Journal of SRI "Geotechnological Problems of Oil, Gas and Chemistry" of ASOIU,
Issue 2, 2025, pp. 68-79
https://doi.org/10.65294/gpogc.2026.04

Pore-scale evaluation of oil samples with distinct physicochemical properties for enhanced oil recovery efficiency

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Abstract. This paper presents a detailed laboratory investigation of the behavior of three types of oil with different physicochemical properties (processed transformer oil, machine oil and paraffinic oil) in a porous medium. The main objective of the study is to establish a scientific basis for increasing the efficiency of oil recovery processes by examining the displacement capabilities of this oil, their interactions with water and their electrokinetic characteristics. During the experiments, the kinematic viscosity, specific gravity, displacement percentage in the porous medium, recovery rate during water injection and electrokinetic behavior of the oil were determined. The results revealed that the physicochemical properties of the oil, particularly viscosity and specific gravity, significantly influence their behavior in porous media. Among the oil tested, the paraffinic oil with the lowest viscosity demonstrated the highest displacement capability (57.5%) and the highest recovery rate during water flooding (58.6%) compared to the others. Transformer oil, which had the highest viscosity, exhibited the lowest displacement performance. A comprehensive analysis of resistance changes during water flooding showed that paraffinic oil displayed more stable resistance within the rock. Electrokinetic studies revealed a correlation between the oil's electrokinetic behavior and their specific gravity and viscosity. The flow rates of the oil under different pressures were also examined and various flow characteristics (viscous-plastic and viscous behavior) were observed both within the porous medium and under normal conditions. In addition, the experimental workflow was standardized to ensure consistent boundary conditions for reliable comparison of the oils. The study further offers a methodological basis for future work linking pore-scale flow behavior with overall recovery efficiency. The findings demonstrate that optimizing the physicochemical properties of oil used in oil recovery, especially by adjusting viscosity and specific gravity, can significantly enhance production efficiency. The high displacement and recovery performance of paraffinic oil indicates promising potential for its more effective application in reservoir development. These results are not only practically important for the oil industry but also provide a foundation for future research on fluid flow and interactions in porous media.

Keywords. Production, rock, oil, displacement, porous medium, viscosity, specific gravity, electrokinetics.

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1. Introduction. To purposefully control the oil recovery process, the optimal conditions for the displacement of oil, gas, water and their mixtures from rocks must be studied. The interactions between liquids and gases with solid bodies, as well as the interactions between liquids and gases themselves, play a crucial role in oil recovery. By examining these processes, it becomes possible to determine the optimal mode of oil recovery [1,2].

The displacement of viscous fluids in porous media is of particular importance in the oil and gas industry, in the management of groundwater resources and in many other geological and engineering applications. One of the key factors determining the efficiency of this process is the set of physicochemical properties. Physicochemical parameters influencing fluid flow in porous media, such as viscosity, surface tension, salinity and ionic composition and their interaction with the pore structure and surface characteristics of the medium can significantly alter the kinetics and outcomes of displacement processes [3,4].

Recent studies show that the nature of fluid flow in porous media is not governed solely by physical parameters but is also closely linked to chemical interaction mechanisms [5]. In particular, the ability of chemical agents to penetrate porous structures and the changes they induce on pore surfaces significantly affect displacement efficiency. Research indicates that modifying the ionic composition or applying nanoparticle-based reagents can be used to control capillary forces within the porous structure and the spread and reaction dynamics of these reagents are directly related to the controllability of the displacement process [6,7]. Understanding the main mechanisms of these processes requires considering factors such as surface energy, capillary forces and sorption phenomena in porous media [8,9].

Additionally, methods that facilitate fluid movement through pores by means of surfactants have been widely investigated. In particular, studies have shown significant results regarding the optimization of physicochemical properties of surfactants and polymers used in oil reservoirs to enhance their efficiency. Such approaches open new opportunities for a deeper understanding of the structural characteristics of porous media [10].

Experimental work has also shown that variations in temperature and pressure intensify physicochemical effects and play a decisive role in optimizing the displacement kinetics of viscous fluids. Comprehensive investigation of these mechanisms is not only of theoretical importance but also ensures the development of more efficient application methods in industry [11]. Considering these points, continued research on displacement processes in porous media and the analysis of obtained results through integrative models have opened new directions and perspectives in this field [12].

2. Methodology. The experimental methodology was designed to systematically evaluate the behavior of viscous oil samples within a controlled porous medium under predefined hydrodynamic and physical conditions. All procedures were carried out to ensure reproducibility and to accurately capture the influence of fluid properties, pressure differentials and flow regimes on displacement performance. The displacement of the viscous fluids (oil) under investigation in the porous medium was carried out according to the scheme shown in Figure 1.

