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Numerical prediction of the electrical waveform effect on electrocoalescence kinetic

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ABSTRACT

The effect of external electric field characteristics on the binary water droplet coalescence in stagnant oil has been studied using Computational Fluid Dynamics (CFD) simulations. Volume of Fluid (VOF) approach is applied as a multiphase model, in which the hydrodynamic equations consisting of Navier–Stokes and interface tracking equations are solved using finite volume discretization scheme. Dipole-induced-dipole (DID) model is utilized to calculate the electrostatic force on water droplets. Different types of electrical waveforms have been implemented using appropriate potential functions. The studied electrical voltages are sine, triangle, sawtooth, pulsed DC, and bipolar square waveforms. The predicted kinetic for electrocoalescence is in good agreement with the experimental data of the literature. The results demonstrated that a bipolar square wave provided the most efficient waveform, while sine and pulsed DC voltages gave lower efficiencies due to the time variation and off-time intervals, respectively. Triangle and sawtooth waveforms produced the least efficient waveforms. In addition, the effect of frequency has been studied for the aforesaid electrical waveforms in the adopted binary drop system. No significant differences have been proved in the approaching time of the drops from the studied frequencies. The results revealed that the electric fields with higher value of root mean squares (RMS) result in more efficient electrocoalescences. Furthermore, it was manifested that the higher voltage amplitude in every waveform improves this phenomenon.

Keywords: Electric field; Potential function; Frequency; Water-in-oil; Coalescence; Micro-scale; CFD

1. Introduction

Generally, crude oil, produced from petroleum reservoirs contains some water. In offshore fields the fraction of water is more significant. When the pressure of the extracted mixture is relieved through the valves, an emulsion of small water drops in oil is formed. The water has to be separated before the crude oil is pumped toward the refineries. The residence time in gravity separators mainly depends on the sedimentation velocity of the smallest drops (e.g., $d < 100\,\mu m$) (Chiesa, 2004). It is possible to improve separation efficiency of water by the means of lengthening residence time in the tanks, reducing the crude oil viscosity, and enlarging the water droplets. The first two methods lead to larger equipment and increased energy consumption, respectively. Enlarging water droplets in some extent can be conducted by using chemical surfactants, which is harmful from an environmental viewpoint (Berg et al., 2010). However, electrostatic fields can be used to assist merging the small water drops into larger ones that is so-called electrocoalescence. During the past century, electrocoalescence has been used in different techniques using different voltage waveforms, flow characteristics, and electrode shape and coating (Lundgaard et al., 2006). Eow et al. (2001) and Eow and Ghadiri (2002) have reported a detailed review of these techniques. Zhang et al. (1995) have suggested that the electric field induces charges of opposite sign on the neighboring surfaces of two water drops in oil. In that case, the drops are polarized due to redirection of induced dipoles. For effective dipole coalescence, the droplets have to be brought into close contact with each other (Eow et al., 2001).

To model electrocoalescence efficiency of two adjacent drops one needs to know how the electrical waveforms

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Nomenclature

d	distance between drop centers
D_0	droplets diameter
E	instant electric field intensity
E_0	electric field amplitude
f	frequency
F	force
g	gravity acceleration
K	coefficient of dipole–dipole force
L	distance between the electrodes
n	normal vector of interface
p	dipole moment
P	pressure
r	drop radius
s	separation distance between the drops
t	time
T	period time
$\mathbf{u}$	velocity vector
u	velocity component in x-direction
v	velocity component in y-direction
V	instant voltage
V_0	voltage amplitude
$\mathbf{X}$	position vector

Greek letters

α	volume fraction
ε	permittivity
κ	curvature
μ	dynamic viscosity
ρ	density
σ	interfacial tension
φ	permittivity ratio function

Subscripts

c	critical
d	dipole–dipole force
o	oil
s	surface force
w	water

influence on the electric forces between the drops (Chiesa, 2004). Electrostatic forces are special since they can act over large distances. This is different from hydrodynamic forces, which are near field forces. Different voltage source like DC, AC, and even pulsed DC are used for electrocoalescence. The effects of the electrostatic field can be explained by body forces acting on water drops (Lundgaard et al., 2006). Optimum water separation can be adjusted by an adaptive control on high voltage circuit, the voltage shape, and amplitude (Berg et al., 2010).

