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Electrocoalescence of binary water droplets falling in oil: Experimental study

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ABSTRACT

The approaching movement and consequent coalescence of binary water droplets falling in stagnant oil and exposed to an external electric field are investigated using a high speed camera. Different situation of the droplets and electric field intensities are applied in the experiments. The qualitative results of the experimental observations are exhibited through the scaled images of the binary droplets snapshots in milliseconds. Furthermore, different approaching trends of the droplets are presented as quantitative plots and discussed based on the theoretical electrostatic and hydrodynamic models. The effect of the applied voltage amplitude, initial distance of the drop pair, and skew angle of the electric field are investigated. The experimental results prove the electrostatic theories; as acceleration in electrocoalescence demonstrated using a stronger electric field as well as closer distance between the droplets. It was also revealed that the skew angle of the electric field decelerates the electrocoalescence until alignment of the droplets.

Keywords: Electrocoalescence; Drop; Separation mechanism; Microscale; Snapshot; Visualization

1. Introduction

The water content of extracted crude oil, especially in offshore fields, increases during a reservoir life time as production schemes lift more water with oil from water-drive formations and water-flooded zones. The extracted mixture is passed through the pressure relief valves; in which an emulsion of small water drops in oil is formed. The water has to be separated before the crude oil is pumped. In the petroleum industry, oil–water separation is conducted in large vessels through several stages. The buoyancy force is used to separate the heavier phase (water droplets) and form a sub-layer at the bottom of the separation vessels. The speed of the sedimentation process is controlled by the terminal velocity, which is given by Stokes equation (Noik et al., 2006):

$$V_s = \frac{\rho_w D_0^2}{18\mu_0}\left(1 - \frac{\rho_o}{\rho_w}\right) g \tag{1}$$

It implies terminal velocity of the droplets is proportional to the square of the droplet diameter. The residence time in gravity separators mainly depends on the sedimentation velocity of the smallest drops (e.g., $d < 100\,\mu m$) (Chiesa, 2004). Therefore, the only way to speed up the separation process is to force small water droplets to coalesce into larger ones. The most familiar way is achieved by applying electric field for water in oil emulsion. The electric field gives rise to attractive forces between the droplets and increases the probability of coalescence.

It has found that, in the process of binary drop collision, pressure is built up in the between gap and while the kinetic energy tries to drain the oil film, they lose the kinetic energy (Mohammadi et al., 2012). Electrostatic forces are different from hydrodynamic forces since they can act over large distances, while hydrodynamic forces are near field forces. That is, a mass element just acts on the adjacent elements. The separation process applied on water in oil (w/o) emulsions, where the electric field is used to assist merging small water droplets

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Nomenclature

A	droplet projection area, m^2
C	coefficient, dimensionless
d	distance between drop centers, m
D_0	initial droplets diameter, m
e_r	direction of relative motion, dimensionless
E_0	electric field intensity, V m^{-1}
F	force, N
g	gravity acceleration, m s^{-2}
K	coefficient of dipole–dipole force, dimensionless
m	mass of droplet, kg
p	dipole moment, C m
r	drop radius, m
R	reduced radius, dimensionless
s	separation distance between the drops, m
t	time, s
$\mathbf{u}$	velocity vector of droplet, m s^{-1}
$\mathbf{v}$	velocity vector of oil, m s^{-1}
v_r	relative velocity, m s^{-1}
v_s	terminal velocity of droplet, m s^{-1}
V	volume, m^3

Greeks letters

ε	relative permittivity, dimensionless
μ	dynamic viscosity, Pa s
ρ	Density, kg m^{-3}
γ	interfacial tension, N/m
φ	Permittivity ratio function, dimensionless
ψ	Electric field angle,°

Subscripts

b	buoyancy
d	droplet
D	drag
E	electrical
F	fluid
g	gravity
o	oil
r	radial direction
θ	tangential direction
w	water

into larger ones, is usually called electrocoalescence. This process is based on the very different electrical properties of oil and water, since water has much higher dielectric permittivity and conductivity values than oil. The effects of the electrostatic field can be explained by body forces acting on water drops. This force may be from the charged drops, resulting in electrophoretic forces, or caused by polarized drops in divergent fields, leading to dielectrophoretic forces (Raisin et al., 2008).

Lundgaard et al. (2002) have categorized the electrocoalescence mechanism in four possible scenarios as: longer time of contact between drops, surface instability, electrostriction of the interfacial layer, and shockwaves from electric breakdown. They carried out some experiments on water droplet pairs in stagnant oil subjected to an AC electric field. They have suggested that several factors may influence the electrocoalescence process, consisting of magnitude and shape of the applied voltage. However, they have noticed that their experiments cannot confirm or reject any of the probable proposed mechanisms for electrocoalescence.

The possibility of electrical discharges between water droplets was suggested by Lundgaard et al. (2002). However, this mechanism has been severely doubted to motivate coalescence of water droplets in oil Lundgaard et al. (2006). They revealed that electrical discharges between close droplets appear impossible in the case of water droplets in oil. They argued on minimum required potential difference for electron avalanches in the surrounding oil phase. Accordingly, they proved potential difference between two electrically neutral droplets is lower than the minimum Paschen voltage for self-sustained discharge in the oil phase.

Allan and Mason (1961) have conducted some experiments on drop–interface coalescence in an electric field and later Brown and Hanson (1965) have performed the same experiments. They concluded that a drop coalesces on a flat interface by the film drainage mechanism and the electric field accelerates the coalescence. Allan and Mason (1962) have conducted some experiments on drop–drop coalescence in which the drops were moved in a laminar shear flow until they were slipped on each other. In their experiments the electric field was applied on the drops when brought into contact. They reported that coalescence was speeded up with increasing field strength and concluded the electric field was responsible for interfacial film rupture.

Taylor (1996) has studied the effects of a pulsed DC field on electrocoalescence of a bulk emulsion and introduced some distinct time intervals. Taylor has reported that during the rise time and fall-time of voltage, a drop responded immediately and moved toward an adjacent drop although no movement was observed during the off-time. Eow and Ghadiri (2003) performed some experiments to study the effect of the direction of the applied DC field on two water drops sited on Perspex microscopic cell. They have confirmed the skew angle of 54.78 as the drop-drop attraction limit.

Pedersen et al. (2004) conducted a few experiments on two falling droplets exposed to an external electric field. They investigated the skew angle of electric field and the distance between the droplets in two experiments under the same electric field strengths. They reported that the droplets started immediately to move toward each other when the voltage was turned on. They illustrated the droplets became more aligned with the applied electric field during the approach.

Chiesa (2004) has investigated coalescence and kinematics in a stagnant water-in-oil emulsion subjected to a sinusoidal voltage. Chiesa (2004) has confirmed the average drop size increases with time under the effect of the electrical field. Chiesa et al. (2005) have performed an experimental and theoretical study to investigate kinematics of droplets when exposed to an electric field. The majority of their experiments have focused on the behavior of a falling drop onto a stationary interface and only one experiment illustrates falling of two water droplets in oil. Later, Chiesa et al. (2006) have observed a droplet falling onto a stationary interface at different oil viscosity. They have suggested that oil viscosity indirectly influences the time of coalescence since the impact velocity of the water droplet increases in low viscosity oil.

From the reviewed experimental studies it could be inferred that most of the researches have focused on electrocoalescence of drop-interface, droplet–droplet sited on surface, or bulk emulsion. Among whole, only Pedersen et al. (2004) and Chiesa et al. (2005) have studied electrocoalescence of binary falling drops for two and one experiments, respectively.

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