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Original article

Comprehensive Experimental Analysis of Electromagnetic Field Effects on Enhanced Oil Recovery through Optimized Magnetic Field-Induced Fluid Dynamics

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ABSTRACT

Background: The behavior of reservoir fluids under the influence of magnetic fields has significant implications for fluid transport and enhanced oil recovery. This study investigates the electrokinetic properties of reservoir fluids and fluid discharge behavior under varying pressure conditions in the presence of magnetic fields.

Aim: The primary aim of this study is to investigate the effects of magnetic fields on the electrokinetic properties of reservoir fluids and their fluid discharge behavior under varying pressure conditions. By conducting comprehensive experimental analyses, the research seeks to determine the optimal magnetic field intensity that enhances fluid conductivity, ion mobility and water displacement efficiency. The study also aims to evaluate the role of magnetic fields in mitigating pressure-induced compaction in porous media and establishing stable fluid flow conditions. The findings are expected to contribute to the advancement of enhanced oil recovery (EOR) techniques by integrating magnetic field technology to optimize oil field development, particularly in mature and low-permeability reservoirs.

Materials and methods: A custom experimental setup, including a high-pressure column, PVT bomb, electromagnet, measurement and control devices was developed to simulate reservoir conditions. Magnetic field intensities ranging from 40 to 150 mT were applied to study their effects on voltage, resistance, and water discharge during pressure variations (1.6–14.4 atm).

Results: The application of magnetic fields significantly enhanced the electrokinetic properties of reservoir fluids. At an optimal intensity of 125 mT, ion mobility and fluid conductivity were maximized, leading to a peak water discharge volume of approximately 75 m^3 at 8–9 atm. Beyond this pressure, a dynamic equilibrium stabilized fluid flow. Resistance and voltage values decreased substantially under magnetic fields, highlighting their role in mitigating pressure-induced compaction in porous media.

Conclusion: This study demonstrates the transformative effects of magnetic fields on the electrokinetic properties and discharge behavior of reservoir fluids. The optimal magnetic field intensity of 125 mT enhanced ion mobility, fluid conductivity and water discharge, achieving a peak discharge volume of approximately 75 m^3 at 8–9 atm. These findings emphasize the role of magnetic fields in reducing flow resistance and stabilizing fluid flow under high-pressure conditions, particularly by mitigating pressure-induced compaction in porous media. Additionally, the observed dynamic equilibrium beyond 8 atm suggests that magnetic fields can maintain fluid conductivity and discharge stability despite increasing pressures. These advancements pave the way for employing magnetic field technology to enhance oil recovery, especially in challenging environments such as mature or low-permeability reservoirs.

Keywords: *magnetic field; reservoir fluids; electrokinetic properties; enhanced oil recovery; porous media; water discharge; resistance; voltage.*

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Оригинальное исследование

Комплексный экспериментальный анализ влияния электромагнитного поля на повышение нефтеотдачи посредством оптимизированной динамики жидкости, индуцированной магнитным полем

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АННОТАЦИЯ

Обоснование. Поведение пластовых жидкостей под воздействием магнитных полей имеет значительные последствия для транспортировки жидкости и повышения нефтеотдачи. В этом исследовании изучаются электрокинетические свойства пластовых жидкостей и поведение сброса жидкости в условиях переменного давления в присутствии магнитных полей.

Цель. Основная цель данного исследования – изучить влияние магнитных полей на электрокинетические свойства пластовых флюидов и их поведение при вытеснении жидкости в условиях изменяющегося давления. Проведение комплексного экспериментального анализа направлено на определение оптимальной интенсивности магнитного поля, способствующей повышению проводимости жидкости, подвижности ионов и эффективности вытеснения воды. Исследование также направлено на оценку роли магнитных полей в снижении давления – индуцированной уплотняемости пористой среды – и обеспечении стабильного течения флюидов. Ожидается, что полученные результаты внесут вклад в развитие технологий увеличения нефтеотдачи путем интеграции технологии магнитных полей для оптимизации разработки нефтяных месторождений, особенно зрелых и малопроницаемых пластов.

Материалы и методы. Для моделирования условий пласта была разработана специальная экспериментальная установка, включающая колонну высокого давления, PVT-бомбу, электромагнит, измерительные и контрольные приборы. Интенсивности магнитного поля в диапазоне от 40 до 150 мТл применялись для изучения их влияния на напряжение, сопротивление и сброс воды при колебаниях давления (1,6–14,4 атм).

Результаты. Применение магнитных полей значительно улучшило электрокинетические свойства пластовых жидкостей. При оптимальной интенсивности 125 мТл подвижность ионов и проводимость жидкости были максимальны, что привело к пиковому объему сброса воды приблизительно 75 м³ при 8–9 атм. За пределами этого давления динамическое равновесие стабилизировало поток жидкости. Значения сопротивления и напряжения существенно снизились под действием магнитных полей, что подчеркивает их роль в смягчении уплотнения, вызванного давлением, в пористых средах.

Заключение. Это исследование демонстрирует преобразующее воздействие магнитных полей на электрокинетические свойства и поведение разряда пластовых жидкостей. Оптимальная напряженность магнитного поля 125 мТл увеличила подвижность ионов, проводимость жидкости и разряд воды, достигнув пикового объема разряда приблизительно 75 м³ при 8–9 атм. Эти результаты подчеркивают роль магнитных полей в снижении сопротивления потоку и стабилизации потока жидкости в условиях высокого давления, в частности, путем смягчения уплотнения, вызванного давлением, в пористых средах. Кроме того, наблюдаемое динамическое равновесие за пределами 8 атм предполагает, что магнитные поля могут поддерживать проводимость жидкости и стабильность разряда, несмотря на возрастающее давление. Эти достижения прокладывают путь к использованию технологии магнитного поля для повышения нефтеотдачи, особенно в сложных условиях, таких как зрелые или низкопроницаемые коллекторы.

