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Zhang, L, He, L, Ghadiri, M et al. (1 more author) (2015) Effect of surfactants on the deformation and break-up of an aqueous drop in oils under high electric field strengths. Journal of Petroleum Science and Engineering, 125. 38 - 47. ISSN 0920-4105

https://doi.org/10.1016/j.petrol.2014.11.014

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Effect of surfactants on the deformation and break-up of an aqueous drop in oils under high electric field strengths

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Abstract: Understanding the deformation and break-up of drops is of great significance in various applications such as emulsification and phase separation. Most practical systems contain surface-active agents that are present as impurities affecting the properties of the system, e.g. modifying the rigidity of the film that affects emulsion stability. In this paper, the effect of surfactants on the deformation and break-up of an aqueous drop in an immiscible dielectric oil under the action of an electric field is addressed. The experiments were carried out on a single drop in a microscopic cell under an applied external electric field. A nonionic surfactant, polyethylene glycol sorbitan monolaurate (Tween 20), and an ionic surfactant, sodium dodecyl sulfate (SDS), were used at different concentrations. The drop adopted in most cases a prolate shape. However, the presence of the surfactant affected both the extent of deformation and the modes of break-up. The drop deformation extent increased rapidly with the surfactant concentration, while smaller drops deformed less under the same external electric field strength.

When the surfactant concentration was high, the position of break-up could be from both poles along the main axis of the drops in the direction of the electric field.

Keywords: Electric field, liquid drop deformation, liquid drop break-up, emulsion

1. Introduction

Electro-coalescence of aqueous droplets in oils is used extensively in the oil industry to separate water from oil. Under an electric field the drops deform and coalesce faster, enhancing the phase separation (Eow and Ghadiri, 2002). However beyond a threshold of the electric field, the drops disintegrate into small droplets (Sjöblom, 2006; Tuan et al., 2009). The formation of small droplets is of special concern, since their separation becomes extremely difficult and their presence can lead to short-circuiting of the electro coalescer.

Most practical systems contain surface-active agents often as impurities. These affect the system behaviour, for example modifying the rigidity of the film and hence the emulsion stability (Kokal, 2005). The accumulation of surfactants at the interface between two immiscible liquids alters the local thermodynamic environment, and consequently, the nature of the macroscopic interfacial boundary conditions for the dynamics and, in certain cases, the kinematics of a two-fluid flow (Ha and Yang, 1998). Adsorption of surfactants lowers the interfacial tension and hence the stress needed to deform or break the drops. The presence of surfactants interacts with the effect of the electric field in stressing the drops. Nishiwaki (1988) and Moriya et al., (2006) found the deformation due to electric field was proportional to the drop radius and the viscosities of the drop and medium phases. Ha and Yang (1995) used the small deformation theory to examine the effect of insoluble surface-active agents on the drop deformation and stability in a uniform electric field. Generally, drop deformation and break-up in high electric fields when surfactants are present are very complex phenomena, and there is little systematic study of their interactions, hence the reason for this investigation.

2. Mechanisms of droplet deformation and breakage influenced by electric field and surfactant

An aqueous spherical drop suspended in an immiscible dielectric medium deforms under the influence of an external electric field into an elongated prolate spheroid in the direction of the electric field due to the electric stress on the surface (Nishiwaki et al., 1988; Taylor, 1996; Venugopal et al., 1993). However, the drop deformation is resisted by the interfacial tension, which will keep the spherical shape of the drop. Taylor (1964) assumed that the drop takes the shape of a prolate spheroid (Figure 1) under static conditions, such that the pressure difference across the drop interface is the same at any point on the surface. This pressure difference is due to the effect of interfacial tension and electrostatic pressure.

Figure. 1 Schematic diagram of a water droplet deformation in electric field

Balancing the two pressure differences at the drop pole and the equator

$$\Delta p_{pole} = \Delta p_{eq} \qquad (1)$$

gives

$$E_0\sqrt{\frac{2r_0\varepsilon}{\gamma}} = 2(\frac{b}{a})^{\frac{4}{3}}(2-\frac{b}{a}-(\frac{b}{a})^3)^{\frac{1}{2}}\,I \qquad (2)$$

where

$$I = \frac{1}{2}e^{-3}\ln(\frac{1+e}{1-e}) - e^{-2} \qquad (3)$$

here e is the eccentricity defined by

$$e = \sqrt{1-b^2/a^2} \qquad (4)$$

and a, b are the lengths of the major and minor axes of the prolate spheroid. Eq (2) shows the deformation of the drop in the electric field is related to drop size, r, continuous phase permittivity, ε, interfacial tension between two liquids, γ, and the electric field strength, E_0.

The charges present in the highly polar liquid can easily accumulate at the interface between the drop and the continuous phase, generating high electrically-induced stresses at the interface (Megias-Alguacil et al., 2004). The drop elongation increases with the field up to a limiting aspect ratio, above which the droplet becomes unstable. The corresponding field is called the critical field (Miksis, 1981).

In the presence of a surfactant on the interface between water and oil the interfacial tension is lower (Alguacil, et al., 2006). It was demonstrated that the electric deformation of droplets is proportional to γ^{-1}(Edwards et al., 1991; Shimomura and Ito, 2002).

According to Eq (2), the limiting aspect ratio a/b for a stable prolate spheroid is equal to about 1.9. Taylor's model can be applied to experimental data with DC and low frequency alternating voltages (AC). In AC fields, raising the frequency makes the inertia forces comparable to the capillary and electric forces, and higher fields are required to reach the critical elongation. Other expressions for the critical field can be found in the literature (Atten, 1993; Waterman, 1965), where it is reported to be proportional to the ratio $(\gamma/r)^{1/2}$. Miksis (1981) numerically computed the drop shape in a uniform electric field, showing that shape is mainly determined by the dielectric constant of the drop. The results of this analysis showed that when the dielectric constant is larger than a critical value the drop will develop two obtuse-angled conical points at its ends, known as Taylor cones (Taylor, 1964), for a certain field strength.Above the critical field strength, formation of a thin jet or ejection of small droplets at both ends of the drops has been observed. However, the observed drop disintegration is not always like the Taylor cone-jet formation. Different instabilities from the ends of the droplet were observed, leading to ejections of droplets of various sizes to very fine clouds. The instability sometimes ended with separation into few droplets or a more explosion-like event (Sjöblom, 2006).

When the break-up of a large drop into the smaller droplets occurs, a large amount of surface energy is needed and the Laplace pressure (pressure difference between the pressure inside and outside the droplet) will increase. The adsorption of surfactant reduces the interfacial tension, that will decrease the Laplace pressure and make the droplets deform and break up easily (Sjöblom, 1996; Lucassen-Reynders and Kuijpers, 1992).

Berg et al. (2002) reported increasing the conductivity of the water phase did not induce any noticeable effect on the critical field strength. This is expected, due to the huge difference in conductivity of water and oil. The influence of surface characteristics was also investigated by adding asphaltenes. Adding these compounds leads to a decrease in the stability of the water drops in an electric field, presumably due to the lowering of the interfacial tension. Water drops with asphaltene saturated surfaces are reported to exhibit elongation more than twice the break-up value of a/b=1.9 (Sjöblom, 2006) and significantly lower critical electric field strengths compared to clean drops.

Crude oil contains natural surfactants such as asphaltenes, resins, waxes, and naphthenic acids, and surfactants are also added to the system to act as demulsifiers. The effect of surfactants on the drops deformation and break-up mechanisms is therefore of high interest. Nevertheless, the currently available literature on drop behaviour in high electrostatic fields influenced by surfactant does not seem to give a concise view on the actual phenomena for drop break-up. This is addressed in this work by microscopic observations of drop deformation and disintegration in a uniform DC electric field in the presence of surfactants.

