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A novel bench size model coalescer: dehydration efficiency of AC fields on water-in-crude-oil emulsions

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ABSTRACT

We describe herein the design of a small ac electrostatic model coalescer for investigating coalescence efficiency of water in oil emulsions. The function of the model coalescer is tested on emulsions with different water cuts. In the coalescer, coalescence takes place in a couette flow in the bulk emulsion. The electric field has a high utilization factor, and the electrodes are insulated to avoid drop charging. The set-up allows for independent setting of retention time and shear rate of the emulsion. Temperature can be adjusted up to 80 °C, and AC voltage level, frequency and shape can be varied. Efficiency is measured optically and by checking speed of water precipitation. Several parameters have been studied to determine their influence on the electrostatic dehydration process of water-in-crude-oil emulsions. Temperature, wave form, water content, droplet size but also rotational speed were found to play an important role in the process according to what was expected theoretically.

Index Terms — separation, oil, electrical engineering, chemical engineering, electrical equipment industry.

1 INTRODUCTION

The formation of a water-in-crude oil emulsion is a well-known problem in the oil industry, as asphaltenes, inorganic particles and surfactants naturally present in the crude oil stabilize the emulsion [1]. There exist several techniques to enhance the separation of these two phases, such as chemical demulsification, pH adjustments, gravity or centrifugal settling, filtration, heat treatment and electrostatic demulsification. Electrical demulsification is considered to be the best method regarding energy efficiency and environmental impact, as it permits a reduction of the heat, and avoids the use of chemical additives [2]. Electrocoalescence has been used in the industry for several years and has been reviewed elsewhere [3, 4]. Application of an electric field polarizes the water droplets and assists the merging of small droplets into larger ones. Some coalescence can occur due to Brownian motion and differential segmentation, but these effects are insignificant compared to electrocoalescence [5]. State-of-the-art CECs are in-line flow devices designed to increase the mean size of water droplets by merging and, therefore, to reduce the time required for their sedimentation under gravity. Though, the control and increase of their efficiency remain, to date, particularly challenging as the numerous phenomena involved in electrocoalescence are far from being fully understood [6].

Electrocoalescence efficiency in compact coalescers is explained by electrostatic dielectrophoretic attractive forces acting between adjacent drops that are brought close by a shear flow in the bulk emulsion [7]. Long range electrophoretic forces are considered of less importance as water drops are likely to be charge neutral, both because the electrodes in a compact coalescer is insulated, and because the drops will discharge due to a high conductivity in a crude oil.

Experiments on coalescence efficiency have hitherto either been done for stagnant emulsions, or in emulsions in a flow using either flow loops or viscosimeters. A stagnant emulsion will not be representative as – in a low water cut emulsions – drops will remain too far apart for dielectrophoretic forces to act [8]. Flow loops has the disadvantage that it is difficult to freely adjust retention time of the emulsion in the electric field from the flow regime (laminar/turbulent). Using viscosimeters has shown informative results [4, 9]. However, there are concerns that this may not be representative for the bulk process taking part in a compact coalescer. In the coalescer the electric field is fairly homogeneous and electrodes are insulated, while in the viscosimeter the electric field will be inhomogeneously concentrated at sharp edges in the bob, and maybe more severe the electrodes are metallic and the electrode gap very small resulting in drop charging. One is therefore afraid that the coalescence will be a surface process with charged water drops, not representative for the realistic bulk process with charge neutral drops

The present paper focuses on the building up of a new bench size model coalescer with an internal Couette flow in the emulsion, and with insulated electrodes and a large active volume to provide a uniform electric field in the bulk oil. This all allows for independent adjustment of all parameters of interests. Herein several parameters will be studied to determine their influence on the electrostatic dehydration process of water-in-crude-oil emulsions.

2 EXPERIMENTAL

2.1 PREPARATION OF THE EMULSIONS

Unless specified otherwise, water-in-oil emulsions were prepared using, for the oil phase, 80 vol.% crude oil from the Heidrun oilfield on the Norwegian Continental Shelf (kindly provided by Statoil) and for the water phase, 20 vol.% of synthetic brine consisting of 3.5 wt. % NaCl in Milli-Q water ($> 18.2 \text{ M}\Omega\cdot\text{cm}$). Prior to the emulsification process, the samples were heated at $70 \text{ }^\circ\text{C}$ for 60 minutes to solubilize the waxes in the oil. Emulsification was carried out with a Heidolph DIAX 900 ultra turrax (tool 10G) at 11600, 15200 or 18800 rpm for 60 s. The emulsion was immediately poured into the test tube for further testing.

