Crude Oil Demulsification Using Electro-Coalescence Method: A Comprehensive Review

Ahmed SH. Minjal[1*], Khalid M. Mousa Al-zobai[2], Salam K. Al-Dawery[3]

Authors affiliations:
1*) Dept. of Chemical Engineering, Al-Nahrain University, Baghdad, Iraq.
ahmedshallall@outlook.com

2) Dept. of Chemical Engineering, Al-Nahrain University, Baghdad, Iraq.
khalid.m.mousa@nahrainuniv.edu.iq

3) University of Nizwa, Sultanate of Oman.
salam@unizwa.edu.om

Paper History:

Received: 10th Oct. 2024

Revised: 21st Oct. 2024

Accepted: 7th Nov. 2024

Abstract

The separation of water from crude oil emulsions is a critical and complex challenge in petroleum production and processing. Water-in-oil (W/O) emulsions increase viscosity, pose corrosion risks, reduce refining efficiency, and raise significant environmental concerns. Traditional separation methods often struggle with stable emulsions containing small droplets due to limitations in cost, environmental impact, and effectiveness. Electro-coalescence demulsification has emerged as a promising technique that applies electric fields to enhance droplet coalescence, facilitating efficient water removal. This comprehensive review examines the influence of electrode geometry on electro-coalescence systems in depth, synthesizes key findings from numerous studies, and provides a detailed analysis of electrode spacing calculations, critical conditions for effective demulsification, and optimal operational parameters. By exploring these aspects comprehensively, the review offers insights into how electrode design affects demulsification efficiency, guiding future advancements in crude oil processing and contributing to more sustainable practices in the petroleum industry.

Keywords: Electro-Coalescence, Demulsification, Electrode Geometry, Water-in-Oil Emulsions, Electrode Materials

إزالة استحلاب النفط الخام باستخدام طريقة التحلّل الكهربائي: مراجعة شاملة

احمد شلال منجل، خالد مخلف موسى الزوبعي، سلام كاظم الدواري

الخلاصة:

فصل الماء عن مستحلبات النفط الخام: تحدٍ حيوي ومعقد في إنتاج ومعالجة البترول. تزيد مستحلبات الماء في الزيت (W/O) من اللزوجة، وتشكّل مخاطر التآكل، وتقلل من كفاءة التكرير، وتثير مخاوف بيئية كبيرة. غالبًا ما تواجه طرق الفصل التقليدية صعوبات مع المستحلبات المستقرة التي تحتوي على قطرات صغيرة بسبب محدوديات في التكلفة، والتأثير البيئي، والفعالية. ظهرت تقنية إزالة الاستحلاب بالتحلّل الكهربائي كنهج واعد يستخدم المجالات الكهربائية لتعزيز تلاحم القطرات، مما يسهل إزالة الماء بكفاءة. تستعرض هذه المراجعة الشاملة تأثير هندسة الأقطاب الكهربائية على أنظمة التحلّل الكهربائي بعمق، وتجمع بين النتائج الرئيسية من العديد من الدراسات، وتقدم تحليلًا مفصلاً لحسابات تباعد الأقطاب، والظروف الحرجة للتحلّل الفعال، والمعايير التشغيلية المثلى. من خلال استكشاف هذه الجوانب بشكل شامل، تقدم المراجعة رؤى حول كيفية تأثير تصميم الأقطاب الكهربائية على كفاءة إزالة الاستحلاب، موجهةً التقدمات المستقبلية في معالجة النفط الخام ومساهمة في ممارسات أكثر استدامة في صناعة البترول.

1. Introduction

Crude oil, a complex mixture of hydrocarbons and other organic compounds, is seldom extracted in a pure form. It often contains significant amounts of water and other impurities, which become emulsified during extraction, transportation, and processing. These water-in-oil (W/O) emulsions are stabilized by natural surfactants such as asphaltenes, resins, waxes, and fine solid particles inherent in crude oil[1], [2], [3]. The stability of these emulsions presents substantial challenges in the petroleum industry, affecting transportation, refining processes, equipment integrity, and environmental safety.

The presence of emulsified water increases the crude oil's viscosity, hindering its flow through pipelines and requiring higher pumping pressures [4]. This increased viscosity leads to higher energy consumption and operational costs. Additionally, the risk of pipeline blockages escalates, potentially leading to shutdowns and safety hazards[5]. The higher frictional resistance due to increased viscosity necessitates more robust infrastructure and can accelerate wear and tear on equipment[6]

Water, especially when containing dissolved salts and gases like carbon dioxide (CO_2) and hydrogen sulfide (H_2S), becomes highly corrosive[7], [8]. It can cause uniform corrosion and localized attacks such as pitting and stress corrosion cracking in pipelines and storage tanks [9], [10]. Corrosion not only demands costly maintenance and replacement but also poses significant safety risks due to potential leaks and failures [11]. In offshore environments, the combination of saline water and crude oil exacerbates corrosion processes, requiring expensive corrosion inhibitors and protective coatings [12].

Water in crude oil can interfere with refining processes, such as distillation and catalytic reactions [13]. It can lead to reduced yields, increased energy consumption, and equipment fouling [14]. Water can cause emulsions in desalting units, complicate phase separation, and lead to the formation of hydrates that can block equipment[15]. Additionally, water can cause catalyst deactivation due to hydrothermal degradation and poisoning, affecting the efficiency of hydrocracking and hydrotreating processes[16].

Improper disposal of produced water, which often contains hydrocarbons, heavy metals, radioactive materials, and other contaminants, can lead to severe environmental pollution [17], [18]. Discharge of untreated produced water can harm aquatic life, contaminate soil and groundwater, and pose health risks to nearby communities [19], [20]. Regulatory agencies have stringent guidelines for produced water disposal, necessitating effective separation and treatment technologies [21].

Traditional methods for separating water from crude oil include chemical demulsifiers, thermal methods, mechanical separation techniques, and membrane separation[22], [23], [24]. However, these methods have limitations related to cost, environmental impact, and effectiveness, particularly with stable emulsions containing small droplets[25], [26].

Electro-coalescence demulsification leverages electric fields to induce droplet polarization and movement, enhancing coalescence into larger droplets that can be separated more easily [27], [28]. The technique applies direct current (DC), alternating current (AC), or pulsed electric fields to the emulsion [29], [30]. This method offers advantages such as effectiveness in handling stable emulsions with fine droplets, environmental friendliness due to reduced chemical usage, energy efficiency compared to thermal methods, and the ability to integrate with existing processing facilities.

Despite these advantages, challenges such as equipment complexity, energy demand, and electrode fouling remain. The design of the electro-coalescence system, particularly the geometry and material of the electrodes, plays a crucial role in addressing these challenges[10], [31]. By optimizing electrode geometry, it is possible to enhance the electric field distribution within the emulsion, improving droplet coalescence while minimizing energy consumption and equipment wear[32], [33].