3. Experimental set-up and procedure

3.1 Experimental set-up

The experiments were designed to study the deformation and breakup of a water drop in a dielectric oil in a uniform electric field. A schematic diagram of the overall experimental set-up is shown in Figure 2. The system consists of a microscopic cell equipped with two electrodes connected to a high voltage unit. The process is observed using a micro lens (Leica Monozoom 7) connected to a high speed digital video camera (Redlake MotionXtra HG-100K Motion Analyser), with the framing rate of up to 100,000 frames/sec (the highest rates at reduced resolution).

Figure 2 Schematic diagram of experimental set-up

The microscopic cell was made of Perspex to facilitate visualisation of the phenomena occurring during the deformation and breakup. As illustrated in Figure 3, the thick Perspex sheet of the base of the cell is designed to provide stability and insulation to the cell. The grounded electrode was fixed in position at the bottom of a Perspex container, while the distance between the two electrodes could be varied by moving the high voltage electrode attached to the movable upper part. Both electrodes were polished brass plates with dimensions of 90 mm ×25 mm. A small hole is located in the middle point of the moveable upper part and the high voltage brass plate electrode. The volume of single liquid droplets were controlled by using micro syringe and then injected into the cell from this hole. The volume range of the micro syringe is from 0.4 to 4 μl, with the corresponding drop radii from 450 to 895 μm, respectively. A uniform DC electric field was generated from a high-voltage power supply (Hunting Hi-Volt model, Miles Hi-Volt Ltd) with a variable positive-polarity voltage from 0 to 25 kV and a maximum safety current of 20 mA. The deformation and break-up of droplets in the high electric field can be investigated by this experiments set-up.

Figure 3 Schematic diagram of microscopic cell set-up

After a drop was placed in the region between the two electrodes, the electric field was applied and the process of drop deformation and break-up was recorded continuously by the high speed digital video camera. Data analysis was performed by playback of the video recordings. The image analysis software Image-Pro Plus package (Media Cybernetics Ltd) was used to measure the droplet size, degree of drop deformation and onset of drop breakage. With these arrangements, parameters such as the size and number of drops in the system, the type of applied electric field, the location of the drops between the electrodes, and the properties of the system can be easily controlled and manipulated.

3.2 Experimental materials

The essential condition for the electrocoalescence is that the dispersed phase (i.e. the aqueous phase) should have a significantly higher electrical conductivity and permittivity than those of the continuous phase (i.e. the organic oil). Therefore, in this work sunflower oil (obtained from Morrisons Ltd.) was used as the dielectric liquid for the continuous phase, while distilled water or a surfactant solution was the dispersed phase. The properties of the liquids used in this research are given in Table 1.

Two kinds of surfactants, a nonionic, polyethylene glycol sorbitan monolaurate (Tween 20, Sigma), and an ionic, sodium dodecyl sulfate (SDS, Sigma), were used in order to investigate their role in the deformation and break-up of a drop. All materials were used as received without further purification. In all experiments, the surfactants were first dissolved in the distilled water. It has been experimentally shown that the addition of the surfactant does not significantly change the bulk liquid properties (Ha and Yang, 1998).

The conductivity of the liquids was measured using a conductivity meter, Model 4310 from

Jenway Products Inc. Liquid viscosity was measured using Bohlin CVO Rheometer from Malvern Instruments Inc. The viscosity did not change with the shear rate, as the continuous phase was incompressible Newtonian liquid. The density was measured using a volumetric flask. The dielectric constant of the liquids was obtained from the suppliers and literature (Eow and Ghadiri, 2003).

Table 1 The properties of the liquid used in the experiment

The presence of surfactant reduces the surface tension of the water. The surface tension and interfacial tension were measured according to a technique based on the pendant drop method, using a contact-angle measuring instrument, EasyDrop from Kruss GmbH. This method is based on the principle that the shape of a droplet suspended in another phase is governed by the balance between gravity and interfacial tension forces (shown in Figure 4). The interfacial tension was calculated by Young–Laplace equation.

Figure 4 Shape of the drop in different conditions (a) distilled water in air, (b) distilled water in sunflower oil, (c) 10^3 ppm SDS solution in sunflower oil

The interfacial tension of the SDS solution - sunflower oil system and Tween 20 solution–sunflower oil system in different concentrations (wt) are given in Figure 5. The results clearly show that the interfacial tension changes strongly with the concentration of the surfactant. However, after reaching the CMC (critical micellar concentration), its decrease rate slows down.

Figure 5 Interfacial tension of the SDS solution - sunflower oil system and Tween 20 solution–sunflower oil system in different concentrations (wt)

4 Results and discussion

4.1 Effect of droplet size

The deformation of distilled water drops of different sizes in sunflower oil under various levels of applied D.C. electric field is given in Figure 6. The electric field strength is calculated as the ratio of the applied potential difference to the separation distance between the two electrodes. Here, the extent of drop deformation is expressed as D, the ratio of the length of the major axis, a, to that of the minor axis, b, of a prolate solution drop: $D = a / b$. The liquid drops in all experiments are carefully injected by a microsyringe needle with accurate volumes. The extent of deformation and the drop size are all measured by Image Pro Plus software.

Figure 6 Extent of deformation of distilled water drops in sunflower oil as a function of the electric field strength. Average radii of the drops: ■: 607±13μm and ▲:789±18μm, interfacial tension: γ =32 mN/m.

As Figure 6 shows the bigger drops deform more than small drops at the electric field strengths higher than 320 V/mm. Similar results are obtained for the deformation extent of SDS solution drops of different sizes (459±7μm, 626±14μm and 791±17μm), where the concentration of the surfactant is 5×10^4 ppm (Figure 7). The pressure difference across the interface of a drop with radius, r, due to surface tension is given by:

$$\Delta p = 2\gamma / r$$

It can be seen that at constant interfacial tension, the pressure difference will decrease with drop size, therefore the shape stability is higher for smaller drops (Sjöblom, 2006).

Figure 7 Extent of deformation of 5×10^4 ppm SDS solution drops in sunflower oil as a function of the electric field strength.

Average radii of the drops:■: 459±7μm, ●: 626±14μm and ▲: 791±17μm, interfacial tension: γ =3 mN/m.

4.2 Effect of surfactant

The deformation of different solution drops in sunflower oil as a function of applied DC electric field is given in Figure 8.

Figure 8 Extent of deformation of liquid drops in sunflower oil as a function of the electric field strength. The average radii and interfacial tensions are as follows: ▲: distilled water, 607±13 μm, γ=32 mN/m; ●: Tween 20 solution, 621±9 μm, γ=5 mN/m; ■: SDS solution, 626±14 μm; γ=3 mN/m. The concentration of Tween 20 and SDS are 5×10^4 ppm.

As illustrated in Figure 8, at same electric field strength, the two systems with surfactant solutions have larger deformations as compared with pure distilled water drop. In addition, at the same concentration of SDS solution (5×10^4 ppm), drops deform easier than Tween 20 solution drops. This is because at this concentration, the SDS solution–sunflower oil system has a lower interfacial tension than that of Tween 20 system. Under the electric field, a drop will be elongated more because of the weakness of surface forces (as a result of the presence of surfactant). Images presented in Figures 9 a)–e) show the deformation of SDS solution drop at 0, 75, 125, 175, 190 V/mm electric filed strength. The concentration of the surfactant is 5×10^4 ppm, interfacial tension is 3mN/m, and mean radii of drops is 607±13μm. As shown in Figure 9, the degree of deformation of drop increases rapidly with the electric field strength, and the drop becomes unstable when the electric field reaches a critical value of 190 V/mm.

