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Study on the transient response of water-in-oil droplet interface to electric field

Limin He[a,c,*], Haipeng Yan[a], Xiaoming Luo[a,b], Juhang Cao[a], Jing Wang[a], Donghai Yang[a]

[a] College of Pipeline and Civil Engineering, China University of Petroleum, No. 66 Changjiang West Road, Qingdao 266580, PR China
[b] Shandong Provincial Key Laboratory of Oil & Gas Storage and Transportation Safety, China University of Petroleum, No. 66 Changjiang West Road, Qingdao 266580, PR China
[c] Qingdao Key Laboratory of Circle Sea Oil & Gas Storage and Transportation Technology, China University of Petroleum, No. 66 Changjiang West Road, Qingdao 266580, PR China

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ABSTRACT

The transient response of water-in-oil droplet interface to electric field, which is important to intensification of separation processes of emulsions, was theoretically and experimentally investigated in this paper. A mathematic model was developed to find out the dynamic mechanisms of the transient process. By discussing the interface velocity and the stresses on the interface, the effects of two mainly governed dimensionless numbers, electric capillary number (Ca) and Ohnesorge number (Oh), on the oscillation modes were explained in detail. A greater Ca or Oh leads to a transformation of oscillation modes from underdamping to overdamping. For the amplitude of the first overshoot (A_m) which monotonically decreases with Oh, however, there exists a critical Ca at which A_m reaches its peak value. Afterwards, with the help of high speed photography, the rising time of overdamping mode was investigated. Despite of very small discrepancy, good agreement between model predictions and experimental results of the scaling law of the dimensionless rising time was observed. The results indicate that the dimensionless rising time shows a linear relationship with Ca under semi-log coordination. This valuable scaling law could provide reference for the optimizing design of oil–water separation devices.

1. Introduction

The stable water in oil emulsion (W/O) produced by oilfield always contains large amounts of surface active agents and electrolyte etc., which significantly change the interfacial rheology and have an effect on the behavior of deformation, coalescence and breakup of water droplet (Amarouchene et al., 2001). The transient response behavior of the deformed droplet to the electric field is closely related to these properties (Berg et al., 2010), which could be used to characterize the interfacial properties and explore the main factors. The method of oil/water separation process intensification can be thus developed pertinently, and the separation devices can be optimized accordingly.

Besides petroleum engineering, the exploration of the transient response behavior of droplet with different interfacial properties is significant to many other fields. For instance, different cells could be identified by analyzing the characteristics of interface motion under electric field (Fedosov et al., 2011); droplets or fibers with different properties and scales could be produced by changing the interfacial transient response to the electric field (Deng and Gomez, 2012; Raisin et al., 2013; Herran and Coutris, 2013).

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* *Corresponding author at*: College of Pipeline and Civil Engineering, China University of Petroleum, No. 66 Changjiang West Road, Qingdao 266580, PR China.

E-mail address: upcyhp@163.com (L. He).

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Under the electric field, the steady-state deformation of droplet could be affected by many parameters, such as the ratios of viscosity, dielectric constant and conductivity of droplet to those of continuous phase (Taylor, 1966). The spherical droplet may deform into prolate or oblate due to the different ratios of dielectric constant and conductivity (Baygents et al., 1998; Shadloo et al., 2013). Eow et al. (2001, 2003) and Eow and Ghadiri (2003) experimentally found that the deformation degree of droplet mainly relies on the conductivity, viscosity of continuous phase, oil–water interfacial tension and density, etc. Through the detailed investigations on the law of droplet deformation under AC electric field, Ye (2010) reported that the deformation degree is a function of conductivity, radius of drop and oil–water interfacial tension. Yan et al. (2015a,b) pointed out that the elasticity resistance also plays an important role on the droplet deformation. Lesaint et al. (2009) figured out the influences of electric field waveform, intensity, frequency and ambient temperature on the droplet deformation.

The theoretical study focuses on the mechanical model of steady-state deformation of droplet subjected to DC or AC electric field. Taylor (1964) established a theoretical model to predict the steady deformation of droplet under DC electric field. By analyzing the forces on the body of droplet, Ajayi (1978), Saville (1997) and Feng (1999) established their own models for droplet steady-state deformation under DC electric field. Torza et al. (1971) developed a theoretical model for droplet deformation under AC electric field and experimentally explored the rules of deformation. On the basis of these models, the critical conditions for droplet breakup and the flow outside or inside the drop have also been discussed in detail (Eow et al., 2001, 2003; Eow and Ghadiri, 2003; Ye, 2010; Yan et al., 2015a,b). Unlike the steady state deformation, however, the experimental and numerical studies on the transient process of droplet behavior in the electric field have received less attention, including the mode and rising time for the deformation and breakup etc., which play an important role in practical applications, for example the electrospray (Deng and Gomez, 2012).