This review aims to provide a comprehensive understanding of the role of electrode geometry in electro-coalescence systems. It synthesizes findings from a wide range of studies, analyzing electrode design, material selection, operational parameters, and the interplay between these factors. By examining these aspects, the review seeks to guide future advancements in electro-coalescence technology, contributing to more efficient and sustainable crude oil processing practices.

2. Electrode Geometry in Electro-Coalescence Systems

Electrode geometry is pivotal in determining the electric field distribution within the emulsion, which influences droplet behavior. The design affects field intensity, uniformity, and gradient, all of which are critical for efficient demulsification[34].

Various electrode configurations have been explored to optimize electric field characteristics. Parallel plate electrodes consist of two flat, conductive plates with the emulsion flowing between them[35], [36]. This configuration produces a uniform electric field, promoting consistent droplet polarization. Its simple design makes it easy to manufacture and maintain, and it is suitable for large-scale applications. However, uniform fields may be less effective for small droplets, as they may not generate sufficient dielectrophoretic forces to induce coalescence. Additionally, flat surfaces may accumulate deposits, reducing efficiency over time[37].

Needle-plate electrodes feature sharp needle electrodes facing a flat plate, creating non-uniform electric fields with high-intensity gradients near the needle tips[38], [39]. This configuration enhances field gradients, making it effective for polarizing small droplets. However, high field intensities can cause electrical discharge and electrode degradation due to erosion[40].

Wire-mesh or grid electrodes use conductive meshes or grids to create a combination of uniform and non-uniform fields. This versatility allows them to be effective for emulsions with varied droplet sizes, and the mesh structure can induce turbulence, increasing droplet collision frequency[41]. However, mesh openings may become obstructed by solids, and precision manufacturing is required[42].

Cylindrical and coaxial electrodes employ cylindrical geometries, with one electrode inside another [43]. They create radial electric fields, which can be effective for continuous flow systems and offer space efficiency due to their compact design[44]. Careful design is required to manage the non-uniform field distribution, and maintenance can be challenging due to access difficulties.

Hybrid configurations combine features from different electrode designs to optimize performance. They offer customized field profiles tailored to specific emulsion characteristics, potentially enhancing efficiency through synergistic effects[45]. However, these designs may be more complex and costly due to increased design and manufacturing challenges.

Electrode materials must balance electrical conductivity, corrosion resistance, mechanical strength, and cost. Common materials include stainless steel, which offers good corrosion resistance and is cost-effective [31], [46]; copper, which has high conductivity but is prone to corrosion [[47]; aluminum, which is lightweight with moderate conductivity but less corrosion-resistant [48]; and graphite or carbon-based materials, which offer good conductivity and chemical inertness [49].

Surface treatments and coatings can enhance electrode performance. Hydrophilic coatings increase wettability to water, promoting droplet adhesion and coalescence [50]Materials such as oxides, silanes, and polymer brushes are used for this purpose. Anti-fouling coatings prevent the deposition of asphaltenes and solids, maintaining consistent performance and reducing maintenance needs [51]. Techniques such as anodization, laser ablation, and nanomaterial deposition are employed to create these surfaces[52], [53].

The characteristics of the electric field depend on electrode geometry and configuration. Uniform fields promote consistent droplet polarization but may be less effective for small droplets due to insufficient dielectrophoretic forces[54], [55]. Non-uniform fields generate dielectrophoretic forces that attract droplets to regions of higher field intensity, enhancing coalescence of smaller droplets. Field gradients are important for inducing droplet deformation and movement, which can increase the likelihood of coalescence[56].

Optimizing the field distribution involves balancing field strength, gradient, and uniformity to maximize coalescence while minimizing energy consumption and equipment stress. Careful electrode design can enhance demulsification efficiency by creating electric fields that effectively interact with the specific properties of the emulsion being treated[57], [58], [59].

3. Mechanism of Electro-Coalescence in Crude Oil Emulsions

These emulsions can be destabilised using electro-coalescence, wherein an external electric field is applied that enhance the coalescence of the water droplets with the oil phase and separate the two easily.

3.1 Mechanism Overview

Electro-coalescence operates through several interrelated steps:

1. Droplet Polarization
2. Droplets movements and alignment.
3. Droplet Deformation and Droplet Approach
4. Film Drainage and Rupture
5. Coalescence and Separation

Droplet Polarization When an electric field is applied to the emulsion, polarisation of water droplets occurs, due to the difference of dielectric constants for water and oil. Figure 1 shows the induced dipoles build up in the droplets with positive and negative charges located at opposite ends with the droplet sending induced dipoles in the direction of the electric field.[60]

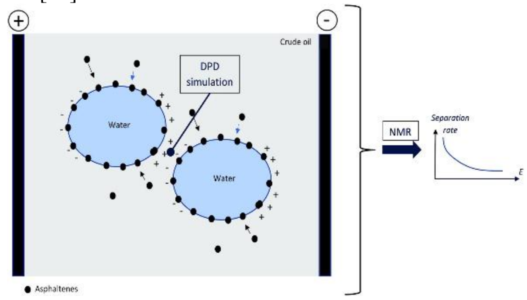

Figure (1): Schematic Diagram of Spherical water droplets inside oil where generated and had induced dipoles with charges on the poles along the electric field lines were depicted.[60]

Droplet Motion and Alignment. Electrostatic forces act on the polarized droplets that cause them to move and align on the field lines. Droplets are guided toward areas of higher field intensity as shown in Figure 2, therefore stimulating droplet collisions, using dielectrophoretic forces in non-uniform electric fields. [61]

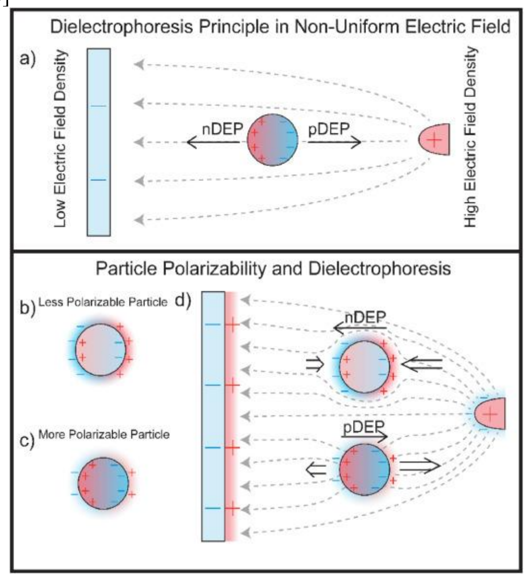

Figure (2): Schematic Diagram of dielectrophoretic forces, and that move towards each other in response to an electric field, aligning in the direction of the field.[61]

Droplet Deformation and Approach Upon coming together with droplets this electric field causes deformation, stretching droplets along the field direction. The result is an increase in the contact area between approaching droplets and a decrease in the width of the oil film that separates them [62].