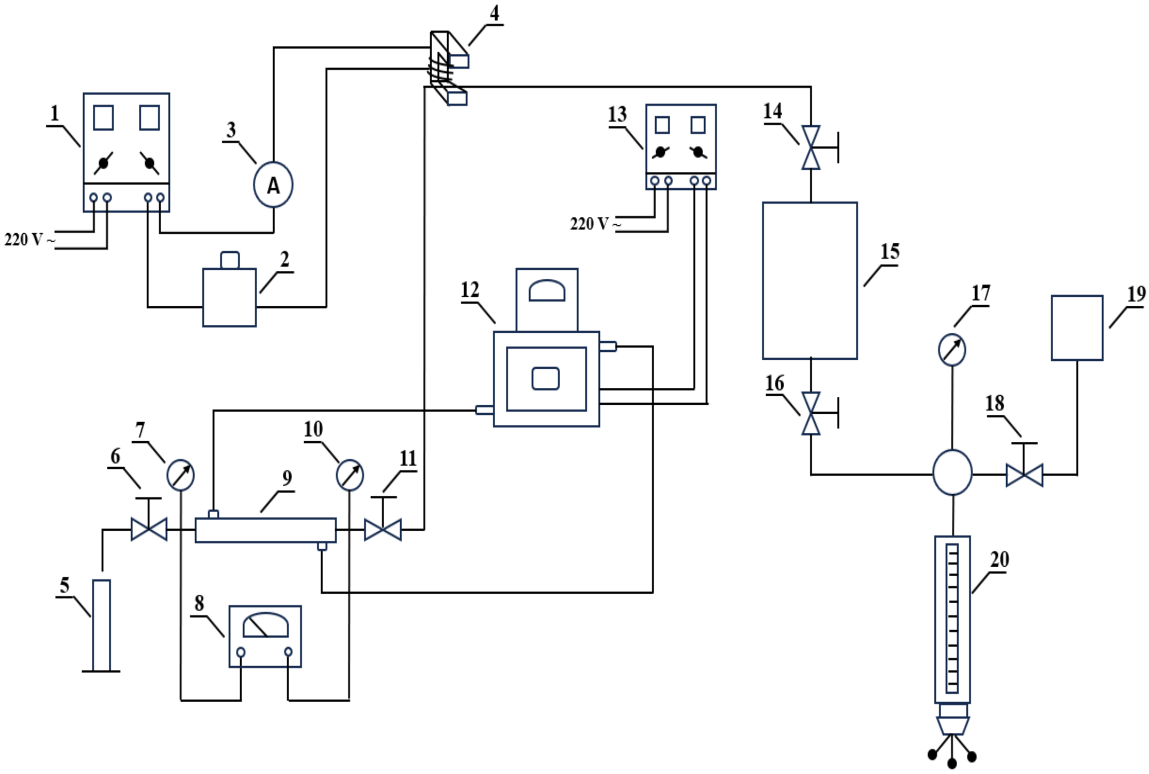


Figure 1. Schematic representation of the experimental setup.

The experimental setup consists of the following components: USA-4A type current regulators (1,13), SUNTEK 2000 VA voltage stabilizer (2), volt-ammeter (3), electromagnet (4), measuring cylinder (5), valves (6,11,14,16,18), manometers (7,10,17), URV-2M potentiometer with high input resistance (8), high-pressure column (9), thermostat (12), PVT-type high-pressure bomb (15), liquid tank (19) and a pressure applicator (20).

A linear reservoir model 120.4 cm in length and 4.2 cm in diameter was used and its inner surface was coated with epoxy adhesive to ensure insulation. The model was filled with a porous medium consisting of a mixture of 75% quartz sand and 25% clay. To achieve a densely packed porous medium, the column was filled in stages using a vertical vibration–tamping method, ensuring tight placement of the sand–clay mixture within the tube. The porous medium was then saturated with the test liquid using the PVT bomb (15) and both the liquid and porous medium were pre-vacuumed.

It should be noted that, to completely remove air trapped in the pores, periodic pressurization and rapid pressure release were applied during injection. When pressure increased inside the column, partial dissolution of gas and its filtration under a high pressure differential ensured effective removal of gas from the porous medium. Afterwards, the viscous liquid was introduced into the porous medium in a single-phase state from the PVT bomb. For this purpose, the high-pressure column (9) was connected to the PVT bomb and the viscous liquid was displaced into the pores using the press (20). At the end of the displacement, the total volume of oil collected in the measuring container was recorded.

The next stage of the experiment involved displacing the remaining oil inside the porous medium with water. For this, the outlet valve of the bomb was closed and the inlet valve opened. The inlet was connected to a gas line (nitrogen or carbon dioxide) and a pressure of 4-5 atm was applied to lower the piston. Then the gas line was disconnected and the bomb inlet was connected to a vacuum pump. After 10-15 minutes of vacuuming, ensuring complete degassing, the bomb was prepared for water filling. To prevent air entry, the inlet valve was first closed, water was added to a funnel to a certain level and then the inlet valve was opened so that water could enter the bomb. As the water level in the funnel decreased, additional water was added until the bomb was completely filled.

Using this method, the volume of water entering the bomb was determined to be 800 ml. After removing any possible remaining air pockets, the device was activated. The inlet valve of the bomb was closed, the outlet valve opened and oil was supplied to the press from the tank. Then the line between the tank and the press was closed, the bomb inlet opened and oil entered from below, pushing the piston upward. As the piston rose, it displaced the water above it into the porous medium.

At the beginning of the experiment, a lower pressure (5-8 atm) was used because water required some time to reach and displace oil from the porous medium. This also ensured uniform wetting of the rock. Once the first oil droplets appeared in the measuring cylinder at the column outlet, the pressure was gradually increased. Higher pressures were applied step by step within specific time intervals until a steady rate of oil droplets was achieved. This pressure was then selected as the operating pressure. In our case, it was 20 atm.