Ключевые слова: *магнитное поле, пластовые жидкости, электрокинетические свойства, повышение нефтеотдачи, пористые среды, разряд воды, сопротивление, напряжение.*

Как цитировать:

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Түпнұсқа зерттеу

Магнит өрісінен туындаған сұйықтықтың оңтайландырылған динамикасы арқылы электромагниттік өрістің мұнай өндіруді арттыруға әсерін кешенді эксперименттік талдау

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АННОТАЦИЯ
Негіздеу. Магнит өрістерінің әсерінен қабат сұйықтықтарының әрекеті сұйықтықты тасымалдауға және мұнай өндіруді арттыруға айтарлықтай әсер етеді. Бұл зерттеу қабат сұйықтықтарының электрокинетикалық қасиеттерін және магнит өрістерінің қатысуымен өзгермелі қысым жағдайында сұйықтықты төгу әрекетін зерттейді.
Мақсаты. Бұл зерттеудің негізгі мақсаты-магнит өрістерінің қабат сұйықтықтарының электрокинетикалық қасиеттеріне әсерін және олардың өзгеретін қысым жағдайында сұйықтықты ығыстыру кезіндегі әрекеттерін зерттеу. Кешенді эксперименттік талдау жүргізу сұйықтықтың өткізгіштігін, иондардың қозғалғыштығын және судың ығысу тиімділігін арттыруға ықпал ететін магнит өрісінің оңтайлы қарқындылығын анықтауға бағытталған. Зерттеу сонымен қатар магнит өрістерінің қысымды төмендетудегі рөлін – кеуекті ортаның индукцияланған тығыздығын – және сұйықтықтардың тұрақты ағынын қамтамасыз етудегі рөлін бағалауға бағытталған. Алынған нәтижелер мұнай кен орындарын, әсіресе жетілген және өткізгіштігі төмен қабаттарды игеруді оңтайландыру үшін магнит өрісі технологиясын біріктіру арқылы мұнай өндіруді арттыру технологияларын дамытуға үлес қосады деп күтілуде.
Материалдар мен әдістер. Қабаттың жағдайын модельдеу үшін жоғары қысымды баған, PVT бомбасы, электромагнит, өлшеу және бақылау құралдары бар арнайы эксперименттік қондырғы жасалды. 40-тан 150 мТл-ге дейінгі магнит өрісінің қарқындылығы олардың кернеуге, кедергіге және қысымның ауытқуы кезінде судың ағуына әсерін зерттеу үшін қолданылды (1,6–14,4 атм).
Нәтижелері. Магнит өрістерін қолдану қабат сұйықтықтарының электрокинетикалық қасиеттерін едәуір жақсартты. 125 мТл оңтайлы қарқындылықта иондардың қозғалғыштығы мен сұйықтықтың өткізгіштігі максималды болды, бұл 8–9 атм кезінде судың ең жоғары ағызу көлеміне шамамен 75 м³ әкелді. Бұл қысымнан тыс динамикалық тепе теңдік сұйықтық ағынын тұрақтандырды. Магнит өрістерінің әсерінен қарсылық пен кернеу мәндері айтарлықтай төмендеді, бұл олардың кеуекті ортадағы қысымнан туындаған тығыздағышты жұмсартудағы рөлін көрсетеді.
Қорытынды. Бұл зерттеу магнит өрістерінің электрокинетикалық қасиеттеріне және қабат сұйықтықтарының разрядтық әрекетіне трансформациялық әсерін көрсетеді. Магнит өрісінің оңтайлы кернеуі 125 мТл иондардың қозғалғыштығын, сұйықтықтың өткізгіштігін және судың разрядын арттырып, разрядтың ең жоғары көлеміне 8–9 атм-да шамамен 75 м³ жетті. Бұл нәтижелер магнит өрістерінің ағынға төзімділікті төмендетудегі және жоғары қысымды жағдайда сұйықтық ағынын тұрақтандырудағы рөлін, атап айтқанда кеуекті ортадағы қысымнан туындаған тығыздағышты жұмсарту арқылы көрсетеді. Сонымен қатар, 8 атм-ден тыс байқалған динамикалық тепе-теңдік магнит өрістері қысымның жоғарылауына қарамастан сұйықтықтың өткізгіштігін және разряд тұрақтылығын сақтай алады деп болжайды. Бұл жетістіктер мұнай өндіруді жақсарту үшін магнит өрісі технологиясын қолдануға жол ашады, әсіресе жетілген немесе өткізгіштігі төмен коллекторлар сияқты қиын жағдайларда.
Негізгі сөздер: *магнит өрісі, қабат сұйықтықтары, электрокинетикалық қасиеттері, мұнай берудің жоғарылауы, кеуекті орта, су разряды, кедергі, кернеу.*

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Introduction

Enhanced Oil Recovery (EOR) has emerged as a critical field of research in petroleum engineering, aimed at maximizing oil recovery from reservoirs that conventional methods leave behind. Among the array of EOR techniques, waterflooding is one of the most established and widely employed. It involves injecting water into the reservoir to displace oil towards production wells. While effective waterflooding often faces challenges such as poor sweep efficiency, high water cut and issues stemming from reservoir heterogeneity. Addressing these limitations has led researchers to explore innovative methods, including the application of physical fields such as magnetic, electric and ultrasonic fields, to improve recovery [1–3].

Previous researches have revealed that waterflooding efficiency can be enhanced by altering the properties of the injected water or the reservoir itself. Studies on magnetic water treatment suggest that exposing water to magnetic fields can modify its structural and dynamic properties, such as viscosity, ion mobility and surface tension. These changes can influence interactions between the injected fluid and reservoir rocks, potentially improving the displacement efficiency of trapped oil. For instance, magnetic fields have been shown to reduce scale formation and improve fluid mobility, which are key factors in mitigating injectivity and production issues [4,5].