4. Film Drainage and Rupture:

The pressure difference between electric field and the attractive forces between opposite charges cause the oil film between the droplets to drain. When the film becomes so thin that van der Waals forces become significant the film ruptures, see Figure 3 [63]

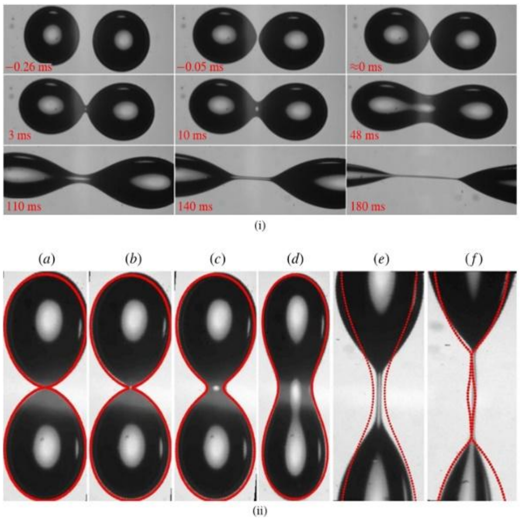

Figure (3): Schematic Diagram of Thinning oil film between two deformed droplets, represented to a point at which the film breaks. [63]

When the interfacial film breaks, droplets join to become larger droplets. The larger droplets are able to separate from the oil phase on account of their increased mass, so that they have a greater settling velocity and thus can be separated from the oil by the action of gravity[64].

While chemical reactions are minimal, the key interactions facilitated by the electric field include:[65]

1. Polarization of Water Droplets:

Water Droplet + Electric Field → Polarized Water Droplet

2. Coalescence of Polarized Droplets:

$$\text{Polarized Droplet}_1 + \text{Polarized Droplet}_2 \xrightarrow{\text{Electric Forces}} \text{Coalesced Droplet}$$

5. Main Findings from Previous Studies

Research has extensively explored factors influencing electro-coalescence efficiency, providing valuable insights into electrode design, operational parameters, and emulsion characteristics.

Electrode spacing affects the electric field strength and must be optimized to enhance demulsification without causing dielectric breakdown. The electric field strength is calculated using the equation:

$$\boldsymbol{E} = \frac{\boldsymbol{V}}{\boldsymbol{d}} \qquad \ldots\ldots(1)$$

Where $\boldsymbol{V}$ is the applied voltage and $\boldsymbol{d}$ is the electrode spacing. Reducing the electrode spacing increases the electric field strength, enhancing droplet polarization [66]. However, excessively small spacing may cause dielectric breakdown of the emulsion, leading to electrical discharge and equipment damage [67]. Spacing must also allow sufficient emulsion flow without causing excessive pressure drops, ensuring that droplets have adequate residence time in the electric field to coalesce[68], [69].

Sjöblom et al. (2021) [60] found that an optimal spacing of 5 mm at 10 kV was effective for a specific emulsion, emphasizing the importance of tailoring spacing to the properties of the emulsion. Eow Mojtaba; Sharif Adel O. (2003) [70] used computational modeling to demonstrate that smaller droplets require tighter spacing to achieve sufficient electric field strength for coalescence. Wang et al. (2024) [64] investigated the influence of electrode geometry and spacing on demulsification efficiency, concluding that optimal spacing depends on electrode shape and emulsion conductivity.

Identifying and surpassing the critical electric field strength Ecrit is essential for effective electro-coalescence. Ecrit is the threshold electric field strength required to initiate droplet coalescence[71]. Factors influencing Ecrit include droplet size, with smaller droplets having higher Ecrit due to their lower polarizability [72]; viscosity, as higher viscosity impedes droplet movement [73]; interfacial tension, which affects droplet deformation[74]; and emulsion conductivity, which determines how electric fields interact with droplets [75].

The application of alternating current (AC) fields induces droplet oscillation, enhancing collisions and coalescence [76], [77]. The optimal frequency of the applied field is related to the droplet relaxation time ($\boldsymbol{\tau}$), calculated as:

$$\boldsymbol{\tau} = \frac{\boldsymbol{\mu}_{\mathbf{d}} \boldsymbol{R}^{2}}{\boldsymbol{\gamma}} \qquad \ldots\ldots(2)$$

where $\boldsymbol{\mu}_{\mathbf{d}}$ is the viscosity of the dispersed phase, $\boldsymbol{R}$ is the droplet radius, and $\boldsymbol{\gamma}$ is the interfacial tension.[78]

The optimal frequency is then:

$$\boldsymbol{f}_{\mathbf{opt}} = \frac{\mathbf{1}}{\mathbf{2}\boldsymbol{\pi}\boldsymbol{\tau}} \qquad \ldots\ldots(3)$$

Pulsed electric fields (PEF) apply high-intensity pulses that disrupt interfacial films, enhancing coalescence while potentially reducing energy consumption [79]. Different waveform shapes, such as square, sinusoidal, and triangular, can affect droplet dynamics and influence demulsification efficiency [74].

Latham I. W. [80] determined that Ecrit of 1.5 kV/cm was necessary for heavy crude oil emulsions, highlighting the influence of viscosity and stabilizing agents. Shen et al. (2021) [81] showed that PEF reduces Ecrit compared to continuous fields, enhancing efficiency and reducing energy consumption. Niu et al. (2020) [82] reviewed the influence of electric field parameters on demulsification efficiency, finding that optimal electric field strength and frequency depend on emulsion properties.

Optimizing operational parameters enhances demulsification efficiency. The electric field strength must exceed Ecrit but remain below breakdown limits. The frequency of the applied field should match the droplet relaxation time to maximize droplet response.

Higher temperatures reduce oil viscosity and interfacial tension, enhancing droplet mobility and coalescence [83], [84]. However, energy costs and equipment limitations must be considered when increasing temperature [85].

Lu Yongguang (2014) [86]demonstrated that nanostructured electrodes improved coalescence rates by 25%.

Combining electro-coalescence with other methods can address challenges posed by different emulsion types. The use of chemical demulsifiers in conjunction with electro-coalescence can reduce chemical usage while maintaining efficiency [87]. Mechanical agitation enhances droplet collisions, complementing the effects of the electric field [88]. Preheating the emulsion reduces viscosity before electric field application, improving effectiveness [89]. Ahmed and Hassan (2016) [90] combined preheating with electric fields for optimal results, while Fallah Manouchehr et al. (2016) found synergy between mechanical and electro-coalescence methods.

Computational models aid in understanding and optimizing electro-coalescence. Computational fluid dynamics (CFD) simulations can model fluid flow and electric field interactions, providing insights into system behavior [91]. Molecular dynamics (MD) simulations study interactions at the molecular level, offering detailed understanding of emulsion stability and droplet behavior [92]. Machine learning algorithms can predict optimal parameters based on historical data and patterns, enhancing process control.

Teo Say Hwa et al. (2019) [93] developed models for electric field-induced coalescence, while Duan Xianyu et al. (2017) [94] conducted multi-scale modeling of electro-coalescence processes, integrating macroscopic and microscopic phenomena.

Ma Mengqin et al. 2022 [95] provided a comprehensive review of enhanced oil-water separation methods, emphasizing the importance of sustainability and efficiency.

