

Original article

Experimental investigation of electric field-assisted in-situ conditioning of shale oil for reducing CO₂ minimum miscibility pressure

Wentong Zhang^{1,2}, Qixin Jia¹, Hai Huang³*, Juntai Shi³, Qiang Li², Huazhou Andy Li⁴

¹College of New Energy and Electrical Engineering, Xi'an Petroleum University, Xi'an 710065, P. R. China

²State Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum, Beijing 102249, P. R. China

³College of Petroleum Engineering, Xi'an Petroleum University, Xi'an 710065, P. R. China

⁴School of Mining and Petroleum Engineering, Faculty of Engineering, University of Alberta, Edmonton T6G 1H9, Canada

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Abstract:

Electric-field-assisted conditioning constitutes a promising approach for improving carbon dioxide-oil miscibility during carbon dioxide flooding. However, studies to date have mainly focused on simplified model oils, and the miscibility behavior of real shale oil remains insufficiently understood. In this work, a custom-designed electric-field conditioning system was developed to investigate the physicochemical evolution of real shale oil and its subsequent carbon dioxide miscibility. While current and temperature were monitored during conditioning, viscosity, carbon number distribution and carbon dioxide minimum miscibility pressure were systematically characterized. The results show that current and temperature initially increased and subsequently declined with the attenuation of electrochemical reactions. Dark brown deposits accumulated on the electrode surfaces, which were likely associated with heavy polar components, accompanied by a progressive weakening of the electrochemical process. Electric-field conditioning induced hydrocarbon redistribution, characterized by decreases in light and heavy fractions and the enrichment of medium fractions, together with reduced shale oil viscosity. The conditioned shale oil exhibited a lower carbon dioxide minimum miscibility pressure, while excessively strong electric fields provided less pronounced miscibility enhancement, indicating the existence of an optimal conditioning intensity. These findings underscore that electric-field-induced electrochemical conditioning can regulate shale oil composition and physicochemical properties, thereby favoring carbon dioxide-oil miscibility and providing a potential strategy for coupling enhanced shale oil recovery with carbon storage.

1. Introduction

Carbon capture, utilization, and storage (CCUS) is a promising pathway for simultaneously mitigating carbon emissions and enhancing hydrocarbon recovery (Langie et al., 2022; Zhang et al., 2023; Bai et al., 2025; Ni et al., 2026). Among the various existing CCUS strategies, CO₂ flooding has attracted considerable attention for shale oil development,

since it can improve oil recovery while enabling the long-term geological storage of anthropogenic CO₂ (Zhou et al., 2024; Liu et al., 2025b, 2025a; Zhang et al., 2026a). Nevertheless, the high abundance of nanopores, ultra-low permeability, and high heterogeneity of shale substantially hinder CO₂ transport and interphase mass transfer (Wei et al., 2024), thereby delaying oil swelling, hydrocarbon extraction, and the establishment

of dynamic miscibility for CO₂ and oil (Wang et al., 2024; Hu et al., 2025; Cai et al., 2026). The recovery of CO₂ flooding is largely governed by the degree of CO₂-oil miscibility (Fu et al., 2024; Yang et al., 2024; Zhuang et al., 2025). Once miscibility is achieved, the fluid-fluid interface and the associated capillary forces are eliminated, leading to enhanced microscopic displacement efficiency (Lu et al., 2026; Zhang et al., 2026a). The minimum miscibility pressure (MMP) establishing dynamic miscibility between CO₂ and crude oil at a given temperature is therefore regarded as a key parameter controlling the performance of CO₂ flooding (Fan et al., 2024; Jia et al., 2024a; Chen et al., 2026). However, the MMP of shale oil usually exceeds the original formation pressure in low-pressure reservoirs, restricting CO₂ flooding to immiscible or near-miscible conditions and severely compromising recovery efficiency. Accordingly, developing effective approaches to reduce the MMP has become a critical prerequisite for economically viable CO₂-enhanced shale oil recovery (Wang et al., 2022). Achieving CO₂ miscible flooding by increasing the gas injection pressure to reach the MMP can be challenging and costly (Ren et al., 2026). Therefore, developing effective approaches to lower the MMP without increasing reservoir pressure, and thus improving the efficiency and economic feasibility of CO₂ flooding, has become a major research target.

Various approaches have been proposed to reduce the MMP, including solvent-assisted injection and the application of chemical additives such as surfactants (Zhang et al., 2020; Saira et al., 2021; Guan et al., 2025; Tao et al., 2025). Solvents reduce the MMP by enhancing CO₂ solubility, extracting light hydrocarbons, promoting crude oil swelling, and accelerating molecular mass transfer (Lv et al., 2023, 2024). Depending on their composition, miscible solvents can generally be classified as single-component and multicomponent systems (Song et al., 2024). Surfactants, owing to their amphiphilic molecular architecture, effectively reduce the CO₂-oil tension and enhance interfacial mass transfer, thereby facilitating dynamic miscibility (Gong et al., 2025). Nevertheless, these approaches typically suffer from high material demand, elevated operational costs, potential formation damage, and environmental concerns associated with chemical injection. Consequently, it is highly desirable to develop a clean, economical and efficient strategy to reduce the MMP.

Recently, electric field-assisted CO₂ flooding has emerged as a promising alternative because it can regulate the physicochemical properties of crude oil and strengthen CO₂-oil interactions without introducing chemical additives (Karna et al., 2021; Huo et al., 2025). Previous studies have demonstrated that an applied electric field induces charge accumulation and dipole reorientation at the oil-water interface, thereby altering the interfacial physicochemical properties of crude oil. Furthermore, electric field treatment can modify crude oil composition and exhibit considerable potential for enhancing CO₂-oil miscibility (Jia et al., 2024b; Li et al., 2024, 2025). Despite these encouraging findings, existing studies have primarily relied on simulated oils composed of single-component or simplified hydrocarbon mixtures (Zhang et al., 2025, 2026b). In contrast, real shale oil is an inherently

complex multicomponent system comprising saturates, aromatics, resins, asphaltenes, as well as various heteroatom-containing compounds, whose physicochemical properties and electrochemical responses differ substantially from those of model oils (Alomair et al., 2026). Consequently, it remains largely unexplored whether electric field conditioning can effectively reduce the MMP of real shale oil.