The interaction of magnetic fields with reservoir fluids is supported by electrokinetic theory, which describes how electric charges in fluid systems respond to external stimuli. When subjected to magnetic fields, the movement of charged particles such as ions can be altered, leading to changes in conductivity and flow behavior. This effect, combined with the hydrodynamic forces in porous media, can help overcome capillary pressures and mobilize residual oil [6–8].

In addition to magnetic fields, advancements in waterflooding research have highlighted the importance of modifying water chemistry, such as by adding surfactants or polymers, to enhance recovery. These approaches aim to reduce interfacial tension between oil and water or improve the rheological properties of the injected fluid to achieve better sweep efficiency. The integration of physical fields, such as magnetic fields, into these chemical methods offers a promising avenue for hybrid EOR techniques [9–12].

This study seeks to build on these foundational theories by investigating the combined effects of magnetic fields and pressure variations on electrokinetic properties and fluid discharge behavior under simulated reservoir conditions. By addressing gaps in the understanding of how magnetic fields interact with reservoir fluids, this research contributes to the development of more efficient and sustainable EOR methods. The findings are expected to provide insights into optimizing waterflooding operations and enhancing oil recovery in challenging reservoir environments [13,14].

Methodology

The experiments were conducted on the setup described in Figure 1. The setup includes a YCA-4A type regulator (1), SUNTEK 2000 VA type variac transformer (2), volt/ammeter (3), electromagnet (4), graduated cylinder (5), valves (6,10,12,14,17), manometers (7,9,15), high-pressure column (8), URV-2M type potentiometer with high input resistance (11), tank for liquids (16), PVT type high-pressure bomb (13), measurement press (18).

The column (8) is resistant to high pressure and has a hollow cylindrical shape with an internal diameter of 31 mm and a length of 320 mm. The column is secured at both ends with metal caps and reinforced with rubber rings called seals. To measure potential differences in the porous medium, a high-resistance tungsten wire was used, with one side firmly attached to the porous medium and the other side conductive to liquids, coated with a fluoroplastic layer that isolates the rock. Electrical insulation of the porous medium from the inner surface of the column was ensured by an epoxy adhesive applied along inside the column. This approach also aims to prevent fluid leakage between the porous medium and the column body.

The experiment was carried out in the following sequences:

Firstly, a model of the combined oil was created in the PVT bomb (13). The sample of reservoir oil was transferred from the sampling device to the PVT bomb and the saturation pressure of the system was determined.

The permeability of the porous medium to air is determined based on a known method. The volume of the pores is calculated both by the “weight method” and by filling the porous medium with air up to a certain pressure and applying the gas equation of state.

The porous medium is filled with the investigated liquid using the PVT bomb. Porous medium is pre-vacuumed from water. A volume of liquid equal to ten times the pore volume is injected into the porous medium. It should be noted that to completely expel the air in the pores, the pressure in the system is periodically increased and the liquid is sharply released during the injection of the liquid into the rock.

Due to the partial dissolution of gas during the increase in pressure in the column and the high-pressure difference, the porous medium is effectively cleaned of gas by gas filtration in the column. The pressure in the column is raised 10 MPa higher than the saturation pressure determined in the PVT bomb. This is done to prevent gas separation when the gas-liquid mixture passes into the porous medium.

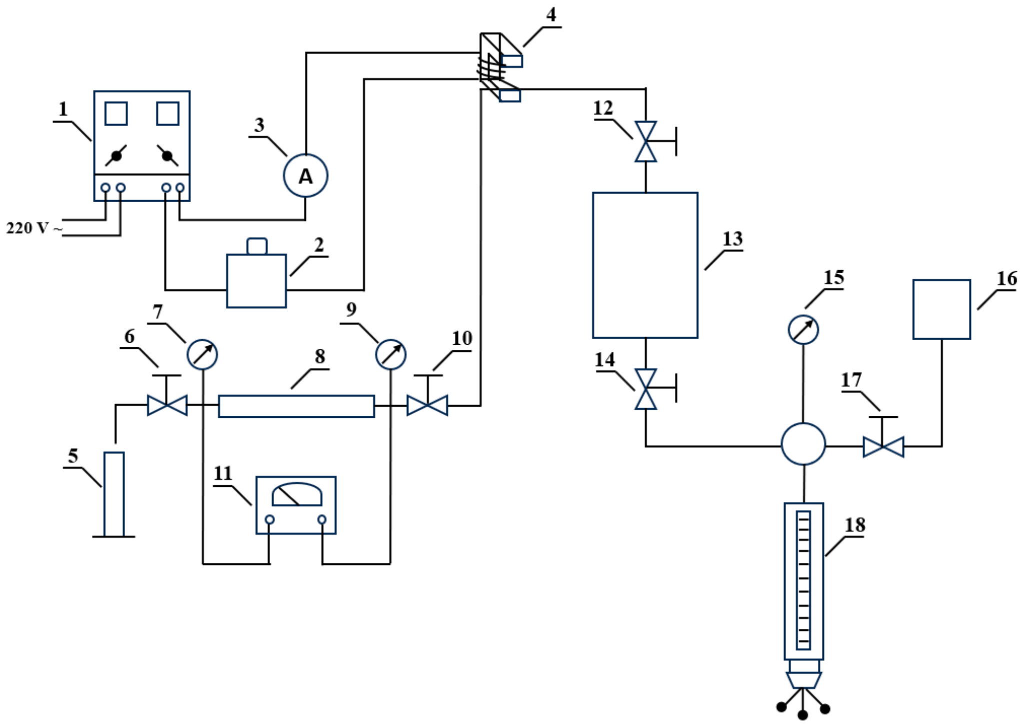

Figure 1. The schematic diagram of the experimental setup

1 – YCA-4A type regulator; 2 – SUNTEK 2000 VA type variac transformer; 3 – volt/ammeter; 4 – electromagnet; 5 – graduated cylinder; 6, 10, 12, 14, 17 – valves; 7, 9, 15 – manometers; 8 – high-pressure column; 11 – URV-2M type potentiometer with high input resistance; 13 – PVT type high-pressure bomb; 16 – tank for liquids; 18 – measurement press.

