Experimental studies on the effect of electrostatic boundary conditions and frequency on the performance of a tri grid electrostatic coalescer

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Abstract

In this work, we explore the effect of electric field distribution and two different frequencies in a trigrid coalescer and its effect on electrocoalescer efficiency. Specifically grounding water at the bottom of the coalescer is found to be effective. The effect of frequency on emulsion breakup is essentially due to chaining tendency of water droplets at high frequencies. The reason for this could be reduced electrostatic force between drops at higher frequencies due to higher capacitance of interstitial oil film between two droplets. Moreover, at low frequencies significant bouncing of drops from interface is observed, leading to lower separation rates.

Keywords: Frequency, Electrocoalescence, Chaining, Electric field, Separation

1. Introduction

The coalescence of droplets in a water-in-oil emulsion involves merging of water droplets, resulting in an increase in the droplet size, that enhances the settling velocity of the droplets and thereby separation of water from a water-in- oil emulsion. The process of droplet coalescence is thus fundamental to breaking

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of emulsions. There are various techniques used for emulsion breaking such as centrifugation, chemical demulsification, gravity sedimentation etc [1, 2]. The most popular method used in oil refineries is to coalesce droplets using electrostatic fields [3, 4]. Amongst commercial electrocoalescers [5, 6] the tri grid electrode configuration is most commonly used. In a trigrid electrocoalescer, droplets in the bulk oil coalesce and grow bigger due to electrocoalescence un- der the electric field generated by the three grids in the coalescer. These bigger droplets settle down and ultimately coalesce with the oil-water interface at the bottom of the coalescer. The separated water form a water pool at the bottom of the coalescer.

Most commercial desalters use AC electric fields. The frequency typically used is the same as the frequency of the electrical power commercially available (for example 50 Hz in India). The change in frequency above or below this typical value can significantly affect droplet coalescence. Brown and Hanson[7] investigated the effect of frequency on coalescence of aqueous drops at the water/oil interface and found a very weak effect on coalescence, which they attributed to "mechanical effects" rather than "electrical effects" and argued that the external frequency of the order of the natural frequency could be the optimal frequency. Bailes and Larkai[8, 9] conducted experiments, but importantly using insulated electrodes, on the effect of pulsed DC electric field with a frequency in the range of 0.5 and 60 Hz and proposed a dielectric relaxation theory. In this theory, they argued that the charging and discharging of the emulsion due to the absence of ohmic current in their setup which had insulated electrodes, led to an optimal frequency which was determined by the relative loss and storage electric moduli of the emulsion and the insulation capacitance. Based on the experimental setup of Bailes and Larkai[8, 9], Midtgard[10] proposed the elec trostatic field theory as well as the circuit analysis theory and recommended the

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optimum pulsed field parameters which did not result in the chain formation. A similar analysis was done in the cylindrical geometry, with insulated electrodes, by Yang[11] who found that there could be more than one optimal pulsed electric field frequency depending upon the volume fraction of the emulsion.

An important aspect which is non-trivially affected by the frequency of applied field is the chaining of droplets. It was found that the droplets not only chain in an electrode-to-electrode manner, but are also found in the bulk, typically orienting along the field direction [1, 12, 13]. It is known that high frequencies promote chain formation although the reason thereof is still unexplained [11, 14–16]. Chen et al.[17] conducted experiments and particle dynamics simulations on emulsions under AC fields. Their experimental study suggested tendency to form chains at frequencies of the order of around $2 - 10$ Hz. Shorter chains were formed between $6-10$ Hz, and upto 1 KHz, short chains were formed. They did not attempt to explain this aspect in their simulations though. Ingebrigtsen et al.[18] observed increased chaining as the frequency was increased from 1 Hz to 1 KHz, although the mechanism involved was not explained. A similar observation was made by [19] who found reduced oscillations of droplets at higher frequencies, and higher chain formation.

Several studies were conducted in different configurations to understand the effect of frequency on electrocoalescence. Lesaint et.al.[20] conducted electro- rheological experiments and found a decrease in viscosity which suggested in- crease in dehydration as frequency is increased from 50 Hz to 5 KHz. Similarly Zhang et.al.[21] observed that 2 kHz was the optimum frequency of an electrocoalescence process in their setup. The optimal frequency was argued to correspond to the reciprocal of the natural frequency where the droplet deformation is the maximum. Since the natural frequency of oscillation scales as $\gamma/\rho a^3$, where γ, ρ and a are interfacial tension, density and size of the droplet, the relevant natural frequency can change as the droplet size in an emulsion in- creases with time during electrocoalescence. Experimental results of [22] showed that when pulsed DC electric field is used, the separation is best achieved when the frequency is changed during the course of dehydration of the emulsion. They argued that the size of the droplet corresponds to an optimal frequency, and since the droplet size itself changes during the course of dehydration, the most effective frequency also changes. Other studies such as those by Li et al, found an optimal pulsed electric field frequency of 4 kHz (Li et al.[23]) in a limited range of frequencies that they investigated (1-6 kHz). The optimality in frequency was attributed to natural frequency of oscillation of the

droplets as well as to the charge relaxation time. The concept of enhanced coalescence of droplets at frequencies of the order of natural frequencies due to enhanced deformation of the droplets was further systematically established in a series of works [24–27]. The relation to the charge relaxation time to the optimum frequency though can be contested since the reciprocal of charge relaxation time even for deionized water corresponds to a frequency of around 282 kHz. The optimal frequency seems to be specific to electrode design as well for reasons not very well understood, for example Li et.al.[28] found 100 Hz to be an optimal frequency for different wave forms used in a V shaped geometry.