To address these knowledge gaps, a custom-designed electric field-assisted conditioning system was developed to study the impact of electric field treatment on the physicochemical properties and CO₂ miscibility of real shale oil. The electrochemical behavior of the shale oil-water system was monitored by continuously recording current and temperature variations during treatment. Subsequently, the viscosity, carbon number distribution, and MMP of shale oil were systematically characterized before and after conditioning. Finally, the mechanisms responsible for electric field-enhanced miscibility were investigated. As opposed to previous studies based on simplified model oils, this work systematically reveals the electrochemical conditioning behavior of real shale oil and establishes the link between electric field-induced compositional evolution and MMP reduction. Moreover, given the rapid deployment of renewable energy in modern oilfields, the proposed strategy offers a compelling pathway to integrate green electricity with CCUS for low-carbon, high-efficiency shale oil development.

2. Experimental methodology

2.1 Materials

Oil samples were collected from the eastern Zhidan area of the Ordos Basin, China. The Chang 7 Member represents a typical continental lacustrine shale oil reservoir characterized by organic-rich source rocks and self-sourced hydrocarbon accumulation. The oil exhibited a dynamic viscosity of 13.53 mPa·s at ambient temperature, which decreased to 2.21 mPa·s at 59.2 °C, indicating pronounced temperature-dependent fluidity. The analysis of saturates, aromatics, resins, and asphaltenes revealed a composition of 82.12 wt% saturates, 12.58 wt% aromatics, 4.97 wt% resins, and 0.33 wt% asphaltenes, suggesting this as a light shale oil dominated by saturated hydrocarbons with a relatively low content of heavy fractions.

Given that the composition of formation water significantly influences electrochemical reactions and interfacial behavior under an electric field, a 0.1 mol/L NaCl solution was employed as the aqueous phase to provide a controlled electrolyte environment while minimizing the confounding effects of complex ionic species. This simplified electrolyte system enabled the intrinsic effect of electric field on shale oil evolution and the subsequent CO₂ MMP to be analyzed without interference from complex formation water chemistry.

2.2 Electric field-assisted conditioning of shale oil

The experimental instrument used for the electric field-assisted conditioning of the shale oil-water system is schemat-

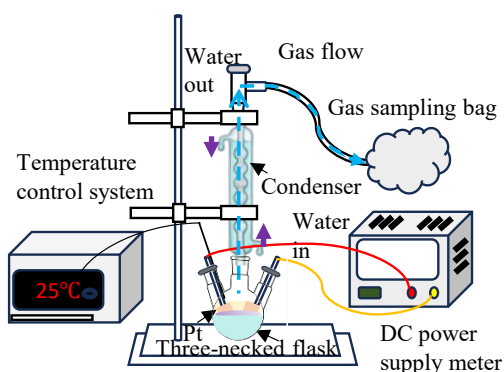


Fig. 1. Experimental setup for the electric-field-assisted conditioning of shale oil.

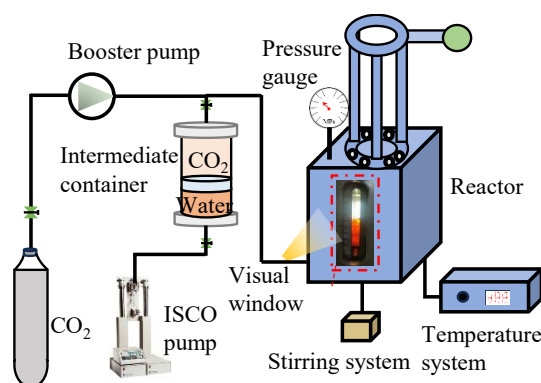


Fig. 2. Experimental device for measuring the MMP of shale oil.

ically illustrated in Fig. 1. The system comprises a 250 mL three-neck round-bottom flask equipped with two platinum plate electrodes, a regulated direct current (DC) power supply, a temperature monitoring system, a reflux condenser, and a gas sampling bag. The platinum electrodes are positioned at the oil-water interface, while the DC power supply delivers the preset voltage and continuously records the current throughout the experiment. The temperature monitoring system continuously records the temperature evolution of the shale oil-water system during conditioning. A condenser is installed to minimize the loss of volatile hydrocarbons, and a gas sampling bag is connected to the system to collect any gaseous products generated during conditioning. Noticeable gas evolution is observed only under the 20 V condition. In this study, DC voltages of 5, 10, 15, and 20 V were set on the shale oil-water system. Under the applied electric field, interfacial electrochemical reactions occurred at the oil-water interface, resulting in changes in the molecular composition and physicochemical properties of shale oil. To evaluate the influence of electric field treatment on CO₂-oil miscibility following conditioning, the treated shale oil samples were subjected to MMP measurements.

During each conditioning experiment, 100 mL of shale oil and 100 mL of the electrolyte solution were introduced into the three-neck round-bottom flask. Two platinum plate electrodes were carefully positioned at the oil-water interface before the DC power supply was connected to apply electric

fields of different intensities. The conditioning process was maintained for 24 h, during which the current and temperature were logged at 1-h intervals to monitor the electrochemical behavior of the oil-water system. After conditioning, the reaction mixture was allowed to cool naturally to ambient temperature and was subsequently transferred into a separatory funnel. Following complete phase separation, the treated oil phase was carefully collected for detailed characterization, including viscosity measurement, carbon number distribution analysis, and MMP determination.