PVT bomb is filled with water and connected to a column. Subsequently, a tank (16) filled with transformer oil, which serves as the compression mechanism, is linked to the PVT bomb through a hydraulic press (18). Initially, the inlet (14) and outlet (12) valves of the bomb are closed and transformer oil is transferred from the tank to the hydraulic press. The inlet and outlet lines of the bomb are then opened, while the inlet line of the column (10) is kept open and the outlet line (6) remains closed. After sealing the line leading from the tank to the press, the press injects oil into the bomb from below. This process raises the piston within the bomb, forcing the water inside the bomb into the column.

An electromagnet (4) is installed on the line near the column's inlet. The purpose of this setup is to expose the incoming water to a magnetic field, magnetizing it before it enters the column. The intensity of the magnetic field is regulated within the required range using a variac transformer (2). The measurement of the magnetic field induction of the electromagnet device was conducted by varying the voltage (U) of the variac transformer, measured in volts. The resulting magnetic field intensity (H), generated by the electromagnet, was recorded in millitesla by using magnetometer. This setup allowed for precise control and monitoring of the relationship between the input voltage and the corresponding magnetic field strength, providing valuable insights into the device's performance characteristics under different operating conditions. The results in Table 1 show how the voltage (U) affects the magnetic field intensity (H) generated by the device.

Table 1. Measurement of the Magnetic Field Induction of the Electromagnet Device

U, V	H, mT
5	40
10	80
15	107
20	125
25	140
30	150

Before initiating the experiment, the initial voltage and resistance values are recorded. The experiment is conducted at a pressure of P = 1.6 atm, across a pressure range of 1.6–14.4 atm. The intensities of the electromagnet's magnetic field 40, 80, 107, 125 and 140 mT are investigated sequentially for each pressure level mentioned.

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Initially, using the press, oil is injected into the bomb at a pressure of 1.6 atm, displacing the water into the porous medium of the column. The pressure is maintained constant at 1.6 atm during this phase. Afterward, a 2-minute wait ensures the water completely saturates the porous medium. Once the waiting period concludes, the column's outlet line is opened and the amount of expelled water is measured using a graduated cylinder (5). Simultaneously, the resistance and voltage values are recorded. This procedure is repeated periodically for each magnetic field intensity value at the specified pressures and the results are analyzed.

Table 2. Physicochemical properties of tap water used in the experiments

Measured Indicators	Results
pH	7.3
Total Dissolved Solids (TDS), mg/l	759
Hardness, mg/l	241
Alkalinity, mg/l	175
Turbidity (NTU)	0.56
Residual chlorine, mg/l	< 0.02
Calcium (Ca), mg/l	30
Magnesium, Mg, mq/l	41
Fe, mg/l	< 0.01
Mn, mg/l	< 0.005

Water Quality Analysis. The tap water used in the experiments was analyzed to determine its physicochemical properties prior to magnetic field application. The measured indicators, including pH, total dissolved solids (TDS), hardness, alkalinity, turbidity and concentrations of key ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), iron (Fe) and manganese (Mn), are presented in Table 2. These properties are critical for understanding the water's behavior under magnetic field influence and its role in enhanced oil recovery.

Results and Discussions

Research was conducted according to the specified methodology and the results were evaluated. Accordingly, graphs were plotted to show the dependence of voltage, resistance and the amount of discharged water on pressure, respectively (Fig. 2–4).

Figure 2 illustrates the relationship between the measured voltage (U, in millivolts) and the pressure (P, in atmospheres) during experiments conducted under varying magnetic field intensities. The experiment includes one control condition (without the application of a magnetic field, red line) and six different magnetic field intensities (H, measured in milliteslas). The red curve represents the control scenario where no magnetic field is applied. In this case, the voltage decreases progressively with increasing pressure up to P = 8 atm, beyond which it stabilizes at a plateau of approximately 50 mV. This baseline behavior indicates that pressure variations alone reduce the voltage due to changes in the fluid's electrokinetic properties, potentially resulting from a decrease in ionic mobility or a disruption in the natural electrochemical equilibrium.

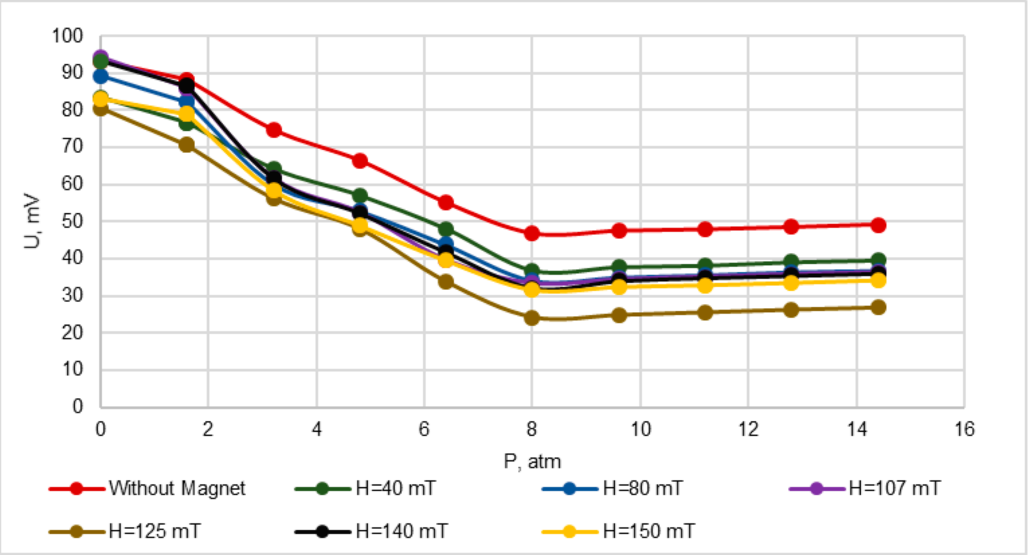

Figure 2. The graph of voltage over pressure with and without application of electromagnet

