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Electrically stressed water drops in oil

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ABSTRACT

The deformation of water droplets in an electric field has been studied in hydrocarbon liquids. A water drop will elongate in an electric field due to the electrostatic pressure, and becomes unstable when a critical field limit is reached. By applying different voltage waveforms it is possible to measure both transient, time varying and static effects. An experimental method has been developed to study the rheological properties of the water droplet. The experimental results in surfactant-free model oil are in good agreement with classic Taylor theory. In diluted crude oil a correlation was found between the drop behavior in an electric field and the interface elasticity modulus, measured by dilational interfacial rheology. The static drop deformation was reduced with increasing elastic modulus due to adsorption of polar surfactants to the water/oil interface. Drop surface oscillations will be damped by the viscosity of the bulk liquid. The dynamic drop behavior was studied in viscosity standards prepared from different concentrations of polystyrene in toluene. The drop oscillations were modeled as damped oscillator, and the influence of viscosity on the eigen-frequency and damping coefficient was studied for different drop sizes. The oscillations can also explain the premature break-up of water droplets sometimes observed in the experiments.

1. Introduction

During crude oil production both oil and water phases are co-produced. Severe depressurizations in the extraction and transportation processes lead to formation of water-in-oil emulsions. These emulsions can be very stable due to the presence of surface active agents in the crude oil, such as asphaltenes, resins and naphtenic acids. Asphaltenes and resins are the heaviest and most polar fraction of the crude oil, and are believed to be the major components responsible for emulsion stabilization [1]. The production of such emulsions is highly undesirable during crude oil processing, leading to troubles in flowing due to increased viscosity, corrosion of equipment and deactivation of catalysts due to free water and the contaminations it may contain.

Water and oil separation is commonly carried out in large gravitation settling tanks. Due to the low density difference between water and crude oil and the presence of very small water droplets in the emulsion, the water drop settling time may be very long. There are three common ways of improving separation efficiency; by increasing the residence time in the separator, reducing the viscosity of crude oil, or increasing the radii of water droplets. Increasing residence time means larger equipment or reduced production flow. Decreasing the viscosity may be done by heating the crude oil, leading to increased energy consumption. Finally, increasing the size of droplets is possible through an enhancement of coalescence, enabled either by using chemical emulsion breakers, which may be detrimental on an environmental point of view, or by electric fields.

The latter process, called electrocoalescence is a promising technique for improving performance of coalescers and reducing their volume, a real challenge especially for off-shore production. The first patent on electrocoalescence was filed in 1908 [2], observing the coalescence mechanism when a high potential was applied to a pair of electrodes in a water-in-oil emulsion. The principle is simple; in an electric field the electrostatic forces tend to align the water droplets in chains along the electric field, and an attractive force will bring the drops into contact. When the drops are close a field induced jet-like instability may form on one of the drop surfaces, thereby enhancing the coalescence efficiency by puncturing the oil film separating the drops [3]. In this process bigger droplets are formed and the gravitation settling velocity is increased according to Stokes' law.

Electrocoalescence can be studied at different scales: The macro-scale describes the full-size coalescer operating in an industrial process, where the overall efficiency of the coalescer can be observed. At the smaller meso-scale the water-in-oil emulsion is treated as a multiparticle system where the drops interaction with turbulent flow and electric field can be studied. In multiparti-

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cle modeling water droplets are usually considered as conductive spheres. In the micro-scale system single water drops and drop pairs are treated in details on surface deformation, drop merger and breakup in an electric field and oil flow. Several important parameters can be derived from micro-scale experiments, e.g. the coalescence probability of two colliding droplets, and the stability of single water drops aged in different crudes. Both parameters are important for the understanding of water-in-oil emulsion stability, and are essential for multiparticle coalescence modeling. The smallest nano-scale considers the oil/water chemistry and how surfactants affect the interfaces and emulsion stability.

Thus, for a better understanding of electrocoalescence mechanisms, we have in this work carried out micro-scale experiments where single drops are submitted to electrical fields, and studied their dynamic behavior and the rheology of the water/oil interface. For this purpose, we have developed an experimental method called "electrically stressed water drops in oil" [4]. The deformation and instability formation of an interface depends both on the presence of surfactants and the viscosity of the bulk oil. This study was carried out with surfactant free interfaces, and water drops in diluted crude oil.

2. Static deformation of droplets in electric fields

When water-in-oil emulsions are modeled, the water drops are frequently treated as rigid spheres. However, when an electric field is applied to an elastic conductive body like a water drop, its shape will change due to the electrostatic pressure. A water drop will elongate, and at a critical deformation it will become unstable and break up due to electric field forces [5]. This was first explained by Taylor [6], who developed the classic theory for water drops in dc fields. However, the classic theory only considers an ideal interface, only characterized by its interfacial tension. In reality the interface has a finite thickness, and for real water-in-crude oil emulsions surface rheology will play an important role by modification of the surface layer.

