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Electrocoalescence modeling: an engineering approach.

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Abstract

In a stagnant water-in-oil emulsion subjected to an external AC electrical field, charges induced on the water drops will cause adjacent drops to attract each other. Simulations and experimental observations are here compared. A discrete particle model of the emulsion is implemented and used to calculate the two-dimensional motion of the individual, spherical water drops directly from the forces acting on them. The hydrodynamic interaction between the drops and the interstitial oil phase is taken into account, together with the effect of the electrical field. In our model, coalescence is assumed to occur when two drops collide. Experiments have been performed to observe the behavior of water drops in oil exposed to a homogeneous electrical field. The optical observations are compared to the results obtained from the discrete particle model. Good agreement between the predicted and measured volumetric drop distribution is found for low water volume fractions.

Introduction

The oil extracted from offshore reservoirs will normally contain a large and, during the reservoir lifetime, increasing percentage of water in the oil. When the water-oil mixture is passed through the pressure relief valve, an emulsion with a high percentage of small water drops is formed. Before the oil is pumped on-shore or into tankers, it is desirable to extract the water from this emulsion. Today the separation tanks are mainly built or operated as gravity separators with low flow rates and long residence times, lasting from minutes to tens of minutes. The residence time mainly depends on the sedimentation velocity of the smallest drops (e.g., $d < 100$ μm). Electrostatic fields are to some extent used to help smaller drops to coalesce into larger drops that sediment quicker. The sedimentation velocity increases proportionally to the square of the diameter of the drops. Frequently, investigations on electro-coalescence are done on emulsions focusing on bulk behavior. The understanding of the electrostatic mechanisms active in the electro-coalescence process is often quite superficial. Traditionally, electro-coalescers have utilized DC or pulsed DC fields and laminar liquid flow. However, recently, [1] showed that by applying a combined AC field and turbulence on the emulsion the coalescence rate is increased and the sedimentation time is significantly reduced. This effect on the coalescence is believed to be caused by the electric field around and between the drops. Polarization of the water drops is induced by the external electric field. The electrostatically induced field and forces increase when polarized water drops approach each other. Additionally, velocity fluctuations associated with the turbulent flow cause a high impact rate between drops.

One may model the electro-coalescence process by separating the coalescence efficiency that can be achieved when two drops come close to each other, and the collision rate between drops. One then needs to know how the magnitude, frequency and distribution of the electric field influence the coalescence efficiency and how turbulence and electric field forces influence the impact rate between drops. A numerical tool for the simulation of the electro-coalescence phenomena is implemented in the present work. The numerical simulator works as a design tool which gives research scientists and engineers the possibility of gaining an idea of the complex physics involved in the electro-coalescers.

The two-dimensional motion of each spherical drop can be directly calculated from the forces acting on it. The interaction between the drops and the interstitial oil phase as proposed by Michaelides [8], together with the effect of the electrical field on the kinematics of the drops as outlined by Davis [3], is taken into account. Our collision model is based on conservation laws for linear and angular momentum, and coalescence is assumed to occur when two drops collide. In the present paper, the numerical simulation tool is briefly presented and the validity of the model implemented for the calculation of electrical forces between drops is assessed. Numerical simulations of the electro-coalescence phenomena in a stagnant emulsion are performed and compared to experimental observations. Good agreement is observed between the predicted and measured volumetric drop distribution for water-in-oil emulsions with a water volume fraction below 2%.

An analytical model for the electrical forces acting on the drops

When two water drops get close, the fields around the drops will mutually influence each other. Adding more drops will enhance this problem. Considering the difficulties due to these mutual influences one realizes that this approach is not feasible. A simplified model to calculate the electrical forces acting between the water drops is necessary to keep the problem easier to handle numerically. Lundgaard et al. [7] reviews a simplified analytical model for the electric force between two uncharged metallic spheres. The Laplace equation $\nabla^2\Phi = 0$ is solved in order to determine the resulting electric potential Φ with which the field E is calculated from $E = -\nabla\Phi$. Davis [3] calculates the maximum electrical field on the sphere with radius r_2 as:

$$E_{r_2}^{Max} = E_0 \cos\theta \cdot E_3 \tag{1}$$

where E_3 is a function of the distance between the spheres normalized with the radius of the sphere itself. $E_3(s/r_2)$ has a high value for small values of s/r_2 see [3]. This means that the field of a drop with radius r_2 is highly influenced by the presence of another drop in its vicinity. On the other hand, the electrical field is almost undisturbed by the presence of the drops when $s/r_2 > 1$. Let d be the distance between the drop centers: $d = r_2 + r_1 + s$. The components of the electrical force on the drop r_2 see Davis [3], read:

$$F_r = 4\pi\varepsilon_{oil} r_2^2 E_0^2 (f_1 \cos^2\theta + f_2 \sin^2\theta) \tag{2}$$

$$F_\theta = 4\pi\varepsilon_{oil} r_2^2 E_0^2 f_3 \sin 2\theta \tag{3}$$

where $f_{k=1,2,3}$ are expressed by a complicated series depending on the ratio $s/r_2 \leq 1$, see Lundgaard et al. [7]. One quickly realizes that even if the background field is low, the field and forces between adjacent drops from the induced polarization may become large. The electrical force becomes repulsive when the angle $\theta \geq 54.7°$. Eq. (2)-(3) have a validity limited to a two-drop system, but in the present work they are used to calculate the electrical forces in a multi-drop system such as a water-in-oil emulsion with a low water content. This is considered to be

a satisfactory approximation as long as the water volume fraction in the emulsion is below 5%, ($[H_2O] < 0.05$), see [2].
When going from a two drop model case to a multi drop case, one must be aware that the presence of the water drops in the emulsion between the electrodes will result in an increased stress in the oil. Generally, if one puts two dielectrica having different permittivities in series between two plane electrodes, the field in the higher permittivity dielectric will be reduced. The field in the lower permittivity dielectric will be enhanced compared to an average field magnitude $|E| = V/|d|$ where V is the voltage and d the distance between the electrodes.

The Discrete Element Method (DEM)

Consider n spherical drops that follow a trajectory given by:

$$m_i \frac{\mathrm{d}v_i}{\mathrm{d}t} = F_{i,\text{flow}} + F_{i,\text{external}} + F_{i,\text{collisions}} \quad (4)$$

$$\frac{\mathrm{d}x_i}{\mathrm{d}t} = v_i, \quad (5)$$

where $i = 1,\ldots,n$ and v_i are the velocities of the ith drop and where mass transfer has been neglected. Forces from the flow are drag forces, virtual mass forces etc, see for instance Michaelides [8]. Gravity is the typical external force. In the present study the dielectrophoretic forces between the drops due to an average electric field are also present, and have to be taken into account to describe the kinematics of the system of drops in a realistic way. Inter-drop and wall-drop forces are caused by collisions. The hard sphere model approach is used in the present work and a simplified version of the drop-wall collision model is used see [2]. A sequence of binary collisions needs to be handled, since collisions are assumed to happen instantaneously. The drop-drop collisions are considered in the present work to be ideally plastic, since coalescence is assumed to occur whenever two drops collide. The model used in the present work does not describe the complex physics of the coalescence phenomenon, however it is considered to be a satisfactory approximation for the present study. The velocity of the drop immediately after the collision is computed algebraically from the velocities of the drops immediately before the collision. Conservation of mass and momentum is fulfilled. A technique for sequencing multiple collisions within one basic time step is pointed out by Hoomans et al. [5] and is used in the present work. When the spherical drop moves in straight trajectories, the time until a collision between drop i and j occurs, is given by:

$$t_{ij} = \frac{-r_{ij}\cdot v_{ij} - \sqrt{(r_{ij}\cdot v_{ij})^2 - |v_{ij}|^2\left(|r_{ij}|^2 - (r_i + r_j)^2\right)}}{|v_{ij}|^2}, \quad (6)$$

where r is the drop radius and

$$r_{ij} = x_i - x_j, \quad (7)$$

$$v_{ij} = v_i - v_j, \quad (8)$$

where x_i and v_j are the positions and velocities of the drops.

