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REVIEWS

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Effectiveness of electrokinetic-enhanced oil recovery (EK-EOR): a systematic review

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Abstract

Hydrocarbons continue to play an important role in providing affordable energy to meet rising energy demand. Amidst growing concerns on the environmental impact of oil and gas production processes, many researchers are increasingly exploring environmentally sustainable methods of extracting hydrocarbons from the reservoir. The introduction of direct current into the pore space activates mechanisms that enhance fluid flow, reduces produced water, decreases associated hydrogen sulfide production, and leaves no material footprint on the environment. Previous laboratory studies and field applications have reported varying degrees of success of the EK-EOR mechanism. However, the mechanism and effectiveness of this technique remain unclear. This systematic literature review provides an opportunity to critically evaluate laboratory results, establish a basis for the effectiveness of the EK-EOR mechanism and identify possible future research directions. In this study, 52 articles were identified and reviewed in a selection process that adhered to the PRISMA protocol. Data extracted from these articles were fed into the EK-EOR model, and Monte Carlo simulation (10,000 iterations) was used to determine the success rate of the EK-EOR process. Insights obtained from the simulation indicate that EK-EOR alone is not effective (with a success rate of 45%). Insights from published laboratory experiments indicate that interstitial clay affects the electro-osmotic permeability of reservoir rocks which determines the effectiveness of the EK-EOR mechanism. Salt deposition on the cathode and generation of gases (oxygen and chlorine at the anode) are significant limitations of the EK-EOR. The review concludes by identifying future areas of application of EK-EOR.

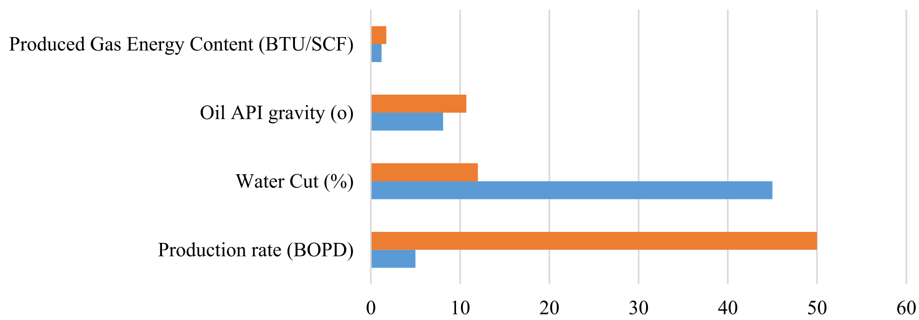
Keywords: Electrokinetic-enhanced oil recovery, Electrically enhanced oil recovery, Zeta potential, Monte Carlo simulation, Current density, Electrical potential, Direct current

Introduction

In a report by the International Energy Agency [4], hydrocarbons accounted for 81.3% of the world's total energy supply in 2018, consisting of 31.6% Oil, 22.8% Natural gas and 26.9% Coal. Amidst growing concern over climate change and the need to transition to a low-carbon economy, the proportion of hydrocarbons in the total energy supply mix is expected to decrease in the coming years. Nonetheless, hydrocarbons are still projected to play an important role in meeting the growing energy needs of developing and developed economies [43]. Hydrocarbons provide a cheaper and more stable energy source when compared to existing alternative energy sources. However, there is a need to minimize the environmental footprint of the hydrocarbon production process. Emissions of greenhouse gases (GHGs) from hydrocarbon production processes differ considerably based on crude oil type, production practices, and recovery technologies [29]. Energy-intensive secondary and tertiary recovery technologies such as Chemical EOR, Steam flooding and Waterflooding (plus Injection and Wastewater treatment) have substantial effects on the environment [23]. To mitigate the impact of these recovery processes, other methods of cleaner recovery techniques have been proposed by researchers; Magnetic Field [30, 35] and ultrasonic waves [31, 57].

The use of an electric current in improving oil recovery presents an interesting solution to cleaner hydrocarbon production. Its application was previously limited to the production of heavy oil reservoirs where it recorded significant improvements with corresponding lower environmental footprint. In electrokinetic-enhanced oil recovery (EK-EOR), electric current is introduced into the reservoir via electrodes attached to both the Production and Injection wells. The electrical current supports the hydrodynamic movement of fluid from the injection well into the production well. Successful deployment of this technique were recorded in heavy oil fields in the Santa Maria Basin, CA (USA), the Eastern Alberta (Canada) Plains, Little Tom Field Texas, Schoonebeek reservoir, Netherlands and also on the Rio Panon Field, Brazil [28, 37, 48, 50]. During these field applications, EK-EOR was observed to have some inherent advantages over the conventional-enhanced oil recovery techniques. Some of these advantages include; reduction in water production, decrease in produced oil viscosity, marked reduction of Hydrogen Sulfide (H_2S) production and no depth limitation [2, 5, 64]. In addition to these advantages, compared with existing EOR methods, EK-EOR have the added advantage of not requiring a working fluid, being effective with reactive clay minerals, having no emissions concern and limited thief zone concerns [62]. EK-EOR is a subset of electrical-enhanced oil recovery (EEOR). Although both terms are sometimes used interchangeably, the difference between the two is found in their operating mechanisms. While EEOR covers all recovery methods that are directly or indirectly run by electrical current, in EK-EOR the electric current itself is the means of enhancing recovery. For more clarity, in EEOR electric current can be converted to sound energy (ultrasonic waves) and/or mechanical energy whereas in EK-EOR, the current itself are introduced to the reservoir to alter; wettability of the rocks, surface/interfacial tension, induce electroosmosis and/or alter permeability (electrophoresis and electromigration). Figure 1 captures some of the effect of EK-EOR when applied to a heavy oil field in Santa Maria Basin, CA, as outlined by Wittle et al. [62].

In addition, growth in laboratory studies conducted at core scale on EK-EOR has been recorded over the last 12 years (as observed in Fig. 2). These studies demonstrate an improvement in oil recovery at higher efficiency, lower cost, less time and more importantly lower carbon footprint of oil production processes [9, 62],Shalabi et al. 2012; [19, 53, 65]. The basis for the success of EK-EOR was thought to be the reduction of oil viscosity through an increase in reservoir temperature. However, recent work suggests that the EK-EOR mechanism could be more complex. Some of these studies focused on the ionic interaction of connate water and the reservoir rock mineral surface with electricity [6, 51, 54, 56, 59]. Other laboratory investigations performed on



	Production rate (BOPD)	Water Cut (%)	Oil API gravity (o)	Produced Gas Energy Content (BTU/SCF)
EK-EOR	50	12	10.7	1.73
Baseline	5	45	8.1	1.197

EK-EOR Baseline

Fig. 1 EK-EOR effect on production parameters of Santa Maria Heavy Oil field [62]