2.1. Classical theory of drop elongation and break-up

In the absence of an electric field the interfacial tension γ will keep the water drop spherical with radius r_0 when the gravitational effects are negligible, i.e., the body forces $\Delta\rho g$ are small compared to surface tension forces γ/r_0^2. In this case the Bond number $Bo = \Delta\rho g r_0^2/\gamma \ll 1$. The pressure difference across the interface of a drop of radius r_0 due to surface tension is then given by the Young–Laplace equation

$$\Delta P = \gamma\left(\frac{1}{r_1}+\frac{1}{r_2}\right) = 2\frac{\gamma}{r_0} \tag{1}$$

The shape stability is consequently higher for smaller drops. For two immiscible liquids like oil and water this pressure difference is called the capillary pressure. When a uniform electric field is applied, the drop deforms due to the electrostatic pressure on the surface, and elongates in the direction of the electric field. The simplest reliable model describing the drop's steady state deformation was developed by Taylor. The Taylor model is based on the following assumptions:

- The drop is charge neutral.
- The interface is surfactant free, which means that the interfacial tension between the drop and the continuous phase is constant and independent of the deformation.
- The drop is a perfect conductor ($\varepsilon_d \to \infty$) and the continuous phase is dielectric.

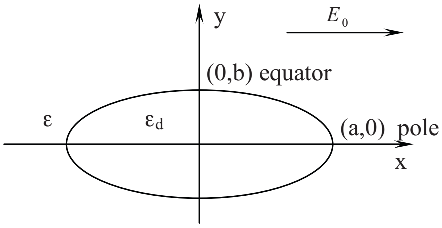

Fig. 1. Water drop deformation in an electric field.

The model assumes also that the drop takes the shape of a prolate spheroid, shown in Fig. 1. It has been shown theoretically that this conjecture is very accurate [7].

a, *b* and *c* are the spheroid's semi-axis. Note that *c*, the semi axis perpendicular to the *xy* plane, is equal to semi-axis *b* in the prolate spheroid geometry.

The Taylor model states that the pressure difference across the drop interface is the same at any point on the surface. It is then sufficient to calculate Δp at two points, on the pole ($x = a$) and the equator ($x = b$) of the spheroid. This pressure difference is due to the opposite contributions of the interfacial tension and the electrostatic pressure. The pressure difference, or normal stress discontinuity, due to the interfacial tension in the spheroid is given by the Young–Laplace equation (1), while the electrostatic pressure is equal to $1/2\varepsilon E^2$, where E is the value of the electric field on a given point of the surface. Balancing the two pressure differences $\Delta P_{pole} = \Delta P_{equator}$ and assuming volume conservation (incompressibility) one obtains

$$E_0\sqrt{\frac{2r_0\varepsilon}{\gamma}} = 2\cdot\left(\frac{b}{a}\right)^{4/3}\left(2-\frac{b}{a}-\left(\frac{b}{a}\right)^3\right)^{1/2} f(e) \tag{2}$$

where

$$f(e) = \frac{1}{2}e^{-3}\ln\left(\frac{1+e}{1-e}\right) - e^{-2} \tag{3}$$

e being the eccentricity of the drop, $e = \sqrt{1-b^2/a^2}$, and E_0 is the applied uniform electric field. The left hand side of Eq. (2) is the square root of electrostatic versus capillary pressure, also called the electric Weber number, while the right hand side is a pure geometric function of the drop semi-axis *a* and *b*. The drop elongation increases with the electric field until it reaches a stability limit at ratio $a/b \cong 1.9$. Above this value the electrostatic pressure exceeds the capillary pressure, and the drop will break up. The value of the applied electric field at break up is called the critical field E_c, given by

$$E_c = 0.648\sqrt{\frac{\gamma}{2\varepsilon r_0}} \tag{4}$$

2.2. Extension of the classical model for dielectric drops

As mentioned above, the Taylor model assumes a perfectly conductive drop. This condition may be considered as a limitation of the model, when one would like to describe real systems where the drop's permittivity may be finite. Therefore, it seems interesting to extend the model mentioned above, in order to become valid for any permittivity value of the drop.

For a conductive drop the internal electric field is zero, which is not the case for a dielectric drop where the internal field contributes to the pressure equilibrium across the interface. The internal field E_i of a dielectric ellipsoid is easily derived by solving Laplace's equation in prolate spheroid geometry, giving

$$E_i = E_0\left[1-\left(1-\frac{\varepsilon_d}{\varepsilon}\right)\left(1-e^2\right)f(e)\right]^{-1} \tag{5}$$