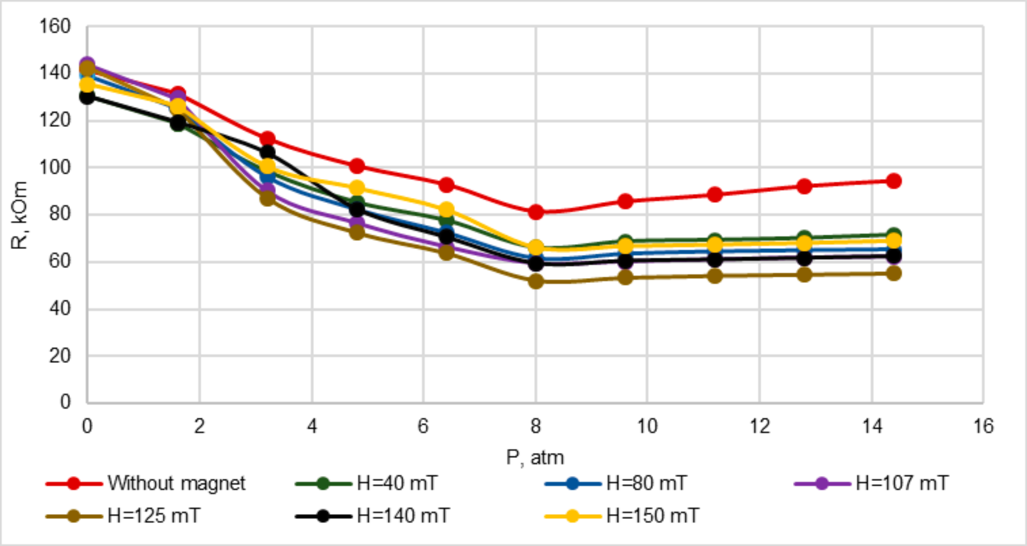

Figure 3. The graph of resistance over pressure with and without application of electromagnet

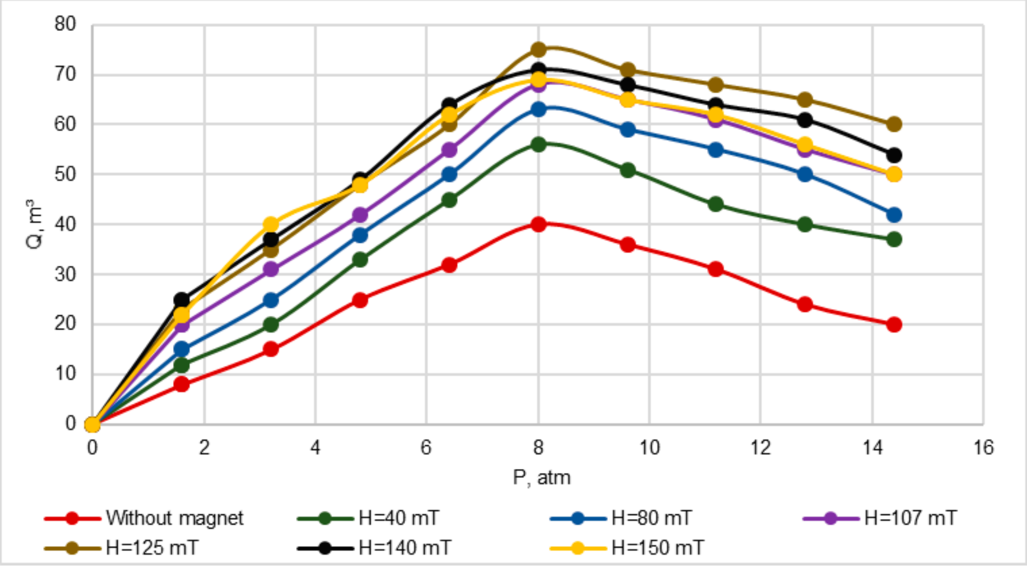

Figure 4. The graph of discharged water over pressure with and without application of electromagnet

Under the influence of a magnetic field, the voltage exhibits a more pronounced decrease with increasing pressure, indicating that the magnetic field enhances the system's response to pressure changes. For weaker magnetic field intensities (H = 40 mT and H = 80 mT), the voltage stabilizes at a higher value compared to stronger field intensities. For 107 mT of magnetic field intensity, the voltage of rock reduced from 94.3 mV to 36.3 mV with 61% drop. When it comes to magnetic field intensity increases to H = 125 mT and H = 140 mT, the voltage decreases further, lowest values observed at H = 125 mT, which is considered approximately 66% decrease and it reduced to minumum witnessed value during experiment, which is about 27 mV of stabilization voltage. Whereas, for 150 mT, the stabilization voltage again increased and the decline percentage for voltage is reduced to 60%. This trend reveals that higher magnetic field intensities till 150 mT have a more significant impact on reducing the voltage under pressure. The observed behavior can be attributed to the interaction between the applied magnetic field and the charged particles or ions in the fluid. Magnetic fields influence the movement of ions, leading to alterations in the electrokinetic

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properties of the fluid, including a potential increase in ion mobility or reorganization of ionic distribution. This effect becomes more pronounced with stronger magnetic fields, resulting in greater reductions in voltage.

It is also noteworthy that the voltage stabilization occurs at approximately ΔP = 8 atm for all cases, indicating that the pressure-induced changes in the system reach a saturation point beyond which further increases in pressure have minimal impact. This behavior suggests a dynamic equilibrium in the system where the combined effects of pressure and magnetic field stabilize the electrokinetic properties of the fluid.