Oil displacement by water was performed at this operating pressure. At 5-minute intervals, the amount of water entering the system (determined from the press), voltage, resistance, produced oil volume and produced water volume were measured and recorded. The experiment continued until the water content in the produced mixture reached 5-6% of the total.

3. Methodology. The kinematic viscosities and specific gravities of the three oil under study (processed transformer oil, machine oil and paraffinic oil) were determined in laboratory conditions using a capillary viscometer and a hydrometer. The kinematic viscosity was found to be 198 mm^2/s for processed transformer oil, 47.49 mm^2/s for machine oil and 24.9 mm^2/s for paraffinic oil (Figure 2). The specific gravity values were 0.971 kg/m^3 for processed transformer oil, 0.85 kg/m^3 for machine oil and 0.84 kg/m^3 for paraffinic oil (Figure 3).

Next, the behavior of the oil, with their previously determined densities and viscosities, within the rock was evaluated by determining their displacement characteristics. For this purpose, the oil samples were first injected into the porous medium according to the methodology described earlier.

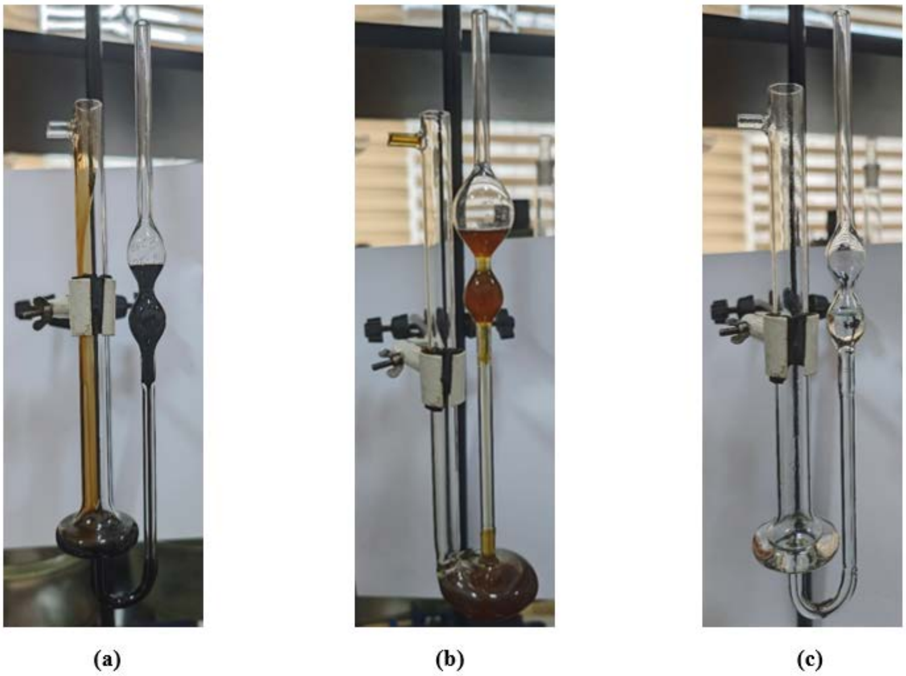


Figure 2. Determination of the kinematic viscosity of the investigated oil using the Engler capillary viscometer.
a – transformer oil, b – machine oil, c – paraffinic oil.

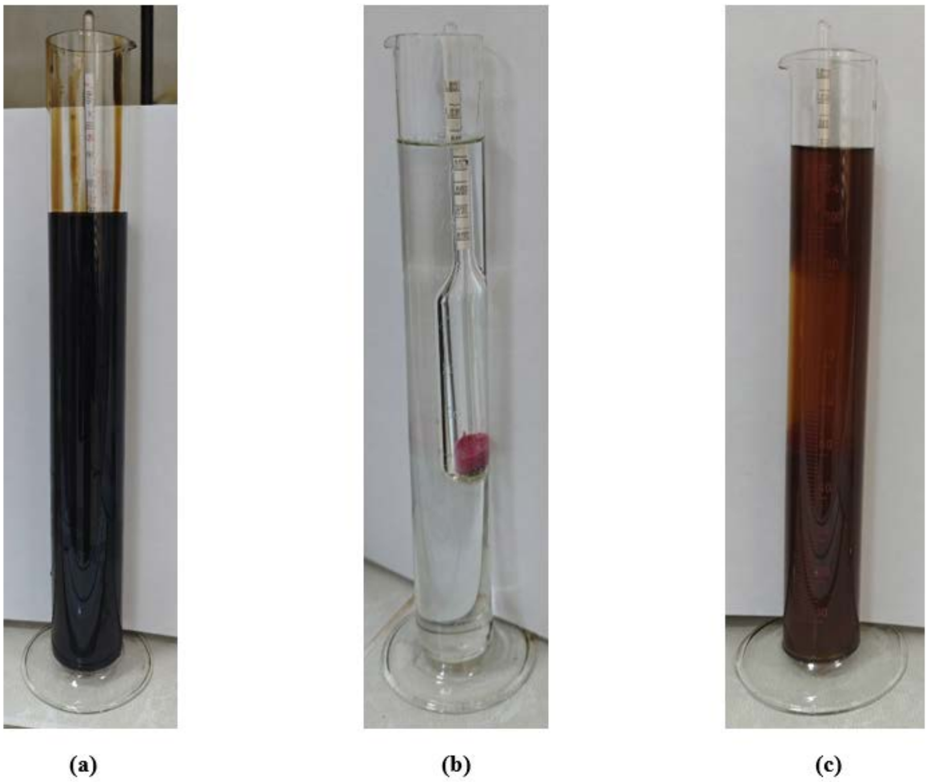


Figure 3. Determination of the specific gravity of the investigated oil using a hydrometer.
a – transformer oil, b – machine oil, c – paraffinic oil.

