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A Dual Grid Level Set Method based study on similarity and difference between interface dynamics for surface tension and radial electric field induced jet breakup

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HIGHLIGHTS

- DGLSM is demonstrated as powerful tool to characterized electrohydrodynamic flow simulations.
- The non-linear jet dynamics under radial electric field is studied.
- The formation of satellite and sub-satellite in electrocapillary jet breakup is explained.
- Effect of electrification on growth rate, breakup time, charge and diameter of drop is evaluated.
- The dynamics of poorly conducting jet under radial electric field is studied.

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ABSTRACT

The present work on *radial electric field induced jet breakup* is an extension of our recent work (Lakdawala et al., 2015b) on *surface tension force induced jet breakup*. A Dual Grid Level Set Method (DGLSM) based numerical study on the non-linear breakup of viscous liquid jets immersed in another viscous fluid under radial electric field is carried out in this work. This leads to a better understanding of the mechanism of electrocapillary jet breakup and subsequent formation of primary and satellite drops, due to the temporal growth of surface perturbation. The influence of the electrical Bond number (B_{oe}) and Reynolds number (Re) on the growth rate, the breakup time, the volume of the primary and satellite drops, and the charge of both primary and satellite drops is analyzed. An excellent agreement of the present numerical with the published analytical results is obtained for different Reynolds numbers ($Re = 10, 100$), wave numbers ($0 < k \leq 1$) and electric Bond number ($0 < B_{oe} < 4$). The results show that electrostatic stresses stabilize the long waves and destabilize the short waves which are in accord with linear stability theory: confirming the robustness of our DGLSM method in simulating two-phase electrohydrodynamic flow. The results indicate that nonlinear contribution from the electrostatic force is very important in analyzing the mechanism of satellite formation. The numerical results reveal that the satellite formation as well as the breakup time is affected significantly when the effect of conduction is weak. For large conduction, the evolution of the thread is close to those obtained for a perfectly conducting core fluid. Finally, we numerically show that the local dynamics may be altered when the conduction is weak compared to the perfect conductor limit.

1. Introduction

In the absence of electric fields, the linear theory reveals that the thread is unstable subject to a perturbation having a wavelength greater than the circumference of the jet. It is observed that a series of small satellite droplets form as the interface thins to rupture, which was tracked through numerical simulations by Lakdawala et al. (2015b). An interesting scenario, which is now attracting increasing attention, is the effect of electric field on the instability of a jet in the liquid–liquid system. In the analysis of electrically charged jet, the applied electric field usually has both radial and axial components. The exact strength of the individual components is difficult to perceive in any given system. Thus, it is customary to study the effect of either radial or axial field individually. Moreover, the axial field induced

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Abbreviation: DGLSM, Dual Grid Level Set Method; EMFD, electro multi-fluid dynamics; LD, leaky dielectric – poor conducting; LSM, Level Set Method

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Nomenclature

Greek symbols

A_0	initial amplitude of perturbation
A_m	instantaneous logarithmic amplitude of perturbation
$\mathbf{B}$	non-dimensional magnetic field
B_{oe}	electric capillary number
$\mathbf{D}$	non-dimensional electric displacement vector
D	non-dimensional drop diameter
$\mathbf{E}$	non-dimensional electric field vector
E_∞	electric field (V/m)
$\mathbf{F}$	body force for electric field
H	Heaviside function
$\mathbf{J}$	non-dimensional current density vector
k	wave number
l_c	characteristic length scale (m)
$\hat{n}$	unit normal vector of the interface
Oh	Ohnesorg number
p	pressure $(\mathrm{N/m^2})$
P	non-dimensional pressure
q_v	volumetric charge density
Q	charge carried by the drop
Q_c	Rayleigh charge limit on drop
r	length in radial direction (m)
R	non-dimensional length in radial direction
R_1	non-dimensional drop/jet radius
R_2	non-dimensional domain length in radial direction
Re	Reynolds Number
$\mathbf{T^e}$	electric stress tensor
t	time (s)
$\hat{t}$	unit tangent vector of the interface
$\vec{u}$	velocity vector (m/s)
u_c	characteristic velocity scale (m/s)
$\mathbf{U}$	non-dimensional velocity vector
We	Weber number
z	length in axial direction (m)
Z	non-dimensional length in axial direction
α	electric permittivity ratio
β	electric conductivity ratio
γ	surface tension (N/m)
δ	Dirac delta function
ϵ	diffused interface thickness
ε	electric permittivity of medium (C/V m)
η	viscosity ratio
κ	interface curvature
λ	non-dimensional wave length of perturbation
μ	dynamic viscosity of medium $(\mathrm{N\,s/m^2})$
ρ	density of the medium $(\mathrm{kg/m^3})$
σ	electrical conductivity of medium (S/m)
τ	non-dimensional time
τ_c	characteristic time scale (s)
ϕ	level set function
χ	density ratio
ω	growth rate of disturbance
Θ	non-dimensional voltage potential