Figure 3 illustrates the variation of resistance (R, kOm) as a function of pressure (P, atm) under experimental conditions with and without the application of magnetic fields of varying intensities. The graph includes results for a control case where no magnetic field is applied (red line) and for cases where magnetic fields of intensities H = 40 mT, H = 80 mT, H = 107 mT, H = 125 mT, H = 140 mT and H = 150 mT are applied. The study examines the impact of magnetic fields on resistance during pressure changes, shedding light on the potential electrokinetic and fluid dynamic effects induced by magnetic field application.

In the absence of a magnetic field (red curve), resistance decreases steadily with increasing pressure, reaching its minimum P = 8 atm. Beyond this point, resistance begins to rise, showing a distinct recovery trend with increasing pressure. This behavior reflects the natural response of the system to pressure changes, where pressure likely reduces the fluid's conductivity due to compaction or reorganization of conductive pathways and at higher pressures, resistance increases as fluid flow characteristics stabilize.

When magnetic fields are applied, the resistance decreases more sharply with rising pressure, compared to the control case and stabilizes at significantly lower values. At magnetic field intensities of H = 40 mT and H = 80 mT, resistance stabilizes at higher values than at stronger field intensities with overall 49% and 55%, respectively. In contrast, for higher magnetic field intensities (H = 107 mT, H = 125 mT), the resistance stabilizes at lower levels, which the lowest resistance observed for H = 125 mT with about 52 kOm. Regarding 140 mT intensity of magnetic field, it is determined that the resistance of rock decreased almost 2 times for its minimum value. However, at the 150 mT magnetic intensity, it is obverved that the percentage of decline for resistance decreased to approximately 51% at the end of experiment. This indicates that higher magnetic field intensities exert a stronger influence on reducing resistance in the system.

The behavior can be explained by the impact of magnetic fields on charged particles and ion movement in the fluid. Magnetic fields influence the alignment and distribution of ions, enhancing their mobility and altering the fluid's conductive properties. This effect becomes more pronounced as the magnetic field intensity increases, leading to greater reductions in resistance. Additionally, the stabilization of resistance values at higher pressures indicates a dynamic equilibrium, where the combined effects of pressure and magnetic fields produce a steady-state condition in the system.

An important observation is that the recovery of resistance beyond P = 8 atm, as seen in the control case, is significantly dampened under magnetic field application. This suggests that magnetic fields mitigate the effects of pressure-induced compaction or reorganization, maintaining lower resistance levels even at higher pressures. The trend highlights the ability of magnetic fields to stabilize fluid flow and conductivity under varying pressure conditions.

The graph in Figure 4 demonstrates the relationship between discharged water volume (Q, m^3) and applied pressure (P, atm) under conditions with and without the application of electromagnetic fields at varying intensities (H, mT). The “without magnet” case (red curve) serves as the baseline, showing a steady increase in discharged water volume up to 8 atm, where it peaks at about 40 m^3. Beyond this pressure, the discharge volume decreases consistently, likely due to factors such as reduced permeability or increased flow resistance at higher pressures.

In contrast, the application of magnetic fields significantly enhances water discharge across all pressure levels. At lower field strengths (40 mT and 80 mT), the discharged water volume shows considerable improvement compared to the “without magnet” case. However, higher field strengths (107 mT, 125 mT and 140 mT) yield even greater enhancements, with 125 mT producing the most notable effect. At this optimal intensity, the maximum discharge volume reaches approximately 75 m^3, occurring around 8-9 atm. This indicates a synergistic interaction between the applied pressure and magnetic field, enhancing fluid mobility more effectively than lower field strengths. Interestingly, while the 140 mT curve demonstrates a high discharge volume, it shows a slight reduction (52%) compared to 125 mT, particularly at peak pressure. This suggests that there may be a saturation effect or diminishing returns as the magnetic field intensity increases beyond an optimal threshold. The discharge at 150 mT increases steadily with pressure, peaking at 69 m^3 around 8 atm. Compared to results for 140 mT, the performance of 150 mT indicates mild reduction as the improvement becomes less pronounced at higher pressures. Beyond 8 atm, the discharged volume at 150 mT declines gradually but remains higher than lower field strengths and the “without magnet” case.

Additionally, it is worth noting that magnetic storms are natural phenomena caused by disturbances in the Earth's geomagnetic field and they occur fairly often. These disturbances can influence sensitive experimental setups, especially those involving electromagnets or other systems reliant on stable electromagnetic fields. Table 3 detailing the intensity of magnetic storms in Baku for October (the month in which the experiment was conducted) provides critical information for analyzing the potential impact on laboratory experiments. The intensity levels of magnetic storms, represented by values from 1 to 8 (as per the scale mentioned below), indicate varying degrees of geomagnetic activity. The experiments were conducted when the intensity of magnetic storms, as per the scale mentioned, fell under “minor disturbances”. These conditions ensured minimal interference from geomagnetic activity, allowing for more accurate and reliable experimental results.