Figure 9 Deformation of SDS solution drops at various applied d.c. electric field strengths: (a) 0 V/mm; (b) 75 V/mm; (c) 125 V/mm; (d) 175 V/mm, (e) 190

V/mm

Figure 10 shows drop deformation as a function of electric field strength for the values of the interface tension (2, 23, 32 mN/m), corresponding to SDS concentrations of (0, 100 and 5×10^4 ppm). The average radii of drops are 789±18μm, 767±12μm and 791±17μm. It can be seen that the deformation of distilled water drop is the lowest of these cases. The drop deformation increases as the concentration of surfactant is increased. Also, the range of field strength for a stable droplet is significantly reduced with the highest surfactant concentration. This is due to a decrease in interfacial tension between the liquids with the concentration of the surfactant, which reduces the resistance to deformation.

Figure 10 Extent of deformation of liquid drops in sunflower oil as a function of the electric field strength. ■: distilled water, γ=32 mN/m, 789±18μm; ●: 100 ppm SDS solution, γ=23 mN/m, 767±12μm; ▲: 5×10^4 ppm SDS solution, γ=3 mN/m, 791±17 μm.

The dimensionless Weber number as defined by Eq. (5), takes account of the parameters that influence the droplet deformation.

$$\mathrm{We}=\frac{2\mathrm{r}\varepsilon\mathrm{E}_0^2}{\gamma_0} \tag{5}$$

where r is drop size, ε is continuous phase permittivity, γ_0 is interfacial tension between two liquids, and E_0 is electric field strength. This dimensionless number measures the importance of the electrostatic energy with respect to the interfacial tension energy.

The results of drop deformation are re-plotted in Figure 11 in terms of the Weber number, where a remarkable unification is observed particularly at low Weber numbers. However there are some deviations from the curve at higher Weber numbers. This is because in the small deformation limit, the effect of the surfactant transport on the drop interface can be effectively neglected, and the Marangoni effect does not considerably influence the steady deformation. When the applied electric field on the drop is sufficiently high, the drop deforms and becomes unstable. The surfactant makes the interface mobile, and the interfacial tension gradient induces additional flow via the Marangoni effect due to nonuniform distribution of surfactants. At high surfactant concentrations, the drops are found to be elongated to a sharp end or long strip shape. Differences in interfacial tension are likely to be present in the elongated and somewhat distorted configuration of the droplet and around necked points. This instigates fluid flow from areas of lower surface tension to areas of larger surface tension. This is especially true at high concentrations, since a small non-uniformity in surfactant can give rise to large Marangoni stresses. Another mechanism that can become important at high surfactant concentrations is surface dilution: as the drop is stretched, the surfactant concentration is diluted due to the increase in interfacial area and the interfacial tension increases accordingly. These considerations could be sufficient to justify some scattering in the deformation vs Weber number relationship. Nevertheless, it is clearly indicated that the degree of drop deformation can be described as a function of Weber number, combining the effect of all important factors.

Figure 11 Extent of deformation of liquid drops in sunflower oil as a function of the electrostatic Weber number for the liquid-liquid systems

4.3 Droplet breakage mechanisms

During the experiments, it is found that when the electrical field strength exceeds a certain critical value, the elongated drop eventually breaks up. The critical electric field for the drop breakage is found to decrease with the drop size and the surfactant concentration. However, the mechanisms and the modes of the breakage are different for the liquid drops with and without surfactant as described below.

Figure 12 shows the breakage process of the distilled water drop of initial radius 912 μm, under an applied electric field of strength 475 V/mm. It can be seen that under the action of high electric force the drop stretches initially, the ends of the mother drop become very sharp, displaying the typical Taylor cones formation, and eventually the drop becomes unstable and breaks up from the poles. The small droplets detached from the mother drop move towards the oppositely charged electrode. After that, the mother drop which lost only a little volume of the small droplets, reaches a new stable state, and the ends of the mother drop will keep the sharp shape rather than a round end.

Figure 12 The break-up of a distilled water drop of radius 912 μm at an applied electric field strength of 475 V/mm, interfacial tension γ =32 mN/m

The surfactant molecules on the surface between the two liquids, modify the surface structure. The interfacial tension gradient induced by a non-uniform distribution of surfactants can be effectively neglected at the low surfactant concentration (Eggleton et al., 2001; Kwak and Pozrikidis, 2001), making the break-up still start from the pole of the drops.

Figure 13 shows the break-up of a 100 ppm SDS solution drop with interfacial tension γ =23 mN/m, and radius of 758 μm at an applied electric field strength of 413 V/mm. Figure 14 shows the break-up of a 100 ppm Tween 20 solution drop with interfacial tension γ =22 mN/m, and radius of 684 μm at an applied electric field strength of 475 V/mm. At the onset of the breakup , a trail of numerous small droplets is ejected from the poles of the mother drop and moves toward the electrodes, while the main drop deforms into a long strip shape like a thread.

Figure 13 The break-up of a100 ppm SDS solution drop of radius 758 μm at an applied electric field strength of 413 V/mm, interfacial tension γ =23 mN/m

Figure 14 The break-up of a100 ppm Tween 20 solution drop of radius 758 μm at an applied electric field strength of 475V/mm, interfacial tension γ =22 mN/m

At high surfactant concentrations (above CMC), when the electric field strength is 175V/mm, the breakage process of a Tween 20 solution drop of radius 780 μm is shown in Figure 15, where the electric field strength is 225V/mm. The breakage process of a SDS solution drop of radius 702 μm is shown in Figure 16. In both cases the concentration of SDS and Tween 20 is 5×10^4 ppm.

Figure 15 The break-up of a 5×10^4 ppm Tween 20 solution drop of radius 702 μm at an applied electric field strength of 175 V/mm, interfacial tension γ =5 mN/m.

Figure 16 The break-up of a 5×10^4 ppm SDS solution drop of radius 780 μm at an applied electric field strength of 175 V/mm and interfacial tension γ =3 mN/m

It can be seen from Figure 15 that at the beginning of the break-up, the drop is stretched rapidly, induced by increasing the electric field. The breakage starts from the end point of the drop and the detached droplets move towards to the opposite electrode. The breakage mode of Tween solution drops is similar at different concentrations.

From Figure 16, it can be seen that in contrast to the low concentration case, after the first break-up, the drop breaks again, taking place at the main axis of the electric field direction, while at the opposite pole the mother drop is stable during the breakage process. This is because the SDS surfactant dissolves in the distilled water and dissociates into anion (negative charge) and a cation (positive); the negative part absorbs on the interface to reduce the interficial tension (Manev and Nguyen, 2005). When the electric field is applied, this part transports toward the positive electrode, while inducing the transport of the surfactant along the interface and resulting in local gradients in interfacial tension (Feigl et al., 2007; Pignolet et al., 2008). This creates a pole at which the local surfactant concentration is very high, as schematically shown in Figure 17. The surfactant accumulates at the end near the positive electrode and significantly reduces the interfacial tension at this point, where the break-up takes place first, and the drop breaks again at the center of the drop. The other pole of the mother drop has higher interfacial tension under a low surfactant concentration and can maintain stable shape during the breakage.

Figure 17 Schematic presentation of the SDS surfactant distribution structure of adsorption layers during the drop deformation when applied electric field

At very low interfacial tensions, under the applied electric field the drop deforms into a long strip shape, which can be easily broken. However, by further increasing the surfactant concentration above CMC point there is no significant decrease in the surface tension, and the breakage mode does not change.

5 Conclusions

The effect of surfactant on the deformation and breakup phenomena of drops suspended in sunflower oil phase under the action of external electric field has been investigated. A type of non-ionic surfactant, polyethylene glycol sorbitan monolaurate (Tween 20), and an ionic surfactant, sodium dodecyl sulphate (SDS) were used at different concentrations.