2.3 Determination of the MMP

The visual apparatus used to determine the MMP of shale oil is schematically illustrated in Fig. 2. The apparatus consists of a CO₂ cylinder, a displacement pump, an intermediate vessel, a high-pressure visual cell equipped with a sapphire observation window, and a computerized data acquisition system. During a typical run, a predetermined volume of shale oil is charged into the visual cell, followed by stepwise CO₂ injection. The system pressure increases stepwise until complete miscibility is achieved, which is identified by the complete disappearance of the oil-gas interface.

Prior to each test, the visual cell was thoroughly cleaned with ethanol and hot water and subsequently dried. The entire experimental system, including the CO₂ cylinder, displacement pump, intermediate vessel, and visual cell was assembled and carefully checked for leakage. The temperature controller was set to 59.2 °C and the reactor was allowed to reach thermal equilibrium before testing. Approximately 150 mL of shale oil was then loaded into the visual cell, and the stirring speed was 500 r/min. After recording the initial oil volume, CO₂ was injected incrementally into the visual cell via the displacement pump. Following each pressurization step, the inlet valve was closed to allow the gas-oil system to reach phase equilibrium before recording the system pressure and fluid volume. This incremental pressurization-equilibration process was repeated until the oil-gas interface completely disappeared and the homogeneous mixture occupied the entire observation window, indicating complete miscibility between CO₂ and shale oil. The corresponding equilibrium pressure was recorded as the MMP. After each measurement, the reactor was depressurized, thoroughly cleaned and prepared for the subsequent experiment. To accelerate CO₂-oil mass transfer and facilitate the establishment of phase equilibrium, a constant stirring speed of 500 r/min was employed in all experiments, without aiming to reproduce the actual flow and mass-transfer conditions within shale nanopores. The same stirring conditions were maintained for all samples during measuring the MMP before and after electric-field conditioning.

3. Results and discussion

3.1 Electrochemical behavior of the shale oil-water system

To characterize the dynamic response of the shale oil-water system during electric-field conditioning, the evolution of temperature and current was monitored throughout the

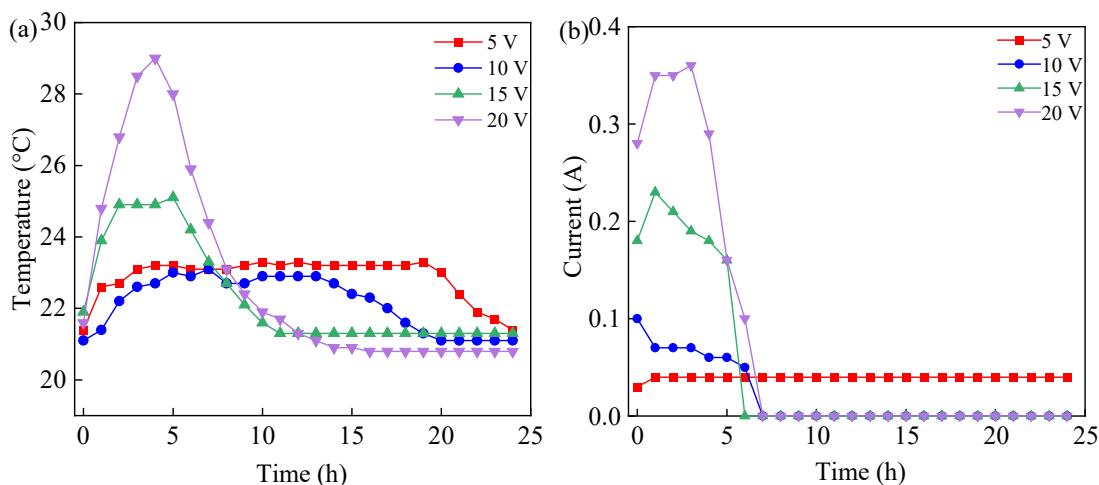


Fig. 3. Dynamic changes in the temperature and current of the shale oil–water system during electric-field conditioning: (a) Temperature with reaction time and (b) current with reaction time.

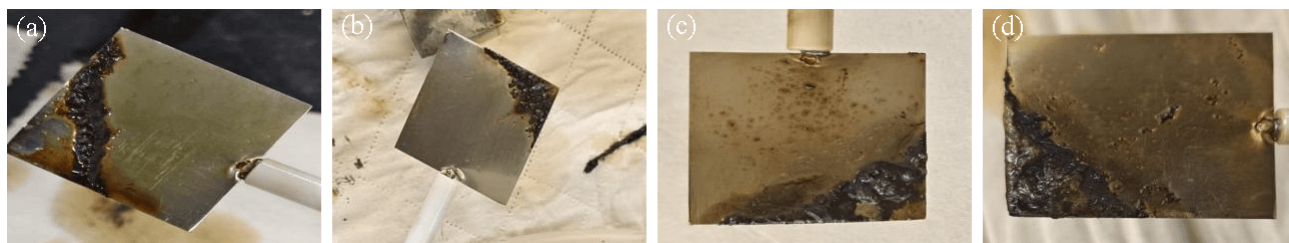


Fig. 4. Shale oil deposits on the platinum electrode sheets after electrochemical treatment under different voltages: (a) 5 V, (b) 10 V, (c) 15 V and (d) 20 V.

treatment process. The temperature evolution of the system in Fig. 3(a) reveals that the temperature initially increases rapidly and then gradually decreases as the electrochemical reaction proceeds. Specifically, peak temperatures reach 23.0, 23.3, 25.1 and 29.0 °C under applied voltages of 5 V, 10 V, 15 V, and 20 V, respectively. The maximum temperature of the shale oil–water system increases slightly with increasing applied voltage. Moreover, the maximum temperature is closely associated with the applied electric field intensity. A higher electric field intensity generates more Joule heat and promotes stronger electrochemical reactions, resulting in a higher temperature of the shale oil–water system. The temperature increase is therefore attributed to the combined effects of Joule heating and electrochemical reactions. This interpretation is further supported by the corresponding variation in the current throughout the experiment.