Subscripts

1,2	fluid 1, fluid 2
b	breakup
m	mean value
p	primary drop
s	satellite drop
ES	electro-static

breakup of a jet can essentially lead to drops with a net charge. Radial electric field induced breakup, on the other hand, leads to drops which are essentially neutral and is addressed in this work. The axial field induced breakup involves simultaneous solution of the charge dynamics, which can be ignored for the breakup in radial field. Axial field therefore needs a different treatment and will be addressed in a separate work. For axial electric fields, the linear theory was derived in earlier studies, for example, Saville (1971) and Mestel (1996), showing a stabilizing effect of axial electric fields, which would lead to the formation of a "Taylor cone" jet. Although considerable work has been done on the effect of the axial field on jet instabilities, the effect of radial electric field on nonlinear dynamics of a jet has not been adequately addressed. Thus, a systematic investigation on nonlinear dynamics of a jet under the radial electric field, using Dual Grid Level Set Method (DGLSM), is the aim of the current study.

The linear analysis of liquid jet under radial electric field is examined by a number of researchers. Basset (1894) was the first, who extended Rayleigh (1878) analysis to investigate the stability of perfectly conducting jet to axisymmetric disturbances. His analysis shows that electrostatic stresses stabilize the long waves and destabilize the short waves, with the transition occurring at wavenumber $k=0.6$. Taylor (1969), Melcher (1963) and Huebner and Chu (1971) extended the analysis for inviscid jet by including both axisymmetric and non-axisymmetric disturbances. Saville (1971) examined the stability of perfectly conducting Newtonian jet of arbitrary viscosity stressed by radial electric fields to infinitesimal amplitude axisymmetric and non-axisymmetric disturbances. His analysis shows that electrostatic stresses tend to destabilize the non-axisymmetric modes. For highly viscous jet, viscous damping of axisymmetric disturbances leads to a situation where the sinuous mode becomes the most unstable (Saville, 1971; Cloupeau and Prunet-Foch, 1989; Yarin et al., 2005). This phenomenon is observed experimentally as kink instabilities. Lopez-Herrera et al. (2005) performed a linear stability analysis for imperfectly conducting liquid jet based on the Taylor–Melcher leaky-dielectric model (Melcher and Taylor, 1969; Saville, 1997). A perfect conducting thread in a radial electric field was studied by Collins et al. (2007) and Wang and Papageorgiou (2011) using finite element and boundary integral method respectively. Their results reveal a larger (volume) satellite drop formation when the field is applied radially. They also observed that the primary drops are elongated in the direction of applied field and the breakup is in general retarded. Recently, Wang (2012) has conducted a study on weakly conducting jet under radial electric field using boundary integral method.

There are few studies related to nonlinear dynamics and breakup of liquid jet under the radial electric field. Setiawan and Heister (1997) performed a temporal analysis of the axisymmetric breakup of a perfectly conducting liquid jet stressed by a radial electric field in the inviscid limit, using an axisymmetric boundary element algorithm similar to that used by Mansour and Lundgren (1990). They prescribed the value of the electric potential on the surface of the jet and considered high electric field strength. They reported results for the jet breakup times and the size of the primary and satellite drops formed at pinch-off. Lopez-Herrera et al. (1999) studied axisymmetric breakup for perfectly conducting Newtonian jet stressed by radial electric field using a one-dimensional algorithm. In contrast to Setiawan and Heister (1997), these authors have prescribed the value of the surface charge carried by jet. Their analysis is restricted to low to moderate