It was found that under the action of electric field bigger drops deformed to a greater extent than smaller drops. In the presence of the surfactant, the interfacial tension reduced greately with the concentration of the surfactant, until the CMC (critical micelle concentration). At a concentration about the CMC, it decreased slowly. Under the same electric field strength the system of surfactant solution drops in sunflower oil had a larger deformation as compared with pure distilled water drops. The main reason is that a liquid-liquid system with surfactant has a lower interfacial tension and this will lead to more drop deformation. The extent of drop deformation is found to show a remarkable unification of all the experimental data by the use of Weber number, but some deviations were observed for the large deformation range.

Furthermore, it is found when the electrical field strength exceeds a critical value, the elongated drop eventually breaks up. For pure water-sunflower oil system, the drop break up started from the pole of the prolate spheroid, where the ends of the mother drop became very sharp. It was observed that in the presence of surfactants a lot of small droplets ejected from the poles of the mother drop and moved toward electrodes, while the main drop deformed into a long strip shape like a thread. The breakage mode of Tween solution drop is similar at different concentrations. However, at high surfactant concentration, the breakage mode of SDS solution drop changed, since a second break up took place at the main axis in the direction of the electric field. This was attributed to the ionic nature of the SDS surfactant.

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Figure 1. Schematic diagram of a water droplet deformation in electric field

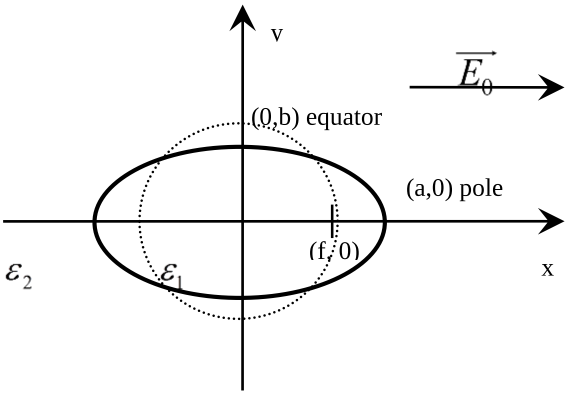


Figure 2. Schematic diagram of experimental set-up

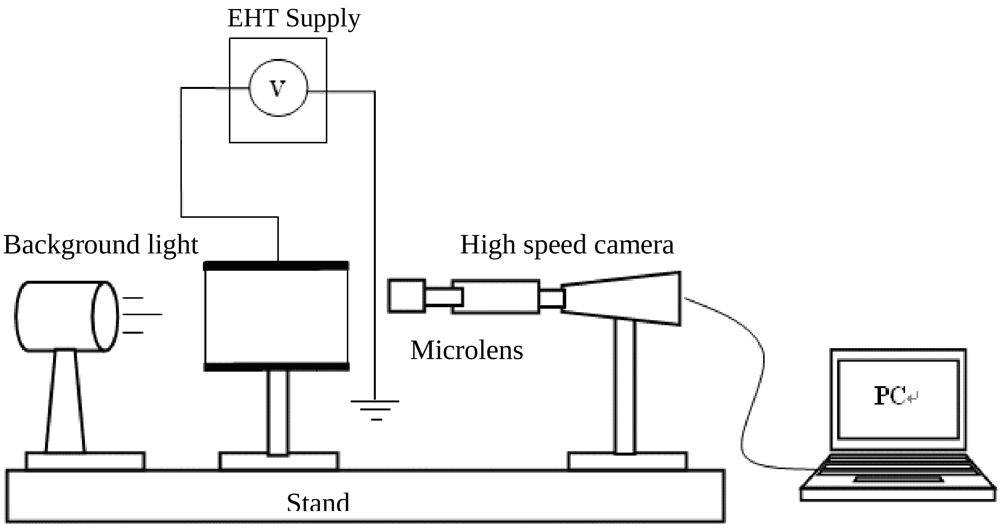


Figure 3. Schematic diagram of microscopic cell set-up

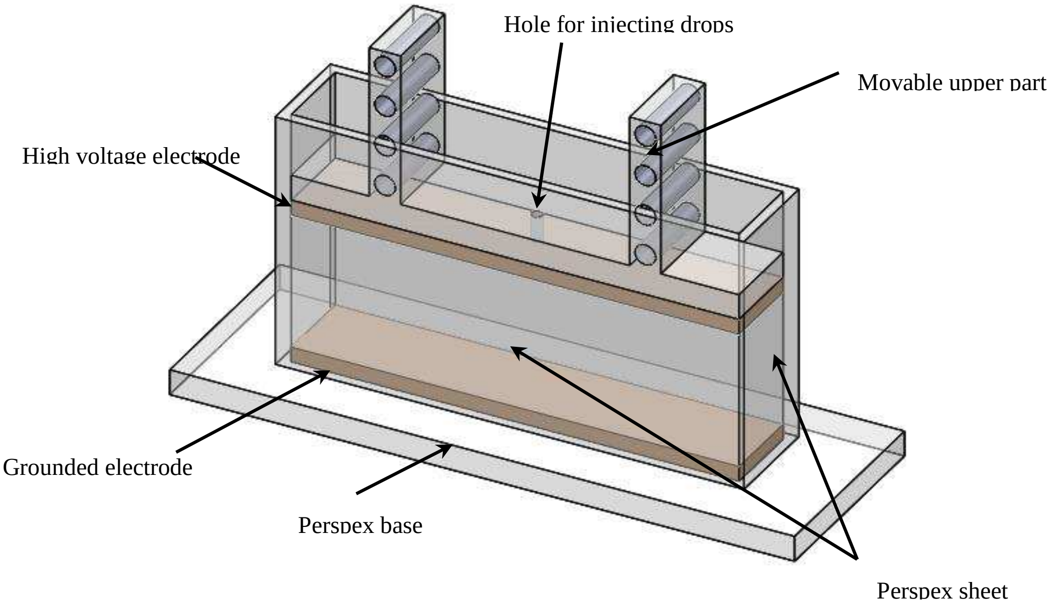


Figure 4. Shape of the drop in different conditions (a) distilled water in air, (b) distilled water in sunflower oil, (c) 10^3 ppm SDS solution in sunflower oil

(a) (b) (c)

Figure 5. Interfacial tension of the SDS solution - sunflower oil system and Tween 20 solution–sunflower oil system in different concentrations (wt)

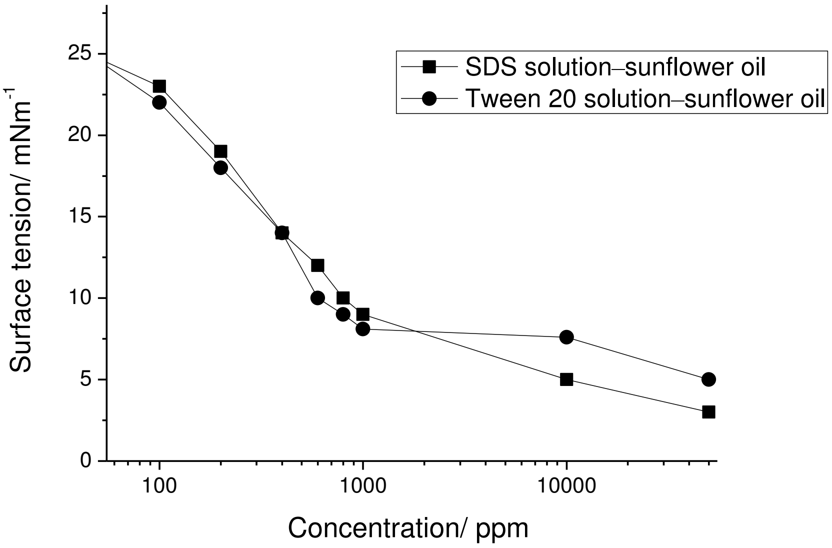


Figure 6. Extent of deformation of distilled water drops in sunflower oil as a function of the electric field strength. Average radii of the drops: ■: 607±13μm and ▲:789±18μm, interfacial tension: γ =32 mN/m