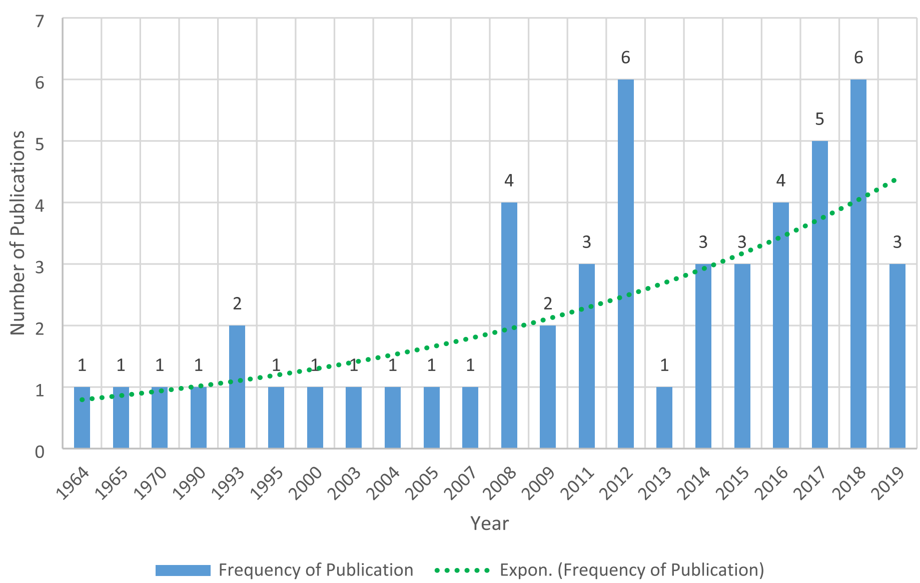


Fig. 2 Frequency of publications by year

both sandstone and carbonate reservoirs reveal that wettability is altered when direct current (DC) is introduced to the reservoir [15, 16, 20, 32, 37, 64, 65].

Despite the claims made by these studies, the question of whether EK-EOR is an effective recovery mechanism in conventional oil reservoirs remains unclear. If it is effective, then what key factors ensure the effectiveness of EK-EOR in these reservoirs? This systematic literature review (SLR) aims to:

1. Critically analyse and evaluate the extant literature and provide a measure of effectiveness of the EK-EOR mechanism.
2. Evaluate existing laboratory results on EK-EOR and identify key factors affecting its effectiveness.

3. Suggest future research directions around EK-EOR

To fulfil these study objectives, the following research questions (RQ) were formulated using the population, intervention, and outcome (PIO) framework:

> *RQ1: Is EK-EOR* (I) *an effective recovery mechanism* (O) *in conventional oil reservoirs*? (P)
> *RQ2: What are the key factors* (O) *affecting the effectiveness of EK-EOR* (I) *in hydrocarbon reservoirs?* (P)

This study is organized as follows: Sect. 2 provides an overview of the review protocol and the process of retrieving and assessing relevant publications. In Sect. 3, the theoretical basis for the effectiveness of the EK-EOR technique is described while Sects. 4 and 5 discuss *RQ1* and *RQ2*, respectively. Section 6 discusses possible future directions of EK-EOR research while Sect. 7 summarizes major findings from the SLR.

Methods

In this study, a systematic literature review (SLR) is used to identify, analyse, and critically assess published literature on EK-EOR and apply the findings to answer the formulated research questions (identified in Sect. 1). To ensure robustness and reproducibility of the SLR, the search process was executed on 3 relevant databases; SCOPUS, Web of Science (Science Citation Index Expanded) and Science Direct. The search keywords used include.

> *Population*—"Hydrocarbon reservoirs" OR "Oil reservoirs" OR "Gas reservoirs" OR "Gas condensate reservoirs" OR "Sandstone" OR "Carbonate"
> *Intervention*—"Electric current" OR "Electrokinetic" OR "Direct current" OR "Voltage" OR "Potential gradient"
> *Outcome*—"Oil displacement efficiency" OR "Residual Oil Saturation" OR "Recovery factor" OR "Oil production" OR "Gas Production"

As captured in Fig. 3, the search strategy employed in the paper identified 126,491 articles under *Population*, 3,907,560 articles under *Intervention* and 563,203 articles under *Outcome*. Combining the search terms using the Boolean operator "AND" reduced the total outputs to 1389 articles. The exclusion criteria were used to select the articles assessed include:

> *Exclusion criteria 1*: The document subject area categorize as Medical, Biological or Agricultural science
> *Exclusion criteria 2*: The contents of the article are not relevant to the subject matter and do not address key words contained in Population, Intervention and Outcome (PIO)

The 1389 articles were then screened on two levels. At the first level, 1268 articles were removed by exclusion criteria 1 and 2, leaving 121 articles to be assessed. The second level of screening involves title and abstract examination, 91 articles were screened out

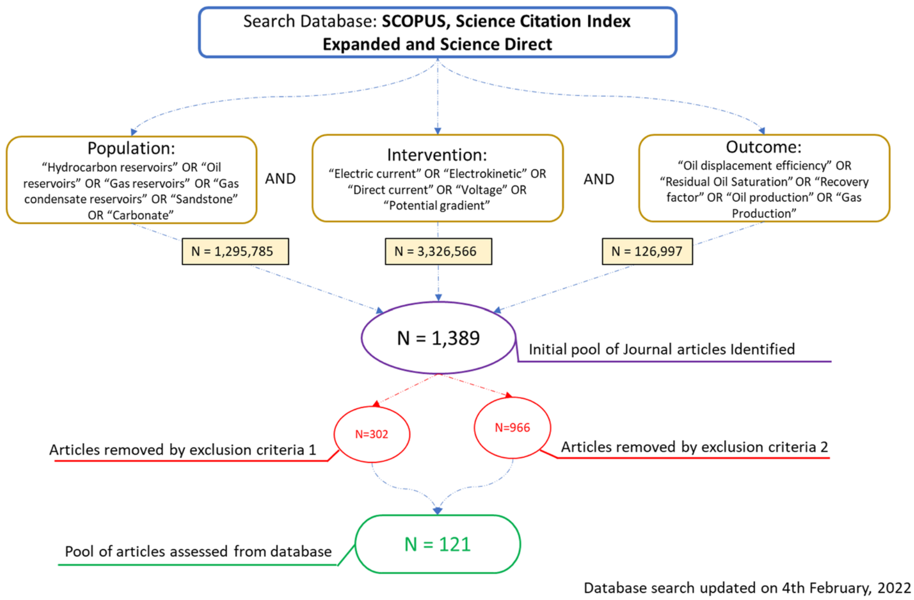


Fig. 3 Search strategy from 3 database

at this level. At the end of the screening exercise, 52 articles were included in the study of the 1437 articles identified (1389 articles from focus databases and 48 from external sources).

The earliest publication in this review dates back to 1964 with a publication by Amba et al. [11]. A renewed interest in this area is evident from the publication growth rate captured in Fig. 2. The interest is thought to be in response to the need to find environmentally sustainable methods of extracting hydrocarbons from the reservoir. The results of all articles containing laboratory experiments were compiled, outlining also their individual experimental conditions. The recovery factor reported in these studies were averaged across reservoir rock types—sandstones and carbonates. The summary of this analysis is captured in Table 1. All laboratory studies reported either an incremental oil recovery or an improvement in permeability after EK-EOR. The average recovery from carbonate cores were lower than same from sandstone cores. Carbonate cores reported average incremental recovery of 12.83% while sandstone cores reported 35.5% average incremental recovery when EK-EOR process was applied. Some of the laboratory studies combined EK-EOR with other conventional EOR methods: waterflooding [15, 33], low-concentration acid (Ansari A. et al. 2016), and surfactant [2],Ansari A. et al., 2015a). The oil type used for the laboratory studies ranged from simpler alkanes n-hexanes to more complex medium, light, and dead oil of varying viscosities.