Table 3. Physicochemical properties of tap water used in the experiments

Date	Time Frames							
	00:00	03:00	06:00	09:00	12:00	15:00	18:00	21:00
01.10.2024	1	1	1	1	1	1	1	1
02.10.2024	1	1	1	1	1	1	1	1
03.10.2024	1	1	1	1	4	5	3	3
04.10.2024	4	4	6	6	6	4	5	5
05.10.2024	3	4	4	6	6	7	7	6
06.10.2024	5	5	4	4	4	5	5	4
07.10.2024	4	4	3	3	3	3	4	5
08.10.2024	5	3	3	3	3	3	3	3
09.10.2024	2	2	1	1	1	1	1	2
10.10.2024	5	7	7	8	8	7	7	8
11.10.2024	7	6	6	6	6	5	4	5
12.10.2024	4	4	3	3	3	4	3	2
13.10.2024	2	2	1	2	2	3	3	3
14.10.2024	2	2	1	1	2	2	2	2
15.10.2024	2	1	1	2	3	4	4	3
16.10.2024	3	3	3	4	4	3	2	2
17.10.2024	2	1	2	2	2	3	2	3
18.10.2024	2	2	3	3	3	4	4	3
19.10.2024	3	2	2	2	2	3	3	3
20.10.2024	3	3	2	2	1	1	1	1
21.10.2024	1	1	1	1	1	1	4	2
22.10.2024	2	2	2	2	2	2	2	2
23.10.2024	2	2	2	2	2	2	2	2
24.10.2024	2	2	2	2	2	3	3	4
25.10.2024	3	2	2	2	2	2	4	4
26.10.2024	3	3	3	2	2	2	3	3
27.10.2024	3	3	2	2	1	2	3	5
28.10.2024	5	5	5	4	4	4	4	3
29.10.2024	3	3	3	2	2	2	3	2
30.10.2024	2	2	2	2	2	2	1	1
31.10.2024	1	1	1	1	1	1	2	2

1 – no significant disturbances; 2 – minor disturbances; 3 – weak geomagnetic storm; 4 – minor geomagnetic storm; 5 – moderate geomagnetic storm;6 – strong geomagnetic storm;7 – severe geomagnetic storm; 8 – extreme storm.

Analysis of Measurement Errors

To ensure accuracy, potential measurement errors were analyzed and considered while evaluating research results. Instrumental precision (volt/ammeter ±0.1 mV, magnetometer ±0.5 mT) was accounted for via error propagation. Pressure fluctuations were mitigated by averaging multiple readings and calculating standard deviation. Fluid leakage was minimized with discharged water volume (±0.1 mL resolution) verified against initial/final volumes. Magnetic field inhomogeneities (±2 mT) were addressed by averaging measurements along the column. Experiments were conducted at 25°C ± 1°C and data from periods of significant geomagnetic disturbances were excluded. These error margins were incorporated and considered into the graphs and analysis, ensuring that the reported trends and conclusions are robust and reliable.

Future work

Furthermore, it is worth to note that future work will explore the long-term effects of magnetic fields and their interactions with varying fluid compositions and geological conditions to validate and extend mentioned findings, as well as include detailed cost-benefit analyses, environmental impact assessments and safety evaluations to facilitate the practical application of this technology in the oil and gas industry.

Conclusions

This study comprehensively investigated the effects of magnetic fields on the electrokinetic properties of reservoir fluids and the behavior of fluid discharge under varying pressure conditions. Based on the results, the following conclusions are drawn:

1. Magnetic fields significantly enhance the electrokinetic properties of reservoir fluids. The study demonstrated that applying magnetic field intensities between 40 and 150 mT results in substantial improvements in ion mobility and fluid conductivity. This leads to a stabilized fluid flow and increased water discharge, particularly under high-pressure conditions.

2. An optimal magnetic field intensity of 125 mT was identified, yielding the most favorable effects on reducing resistance, stabilizing voltage and increasing the discharged water volume. At 125 mT, the resistance of the system decreased significantly and the discharged water volume reached a peak of approximately 75 m^3 at around 8–9 atm, highlighting the field’s role in facilitating fluid movement through porous rocks. Beyond this intensity, a diminishing return effect was observed, indicating a potential saturation point in the magnetic field’s influence on fluid properties.

3. The results revealed distinct trends in the system’s behavior up to and beyond 8 atm. Up to 8 atm, the voltage and resistance values decreased significantly, indicating enhanced fluid conductivity and ion mobility under the influence of magnetic fields. Simultaneously, the discharged water volume increased substantially. These findings demonstrate the progressive improvement in fluid movement and electrokinetic properties up to 8 atm. Beyond 8 atm, the system reaches a dynamic equilibrium where the combined effects of pressure and magnetic fields stabilize electrokinetic properties. This stabilization indicates that magnetic fields mitigate pressure-induced compaction and reorganization in the porous medium.

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4. This research provides critical insights into the potential application of magnetic fields in enhanced oil recovery technologies. By optimizing fluid mobility and reducing flow resistance in porous media, magnetic field technology offers a promising avenue for increasing oil field productivity, particularly under challenging high-pressure conditions.

5. The potential impact of natural geomagnetic activity, such as magnetic storms, on experimental setups was acknowledged. Monitoring geomagnetic activity is crucial for ensuring the reliability and reproducibility of results in magnetic field-related studies.

In conclusion, this study establishes the transformative role of magnetic fields in optimizing fluid transport and enhancing the efficiency of reservoir systems. The findings pave the way for further exploration of magnetic field applications in the oil and gas industry, particularly for improving the recovery rates in mature and low-permeability reservoirs. Future work should explore the long-term effects of magnetic fields and their interactions with varying fluid compositions and geological conditions to validate and extend these findings.

ADDITIONAL INFORMATION

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Конфликт интересов. Автор декларирует отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

