 Minute KWIK-SET epoxy was used for this purpose (Fig. 4).

a) b)

Figure 4. Composite core sample before and after coating with ABRO 4 Minute KWIK-SET epoxy

a) before coating; b) after coating

Casting the core

Fig. 5 illustrates the casting holder: (1) long threaded bolts (minimum length), (2) base holder, (3) sleeve casting base, (4) sleeve, (5) spacer, and (6) stabilizer. The stabilizer, shown separately in Fig. 5 (b), consists of a large metal disk with two pour holes, a threaded bolt, two washers, three nuts, a wing nut, and a spring. The screw–spring assembly maintains the core in a centered position and applies sufficient downward force to prevent flotation during casting. The system is adjustable and can accommodate cores of varying heights.

a) b)

Figure 5. Casting holder

a) setup for casting; b) stabilizer

After pouring the casting material into the annular space and waiting for 24 hours which is necessary for the epoxy-clay composite to cure the casting holder can be disassembled and the core can be taken to a machine shop for facing off (Fig.6).

a)

b)

Figure 6. Core before and after facing off by using a standard lathe in the machine shop

a) before; b) after

Assembling the core

After drilling the pressure ports, if required, and installing the adapters for the pressure measurement lines, the core can be assembled using end caps with O-rings, along with bolts, washers, and nuts (Fig. 7). The threads of the adapters may be coated with a thick layer of ABRO 4 Minute KWIK-SET epoxy, which acts as a sealant. Fig. 8 presents a technical drawing according to which the end caps can be fabricated in a machine shop using a standard lathe.

Figure 7. Assembling parts of the core holder

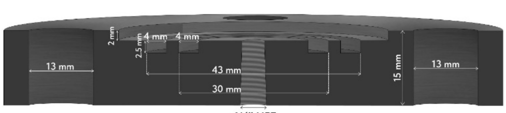

Figure 8. Technical drawing of a lid used to assemble the core

Experimental procedure

The core flooding experiment was conducted according to the following protocol:

1. The core was vacuumed to remove trapped air and check for leaks.
2. The core was saturated with brine to determine pore volume and porosity.
3. Brine was displaced with crude oil to establish initial oil saturation, create connate water saturation, and measure oil permeability at connate water conditions.
4. Brine was injected at a constant rate until the water cut at the outlet reached 50–90%.
5. The core was aged for at least one week to allow gravity segregation, leading to increased oil saturation in the upper part of the model.
6. Brine injection at a constant rate was then repeated.

Steps 3–6 were performed at the target reservoir temperature.

Effluent samples were collected in plastic containers and analyzed using a gravimetric method. Depending on oil properties and experimental conditions, several oil–water separation techniques may be applied, including: (1) gravity separation in an overflow glass column, (2) centrifugation, and (3) adhesion of oil to polyethylene surfaces (Fig. 9).

In this study, separation was carried out using the polyethylene adhesion method as follows:

1. An empty polyethylene test tube (with cap) was accurately weighed.
2. The effluent sample was collected in the tube.
3. The tube containing the sample was weighed.
4. The tube was gently rotated to maximize adhesion of oil to the polyethylene surface.
5. Water was carefully decanted without disturbing the adhered oil.
6. The tube containing only oil was weighed again.

At this stage, the remaining fluid consisted exclusively of oil. The masses of oil, water, and total produced fluid were determined by difference.

If any oil was observed to be removed together with the water during decanting, the drained liquid was collected in a second polyethylene tube and the procedure was repeated to ensure complete separation. If residual water was suspected to remain in the original tube, the tube was heated (open) at 40–60°C to evaporate the remaining water, leaving only oil, after which the final weight was recorded.

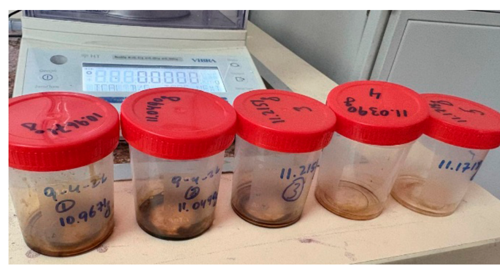

Figure 9. Polyethylene test bottles used to collect effluent from the core

Results and discussion

As shown in Fig. 10, during one hour after vacuuming, the pressure inside the core remained at an average level of −0.9 atm, indicating good integrity of the constructed model.

Further saturation was performed using a high-pressure syringe pump. Depending on the permeability of the sample, different flow rates may be applied at this stage. For very low-permeability cores, it is recommended to install an additional pressure transducer at the outlet of the core holder, as a fast increase in inlet pressure may be misleading and suggest complete saturation, whereas the saturating fluid may not yet have reached the outlet of the core.