It was found that when 800 ml of processed transformer oil was injected into the porous medium, 330 ml of oil was displaced; for the same volume of machine oil, 380 ml was displaced; and for paraffinic oil, 460 ml was displaced. Expressed as percentages, the displacement efficiency was 41.2% for processed transformer oil, 47.5% for machine oil and 57.5% for paraffinic oil.

After determining the displacement efficiency, the next stage was to displace the remaining, trapped oil in the porous medium with water and assess the changes in parameters that are crucial for oil recovery. Following the mentioned methodology, the water-driven displacement of each remaining oil was carried out. It was determined that during water displacement, 310 ml of water and 178 ml of oil were recovered for processed transformer oil; 340 ml of water and 220 ml of oil for machine oil; and finally, 408 ml of water and 200 ml of oil for paraffinic oil. In percentage terms, the final recovery during water displacement consisted of 38.7% water and 48.1% oil for processed transformer oil, 42.5% water and 52.3% oil for machine oil and 51% water and 58.6% oil for paraffinic oil.

The change in resistance generated within the rock during water displacement is presented in Figure 4.

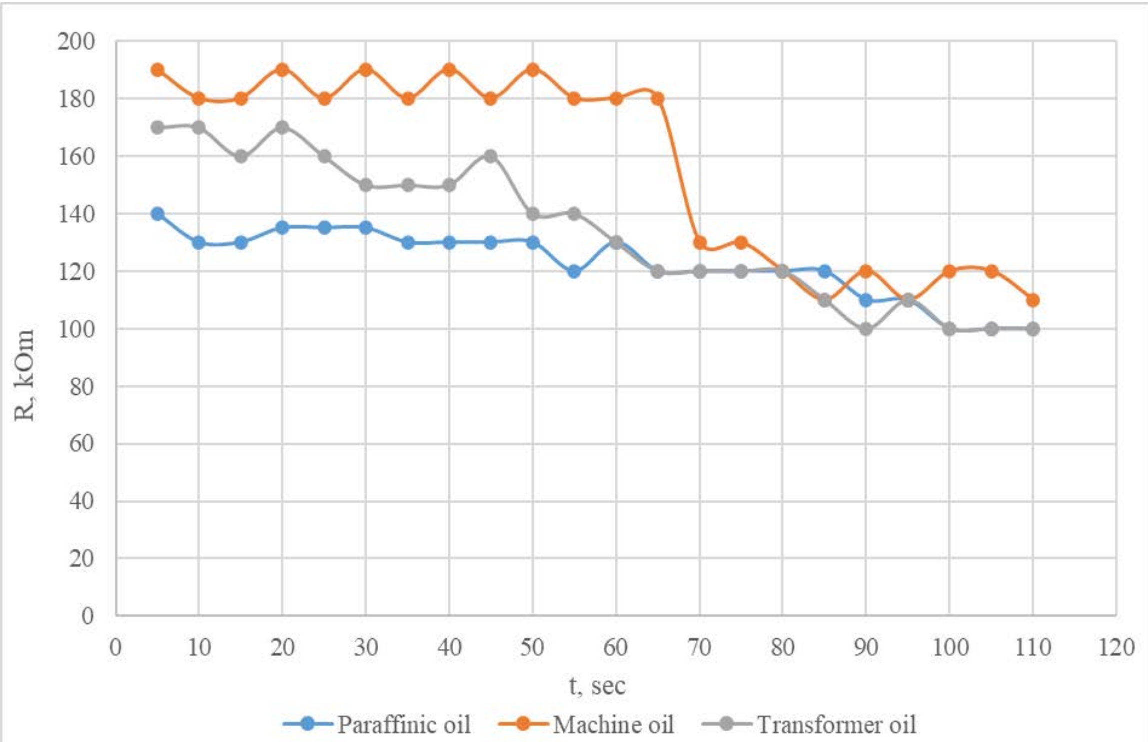


Figure 4. Time-dependent variation of resistance in the rock during waterflooding of the oil.

The experiment was conducted with three different types of oil, paraffin oil, machine oil and transformer oil and by analyzing the time-dependent changes in resistance, it is possible to better understand how each oil interacts with the rock during the displacement process. At the initial stage of the experiment, the resistance values of each oil were as follows: paraffin oil started at 140 kΩ, indicating a more stable interaction with the rock during displacement. Machine oil initially exhibited the highest resistance at 190 kΩ, suggesting stronger resistance to flow, lower permeability and less compressibility under pressure. Transformer oil maintained a resistance of approximately 160 kΩ, reflecting intermediate behavior.