A counter argument to explain high dehydration efficiencies at low frequencies [22, 25], was attributed to the lower droplet deformation [22] at non-resonant frequencies.

Another important configuration, apart from two droplet coalescence and emulsion coalescence is the drop-interface interaction, wherein a droplet of the aqueous phase is released into an oil phase, and the droplet settles and en- counters the oil-aqueous phase interface where it eventually coalesces with the aqueous phase. The interaction can show phenomenon of coalescence, partial coalescence leading to formation of secondary droplets and non-coalescence of the aqueous droplet with the oil-aqueous phase interface. Mousavi et al.[29] found that using Pulsed Electric Fields (PEF) in such systems, use of low frequency, up to 40 Hz, promoted secondary droplets, thereby reducing the dehydration of the emulsion. At high frequencies from 50 Hz to 1 kHz, the formation of secondary droplets was suppressed, Mousavichoubeh et al. [30] leading to better dehydration.

To summarize, there appear to be two physical principles for selection of optimal frequencies in an electrocoalescer. Firstly if the frequency corresponds to the natural frequency of the droplets, the resulting resonance can destabilize the interface and aid coalescence. The second hypothesis says that the effective conductivity of the emulsion could lead to reduction of the electric field in the bulk over emulsion charging time that depends upon the volume fraction of the aqueous phase. This is especially true in systems involving insulated electrodes. Below this time scale, a greatly reduced field in the bulk can lead to poor performance. At higher frequencies though, the field can penetrate the bulk aiding coalescence.

In this work we explore the appropriate frequency range for an efficient operation of a tri grid electrocoalescer; which is one of the most popular commercial configuration of an electrocoalescer. We have carried out experiments on a batch scale Tri grid electrocoalescer and the droplets interactions microscopic under- standing of the

phenomenon was aided to conduct experiments using a cuvette. In this context we set the scope of the present work on following: 1. Several laboratory experiments on electrocoalescers are conducted in insulated vessels such as Perspex (polycarbonate) or acrylic vessels [1, 8, 23]. It is therefore important to know what is the effect of grounding of the bottom water pool on the efficiency of electrocoalescence. 2. What is the effect of frequency on electrocoalescence at different water cuts in a water-in-oil emulsion. 3. The bottom and top regions of an electrocoalescer see different water percentage as well as size of the droplets as electrocoalescence proceeds. Towards this we try to explore the sensitivity and effectiveness of frequency in the bottom and top regions of an electrocoalescer. 4. Specific experiments are then designed to understand the mechanism for the observed variation of electrocoalescence efficiency with the applied frequency of AC fields.

2. Experimental

2.1. Preparation of emulsion

Around 5L of a water-in-sunflower oil emulsion was prepared by mixing sunflower oil and de-ionized water, without adding any surfactant, to get 5,10,20 and 30% volume by volume water in oil emulsions. The physical properties of the fluids used in the experiments are summarized in the Table 1 . Density was measured using a DDM 2909 densitometer, while the liquid viscosity was measured using the Physica MCR 301, Anton Paar Rheometer. A 5L emulsion was made by preparing 1L of the emulsion at a time, using a commercial kitchen blender for 3 minutes and transferred to a tank where it was stirred continuously using a homogenizer Ultra-turrax at 18000 rpm. The tank was subsequently filled with 5L of emulsion and it was ascertained that the initial drop size distribution for all the trials remained nearly the same. The emulsions were judged to be stable when no visible change in droplet size, coalescence events or water separation was observed for 4 hours. The initial drop size of the emulsion distribution Figure 1(a) showed that most of the droplets were free, did not aggregate and were small in size and uniformly distributed. Our microscopy measurements showed that the drop size distribution was in the range of 3 to 11 μm. The entire emulsion was then filled into a horizontal cylindrical coalescer using a

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funnel. The same emulsion was used to conduct de-emulsification experiments for three times by every time re-emulsifying the emulsion using a homogenizer. For fourth trial a fresh emulsion was prepared using the same methodology. The room temperature throughout a typical experiment was controlled at $25°$ C us- ing a room air-conditioner. Exactly the same procedure was used to prepare 1.8L of water-in-sunflower oil emulsion for carrying out experiments to under- stand the mechanism of drop-interface coalescence events. For systems where 40 ml of water-in-silicone oil emulsion was required 2% of de-ionized water and 98% of silicone oil were mixed without adding any surfactant. The system was used to demonstrate the mechanism of water chain alignment and elongation using parallel and vertical plate electrodes in a cuvette.