Fig. 11 shows that the measurement of pressure at the center of the porous medium provides insight into saturation dynamics that cannot be obtained from inlet pressure alone. While inlet pressure increases gradually, reflecting overall flow resistance, the central pressure remains nearly constant at the initial stage, indicating that the fluid has not yet reached the core center and much of the medium remains unsaturated. A sharp rise in central pressure at approximately 8 minutes corresponds to the arrival of the saturation front. After this point, central

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pressure increases alongside inlet pressure, indicating internal pressurization and continued front propagation. Thus, central pressure serves as a reliable indicator of front arrival and saturation progression within the porous medium.

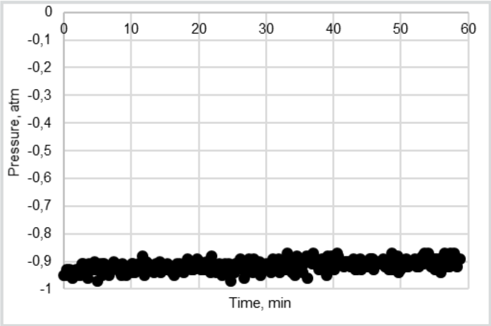

Figure 10. Pressure inside of the core versus time after vacuuming the core holder at room temperature

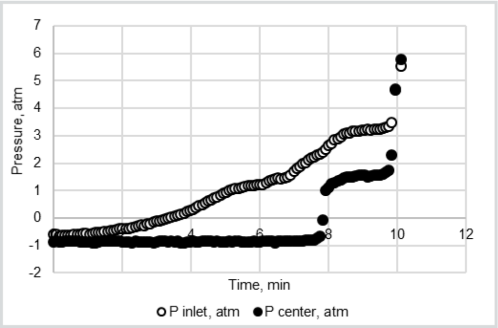

Figure 11. Pressure versus time during the injection of brine at the flow rate of 1 cm3/min into a 2.5 mD sandstone core sample after vacuuming

Measuring water permeability after core saturation can be challenging and may produce misleading results if certain factors are not properly accounted for. One important issue is the use of small-diameter tubing combined with pressure measurement devices positioned at a considerable distance from the core or sand pack. This limitation is particularly relevant in sand pack and fractured core experiments, where relatively high flow rates are required for pressure transducers to detect subtle pressure variations.

As demonstrated in Table 1, even a short outlet line (8 cm in length and 1.5 mm in diameter) introduced a noticeable increase in the measured pressure during brine injection at elevated flow rates (100–220 cm³/min). The growing discrepancy with increasing flow rate can be explained by the nonlinear rise in frictional pressure losses within the narrow outlet tube. At higher flow rates, inertial effects become significant, leading to a disproportionate increase in pressure drop along the outlet line and, consequently, a larger deviation between the two measurement configurations.

Table 1. Effect of a narrow outlet line on measured pressure at different flow rates

Pump rate, rpm	1-With outlet tube (L = 8 cm; D = 1.5 mm)				2-Without outlet tube			
	P, MPa	Mass of brine produced, g	Time, sec	Measured flow rate, cm³/min	P, MPa	Mass of brine produced, g	Time, sec	Measured flow rate, cm³/min
50	**0.011**	35.79	20	107.5	**0.008**	25.37	15	101.6
100	**0.029**	59.19	25	142.24	**0.018**	56.56	24	141.6
200	**0.1**	190.13	51	224	**0.054**	123.1	34	217.51

To minimize such errors, it is recommended to use tubing and fittings with larger diameters so that they do not act as the primary flow restriction. In addition, positioning pressure taps as close as possible to the inlet and outlet of the core can significantly improve the accuracy of pressure measurements.

The injection of oil to establish initial oil and connate water saturation should be continued until the pressure stabilizes, indicating equilibrium conditions within the core (Fig. 12). This step should be conducted at reservoir temperature using native reservoir fluids and rock material to ensure representative wettability and fluid–rock interactions. While some methodologies recommend preliminary cleaning of core samples via Soxhlet extraction with organic solvents, this approach may alter the native state of the rock. The authors of this work advocate for the use of the core material in its preserved state, maintaining the original in-situ oil and water saturation without prior cleaning.

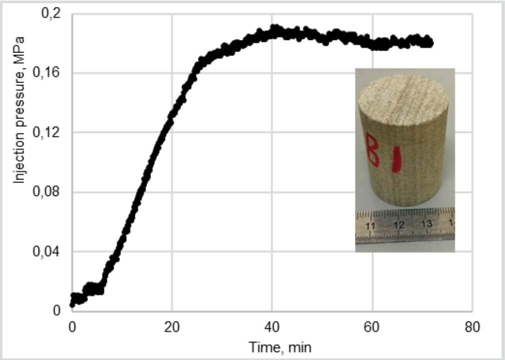

Figure 12. Injection pressure profile during oil injection into a brine-saturated Berea sandstone core
Q = 0.15 cm³/min, μ = 64 cP; D = 2.97 cm, L = 3.8 cm, PV = 4.56 cm³

This approach offers several advantages. First, it preserves the native wettability of the rock, which is often irreversibly altered by solvent extraction. Second, it maintains the original distribution of fluids and surface-active components, including asphaltenes and polar compounds, which play a critical role in fluid–rock interactions. Third, it avoids potential structural and chemical alterations of the pore surface caused by aggressive solvents. As a result, the experimental conditions more closely represent actual reservoir behavior, improving the reliability of permeability and displacement measurements for field applications.