4. Conclusions and Future Directions

Electro-coalescence demulsification offers a promising solution for separating water from crude oil emulsions, with the potential for significant efficiency improvements and environmental benefits. Electrode geometry plays a critical role in enhancing electric field distribution and droplet coalescence. Understanding and surpassing the critical electric field strength, optimizing operational parameters, and integrating multiple methods can address a wide range of emulsion challenges.

Future research should focus on developing advanced electrode materials and coatings, such as smart materials responsive to emulsion conditions [96], [97] and durable anti-fouling and hydrophilic coatings [97]. Innovative electrode geometries, including fractal or biomimetic designs [31], [98], and the use of 3D printing to create complex, customized shapes [99], offer opportunities for enhanced performance.

Process monitoring and control can be improved through real-time sensors that monitor emulsion properties and adjust parameters dynamically, and machine learning algorithms that optimize operations based on data patterns. Comprehensive environmental and economic assessments, including life cycle analysis and economic analysis, are essential to evaluate the sustainability and viability of electro-coalescence technology.

Regulatory compliance and safety considerations must also be addressed. Developing standards for electro-coalescence equipment and operations and establishing safety protocols to manage risks associated with high-voltage equipment are crucial for widespread adoption.

By pursuing these future directions, the petroleum industry can enhance demulsification processes, leading to increased efficiency, cost savings, and reduced environmental impact.

5. References:

[1] S. Kokal, "Crude Oil Emulsions: A State-of-The-Art Review," SPE Production & Facilities, vol. 20, no. 01, pp. 5–13, 2005, doi: 10.2118/77497-pa.

[2] N. H. R. Abdurahman Y.M.; Azhari N. H.; Hayder B.A., "Pipeline transportation of viscous crudes as concentrated oil-in-water emulsions," J Pet Sci Eng, vol. 90, no. NA, pp. 139–144, 2012, doi: 10.1016/j.petrol.2012.04.025.

[3] J. A. Sjöblom Narve; Auflem Inge Harald; Brandal Øystein; Havre Trond Erik; Sæther Ø.; Westvik Arild; Johnsen Einar Eng; Kallevik Harald, "Our current understanding of water-in-crude oil emulsions. - Recent characterization techniques and high pressure performance," Adv Colloid Interface Sci, vol. 100, no. NA, pp. 399–473, 2003, doi: 10.1016/s0001-8686(02)00066-0.

[4] Z. Liu, L. Zou, J. Qiao, C. Shi, and X. Liu, "The influence of the viscosity of crude oil on liquid-dynamic noise characteristics in the volute shell of oil transfer pump," Measurement (Lond), vol. 197, Jun. 2022, doi: 10.1016/j.measurement.2022.111285.

[5] N. E. ; T. Shlegel P.P.; Strizhak Pavel A., "Influence of viscosity, surface and interfacial tensions on the liquid droplet collisions," Chem Eng Sci, vol. 220, no. NA, pp. 115639-NA, 2020, doi: 10.1016/j.ces.2020.115639.

[6] Y. Liu et al., "Experimental Study on Water-in-Heavy-Oil Droplets Stability and Viscosity Variations in the Dilution Process of Water-in-Heavy-Oil Emulsions by Light Crude Oil," Energies (Basel), vol. 17, no. 2, Jan. 2024, doi: 10.3390/en17020332.

[7] M.-H. K. Ese Peter K., "Stabilization of water-in-oil emulsions by naphthenic acids and their salts: Model compounds, role of pH, and soap: Acid ratio," J Dispers Sci Technol, vol. 25, no. 3, pp. 253–261, 2004, doi: 10.1081/dis-120038634.

[8] C. F. Flores Eugenio A.; Hernández E.; Castro Laura V.; García A.; Álvarez Fernando Carballo; Vázquez Flavio, "Anion and cation effects of ionic liquids and ammonium salts evaluated as dehydrating agents for super-heavy crude oil: Experimental and theoretical points of view," J Mol Liq, vol. 196, no. 196, pp. 249–257, 2014, doi: 10.1016/j.molliq.2014.03.044.

[9] Z. M. Z. Wang Jian, "Corrosion of multiphase flow pipelines: the impact of crude oil," Corrosion Reviews, vol. 34, no. 1–2, pp. 17–40, 2016, doi: 10.1515/corrrev-2015-0053.

[10] Z. M. L. Wang Qing Yu; Wang Jian; Han Xia; Zhu Wei; Zhang Jian; Song Guang-Ling, "Corrosion mitigation behavior of an alternately wetted steel electrode in oil/water media," Corros Sci, vol. 152, no. NA, pp. 140–152, 2019, doi: 10.1016/j.corsci.2019.03.008.

[11] S. Hailan et al., "Purification of colloidal oil in water emulsions by cationic adsorbent prepared

from recycled polyethylene waste," Process Safety and Environmental Protection, vol. 183, pp. 771–781, Mar. 2024, doi: 10.1016/j.psep.2024.01.042.

[12] N. A. K. E. Sima Ali; Reiahisamani Narges; Rasekh Behnam, "Bio-based remediation of petroleum-contaminated saline soils: Challenges, the current state-of-the-art and future prospects.," J Environ Manage, vol. 250, no. NA, p. 109476, 2019, doi: 10.1016/j.jenvman.2019.109476.

[13] C. B. Z. ; S. de Oliveira W. J.; Santana C. F.; Santana Cesar Costapinto; Dariva Cláudio; Franceschi Elton; Guarnieri Ricardo A.; Fortuny Montserrat; Santos Alexandre F., "Rheological Properties of Water-in-Brazilian Crude Oil Emulsions: Effect of Water Content, Salinity, and pH," Energy & Fuels, vol. 32, no. 8, pp. 8880–8890, 2018, doi: 10.1021/acs.energyfuels.8b01227.

[14] A. M. Asatekin Anne M., "Oil industry wastewater treatment with fouling resistant membranes containing amphiphilic comb copolymers.," Environ Sci Technol, vol. 43, no. 12, pp. 4487–4492, 2009, doi: 10.1021/es803677k.

[15] J. W. Wu Wei; Shihong Li; Zhong Qi; Liu Fu; Zheng Jinhuan; Wang Jiping, "The effect of membrane surface charges on demulsification and fouling resistance during emulsion separation," J Memb Sci, vol. 563, no. NA, pp. 126–133, 2018, doi: 10.1016/j.memsci.2018.05.065.

[16] W. Faisal and F. Almomani, "A critical review of the development and demulsification processes applied for oil recovery from oil in water emulsions," Chemosphere, vol. 291, Mar. 2022, doi: 10.1016/j.chemosphere.2021.133099.

[17] M. I. Zoubeik Mohamed; Salama Amgad; Henni Amr, "New Developments in Membrane Technologies Used in the Treatment of Produced Water: A Review," Arab J Sci Eng, vol. 43, no. 5, pp. 2093–2118, 2017, doi: 10.1007/s13369-017-2690-0.

