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ORIGINAL CONTRIBUTION

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Selective membrane test for crude oil based model emulsions by use of video-enhanced microscopy

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Abstract A method for testing water/oil emulsion droplet membranes selectively has been demonstrated. The method uses electric fields to induce attraction, membrane thinning and coalescence between aqueous droplets deposited in an oil continuum. The coalescence process is monitored visually by the use of videomicroscopy. A set of model oils containing indigenous surfactants (asphaltenes) from a crude oil has been studied, and the effects of asphaltene concentration, oil phase aromaticity, aging of oils and interfacial exposure time have been investigated. The strength of the field at the point of coalescence is defined as the critical parameter describing membrane strength. In the current experiments a.c. fields were used and droplet sizes were of the order of 500–600 μm.

Key words Water/oil emulsions – Emulsion stability – Membrane strength – Asphaltenes – Electric fields – Videomicroscopy

Introduction

Central to any process involving the handling of emulsions is the prediction and testing of emulsion stability. This applies irrespective of whether stability represents a problem or a benefit. In the oil industry the mixing of water and crude oil during production and transport presents the possibility of emulsions being formed, as natural surfactants stabilize droplets of one liquid in the other. As the emulsified state presents adverse rheological properties compared to the non-dispersed state the problems of resolving such emulsions often need to be addressed. Gravity-enhanced and chemically enhanced separation are much used, along with other mechanical methods. Also, electric fields have long been applied to force the separation of aqueous droplets from an oil continuum [1–3]. Over the years studies have been performed to elaborate on the effects of different variables connected to electrical demulsification. Naturally, the main aim has been to survey the factors leading to more efficient separation, for example, the effect of the pulsation frequency of a d.c. field [4, 5], of the frequency of an a.c. field [6, 7], of the strength of an a.c. field [8], of an a.c. field in turbulent flow conditions [9], and so on.

Taylor [10] made microscopy studies of high-voltage gradients applied to water in crude oil emulsions, classifying two different types of droplet behavior, related to interfacial rheology. Droplet chain formation is encountered when the rigidity of the droplet–oil interlayer hinders compression, preventing coalescence. The second type finds droplets coalescing readily when the interlayer is compressible.

Brown and Hanson [11] studied the effect of oscillating electric fields on the coalescence of water droplets at an oil/water interface by measuring the residence times of droplets at the interface. They concluded that the electric field in addition to increasing the rate of drainage of the film also increased the probability of film rupture at any given thickness of the film; this they suggested could be attributed to electrophoretic effects inside the film, interfacial deformation, local increases in temperature, or mechanical stress on the drop boundary.

Bhardwaj and Hartland [12] studied the effect of aging in the crude oil/water interface. The slow build-up of the interfacial layer on a suspended oil droplet was followed visually with a videomicroscope. It was found that the adsorption of indigenous surfactants from the oil was not complete even within 60 h. Further, the rate of adsorption of added demulsifier was probed by drop-volume dynamic interfacial-tension measurements, and was found to be correlated to the rate of demulsification.

Waterman [13] presented two mechanisms of separation due to the effect of electric fields; first that of attraction between induced dipoles in either a.c. or d.c. fields, and second that of charged particles in a unidirectional field. It was stated that water droplet coalescence in a crude oil continuum should be at least as effective with a.c. fields as with d.c. fields, which he attributed to dipole coalescence being the most important coalescing mechanism.

One way of testing emulsion stability by electrical means is high-voltage time-domain spectroscopy [14, 15]. The permittivity of the emulsion is monitored as a function of increasing strength of an applied field. When a critical field strength (E_{cr}) is reached a drastic change in the permittivity signals that droplet membranes are broken to form a continuous aqueous channel between the electrodes. This critical parameter is thus a measure of the emulsion stability.

The motivation for developing selective membrane testing (SMT) is that the high-voltage time-domain spectroscopy technique operates on large droplet populations with some size distribution. In order to be able to control the effects of droplet size and to avoid the added complexity of polydispersity, SMT uses well-defined mini-populations of down to two droplets. The critical parameters measured will then apply to the specific system under study, and thus to the well-defined membrane of that system.

In the SMT cell a pair of droplets is forced to coalesce. The droplets are brought into contact prior to the field being switched on, so that the effect of the field will be that of making the droplets pull toward each other, narrowing the membrane and eventually forcing it to break. It follows that the actual resistance against membrane compression, thinning and rupture is measured. This resistance is brought about by the chemical and mechanical properties of the interface, for example, the forces between the species of the film and presence of well-adsorbed particles causing long-range steric repulsion.

