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Analysis of Partial Electrocoalescence by Level-Set and Finite Element Methods

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Abstract

The coalescence of a water drop in a dieletric oil phase at a water layer interface in the presence of an electric field is simulated by solving the Navier-Stokes and charge conservation equations with the finite element method. The proprietary software Comsol Multiphysics is used for this purpose. The interface between the oil and water phases is tracked by implementing a level-set approach. Preliminary simulations to assess the sensitivity of the model with respect to some input parameters are reported. In particular, the calculations are very sensitive to the size of the computational grid elements and the interface thickness parameter. Nevertheless, the model is able to reproduce the occurrence of partial coalescence for the experimental case examined. Good quantitative agreement can be obtained if the parameters are suitably tuned.

Introduction

The application of an external electric field is a technique currently used in the oil industry to promote migration and enhance coalescence of droplets in the water-in-oil emulsions formed during the oil extraction process [1, 2]. It is generally acknowledged that the effect of the electric field is to increase film drainage and hence the thinning rate between two coalescing droplets [1]. However, an excessive value of the field strength can reduce the quality of coalescence, as secondary droplets form [3–6] as a result of an incomplete coalescence process. The efficiency of the process would be significantly improved if the operating conditions to prevent partial coalescence from

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occurring were known. In this regard, it has been shown [5] that the ratio between the volume of the secondary droplet formed and the initial drop volume can be described as a function of a dimensionless number which is the product of the Weber and Onhesorge numbers. The same authors have recently addressed the effect of the electric field type on the coalescence quality. Their experimental results have revealed that the volume of the secondary droplet decreases if pulse-DC fields are applied, leading to the transition from partial to complete coalescence under certain conditions [6]. These findings can have an important impact on the development of compact electrocoalescer designs. The aim of this work is to provide a mathematical description of the phenomenon. For this purpose, a finite element approach combined with the level-set method [7] is adopted in this work to analyse the process of partial coalescence. To the authors' knowledge, there are no attempts at predicting numerically the occurrence of incomplete coalescence in the presence of an electric field. The proprietary software Comsol Multiphysics (Comsol, Sweden) software has been used for this purpose, in an attempt to assess the capability of the proposed approach to reproduce and analyses the phenomenon.

Model Equations

A level-set approach is employed to track the boundaries between different phases. The evolution of the boundary is described by the equation: where is a smooth step function which varies from 0 to 1 across different phase domains, is a reinitialization parameter which gives stability to the solution and is related to the thickness of the interface. The fluid velocity is denoted by u (bold letters denote vectors). It should be noted that Eq. (1) is the non-conservative formulation of the level-set equation, which attains convergence more easily but introduces some errors in the calculations. However, the non-conservative formulation is more suitable for a rapid test of the model capabilities. Navier-Stokes and continuity equations are solved using average physical properties for the two phases: where and are the volume fraction weighted density and viscosity, which differ from the pure liquids properties only at the interface. In eq. (2), forces due to surface tension and induced by the electric field are included. The force due to surface tension is calculated as: where is the surface tension coefficient, the local surface curvature, n the outward pointing interface normal vector and d is a smooth approximation of the Dirac function which is non-zero only at the interface. The electric force is calculated from the divergence of the Maxwell tensor: where is the average permittivity. The electric field E is computed by satisfying the charge conservation equation: where is the average conductivity. With reference to the computational domain depicted in Figure 1, the following boundary conditions have been applied in order to solve this set of equations: the upper boundary is kept at a fixed electric potential while the opposite one is earthed and no-slip conditions are prescribed for both boundaries; the domain is axisymmetric; slip conditions are considered on the right boundary, as this allows significant reduction of the simulation domain. The properties of the two liquids correspond to the sunflower oil/water system investigated experimentally by Mousavichoubeh et al. [5] and are reported in Table 1. The interfacial tension is equal to 25 mN mm^{-1}, as measure experimentally. In order to assess the effect of and the mesh element size, the following case is analysed. The initial drop size is 1.196 mm and the electric field strength is 373 V mm^{-1}. Under these conditions, partial coalescence occurs and the ratio between the volume of the secondary droplets formed and the initial drop volume is equal to about 0.088, as measured by Mousavichoubeh et al. [3].

Results

The calculated values of this ratio are reported in Table 2. For all cases, the reinitialization parameter is set equal to 1 m/s, which is comparable to the maximum fluid velocity in the system. The results shown in Table 2 reveal that the tuning of the interface thickness, is strictly connected to the level of mesh refinement (hmax/D is the maximum element size in the computational grid). With, the calculated volume of secondary droplets becomes invariant with the grid element size when this is sufficiently small. In this case the volume ratio of the secondary droplet to that of the initial drop is very close to the experimental value. However, the phenomenology described in the two simulations is different, and the results are compared in Figures 2 and 3. The value of does not produce realistic results and convergence fails in a number of cases of the behaviour observed experimentally is also reported in Figure 4. The numerical results obtained with reproduce the experimental observations exactly, whereas with a jet-like behavior is reproduced. This may be due to the larger interface thickness, which makes the droplet more deformable and the break-up process more difficult, although the predicted volume ratio is very close to the experimental value. problems, and a solution is obtained only for, which, however, provides a higher value of the secondary droplet volume formed as compared to the experiments. Decreasing further the grid element size to 0.02 causes non-convergence again, as should usually be smaller than the maximum grid size. This requirement becomes more critical when is small.

Conclusions

A model to describe partial coalescence in the presence of an electric field has been proposed. It has proved to be capable of reproducing the phenomenon observed in experimental work previously reported in the literature. A satisfactory quantitative agreement can be achieved by the right selection of the interface thickness parameter and computational grid size. This study constitutes the basis for the development of a reliable mathematical description which can be used for the design of a compact and efficient electrocoalescer.

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