[18] R. J. ; dos R. Cassella Luis Gustavo T.; Santelli Ricardo Erthal; Oliveira Eliane Padua, "Direct determination of manganese in produced waters from petroleum exploration by Electrothermal Atomic Absorption Spectrometry using Ir-W as permanent modifier.," Talanta, vol. 85, no. 1, pp. 415–419, 2011, doi: 10.1016/j.talanta.2011.03.084.

[19] A. P. Fakhru'l-Razi Alireza; Abdullah Luqman Chuah; Biak Dayang Radiah Awang; Madaeni Sayed Siavash; Abidin Zurina Zainal, "Review of technologies for oil and gas produced water treatment," J Hazard Mater, vol. 170, no. 2, pp. 530–551, 2009, doi: 10.1016/j.jhazmat.2009.05.044.

[20] Z. V. Khatib Paul, "Water to Value - Produced Water Management for Sustainable Field Development of Mature and Green Fields," Journal of Petroleum Technology, vol. 55, no. 01, pp. 26–28, 2003, doi: 10.2118/0103-0026-jpt.

[21] M. J. Nasiri Iman; Parniankhoy Behdad, "Oil and Gas Produced Water Management: A Review of Treatment Technologies, Challenges, and Opportunities," Chem Eng Commun, vol. 204, no. 8, pp. 990–1005, 2017, doi: 10.1080/00986445.2017.1330747.

[22] D. L. F. Daniel-David A.; Pezron Isabelle; Dalmazzone Christine; Noik Christine; Barré Loïc; Komunjer L., "Destabilisation of Water-in-Crude Oil Emulsions by Silicone Copolymer Demulsifiers," Oil & Gas Science and Technology - Revue de l'IFP, vol. 63, no. 1, pp. 165–173, 2008, doi: 10.2516/ogst:2008002.

[23] B. W. Huang Jie; Zhang Wei; Fu Cheng; Wang Ying; Liu Xiangbin, "Screening and Optimization of Demulsifiers and Flocculants Based on ASP Flooding-Produced Water," Processes, vol. 7, no. 4, pp. 239-NA, 2019, doi: 10.3390/pr7040239.

[24] W. Y. Kang Xia; Yang Hongbin; Zhao Yilu; Huang Zitong; Hou Xiaoyu; Sarsenbekuly Bauyrzhan; Zhu Zhou; Wang Pengxiang; Zhang Xiangfeng; Geng Jie; Aidarova Saule, "Demulsification performance, behavior and mechanism of different demulsifiers on the light crude oil emulsions," Colloids Surf A Physicochem Eng Asp, vol. 545, no. NA, pp. 197–204, 2018, doi: 10.1016/j.colsurfa.2018.02.055.

[25] F. Fallah, M. Khorasani, and M. Ebrahimi, "Comparative study of gel emulsification and direct mechanical emulsification methods," Colloids Surf A Physicochem Eng Asp, vol. 492, pp. 207–212, Mar. 2016, doi: 10.1016/j.colsurfa.2015.12.018.

[26] H. S. Z. Lee Chaolun; Yang Bao, "Separations of Water-In-Oil Emulsions by Electrostatic Field at the Elevated Temperature," J Appl Mech Eng, vol. 07, no. 04, p. NA-NA, 2018, doi: 10.4172/2168-9873.1000312.

[27] M. ; G. Mousavichoubeh Mojtaba; Shariaty-Niassar Mojtaba, "Electro-coalescence of an aqueous droplet at an oil–water interface," Chemical Engineering and Processing: Process Intensification, vol. 50, no. 3, pp. 338–344, 2011, doi: 10.1016/j.cep.2010.09.017.

[28] S. H. G. Mousavi Mojtaba; Buckley M., "Electro-coalescence of water drops in oils under pulsatile electric fields," Chem Eng Sci, vol. 120, no. NA, pp. 130–142, 2014, doi: 10.1016/j.ces.2014.08.055.

[29] M. ; G. Mousavichoubeh Mojtaba; Shariaty-Niassar Mojtaba, "Electro-coalescence of an aqueous droplet at an oil–water interface," Chemical Engineering and Processing: Process Intensification, vol. 50, no. 3, pp. 338–344, 2011, doi: 10.1016/j.cep.2010.09.017.

[30] S. H. G. Mousavi Mojtaba; Buckley M., "Electro-coalescence of water drops in oils under pulsatile electric fields," Chem Eng Sci, vol. 120, no. NA, pp. 130–142, 2014, doi: 10.1016/j.ces.2014.08.055.

[31] Y. C. Shi Jiaqing; Pan Zehao, "Experimental Study on the Performance of a Novel Compact Electrostatic Coalescer with Helical Electrodes," Energies (Basel), vol. 14, no. 6, pp. 1733-NA, 2021, doi: 10.3390/en14061733.

[32] J. S. ; G. Eow Mojtaba, "Electrocoalesce-separators for the separation of aqueous drops from a flowing dielectric viscous liquid," Sep Purif Technol, vol. 29, no. 1, pp. 63–77, 2002, doi: 10.1016/s1383-5866(02)00093-x.

[33] J. S. ; G. Eow Mojtaba, "Electrostatic enhancement of coalescence of water droplets in oil: a review of the technology," Chemical Engineering Journal, vol. 85, no. 2, pp. 357–368, 2002, doi: 10.1016/s1385-8947(01)00250-9.

[34] J. S. ; G. Eow Mojtaba, "Drop–drop coalescence in an electric field: the effects of applied electric field and electrode geometry," Colloids Surf A Physicochem Eng Asp, vol. 219, no. 1, pp. 253–279, 2003, doi: 10.1016/s0927-7757(03)00051-7.

[35] J. S. ; G. Eow Mojtaba, "Electrostatic enhancement of coalescence of water droplets in oil: a review of the technology," Chemical Engineering Journal, vol. 85, no. 2, pp. 357–368, 2002, doi: 10.1016/s1385-8947(01)00250-9.

[36] S. H. G. Mousavi Mojtaba; Buckley M., "Electro-coalescence of water drops in oils under pulsatile electric fields," Chem Eng Sci, vol. 120, no. NA, pp. 130–142, 2014, doi: 10.1016/j.ces.2014.08.055.

[37] S. T. Mhatre Rochish, "Electrocoalescence in non-uniform electric fields: An experimental study," Chemical Engineering and Processing: Process Intensification, vol. 96, no. NA, pp. 28–38, 2015, doi: 10.1016/j.cep.2015.07.025.

[38] S. S. Luo Jarrod; Luo Tengfei, "Effect of electric field non-uniformity on droplets coalescence," Phys Chem Chem Phys, vol. 18, no. 43, pp. 29786–29796, 2016, doi: 10.1039/c6cp06085d.

[39] S. T. Mhatre Rochish, "Electrocoalescence in non-uniform electric fields: An experimental study," Chemical Engineering and Processing: Process Intensification, vol. 96, no. NA, pp. 28–38, 2015, doi: 10.1016/j.cep.2015.07.025.