Numerical solution procedure

The numerical solution follows the lines of Kuipers et al. [4]. The solution of the Navier-Stokes equations, require specification of the porosity α and the drop x- and y- velocity components (v_x and v_y) at the appropriate grid nodes. These values are obtained from the discrete particle model. For each particle, the indices i and j of the cell where its center of mass can be found, are stored. From this information $\alpha(i,j)$ can be calculated based on the area occupied by the particle cell i,j. Since the porosity is an important parameter which considerably influences the oil-phase motion, a detailed check for overlap is carried out in which multiple cell overlap is taken into account, see Hooman et al. [5]. In a computational cell, the porosity is defined as the ratio between the volume of the particles contained in the cell and the entire volume of the cell:

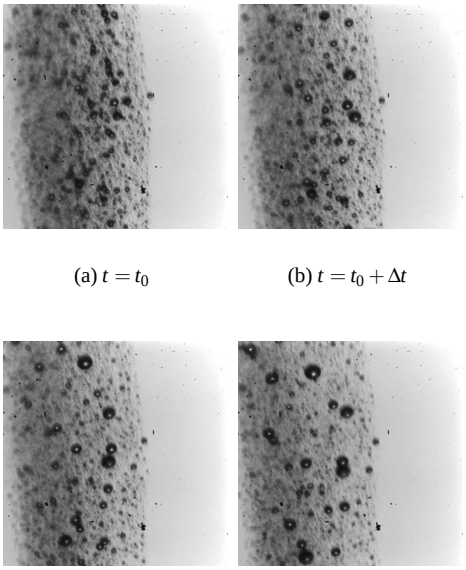
$$\alpha_g = 1 - \frac{2}{3}\frac{\sum A_p}{A_{cell}} \quad (9)$$

where A_p and A_{cell} are the drop volume and the cell volume respectively see Hooman et al. [5].
Firstly, the forces on the particles are recalculated, based on a recently updated velocity field. Events in this context are contact between two drops and contact between drop and wall. Based on the positions and velocities at the end of the previous time step, a new event queue is built. The events are handled, new events are detected, and the cell-particle list and the event queue are updated. The loop runs until no more events will happen during the actual time step.
The system of Eq. (4) is solved by a first order explicit Runge-Kutta (forward Euler) time discretization which reads:

$$y_{n+1} = y_n + dty'_n, \;\; y_0 = y(t_0), \quad (10)$$

where dt is the time step length and y is a general vector with the initial conditions $y(t_0)$. We desire to use a solver with better accuracy and stability properties than the forward Euler's method. The key point is the consistency between the calculations of the point of time a collision occurs and the movement of the particles. Therefore, the numerical scheme has to predict the positions linearly in dt, see Lubachevsky [6] and Sigurgeirson [9]. During the time-step, only particles that are involved in a collision or a wall collision are moved. At the end of the time step, every particle is moved. Finally the volume fraction of particles is calculated.

Experimental results



(a) $t = t_0$ (b) $t = t_0 + \Delta t$

(c) $t = t_0 + 2\Delta t$ (d) $t = t_0 + 4\Delta t$

Figure 1: Water drop growth due to electro-coalescence. $t = \sum_i (t_0 + i\Delta t)$ s with $i = 0,1,2,4$.

Experiments are designed for visual observation of drops or water-in-oil emulsion exposed to electrical field, [7]. The electrode arrangement is placed inside a small test cell $15 \times 15 \times 15\,\mathrm{cm}^3$. The test cell is mounted in a shadow-graphic setup using an optical bench. A water-in-oil emulsion where coalescence is achieved whenever the water drops collide is used in this experiment. The main goal with this experiment is to assess the effect of the electrical field on coalescence and in general on the kinematics of the water-in-oil emulsion. The emulsion is injected in a naphthenic oil under the effect of an electrical field $E_0 \approx \pm 1.2 \times 10^5\,\mathrm{V/m}$. The density difference between the emulsion and the oil phase is small, and therefore the emulsion translates downwards slowly. This allows us to keep the camera focused at the same position during the whole experiment. A high-speed camera with a maximum frame rate