EK-EOR mechanism

The introduction of electric current into the reservoir, has shown significant improvement in hydrocarbon recovery based on laboratory studies [18, 64, 65] and preliminary field deployment [36, 37, 46]. The improved recoveries observed in these studies were

Table 1 Summary of laboratory experiments demonstrating the impact of various factors on electrokinetics

Reference	Porous medium	Porosity and permeability	Pressure and temperature	Oil type	Clay type present	Brine salinity	Ions present	Incremental oil recovery	Electric potential gadient	Remarks
[34]	Carbonate: dolomitic limestone	10–25% 0.1mD–16D	Ambient	–	–	36,100 ppm	Cl^-, H^+, OH^-	8–14%	2.0 V/cm	(1) Accumulation of chlorine gas produced at the anode caused a reduction in electroosmotic flow (2) Porosity, permeability, and clay content identified as key factors affecting electroosmotic flow
[32]	Surrogate sandstone cores	10.2–14.7% 2.16–41.88mD	Ambient	n-Hexane (SG–0.79)	Kaolinite montmorillonite	58,800 ppm	Na^+, Cl^-, Mg^{2+}, SO_4^{2-}, K^+, Ca^{2+}	3%	1.5 V/cm	(1) Viscous drag of oil was observed on the pore walls due to the electroosmotic effect (2) Permeability increase due to enlargement of the capillaries (3) Clay contents between 10 and 15% yielded maximum oil recovery
[2]	Carbonate–mudstones and wackestones	4–27% 0.1–0.2 mD	–	Medium crude (API–29°)	–	–	Non-ionic surfactant, Brine	7%	2.0 V/cm	(1) Simultaneous surfactant flooding yielded a 15% increase in increase in oil recovery compared to sequential flooding (2) Simultaneous surfactant flooding also consumed more power

Table 1 (continued)

Reference	Porous medium	Porosity and permeability	Pressure and temperature	Oil type	Clay type present	Brine salinity	Ions present	Incremental oil recovery	Electric potential gadient	Remarks
[25]	Sandstone	25–26% 200–230 mD	Ambient	Kerosene	6%–Montmorillonite 6%–illite 6%–kaolinite	5000 ppm	Na^+, Cl^-	20–113%	5–150 milliamp	(1) Permeability to kerosene increases and remains higher after each electrical stimulation period
(Ansari et al. [20])	Carbonate	8.8–20.33% 0.22 -2.69 mD	80 °C 3000 psi	Medium crude oil (34.5° API, 3.5 cP)	–	Low concentration Acids (1.2% HCl)	H^+, Cl^-, OH^-	15–35%	1 V/cm	(1) Combining electrokinetics with low concentration acid flooding resulted in enhanced permeability and displacement efficiency by: -Improving pore connectivity through electrical conduction -Enhancing penetration of acid and H^+ ions deeper into the carbonate reservoirs
[64]	Carbonate	22.3–26.0% 0.57–1.38mD	90 °C 2500psi	Dead oil (41.5° API)	–	17,545–23,377 ppm	Na^+, Cl^-, SO_4^{2-}, K^+, HCO_3^-	2–4%	10 mA	(1) Applying Eelectrokinetics during secondary recovery proved unsuccessful due to high brine salinity resulting in salt precipitation and formation damage (2) Gas generation (oxygen and chlorine observed at the anode)

Table 1 (continued)

Reference	Porous medium	Porosity and permeability	Pressure and temperature	Oil type	Clay type present	Brine salinity	Ions present	Incremental oil recovery	Electric potential gadient	Remarks
[13]	Carbonate	3–27% 0.1–0.8mD	Ambient	Medium crude (API–29°)	–	10,000 ppm	Alkyl polyglycoside (APG)	12–15%	2 V/cm	(1) Oil-wet core plugs consume approximately 10 times more water than water-wet core plugs (2) Higher EK yield observed in oil-wet reservoirs as EK-assisted sequential surfactant EOR produced 45% of the original recovery factor in oil-wet while producing 14% of original recovery factor in water-wet core-plugs
[5]	Berea Sandstone	20.4–24.3% 30.6–145.4 mD	Ambient	Light–medium oil (26.3–39.3 API)		40,000 ppm	NH_4^+,Cl^-	9%	2 V/cm	(1) Reduction in injected water required when DC is applied simultaneously (2) Improvement in permeability observed

Table 1 (continued)

Reference	Porous medium	Porosity and permeability	Pressure and temperature	Oil type	Clay type present	Brine salinity	Ions present	Incremental oil recovery	Electric potential gadient	Remarks
[18]	Carbonate	8–28%	Ambient and 80 °C 3000 psi	Light–medium (34°API-29°API)	–	40,000 ppm	NH_4^+, Cl^-, H^+, OH^-	13%	0.5–2.0 V/cm	(1) Increase in acid concentration yielded a corresponding increase in displacement efficiency. However, this is limited by the production of $CaCl_2$ and CO_2 which inhibits oil flow (2) Higher voltage produces a greater electrokinetic driving force and gives a higher displacement efficiency (3) The effect of higher voltage is limited by pressure. An increase in pressure causes consolidation and stabilization of currents. This leads to an increase in absorption of ions by the rock surface, decrease in rock resistance and subsequent decrease in electromigration effect

Table 1 (continued)

Reference	Porous medium	Porosity and permeability	Pressure and temperature	Oil type	Clay type present	Brine salinity	Ions present	Incremental oil recovery	Electric potential gadient	Remarks
[65]	Sandstone	12.32–12.53% 0.1869–0.32md	Ambient temp and 3375 psi	Synthetic white oil	–	3550–35,500 ppm	Na^+, Cl^-	50%	0–15 V	(1) Increase in flow rate observed when voltage was increased until the optimum value of 10 V was reached (2) Viscous dragging of oil molecules by water was affected by brine salinity (3) At low brine salinity, oil displacement efficiency is higher for simultaneous flooding whereas, at high brine salinity, the reverse is true

attributed to electrical double layer expansion of oil-brine-rock interface, movement of charged ions from the anode to the cathode, drag-force transfer of water molecules associated with charged ion movement, disintegration of water molecules into constituent gaseous and ionic phases, movement of colloid particles, viscosity reduction, and thermal mobility of reservoir fluid [32, 34, 49, 62]. Hill [36], while using the concept of coupled flow, identifies 5 mechanisms that occur when electric current is introduced to the reservoir: Joule heating, electromigration, electrophoresis, electroosmosis, and electrochemically enhanced reactions.

Joule heating

Joule heating describes the heating effect that occurs when electric current passes through a medium with a known resistance. It increases reservoir temperature and decreases hydrocarbon viscosity thereby making it easier for fluid to flow to the surface. It takes the largest amount of energy of the 5 DCEOR mechanisms. The frequency of the electric current can be adjusted to initiate inductive heating, microwave heating and/or low frequency heating [53]. Table 2 provides a summary on the principles of operation of each heating method identified.

Electromigration

This involves the movement of either positively charged cations or the negatively charged anions under the influence of electric field [45]. Previous laboratory experiments demonstrate that at high initial ionic concentration and low soil pH (between 2 and 3), electromigration becomes the dominant transport mechanism under DC electric field [3]. However, it ought to be noted that the influence of electric field on the transport mechanisms depend on the pore fluid composition, reservoir rock mineralogy and electrochemical properties of the species generated in the porous medium.