During the first 60 seconds, minor changes in resistance were observed for all oil, but overall, the resistance remained relatively stable, indicating that the oil initially resisted compression and interacted moderately with the rock. After 60 seconds, notable changes occurred: machine oil showed a sharp decrease in resistance, dropping rapidly to around 125 kΩ. This indicates that machine oil was displaced more quickly, leading to faster permeability increase, less structural stability and more pronounced changes in flow characteristics. In contrast, the resistance of paraffin oil decreased more gradually, reaching approximately 120 kΩ after 120 seconds, demonstrating a more stable and consistent displacement with less variable interaction with the rock. Transformer oil also exhibited a gradual decrease, stabilizing around 130 kΩ, indicating moderate stability and a slower increase in rock permeability.

These results clearly show that the physical and chemical properties of the oil significantly affect their displacement behavior. Although machine oil started with high resistance, its rapid decrease indicates faster displacement and permeability enhancement. Paraffin oil maintained more stable resistance, confirming its more consistent impact on the rock. These characteristics are crucial for selecting and applying oil in processes aimed at increasing rock permeability.

The time-dependent variation of voltage in the rock during waterflooding of the oil is illustrated in Figure 5.

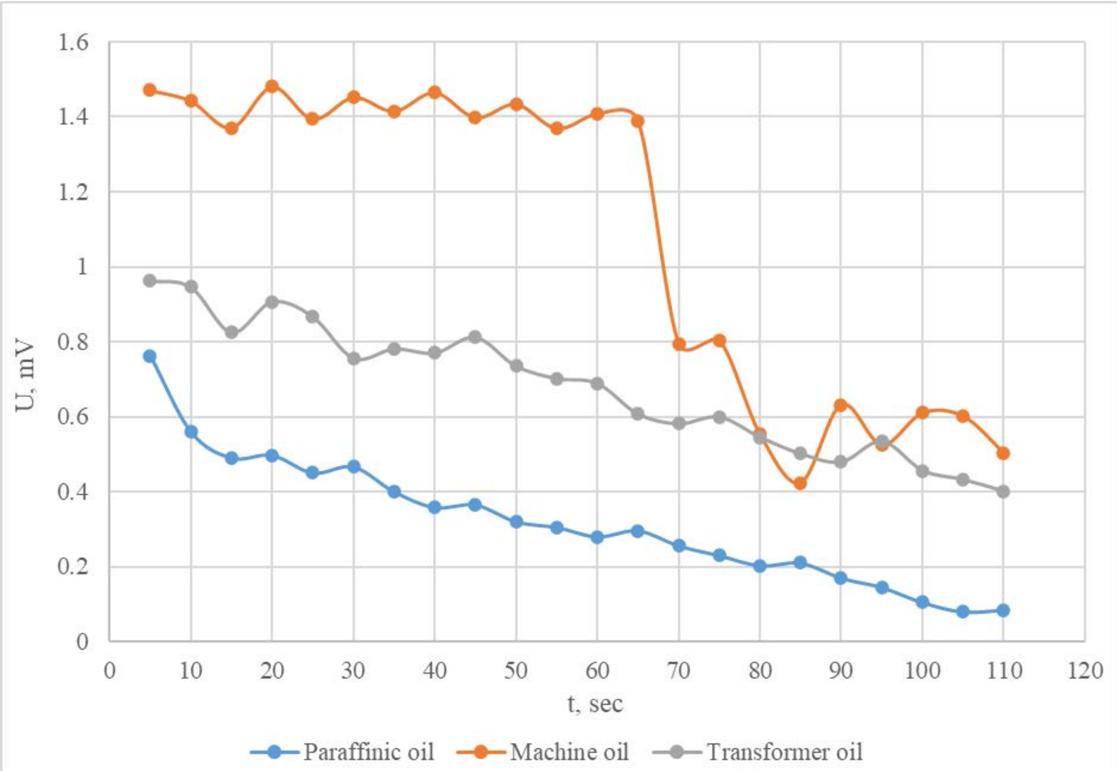


Figure 5. Time-dependent variation of volatge in the rock during waterflooding of the oil.

The graph shows that at the initial moment, machine oil exhibited the highest voltage (1.4 mV), transformer oil an intermediate voltage (0.9 mV) and paraffin oil the lowest voltage (0.8 mV). During the first 60 seconds, machine oil maintained relatively stable voltage, transformer oil showed a gradual decrease and paraffin oil exhibited a stable behavior with a slight decreasing trend. After 60 seconds, voltage in machine oil dropped sharply to approximately 0.5 mV, indicating rapid changes in voltage distribution within the rock and significant variations in the oil's electrokinetic properties during displacement. Transformer oil showed a slower decrease, stabilizing at around 0.6 mV by 120 seconds, while paraffin oil exhibited the least change, with voltage gradually decreasing and stabilizing at 0.4 mV.

These results clarify the electrokinetic behavior of oil during interaction with the rock and allow comparison of their displacement efficiency. The rapid decrease in machine oil's voltage indicates lower electrokinetic stability, whereas paraffin and transformer oil demonstrated greater stability and smaller changes. This information is crucial for considering electrokinetic phenomena in oil field development and for selecting suitable working fluids. The pressure-dependent consumption of the displaced oil is illustrated in Figure 6.