2.2 INSTRUMENTATION

Figure 1 shows a schematic of the in-house model coalescer used herein. The chamber, about 140 mm in diameter, is filled with a heating electrically insulating liquid (Nytro 10X) which circulates through a Julabo MC heating bath to provide a controlled temperature during the experiments. The emulsion is kept in a glass cylinder, 50 mm in diameter, with a 35.6 mm dia. rotor, providing shear to the emulsion. The electric field is applied by two uncovered plane electrodes 55 mm apart. High voltage is fed to the electrodes from a Trek 20/20B HV amplifier, supplied by a Wavetek function generator. Voltage amplitude and waveform is recorded by a Tektronix TDS 2024B oscilloscope. The emulsion separation is recorded by a PixeLINK camera, taking pictures of the glass cylinder every 5 seconds for 1 hour.

This model coalescer presents many advantages over other bench size dehydration efficiency tools used elsewhere. The electrodes are completely insulated; meaning that the droplets are not subjected to any metallic surfaces hence no possibility of charged droplets. The dehydration is observed visually via a window in the test cell.

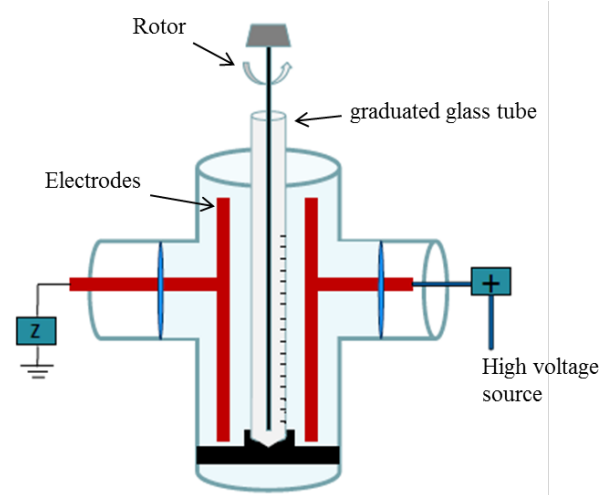


Figure 1. Schematic of the model coalescer. The inner and outer cylinder radius are 35.6 and 45 cm, respectively.

In an electrostatic coalescer water drops are polarized by the external electric field, and the resulting force between adjacent drops from the induced dipole moment will always be attractive [10]. The force is inversely proportional with the distance to the fourth, and is only significant within a distance of the order of the diameter of the smaller drop. When the drops get very close, the attractive forces between the drops increases strongly. As the attractive forces between drops are short-ranged, shear flow is introduced in the liquid to allow drops to get within the range of the electrostatic forces. Charged drops will discharge with a time constant given by the time constant of the bulk oil [11]. In the model coalescer, rotor speed and electric field can be varied independently to study the effect of the two parameters.

2.2.1 CYLINDRICAL COUETTE FLOW

The model coalescer establishes a cylindrical Couette flow in the gap between the inner rotating cylinder and the stationary outer tube. For low Reynolds number the flow is steady, and the velocity has only an azimuthal component. Above a critical angular velocity of the rotor the viscous forces exceed centrifugal forces and the flow becomes unstable, forming a Taylor vortex flow. This was first described theoretically by Taylor in 1923 [12] At even higher Reynolds number the flow will be turbulent. Taylor showed that if only the outer cylinder rotates, the flow will remain stable. It was however, not possible to design the model coalescer this way.

Solving Navier-Stokes equation for an incompressible Newtonian liquid, when only the inner cylinder rotates, gives the azimuthal velocity

$$V(r) = Ar + \frac{B}{r}$$

$$A = -\Omega \frac{\eta^2}{1 - \eta^2} \quad B = \Omega \frac{r_i^2}{1 - \eta^2} \quad \eta = \frac{r_i}{r_o}$$

where Ω is the angular velocity of the rotor and η is the ratio of the inner and outer cylinder radius. For our coalescer $\eta = 35.6/45 = 0.791$. The resulting flow profiles are shown in Figure 2.