For the purpose of exploring different aspects of the method it was applied to water droplets in model oils of asphaltenes in toluene/decane mixtures. It has been established (e.g. Refs. [16–18]) that these components form a film at the water/oil interface which stabilizes the aqueous droplets and prevents coalescence. The main mechanisms associated with this are the formation of a molecular film giving rise to steric stabilization [19] and also the adsorption of particles into the film [20]. As described below, the state of the asphaltenes greatly influences the nature of the film, and thus the stabilizing properties.

The issue of particle-stabilized emulsions is a field of extensive study, due to the high efficiency such stabilization can exhibit. Ramsden [21] reported this feature in 1903, having observed solid particles accumulating at an oil/water interface. Finkle et al. [22] made the connection between the three-phase contact angle and the type of emulsion, the continuous phase being the liquid which best wet the particles. Two conditions remain: first, the particles must be partially wettable by both liquids (the contact angle being between 0° and 180°), and second, the size of the solid particles must be smaller than that of the droplets [23]. Menon and Wasan [24] investigated solid particle-stabilzed water-in-oil emulsions and found a tripling of stability by adding 0.1 wt% dust particles. From this they concluded that the concentration and interfacial packing of solids were essential for stability. The same authors have also investigated the effect of asphaltene adsorption on the hydrophobicity of solid particles (montmorillonite clay) [25]. The mean particle size was 4 μm, which corresponds to the size regime of the asphaltene particles of the current study. Interestingly, Menon and Wasan [25] observed the hydrophobic particles completely coating water drops dispersed in a heptane/toluene oil mixture, preventing interdroplet coalescence under mechanical stress (shaking) – a feature reproduced here. It seems reasonable that such a coated clay particle may in some respects serve as a model for "pure" asphaltene precipitate particles, an important advantage being that of thorough size control.

Experimental

The high-voltage cell for selective membrane testing

The cell is designed in a way which enables visual study of the sample in the horizontal plane, normal to the direction of gravity. This allows monitoring of gravity deformation of the droplets (which is a function of the droplet size and interfacial properties [26, 27]). It is desirable that such deformation is as low as possible, as the droplet geometry can influence the effect of the electric field. This in turn puts some restrictions on the interfacial tension of the systems under study. If the presence of surface-active species results in low interfacial tension, only very small droplets can retain a geometry close to spherical, which may put the droplet size outside a practical experimental range. The SMT cell was designed for use with droplet sizes between 0.4 and 0.8 mm. This range enables simple methods of droplet deposition and manipulation, but is in turn sensitive to interfacial tension.

The cell frame is made from a block of poly(tetrafluoroethylene) into which a central chamber has been cut. Entrances for the electrodes are drilled through the frame walls, forming a slight depression on the cell floor in which the deposited droplets can rest; thus, the droplets are aligned in the field direction between the electrodes. The electrodes are gold-coated brass screws. They can be repositioned along the field axis simply by turning them. This can also be used to move the droplets, for example, when forming the doublets. A consequence is that the electrodes are cylindrical with flat ends, giving field characteristics as shown in Fig. 1. Two injector openings are drilled through the top of the frame. Through these the oil phase can be injected and the droplets deposited.

The transparent cell walls are made from borosilicate glass, effectively hydrophobized with a chlorosilane. The cell can be completely disassembled for thorough cleaning, and all components are resistant to toluene, for example. A sketch of the cell is seen in Fig. 2.

The field characteristics can be controlled from a function generator/amplifier and monitored with an oscilloscope. The generator is a Siwatsu SG-4111. The amplifier was built specially for high-voltage cells by Christian Michelsen Research (Bergen, Norway) and at the design input signal provides tension in the range 0–350 V. The oscilloscope is a Hewlett Packard 54601 A.

The microscope used is an Olympus SZ11 stereomicroscope (1.8–11×) mounted on a tiltable support. An attached black/white charge-coupled device videocamera (Hitachi KP-160) digitizes the image and transfers it to the computer captureboard (Integral Technologies Flashpoint PCI). An image analysis program (Media Cybernetics ImagePro Plus, version 3.0) is then used for handling capture, storage and measurement. A sketch of the experimental apparatus is shown in Fig. 3.