To further evaluate the evolution of the electrochemical process during electric-field conditioning, the current response was analyzed. As shown in Fig. 3(b), the current exhibits a similar trend, increasing rapidly at the initial stage before gradually decreasing with reaction time. Specifically, the maximum current reaches 0.04 A, 0.10 A, 0.23 A, and 0.36 A under applied voltages of 5 V, 10 V, 15 V, and 20 V, respectively. Comparing the temperature and current profiles during the first few hours of the experiment reveals a strong correlation between the two parameters. The increase in current indicates that more intensive electrochemical reactions occur, leading

to greater heat generation and thus a higher temperature of the shale oil–water system. However, except for the 5 V case, both the temperature and current decrease after reaching their peak values within the first few hours of the experiment. This illustrates that the electrochemical reaction gradually weakens as the experiment progresses. Interestingly, under the applied 5 V electric field, a weak current persists throughout the entire experiment. This sustained but relatively weak electrochemical reaction maintains the temperature of the shale oil–water system at approximately 23.2 °C. As the experiment continues, for the higher-voltage cases, the current gradually decreases to zero, signifying that the electrochemical reaction essentially ceased. Subsequently, the current remains close to zero during the later stage of the experiment, while the temperature of the shale oil–water system gradually decreases and eventually returns to ambient temperature.

It is worthwhile to investigate the reason for the gradual attenuation of the electrochemical reaction in the shale oil–water system. After the experiments, Fig. 4 clearly shows that dark brown deposits with a distinctly viscous texture are adsorbed onto the electrode surfaces. These deposits may be associated with the accumulation of heavy polar components, such as asphaltenes and resins. During the electrochemical process, the heteroatoms (e.g., N, O, and S) and conjugated aromatic structures within asphaltenes and resins impart a weak net charge or a substantial dipole moment to these polar macromolecules. Driven by the applied electric field, these

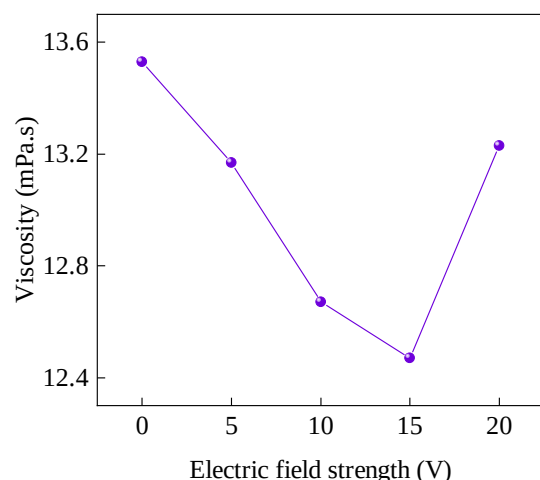


Fig. 5. Viscosity variations of shale oil under different applied electric fields.

polar macromolecules migrate toward the oppositely charged electrode and are eventually adsorbed onto its surface. Under ambient conditions, asphaltenes remain stably dispersed in crude oil through stabilization by resins. However, once they migrate to the electrode surface, charge neutralization disrupts the original colloidal equilibrium, causing the asphaltene molecules to aggregate, overlap and eventually precipitate. Moreover, the deposits are predominantly concentrated at the edges and corners of the electrode plates. This is a typical manifestation of the electric field concentration effect, where the electric field intensity at the edges of the electrode is higher than that at the center. This phenomenon further indicates that the deposition of these heavy components is driven by the applied electric field. The accumulation of deposits on the electrode surface reduced the effective contact area between the electrode and the electrolyte, thereby weakening the electrochemical reaction and diminishing the overall efficacy of the applied electric field.

3.2 Physicochemical evolution of shale oil

Following the electric field-assisted conditioning experiments, the viscosity of the treated shale oil was further studied. Fig. 5 depicts that the viscosity of shale oil exhibits an initial decreasing trend with the applied voltage increasing, followed by a slight rebound above 15 V voltage. Specifically, the initial viscosity of the untreated shale oil is 13.53 mPa.s. After conditioning, the viscosity decreases to 13.17, 12.67, 12.47 and 13.23 mPa.s under applied voltages of 5, 10, 15 and 20 V, respectively. The reduction in viscosity indicates that the electric-field conditioning alters the physicochemical properties of shale oil. This change is likely associated with electrochemical reactions occurring at the oil-water interfacial region, which modified the molecular composition and intermolecular interactions governing the flow behavior of the oil. However, the viscosity reduction is non-monotonic with respect to electric field intensity. Although the minimum viscosity is attained at 15 V, the slight increase observed at 20 V implies that excessively high electric field intensities may trigger secondary reactions, such as the condensation or

recombination of heavier molecular species. Consequently, a comprehensive analysis of the compositional evolution of the shale oil was necessary to elucidate the exact mechanisms driving these viscosity changes.

Because the viscosity of crude oil is fundamentally governed by its molecular composition and intermolecular interactions, its carbon number distribution was characterized. The carbon number distributions of untreated and treated shale oil samples are depicted in Fig. 6. Of note, the sample treated at 20 V was excluded from this compositional analysis. Under 20 V electric field, substantial gaseous products were generated and captured during treatment, causing significant loss of volatile hydrocarbon fractions and altering the representative composition of the liquid phase. Therefore, to ensure a rigorous and reliable comparative analysis, the carbon number characterization was restricted to untreated shale oil and samples treated at 5, 10 and 15 V.