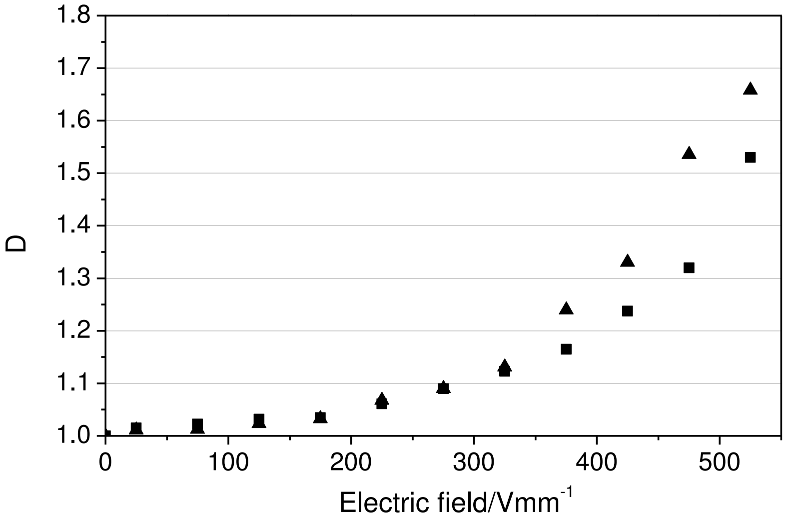


Figure 7. Extent of deformation of 5×10^4 ppm SDS solution drops in sunflower oil as a function of the electric field strength.

Average radii of the drops:■: 459±7μm, ●: 626±14μm and ▲: 791±17μm, interfacial tension: γ=3 mN/m.

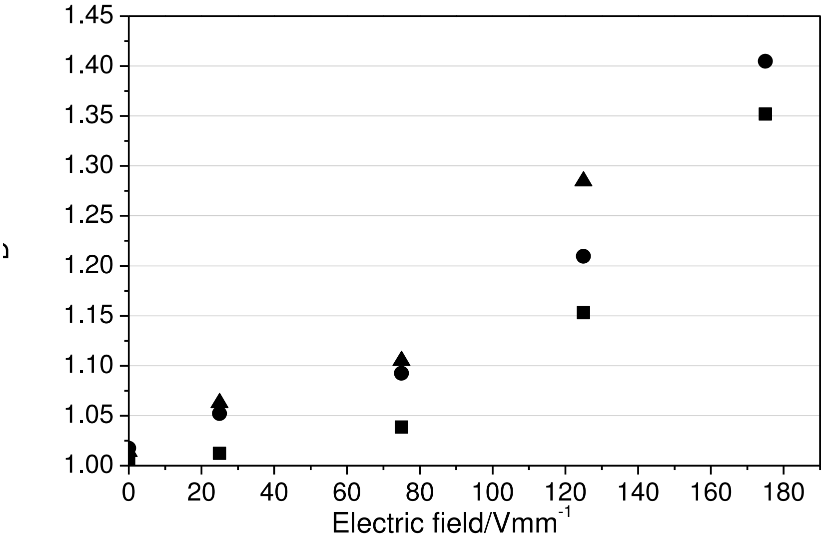


Figure 8. Extent of deformation of liquid drops in sunflower oil as a function of the electric

field strength. The average radii interfacial tension are as follow: ▲: distilled water, 607±13 μm, γ=32 mN/m; ●: Tween 20 solution, 621±9 μm, γ=5 mN/m; ■: SDS solution, 626±14 μm; γ=3 mN/m. The concentration of Tween 20 and SDS are 5×10^4 ppm.

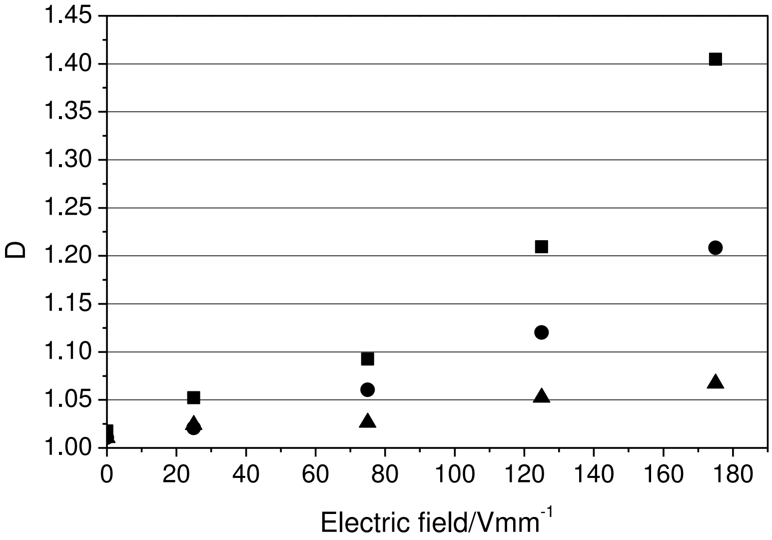


Figure 9. Deformation of SDS solution drops at various applied d.c. electric field strengths:

(a) 0 V/mm; (b) 75 V/mm; (c) 125 V/mm; (d) 175 V/mm, (e) 190 V/mm

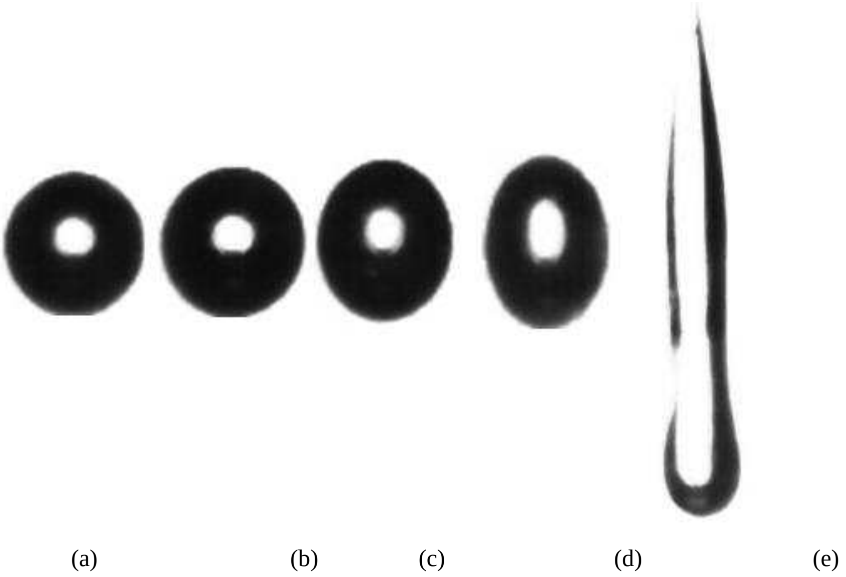


Figure 10. Extent of deformation of liquid drops in sunflower oil as a function of the electric

field strength. ■: distilled water, γ=32 mN/m, 789±18μm; ●: 100 ppm SDS solution, γ=23 mN/m, 767±12μm; ▲: 5×10^4 ppm SDS solution, γ=3 mN/m, 791±17 μm.