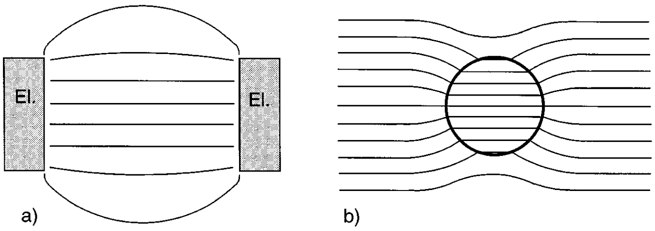

Fig. 1 **a** Field lines between flat electrode surfaces. **b** The effect on the field lines of a high-permittivity droplet in a medium of lower permittivity

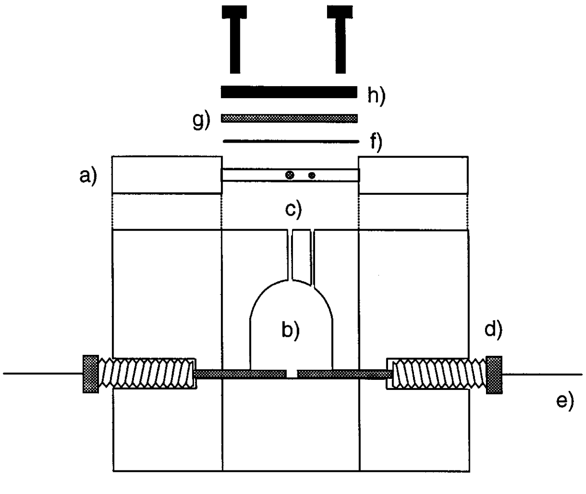

Fig. 2 The selective membrane testing (SMT) cell. *a* Teflon frame, *b* sample chamber, *c* dispenser entry, *d* adjustable electrode, *e* connector, *f* chemically resistant fairing, *g* transparent cover plate, *h* aluminium support

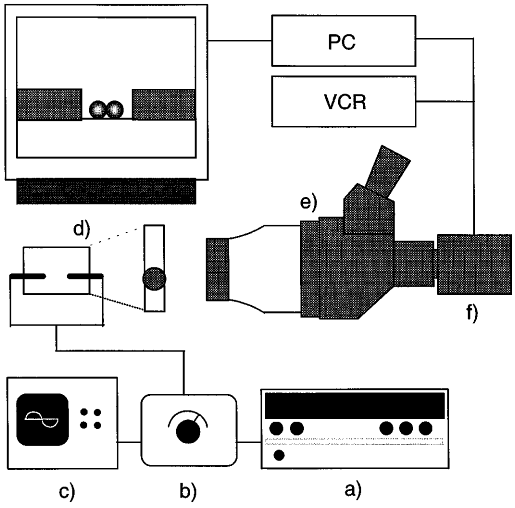

Fig. 3 The complete apparatus. *a* Signal generator (controls frequency and delivers tension for the amplifier), *b* amplifier, *c* oscilloscope, *d* the SMT cell, *e* stereomicroscope, *f* charge-coupled device videocamera

Operation of the cell

The oil phase (known amount by weight) is injected through one of the top injector openings. The cell is placed in a support and a number of aqueous phase droplets are deposited through the other opening. After a rest time, during which the surface-active species of the oil phase have migrated to the interface and formed an interlayer, the electrodes are moved to push the droplets to form a linear aggregate (usually a doublet). The electrodes are then retracted to a suitable distance from the aggregate to avoid direct charging. The aggregate is observed to ensure a minimum lifetime (90 s was used) before the electric field is switched on and gradually increased until critical conditions (e.g. critical field strength) are reached and the membrane ruptures, resulting in coalescence. The entire process is observed through the microscope and droplet size and electrode separation are determined from calibrated images. From these data and the voltage at the point of rupture the critical field strength of the membrane can be found. The a.c. frequency was fixed at 1.4 kHz.

The chemical systems

As model systems, water-in-asphaltene model oil emulsions were chosen for the broad and interesting range of properties such oils can exhibit (see later). Also, the importance of asphaltenes in water in crude oil emulsion stability adds to the interest of such systems.

The first experimental matrix sought to study the influence of four variables expected to have some impact on the membrane properties: the asphaltene concentration, the solvent composition in the oil phase, the aging of the oils and the exposure time of the droplets to the oil phase.

