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Critical electric field strength for partial coalescence of droplets on oil–water interface under DC electric field

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Water droplets dispersed in crude oil have to be separated and this is most commonly done by electrical dehydration. Under high strength electric fields, partial coalescence may occur and leave fine secondary droplets, which reduce the separation efficiency. The critical electric field strength (E_{crit}) for partial coalescence occurrence depends on several factors. In this paper, the effects of droplet radius, conductivity, interfacial tension, viscosity (changed by adding alkali, surfactant, and polymer respectively) and oil density on E_{crit} have been studied experimentally. E_{crit} increases linearly with the inverse of the square root of droplet radius, $R^{-0.5}$, but the slope $E_{crit}/R^{-0.5}$ (k) can be changed. Increasing surfactant concentration reduces E_{crit} and the slope k decreases, which indicates reducing interfacial tension promotes partial coalescence. Whereas, adding alkali or polymer improve E_{crit} and the slope k increases with the increase of its concentration, because of the changes in water conductivity or viscosity. In addition, E_{crit} is proportional to the product of density difference and oil viscosity. A proposed formula expressing the E_{crit}, albeit in an empirical way, was given which takes account of the relevant parameters. These results will be of guiding significance to the choice of electrical field strength for electro-dehydration.

1. Introduction

In petroleum and chemical industry, separation of water and oil is crucial since it is troublesome from the oilfield sewage treatment, product quality and energy consumption of transportation viewpoints. Water-in-oil emulsions commonly exist in the oil and chemical industries (Eow et al., 2001; Eow and Ghadiri, 2002; Zolfaghari et al., 2016). When the droplets come in contact with the oil–water interface, the film between the droplet and the interface starts thinning and eventually ruptures, then the droplet coalesces with the bulk water. There are two coalescence patterns: complete coalescence, i.e. the droplet merges with the bulk water completely; and partial coalescence, where smaller secondary droplets are produced (Blanchette and Bigioni, 2006; Charles and Mason, 1960a, 1960b; Chen et al., 2006a; Paulsen et al., 2014). Charles and Mason (1960a, 1960b) were the first to report on droplet-interface partial coalescence. They attributed the process to Rayleigh–Plateau instability generated by capillary waves. As the liquid film between the droplet and interface ruptures, rapid expansion of the contact region gives rise to a surface capillary wave, propagating along the droplet surface and finally converging at droplet summit to elongate it. Simultaneously, capillary pressure inside the droplet and gravity drains the droplet fluid into the bulk. These two competing process result in necking of the droplet, and eventual fluid break-up due to the instability. However, Blanchette and Bigioni (2006) were against the

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Nomenclature

a	Intercept
A	The projected area of the droplet, m^2
b	Slope
Bo	Bond number
C_d	Drag coefficient
d	Diameter, m
E	Electric field strength, $kV\,m^{-1}$
E_{crit}	Critical electric field strength, $kV\,m^{-1}$
F_A	Virtual mass force, N
F_B	Buoyancy force, N
F_D	Drag force, N
F_E	Electric force, N
g	Gravitational acceleration, $m\,s^{-2}$
H	Thickness, m
G	Gravity force, N
k	Slope of E_{crit} and $R^{-0.5}$, $v\,m^{-0.5}$
L	Distance between two electrodes, m
Oh	Ohnesorge number
ΔP	Additional pressure, N
Q	Charge, C
R	Radius, m
Re	Reynolds number
S	Surface area of sphere, m^2
U	Applied voltage, V
We	Weber number
WO	Weber number multiplied by Ohnesorge number

Greek symbols

ρ	Density, $kg\,m^{-3}$
$\Delta\rho$	Density difference, $kg\,m^{-3}$
ρ_*	Density ratio
μ	Viscosity, Pa s
μ_*	Viscosity ratio, Pa s
σ	Interfacial tension, $N\,m^{-1}$
φ	Induced charge, C
θ	Angle between the electric field direction and the droplet radius, $^\circ$
ε	Relative permittivity
ε_0	Permittivity of free space, $F\,m^{-1}$
κ	Conductivity, $S\,m^{-1}$

Super/subscripts

1	Water phase
2	Oil phase

Rayleigh–Plateau instability mechanism. Instead they suggested the partial coalescence to be dependent on the rates of vertical and horizontal collapse, when gravitational effects are negligible. Under these conditions, to get secondary droplet, the vertical collapse rate has to be sufficiently slow.

