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A systematic study on numerical simulation of electrified jet printing

A. Rahmat [a,b,c], B. Koc [a,b,c], M. Yildiz [a,b,c,*]

[a] Faculty of Engineering and Natural Sciences, Sabanci University, Tuzla, 34956 Istanbul, Turkey
[b] Integrated Manufacturing Technologies Research and Application Center, Sabanci University, Tuzla, 34956 Istanbul, Turkey
[c] Composite Technologies Center of Excellence, Sabanci University-Kordsa, Istanbul Technology Development Zone, Sanayi Mah. Teknopark Blvd. No: 1/1B, Pendik, 34906 Istanbul, Turkey

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ABSTRACT

In this paper, a numerical model based on a systematic study of electrified jet printing is presented. The Volume of Fluid (VOF) method which suits for modeling multiphase flows with a continuous interface is used. The surface tension force is calculated with the Continuum Surface Force (CSF) method and the electric forces are added to the momentum equation by taking the divergence of the Maxwell stress tensor. A systematic study is carried out by introducing three dimensionless numbers, namely Reynolds, Electro-Weber and Weber numbers. Employing these dimensionless numbers, the number of effective parameters is reduced, and a relative comparison of the importance of competing forces on the process becomes possible. It is observed that the electric forces contribute to the formation of the jet by acting on its tip, and by pulling the jet towards the deposition surface. The results show that an increase in Reynolds and Electro-Weber numbers both lead to form a thinner jet. It is also observed that further increase in Electro-Weber and Reynolds numbers leads to the formation of an unstable jet.

1. Introduction

Applying electric potential to a multiphase system generates Electrohydrodynamic (EHD) forces on the interface between fluid phases. Since the EHD forces can be adjusted by an external electrical potential, it can be used to control a broad range of natural phenomena and physical applications including jet printing. The jet printing can be used in numerous applications especially in micro-scale systems ranging from soft tissue printing in biological systems [1], solar cells [2,3] and manufacturing electronic devices [2,4], amongst others. In the EHD jet printing, the printing quality can be controlled by means of an applied electric potential which induces the EHD forces on the fluid interface leading to the formation of a Taylor cone. This results in the deposition of a more than one order of magnitude thinner liquid film compared to the nozzle diameter. This feature makes the EHD jet printing a strong alternative for other means of jet printing methods such as piezo-type printing [5,6], specially in practices where micro-scale diameters of deposition film is of interest.

The early investigations on the EHD jet and drop formation were carried out by Zeleny [7,8] and later by Taylor [9]. Thereafter, many experiments have been done to examine the effect of different parameters on the Taylor cone jet and printing features. The studies of Barrero et al. [10], Higuera [11] and Hayati et al. [12,13] are just a few examples of previous attempts to discover the phenomenon and examine the relative importance of different physical and environmental parameters on the printing process. Barrero et al. [10] investigated the effects of electric conductivity and viscosity on the motion of liquid film inside the Taylor cone. They realized that there is a recirculation meridional motion induced by the tangential electric stress. The recirculation moves towards the tip of the jet along the cone surface and away from it along the axis. They also reported that the recirculation motion increases when electric conductivity and viscosity of the printing liquid decrease. Hayati et al. [12,13] studied the mechanism of the stable jet formation and stated that the electric conductivity of the printing liquid has a significant impact on the phenomenon. For small magnitude of electric conductivity (insulators), little disrupture is observed due to the insufficient free charges in the bulk of the fluid. On the other hand, they reported that for large magnitudes of electric conductivity (conductive materials), the printing is unstable and sparks are observed in higher electric potentials. For moderate magnitudes of electric conductivity (leaky dielectrics), however, the jet is formed for specific ranges of electric potential. Nevertheless, the complexity of the phenomenon and influence of numerous physical and environmental parameters have hindered

* Corresponding author at: Faculty of Engineering and Natural Sciences, Sabanci University, Tuzla, 34956 Istanbul, Turkey.
E-mail address: meyildiz@sabanciuniv.edu (M. Yildiz).

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efforts to convey a well-studied systematic approach to the problem. Yet, one of the exceptions is the experiments of Lee et al. [14] on the optimization and classification of the jetting modes employing a systematic approach to the problem. They constructed maps of printing regimes for different volume concentrations of a binary mixture and illustrated that how the printing pattern may change from dripping to pulsating, cone-jet, tilted jet and multi-jet, due to the variations of electric potential and injector feed rate. Experimental limitations on the selection of material properties may motivate researchers to employ numerical simulations as an available alternative for a systematic study on the EHD jet printing.

Although one may refer to previous studies in the literature for the formation of Taylor cone jet and the effects of various parameters on it, to the best knowledge of the authors, there is no comprehensive study on the development of EHD jet printing. The present study tries to numerically elaborate the behavior of EHD jet printing under the influence of various parameters. In the EHD jet printing, the number of dimensional parameters that influences the formation of the liquid jet is large. Therefore, a set of dimensionless groups is used to model the problem. The present study introduces a systematic approach by using dimensionless numbers that represent the relative importance of different forces for studying a complex phenomenon with numerous influential parameters. Here, for the specific problem of interest with applications in micrometer scale, the gravitational force can be neglected while the surface tension and EHD forces are known to be the dominating forces. On the other hand, the injector inlet feed rate and fluid physical properties are the other important parameters that highlight the effect of inertial and viscous forces. Based on these set of forces, three dimensionless numbers are introduced as Reynolds number (Re), Weber number (W) and Electro-Weber number (Ew) representing the relative importance of inertia to viscous, surface tension and EHD forces, respectively.

