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INVESTIGATION OF FLUID DYNAMICS IMPACT WITH MAGNETIC FIELD APPLICATIONS ON ENHANCED OIL RECOVERY IN POROUS MEDIA

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ABSTRACT

This study investigates the impact of magnetic fields on the electrokinetic properties of reservoir fluids and fluid discharge behavior under varying pressure conditions. A custom experimental setup was developed, comprising a high-pressure column, PVT bomb, electromagnet and multiple measurement and control devices, to simulate reservoir conditions accurately. The study systematically examined the influence of magnetic field intensities ranging from 31831 to 119366 A/m on voltage, resistance and water discharge across pressure variations between 1.6 and 14.4 atm. The results demonstrate that magnetic fields positively influence fluid behavior, significantly enhancing ion mobility and fluid conductivity. This enhancement leads to increased water discharge and stabilized fluid flow, particularly under high-pressure conditions. Notably, an optimal magnetic field intensity of 99472 A/m was identified, yielding the most favorable effects on reducing resistance, stabilizing voltage and increasing discharged water volume. At this intensity, the resistance of the system decreased significantly and the discharged water volume peaked at approximately 75 m^3 around 8-9 atm, highlighting the field's role in facilitating fluid movement through porous media. Beyond this intensity, a diminishing return effect was observed, indicating a potential saturation point in the magnetic field's influence on fluid properties. These findings provide valuable insights into the role of magnetic fields in optimizing fluid transport in porous media, offering potential advancements for enhanced oil recovery techniques. The study underscores the transformative potential of magnetic fields in improving fluid mobility and recovery efficiency in oil reservoirs, paving the way for further exploration and application of this technology in the oil and gas industry.

Keywords: magnetic fields; electrokinetics; discharged water volume; pressure effects; fluid mobility; porous media; flow resistance; magnetic field intensity; oil recovery.

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1. 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 ranks as one of the most established and widely employed. In this method, water is injected into the reservoir to mobilize and direct oil to the 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 [1-6].

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 [7-12].

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 [13-17].

In addition to magnetic fields, advancements in waterflooding research have highlighted the importance of modifying water chemistry, such as by adding surfactants or pol-

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ymers, 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 [18-23].

Furthermore, the integration of magnetic fields with pressure variations introduces a dynamic interplay that could significantly enhance the efficiency of waterflooding. Pressure changes within the reservoir can alter the flow dynamics of fluids, affecting the distribution and movement of oil and water phases. When combined with magnetic fields, these pressure variations may amplify the electrokinetic effects, leading to improved mobilization of residual oil. This synergistic approach could be particularly beneficial in heterogeneous reservoirs, where uneven permeability often leads to bypassed oil zones [24-27].

Unlike traditional chemical EOR methods, which often require significant amounts of additives and can pose environmental risks, magnetic field-based techniques are relatively clean and can be easily integrated into existing waterflooding infrastructure. This approach minimizes the use of chemicals, reduces the carbon footprint of EOR operations and is scalable for a wide range of reservoir conditions, from small-scale pilot projects to large-scale field implementations [28-31].

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.

2. Methodology

Figure 1a illustrates a schematic representation of the experimental setup, detailing the key components utilized in the study. To complement this, figure 1b presents an actual photograph of the experimental setup, providing a visual reference to the physical arrangement of the equipment used during the experiments. 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, 13, 15, 17), manometers (7, 9, 16), high-pressure column (8), URV-2M type potentiometer with high input resistance (11), circulating bath (12), PVT type high-pressure bomb (14), tank for liquids (18), measurement press (19).

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 (14). 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 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