Electrophoresis

Electrophoresis applies specifically to charged colloidal particles suspended in a solution. This transport mechanism becomes dominant when surfactants are introduced into the reservoir [22, 52]. The resultant micelles (charged particles) formed as a result of the surfactant reacting with the reservoir fluids can be transported under the influence of an electric field. Electrophoretic transport becomes more dominant when the hydrophobic molecules become attached to the charged micelles [32]. Although experiments are still being performed to investigate the efficiency of electrophoresis in recovering hydrocarbons, it is very important to mention that clay type play a significant role [3].

Electrochemically enhanced reactions

This electrokinetic transport mechanism describes two types of reactions that occur: breakdown of complex hydrocarbons into simpler by-products in situ, and then reaction between the fluid and rock matrix minerals due to changes in fluid pH or electron activities in the reservoir.

Theoretical basis for EK-EOR

In building the analytical models for estimating electroosmotic flowrate model, the following assumptions were made [11, 25]: (a) fluid flow through pore throat is represented by flow in a capillary tube as shown in a horizontal cross-section Fig. 4; (b) hydrodynamic equations for viscous liquids are valid for the entire flow region, (c) laminar flow conditions prevail because of the small thickness of the double layer in comparison with the capillary diameter, and (d) external electrical potential gradient is superimposed on the walls of the capillary tube [11, 25].

If φ represents the electrical potential when the liquid is at rest and iRx represents the imposed current along the x-axis, then the total potential due to the addition of external potential is given by

$$\psi = \varphi - \mathrm{iRx} \tag{1}$$

When the force produced by the electric field F, resisted by pressure drop along the capillary tube $P|_{\partial x}$, is balanced by the frictional force in the liquid, Eq. (2) results.

$$F - P|_{\partial x} = -\eta.\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

Using vector calculus notation for a general coordinate system ∇, Eq. (2) can be simplified:

$$F - P|_{\partial x} = -\eta.\nabla^2 u \tag{3}$$

where $\nabla^2 = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}$

Volumetric velocity is constant along the walls of the $\frac{\partial u}{\partial x} = 0$

But the force generated by the electric field F, can be derived from the volume charge density δ,

Table 2 Comparative analysis between various thermal Electrical EOR techniques as presented by Rehman and Meribout [53]

EK-EOR type	Areas of application (suitability)	Limitations
Induction heating	-Reservoirs with thief zones -Reservoirs where thermal EOR is not suitable -Reservoirs having low in situ water saturation	-Heating applies to only near well bore areas
Low-frequency electric heating	-Can be used as alternative to steam injection depending on the energy supplied -Reservoirs comprising of high permeability streaks or fractures	-Heating temperature limited by the boiling point of water
Microwave heating	-Heavy oil reservoirs -Reservoirs with target areas directly exposed to microwaves without any hurdles	-Require shut down of production -Penetration depth of high frequency is limited -Source may get damaged because of extensive heat production -Not applicable to water flooded reservoirs

$$F = \delta.i.R \tag{4}$$

From Poisson's equation

$$\nabla^2\varphi = \frac{-4.\pi.\delta}{D} \tag{5}$$

Substituting for $\delta = \frac{-D.\nabla^2\varphi}{4.\pi}$ in F,

$$\mathrm{F} = \delta.\mathrm{i.R} = \frac{-i.D.R}{4.\pi}\nabla^2\varphi \tag{6}$$

By substituting for F, Eq. (6) becomes

$$\frac{i.D.R}{4.\pi}\nabla^2\varphi + P|_{\partial x} = \eta.\nabla^2 u \tag{7}$$

For pure electroosmotic effect, we eliminate the effect of pressure gradient along the walls of the capillary tube by equating $P|_{\partial x} = 0$. Equation (16) reduces to [36],

$$\frac{i.D.R}{4.\pi}\nabla^2\varphi = \eta.\nabla^2 u_e \tag{8}$$

Expressing ∇^2 in terms of cylindrical coordinates (x, r, θ), and assuming φ and u_e are independent of x and θ [49],

$$\frac{i.D.R}{4.\pi.\eta}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r}\right)\right] = \left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_e}{\partial r}\right)\right] \tag{9}$$

Integrating and assuming no slip at the capillary wall, i.e., potential at the mobile layer, φ_l decreases to potential at the fixed layer, φ_s.

$$u_e = \frac{i.D.R}{4.\pi.\eta}(\varphi_l - \varphi_s) \tag{10}$$

$$u_e = \frac{E.D}{4.\pi.\eta.\mathrm{L}}(\varphi_l - \varphi_s) \tag{11}$$

where E is the electrical potential for pure electroosmotic effect, and it is given by $E = i.R.L$

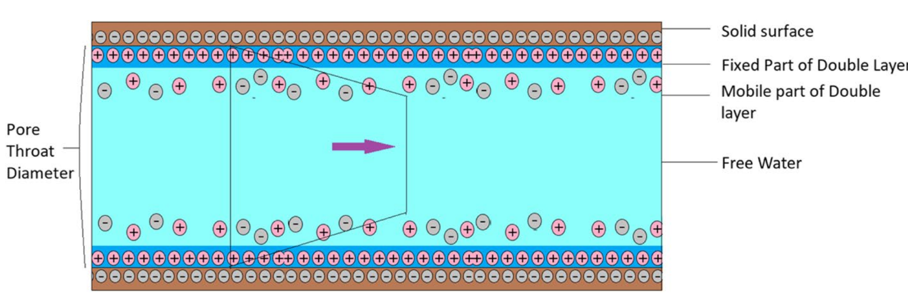


Fig. 4 Schematic illustrating electric double layer principle using capillary tube

Equation (11) shows that the electroosmotic velocity is dependent on the potential difference between the mobile and fixed region of the electrical double layer. This difference is known as zeta potential and was represented by

$$\zeta = (\varphi_l - \varphi_s) \tag{12}$$

Substituting for zeta potential, Eq. (11) reduces to

$$u_e = \frac{E.D.\zeta}{4.\pi.\eta.\mathrm{L}} \tag{13}$$

In an EK-EOR process, the total flowrate is expected to be a function of both the hydrodynamic pressure gradient and the electric potential gradient. Assuming Darcy's law is applicable in the flow region, the electrical potential applied in a reservoir where oil was already flowing hydro-dynamically increases oil recovery. The key however is to apply the electric potential in the same direction as the pressure drop. The total flow rate observed can be obtained by combining both flows due to pressure drop and potential difference.

$$q_t = q_p + q_e \tag{14}$$

From Eq. (13), flow due to electric potential gradient can be represented by

$$q_e = \frac{A.E.D.\zeta}{4.\pi.\eta.\mathrm{L}} \tag{15}$$

Substituting Eq. (15) into (14), and representing q_p, by the basic Darcy equation:

$$q_t = \frac{A.K.\Delta p}{\mu.L} + \frac{A.E.D.\zeta}{4.\pi.\eta.\mathrm{L}} \tag{16}$$

For practical engineering calculations, it is assumed that the electroosmotic coefficient would remain fairly constant for a given rock type. It is termed electroosmotic permeability coefficient K_e [32]:

$$K_e = \frac{D.\zeta.\mu}{4.\pi.\eta.} \tag{17}$$

Substituting into Eq. (16),

$$q_t = \frac{A.K.\Delta p}{\mu.L} + \frac{A.K_e.E}{\mu.L} \tag{18}$$

$$\frac{q_t}{q_p} = 1 + \frac{K_e.E}{K.\Delta p} \tag{19}$$

$$\frac{q_t - q_p}{q_p} = \frac{K_e.E}{K.\Delta p} \tag{20}$$

The incremental recovery from EK-EOR strongly depends on the permeability of the porous media. The higher the permeability the less significant the effect of EK-EOR will become. This is demonstrated in Eqs. (18)–(20). Equation (20) shows that the ratio of K_e/K estimated from laboratory data can be used as a preliminary test for the success of EK-EOR in any given reservoir.