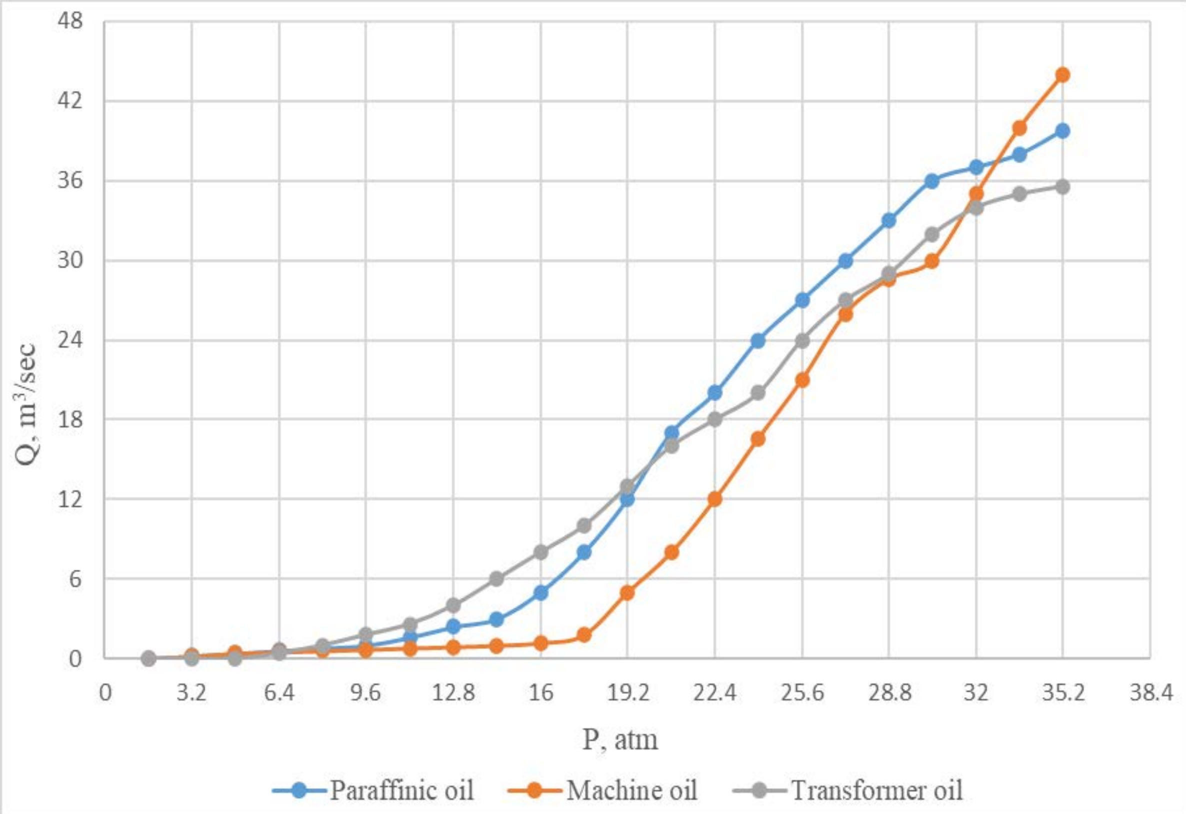


Figure 6. Pressure-dependent oil consumption during waterflooding of the oil.

The graph shows that within the initial pressure range (0–14 atm), the consumption values for all oil were very low, with no significant changes observed. As the pressure increased (beyond 16 atm), consumption rose sharply. At this stage, paraffin oil exhibited the highest increase in consumption, which can be attributed to its lower viscosity and easier flow through the rock. Machine oil initially showed the lowest consumption, but after 25 atm, its consumption rate increased significantly, reflecting its higher initial resistance and stronger interaction with the rock, requiring more energy for displacement. Transformer oil initially showed intermediate behavior, but its final consumption increase was lower compared to the other oil, which is directly related to its viscosity characteristics.

Overall, the results indicate that oil consumption increases nonlinearly with pressure, highlighting the influence of pressure on oil mobility within the rock. Paraffin oil demonstrated higher permeability and effective displacement potential at high pressure, while the lowest efficiency was observed for refined transformer oil. This information is critical for selecting oil types and defining application strategies during oil field development.

The complex analysis of the electrochemical properties of the oil during waterflooding in the porous medium revealed that the studied oil exhibit viscoplastic behavior within the rock. To determine the properties of these oil samples under normal conditions, a special laboratory experimental setup was developed and experiments with the collected oil were repeated several times (Figure 7).