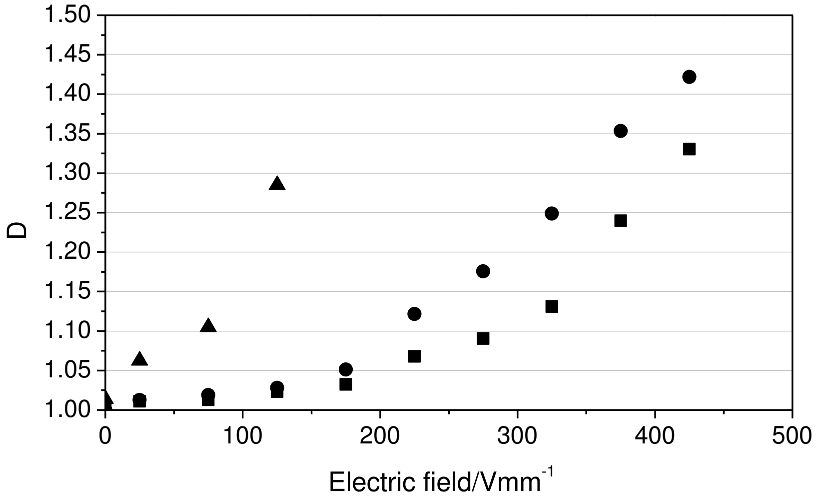


Figure 11. Extent of deformation of liquid drops in sunflower oil as a function of the electrostatic Weber number for the liquid-liquid systems

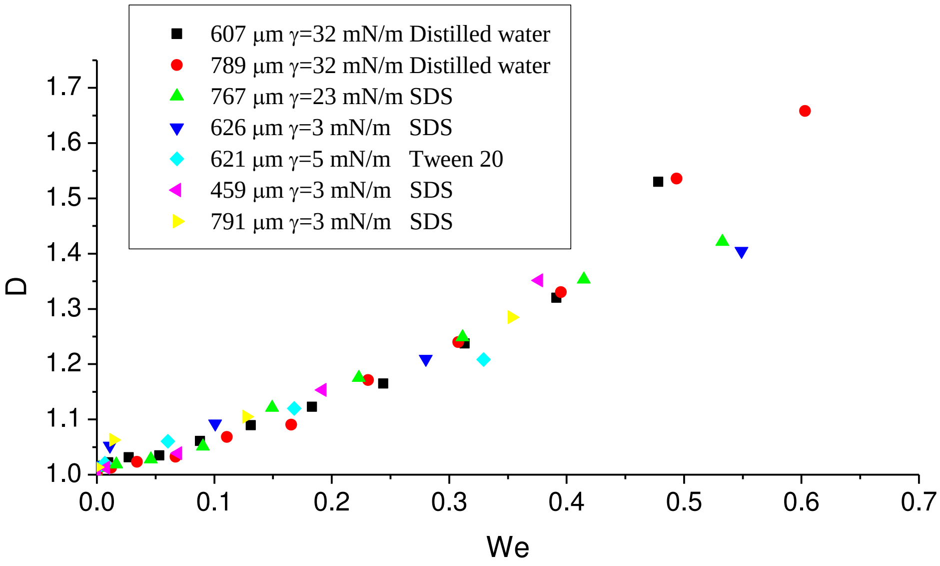
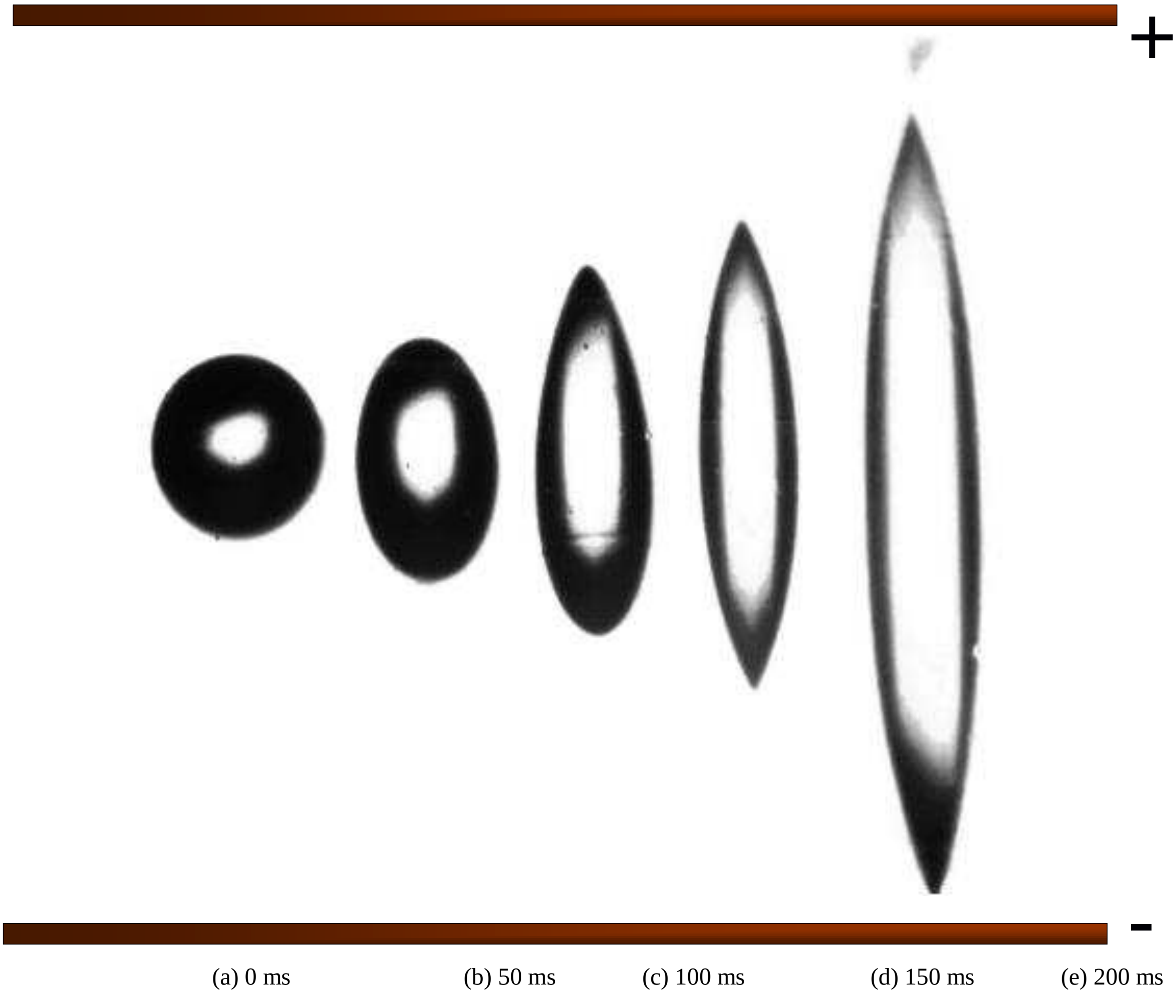


Figure 12. The break-up of a distilled water drop of radius 912 µm at an applied electric field strength of 475 V/mm, interfacial tension γ =32 mN/m



(a) 0 ms (b) 50 ms (c) 100 ms (d) 150 ms (e) 200 ms

Figure 13. The break-up of a100 ppm SDS solution drop of radius 758 μm at an applied electric field strength of 413 V/mm, interfacial tension γ =23 mN/m