2.2. Horizontal cylindrical tri grid setup

To study the effect of frequency on the water separation, an acrylic horizontal cylindrical tri grid vessel of capacity 5L, diameter 14 cm and length 32 cm was designed and fabricated as shown in the Figure 2. The tri grid configuration is the most common configuration in commercial electrocoalescers [5, 6]. Three sets of grid electrodes, made up of stainless steel grade SS 304 each of length 29 cm were mounted across both the flanges of the vessel, 2 cm from the top of the vessel and 3 cm apart from each other as shown in the Figure 2. All the three sets of the grid electrodes consisted of twenty five small metal rods each of diameter 5 mm, welded at a distance of 1 cm from each other and oriented at right angles with respect to a central long electrode. 5L of water in sunflower oil emulsion was prepared by mixing 90% sunflower oil, 10% deionized water as discussed in the previous section. The emulsion was filled with the help of a funnel in a cylindrical tri grid electrocoalescer vessel. A sinusoidal AC electric field of strength 1 kV/cm rms was applied using a TREK amplifier Model 5/80 High-Voltage Power Amplifier with a gain of 1000 to energize the tri grid electrodes. The other setups used in this work are shown in the Figure 3. Frequency variation was done with the help of an Agilent function generator (Model 33220A). A multimeter (Keithley Tektronics Company, Model 2002 Multi meter) was used to measure the current flowing through the emulsion. Experiments were carried out for two different configurations. The upper and lower sets of electrodes were kept live while the middle electrode was grounded. Initially water was filled in the vessel to a predetermined level. In the first configuration, the water at the bottom of the vessel

was grounded (Grounded system). In the other configuration, the water at the bottom was not grounded (non Grounded system). In both the configurations, the water cut was varied and experiments were performed for 5%, 10%, 20% and 30% water cut.

The electrocoalescer operational performance improved with an increase in the initial water level in the vessel [31]. In view of this, optimization of the initial level of water in the vessel was found for different water cuts. These are reported as tables in the Appendix. The level of water which gave the best performance was then selected for further studies. At a very low level of water, the field in the region between the lower electrode and the interface was low while at very high values of interface level the operation was found to be unsafe due to electrical sparking between the interface and the lower electrode. During the breakup of the water-in-oil emulsion, the separated water leads to an increase in the water level at the bottom. The change in the level of water at the bottom of the electrocoalescer during a typical dehydration experiment was 2.7 cm for 10% water cut. The optimum level for 10% water cut was observed to be 3 cm. This small change in the level of water changes the electric field by 11% (1 kV/cm to 1.11 kV/cm) and was ignored in making inferences about the optimum level. Since the unit was operated such that both the oil and water phases are in the batch mode, simultaneous adjustment of the oil-water interface level was not attempted. Experiments were then conducted at different frequencies in the grounded and non grounded system.

2.3. Vertical cylindrical coalescer

The horizontal cylindrical tri grid coalescer did not allow clear visualisation of the coalescence process due to its larger volume. Therefore to make visual observations at the interface and to establish the generality of the results with respect to the electrode set up as well as to understand the mechanism of coa- lescence with respect to frequencies, batch experiments were conducted in a 2L vertical cylindrical vessel and the phenomena was recorded at the interface. The electrode arrangement was as shown in the Figure 3 e in the experi- mental set up shown in the Figure 3. Two sets of grid electrodes each of length 12 cm and diameter 5 mm were mounted across the acrylic stand, the lower electrode was kept at 5 cm from the bottom of the vessel and was completely submerged in the water so as to electrically ground the water kept at the bot- tom of the vessel. The upper electrode was kept at 15 cm from the bottom of the vessel and was wired live. The interface was at 15 cm from the bottom of the vessel. Both the sets of grid electrodes consisted of six small horizontal electrodes

each of diameter 3 mm, welded at a distance of 1 cm from each other and were oriented at a right angle with respect to the vertical electrode. The distance between the live electrode and the interface was 5.5 cm.

2.4. Cuvette coalescer

To further confirm the alignment and elongation of water chains, experi- ments were also carried out in a square cross section plastic cuvette using two configurations, namely vertical plate and parallel plate electrodes as shown in the Figure 3 f and g. Parallel plate electrodes were of dimension 4.5 cm height and 1 cm width. In each arrangement the electric field was kept at 1 kV/cm. The idea here was also to check the effect of the relative direction of electric field with respect to gravity on the water separation.

3. Results and discussion

3.1. Horizontal cylindrical tri grid setup

Figure 4 shows the variation of time required for 90% separation with water cut and frequency of the applied field maintained at 50 Hz. It can be seen from the Figure 4, that as the water cut increases from 5 % to 30%, the time for 90% separation of water from water-in-oil emulsion reduces from 17 minutes to 11 minutes, in the non grounded system. The water separation was also confirmed by using Karl Fischer titration. This titration gives the percentage by weight of residual water in the sample. The readings of the same are presented in the Appendix in the form of table. This result is in accordance with the time of coalescence predicted using two drops interaction as $t = (8/15) [\eta/(\varepsilon\ E^2)][(L/2a)^5 - 1]$, where η is the dynamic viscosity of the oil, L is the initial distance of drops centers, ε is the oil permittivity, E is the electric field and a is the droplet size [32]. Substituting $L/a = (4\pi/3\varphi)^{1/3}$ in the equation, the scaling is obtained as $t = (8/15\ t_r)[(\pi/6\varphi)^{5/3})-1]$ where t_r is $\eta/(\varepsilon\ E^2)$, the electrohydrodynamic time scale and the inverse relationship between (t+1) and φ is verified as shown in the inset of Figure 4. It shows that the separation time decreases with an increase in the water cut. A similar trend was seen for the grounded system. The separation time in the grounded case was reduced by half of the corresponding non grounded system since the region between the lower electrode and the interface now experienced significant electric field. The electric field distribution was improved by grounding the water at the bottom of the vessel. The effect of grounding

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the water at the bottom of the vessel on water separation time is shown in the Figure 4. The theoretical scaling of $t+1 \sim \varphi^{-5/3}$ is much higher than $t+1 \sim \varphi^{-1/3}$ observed in experiments. The slow kinetics observed in experiments can be attributed to many body effects and hindered settling in emulsions.