[40] H. K. Hadidi Reza; Manshadi Mohammad K.D., "Numerical simulation of a novel non-uniform electric field design to enhance the electrocoalescence of droplets," European Journal of Mechanics - B/Fluids, vol. 80, no. NA, pp. 206–215, 2020, doi: 10.1016/j.euromechflu.2019.10.010.

[41] N. A. F. Kakhki Mohammad; Rahimpour Mohammad Reza, "Effect of current frequency on crude oil dehydration in an industrial electrostatic coalescer," J Taiwan Inst Chem Eng, vol. 67, no. NA, pp. 1–10, 2016, doi: 10.1016/j.jtice.2016.06.021.

[42] J. S. ; G. Eow Mojtaba, "Electrostatic enhancement of coalescence of water droplets in oil: a review of the technology," Chemical Engineering Journal, vol. 85, no. 2, pp. 357–368, 2002, doi: 10.1016/s1385-8947(01)00250-9.

[43] J. S. ; G. Eow Mojtaba; Sharif Adel O., "Experimental studies of deformation and break-up of aqueous drops in high electric fields," Colloids Surf A Physicochem Eng Asp, vol. 225, no. 1, pp. 193–210, 2003, doi: 10.1016/s0927-7757(03)00330-3.

[44] M. M. Ghadiri C.M.; Arteaga P.A.; Tüzün Ugur; Formisani Brunello, "Evaluation of the single contact electrical clamping force," Chem Eng Sci, vol. 61, no. 7, pp. 2290–2300, 2006, doi: 10.1016/j.ces.2005.05.009.

[45] S. Mhatre et al., "Electrostatic phase separation: A review," Apr. 01, 2015, Institution of Chemical Engineers. doi: 10.1016/j.cherd.2015.02.012.

[46] K. M. ; A. AlAqad Abdalla M.; Al Hamouz Othman Charles S.; Saleh Tawfik A., "Silver nanoparticles decorated graphene modified Carbon paste electrode for molecular methimazole determination," Chemical Data Collections, vol. 11–12, no. NA, pp. 168–182, 2017, doi: 10.1016/j.cdc.2017.09.003.

[47] Z.-Y. L. Luo Shu-Shen; Mo Dong-Chuan, "Cauliflower-like Nickel with Polar $Ni(OH)_2$/NiO x F y Shell to Decorate Copper Meshes for Efficient Oil/Water Separation.," ACS Omega, vol. 4, no. 24, pp. 20486–20492, 2019, doi: 10.1021/acsomega.9b02152.

[48] H. F. A. Makki Imama Raed, "Aluminum Rubbish as a Coagulant for Oily Wastewater Treatment," Journal of Engineering, vol. 22, no. 7, pp. 55–71, 2016, doi: 10.31026/j.eng.2016.07.04.

[49] H. H. Yuan Zhiming; Shen Liwei; Xu Junbo; Feng Xuening; Yang Ying; Zhang Zejun; Luo Yue; Yan Xuemin; Mi Yuanzhu, "Demulsification of crude oil emulsion using carbonized cotton/silica composites," Colloids Surf A Physicochem Eng Asp, vol. 617, no. NA, pp. 126421-NA, 2021, doi: 10.1016/j.colsurfa.2021.126421.

[50] A. Y. L. ; L. Tang Cheng Hao; Wang Yuxiang; Kan CW, "Effect of Hydrophilic-lipophilic Balance (HLB) Values of PEG-based Non-ionic Surfactant on Reverse Micellar Dyeing of Cotton Fibre with Reactive Dyes in Non-aqueous Medium," Fibers and Polymers, vol. 19, no. 4, pp. 894–904, 2018, doi: 10.1007/s12221-018-8061-y.

[51] L. Z. Kang Liang; Yao Shuang; Duan Chongxiong, "A new architecture of super-hydrophilic β-SiAlON/graphene oxide ceramic membrane for enhanced anti-fouling and separation of water/oil emulsion," Ceram Int, vol. 45, no. 13, pp. 16717–16721, 2019, doi: 10.1016/j.ceramint.2019.05.195.

[52] T. Liang, J. R. Hou, M. Qu, J. X. Xi, and I. Raj, "Application of nanomaterial for enhanced oil recovery," Apr. 01, 2022, China University of Petroleum Beijing. doi: 10.1016/j.petsci.2021.11.011.

[53] R. V. Mateos S.; Valiente Mercedes; Díez-Pascual Ana M.; San Andrés María Paz, "Comparison of Anionic, Cationic and Nonionic Surfactants as Dispersing Agents for Graphene Based on the Fluorescence of Riboflavin," Nanomaterials (Basel), vol. 7, no. 11, pp. 403-NA, 2017, doi: 10.3390/nano7110403.

[54] M. Mousavichoubeh, M. Shariaty-Niassar, and M. Ghadiri, "The effect of interfacial tension on secondary drop formation in electro-coalescence of water droplets in oil," Chem Eng Sci, vol. 66, no. 21, pp. 5330–5337, Nov. 2011, doi: 10.1016/j.ces.2011.07.019.

[55] J. S. ; G. Eow Mojtaba; Sharif Adel O., "Electrostatic and hydrodynamic separation of

aqueous drops in a flowing viscous oil," Chemical Engineering and Processing: Process Intensification, vol. 41, no. 8, pp. 649–657, 2002, doi: 10.1016/s0255-2701(01)00183-0.

[56] J. S. ; G. Eow Mojtaba; Sharif Adel O.; Williams T.J., "Electrostatic enhancement of coalescence of water droplets in oil: a review of the current understanding," Chemical Engineering Journal, vol. 84, no. 3, pp. 173–192, 2001, doi: 10.1016/s1385-8947(00)00386-7.

[57] J. S. ; G. Eow Mojtaba, "Drop–drop coalescence in an electric field: the effects of applied electric field and electrode geometry," Colloids Surf A Physicochem Eng Asp, vol. 219, no. 1, pp. 253–279, 2003, doi: 10.1016/s0927-7757(03)00051-7.

[58] J. S. ; G. Eow Mojtaba, "Electrocoalesce-separators for the separation of aqueous drops from a flowing dielectric viscous liquid," Sep Purif Technol, vol. 29, no. 1, pp. 63–77, 2002, doi: 10.1016/s1383-5866(02)00093-x.

[59] M. S.-N. Mousavichoubeh Mojtaba; Ghadiri Mojtaba, "The effect of interfacial tension on secondary drop formation in electro-coalescence of water droplets in oil," Chem Eng Sci, vol. 66, no. 21, pp. 5330–5337, 2011, doi: 10.1016/j.ces.2011.07.019.

[60] J. Sjöblom, S. Mhatre, S. Simon, R. Skartlien, and G. Sørland, "Emulsions in external electric fields," Aug. 01, 2021, Elsevier B.V. doi: 10.1016/j.cis.2021.102455.