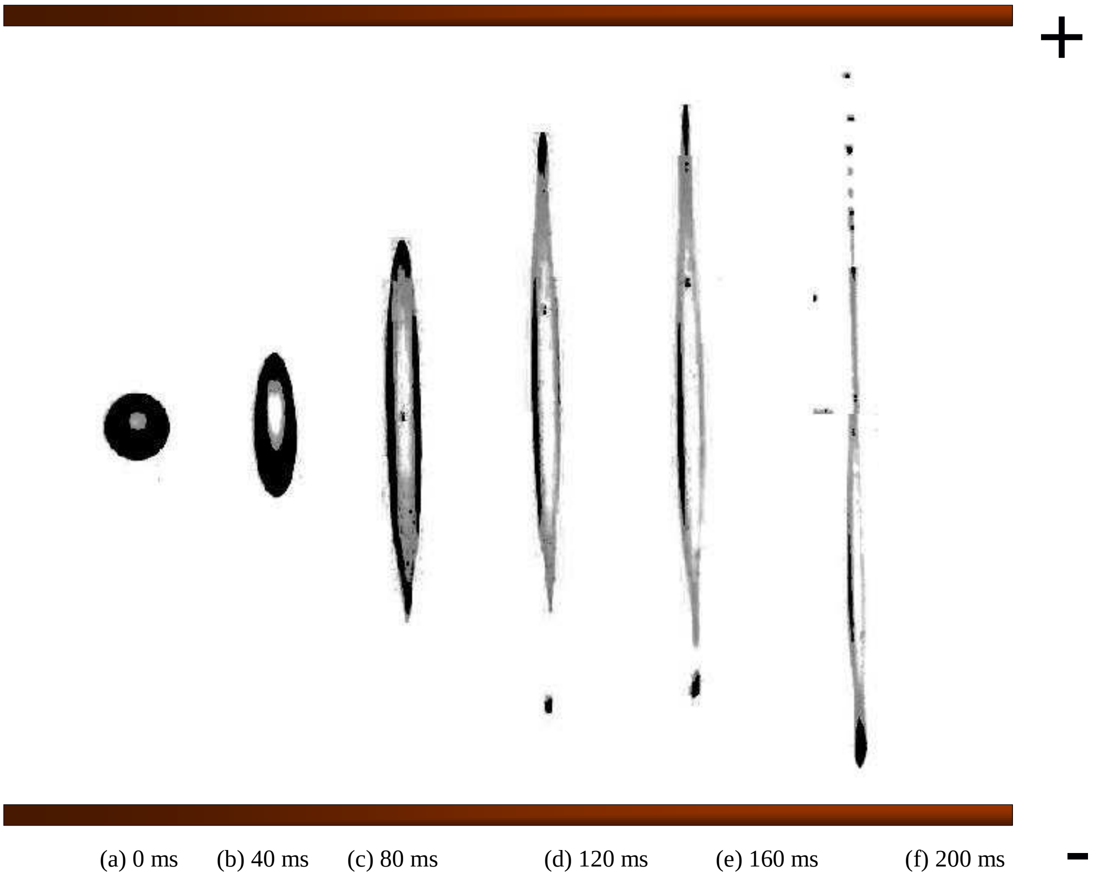
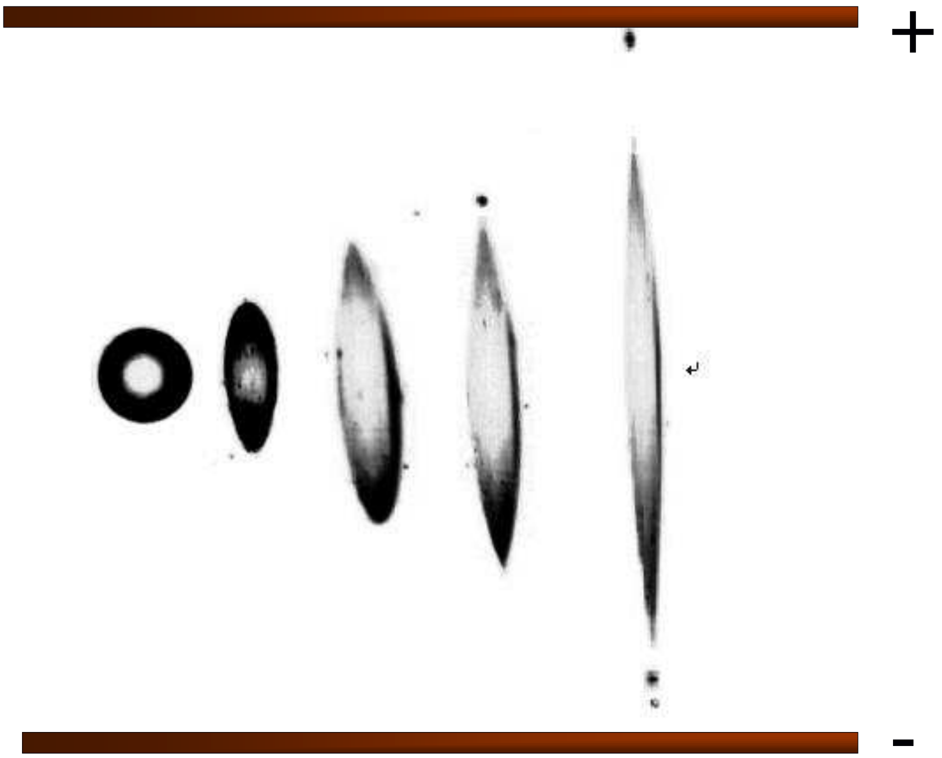
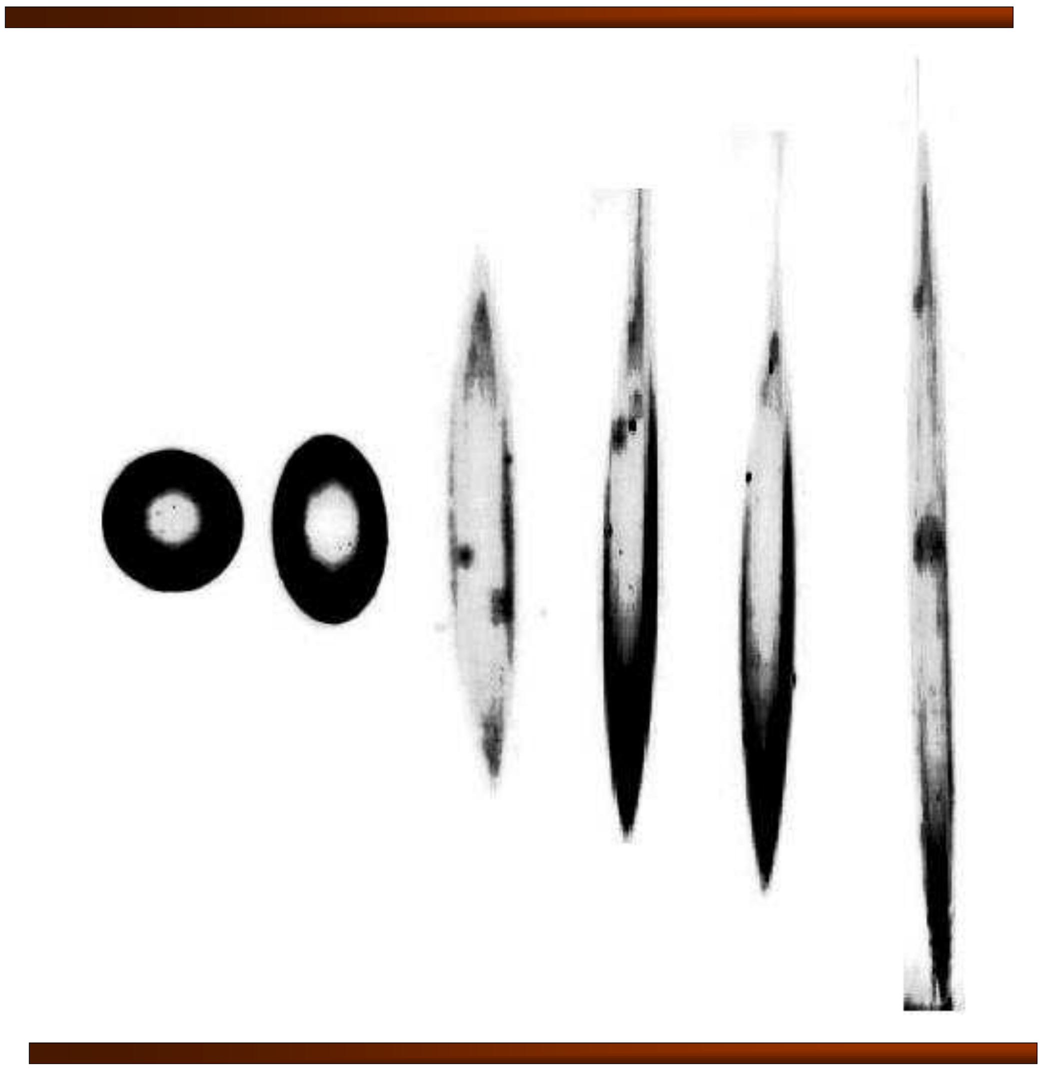