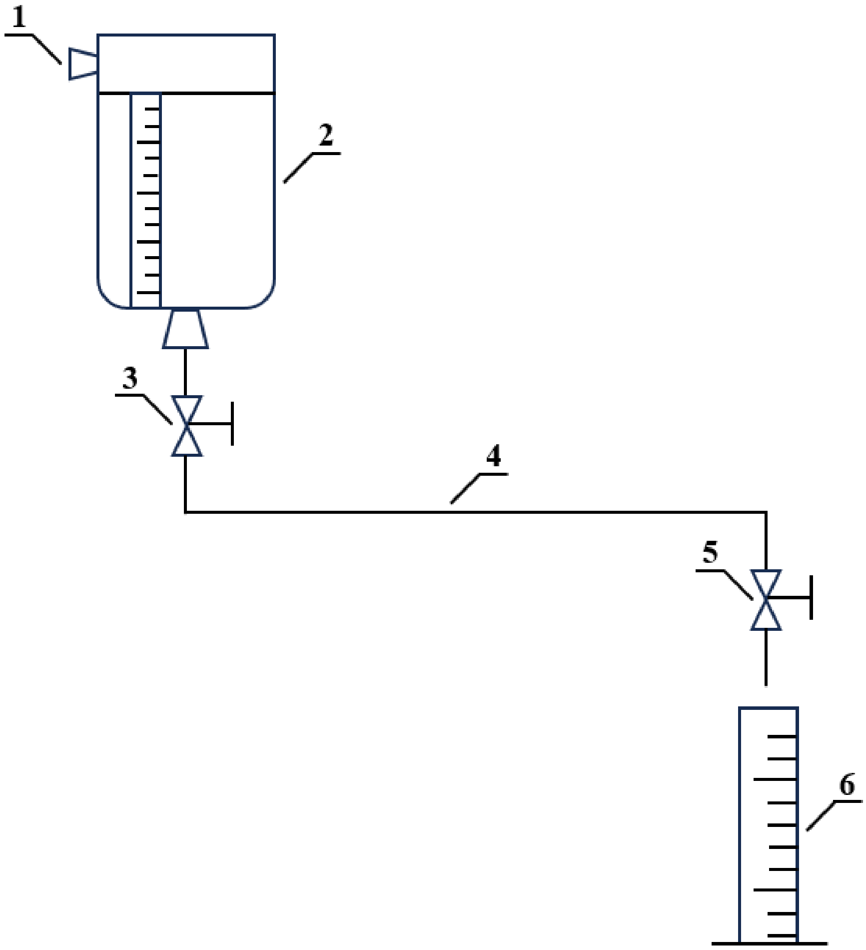
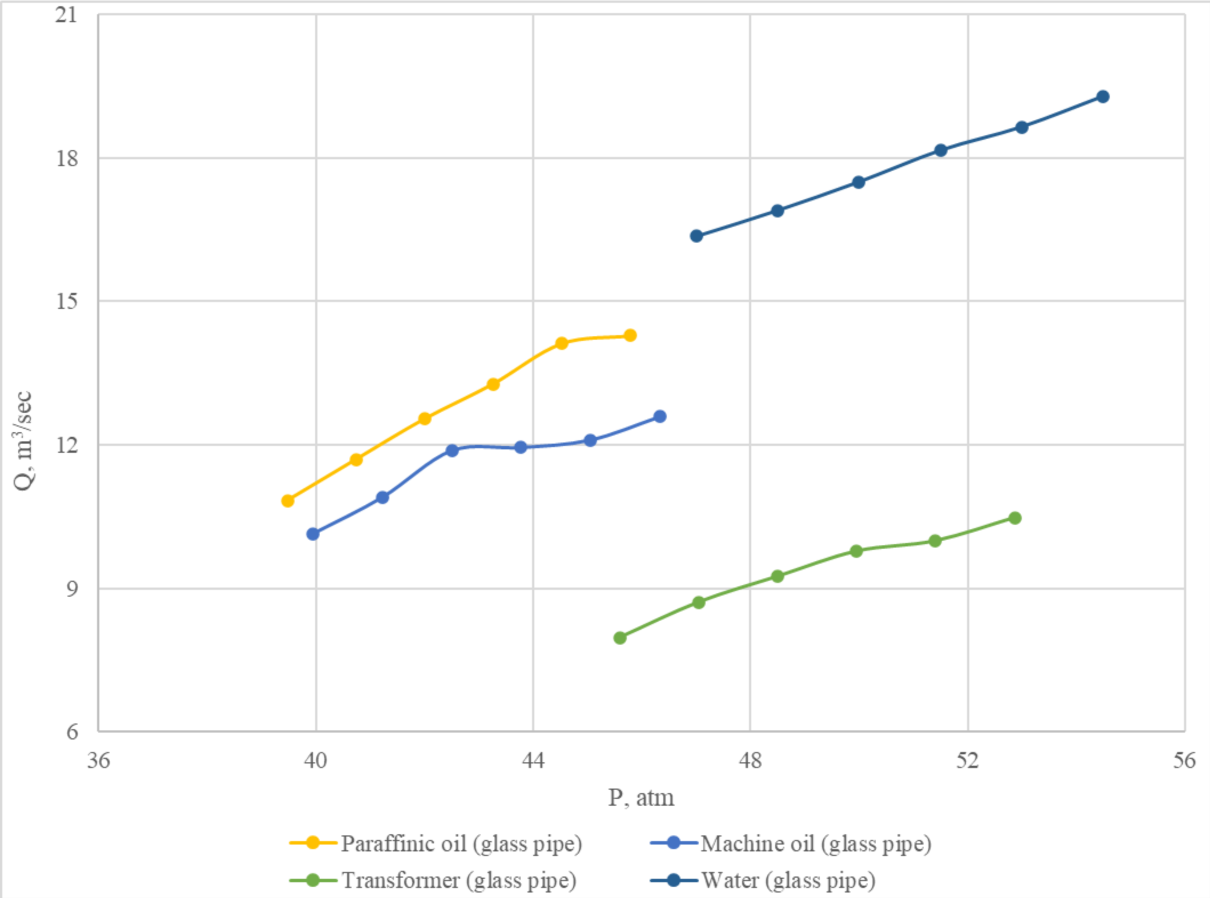


Figure 7. Schematic diagram of the experimental setup.