The concentration of asphaltenes and thus the available amount of surfactants will expectedly play an important role. Firstly, to achieve stability there must be a minimum amount of surfactant to completely cover the dispersed area. Increased concentrations may influence the equilibrium of dissolved-to-adsorbed surfactant, and also the aggregative behavior of the surfactant. Regarding concentration, there is also a practical consideration: the current SMT cell does not support the study of very opaque oils, for example, asphaltene-rich crudes. Asphaltene model oils (asphaltene in toluene/decane mixtures) containing 1–2% asphaltenes gave adequate transparency. Concentrations in the range 0.1–1% should be sufficient for the stabilization of the interfacial area used in the current study.

Another factor is the time needed for the oils to equilibrate. The asphaltenes used in this study originated from pentane (Lab Scan, HPLC grade, 95%) precipitation from a crude oil containing about 8% C5 insolubles (the ratio of crude-to-pentane being 1:5). To find suitable concentration/solvent regimes, 0.1, 0.5 and 1 wt% asphaltenes were attempted, dissolved in solvent mixtures of decane/toluene (Merck, zur Synthese, >95%/Lab Scan, AR, 99.5%) at ratios of 70/30, 60/40, 50/50 and 40/60 v/v. The solids were first dissolved in toluene, and decane was added after 20 h. The progression of visible (>0.3 μm) asphaltic precipitation is given in Table 1. From these results it was decided to use toluene/decane ratios of 40/60, 50/50, 60/40, 70/30 and 100/0 v/v.

In order to establish the reproducibility and reasonable error margins for the critical field strength the electrocoalescence experiment was repeated 10 times for the 1% asphaltene in 60/40 toluene/decane oil. The results are shown in Table 2.

The effect of droplet size on the critical field strength may be estimated from theoretical considerations [28, 29]. It was found, however, that this influence was less important for the particulate or semiparticulate membranes, as long as the droplets were of approximately the same size and this size was kept within certain margins. Table 3 indicates this feature. It seems clear that for systems of molecular membranes the size effect should be more pronounced and quite influential on the critical parameters (see Discussion for further comment).

All aqueous phases were distilled/filtered/ion-exchanged water of high purity. In this way, the electrolytic contribution to the effect of the electric field (and possible influence on the organization of the membrane species) could be neglected.

Results

The tests of reproducibility of the critical field strength are summarized in Table 2. For oils without significant amounts of visual particles (exemplified by the 2-week old 1% asphaltenes in 60/40 toluene/decane oil) the observed maximum offset from the mean (77.3 V/cm, based on six measurements, four discarded as outliers – see Discussion) was +3.5% and −3%, and the standard deviation was 1.75. In the tables, results are presented with the +/− offset from the mean (see Discussion).

Table 3 shows how the droplet size (within the experimental size domain) influences the critical field strength. Experiments were made with the 1% asphaltene in 70/30 toluene/decane oil, aged by 2 and 56 days (the oldest one containing visible particles). As seen from the table, the membrane strength decreases with increasing droplet size for both ages, but the effect is slightly more distinct for the less-aged oil. This may result from the higher nonuniformity of the more particulate membrane of the aged oil.

The effect of asphaltene concentration and solvent aromatic/aliphatic ratio is found in Table 4 and Fig. 4. The oil phases were aged between 1 week and 10 days after addition of decane. At this time particle precipitation was observed in all 40/60 toluene/decane oils, even the one containing only 0.1% asphaltenes. The general trend was increased resistance to electrocoalescence with increased concentration of surfactant and decreasing aromaticity. Additionally, the occurrence of

Table 1 Asphaltene precipitation from model oils

Asph. content w%	Ratio decane/toluene, v/v							
	70/30		60/40		50/50		40/60	
1	■	■	▨	■	□	□	□	□
0.5	■	■	□	■	□	□	□	□
0.1	▨	■	□	▨	□	□	□	□

L	R	
		L: Within 48 hours. R: 1 week – 10 days.
■	■	Significant asphalthene precipitation.
▨	▨	Only very slight precipitation.
□	□	No visible precipitation.

Table 2 Reproducibility of measurements

Exp. no.	E_{cr}[a]	+/−[b]	+/− (%)
1	75	2.3	2.97
2	77	0.3	0.39
3	0		
4	80	2.7	3.49
5	0		
6	78	0.7	0.91
7	78	0.7	0.91
8	47		
9	0		
10	76	1.3	1.68
Ave.[c]	77.33		
SD	1.75		
Range	5		

[a] In volts per centimeter for water droplets (500 μm +/−20 μm) deposited in 1% asphaltenes in 60/40 toluene/decane (oil aged 2 weeks).

[b] Deviation from the average value obtained from experiments 1, 2, 4, 6, 7 and 10.