The Reynolds number is given by

$$Re = \Omega r_i \frac{r_o - r_i}{\nu}$$

where ν is the kinematic viscosity. For $\nu = 0.8$ transition to vortex flow occurs when $Re_{crit} = 94.7$ [13]. Emulsion viscosity will strongly depend on the type of crude oil and temperature. Based on the last equation, for a typical value of 25 cP we find that the flow becomes unstable when the rotor speed exceeds about 180 rpm.

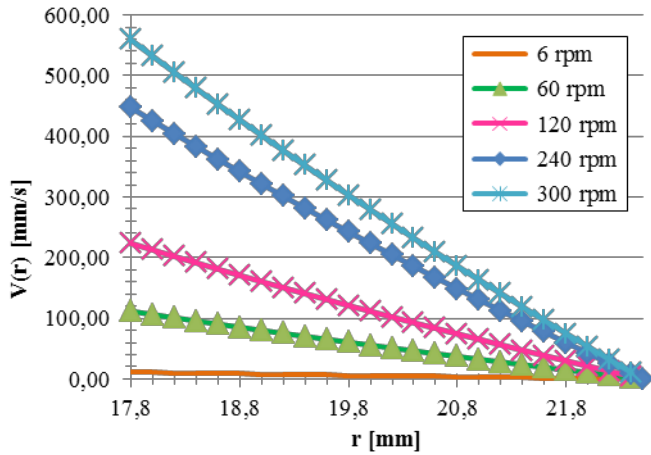


Figure 2. Flow profiles calculated for the model coalescer at various shear rates.

2.2.2 APPLIED VOLTAGE

The emulsion in the model coalescer is insulated from the electrodes by the glass tube, meaning that a bridge of water droplets cannot cause a short circuit and will not be charged by induction from metallic electrodes. As the resistivity of the insulator is much higher than the resistivity of the emulsion, a DC voltage will end up across the insulation and there will be no field in the emulsion to drive the coalescence. This is overcome by applying an AC voltage with a high enough frequency to get a capacitive voltage distribution [11]. It is preferred to use a bipolar square wave voltage (BSV). The electrostatic force stretching a water drop is proportional to $|E|$, while the attraction force between two adjacent drops is proportional to E^2 . Now, the rms value of a bipolar square wave voltage is the same as for a DC voltage with the same amplitude. Thus E^2 and the drop stretching take a constant value and there will be no drop oscillations. Further, there will not be any frequency dependence in the attraction force between the droplets.

2.3 DROPLET DISTRIBUTION DETERMINATION

The droplet sizes were measured using a KEYENCE VH-2100 microscope, and analysed using the freeware ImageJ. A drop of diluted emulsion (emulsion to crude oil ratio 1:8) was placed on the microscope glass immediately after preparation. At least 800 droplet diameters were determined

in order to produce a reliable size distribution curve. The distribution was measured to be centred on the diameters 40-60 μm for the emulsion prepared at 11600 rpm, 10-20 μm at 15200 rpm and 5-10 μm at 18800 rpm. This is a representative distribution for the emulsion reaching industrial separation facilities, which usually contains water droplets with diameters 5-50 μm [2].

3 RESULTS AND DISCUSSION

For all the experiments described hereafter, unless mentioned otherwise, the emulsions were prepared at 11600 rpm for 60 s, meaning that the droplets were measured to be ca 40-60 μm . The 4 kV/cm electric field was applied for 5 s with a square waveform and the shear rate of the rotor was 120 rpm. Moreover an emulsion not submitted to any electric field was studied and no visible separation was observed after 60 minutes.

3.1 INFLUENCE OF THE FREQUENCY

The influence of frequencies ranging from 100-5000 Hz has been studied, and the results are shown Figure 3. The results show that there is no significant relation between frequency and dehydration efficiency in this range, as the deviations in this range can largely be attributed to random variations between experiments except maybe for 5000 Hz where the destabilization seems to occur faster than for the other studied frequencies. Nevertheless after less than 20 minutes, the degree of separation is similar to the ones obtained by lower frequencies. This is consistent with the predictions made by Mohammadi et al. [14] and the experiments conducted by S. Less et al. [4], which both show that the frequency dependencies are not significant to the results.