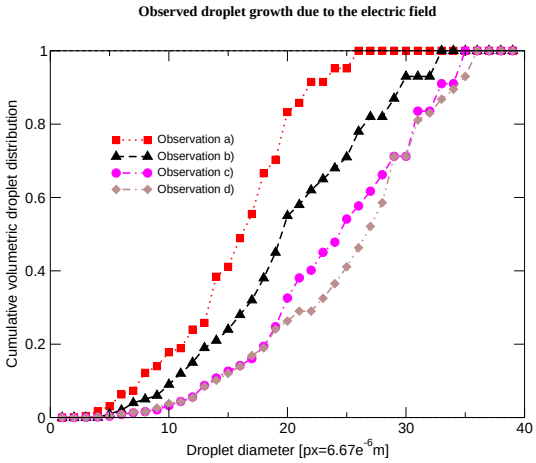


Figure 2: Cumulative volumetric drop distribution obtained from the photograms of Fig. 1

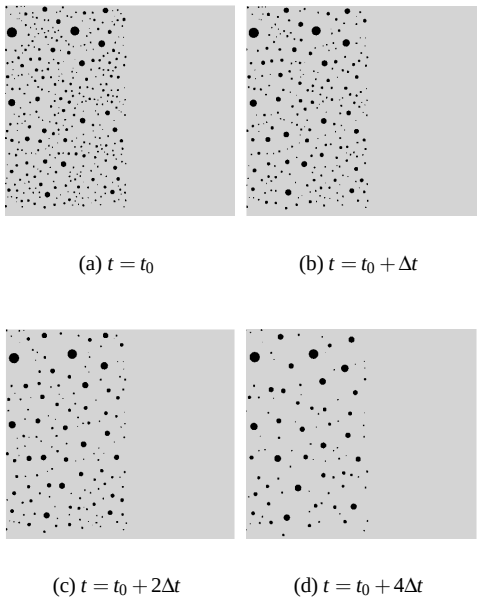
of 32000 frames/sec is used to record the trajectory of the moving drops. The voltage source is a HV-amplifier (High Voltage) $(\pm 20 \times 10^3\,\mathrm{V}, 0 - 20 \times 10^3\,\mathrm{Hz})$. A 50 Hz sinusoidal voltage is used in these experiments. Fig. 1 shows four photograms of the emulsion taken at different times: $t = \sum_i (t_0 + i\Delta t)\,\mathrm{s}$ with $i = 0, 1, 2, 4$. The light grey zone in Fig. 1 represents the pure oil phase while the dark one is the emulsion injected in the pure oil phase. The black circles are the water drops. The size of the photograms is 512×512 pixels. At the beginning, the water drops' average size is approximately 20μm while at time $t = t_0 + 4\Delta t$ it has increased about 30%. The average drop size increases due to the effect of the electrical field acting on the emulsion.

Fig. 2 shows the cumulative volumetric drop distribution obtained from the photograms of Fig. 1. It is once again possible to observe how the water drops average size increases during the experiment.

Numerical results

A numerical simulation of the water-in-oil emulsion is performed. First of all, a mesh independency study of the result is undertaken and a time step of $10^{-6}\,\mathrm{s}$ is chosen. The experimental drop size distribution at time $t = t_0$ is used at the beginning of the numerical simulation. A simplified model where the electrostatic, drag, Magnus, and gravitational forces are employed, is used in the present work.

Fig. 3 shows the numerical prediction of the water drop growth due to the effect of the electrical field acting on the emulsion. Fig. 3 resembles qualitatively what is observed in Fig. 1: the average drop size increases about 30%. The electro-coalescence phenomenon seems properly described by the simplified model



(a) $t = t_0$ (b) $t = t_0 + \Delta t$

(c) $t = t_0 + 2\Delta t$ (d) $t = t_0 + 4\Delta t$

Figure 3: DEM prediction of the water drop growth due to electro-coalescence.