[c] Average of the six accepted values.

Table 3 Effect of droplet size

Oil age[a]	Size of droplet 1[b]	Size of droplet 2[b]	E_{cr}[c]
2	500	500	53
2	600	600	36
2	500	600	48
56 [d]	500	500	120
56 [d]	600	600	113
56 [d]	500	600	116

[a] In days after addition of decane.

[b] In micrometers (+/−20 μm).

[c] In volts per centimeter.

[d] Asphaltene particles were visible in the aged oil.

Table 4 Effect of asphaltene concentration and oil-phase aromaticity

Asphaltene concentration, wt% of oil	Solvent aromaticity vol % toluene	E_{cr}, V/cm[a]	E_{cr} high, V/cm[b]	E_{cr} low, V/cm[b]	+/−, V/cm	+/− (% of average)
0.1	40	90	93	87	3	3.33
0.1	50	63	64	62	1	1.59
0.1	60	49.5	50	49	0.5	1.01
0.1	70	31	33	29	2	6.45
0.1	100	0	0	0	0	0
0.5	40	102	106	98	4	3.92
0.5	50	70.5	70	71	0.5	0.71
0.5	60	55	56	54	1	1.82
0.5	70	41	43	39	2	4.88
0.5	100	0	0	0	0	0
1	40	117	113	121	4	3.42
1	50	89	86	92	3	3.37
1	60	73	76	70	3	4.12
1	70	59	61	57	2	3.39
1	100	0	0	0	0	0

[a] Average of high and low critical field strength.

[b] The high and low of the two values from which E_{cr} is calculated (see Discussion).

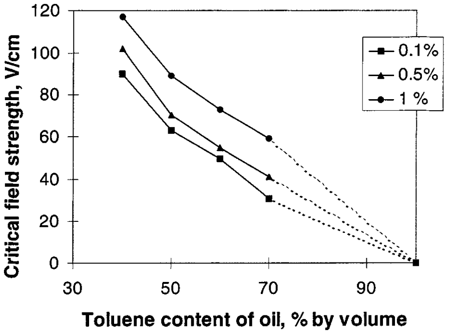

Fig. 4 Effect of asphaltene concentration and oil-phase aromaticity

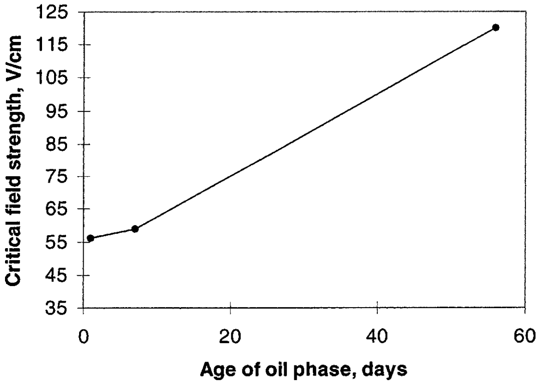

Fig. 5 Effect of aging of the model oil (1% asphaltenes in 70/30 toluene/decane)

particles in the micrometer size domain causes a steeper increase in the membrane strength, relative to the trend for the more toluene-rich oils. This indicates that the particles increase the strength of the membrane.

As the oils age more of them show precipitating asphaltene particles. Figure 5 shows how the critical field strength for droplets deposited in the 70/30 toluene/decane oil with 1% asphaltenes increases from day 1 to day 56. On day 56 the oil contains visible particles.

The effect of the time of exposure between the droplets and the oil phase is seen in Fig. 6. The oil is 1% asphaltenes in 60/40 toluene/decane. A very steep increase is seen in the critical field strength as the exposure time increases. After 16 h the droplet surfaces are clearly covered by a semisolid layer. At this time there are no visible asphaltene particles in the oil, which means that the origins of the layer must be smaller constituents, perhaps molecules or aggregates precipitating at the interface.

Discussion

Theoretical considerations

Aqueous droplets in an electric field are subject to polarization, both by reorientation of polar compounds in the droplet–medium interface and by redistribution of the droplets ionic internals (when the aqueous phase is an electrolyte). The attraction increases with the strength of the field and the size of the droplets [28, 29]. The efficiency of electrically induced flocculation in disperse systems is obviously higher the larger the droplets. Another point in this regard is that the larger the droplets the more easily they will deform upon contact. Both a stronger field attraction and a higher membrane deformability increase the possibility of film rupture and concomitant coalescence.