Insights from EK-EOR field deployment

EK-EOR field demonstrations on heavy oil reservoirs were reported by Hill et al. [37], Wittle et al. [62], and Hill [36]. In these studies, field demonstrations were conducted at Santa Maria Basin, California (USA) and the Eastern Alberta (Canada) Plains. The Santa Maria Basin comprised of unconsolidated sand of 30.5 m thickness and located at a depth of approximately 850 m below ground surface (BGS). While the Eastern Alberta Plains was an 11-m-thick unconsolidated, braided stream sand at a depth of approximately 517 m BGS. Table 3 captures the apparent advantages of EK-EOR compared to other EOR techniques. In addition to its application on heavy oil reservoirs, EK-EOR has also been applied to remediate contaminated soils (Döring et al. 2003). However, changes to produced fluid chemistry were reported during EK-EOR deployment. Some of the observed changes include: increase in BTU content of the produced gases, reduction in produced H_2S and increase in overall gas production rate. Propagation of the electric current away from the near wellbore region was an important challenge observed at field scale.

Effectiveness of EK-EOR

To address *RQ1*, a stochastic simulation was conducted based on the parameters identified in Sect. 3. The objective of the simulation was to determine the probability of obtaining higher incremental recovery when the EK-EOR process is initiated. A probability above 50% is considered effective.

Design of stochastic experiment

A simple experimental set-up with cylindrical core of dimensions (7 cm long and 2.5 cm diameter) as captured in Fig. 5. Values of the parameters used in the simulation were extracted from reviewed laboratory experiments in Table 1.

The dimensions of the core sample and fluid type were kept constant during the simulation while other parameters were varied according to the probability distributions given in Table 4.

Results discussion

The results of the simulations are given in Fig. 8a, b. Insights from the result reveal that the probability of obtaining above 5% additional recovery due to the EK-EOR process is lower than 50% (actual value 45%). For EK-EOR recovery above 50%, the probability declines further to 27%. This implies that when standalone EK-EOR process is initiated, there is a 55% chance of having a marginal lower recovery. This is evident from the frequency distribution of the values obtained (see Fig. 6b). The result of the stochastic simulation reveals that standalone EK-EOR is not an effective method of enhancing oil recovery.

Factors affecting the performance of EK-EOR

To address *RQ2* and to deduce insights from laboratory studies, this section identifies factors that affect the effectiveness of the EK-EOR process. As identified in the previous section, there are various factors attributable to the success or failure of the electrokinetic process in the reservoir. Summarily, these factors manipulate the Oil-Brine-Rock (OBR) interfaces to alter the wettability of the rock surface which either favours or inhibits the EK-EOR mechanism.

Rock mineral, clay type, and structure

The pH, zeta potential, and thickness of the electric double layer affects the wettability of the reservoir rock. Several studies indicate that altering the water chemistry can also alter the surface structure of the rock mineral [9, 10, 14, 24, 63]. For example, because of the structural imbalances found in the silica or aluminium layer making up clay particles, clay minerals have a net negative charge. Consequently, when the clay or rock minerals come in contact with brine, the cations in the brine solution are absorbed into the mineral surface [41]. The type of clay present in the rock matrix play a very important role in oil recovery by EK-EOR, especially in sandstone reservoirs. In an earlier work carried out by Anbah et al. [12], marked changes in electroosmotic flow were observed when the clay content of the surrogate cores were changed from montmorillonite to kaolinite. Figure 7 reveals a progressive increase in normalized flowrate when kaolinite, illite, and montmorillonite clays were added to the silica base. During the EK-EOR process, sandstone cores containing clay exhibited higher oil recovery than cores with little clay [11, 12, 25]. However, the amount of clay present in the pore structure is also important. A study carried out by Ghazanfari et al. [32] on the effect of clay (kaolinite and montmorillonite) content revealed that at higher clay content, oil recovery was limited by low

Table 3 Advantages of EK-EOR on heavy oil reservoirs [37]

Process limitation	EK-EOR	Steam flood	CO_2 flood	Fire flood	Surfactant flood	Co-solvent flood
Front end costs	Power supply cables Electrodes	Steam Generator Compressor Transmission lines	CO_2 supply compressor Transmission lines	Compressor Transmission lines	Mixing tanks Pumps Transmission lines	Mixing tanks Pumps Transmission lines
Uniform sweep	Yes	No-thief zones	No-thief zones	No-thief zones	No-thief zones	No-thief zones
Depth limitations	No	$\leq$ 2500 ft	No	No	No	No
Water demand	Nil	Very high	None	None	High	Variable
Operational limitations	None	Emission and water supply limits	None	None	Hazardous chemicals	Hazardous chemicals
Reservoir and crude type	High and low permeability	High permeability non-reactive matrix	High permeability	High permeability	High permeability	High permeability
Maturity	Field demonstrated	Commercial	Commercial	Commercial	Pilot tested	Pilot tested

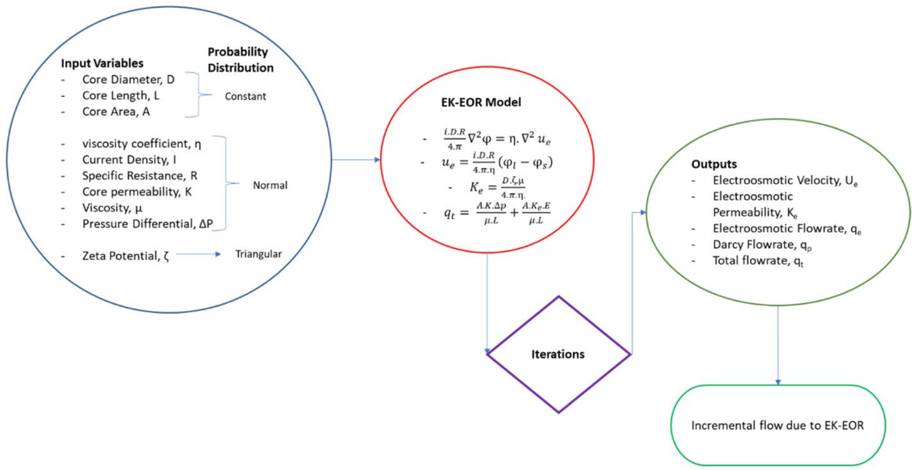


Fig. 5 Design of stochastic experiment

Table 4 Probability density distribution of selected variables

Parameters	Probability distribution	Range		
		Mean	***Standard deviation***	
Liquid viscosity coefficient	Normal	2 Ns/m^2	0.45	
Current density	Normal	0.07 A/m^2	0.55	
Specific resistance	Normal	6 Ω-m	0.75	
Core permeability	Normal	0.02 D	0.4	
Viscosity	Normal	50 cp	0.5	
Pressure differential	Normal	40 atm	0.65	
		Minimum	*Most likely*	*Maximum*
Electric potential in the mobile layer	Triangular	0.035 V	0.035	0.05
Electric potential in the fixed layer	Triangular	0.025 V	0.025	0.035

10,000 iterations of incremental recovery from EK-EOR were ran and the probability of obtaining values greater than 5%, 10%, 35%, and 50% were obtained using ` Carlo simulation

charge efficiency whereas, at low clay content, the recovery was influenced by colloidal transport.