Figure 5 shows the effect of frequency on the time required for 90% separation of water from the water in oil emulsion. We call this case as the control case where the same frequency is applied between all electrodes. It is seen that at lower water cut i.e. 5% and 10%, there is no significant effect of frequency on water separation. The time required for 90% water separation from the 5% water cut emulsion with increase in frequency from 10 Hz to 5 kHz was almost same. The time required was around 8 minutes in case of bottom grounding and 17.5 minutes in case when bottom was not grounded. The time required for 90% water separation from the 10% water cut emulsion with increase in frequency from 10 Hz to 5 kHz was almost same when the bottom was not grounded. The time required was around 14 minutes. However an unmistakable effect of frequency was observed for higher water cuts of 20% and 30%. The frequency effect was further enhanced when the frequency increases to 5 kHz. Experiments were not conducted beyond 5 kHz due to the limitations of the amplifier. Thus efficient electrocoalescence is observed at higher frequencies for higher water cuts with the bottom grounded configuration.

Figures 6 a,b, c and d show the transient change of current for three different water cuts 5%,10% and 20% for grounded vessel configuration. At 1 kHz, for low water cuts of 5% and 10%, the current rises up to around 100% of Imax in 2.5 minutes and 2 minutes respectively. In this period the water separation was negligible and the increase in current was a result of chaining and ordering of water droplets. The current subsequently monotonically falls down with a corresponding increase in separation of water. This is due to the process of coalescence of bigger droplets and their subsequent gravity settling in next 7.5 minutes for 5% water cut and 5.5 minutes for 10% water cut, resulting in complete separation of water from the emulsion[33]. Figure 6 c and d also shows the variation of current and water separation with time in the case of 20% water cut for 100 Hz and 1 kHz respectively. It is seen that the dynamics in the case of 1 kHz is indeed faster than at 100 Hz. What is more remarkable is the large fluctuations seen in the current in the case of 1 kHz. This indicates formation and coalescence of long chains of droplets, not seen in 100 Hz, wherein the current vs time is relatively smooth. It should be noted that there indeed is a current limiting device in the amplifier used in this work. However in the range of parameters studied, the applied voltage never dropped to zero because of water chaining and action of

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current limiter.

In a tri-grid electrocoalescer, the region between the upper and middle elec- trodes (upper region) and the lower electrode and the interface (lower region) are different in an important aspect. As the electrocoalescence progresses, while the upper region has lower water content , the lower region experiences higher water cut with time of operation. Experiments were therefore conducted by applying variable frequencies in the two different regions of the tri grid electro- coalescer. To determine whether the high frequency effect on rapid coalescence is predominant in the lower or upper region of the electrocoalescer, experiments with variable frequency were conducted by maintaining the coalescer in the grounded configuration. An optimized level of water at the bottom of the vessel was maintained and experiments were conducted in two ways by using two high voltage power amplifiers. In the first case, in region between the upper and middle set of grid electrodes, a constant frequency of 50 Hz was applied while in the region between the lower set of the grid electrodes and the water at the bottom of the vessel, the frequency was varied from 1 Hz to 5 kHz (called case A, bottom variable frequency). In the second case, experiments were conducted by applying a constant frequency of 50 Hz in the lower region and the frequency was varied from 1 Hz to 5 kHz in the upper region as shown in the Figure 2b (called case B, top variable frequency).

As seen from the Figure 7, in case A with bottom variable frequency, the coalescence process was much faster than the control case and a greater sensi- tivity of the separation of water to the frequency was observed. Since in the bottom region where variable frequency is applied, the water volume fraction increases with time, the high frequency applied in this region is more effective [34]. On the contrary, separation time was found to increase with an increase in frequency, when variable frequency was applied in the upper region of the electrocoalescer(case B).

3.2. Vertical cylindrical coalescer

To ascertain the robustness of the mechanism and to aid visualization, a smaller capacity (1L) vertical cylindrical coalescer with similar electrode ar- rangement was employed. It was seen that the smaller droplets grew in size and coalesced into bigger droplets which formed chains which grew longer, thereby increasing the effective weight of the chains. These chains then moved under gravity to reach the emulsion-water interface and these entire chains were found to coalesce at the emulsion-interface with the water pool below, thereby lead- ing to faster coalescence. On the other hand,

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at lower frequencies of 50 and 100 Hz, the smaller droplets in the region between the live electrode and the interface, coalesced into bigger droplets and exhibited bounce off from the interface leading to non coalescence and a longer separation time (see videos in supplementary material).