[61] D. E. Hagness, Y. Yang, R. D. Tilley, and J. J. Gooding, "The application of an applied electrical potential to generate electrical fields and forces to enhance affinity biosensors," Biosens Bioelectron, vol. 238, p. 115577, Oct. 2023, doi: 10.1016/j.bios.2023.115577.

[62] Y. Zhou, B. Li, M. Zhang, Z. Sun, Z. Wang, and J. Wang, "Effect of dielectrophoresis on the coalescence of binary droplets under a non-uniform electric field," Chem Eng Sci, vol. 224, p. 115739, Oct. 2020, doi: 10.1016/j.ces.2020.115739.

[63] S. Roy, V. Anand, and R. M. Thaokar, "Breakup and non-coalescence mechanism of aqueous droplets suspended in castor oil under electric field," J Fluid Mech, vol. 878, pp. 820–833, Nov. 2019, doi: 10.1017/jfm.2019.665.

[64] K. Wang et al., "Efficient electro-demulsification of O/W emulsions and simultaneous oil removal enabled by a multiscale porous biocarbon electrode," Chemical Engineering Journal, vol. 481, Feb. 2024, doi: 10.1016/j.cej.2024.148655.

[65] S. V. Less Regis, "The electrocoalescers' technology: Advances, strengths and limitations for crude oil separation," J Pet Sci Eng, vol. 81, no. NA, pp. 57–63, 2012, doi: 10.1016/j.petrol.2011.12.003.

[66] T. K. Szymborski Piotr M.; Hołyst Robert; Garstecki Piotr, "Ionic polarization of liquid-liquid interfaces; dynamic control of the rate of electro-coalescence," Appl Phys Lett, vol. 99, no. 9, pp. 094101-NA, 2011, doi: 10.1063/1.3629783.

[67] C. S. Lesaint Øyvind; Glomm Wilhelm R.; Simon Sébastien; Sjöblom Johan, "Dielectric response as a function of viscosity for two crude oils with different conductivities," Colloids Surf A Physicochem Eng Asp, vol. 369, no. 1, pp. 20–26, 2010, doi: 10.1016/j.colsurfa.2010.07.011.

[68] H. W. ; U. Yarranton P.; Sztukowski Danuta M., "Effect of interfacial rheology on model emulsion coalescence II. Emulsion coalescence.," J Colloid Interface Sci, vol. 310, no. 1, pp. 253–259, 2007, doi: 10.1016/j.jcis.2007.01.098.

[69] O. W. Urdahl N.J.; Førdedal H.; Williams T.J.; Bailey A.G., Compact Electrostatic Coalescer Technology, vol. NA, no. NA. 2001. doi: NA.

[70] J. S. ; G. Eow Mojtaba; Sharif Adel O., "Experimental studies of deformation and break-up of aqueous drops in high electric fields," Colloids Surf A Physicochem Eng Asp, vol. 225, no. 1, pp. 193–210, 2003, doi: 10.1016/s0927-7757(03)00330-3.

[71] A. M. B. Imano Abderrahmane, "Deformation of water droplets on solid surface in electric field.," J Colloid Interface Sci, vol. 298, no. 2, pp. 869–879, 2006, doi: 10.1016/j.jcis.2005.12.041.

[72] B. U. ; P. Felderhof D., "Longitudinal and transverse polarizability of the conducting double sphere," J Appl Phys, vol. 88, no. 9, pp. 4947–4952, 2000, doi: 10.1063/1.1315325.

[73] J. de A. Dong Valmor F.; Tsouris Costas, "Effects of Applied Electric Fields on Drop—Interface and Drop—Drop Coalescence*," J Dispers Sci Technol, vol. 23, no. 1–3, pp. 155–166, 2002, doi: 10.1080/01932690208984196.

[74] Y. K. Han Joel; Maldarelli Charles, "Surfactant and dilatational viscosity effects on the deformation of liquid droplets in an electric field.," J Colloid Interface Sci, vol. 607, no. Pt 1, pp. 900–911, 2021, doi: 10.1016/j.jcis.2021.07.105.

[75] X. G. Niu Fabrice; deMello Andrew J.; Edel Joshua B., "Electro-coalescence of digitally controlled droplets.," Anal Chem, vol. 81, no. 17, pp. 7321–7325, 2009, doi: 10.1021/ac901188n.

[76] C. Lesaint, W. R. Glomm, L. E. Lundgaard, and J. Sjöblom, "Dehydration efficiency of AC electrical fields on water-in-model-oil emulsions," Colloids Surf A Physicochem Eng Asp, vol. 352, no. 1–3, pp. 63–69, Dec. 2009, doi: 10.1016/j.colsurfa.2009.09.051.

[77] C. B. Lesaint Gunnar; Lundgaard Lars E.; Ese Marit-Helen Glomm, "A novel bench size model coalescer: dehydration efficiency of AC fields on water-in-crude-oil emulsions," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 23, no. 4, pp. 1–6, 2016, doi: 10.1109/tdei.2016.7556473.

[78] A. K. A. Chesters, "The modelling of coalescence processes in fluid-liquid dispersions : a review of current understanding," Chemical Engineering Research & Design, vol. 69, no. 4, pp. 259–270, 1991, doi: NA.

[79] P. J. Bailes, "An electrical model for coalescers that employ pulsed DC fields," Chemical Engineering Research & Design, vol. 73, no. 5, pp. 559–566, 1995, doi: NA.

[80] J. ; R. Latham I. W., "Disintegration of Pairs of Water Drops in an Electric Field," Proc R Soc Lond A Math Phys Sci, vol. 295, no. 1440, pp. 84–97, 1966, doi: 10.1098/rspa.1966.0227.

[81] Y. Shen and A. R. Badireddy, "A Critical Review on Electric Field-Assisted Membrane Processes: Implications for Fouling Control, Water Recovery, and Future Prospects," Membranes (Basel), vol. 11, no. 11, p. 820, Oct. 2021, doi: 10.3390/membranes11110820.

[82] D. Niu et al., "Review of the application of pulsed electric fields (PEF) technology for food processing in China," Food Research International, vol. 137, p. 109715, Nov. 2020, doi: 10.1016/j.foodres.2020.109715.

[83] B. Bera, R. Khazal, and K. Schroën, "Coalescence dynamics in oil-in-water emulsions at elevated temperatures," Sci Rep, vol. 11, no. 1, p. 10990, May 2021, doi: 10.1038/s41598-021-89919-5.

[84] Z. Wang, S. Gu, and L. Zhou, "Research on the static experiment of super heavy crude oil demulsification and dehydration using ultrasonic wave and audible sound wave at high temperatures," Ultrason Sonochem, vol. 40, pp. 1014–1020, Jan. 2018, doi: 10.1016/j.ultsonch.2017.08.037.

[85] M. de O. Fortuny Cesar B. Z.; Melo Rosana L. F. V.; Nele Márcio; Coutinho Raquel C. C.; Santos Alexandre F., "Effect of Salinity, Temperature, Water Content, and pH on the Microwave Demulsification of Crude Oil Emulsions†," Energy & Fuels, vol. 21, no. 3, pp. 1358–1364, 2007, doi: 10.1021/ef0603885.