A proper pressure versus time (or injected volume) curve during oil injection should resemble that shown in Fig. 12. The example illustrates the injection of 64 cP oil into a short (3.8 cm) Berea sandstone core sample. The stabilized injection pressure should be used to calculate the permeability to oil at connate water saturation. This value is subsequently used to determine the oil mobility ahead of the displacement front and, ultimately, to evaluate the mobility ratio.

Prior to injection into the core sample, crude oil should be filtered to remove particulate solids and prevent plugging at the core inlet face. Omitting this step may prevent pressure stabilization during injection, as suspended particles can accumulate at the core entrance and progressively reduce permeability.

Water flooding is subsequently performed to displace a portion of the mobile oil until water breakthrough occurs. If the objective of the experiment is to evaluate the extent to which gravity segregation can reduce water cut through the accumulation of mobile oil in the upper part of the core, the injected water volume during this stage must be selected carefully. Depending on the oil viscosity, different relationships between the percentage of produced mobile oil, water cut, and injected water volume may be observed.

Fractional flow calculations based on the relative permeability model (Fig. 13) described by Equations (1) and (2) were used to demonstrate this behavior:

$$k_{rw} = 0.1[(S_w - S_{wr})/(1 - S_{or} - S_{wr})]^2 \quad (1)$$

$$k_{ro} = [(1 - S_{or} - S_w)/(1 - S_{or} - S_{wr})]^2 \quad (2)$$

$$S_{or} = S_{wr} = 0.3 \quad (3)$$

when k_{rw} – relative permeability to water; k_{ro} – relative permeability to oil; S_w – water saturation; S_{wr} – irreducible water saturation; S_{or} – residual oil saturation.

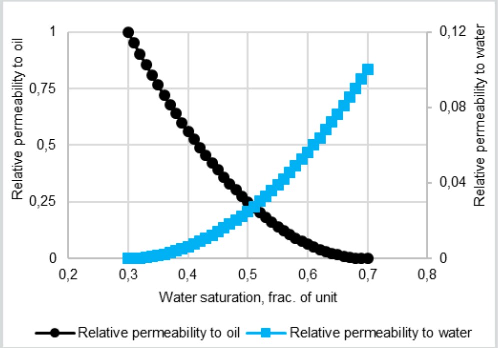

Figure 13. Relative permeability curves generated by equations (1–2)

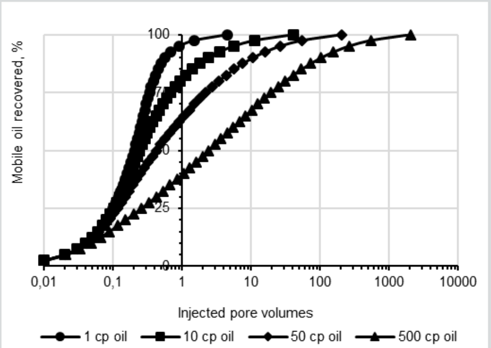

Figure 14. Results of fractional flow calculations used to assess the oil displacement dynamics for different oil viscosities

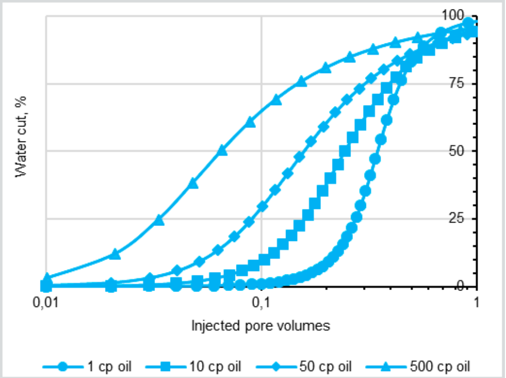

Figure 15. Results of fractional flow calculations used to assess the water cut dynamics for different oil viscosities

In fact, when highly viscous oils are used (i.e., under unfavorable mobility ratio conditions), water breakthrough may occur at an early stage of water flooding. Fractional flow calculations (Fig. 14) demonstrate that, for 500 cP oil, only approximately 40% of the mobile oil is displaced after the injection of 1 PV of water, while the water cut already reaches about 95%. This indicates that a substantial fraction of mobile oil (approximately 60%) remains in the model and may subsequently be redistributed by gravity during the shut-in period following water breakthrough.