Chen et al. (2006a) found the process of partial coalescence can be divided into two stages: propagation of surface waves and capillary pinch-off. The first stage is the same as the description of Charles and Mason (1960a, 1960b), which is related with Rayleigh–Plateau instability. In the second stage, the column, caused by the uplifting effect of the capillary wave at droplet top, becomes sufficiently thin for capillary instability to set in. A neck forms near the base of the column, and eventually a secondary droplet pinches off.

There are four dimensionless numbers of the system governing coalescence patterns: the Ohnesorge number Oh, the Bond number Bo, and the density and viscosity ratios (Blanchette and Bigioni, 2006; Chen et al., 2006b; Paulsen et al., 2014) between the droplet and the continuous phases:

$$\mathrm{Bo} = \frac{\Delta\rho g R^2}{\sigma} \tag{1}$$

$$\mathrm{Oh} = \frac{\mu_1}{\sqrt{(\frac{\rho_1+\rho_2}{2})\sigma}} \tag{2}$$

$$\rho_* = \frac{\rho_1}{\rho_2} \tag{3}$$

$$\mu_* = \frac{\mu_1}{\mu_2} \tag{4}$$

where subscripts 1 and 2 represent the droplet and oil, ρ is density and $\Delta\rho = \rho_1 - \rho_2$, g is gravitational acceleration, σ is interfacial tension, and μ is viscosity.

The critical Oh number for partial coalescence is about 0.03 (Blanchette and Bigioni, 2006; Ray et al., 2010). Blanchette and Bigioni (2006) found the critical Oh number is 0.026 ± 0.003 at low Bond numbers. Mahamed-Kassim and Longmire (2004) proposed that partial coalescence occurs if Bo·Oh < 0.02–0.03. However, Chen et al. (2006a) observed complete coalescence for a much lower Bo·Oh = 3.19×10^{-6}. The critical value is different as the experimental materials are different.

Chen et al. (2006b) reported partial coalescence occurs for an intermediate range of droplet sizes; it is demoted by water viscosity for smaller droplets and by water density for larger ones. Blanchette and Bigioni (2006) found the viscosity of the liquid determines the extent of capillary waves propagating. For very viscous liquids, capillary waves are damped, leading to complete coalescence.

Paulsen et al. (2014) studied the effect of viscosity, interfacial tension, droplet diameter and distance between droplet and interface. They found capillary waves are visible in the less viscous oil. Blanchette et al. (2009) demonstrated that the interfacial tension ratio between droplet and continuous phase also affected the interface coalescence.

Applying an electric field can accelerate the coalescence process, which is commonly used to achieve emulsion dehydration in industry (Atten and Aitken, 2010; Eow and Ghadiri, 2002; Lundgaard et al., 2006). While a droplet coalesce with the interface under an electric field, the electrostatic pressure can locally change the droplet-interface shape and accelerate the rupture of the oil film, hence promote the coalescence (Aryafar and Kavehpour, 2009). Unfortunately, if the applied electric field strength is too high, only a part of the droplet can merge into the bulk phase, and partial coalescence occurs (Aryafar and Kavehpour, 2009; Hamlin et al., 2012; Mousavichoubeh et al., 2011a, 2011b). Non-coalescence or bounce may occur in some drastic situation (Allan and Mason, 1962; Chabert et al., 2005; Hamlin et al., 2012; Mousavi et al., 2014; Ristenpart et al., 2009).

The coalescence pattern depends on electric field parameters and physical properities, such as conductivity, permittivity, viscosity etc. (Bird et al., 2009; Chabert et al., 2005; Hamlin et al., 2012; Hellesø et al., 2015; Ristenpart et al., 2009; Thiam et al., 2009). Hamlin et al. (2012) found the coalescence pattern went through complete coalescence, partial coalescence and non-coalescence with increasing DC electric field strength. The conductivity is proved to be important in partial coalescence and there is a threshold above which the droplet bounce off. The coalescence pattern is also related with the properties of the oil phase and experiments have been conducted with different oils (Chiesa et al., 2006; Hamlin et al., 2012; Mousavi et al., 2014).

Partial coalescence produces very small droplets, which is undesirable as they are more difficult to remove from oil. Mousavichoubeh et al. (2011b) used the product of Weber number ($\mathrm{We} = 2R\varepsilon_2\varepsilon_0E^2/\sigma$) and Ohnesorge number (Oh) to get a new dimensionless number WO, which describes the ratio of the electrical stress energy that causes necking over the energy required for pumping fluid out of the droplet. There is a tendency that increasing the electric field strength results in increasing the radius of secondary droplet (Hamlin et al., 2012; Mousavichoubeh et al., 2011a, 2011b). Mousavichoubeh et al.