To evaluate the compositional evolution of shale oil induced by electric-field conditioning, the carbon number distributions of the untreated and conditioned shale oil samples were compared. Fig. 6 shows that all shale oil samples exhibit a consistent unimodal carbon number distribution, with the dominant hydrocarbons concentrated in the C₁₁-C₂₅ range. Although the overall distribution profile remains largely intact after electric field treatment, noticeable shifts in the relative abundances of individual carbon number fractions are observed. These results indicate that the applied electric field does not fundamentally alter the overall molecular distribution of shale oil but promotes the redistribution of hydrocarbons among different carbon number fractions. Such compositional evolution is consistent with the observed reduction in viscosity.

To quantitatively evaluate this compositional evolution, hydrocarbons were further classified into three distinct fractions: light hydrocarbons (C₁-C₁₀), medium hydrocarbons (C₁₁-C₂₅), and heavy hydrocarbons (C₂₆-C₃₅), with the corresponding fractional compositions presented in Fig. 7. Fig. 7(a) indicates that the proportion of light hydrocarbons in the untreated shale oil is 21.97%, which slightly decreases to 20.90%, 20.30% and 21.04% following treatment at 5, 10 and 15 V, respectively. These results indicate that the light-hydrocarbon fraction decreases slightly after electric-field treatment. Fig. 7(b) shows that the proportion of medium hydrocarbons in the untreated shale oil is 71.73%, which increases to 73.04%, 73.51% and 73.14% under 5, 10 and 15 V, respectively. This indicates that the medium hydrocarbon fraction becomes enriched after electric field treatment. Fig. 7(c) reveals that the proportion of heavy hydrocarbons in the untreated shale oil is 6.31%, which decreases slightly to 6.06%, 6.20% and 5.82% after treatment under 5, 10 and 15 V, respectively. These results demonstrate a slight reduction in the heavy hydrocarbon fraction following electric field treatment. Overall, electric field treatment induces a systematic redistribution of hydrocarbon fractions, characterized by a simultaneous depletion of light and heavy fractions alongside a corresponding enrichment of medium hydrocarbons.

The enrichment of medium hydrocarbon fraction accompanied by a slight reduction in the heavy hydrocarbon fraction suggests that electric field promotes the compositional

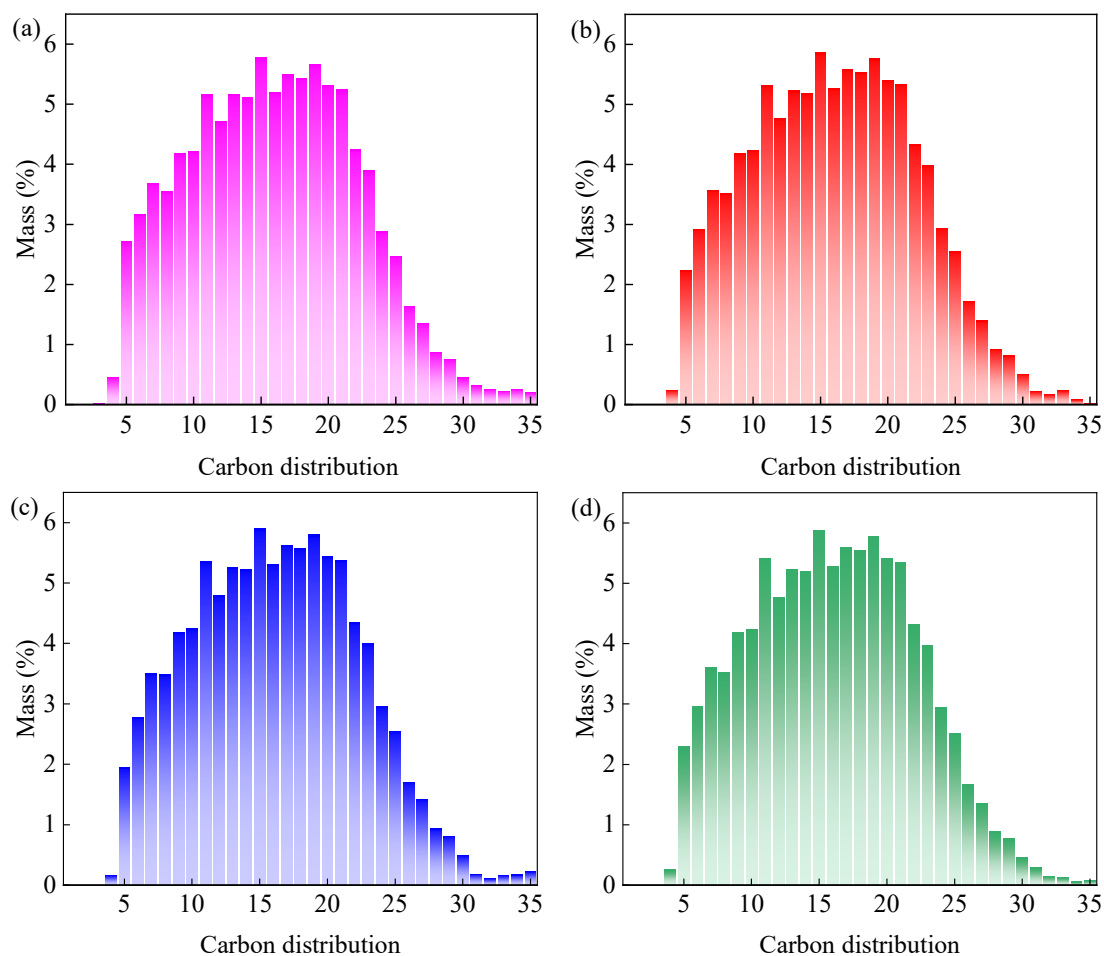


Fig. 6. Carbon number distribution of shale oil under different applied electric fields: (a) 0 V, (b) 5 V, (c) 10 V and (d) 15 V.