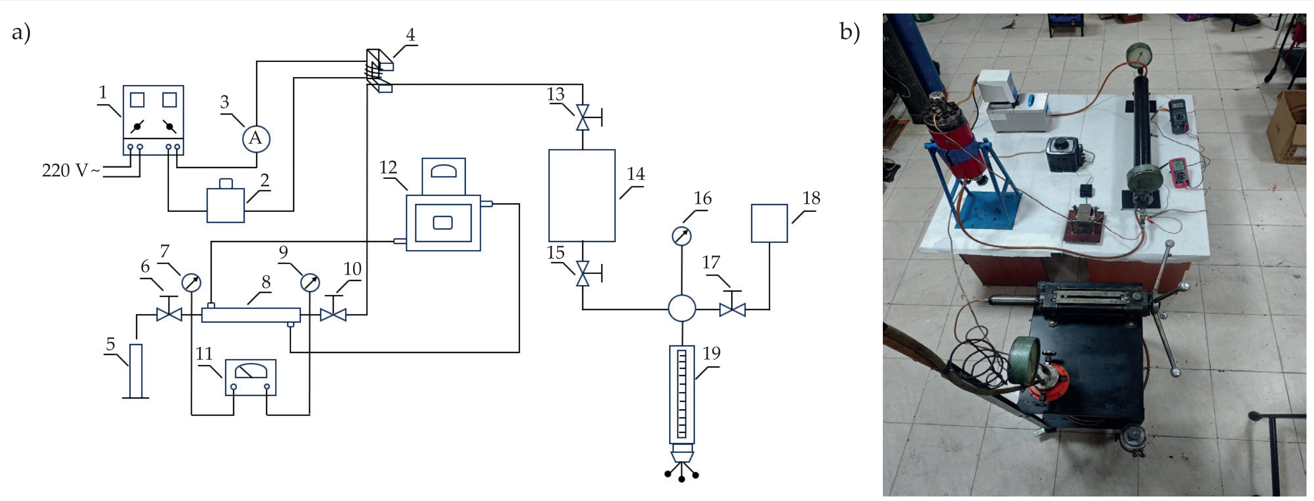


Fig. 1. a) the schematic diagram of the experimental setup, b) actual photograph of the experimental setup

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.

The PVT bomb, which has a cylindrical shape with a volume of 800 mL, a diameter of 8 cm, and a height of 20 cm, is filled with water and connected to a column. The PVT bomb, which passes through the electromagnetic field created by the electromagnet (4), is connected to the PVT bomb with a copper pipe. For this purpose, it is important that the pipes are made of non-magnetic material and able to release the magnetic field (in our case, it is copper). Subsequently, a tank (18) filled with transformer oil, which serves as the compression mechanism, is linked to the PVT bomb through a hydraulic press (19). Initially, the inlet (15) and outlet (13) 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.

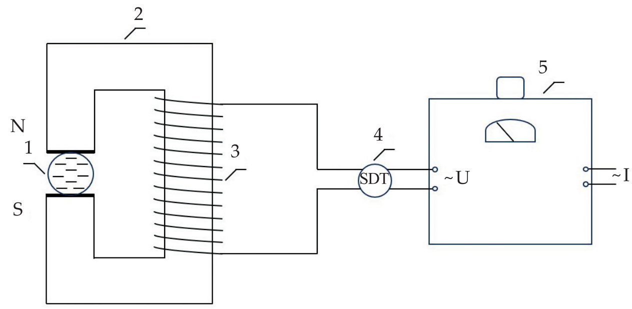
An electromagnet (4) is installed on the line near the column's inlet. The electromagnet setup schematically is described in figure 2. The electromagnet has a power of 1.3 kW, operates with a current of 4.2 A and a voltage of 220 V.

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. The electromagnet operates with a constant magnetic field and it is powered by an alternating current (AC) supply. Therefore, a variac transformer was used, which includes a rectifier to regulate and convert the alternating current into direct current (DC), ensuring a stable magnetic field for effective magnetic treatment. The electric current is maximum 2A. 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 A/m 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.

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 31831, 63662, 85148, 99472, 111408 and 119366 A/m are investigated sequentially for each pressure level mentioned. These specific magnetic field strengths were chosen based on a combination of literature review, preliminary experimental results and practical feasibility within the context of reservoir conditions. It is indicated that these field strengths are within the range that can effectively influence fluid flow and electrokinetic behavior in porous media.

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.

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.



1–copper pipe flowing liquid, 2–electromagnetic nuclear coil
3–copper coils, 4–step-down transformer, 5–variac transformer

Fig. 2. The schematic diagram of the magnet setup

Table 1
Measurement of the magnetic field induction of the electromagnet device

U.V	H.A/m
5	31831
10	63662
15	85148
20	99472
25	111408
30	119366

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

3. 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. 3-5).

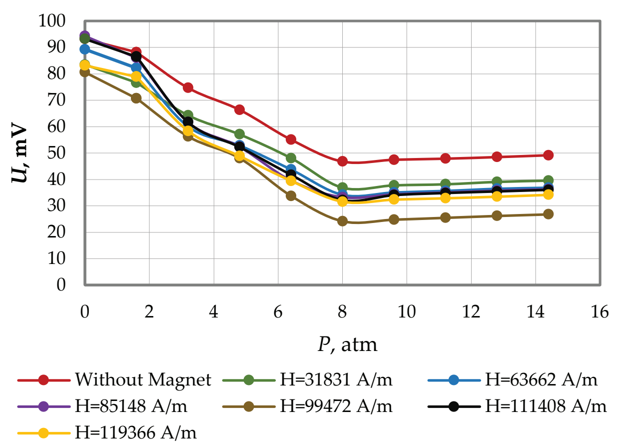


Fig. 3. The graph of voltage over pressure with and without application of electromagnet