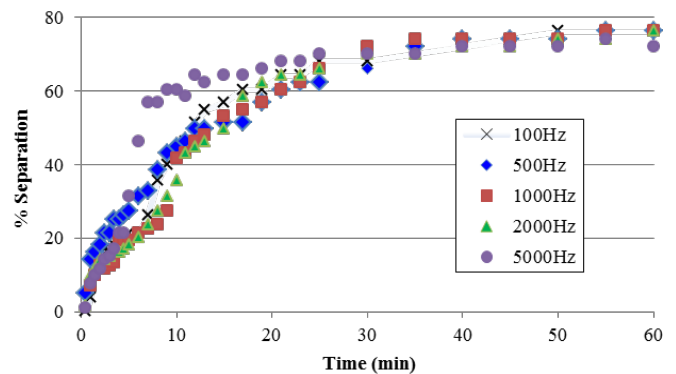


Figure 3. Degree of separation as a function of time for emulsions subjected to a 4 kV/cm electric field for 5s. Influence of the frequency.

3.2 INFLUENCE OF THE ROTOR SPEED

The influence of the rotor speed was investigated with four different shears; 0, 60, 120 and 240 rpm, and the results are shown Figure 4. It is obvious that the rotor speed has a large influence on separation rate and efficiency. For instance after 60 minutes, when a shear of 60 or 120 rpm is applied, the visualized amount of separated water is ca 80% while it is only ca 65 % when no shear was applied. Besides, the onset of separation occurs much earlier. The

fastest separation is obtained when the rotor speed was 60 rpm. Indeed, after only 10 minutes; 68% of the water present in the emulsion can be retrieved, while with a rotor speed of 120 rpm, only 44% of separated water can be observed at the bottom of the glass cell. Nevertheless, after 60 minutes, the differences between these two rotor speeds has disappeared (ca 80% of separation). Less et al. [2] found that the rate of separation increased for high shear rates over lower shear rates, but it was not specified what was defined as high and low shear. The rotor used in our setup did not allow speeds lower than 60 rpm, so it was not possible to investigate the effects of even lower speeds. For a high rotor speed (240 rpm), the dehydration efficiency collapses. It becomes even less efficient than when there is no shear applied. After 60 minutes only 30% of the water present in the emulsion can be retrieved (65% when there is no shear). A possible explanation would be that the thin film covering the droplets cannot break fast enough for coalescence to occur during the time where the droplets are in proximity of each other. It is also possible that at sufficiently high rotor speeds, the sample might get slightly re-emulsified leading to a competition with coalescence. But, as stated in Section 1), for an emulsion with a typical viscosity value of 25 cP, we find that the flow becomes unstable when the rotor speed exceeds about 180 rpm which is below the shear rate applied here.

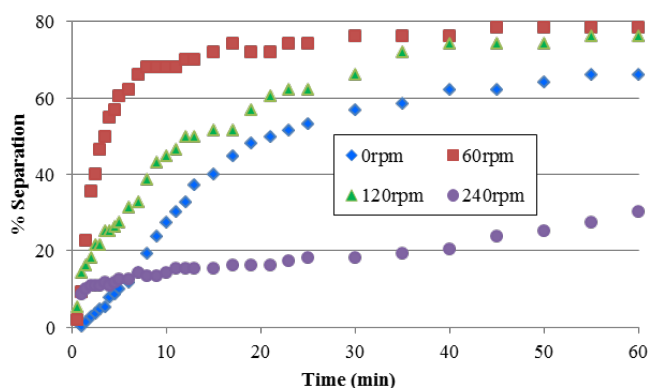


Figure 4. Degree of separation as a function of time for emulsions subjected to a 4 kV/cm electric field for 5s. Influence of the rotor speed.

3.3 INFLUENCE OF THE WATER CONTENT

The influence of the amount of water in the emulsion has been studied and the results are shown Figure 5. Destabilization of emulsions with 5, 10 or 20 vol.% of water, as a function of time were measured. It is obvious from the observation of this Figure that the best separation yield is obtained for higher water cuts. This was expected since a higher water cut means a shorter distance between droplets increasing the probability of meeting, hence coalescence.