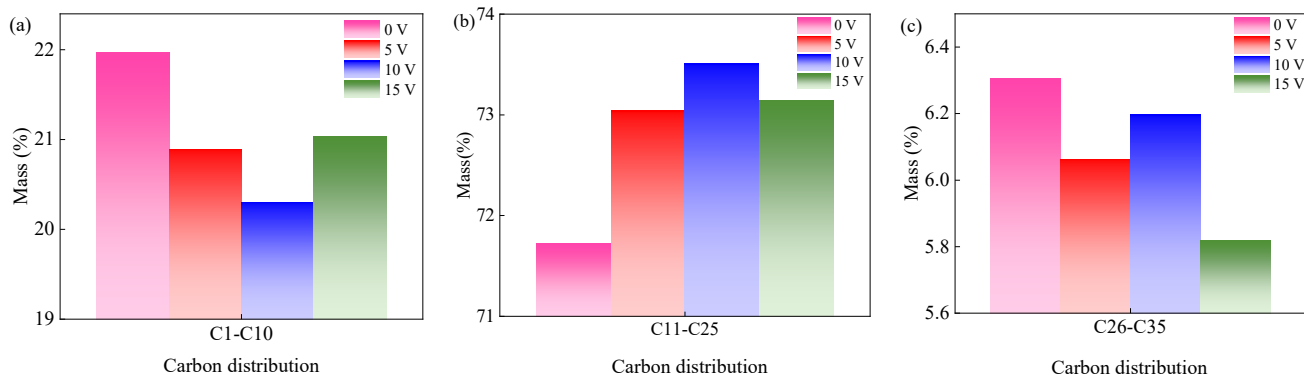


Fig. 7. Compositional evolution of shale oil under different applied electric fields: (a) C₁-C₁₀, (b) C₁₁-C₂₅ and (c) C₂₆-C₃₅.

evolution of shale oil during electrochemical treatment. In addition, the reduction in light hydrocarbon fraction may be attributed to the volatilization of low-carbon hydrocarbons under the applied electric field. Although no significant gaseous hydrocarbons were collected under the 5-15 V conditions, a small amount of volatile light hydrocarbons may have escaped from the liquid phase during the conditioning process, resulting in a slight decrease in the light hydrocarbon fraction. The redistribution of hydrocarbon fractions, particularly the enrichment of medium hydrocarbons and the reduction in

heavy hydrocarbons, is consistent with the viscosity reduction observed in Fig. 5, indicating that electric field treatment effectively modified the molecular composition and rheological properties of shale oil. The reduction in viscosity and the redistribution of hydrocarbon fractions are expected to facilitate CO₂ dissolution and mass transfer in shale oil, thereby improving CO₂ miscibility.

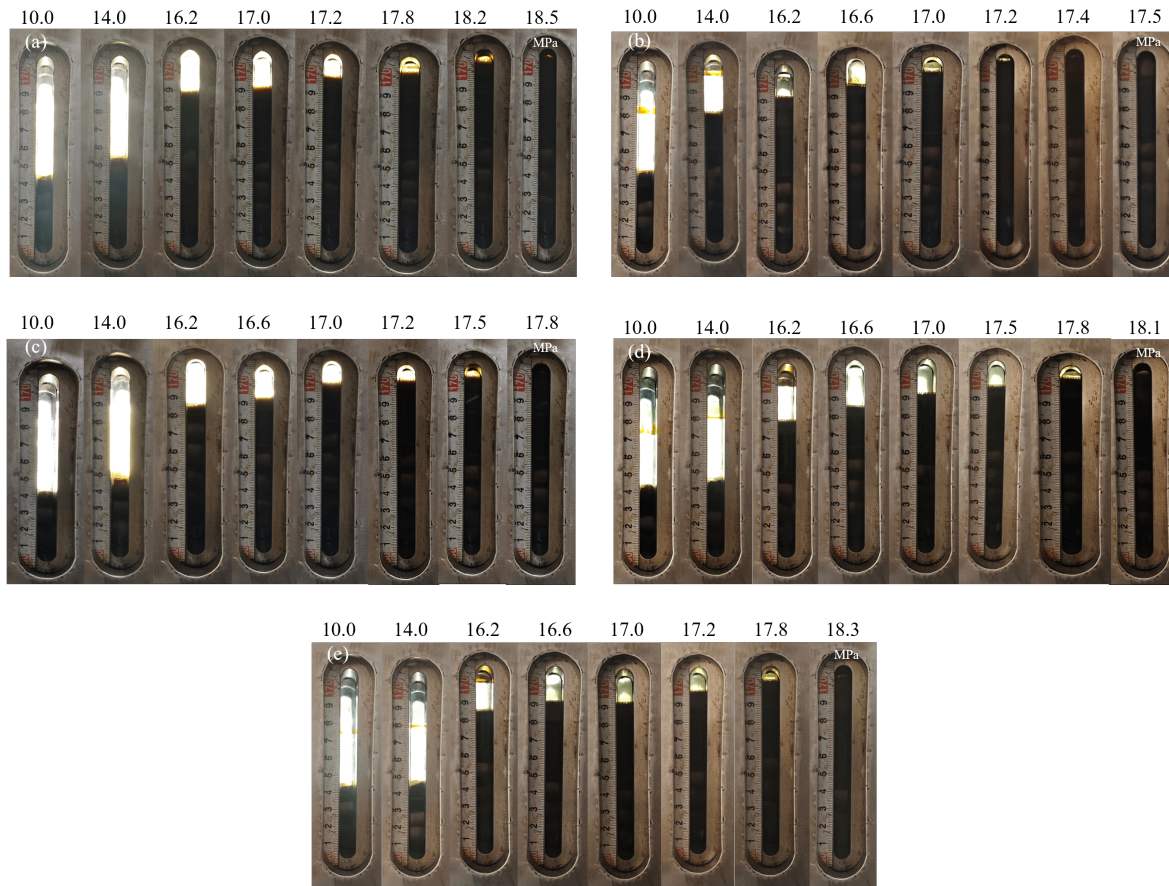


Fig. 8. Visual determination of the MMP for shale oil before and after conditioning under varying electric field intensities: (a) 0 V, (b) 5 V, (c) 10 V, (d) 15 V and (e) 20 V.