In contrast, when low- or moderate viscosity oils (1–10 cP) are used, the injection of large water volumes (>1 PV) is generally not recommended, as it may result in the displacement of most of the mobile oil from the core. As shown by the fractional flow calculations (Fig. 14 and 15), the injection of 1 PV of water produces approximately 80–95% of the mobile oil, while the water cut increases to 95–97%. Under such conditions, the remaining oil saturation may become too low to be reliably quantified when displaced from the core using conventional laboratory methods. Small residual oil volumes may be lost due to spreading along the surfaces of the outlet tubing or may remain undetected because of experimental uncertainties associated with gravimetric measurements.

In general, the performed analysis indicates that the injected water volume prior to shut-in must be selected according to oil viscosity. For highly viscous oils (500 cP), early water breakthrough at ~95% water cut still leaves approximately 60% of the mobile oil within the model, creating favorable conditions for gravity-driven oil redistribution during shut-in. In contrast, for low- and moderate-viscosity oils (1–10 cP), the injection of only 1 PV of water already displaces ~80–95% of the mobile oil, leaving too little remaining oil saturation for reliable evaluation of gravity segregation effects.

When dealing with low- or moderate-viscosity oils (1–10 cP), a more appropriate laboratory approach should ensure that a considerable amount of mobile oil remains in the core after water flooding reaches high water cut values. If the core does not contain any macroscale heterogeneity (e.g., a partially penetrating fracture), the favorable mobility ratio will result in a close to piston-like displacement, producing a steep relationship between oil displacement, water cut, and injected water volume. In contrast, if a high-permeability channel is artificially drilled halfway into the core from the injection side (Fig. 16), the injected water will preferentially flow through this channel and bypass a significant portion of the oil in the adjacent matrix (Fig. 17). As a result, high water cut values may be reached at the outlet while a substantial amount of oil still remains in the first half of the core. During the subsequent shut-in and aging period, gravity segregation may result in the redistribution of fluid saturations within the core, with oil migrating upward and water moving downward.

Figure 16. Core sample with a 3 mm diameter channel drilled halfway into the core

Figure 17. Visualization of water bypassing oil retained in the matrix adjacent to the channel

The developed laboratory methodology demonstrated that gravity segregation in vertically aged oil–water saturated cores strongly depends on oil viscosity and flow heterogeneity. Fractional flow analysis showed that for 500 cP oil, water breakthrough at ~95% water cut still leaves approximately 60% of the mobile oil inside the porous medium after 1 PV of injected water, creating favorable conditions for gravity-driven redistribution during shut-in. In contrast, for low-viscosity oils (1–10 cP), injection of 1 PV displaced ~80–95% of the mobile oil, leaving insufficient remaining saturation for reliable segregation analysis unless artificial high-permeability channels were introduced. The proposed epoxy-sealed core assembly provides a practical and low-cost platform for investigating these processes and may serve as a laboratory basis for field technologies aimed at reducing water cut in highly watered wells.

Conclusion

- A low-cost epoxy-sealed core holder methodology was developed for gravity segregation studies;
- For 500 cP oil, ~60% of the mobile oil remained in the core after 1 PV injection at ~95% water cut;
- For 1–10 cP oils, 1 PV injection displaced ~80–95% of the mobile oil;
- Artificial 3 mm channels promoted early water breakthrough while preserving oil in the adjacent matrix;
- During vertical aging, oil migrated upward while water moved downward due to gravity segregation;
- The methodology may support development of shut-in technologies for reducing water cut and improving oil recovery.

ADDITIONAL INFORMATION

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Authors' contribution. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work. The greatest contribution is distributed as follows: Marat Sagyndikov – project conceptualization, funding acquisition, and research supervision; Iskander Gussenov – methodology development, fractional flow calculations, and technical interpretation of results; Yerzhan Melis – laboratory work planning and manuscript editing; Zhanabay Matkir – experimental implementation and laboratory data acquisition.

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Источник финансирования. Работа была выполнена в рамках проекта «AP22787244 Разработка инновационной технологии скважинной добычи для увеличения нефтеотдачи, снижения операционных затрат и углеродного следа», при финансовой поддержке Коммитета науки Министерства науки и высшего образования Республики Казахстан.

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Вклад авторов. Все авторы подтверждают соответствие своего авторства международным критериям ICMJE (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией). Наибольший вклад распределён следующим образом: Сагындиков М. – разработка концепции исследования, привлечение финансирования и научное руководство проектом; Гусенов И. – разработка методики исследования, выполнение расчётов и интерпретация результатов; Мелис Е. – планирование лабораторных работ и редактирование рукописи; Маткир Ж. – проведение лабораторных экспериментов и сбор экспериментальных данных.

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