The electro-jet printing is a suitable alternative for various methods of additive manufacturing of soft materials including polymers. This method has been experimentally used in additive manufacturing community to 3D bioprint scaffolds [15] and print films [14] with the diameter of around one order of magnitude smaller than the nozzle diameter. This is a notable achievement in additive manufacturing specially in micro-scale problems where surface forces are dominant. We believe that this study is a good guideline to implement the electro-jet printing process in additive manufacturing of soft and polymeric materials. It provides an insight into the suitable ranges of influential parameters to maintain desirable printing patterns.

In the following chapters, the governing equations and numerical method is presented in Section 2, the problem setup is shown in Section 3, the results are represented in Section 4 and finally the concluding remarks are given in Section 5.

2. Governing equations and numerical method

The general governing equations for an incompressible, isothermal, two-phase, viscous flow can be represented as,

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

$$\rho \frac{\mathrm{D}\mathbf{u}}{\mathrm{Dt}} = -\nabla p + \nabla \cdot (\mu(\nabla \mathbf{u} + \nabla \mathbf{u}^{\ddagger})) + \rho \mathbf{g} + \mathbf{f}_{(s)} + \mathbf{f}_{(e)}, \tag{2}$$

where $\mathbf{u}$, p, ρ and μ stand for velocity vector, pressure, density and viscosity of the fluid, respectively, the superscript ‡ denotes the transpose operation, and $\mathrm{D/Dt} = \partial/\partial \mathrm{t} + \mathbf{u} \cdot \nabla$ represents the material time derivative. The $\mathbf{f}_{(s)}$ and $\mathbf{f}_{(e)}$ are the surface tension and Electro-hydrodynamic (EHD) forces, respectively and $\mathbf{g}$ is the acceleration vector. In this study, normal letters indicate scalar quantities and bold letters represent vectors and tensors.

For simulating two-phase flow problems, the Volume of Fluid (VOF) [16] method is used to track the interface between fluid phases. In the VOF method, the volume fraction α is calculated by solving an evolution equation as,

$$\frac{\partial \alpha}{\partial t} + \mathbf{u} \cdot \nabla \alpha = 0. \tag{3}$$

Fluid properties are smoothed on the interface by,

$$\xi = \alpha \xi_1 + (1 - \alpha)\xi_2, \tag{4}$$

where ξ can be any physical fluid property such as density, viscosity, electrical conductivity or permittivity whichever is appropriate. The subscripts (1) and (2) refer to different fluid phases.

To account for the surface tension force, the Continuum Surface Force (CSF) [17] method is applied by using the divergence theorem and imposing a volumetric force ($\mathbf{f}_{(s)}$) on the interface by employing the following equation as,

$$\mathbf{f}_{(s)} = \gamma \kappa \nabla \alpha. \tag{5}$$

Here, surface tension coefficient, γ, is taken to be constant. The κ represents interface curvature, $-\nabla \cdot \hat{\mathbf{n}}$, and $\hat{\mathbf{n}}$ is unit surface normal vector $\mathbf{n}/|\mathbf{n}|$.

In order to implement the EHD forces, the electrostatics and hydrodynamics are coupled together through the Maxwell stress tensor. The stress induced in an incompressible liquid medium due to the presence of an electric field can be described as [18,19],

$$\mathrm{T^e} = \mathbf{DE} - 0.5(\mathbf{D} \cdot \mathbf{E})I, \tag{6}$$

where the contribution from the induced magnetic field is neglected. Here, $\mathbf{E}$ is the electric field vector and obtained by taking the gradient from electric potential $\mathbf{E} = -\nabla \phi$, that can be obtained by solving,

$$\nabla \cdot (\sigma \nabla \phi) = 0, \tag{7}$$

where σ is the electrical conductivity and $\mathbf{D}$ is the electric displacement vector,

$$\mathbf{D} = \varepsilon \mathbf{E}, \tag{8}$$

where ε is the electric permittivity. For practical purposes, it may prove more convenient to express this electric stress as an electric force per unit volume ($\mathbf{f}_{(e)}$) through taking the divergence of the Maxwell stress tensor,

$$\mathbf{f}_{(e)} = \nabla \cdot \mathrm{T^e} = \nabla \cdot (\mathbf{DE} - 0.5(\mathbf{D} \cdot \mathbf{E})I). \tag{9}$$

If we use the Gauss' Law for electricity in a dielectric material, namely,

$$\nabla \cdot \mathbf{D} = q^{\nu}, \tag{10}$$

and for a medium with polarization independent on mass density and temperature, Eq. (9) can be rewritten as,

$$\mathbf{f}_{(e)} = q^{\nu}\mathbf{E} - 0.5\mathbf{E} \cdot \mathbf{E} \nabla \varepsilon, \tag{11}$$

where q^{ν} is the volume-charge density of free charges. It is worthy to mention that the first term on the right hand side of Eq. (11) is the Coulomb force due to the interaction of the free charges with the electric field; while, the second term is the polarization force which acts along the direction normal to the interface as a result of term $\nabla \varepsilon$.

In this paper, the finite volume method is used to discretize the continuity and momentum equations. The momentum equation (Eq. (2)) is solved by a second-order upwind formulation both in time and space. The PRESTO! method [20] is employed to calculate the pressure field, and the pressure and velocity fields are coupled using the SIMPLE scheme [21,22].