Figure 14. The break-up of a100 ppm Tween 20 solution drop of radius 758 μm at an applied electric field strength of 475V/mm, interfacial tension γ=22 mN/m



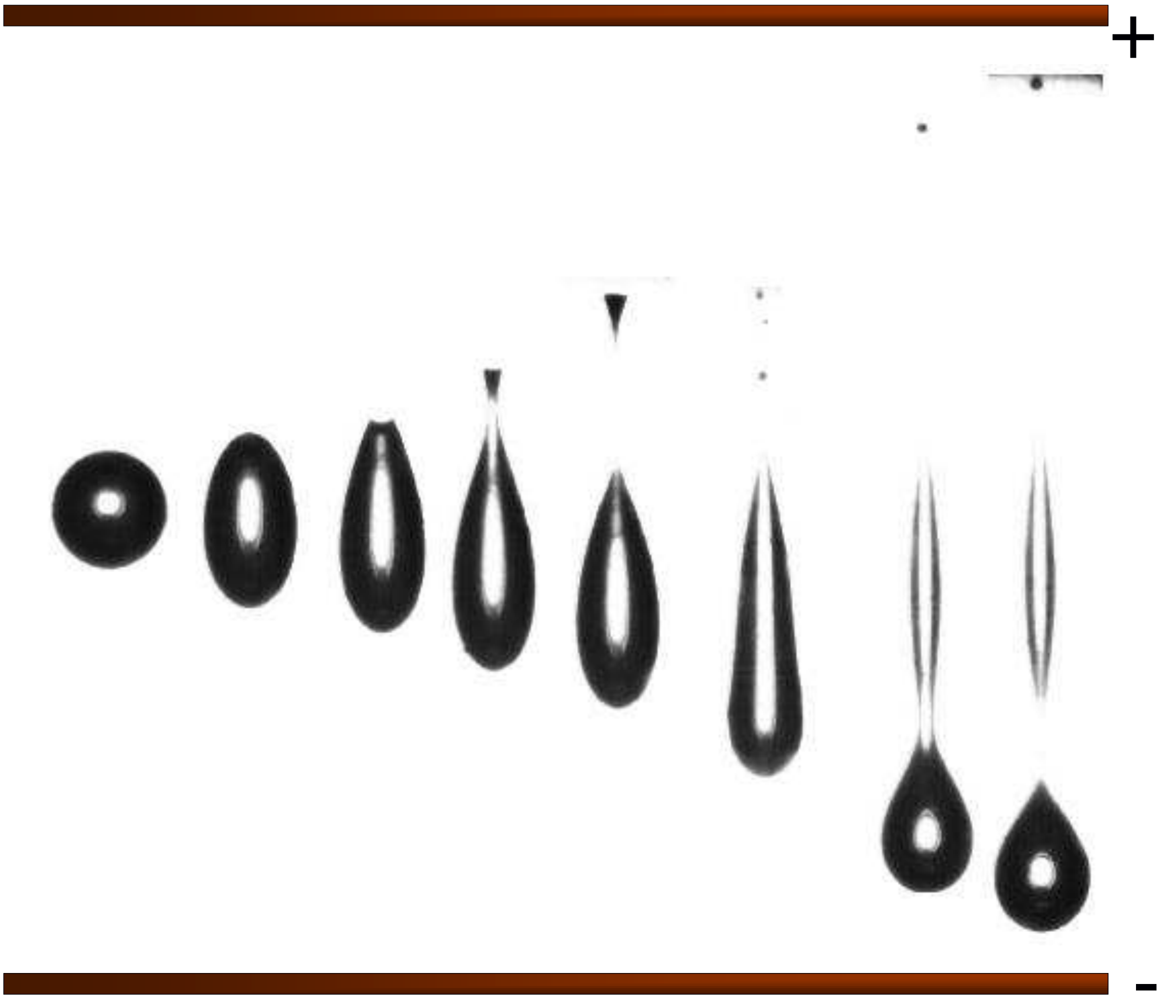
(a) 0 ms (b) 50 ms (c) 100 ms (d) 150 ms (e) 200 ms

Figure 15. The break-up of a 5×10^4 ppm Tween 20 solution drop of radius 702 μm at an applied electric field strength of 175 V/mm, interfacial tension γ =5 mN/m.



(a) 0 ms (b) 40 ms (c) 60 ms (d) 100 ms (e) 120 ms (f) 140 ms

Figure 16. The break-up of a 5×10^4 ppm SDS solution drop of radius 780 µm at an applied electric field strength of 175 V/mm and interfacial tension γ =3 mN/m



(a) 0 ms (b) 120 ms (c) 200 ms (d) 240 ms (e) 260 ms (f) 312 ms (g) 348 ms (h) 360 ms

Figure 17. Schematic presentation of the SDS surfactant distribution structure of adsorption layers during the drop deformation when applied electric field

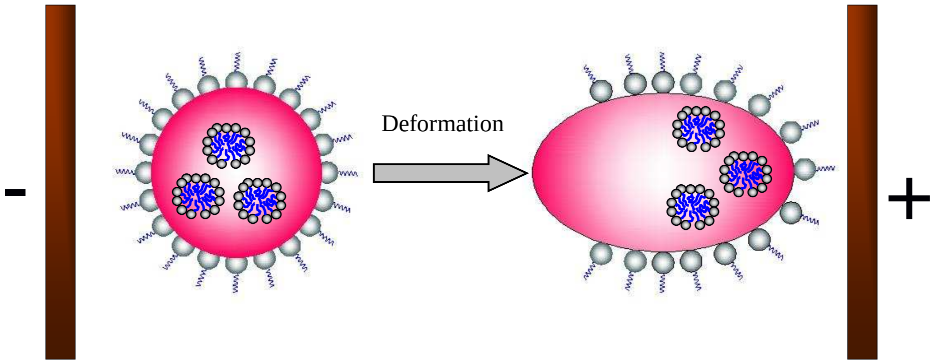

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Table 1 The properties of the liquid used in the experiment

Liquids	Conductivity (μs/m)	Viscosity (Pa·s)	Surface tension (mN/m)	Density (kg/m^3)	Dielectric constant
Distilled water	100	9.77×10^{-4}	73	998	83.1
Sunflower oil	27	1.163×10^{-2}	32	905	4.9

The measurements are at 1 atm and 20ºC