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Numerical and experimental study on electric field driven coalescence of binary falling droplets in oil

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ABSTRACT

The movement and coalescence of binary water droplets falling in stagnant oil exposed to an external electric field is studied. The electrostatic forces in competition with the viscous forces effect on electrocoalescence of the droplets. An electrohydrodynamic (EHD) model is developed based on Computational Fluid Dynamics technique in conjunction with an electrostatic model. Volume of Fluid (VOF) approach is applied in the hydrodynamic model which able to consider circulation streams inside and outside of drops, surface tension effects and interface tracking. The effect of applied voltage amplitude, initial distance between the drops, and skew angle of the electric field are investigated. Both the simulation and experimental results verified an improvement in electrocoalescence rate could be achieved using either a stronger electric field or closer drops. It was also revealed that a larger skew angle of the electric field slows down the approaching movement of the drops until they become relatively aligned with the field. The numerical results are compared and validated against the experimental observations. The velocity vectors and the pressure profiles are analyzed to improve understanding of the microscale phenomena in electrocoalescence.

1. Introduction

The extracted crude oil passes through the choke valves from the petroleum reservoir to the production facilities. Because of the shear stress and pressure drop, the water phase is blended and fully dispersed as small droplets in crude oil. The problem of emulsified water in the extracted crude oil increases, as production schemes lift more water with oil from water-drive formations and water-flooded zones. Separation of water drops from crude oil generally is conducted in several stages, consisting of settling in large tanks and subsequent electrocoalescers.

The sedimentation rate of the water droplets is proportional to the square of the droplet diameter. Therefore, the only way to speed up the separation process is to force small water droplets to coalesce into larger ones. Coalescence of two droplets depends on complete drainage of trapped continuous phase film between them. This film resists against the approaching movement of droplets, called the film thinning force. Taylor [1] has suggested that formation of drop chains in emulsions depends on the crude oil type and chemical additives. Taylor has stated that this chains formation results from inefficient drop–drop coalescence due to a rigid interfacial film. The electric field is used to induce the attractive forces between the droplets and increase the probability of coalescence. The electrical forces are responsible to overcome the increasing trend of film thinning force.

The separation process applied on water in oil (w/o) emulsions, where the electric field is used to assist merging small water droplets into larger ones is usually called electrocoalescence. This process is based on the very different electrical properties of oil and water; as water having 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, lead to dielectrophoretic forces [2].

Most of the literature has focused on experimental investigation of electric field effect on the drops; while less attention has been paid to the phenomena occurring in coalescence of two drops and the computational studies of drop collision are very limited. Brazier-Smith et al. [3] studied the influence of an electric field on two conductive droplets using a boundary-integral method without considering viscous effects. Williams and Bailey [4] have investigated coalescence rate of conducting drops in an external electric field both theoretically and experimentally. However, they used an estimated solution for electric field induced forces, which is not valid

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Nomenclature

d	distance between drop centers, m
D_0	initial diameter of droplet, m
E_0	electric field intensity, V m^{-1}
F	force, N
g	gravity acceleration, m s^{-2}
K	coefficient of dipole–dipole force, dimensionless
p	dipole moment, C m
r	drop radius, m
s	separation distance between the drops, m
t	time, s
u	velocity vector, m s^{-1}

Greeks letters

ε	relative permittivity, dimensionless
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
σ	interfacial tension, N m^{-1}
φ	permittivity ratio function, dimensionless
ψ	electric field skew angle, degree

Subscripts

d	dipole-dipole
e	electrical
o	oil
r	radial direction
θ	tangential direction
w	water

at very close distances. Furthermore, hydrodynamic interactions between the drops were not taken into account, which resulted in a substantial over-prediction of the coalescence rate. Later, the effects of hydrodynamic on two drop collision and coalescence have been investigated for different drop motions [5]. This study on collision and coalescence of drops has shown that hydrodynamic interactions significantly reduce collision and coalescence rates.

Pedersen et al. [6] 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 towards each other when the voltage was turned on. They illustrated the droplets became more aligned with the applied electric field during the approach. Later, Chiesa et al. [7,8] have followed the experimental and theoretical studies 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. Furthermore, they have presented a model essentially based on a Lagrangian framework for the drops. They assumed the drops as rigid particles and the summation of different acting forces to ideally drive the drops. They considered the fluid state of the drops by using some modified closure models for drag force and film-thinning force. However, their model becomes dependent on tuning parameter of slip length and the aforementioned sub-models.

Melheim and Chiesa [9] have modified a model, so-called "cluster integration method". Due to the lack of a precise model for coalescence efficiency, they assumed each neighboring leads to coalescence. However, this might be an invalid approximation, regarding to the applied electric field intensity, as illustrated by them. Moreover, depending on the local angle of the electric field and the connecting line of the centers of the drops, the validity of the approximation is more doubtful. Bjørklund [10] has used the level-set method in combination with the ghost-fluid method to simulate droplet dynamics in the presence of an electric field in two-dimensional Cartesian coordinate system.

From the reviewed experimental studies it could be stated that only Pedersen et al. [6] and Chiesa et al. [7] have studied electrocoalescence of binary falling drops for two and one experiments, respectively. Both of these works have used same averaged electric fields strength of 2.8 kV/cm. Furthermore, they only have reported approaching movement of droplets as plot and no images of the colliding drops have been presented.

Our previous numerical researches on coalescence and electrocoalescence of binary droplets suggested the lack of the collision and coalescence images to be used as a benchmark in the development of numerical studies [11–13]. In CFD studies, such as those of VOF approach, these images are very useful to study the dynamics of droplet-droplet electrocoalescence. Accordingly, in the earlier experimental study, some detailed images of binary falling droplets and consequent coalescence under the effect of an electric field have been presented [14]. The experimental observations were exhibited through the scaled images of droplets snapshots in milliseconds.

In complement to the previous studies, a numerical research is presented using a modified electrohydrodynamic (EHD) model. The modified model is based on Computational Fluid Dynamics (CFD) method in combination with the dipole-induced-dipole (DID) model as electrostatic part. The numerical model is implemented for equivalent initial conditions of the experiments to predict the dynamic of electrocoalescence of binary falling droplets within the oil. The visual and plotted data of the experiments are applied to compare and evaluate numerical results. The velocity vectors and the pressure profiles achieving through numerical simulations are analyzed to recognize the microscale phenomena in electrocoalescence.

2. Experimental set-up

The experimental set-up is schematically shown in Fig. 1, which is an arrangement of a cubic cell, two microsyringes, a background light, and a high-speed digital video camera. The test-cell can be used to study motions of water droplets in stagnant oil subjected to a homogeneous electric field between the parallel electrodes. The electrodes were placed vertically inside the cubic test cell while the gap between them was set at 50 mm [14]. Two droplets were released simultaneously at the preferred locations and then slowly fell down within inter-electrode region of the test-cell. Once the electric field was exerted, the droplets started immediately to move towards each other and finally coalesced. The position of the droplets was identified from the extracted sequential frames of recorded video.

The properties of the water and oil phases used in the experiments are given in Table 1.

3. Model description

An electrohydrodynamic model is developed based on Computational Fluid Dynamics (CFD) technique in combination with an