Discussion of results

Regarding reproducibility, as seen in Table 2, four of the ten parallels deviate strongly from the remaining six. These six have a mean value of 77.3 V/cm and a standard deviation of 1.75. All six fall within +/− 3.5% of the mean value. Three of the remaining results were doublets collapsing prior to the field being switched on. This indicates how critical the stage of doublet formation is. If excess mechanical force is used the thinning of the membrane is affected, even to an extent which causes immediate rupture. The last deviating value (about 60% of the mean of the six) may result from such excess stress upon doublet formation; however, another factor could manifest itself – uneven droplet exposure. When the droplets are deposited they rest on the cell floor, which means that a part of the droplet has been exposed to the oil only briefly (during the actual deposition). If this droplet segment becomes the point of contact when the doublet is formed, the membrane may exhibit properties not representative of the rest of the droplet/oil interlayer. Indeed, when working with particle-rich oils the difference in exposure manifests itself as a visually different area of the droplet surface. Attempts to counter the problem were made by moving the droplets during the rest time. This resulted in stable, reproducible values, but might obviously introduce a risk of influencing the formation of the interlayer nonetheless. Working with particle-rich oils the number of outliers in the critical field values was sometimes seen to increase, indicating a rise in the importance of uneven exposure to the film properties. This seems natural to the extent that the main stability contribution comes from the inclusion into the film of particles undergoing thermal or hydrodynamic movement in the oil.

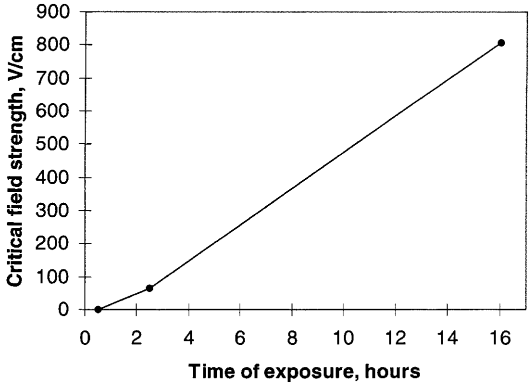

Fig. 6 Effect of the time of exposure of the interface (1% asphaltenes in 60/40 toluene/decane)

The above results caused the following practice to be adopted. Due to the time-consuming nature of the experiments each was repeated once. If the two values obtained fell within the suggested error limits the mean was accepted as the result. If this was not the case a third experiment was performed and the mean of the best two values was accepted.

As seen in Table 3 the importance of the droplet size manifested itself, especially in the case of membranes with a modest presence of large particles. The trends are

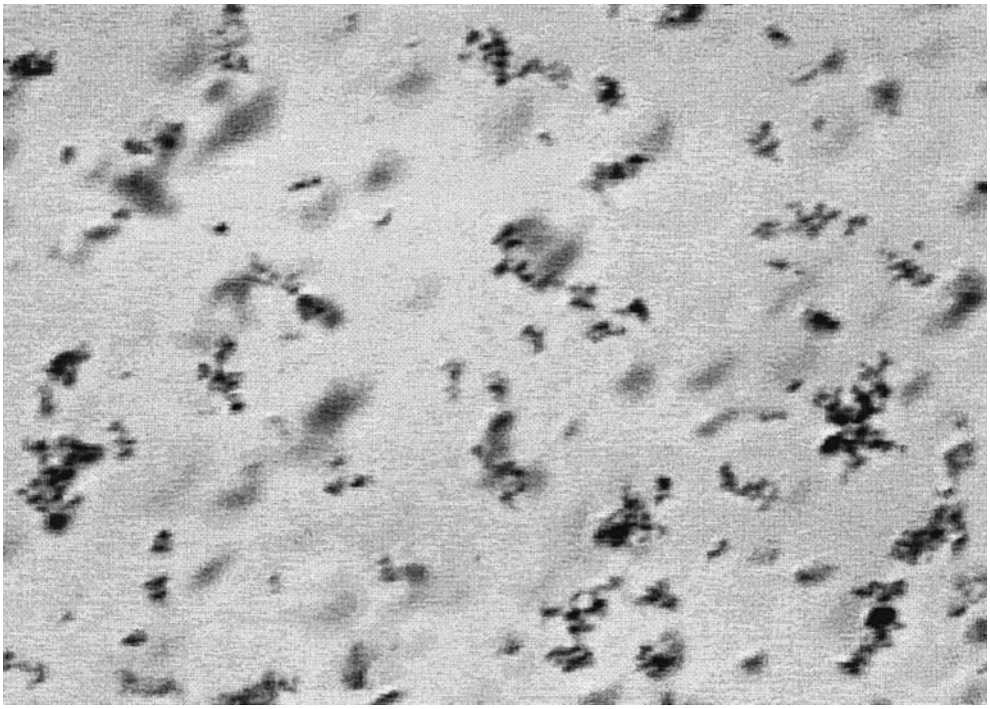

Fig. 7 Flocs of asphaltene particles in 1% asphaltene in 70/30 decane/toluene oil. The baseline of the image is 0.15 mm