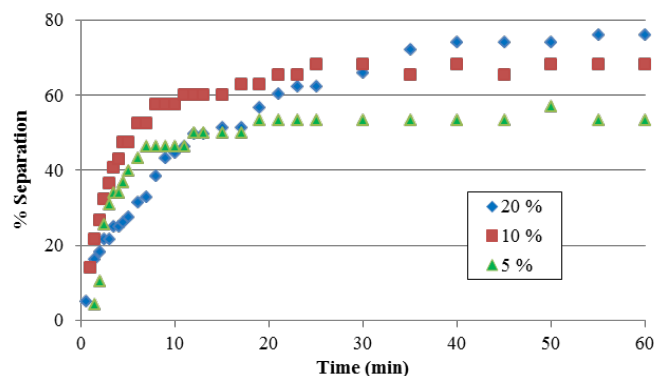


Figure 5. Degree of separation as a function of time for emulsions subjected to a 4 kV/cm electric field for 5s. Influence of the water content.

3.4 INFLUENCE OF THE TEMPERATURE

The crucial influence of the temperature on the dehydration efficiency is shown Figure 6. For all the systems studied the dehydration efficiency increased with increasing temperature. For instance after 10 minutes, only 44% of the water present in the emulsion was separated at 20 °C, while it was 66 and 76 % at 40 and 60 °C, respectively. These results were expected since sedimentation speed is proportional to 1/viscosity; an increase in temperature will cause a drop of the viscosity of the emulsion hence a higher sedimentation speed. Moreover, one can observe that after 60 minutes, the same equilibrium was reached at 40 and 60 °C, ca 85% of separation, while at 20 °C only 75% of water was retrieved.

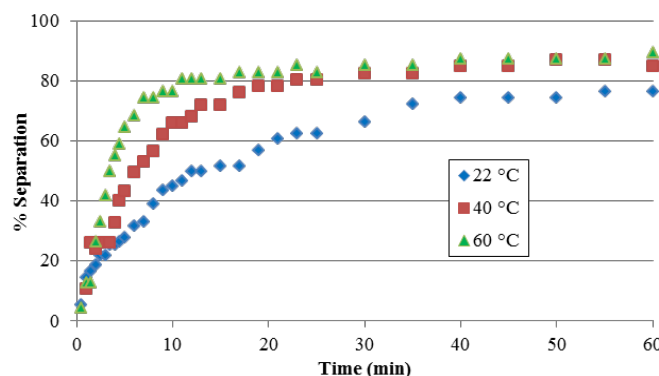


Figure 6. Degree of separation as a function of time for emulsions subjected to a 4 kV/cm electric field for 5s. Influence of temperature.

3.5 INFLUENCE OF THE WAVE FORM

The influence on the emulsion of sinusoidal and square waveform signals were investigated, and the results are shown Figure 7. It is clear that the choice of waveform signal is important, as the sinusoidal waveform seems less efficient than the square waveform signal. Theory predicts the square waveform to be 1.41 times more effective than the sine waveform. This trend was almost consistent with the results obtained here, that showed a ratio between separations obtained with square waves to separations obtained with sine waves to be between 1.1 and 1.2. However for the same RMS value, the sinusoidal wave ($URMS = U_{max}/\sqrt{2}$) form is more efficient than the square

wave form (URMS = Umax). Consequently, for the same energy input, the sinusoidal wave form is more efficient than the square one.

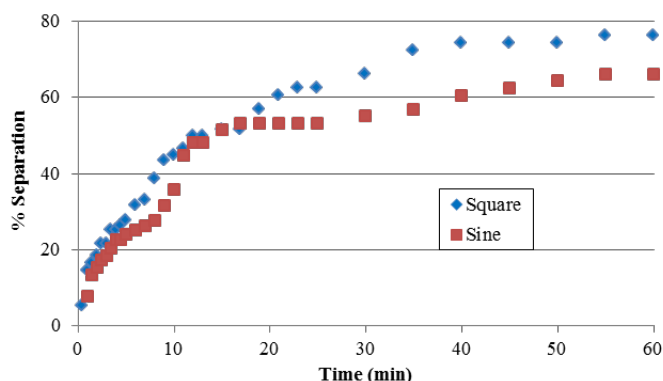


Figure 7. Degree of separation as a function of time for emulsions subjected to a 4 kV/cm electric field for 5s. Influence of the electric field wave form.