3.3. Cuvette coalescer

To ascertain the effect of relative orientation of the chains and the interface, a cuvette coalescer was employed. When the electrodes are vertical, chains are parallel to the interface and perpendicular to gravity. On the other hand when the electrodes are horizontal, the chains are perpendicular to the inter- face and in the direction of gravity. In the first arrangement when two plate electrodes were held vertically in the cuvette, long horizontal water chains were observed between the electrodes. These chains were held between the electrodes without any appreciable coalescence(Figure 8a and b at frequencies of 1 and 5 kHz). On the other hand when the experiments were performed with the plate electrodes held horizontally, such that the direction of the electric field was parallel to the gravity, shorter water chains were formed. These chains then moved to the interface with a greater velocity, on account of a greater effective size, and thereby density, and coalesced with the interface of emulsion and the aqueous phase at the bottom of the cuvette in a very short period of time(results presented at frequencies of 1 and 5 kHz as shown in the Figure 8c and d)(Videos are available in supplementary material).

The above observations then explain the results obtained in the tri grid coalescer. In case A of variable frequency in the bottom region, the droplet chaining is enhanced at higher frequencies which coalesce with the emulsion- water interface. This significantly enhances the coalescence rate in case A as compared to the control case. On the contrary in case B, the water chains formed between the upper and middle electrodes, remain straddled there, resulting in poor efficiency with respect to the control case.

A possible mechanism to explain chain formation at higher frequencies can be conjectured as follows: at very small separation δ between the two drops, the capacitance of the intervening oil film is given by $C = (A\varepsilon_m)/\delta$ where A is proportional to square of a the droplet size. The charging time of the drops is (ε_w/σ_w) where ε_w and σ_w are permittivity and conductivity of water respectively. The charging time of two drops when the gap is δ is given by

$(\varepsilon_m/\sigma_w)(a/\delta))$. Therefore as δ tends to zero, the charging time can increase significantly. For $\varepsilon_m = 2 \times 8.854 \times 10^{-12}$ SI units, $\sigma_w = 10^{-4}$ S/m, a= 10^{-4}m, $\delta = 10^{-9}$m, the charging time can increase to around 2 ms suggesting non coalescence and chaining at kHz of frequencies, essentially due to insufficient charging and reduced Maxwell stresses at the interface.

4. Conclusions

Bottom grounding of water in an electrocoalescer was found to have a significant impact on the efficient separation of a water-in-oil emulsion. The water separation time was reduced by almost 50%, when the vessel was electrostat- ically grounded at the bottom by keeping an optimum level of water. This is due to an effective and strong uniform electric field distribution in the region between the bottom electrode and the emulsion-water interface. The level of water kept at the bottom of the vessel was optimised depending upon the wa- ter cut present in the emulsion, thereby enabling safe operation without any fluctuations in current and short circuiting.

Frequency effect was found to be more prominent for high water cut and it was more significant when the frequency was increased to 1 kHz upto 5 kHz. The effect of high frequency was most effective when applied in the bottom region of the vessel. This could be attributed to sudden formation of water chains in the bulk and their coalescence with the oil-water interface below, thereby further assisting in reduction of water separation time.
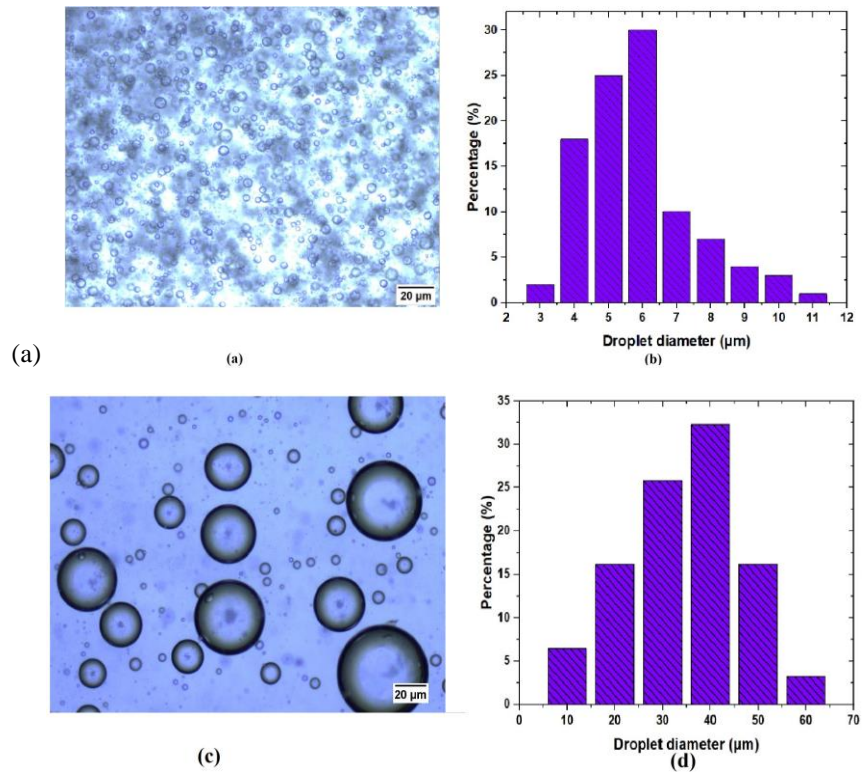
(a)

