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Electrically induced deformations of water–air and water–oil interfaces in relation with electrocoalescence

Jonathan Raisin*, Jean-Luc Reboud, Pierre Atten

G2Elab (CNRS, Grenoble INP and Joseph Fourier University), BP 166, 38042 Grenoble Cedex 9, France

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ABSTRACT

In connection with the phenomenon of electrocoalescence of water droplets in oil, the electrically induced deformations of some water–oil interfaces are studied. Such problems involve the strong coupling of hydrodynamics and electrostatics as well as the accurate tracking/capturing of the evolving interfaces. The paper presents a Finite–Element Arbitrary Lagrangian–Eulerian (FE–ALE) approach in deforming meshes to investigate the time-dependent deformation of the interface between highly conductive water and an insulating immiscible fluid. The developed numerical scheme is first tested and then used to solve two 2D axisymmetric EHD problems. Computed results are compared with predictions from asymptotic developments and with experimental measurements.

1. Introduction

The influence of an electric field on the deformation and stability of free drops, menisci and pendent or sessile drops has been investigated by numerous authors considering most often the simple case of an interface between a conducting liquid and an insulating fluid. The first basic study in this domain of Electrohydrodynamics (EHD) dates back to Rayleigh who examined the stability of an isolated perfectly conducting charged drop [1]; another study tractable by linear analysis concerned the oblate or prolate deformation of a liquid drop subjected to a uniform electric field depending on the permittivities and conductivities of the two fluid media [2]. Long after the experimental observations on the dynamics of drops formation [3,4], the reference theoretical work concerning free drops is due to Taylor who used the ellipsoidal approximation to determine the steady finite deformation and the stability of an uncharged drop in a uniform field [5]. Following these pioneering works, many theoretical and experimental studies were developed to determine the equilibrium shape of electrified free and pendent drops [6–10]. A detailed study of the dynamics of drop formation in an electric field was also performed in the case of inviscid fluids [11].

The electrically induced or aided atomization of liquids is used in many applications like spray coating [12] and crop spraying [13]. An extensive activity has been devoted to the characterization of the various spraying modes [14,15] and to the understanding of the cone-jet mode [16,17]. Note that drops with a charge above the Rayleigh limit as well as uncharged drops in a strong field give rise to a transient spraying [18].

There is another domain of EHD where the electric field is used not to deform and disrupt menisci or drops but to make drops pairs coalesce. This phenomenon of merging conductive liquid droplets suspended in an insulating liquid (or gas), under the action of an electric field is called electrocoalescence [19]. It is, e.g., used in the petroleum industry to break the water-in-oil emulsions arising at the outlet of the crude oil wells and also in refineries where fresh water is added and finely emulsified to extract the salts from the oil. The electrocoalescers can dramatically increase the mean size of water droplets in the suspension and, therefore, drastically reduce the time required to separate water and oil phases under the gravity effect. Now, state-of-the-art devices are in-line treaters that promote electrocoalescence in a very limited time [20]. Though, the control and increase of their efficiency remain sometimes very difficult as the numerous processes involved in electrocoalescence are far from being fully understood. Another domain of application, more recent, where this phenomenon of drops merging under the action of an electric field migh becoming increasingly used is the lab-on-a-chip domain devoted to various chemical or biological analyses on very small amounts of products. For instance, by using an appropriate electric field, two droplets of reactants can be handled and be merged inducing a chemical reaction or test.

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* Corresponding author.
E-mail addresses: jonathan.raisin@grenoble.cnrs.fr (J. Raisin), jean-luc.reboud@grenoble.cnrs.fr (J.-L. Reboud), pierre.atten@grenoble.cnrs.fr (P. Atten).

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The action of an electric field on suspended droplets of conducting water is, first, to polarize them and to promote their attraction. For nearly contacting droplets the interaction force is strong; it induces a deformation of the facing surfaces and, for free droplets, a relative motion which often result in their merging. In this phenomenon of electrocoalescence, it is necessary to distinguish the stage of build-up of drops pairs by the fluid motion (during which some droplets are brought in very close proximity), from the second stage, the coalescence itself, during which the interfaces deform, can disrupt and lead to merging [21]. The determination of the probability of coalescence of two nearly colliding droplets as a function of the main parameters of the problem (electric field, drops size distribution, water volume fraction and flow properties) is a difficult problem. A prerequisite is a good description of the evolution of the interfaces up to their contact (and the subsequent droplets coalescence). Dynamical solutions for this EHD problem require an appropriate numerical technique capable of accounting for the strong coupling of hydrodynamics and electrostatics and for the interfaces deformation.

For the EHD problems involving interfaces between nonmiscible fluids, one must distinguish between stability problems of static deformed interfaces and those where time dependent interfaces deformation related with fluids motion is studied. In the former case, a classic bifurcation problem is recovered and the basic equation is the electrically modified Young–Laplace equation (see studies [1,2,5–10]). In the latter case, it is necessary to determine the motion of the fluids and therefore to solve the Navier–Stokes equations (or Euler equations for inviscid fluids) and different numerical approaches have been proposed. After the initial approaches based on ellipsoidal approximation and computation of electric field around elongated single drop or drops pair [5], different numerical methods were used to simulate the transient evolution of interfaces under the influence of electrostatic forces. Two types can be distinguished in the literature, each having its own strengths and weaknesses.