3.3 Effect of electric field treatment on the CO₂ MMP

Given that viscosity reduction and hydrocarbon redistribution are expected to strengthen CO₂-shale oil interactions, the impact of electric field treatment on the MMP was systematically evaluated. The visual determination processes of the MMP before and after electric-field conditioning are illustrated in Fig. 8. As the system pressure gradually increases, CO₂ continuously dissolves into the shale oil, resulting in progressive oil swelling and a corresponding increase in the liquid level. Meanwhile, the oil-gas interface gradually moves upward. Upon reaching a threshold pressure, the distinct phase boundary completely vanishes, indicating that complete miscibility between CO₂ and oil is achieved. The equilibrium pressure was recorded as the MMP. From the variation in the oil-gas interface height, it can be observed that the treated shale oil exhibits a higher oil-gas interface than the untreated shale oil under the same pressure. This enhancement indicates a superior swelling capacity, which corresponds to a reduced MMP.

To evaluate the role of electric-field conditioning on CO₂-shale oil miscibility, the MMP of shale oil before and after conditioning was determined. It can be seen in Fig. 9(a) that the height of the oil-gas interface increases with increasing

pressure. When the interface height reaches 11 cm, the oil-gas interface completely disappears. Based on this criterion, the MMP values of shale oil were determined. Fig. 9(b) shows that the MMP of the untreated shale oil is 18.5 MPa. Following electric field treatment, the MMP decreases to 17.5, 17.8, 18.1, and 18.3 MPa under applied voltages of 5, 10, 15, and 20 V, respectively. While all treated samples exhibit reduced MMP values compared to the untreated shale oil, the magnitude of the MMP reduction is non-monotonic with respect to the applied electric-field intensity. It is also observed that the 5 V treatment produces the greatest reduction in MMP, whereas a further increase in the applied voltage results in a slight increase in the MMP. It should be noted that the MMP measured at 20 V reflects not only electric field-induced conditioning but also the pronounced compositional disturbance caused by volatile-component loss. These results indicate that a moderate electric field intensity is more effective than a higher electric field intensity in enhancing the miscibility between shale oil and CO₂. Interestingly, although the 5 V treatment did not produce the lowest viscosity, it resulted in the greatest reduction in MMP, whereas the lowest viscosity was obtained at 15 V. This discrepancy indicates that viscosity reduction alone cannot account for the variation in CO₂-oil miscibility; instead, the MMP response is likely governed by the combined

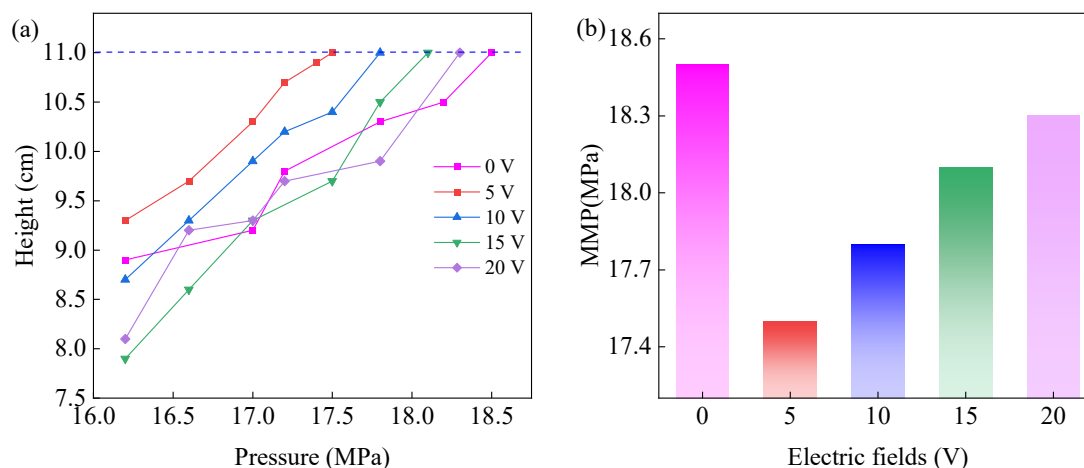


Fig. 9. MMP determination of shale oil before and after conditioning under different electric field strengths: (a) Variation in oil-gas interface height with pressure and (b) summary of MMP values.