Figure 1: After homogenization droplet size distribution of water-in- sunflower oil emulsion where (a) Photograph of the initial emulsion before applying electric field (b) Initial drop size distribution before applying electric field (c) Photograph of the initial emulsion after applying electric field (d) Initial drop size distribution after applying electric field.
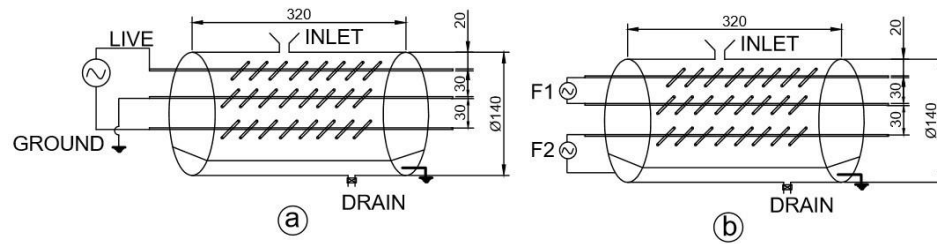
13

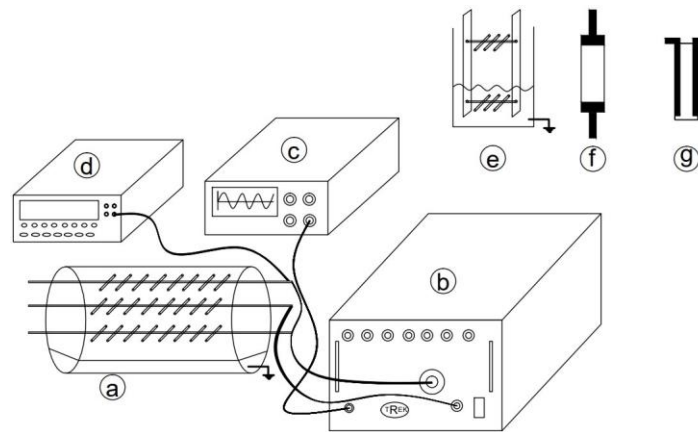**Figure 2:** Schematic for Electrical connections (a) Constant fre- quency (b) Variable frequency (all dimensions are in mm).

Figure 3: Experimental Setup is shown in figure where (a) Tri grid coalescer (b) TREK (c) Frequency amplifier (d) Keithley multimeter (e) Drop interface set up (f) Vertical field cuvette set up (g) Horizontal field cuvette set up where shaded portion represent electrodes.
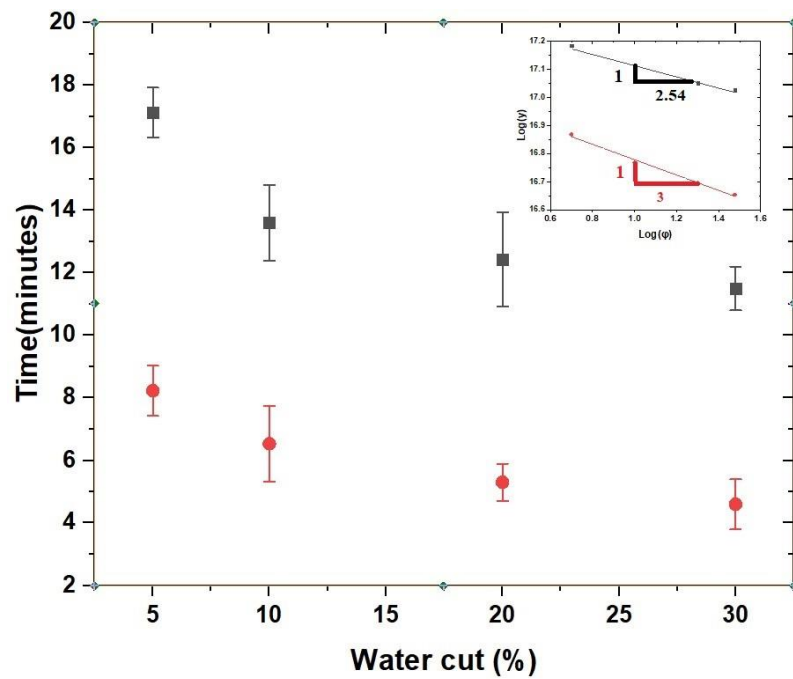
Figure 4: Water separation time for different water cut with and without bottom grounding at 1 kV/cm, 50 Hz frequency where filled represent without bottom grounding and filled represent with bottom grounding. Inset figure represent the theoretical scaling of t+1 $\sim \varphi$
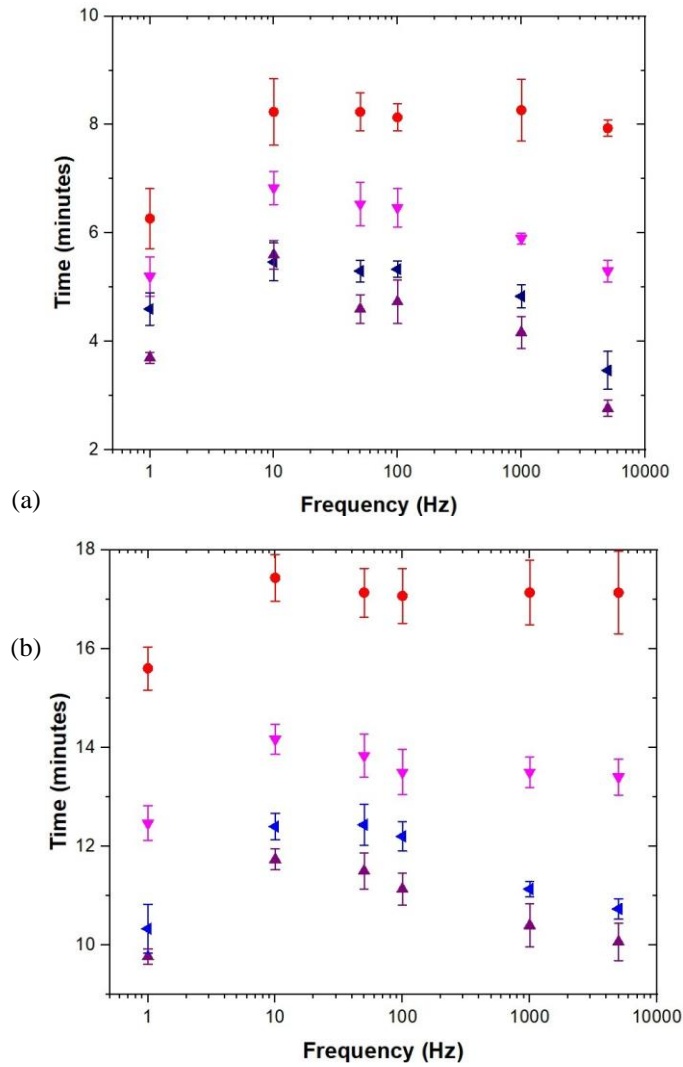
(a)