Interface tracking methods use markers (front tracking) or a separate grid to locate the interface. For instance, Boundary Integral techniques or Boundary Element methods [6,22–26] are very efficient in problems where there is a small surface to volume ratio. Indeed, avoiding volume discretization saves a considerable amount of computational ressources and allows finer description of the interfaces. However, this strongly constrains the applicability range of the method which is, in practice, mainly devoted to the resolution of Laplace equations, i.e. electric field in a perfect dielectric medium and potential or Stokes flow. Another example is Finite Element–Arbitrary Lagrangian–Eulerian (ALE) methods, which associate deformation of interfaces and resolution of electrostatics and fluid dynamics equations in moving meshes [8,11,27]. Leaky dielectric models or Navier–Stokes equations can be taken into account [28]. These methods offer high accuracy at relatively low computational cost but cannot handle topological changes such as merging or splitting interfaces.

Interface capturing methods can overcome this difficulty as the interface is not tracked explicitly but rather obtained by geometrical reconstruction. Simulations of complete sequence including topological changes using the Volume of Fluid (VOF) or Level Set methods have been developed in [29–31]. Interfacial forces are transformed in volume terms through a continuum surface force model (CSF) [32]. However, accuracy of interfaces location and curvature strongly depends on the initial mesh and adaptive grids are often required to decrease the computational load. Moreover, numerical treatment of very thin liquid films remains challenging.

This paper presents different numerical simulations, in 2D axisymmetric geometries, performed with the commercial software COMSOL MULTIPHYSICS™ involving water-air and water-oil interfaces. A general model is developed to solve transient electrohydrodynamic problems by using an ALE approach for mesh deformation. That choice allows us to accurately track and parameterize the fluid–fluid interfaces. Moreover, it enables an easy computation of the electrostatic pressure term and makes possible further improvements of surface forces models such as, for example, adsorption/desorption and interfacial transport of surfactants.

In a first part of the paper, the mathematical formulation of the problem is detailed and some important aspects of the numerical scheme are briefly recalled. Then, some basic validations of the model are presented: free oscillations of an initially elongated droplet and transient elongation of a conducting droplet in an electric field are compared with analytical results (respectively frequency and damping of oscillations, and steady electrically induced elongation).

A second part concerns the deformation and static instability of an initially horizontal interface between water and an insulating fluid, electrically influenced by a metallic sphere located just above it. Comparisons with results of experiments performed in the case of water–air and water–oil interfaces are presented.

Finally, the case of two conductive drops anchored on facing capillary tubes at different electric potential is considered as a first step to the study of the motion, deformation and coalescence of two closely spaced droplets suspended in an insulating fluid under the action of an electric field. The critical conditions, corresponding to the maximum potential difference that can be applied before coalescence for a given spacing between the drops, are widely studied and compared with results from experiments and from an asymptotic approach in the common range of application.

The two latter studies consist in the determination of static deformation and static equilibrium limits and could have been treated as a numerical bifurcation problem. However, a transient formulation of the fluid dynamics equations has been retained to allow further investigations on the electrocoalescence of free droplets in stagnant liquids or shear flows.

2. Mathematical and numerical model

2.1. Governing equations

The developed model aims at computing the transient deformation generated by the action of an electric field on any interface between a perfectly conducting liquid (water – domain 1) and a perfectly dielectric fluid (air or oil – domain 2), as presented on Fig. 1. Assuming that both fluids (characterized by their mass density ρ_i and viscosity μ_i) are incompressible, the velocity fields $\mathbf{u_i}$ and pressure p_i, in water and in the dielectric fluid, can be calculated by solving separately the time-dependent Navier–Stokes equations in each medium i

$$\rho_i \frac{\partial \mathbf{u_i}}{\partial t} - \nabla \cdot \left[\mu_i \left(\nabla \mathbf{u_i} + (\nabla \mathbf{u_i})^T \right) \right] + \rho_i (\mathbf{u_i} \cdot \nabla) \mathbf{u_i} + \nabla p_i = \mathbf{F_i}, \tag{1}$$

$$\nabla \cdot \mathbf{u_i} = 0. \tag{2}$$

This also ensures (through the resolution of the continuity equation (1)) the volume conservation of closed domains (droplets). In the absence of space electric charges in the dielectric fluid, the volume force field $\mathbf{F_i}$ expresses the gravitational force ($\mathbf{F_i} = \rho_i \mathbf{g}$). Depending on the scale of the experimental configuration studied it will either be considered or neglected. When air is chosen as the dielectric fluid, its dynamics can be neglected and the pressure inside the domain 2, p_2, can be considered as uniform. In