in accordance with what is expected – the larger the droplets, the more easily the membrane ruptures. First, the dipole moment, and thus the electrically induced interdroplet force of attraction, increases with droplet size. Second, two otherwise equal membranes of two differently sized droplets may behave differently under compression. The smaller the droplets the higher the resistance to deform and flatten at the contact zone. Note that the difference in critical field strength between droplet pairs of different size is lower for the more aged oils (between a pair of two 500 μm drops and a pair of two 600 μm drops – 2 days: ΔE = 17 V/cm; 56 days: ΔE = 7 V/cm). This is most probably a manifestation of the increasing inhomogeneity which accompanies the inclusion of particles into the film. Such an effect will certainly reduce the reproducibility of the data acquired, but the trend still remains – the larger the droplets, the lower the critical field strength.

In connection with the asphaltene concentration, the state of the asphaltenes present in the oil will be significant [30]. A film of asphaltene monomers or low-coordinate aggregates will exhibit other mechanical properties than a film containing asphaltene particles as well [31]. As the solvent (oil phase) composition affects the aggregative state of the asphaltenes, varying the aromaticity of the oil may severely influence the membrane properties and thus the membrane strength. Toluene is an excellent solvent, giving predominantly monomeric asphaltene molecules at relevant concentrations [32]. Aliphatic hydrocarbons, such as decane, are poor solvents, resulting in a higher fraction of the asphaltenes remaining particulate or strongly aggregated. Hence, the aromatic/aliphatic balance in the oil enables manipulation of the state of the asphaltenes. This is recognized in the data of Table 4.

It is interesting to note the influence of the transition to a higher presence of particles on the critical field strength. The curves in Fig. 4 all indicate a steeper increase in E_{cr} for the oils showing visible particles (40/60 toluene/decane). The oils in which asphaltene was dissolved in 100% toluene did not produce membranes strong enough to survive doublet formation, underlining the importance of the inclusion of particles in the film. Regarding the forces within the film, Ese et al. [31] (using the Langmuir–Blodgett technique) suggest that even though the aggregative state of the asphaltenes changes with solvent aromaticity (from 100% toluene to 40/60 toluene/heptane) the forces between the asphaltic species (molecular or particulate) remain largely unaltered. The significant rise in membrane stability observed with the presence of particles can be attributed to long–range steric effects.

Also in less particle-rich oils particles were observed to attach at the water\oil interface, but the interfacial concentration was too low for a rigid particle shell to form. This implies that visible particles (micrometer-sized and above) can no longer be the dominant contributor to membrane resistance to coalescence.