Electrical potential applied

The application of electric potential gradient facilitates fluid flow chiefly through the mechanism of Electroosmosis [32]. When brine with its component ions and salinity comes in contact with the rock mineral surface, an electric diffuse layer is formed [37]. The electric diffuse layer becomes a cation-selective membrane allowing hydrated cations to pass through the pore throats while selectively preventing the anions. The introduction of direct current causes the cations to flow and which in turn leads to the overall movement of the brine [65]. This process is also known as electroosmosis and its intensity is dependent on the direction of the direct current, surface charge, salinity, valence, and ionic composition of the brine. A higher

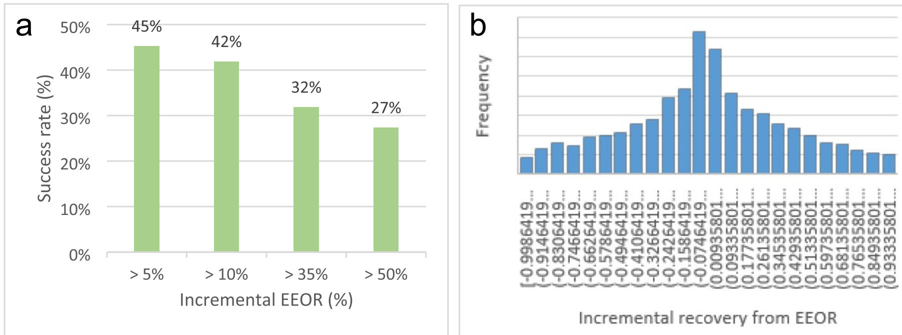


Fig. 6 **a** Success rates of incremental EEOR. **b** Variations in incremental recovery from EEOR during simulation

direct current produces a corresponding higher electroosmotic flow. This principle has been validated by several laboratory experiments [18, 25, 34, 64]. This is captured in Fig. 8. When direct current is applied to the porous media, water undergoes electrolysis; hydrogen ions are formed at the anode while hydroxyl ions are formed at the cathode. This creates a corresponding acidic environment around the anode while an alkaline environment is formed around the cathode. The mineral surface reacts in this environment and alters its wettability to preferentially water wet which also improves oil recovery. The effect of electroosmosis becomes more pronounced as the hydrodynamic permeability decreases. Peraki et al. [49] performed a sensitivity analysis to investigate key parameters that affect electrokinetic flow. Results from their numerical analysis revealed absolute electro-osmotic permeability was a key factor among other factors which include porosity, initial water saturation, applied current density, water resistivity, and applied current density.

However, in an experiment conducted by Ansari et al. [18], it was discovered that the increase in electroosmotic flow as direct current was increased continued until a threshold was reached. This observation was confirmed by a similar study performed by Zhang et al. [65] and Ikpeka et al. [39]. Zhang et al. [65] performed an experiment using sandstone cores with permeability range 0.187 mD to 0.32 mD and porosity of 12.32–12.53%. By increasing the external voltage from 0 to 10 V across the core sample, he observed a corresponding increase in the oil displacement. However, on the application of 15 V across the core sample, it was observed that oil displacement reduced by 43.87% in comparison to the displacement at 10 V as shown in Fig. 9. This phenomenon was explained by [18] as a consequence of a decrease in electromigration. The higher voltage causes an increase in the formation temperature due to the Joule heating effect. The temperature increase causes consolidation and stabilization of currents in the pore space. This leads to an increase in absorption of ions by the rock surface, decrease in rock resistance, and subsequent decrease in electromigration effect.

Permeability of the reservoir rock

The ratio of electroosmotic permeability to hydrodynamic permeability plays a key role in the overall effectiveness of Electrokinetics. A study carried out by Haroun et al.

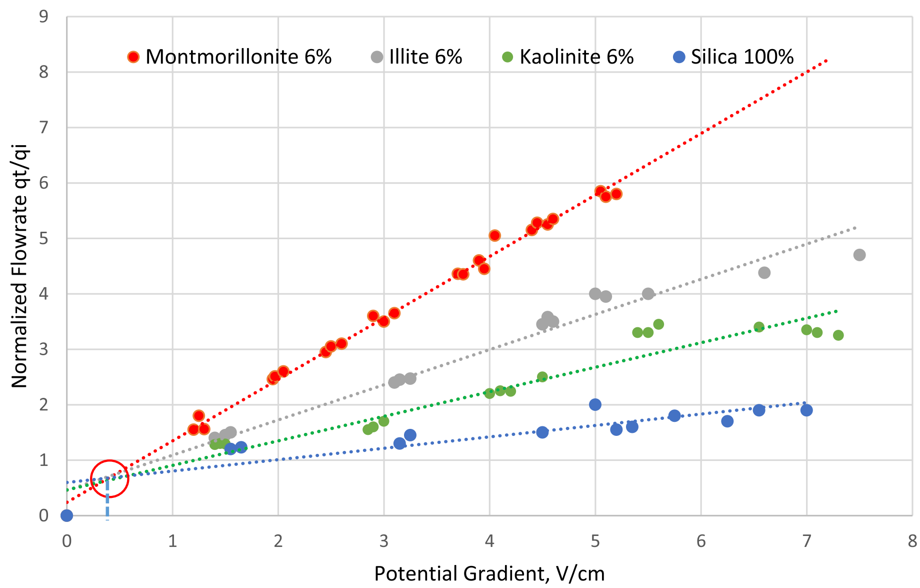


Fig. 7 Potential gradient vs normalized flowrate on clay types (adapted from Chilingar [25]

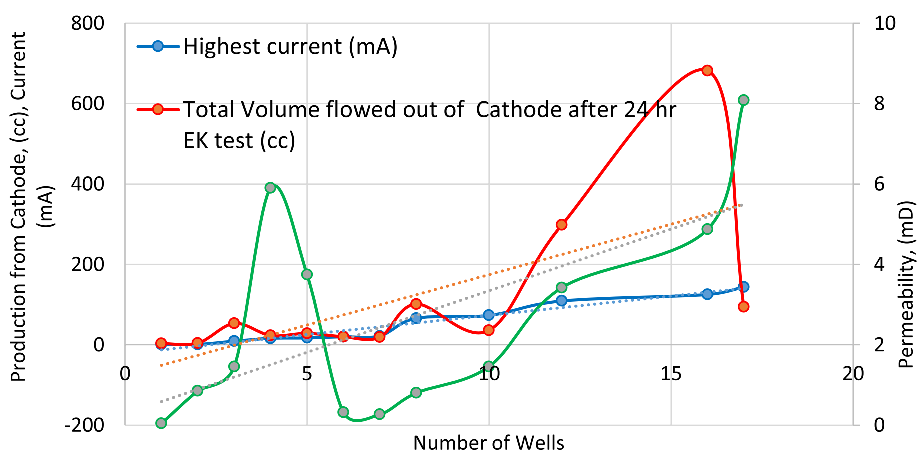


Fig. 8 Coupled effect of current and permeability on electroosmotic flow of carbonate rock (adapted from [33, 34]

[33, 34] identified clay-content, porosity, and permeability as the main contributing rock properties for electrokinetic processes. The study further states that amongst the three factors listed, permeability was the most critical. Researchers observed a remarkable increase in permeability of the porous media during and after the EK-EOR process [11, 12, 25]. Measuring the percentage recovery at a constant potential gradient, from injected pore volume of three core samples with different permeability, Al Shalabi et al. [5] observed a progressive increase in flow due to electrokinetics for each increasing core permeability as shown in Fig. 10. Shalabi et al. (2012) observed a 223% increase in permeability when the electroosmotic potential was applied in the same direction as the pressure gradient. Arsalan et al. (2015) applying electrokinetics to carbonate reservoirs also observed an 11–53% increase in permeability and a corresponding 17–29% increase

in oil recovered. This increased permeability was attributed to the electrophoretic washing effect on colloidal particles under an electric field [47].