REFERENCES

1. Mirzajanzade AK, Iskandarov MA, Abdullayev MA, et al. *Exploitation and Development of Oil and Gas Fields*. Baku; 1960. 444 p.
2. Mammadzade AM. *Nanotechnological Foundations for the Application of Non-Equilibrium Effects of Physical Fields in Oil and Gas Extraction*. Baku; 2021. 207 p.
3. Alvarado V, Manrique E. Enhanced oil recovery: An update review. *Energies*. 2010;3(9):1529–1575. doi: 10.3390/en3091529.
4. Malikov HX, Mammadzade AM, Habibullayeva SA. Improvement of the oil production using magnetic field. *Scientific Proceeding, Scientific Research of Oil, Gas and Chemistry.* 2022;22(1):75–88.
5. Józefczak A, Wlazło R. Ultrasonic studies of emulsion stability in the presence of magnetic nanoparticles. *Advanced in Condensed Matter Physics*. 2015;98219. doi: 10.1155/2015/398219.
6. Asadollahi M. *Waterflooding Optimization for Improved Reservoir Management* [dissertation]. Trondheim: Norwegian University of Science and Technology (NTNU); 2012.
7. Grema AS, Cao Y. Optimization of petroleum reservoir waterflooding using receding horizon approach. 2013 IEEE 8th Conference on Industrial Electronics and Applications (ICIEA); 2013 June 19–21; Melbourne, Australia. Available from: https://ieeexplore.ieee.org/document/6566402.
8. Blunt MJ. *Multiphase Flow in Permeable Media: A Pore-Scale Perspective*. Cambridge: Cambridge University Press; 2017.
9. Yang Y, Zhou Y, Blunt MJ, et al. Advances in multiscale numerical and experimental approaches for multiphysics problems in porous media. *Advances in Geo-Energy Research*. 2021;5(3):233–238. doi: 10.46690/ager.2021.03.01.
10. Blaszczyk M, Sek J, Pacholski P, Przybysz L. The analysis of emulsion structure changes during flow through porous structure. *Journal of Dispersion Science and Technology*. 2017;38(8): 1154–1161. doi: 10.1080/01932691.2016.1226184.
11. Kang WL, Zhou B, Issakhov M, Gabdullin M. Advances in enhanced oil recovery technologies for low permeability reservoirs. *Petroleum Science*. 2022;19(4):1622–1640. doi: 10.1016/j.petsci.2022.06.010.
12. Safarov FE, Lobanova SY, Elubayev BY, et al. Effective EOR methods in high-viscosity oil fields: cyclical gel-polymer flooding and asp flooding. *Kazakhstan journal for oil & gas industry*. 2021;3(8):61–74. doi: 10.54859/kjogi88927.
13. Muskat M. *The flow of homogeneous fluids in a porous medium*. New York: McGraw-Hill Book Company; 1936.
14. Ocheredko TB, Solange B, Matveyeva IS. Methods of enhanced oil recovery at the East-Suleevskaya area of the Romashkinskoye oil field. *Readings of A.I. Bulatov*. Collection of Articles. 2018;2(2):77–84.
15. time-in.ru [Internet]. Magnetic storms in Baku [cited 01 Oct 2024]. Available from: https://time-in.ru/magnitnye-buri/baku.

СПИСОК ИСПОЛЬЗОВАННОЙ ЛИТЕРАТУРЫ

1. *Мирзаджанзаде А.Х., Искандаров М.А., Абдуллаев М.А.* Эксплуатация и освоение нефтяных и газовых месторождений. Баку, 1960. 444 с.
2. *Mammadzade A.M.* Nanotechnological Foundations for the Application of Non-Equilibrium Effects of Physical Fields in Oil and Gas Extraction. Baku, 2021. 207 p.
3. *Alvarado V., Manrique E.* Enhanced oil recovery: An update review // Energies. 2010. Vol. 3. N 9. P. 1529–1575. doi: 10.3390/en3091529.
4. *Malikov H.X., Mammadzade A.M., Habibullayeva S.A.* Improvement of the oil production using magnetic field // Scientific Proceeding, Scientific Research of Oil, Gas and Chemistry. 2022. Vol. 22, N 1. P. 75–88.

5. *Józefczak A., Wlazło R.* Ultrasonic studies of emulsion stability in the presence of magnetic nanoparticles // Advanced in Condensed Matter Physics. 2015. doi: 10.1155/2015/398219.
6. *Asadollahi M.* Waterflooding Optimization for Improved Reservoir Management : dissertation. Trondheim : Norwegian University of Science and Technology (NTNU), 2012.
7. Grema A.S., Cao Y. Optimization of petroleum reservoir waterflooding using receding horizon approach. 2013 IEEE 8th Conference on Industrial Electronics and Applications (ICIEA); 2013 June 19–21; Melbourne, Australia. Available from: https://ieeexplore.ieee.org/document/6566402.
8. *Blunt M.J.* Multiphase Flow in Permeable Media: A Pore-Scale Perspective. Cambridge : Cambridge University Press, 2017.
9. *Yang Y., Zhou Y., Blunt M.J., et al.* Advances in multiscale numerical and experimental approaches for multiphysics problems in porous media // Advances in Geo-Energy Research. 2021. Vol. 5, N 3. P. 233–238. doi: 10.46690/ager.2021.03.01.
10. *Blaszczyk M., Sek J., Pacholski P., Przybysz L.* The analysis of emulsion structure changes during flow through porous structure // Journal of Dispersion Science and Technology. 2017. Vol. 38, N 8. P. 1154–1161. doi: 10.1080/01932691.2016.1226184.
11. *Kang W.L., Zhou B., Issakhov M., Gabdullin M.* Advances in enhanced oil recovery technologies for low permeability reservoirs // Petroleum Science. 2022. Vol. 19, N 4. P. 1622–1640. doi: 10.1016/j.petsci.2022.06.010.
12. *Сафаров Ф.Э., Лобанова С.Ю., Елубаев Б.У., и др.* Эффективные методы повышения нефтеотдачи пластов на месторождениях с высоковязкой нефтью: технологии циклического гелеполимерного заводнения и ASP-воздействие // Вестник нефтегазовой отрасли Казахстана. 2021. Т. 3, №3. С. 61–74. doi: 10.54859/kjogi88927.
13. *Muskat M.* The flow of homogeneous fluids in a porous medium. New York : McGraw-Hill Book Company, 1936.
14. *Очередько Т.Б., Барамбонье С., Матвеева И.С.* Методы увеличения нефтеотдачи пластов на Восточно-Сулеевской площади Ромашкинского нефтяного месторождения. Булатовские чтения. 2018. №2, часть 2. С. 77–84.
15. time-in.ru [интернет]. Магнитные бури в Баку [дата обращения: 01.10.2024]. Доступ по ссылке: https://time-in.ru/magnitnye-buri/baku.

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