The experimental setup consists of these parts: liquid inlet to the flask (1), glass flask valves (3, 5), flow line (4), measuring vessel (6). The glass flask, which has a volume of 4 liters, was filled with the tested oil and the flow rate of the oil discharge over time was determined at predetermined intervals. In order to compare the stability and accuracy of the experimental results, the same experiment was also conducted with water according to the described methodology and the results were processed (Figure 8).

Figure 8. Graph of Oil Flow Rate over Pressure.



The graph illustrated in Figure 8 clearly shows that the three different oil samples studied (refined transformer oil, machine oil and paraffinic oil) exhibit viscous fluid characteristics as a result of the complex analysis of the experimental data obtained using the described methodology. The graph indicates that the results of the experiment conducted with water naturally showed that it is a Newtonian fluid, which proves the stability and accuracy of the results obtained in the mentioned experiments with the oil.

4. Conclusion. Research was conducted in laboratory conditions on three different oil samples with varying physical and chemical properties to study their electrochemical and fluid characteristics both within the rock formation and under normal conditions. The following results were obtained. Studies were conducted under laboratory conditions on three oil samples with different physicochemical properties to investigate their electrochemical and liquid characteristics both within porous media and under normal conditions and the following results were obtained:

1. The kinematic viscosities of the studied oil were determined using a capillary viscometer. It was found that transformer oil had the highest viscosity with a value of 198 mm^2/s, machine oil had a medium viscosity of 47.49 mm^2/s and paraffin oil had the lowest viscosity of 24.9 mm^2/s.

2. The specific gravities of the selected oil were determined using a hydrometer. According to the results, the specific gravity was determined as 0.971 kg/m^3 for refined transformer oil, 0.85 kg/m^3 for machine oil and 0.84 kg/m^3 for paraffin oil.

3. Experiments revealed that the compressibility characteristics of oil with different densities and viscosities differ in a porous medium. Results from compressing 800 ml oil samples into a porous medium showed that refined transformer oil was 41.2% (330 ml) compressed, machine oil was 47.5% (380 ml) compressed and paraffin oil was 57.5% (460 ml) compressed. These results prove that the compressibility capability of paraffin oil in a porous medium is higher compared to the other oil. The difference in the degree of compression is directly related to their physicochemical properties, density and viscosity. The results of the research create an important scientific basis for applying more efficient approaches in the use of different types of oil in porous media.

4. The research determined the changes occurring during the process of displacing residual oil in the rock with water. Experiments showed that as a result of water flooding, the final amounts for refined transformer oil were 310 ml of water (38.7%) and 178 ml of oil (48.1%); for machine oil, 340 ml of water (42.5%) and 220 ml of oil (52.3%); and for paraffin oil, 408 ml of water (51%) and 200 ml of oil (58.6%). These results indicate that the degree of oil recovery during water flooding depends on the type of oil and its interaction with the rock. The higher recovery factor of paraffin oil proves that it has better recovery characteristics in porous media, which is indirectly explained by its physicochemical properties. The results of this research provide valuable information for optimizing important parameters to increase efficiency in oil extraction processes.

5. The nature of the change in resistance during the water flooding of the studied oil in a porous medium was analyzed. The results of the experiments showed that the physical and chemical properties of the oil significantly affect their displacement and flow characteristics. During water flooding of refined transformer oil and machine oil, the rock initially exhibited high initial resistance, which decreased significantly towards the end of the experiment. Paraffin oil, however, showed more stable resistance and created a longer-lasting effect within the rock. These results prove that paraffin oil has a more sustained impact capability in the rock compared to other oil, with minimal change in resistance. These characteristics play an important role in selecting optimal regimes for oil extraction processes, making it necessary to consider the effect of oil displacement on rock permeability.

6. Experiments determined that the electrokinetic behavior of the oil significantly influences their interaction properties with the rock and their displacement capabilities. Initially, the highest voltage was recorded for machine oil (1.4 mV), medium for refined transformer oil (0.9 mV) and the lowest for paraffin oil (0.8 mV). By the end of the experiment, a certain level of decrease was recorded for refined transformer oil and machine oil. For paraffin oil, however, a significant change was observed and the voltage decreased and stabilized at a level of 0.4 mV. These results showed that the partial decrease in voltage during water flooding for refined transformer oil and machine oil and the sharp decrease for paraffin oil, are directly related to their specific gravities and viscosities.

7. The dependence of oil flow rate on pressure during water flooding showed that all three studied oil exhibited viscous-plastic fluid properties within the rock.

8. Based on the dependence of flow rate on pressure for the studied oil under normal conditions, they were observed to exhibit viscous fluid properties.

Conflict of interest.
The authors declare that they have no conflict of interest in relation to this research.

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