Polar components in crude oil

The presence of polar components modifies the surface charge of the crude oil. Asphaltenes and resins are two major surface-active constituents of heavy oil and the difference between the two lies in their solubility in normal paraffin [38, 42]. Because of its polarity, asphaltenes particles are strongly affected by an electric field and its structure adjusts itself to align with the electric field [22]. Kokal et al. [42] observed that asphaltenes displayed both negative charge and positive charge depending on the pH, ionic strength, and salinity of the electrolyte in which it was immersed. Hosseini et al. [38] carried out an experimental study in which they visualized the effect of the current on asphaltenes placed on a glass micromodel embedded with electrodes, by using a high-resolution optical microscope. The chemical structure and complexity of the asphaltenes affect the rate of aggregation under the electric field. Building on this framework, Azari et al. [22] attempted to experimentally determine the electric charge on asphaltenes colloid particles. Their study concludes that the electrophoretic mobility of asphaltenes reduces as the particles grew in size. Carboxyl and hydroxyl groups were responsible for the surface charge and zeta potential when electrolytes come in contact with asphaltene molecules [27]. The introduction of direct field alters the polarity of the asphaltene molecules causing adsorption to clay surfaces have been noted to alter the wettability of the rock surface. Also, the electrokinetic charges on the asphaltenes and resin depend on the pH, salinity, ionic strength, and composition of the aqueous medium in which it is dissolved.

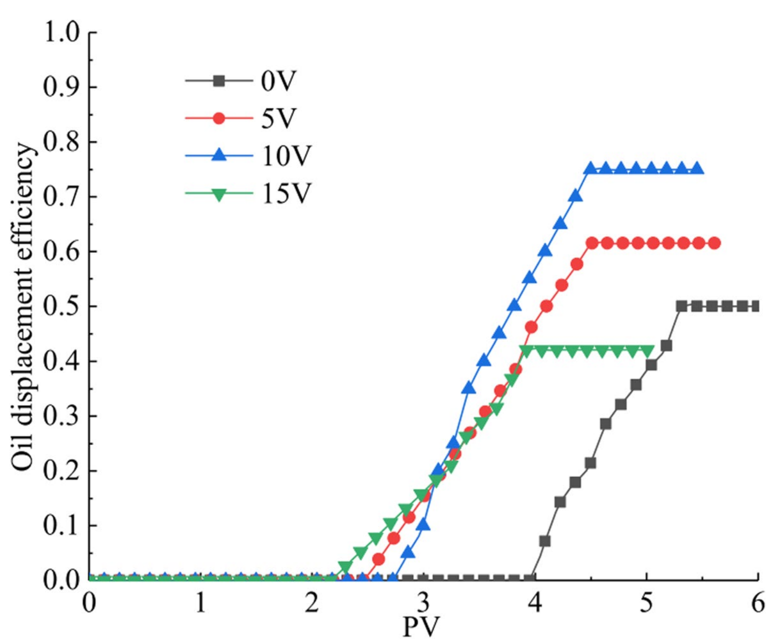


Fig. 9 Results obtained by Zhang et al. [65] showing the relationship between oil displacement and PV under the influence of direct current

Ranking of factors affecting EK-EOR

To identify factors that had the most significant impact on the EK-EOR process, a standalone analysis of the model given in Eq. (20) was conducted using data supplied in Table 2. Results from the analysis revealed that current density, zeta potential, and permeability were the top 3 significant factors affecting the performance of EK-EOR process (Fig. 11).

Discussion and areas of future applications of EK-EOR

The effectiveness of EK-EOR in increasing oil recovery of any porous media is regulated by its ability to (i) modify the wettability of the mineral surface from oil-wet to preferentially water wet or mixed wet, (ii) reduce interfacial tension by releasing H^+ and OH^- ions during electrolysis of water, (iii) control flow velocity via electroosmotic pumping effect, and (iv) alter the thickness of the electric double layer in association with the ionic composition of the injected water. Some of these principles are already being applied in other tertiary recovery techniques such as nanoparticle injection (flooding), low concentration acids flooding, low salinity, and smartwater flooding.

Electrokinetics with low salinity water (LSW) and smart water (SW) flooding

The incremental recovery of low-salinity water flooding is attributed to EDL expansion, clay hydration, swelling, and migration due to salinity differences [40, 41, 44, 64]. Adjusting the ions present in the brine has the potential to affect the zeta potential of the reservoir rock because of the ionic interactions between the brine and the reservoir rock or crude oil [7, 8, 24, 60]. The combined effect of water salinity and electrokinetics presents an interesting area of study. Yim et al. [64], performed laboratory experiments to determine the combined effects of salinity and electrokinetics in recovering hydrocarbon from tight carbonate reservoirs in Abu Dhabi, UAE. An important conclusion from their

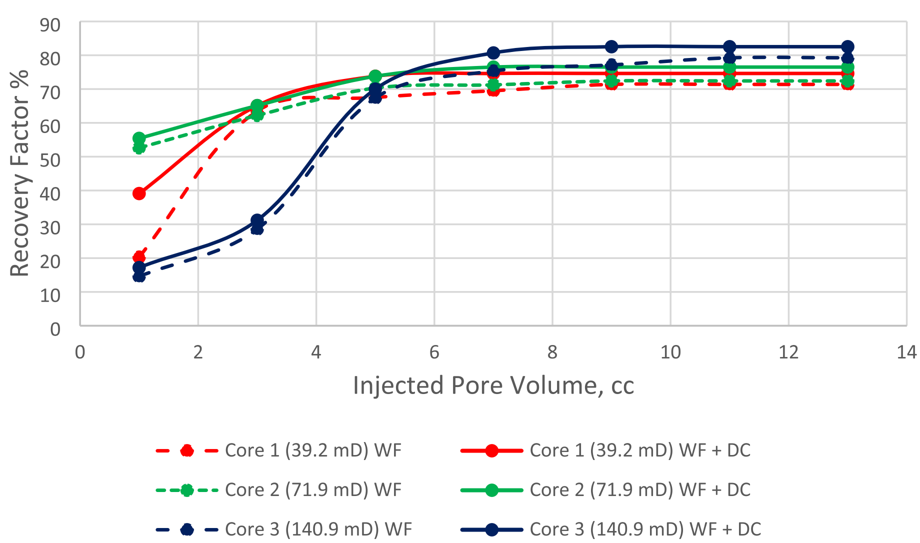


Fig. 10 Light oil recovery factor plotted against pore volume injected at constant potential gradient (adapted from [5])

study is that the concentration of ions in the brine negatively affected the performance of electrokinetics during secondary flooding. This was attributed to the precipitation of salts at the electrodes. However, their experiments reveal an interesting research gap on the role of ion type for the expansion of the electric double layer. The water chemistry can be adjusted in various ways; by dilution with deionized water, or by increasing/decreasing the concentration of individual ions, i.e., Ca^{2+}, Mg^{2+}, Na^{+}, and SO_4^{2-} and observing the fluid behaviour under the influence of direct current. Numerical models validated by experimental data are required to corroborate the effect of water chemistry on the thickness of the electric double layer, zeta potential under the influence of DC.