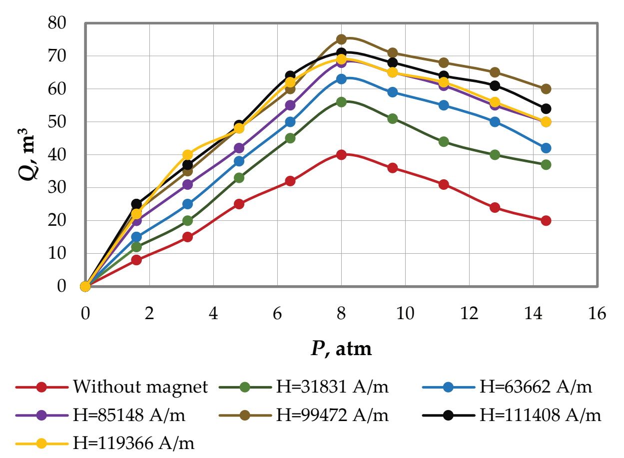


Fig. 4. The graph of discharged water over pressure with and without application of electromagnet

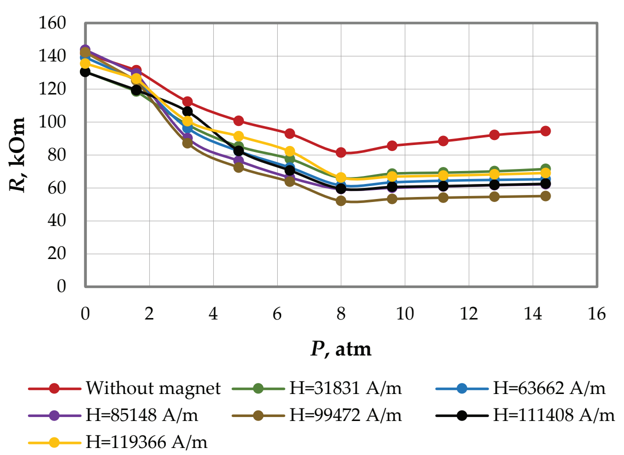


Fig. 5. The graph of resistance over pressure with and without application of electromagnet

Figure 3 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 A/m). 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.

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*=31831 A/m and *H*=63662 A/m), the voltage stabilizes at a higher value compared to stronger field intensities. For 85148 A/m 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*=99472 A/m and *H*=111408 A/m, the voltage decreases further, lowest values observed at *H*=99472 A/m, 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 119366 A/m, the stabilization voltage again increased and the decline percentage for voltage is reduced to 60%. This trend reveals that higher magnetic field intensities till 119366 A/m 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 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 4 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*=31831 A/m, *H*=63662 A/m, *H*=85148 A/m, *H*=99472 A/m, *H*=111408 A/m and *H*=119366 A/m 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=31831 A/m and H=63662 A/m, resistance stabilizes at higher values than at stronger field intensities with overall 49 and 55%, respectively. In contrast, for higher magnetic field intensities (H=85148 A/m, H=99472 A/m), the resistance stabilizes at lower levels, which the lowest resistance observed for H=99472 A/m with about 52 kOm. Regarding 111408 A/m intensity of magnetic field, it is determined that the resistance of rock decreased almost 2 times for its minimum value. However, at the 119366 A/m magnetic intensity, it is observed 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 5 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 (31831 A/m and 63662 A/m), the discharged water volume shows considerable improvement compared to the «without magnet» case. However, higher field strengths (85148 A/m, 99472 A/m and 111408 A/m) yield even greater enhancements, with 99472 A/m 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 111408 A/m curve demonstrates a high discharge volume, it shows a slight reduction (52%) compared to 99472 A/m, 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 119366 A/m increases steadily with pressure, peaking at 69 m^3 around 8 atm. Compared to results for 111408 A/m, the performance of 119366 A/m indicates mild reduction as the improvement becomes less pronounced

Table 3
Magnetic storms in Baku for october [32]

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

Notes:
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

at higher pressures. Beyond 8 atm, the discharged volume at 119366 A/m 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.

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 31831 and 119366 A/m 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 99472 A/m was identified, yielding the most favorable effects on reducing resistance, stabilizing voltage and increasing the discharged water volume. At 99472 A/m, 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.
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.

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.

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