Coalescence of two droplets in a continuous fluid flow occurs in three steps (Prince and Blanch, 1990). In the first step, the droplets approach each other and collide, trapping a small amount of the continuous phase between them, called the separating liquid film. This film then drains until it reaches a critical thickness. At this point, the film rupture occurs resulting in coalescence.

The criterion, which determines two colliding droplets rebound or coalesce, is whether the separating oil film between them drains and the inter-droplet gap reduces to a critical thickness or not. The critical thickness is comparable to that of the molecular interaction distance; typically of the order of 10^2 Å (Mackay and Mason, 1963). It is found that, in the process of collision, kinetic energy is mainly transformed into surface energy. When two droplets approach each other, high pressure is built up in the gap between them, while this pressure build-up causes the droplets to flatten. When the droplets are trying to drain the oil film, they lose the kinetic energy (Mohammadi et al., 2012).

Type of the applied electric field can affect the efficiency of water drop coalescence. Alternating current (AC) is the oldest and most general type of electrostatic field, which is used in crude oil treatment, while direct current (DC) can be used only for the petroleum cuts with low water content (Taylor, 1996). The coalescence rate advances as the electric field intensity is increased. On the other hand, if the field strength becomes too high, drop breakup takes place (Williams and Bailey, 1986). The electric field intensity of about 1 kV/cm is commonly used in the industrial electrocoalescers (Chen et al., 1994).

Electrocoalescence phenomenon can be studied in different scales. The overall efficiency of an industrial electrocoalescer can be studied in the macro-scale. The interaction of the drops with turbulent flow and electric field can be observed in the meso-scale, where a multiparticle system is used to describe the emulsion. In the micro-scale, the movements of the drop pairs are studied in details until drop coalescence in an electric field. Finally, the water/oil interface chemistry and stability can be considered at the nano-scale (Berg et al., 2010).

Most of the literature has been concentrated upon experimental investigation of electric field effect on the drops (Mashayek et al., 2003). The influence of a constant electric field on two conductive droplets has been studied by Brazier-Smith et al. (1971) without considering viscous force effects. Williams and Bailey (1983, 1986) used an estimated solution for electrostatic forces, which neglected the hydrodynamic interactions causing an overprediction of the coalescence rate. Zhang and Davis (1991, 1992) have investigated the effects of hydrodynamic on collision and coalescence of drops. Atten (1993) has proposed an approximate expression for the overall coefficient of collision rate and dipolar interaction between droplets. Zhang et al. (1995) have presented a theoretical model to predict binary drop collision induced by a constant external electric field using analytical solution for drop trajectory. Chiesa et al. (2005, 2006) have performed an experimental and theoretical study for electrocoalescence of binary drops. They used the Lagrangian method in hydrodynamic section, which was not able to consider the fluid nature of the drops. However, they attempted to eliminate this deficiency by using some modified closure models for drag and film-thinning forces. However, this model was dependent on tuning parameter of slip length and the aforementioned sub-models. The difference between the movements of rigid spheres and water drops under the influence of an electric field was illustrated by Chiesa et al. (2005). In addition, they studied constant electric field strength both experimentally and theoretically. Later, Melheim and Chiesa (2006) modified a so-called "cluster integration method" model, which assumed each collision leads to a coalescence, that is, the model ignored coalescence efficiency. Atten et al. (2006) have studied on elongation of two close droplets applying a uniform electric field. They have suggested the surfaces of the drops might lead to more acute shape, immediately prior to their contact. Bjørklund (2009) has used the level-set method in combination with the ghost-fluid method to simulate droplet dynamics in the presence of a constant electric field in two dimensional Cartesian coordinate