[86] C. Y. Lu Yongguang, "Pulsed electric field treatment combined with commercial enzymes converts major ginsenoside Rb1 to minor ginsenoside Rd," Innovative Food Science & Emerging Technologies, vol. 22, no. NA, pp. 95–101, 2014, doi: 10.1016/j.ifset.2013.12.010.

[87] C. H. Lyu Kang; Yang Nannan; Haijun Wang; Wang Jianping, "Combination of Thermosonication and Pulsed Electric Fields Treatments for Controlling Saccharomyces cerevisiae in Chinese Rice Wine," Food Bioproc Tech, vol. 9, no. 11, pp. 1854–1864, 2016, doi: 10.1007/s11947-016-1769-z.

[88] H. Lu et al., "Combination of electric field and medium coalescence for enhanced demulsification of water-in-oil emulsion," Chem Eng Sci, vol. 241, Sep. 2021, doi: 10.1016/j.ces.2021.116680.

[89] P. G. Luo Yongan, "Characterization of a heavy oil–propane system in the presence or absence of asphaltene precipitation," Fluid Phase Equilib, vol. 277, no. 1, pp. 1–8, 2009, doi: 10.1016/j.fluid.2008.10.019.

[90] A. M. ; H. Al-Sabagh M.E.; Desouky S.E.M.; Nasser N. M.; Elsharaky E.A.; Abdelhamid M.M., "Demulsification of W/O emulsion at petroleum field and reservoir conditions using some demulsifiers based on polyethylene and propylene oxides," Egyptian Journal of Petroleum, vol. 25, no. 4, pp. 585–595, 2016, doi: 10.1016/j.ejpe.2016.05.008.

[91] X. Yang, T. Xi, Y. Qin, H. Zhang, and Y. Wang, "Computational Fluid Dynamics–Discrete Phase Method Simulations in Process Engineering: A Review of Recent Progress," Applied Sciences, vol. 14, no. 9, p. 3856, Apr. 2024, doi: 10.3390/app14093856.

[92] S. P. K. M. Pathirannahalage Nastaran; Elbourne Aaron; Weiss Alessia C G; McConville Christopher F; Padua Agilio A. H.; Winkler David A.; Gomes Margarida F. Costa; Greaves Tamar L.; Le Tu C.; Besford Quinn A.; Christofferson Andrew J., "Systematic Comparison of the Structural and Dynamic Properties of Commonly Used Water Models for Molecular Dynamics Simulations.," J Chem Inf Model, vol. 61, no. 9, pp. 4521–4536, 2021, doi: 10.1021/acs.jcim.1c00794.

[93] A. J. T. ; T. Teo Say Hwa; Nguyen Nam-Trung, "On-Demand Droplet Merging with an AC Electric Field for Multiple-Volume Droplet Generation," Anal Chem, vol. 92, no. 1, pp. 1147–1153, 2019, doi: 10.1021/acs.analchem.9b04219.

[94] M. S. Duan Xianyu; Zhao Shuangliang; Fang Shenwen; Wang Fen; Zhong Cheng; Luo Zhaoyang, "Layer-by-Layer Assembled Film of Asphaltenes/Polyacrylamide and Its Stability of Water-in-Oil Emulsions: A Combined Experimental and Simulation Study," The Journal of Physical Chemistry C, vol. 121, no. 8, pp. 4332–4342, 2017, doi: 10.1021/acs.jpcc.6b12168.

[95] J. Y. Ma Mengqin; Yang Yongli; Zhang Xueying, "Comprehensive review on stability and demulsification of unconventional heavy oil-water emulsions," J Mol Liq, vol. 350, no. NA, p. 118510, 2022, doi: 10.1016/j.molliq.2022.118510.

[96] N. Ali et al., "Engineered Hybrid Materials with Smart Surfaces for Effective Mitigation of Petroleum-Originated Pollutants," Oct. 01, 2021, Elsevier Ltd. doi: 10.1016/j.eng.2020.07.024.

[97] N. B. Ali Muhammad; Khan Adnan; Ali Farman; Iqbal Hafiz M.N., "Design, engineering and analytical perspectives of membrane materials with smart surfaces for efficient oil/water separation," TrAC Trends in Analytical Chemistry, vol. 127, no. NA, pp. 115902-NA, 2020, doi: 10.1016/j.trac.2020.115902.

[98] S. T. Mhatre Rochish, "Pin–Plate Electrode System for Emulsification of a Higher Conductivity Leaky Dielectric Liquid into a Low Conductivity Medium," Ind Eng Chem Res, vol. 53, no. 34, pp. 13488–13496, 2014, doi: 10.1021/ie5017893.

[99] Q. W. Sun Dehui; Li Yanan; Zhang Jiahui; Ye Shuji; Cui Jiaxi; Chen Longquan; Wang Zuankai; Butt Hans-Jürgen; Vollmer Doris; Deng Xu, "Surface charge printing for programmed droplet transport," Nat Mater, vol. 18, no. 9, pp. 936–941, 2019, doi: 10.1038/s41563-019-0440-2.

6. Appendix

A. Calculation of Electric Field Strength

To calculate the electric field strength (E) between two electrodes:

$$E = \frac{V}{d}$$

where:
E = Electric field strength $(\mathrm{V/m})$
V = Applied voltage (V)
d = Distance between electrodes (m)
Example:
If the applied voltage is $15{,}000\ \mathrm{V}$ and the electrode spacing is $7.5\ \mathrm{mm}(0.0075\ \mathrm{m})$:

$$E=\frac{15{,}000}{0.0075}=2{,}000{,}000\ \mathrm{V/m}=2\mathrm{MV/m}$$

B. Droplet Relaxation Time and Optimal Frequency

Droplet Relaxation Time (τ) :

$$\tau=\frac{\mu_{\mathrm{d}}R^{2}}{\gamma}$$

where:
μ_{d} = Viscosity of the dispersed phase (Pa.s)
R = Droplet radius (m)
γ = Interfacial tension ($\mathrm{N/m}$)
Optimal Frequency $\left(f_{\mathrm{opt}}\right)$ for AC fields:

$$f_{\mathrm{opt}}=\frac{1}{2\pi\tau}$$

Example Calculation:
Given:
$\mu_{\mathrm{d}}=0.1$ Pa.s
$R=5\times10^{-6}\ \mathrm{m}$
$\gamma=0.025\ \mathrm{N/m}$
Calculate τ :

$$\tau=\frac{0.1\times(5\times10^{-6})^{2}}{0.025}=1\times10^{-10}\ \mathrm{s}$$

Calculate $f_{\mathrm{opt:}}$

$$f_{\mathrm{opt}}=\frac{1}{2\pi\times1\times10^{-10}}\approx1.59\times10^{8}\ \mathrm{Hz}$$

Note: In practice, lower frequencies are used due to equipment limitations and energy considerations.