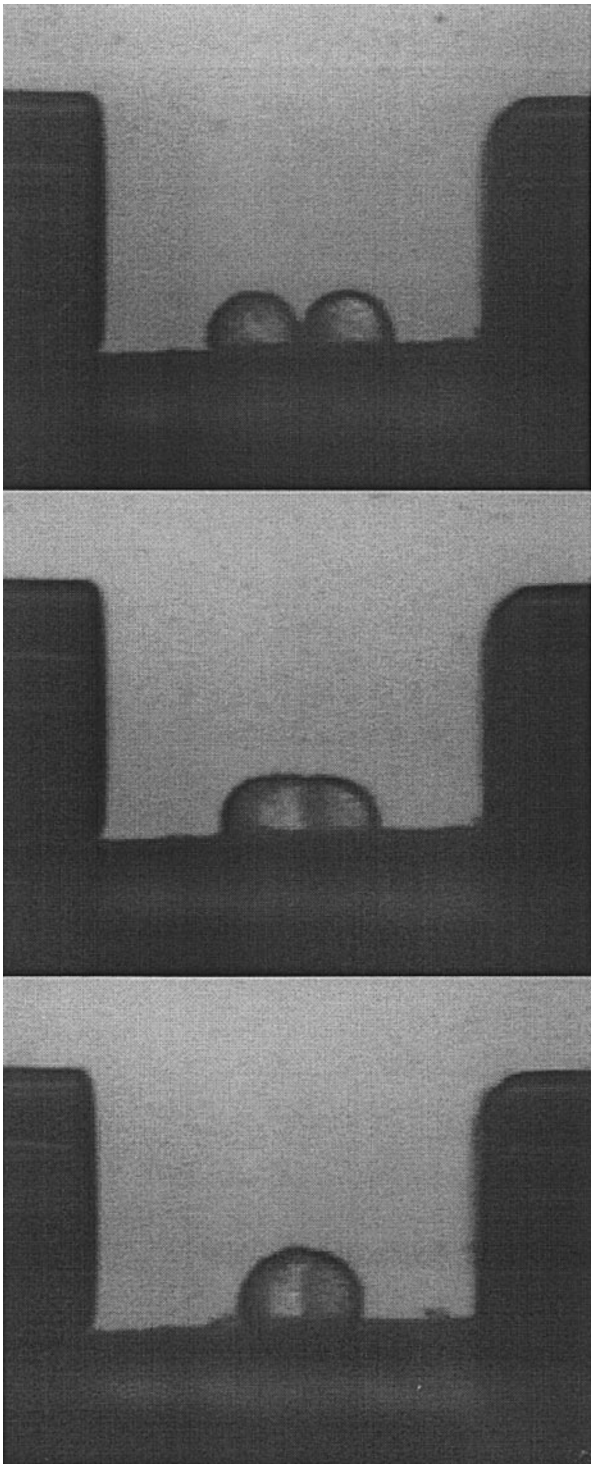

Fig. 8 Electrocoalescence of highly particulate droplet membranes. Note how the particulate structure of the droplet surfaces prevails. Because the droplets are resting in the depression between the electrodes, only about 80% of the droplet profile is visible

Even so, the results for such membranes (probed by using asphaltene model oils with higher toluene/decane ratios) show that such molecular films can obtain considerable strength, especially when taking into account the size of the droplets.

The precipitating asphaltene particles in the model oils were seen to interact, forming networks of flocs. The size of the particles and the flocs (several micrometers, see Fig. 7) indicates that fluid motion in the oil phase may influence how the particles contact the water\oil interface. Experiments with highly particulate asphaltene solution/suspensions (see Results) showed that even though the greater number of particles sedimented to the cell bottom, the droplet surface was after some time covered in a thick particle layer of high rigidity and mechanical strength. Upon application of an electric field across a doublet of such droplets the coalescence resulted in the breaking of the particulate membrane in the contact zone, the coalescence product retaining much of the shell structure of the original pair (Fig. 8). However, it seems reasonable to expect that an electrocoalescence experiment with such a membrane would show lower reproducibility due to the presumably less homogeneous membrane.

It seems natural, then, that the time of exposure of the droplet surface to the surrounding oil might affect the membrane properties. Molecular films, where the adsorption process is quick, would expectedly reach an equilibrium with the oil within moderate time. The time scale for a mixed molecular–particulate film may be different, including processes pertaining to reorganization of species within the film as well as the adsorption of particles from the oil. The study of Bhardwaj and Hartland [12] indicated the importance of the aging of the exposed membrane.

Summary

A method for testing the strengths of individual droplet membranes has been demonstrated. A pair of aqueous droplets were dispensed in an oil containing surface-active species. An electric field induced attraction between the pair forcing the droplet surfaces together until the droplet–droplet membrane ruptured. The field characteristics at the point of rupture are the “critical” parameters for the membrane. A set of model oils containing asphaltenes from a crude oil were used to test different aspects of the method.

As is the case in any microscopy-based technique there is also the advantage of being able to study the systems directly. Besides the critical parameters, other interesting features of the system or the process may be observed, for example, the visual state of the interface – whether particles (above a visual size minimum) adsorb to it or not. Also, whether the coalescence process – the actual merger of the droplets – is quick or slow, signifying certain mechanical properties of the interface.

In principle, the method can be used on any system meeting the requirements of droplet size versus interfacial tension and minimum stability, as well as transparency. For the study of asphaltene model oils, it may experimentally be valuable to operate with lower asphaltene concentrations and longer exposure times on aged oils in order to get thoroughly equilibrated membranes without large (micrometer-sized) particles. Such membranes should be more uniform and may reveal more information on the specific systems.

The experimental setup can be used to explore other factors of the electrocoalescence efficiency, for example, field frequency.

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