3.6 INFLUENCE OF THE DROPLET SIZE DISTRIBUTION

The influence of the water droplets sizes in the emulsion has been studied for two different rotor speeds, 120 and 240 rpm, and the results are shown Figure 8. For a rotational speed of 120 rpm (Figure 8A), the results show that there is no significant relation between droplet size and dehydration efficiency in this range, as the deviations in this range can largely be attributed to random variations between experiments. On the contrary, for a rotational speed of 240 rpm (Figure 8B), one can observe huge differences between droplet size distributions. While the efficiency of separation is reduced for higher rotational speed using droplets in the size range 40-60 μm , higher rotor speeds provides increased separation efficiency for droplets in the size range 5-10 μm . The effect here is evident only after a relatively long period of time (after 20 minutes). The reason for the importance of the rotational speed lies in the fact that the AC field does not provide any relevant droplet migration. For droplets to coalesce they need to be in close proximity to each other over a certain period of time, and an external force is needed to get the droplets into proximity of each other. Lower rotor speeds create the necessary turbulence, but give the droplets a longer time to coalesce. For higher rotational speeds, the flow becomes unstable and the thin film covering the droplets will not destabilize fast enough for coalescence to occur during the time where the droplets are in proximity of each other.

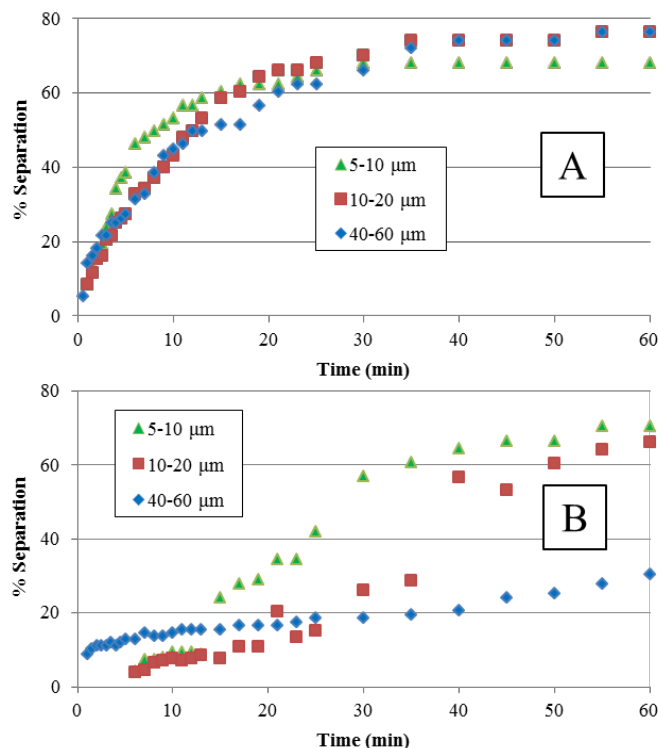


Figure 8. Degree of separation as a function of time for emulsions subjected to a 4 kV/cm electric field for 5s. Influence of the droplet size distribution for two different shear rates, 120 (A) and 240 (B) rpm.

4 CONCLUSION

A bench size in-house model coalescer providing uniform electric fields was conceived in order to study dehydration efficiency of water in crude oil emulsions. Destabilization was investigated with respect to temperature, rotation speed, water content, frequency and waveform of the electric field. Increasing the temperature or the duration of the field (not shown herein) resulted in a faster separation of the water and oil phases. The waveform also affects the separation, and a sinusoidal waveform is more effective than a square waveform for a similar RMS value. Increasing the rotor speed up to a certain level increases also the separation, before it drops again for high speeds. The separation process was shown to be more efficient for higher water contents, but no dependency between water cut and rotor speed was found. Moreover, a clear relationship between frequency and separation efficiency was not found. With this model coalescer, obvious findings are demonstrated that for instance electrocoalescence is more efficient when the inter-droplet distances are small and hence, the probability of collision is high.

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