Electrokinetic-low concentration acids (EK-LCA) flooding

The primary mechanism involved in acidizing operations is the dissolution of scales by the acids thereby creating flow channels with higher permeability around the near well-bore region of the carbonate formation[26, 66],Abdullah et al. 2017; [58, 61]. Introducing EK-EOR to the acidizing operation can delay the absorption of the acids within the formation, increase the depth of penetration, and improve flow velocity of the acid flooding process [19]. Other potential benefits of combining EK-EOR and low concentration acidizing are reduction in interfacial tension, wettability alteration, enhancement of capillary number, better sweep efficiency by targeting un-swept regions of the reservoir through electrophoresis and electro-osmosis, and enhanced penetration depth. Previous studies by the same group focused on estimating the efficiency of displacement, permeability enhancement and minimum current density required to produce oil from the core samples [21], 2016d). Results from their study reveal that simultaneously introducing electrokinetics to the core sample while Waterflooding yielded 13% more recovery than introducing electrokinetics after Waterflooding. However, analytical models

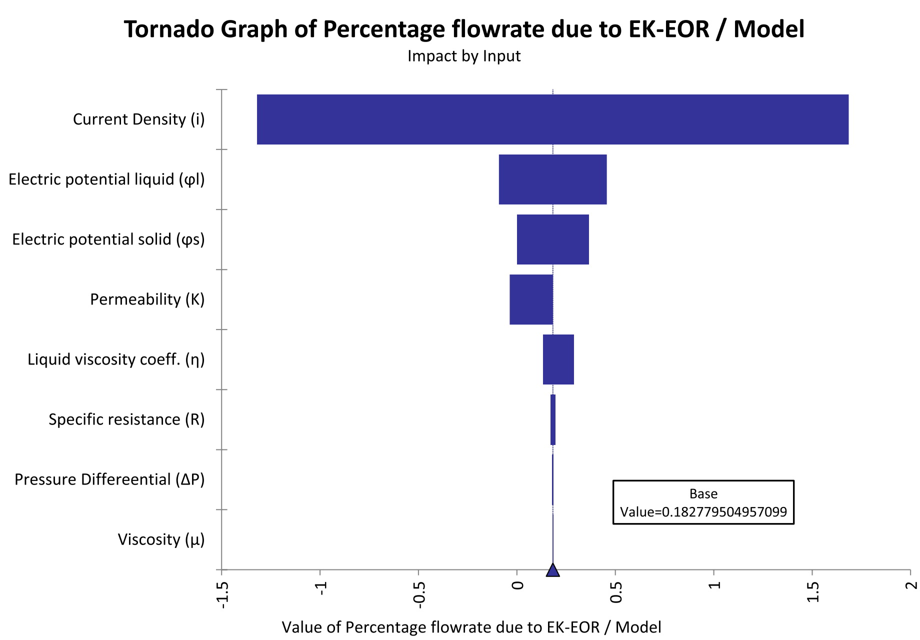


Fig. 11 Ranking of factors affecting performance of EK-EOR process

need to be built to characterize the behaviour of acid ions in the presence of an electric field and its impact on carbonate wettability. The success recorded by laboratory experiments attributed to the enhancement of acid penetration depth needs to be validated using analytical models. Extension of the studies should also be conducted on sandstone reservoirs to characterize the impact of clay type on EK-LCA operation.

Treatment of gas condensate banking

EK-EOR can be applied to mitigate condensate banks formed when pressure drops below dewpoint in a gas condensate reservoir. From published literature reviewed so far on gas condensate treatment, no research has attempted to apply this technique to mitigate gas condensate banking. The introduction of electric current into the pore space of a gas condensate reservoir alters the wettability of the rock surface to support recovery of more condensate. The electric current interacts with the brine, condensate molecules and the minerals of the pore walls. Preliminary experiments conducted by [39] reveals that in the absence of reservoir rock pore surface, EK-EOR affects the interfacial tension of condensate molecules. Detailed experiments are needed to sufficiently capture the impact electric current on treating gas condensate banks.

Conclusion

The SLR concludes that the application of EK-EOR alone is not an effective method of improving production. However, the success rate of EK-EOR can be improved when it is combined with other EOR techniques under certain reservoir conditions. These conditions have significant impact on the efficiency of this technique and are summarized thus:

- The type and amount of interstitial clay present within reservoir rocks affect the productivity of the EK-EOR mechanism. Reservoirs containing montmorillonite clays exhibit more recovery during EK-EOR process than other clay types (kaolinite, illite).
- The effectiveness of EK-EOR in any reservoir depends on the in-situ reservoir permeability. Higher reservoir permeability decreases the effect of the EK-EOR process. The EK-EOR process is more effective in tight reservoirs (0.5 mD to 1.5 mD).
- Salt deposition on the cathode during EK-EOR process is affected by the composition of Connate/formation water and the amount of potential gradient across the electrodes. The effectiveness of the EK-EOR technique is limited by salt deposition at the cathode and the generation of chlorine gas at the anode

Understanding the coupled effect of optimum electric current, salinity and clay content is an important step for the EK-EOR technique. Preliminary studies carried out by researchers show an agreement combining electrokinetics with other EOR techniques; smartwater flooding, low salinity waterflooding, low concentration acid (LCA) flooding. However, further laboratory experiments need to be done to understand and build analytical models that capture the incremental recovery from such combinations. In addition to this, the effect of electrokinetics on the gas phase is yet to be explored. Modelling of the EK-EOR mechanism with more emphasis on the gas phase (below bubble point) is recommended for further research.

Nomenclature

Φ Electric Potential when the fluid is at rest.

φ_l Electric potential in the mobile part of the double layer.

φ_s Electric potential in the fixed part of the double layer.

iRx Imposed external potential along the solid surface.

i Current density.

R Specific resistance.

$\frac{\partial P}{\partial x}$ Pressure gradient along the surface of the solid.

u Volumetric velocity.

η Liquid viscosity coefficient.

δ Volume charge density.

D Dielectric constant.

A Cross-sectional area.

L Length of the capillary tube.

E Electric potential.

u_e Electroosmotic velocity only.

∇^2 Laplace operator.

λ Specific conductivity of the liquid.

ψ Total potential due to the addition of imposed external potential.

ζ Zeta potential.

F Formation resistivity factor (Archie).

K_e Electroosmotic permeability.

μ Viscosity.

R Universal gas constant [8.31451 J/(mol.K)].

T Absolute temperature (K).

ρ Density of the medium.

P Electromagnetic power dissipated per unit volume.

σ Effective conductivity of the medium.

Abbreviations

EK-EOR	Electrokinetic-enhanced oil recovery
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
EEOR	Electrical-enhanced oil recovery
DC	Direct current
RQ	Research question
SLR	Systematic literature review
PIO	Population intervention outcome

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Authors' contributions

PMI conceptualized the paper, extracted literature from database, analyzed all literature, and prepared the first draft of the paper. PR and GGP critically reviewed the manuscript, while JOU both reviewed the manuscript and supervised the findings of the work. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this article.

Declarations

Competing interests
The authors declare no conflict of interest on this work.

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