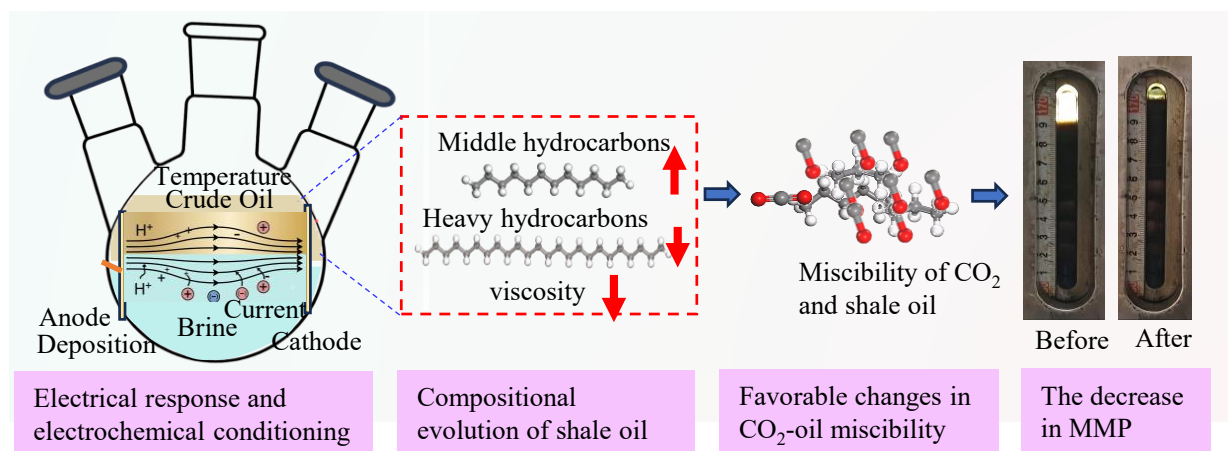


Fig. 10. Schematic diagram illustrating the mechanism of electric field-enhanced CO₂ miscibility.

effects of the physicochemical and compositional changes of shale oil during electric field conditioning. In addition, the progressive increase in MMP from 17.5 MPa at 5 V to 18.3 MPa at 20 V suggests that an optimal electric field intensity exists for electric field-assisted CO₂ flooding to maximize miscibility enhancement and oil recovery performance.

3.4 Discussion of electric field-induced enhancement of CO₂ miscibility

The experimental results consistently demonstrate that electric field conditioning modifies the physicochemical properties of shale oil and thus enhances its CO₂ miscibility. On this basis, the underlying mechanism governing electric field-induced enhancement of CO₂ miscibility is schematically shown in Fig. 10.

Under the externally applied electric field, an electrical driving force was established across the shale oil-water system, resulting in current flow and subsequent electrochemical reactions at the interfacial region. In this context, electric field represents the external stimulus, whereas electrochemical reactions constitute the physicochemical response of the oil-water system. The observed current and temperature variations

provide evidence for the evolution of this electrochemical process. Meanwhile, electrode deposition further indicates that the interfacial environment continuously evolves during conditioning. These electrochemical processes contribute to the compositional evolution of shale oil, including the redistribution of hydrocarbon fractions and the associated reduction in viscosity. Specifically, the enrichment of medium-carbon hydrocarbons together with the reduction in heavy hydrocarbons is consistent with the observed decrease in shale oil viscosity and may contribute to improved molecular mobility. Such compositional and rheological changes may facilitate CO₂ dissolution and mass transfer in shale oil, thereby favoring the development of CO₂-oil miscibility. It is noteworthy that the lowest MMP was obtained under the 5 V treatment rather than at higher applied voltages. With increasing voltage, however, gas evolution became more pronounced, particularly at 20 V, where substantial volatilization prevented reliable carbon number analysis of the remaining oil. According to classical miscibility considerations, the loss of light and volatile hydrocarbons is generally unfavorable for CO₂-oil miscibility and may therefore partly contribute to the gradual increase in MMP at higher voltages. Meanwhile, the more rapid current decay,

enhanced gas evolution, and electrode deposition observed at higher voltages may reduce the duration and effectiveness of electrochemical conditioning. Therefore, the minimum MMP observed at 5 V likely reflects the combined effects of electric field-induced compositional evolution, volatile-component loss, and electrochemical conditioning characteristics, rather than solely the sustained electrochemical reaction at this voltage.

Despite the observed enhancement of CO₂-oil miscibility, the present study was conducted in a bulk-fluid system, while under actual reservoir conditions, shale oil is predominantly confined within micro- and nanoscale pores. Such nanoscale confinement may substantially alter fluid-rock and fluid-fluid interactions, capillary forces and CO₂ mass transfer, leading to physicochemical and miscibility behaviors that differ from those observed in bulk fluids. Therefore, our results clearly demonstrate the effectiveness of electric-field conditioning at the bulk-fluid scale, but their direct applicability to shale nanopores remains to be further established. Future work should extend the present investigation from bulk fluids to nanoconfined systems and clarify whether the electric-field-induced compositional evolution and enhanced CO₂ miscibility observed here can be maintained under shale reservoir pore-scale conditions.

4. Conclusions

In this study, a custom-designed electric field-assisted conditioning system and a high-temperature high-pressure visual apparatus were employed to investigate the influence of electric field treatment on the physicochemical properties of shale oil and its subsequent CO₂ miscibility behavior. The electrochemical evolution of the shale oil-water system was monitored throughout the treatment process, while viscosity, carbon number distribution, and MMP of the shale oil were systematically characterized. The following conclusions were drawn:

- 1) During electric field treatment, both the temperature and current of the shale oil-water system increase rapidly during the initial stage and gradually decrease as the electrochemical reaction proceeds. Higher electric field intensities induce stronger electrochemical reactions accompanied by greater Joule heating, whereas a low electric field (5 V) maintains a relatively stable and sustained electrochemical process.
- 2) Dark brown viscous deposits form on the platinum electrode surfaces after treatment. These deposits are likely associated with the accumulation of heavy polar components, indicating that electrochemical deposition occurred during the treatment process. The accumulation of these deposits gradually reduces the effective electrode area, thereby weakening the electrochemical reaction.
- 3) Electric field treatment modifies the physicochemical properties of shale oil. The viscosity initially decreases and then increases slightly with increasing electric field intensity. Meanwhile, the carbon number distribution is redistributed, characterized by decreases in the light and heavy hydrocarbon fractions and an enrichment of the

medium hydrocarbon fraction.

- 4) Electric field treatment effectively reduces the MMP between shale oil and CO₂. The 5 V treatment produces the greatest reduction in MMP, demonstrating that an optimal electric field intensity is more effective than a higher electric field intensity in enhancing CO₂ miscibility.

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