(b)

Figure 5: (a) Water separation time for different water cut *with grounding* the bottom at 1 kV/cm (b) Water separation time for different water cut *without grounding* the bottom at 1 kV/cm, where

filled ☐ : 5 % water cut, filled ⵕ: 10 % water cut, filled *a*: 20 % water cut, filled *O*: 30 % water cut.
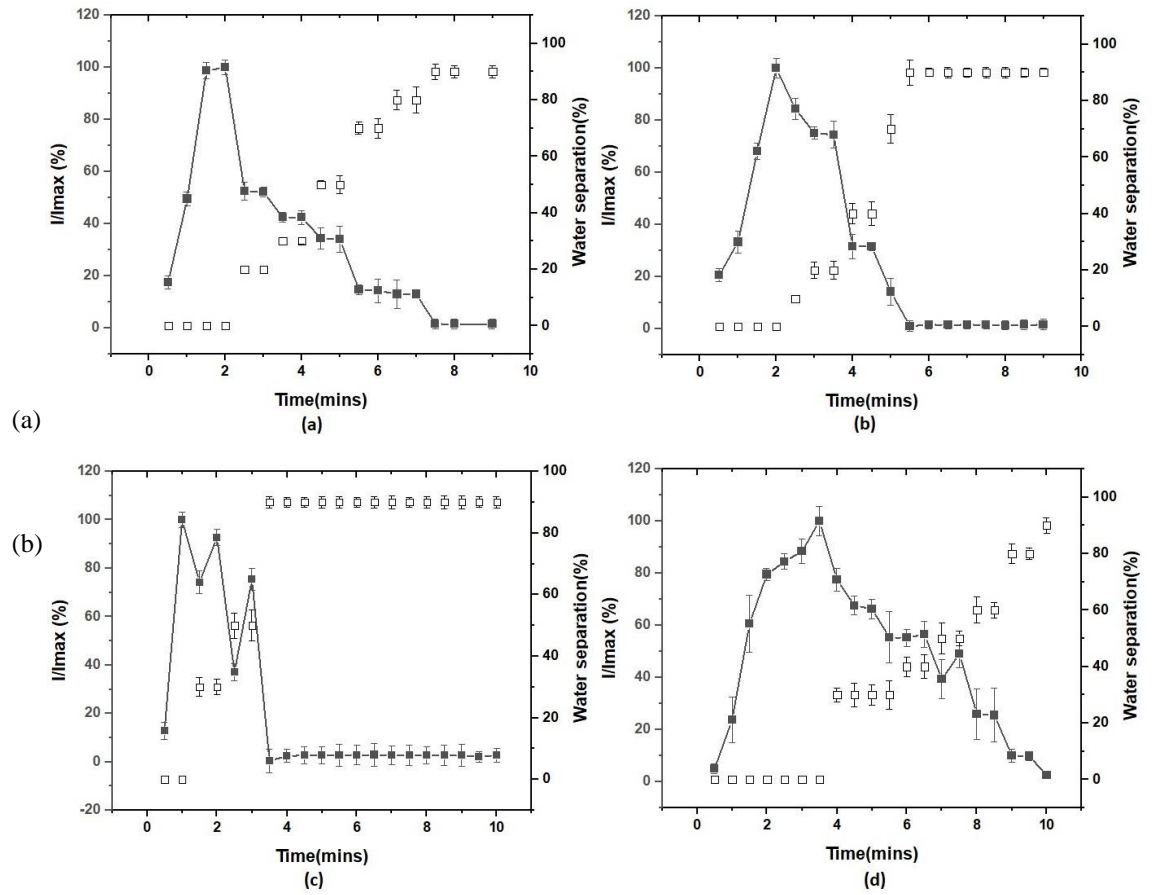
16