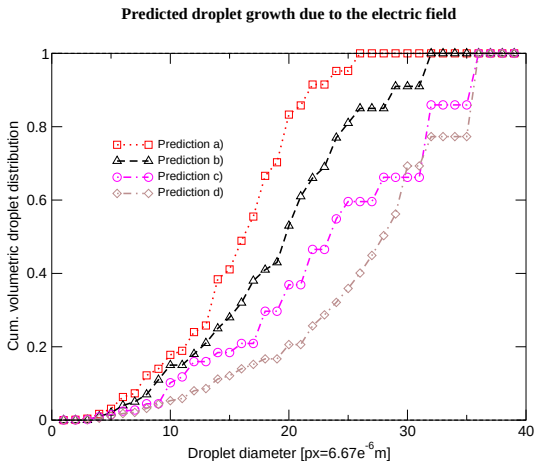
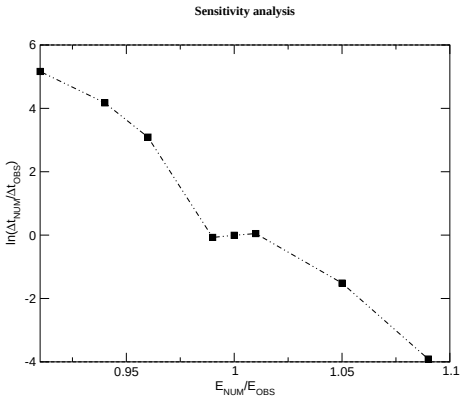


Figure 4: Cumulative volumetric drop distribution obtained from the numerical prediction of Fig. 3

used in the present work to quantify the magnitude of the electrical forces acting on the drops.

Discussion

The numerical predictions obtained in the present work are strongly dependent on the magnitude of the electric field used in the calculation. Let Δt_{OBS} be the time interval between the observations (a) and (b) in Fig. 1 and Δt_{NUM} the time interval between the numerical predictions (a) and (b) in Fig. 3. Fig. 5 shows the dependency of the time interval ratio $\Delta t_{NUM}/\Delta t_{OBS}$ on the magnitude of the elecric field used in the numerical prediction. Let E_{OBS} be the measured electric field between the electrodes. E_{NUM} is the electric field used in the numerical calculation. The ratio E_{NUM}/E_{OBS} is varied between the interval $[0.92 \quad 1.08]$. The electric forces due to the induced charges on the surface of the droplets play an important role on the behavior of the emulsion. A variation of the field magnitude of $\pm 1\%$ does not affect significantly the time interval necessary



(a)

Figure 5: Dependency of the numerical predictions on the electric field magnitude used in the calculation.

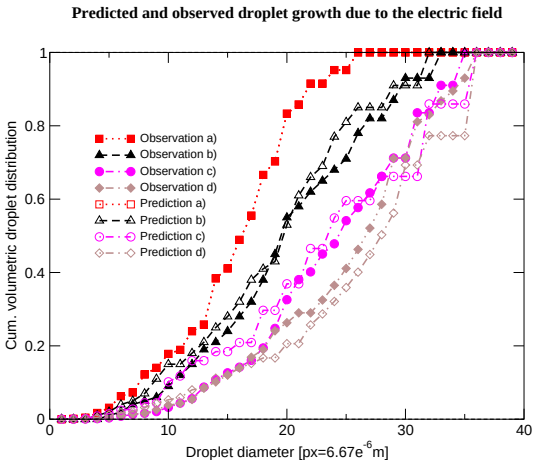


Figure 6: Comparison of the cumulative volumetric drop distribution obtained from the experimental observation and from the numerical analysis.

to predict a droplet distribution similar to the one observed in the experiment. An overestimation of the electric field of 5% accelerate strongly the coalescence process and the time interval necessary to predict a droplet distribution similar to the one observed in the experiment is strongly reduced. An underestimation of the electric field has the opposite effect and the time interval necessary to experience a droplet distribution similar to the one observed in the experiment is strongly increased.

In Fig. 6, the cumulative volumetric drop distribution obtained from the experimental observation and from the numerical analysis are compared. Good agreement is observed. The electric field used in the numerical prediction is $E_{NUM} = E_{OBS}$ and $\Delta t_{NUM} \approx \Delta t_{OBS}$.
The way the electrical forces acting on the drops are calculated in the present work has a limited validity. The good agreement observed indicates that the analytical model for the calculation of the electrical forces gives satisfactory results in the special case of stagnant emulsion considered in the present study. This agreement can be explained by the fact that the water volume fraction in the considered emulsion is below 2% and therefore the probability of finding more than one drop within twice the radius of the smallest drops is relatively low. In the present work, the initial fluid field is at rest. The movement of the drops due to the electrical forces acting on them is given by the drag and the gravitational force. The fluid starts moving because of the drop movement due to the interface momentum transfer term. The magnitude of the velocity field always remains insignificant and the flow regime is laminar.

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