Besides the droplet deformation in electric field, the transient response of droplet interface to the electric field has been also observed extensively in a few electrokinetic phenomena, such as electrowetting (Strani and Sabetta, 1984; Adamiak, 2006; Shamai et al., 2007; Feng and Zhao, 2008; Hong et al., 2008) and dielectrophoresis (Kim et al., 2007). The electrowetting is a phenomenon that a drop will change its shape when exposed to electric field (Shamai et al., 2007). Feng and Zhao (2008) observed the electrical instability phenomenon of droplets in their electrowetting experiments. They found that the electrode–membrane distance influences the electrowetting behaviors. When the electrode–membrane distance is reduced, the contact angle of the droplet jumps and the droplet oscillates in its natural frequency. What's more, the oscillation frequency is heavily dependent on the contact angle, which indicates that the surface properties are very important to the drop transient process (Feng and Zhao, 2008; Hong et al., 2008). Adamiak simulated the shape of droplet placed on a hydrophobic dielectric surface and found that the dynamic process of droplet surface breakup when the voltage is large enough (Adamiak, 2006). Therefore, the study on the transient process of droplet behavior is of great and wide scientific interest.

From perspective of the elastoplastic theory, the deformation of droplet subjected to an external electric field could be treated as the transient response of interfacial film to the excitation of electric stress. However, the transient response of the droplet to an external electric field is rarely investigated. Zhao (2014) and Wang et al. (2012) found that the oscillatory frequency of droplet interface subjected to AC electric field is twice as the input signal. However, according to the research of Raisin (2011), the pseudo-period of the underdamping oscillation in the transient response process relies on the electric capillary number Ca and the Oh number. By applying bipolar transient pulses, Berg et al. (2010) observed oscillations of oil–water interfacial film. They added a term *B*, which represents the elasticity modulus contribution, to the interfacial tension in Taylor's model. Nevertheless, their method is so simple that it cannot reveal the effect of interfacial rheology on the transient response of interfacial film. Vivacqua et al. (2016) developed a linear dynamic model and explained the correlation between the formation of secondary droplets and the amplitude of oscillation of the mother droplet. He et al. (2016) studied the transient response of droplet deformation in a steady electric field by level-set method. They obtained some valuable results, but their analysis was according to physical properties of experimental materials. However, when the analysis is according to dimensionless numbers, the corresponding results will be more universal.

In order to reveal the dynamic mechanisms involved in the transient response of interfacial film to the electric field, in this paper, a mathematic model is developed to describe the response process of a conductive drop in oil under DC electric field in Section 2, and the effects of dimensionless numbers, the electric capillary number Ca and Ohnesorge number Oh, on the process are also discussed in this section. In Section 3, the rising time of the transient response is investigated experimentally. The effects of key factors on the rising time are explored in detail in this section.

2. Mechanisms of response process of droplet

2.1. Theory

For a spherical drop with radius *r* subjected to a DC electric field, we consider it is uncharged and is suspended in oil. Besides, the theoretical model is based on the following assumptions:

(1) The electric field can be considered as uniform since the radius of droplet *r* is much less than the height of the electrodes;
(2) The Bond number $\mathrm{Bo} = \Delta\rho g r^2/\gamma \ll 1$, so the gravitational effects are negligible;
(3) The dielectric constants ε_c and ε_d and the ohmic resistivities Γ_c and Γ_d of the continuous phase and drop are all constants;
(4) The droplet is considered as a conductor so that the electric field inside the drop can be ignored; meanwhile, the ratio of conductivity of the continuous phase to that of drop $R \approx 0$.

The direction of DC electric field strength is shown in Fig. 1(a). Based on the assumptions listed above, the stresses on the point $p(\theta = 0)$ in Fig. 1(b) are analyzed in the following part, and the motion of *p* is obtained according to Newton's Second Law. The motion of point *p* is mainly governed by electric stress, radial hydrodynamic stress, additional pressure and capillary pressure, as shown in Fig. 1(b).

2.1.1. Electric stress

When the DC electric field is applied, the polarization of water droplet, including electronic polarization and orientation polarization, will induce the positive and negative charges on the interface along the direction of the electric field, turning it into a "dipole" (Xie, 2001; Raisin, 2011). The interfacial charges of opposite polarity will induce mechanical stresses at the interface under DC electric field, which drive the movement of interfacial film. As a result, the drop deformation is observed.

The time scale of the polarization is determined by the relaxation time which is given by:

$$\tau = \varepsilon_0 \varepsilon_d \Gamma_d \tag{1}$$

where ε_0 is the permittivity of vacuum, $\varepsilon_0 = 8.85 \times 10^{-12}\,\mathrm{F\,m^{-1}}$. The relative permittivity of the drop $\varepsilon_d \approx 80$, and the ohmic resistivity of the drop $\Gamma_d < 1\,\Omega\,\mathrm{m}$, so the relaxation time