(a)

(b)

Figure 6: Current and water separation with respect to time for different water cut at 1 kV/cm (a) 5 % water cut at 1kHz, Imax = 23.8 μA (b) 10 % water cut at 1kHz, Imax = 34.5 μA (c) 20 %water cut, Imax = 71.1 μA for 100Hz and (d) 20 % water cut, Imax = 76.5 μA for 1kHz, where filled black square represent I/Imax and unfilled black square represent water separation for all cases.
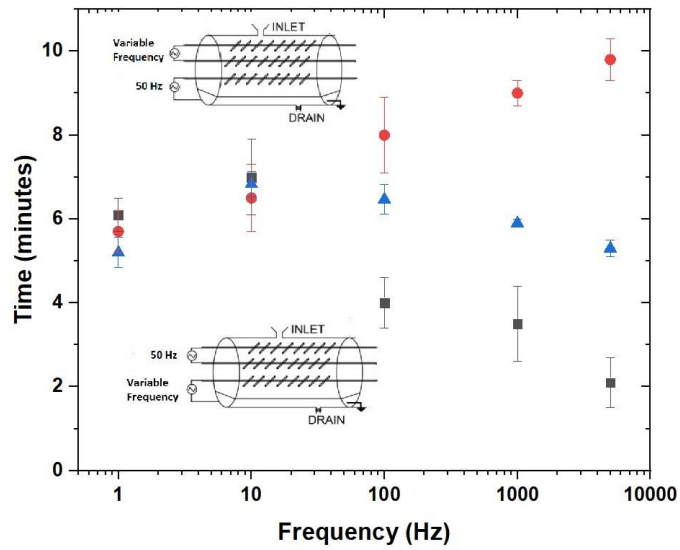
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Figure 7: Water separation time for 10% water cut in two different regions of the electrocoalescer at 1 kV/cm, variable frequency where filled square represents variable frequency in the lower region, filled circle represent variable frequency in upper region and filled triangle represent control case.
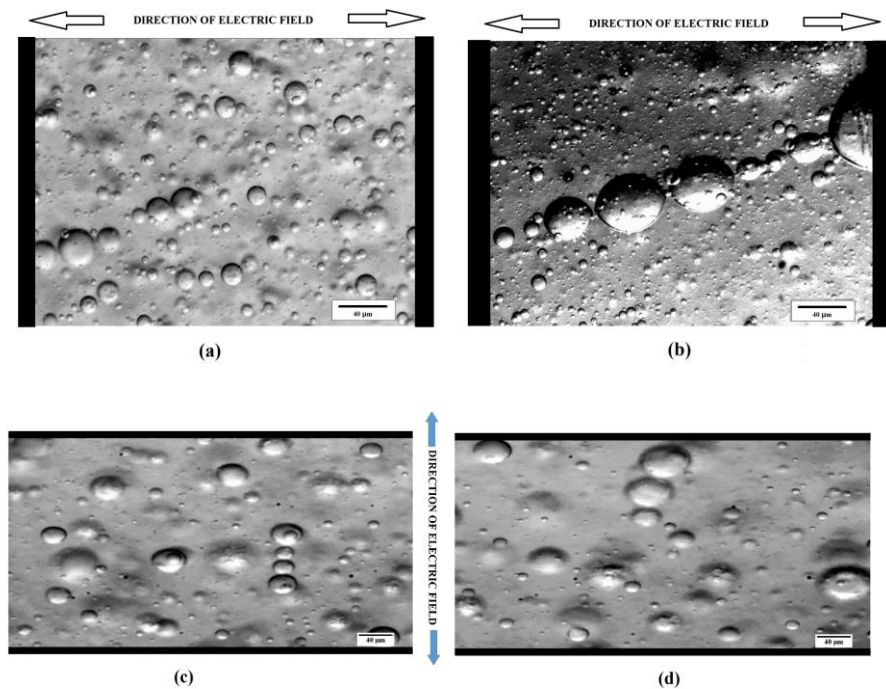
Figure 8: Photomicrograph of water chain formation in the cuvette set up. The electric field is 1 kV/cm (a) horizontal water chains at 1 kHz (b) horizontal water chains at 5 kHz and its elongation in the direction of electric field without appreciable coalescence (c) vertical water chain formation at 1 kHz (d) vertical water chain formation at 5 kHz in the direction of electric field and due to gravity aid the faster coalescence and settling of water drops in the aqueous phase kept at bottom.

Table 1: Properties of the fluids used in this work.

Properties	Sunflower oil	Deionised water	Silicone oil
Density(kg m^{-3})	922	1000	970
Viscosity(mPa s)	46.5	1	330
Dielectric constant	4.9	80	2.7
Conductivity(S m^{-1})	7.62 x 10^{-5}	1.4 x 10^{-4}	1 x 10^{-12}

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