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Fluid Viscosity and Corresponding Effects on Fluid flow, Velocity Magnitude and Electric Field Distribution in Electrohydrodynamic Jetting.

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Abstract. The phenomenon of electrohydrodynamic (EHD) jetting is affected by both the flow and electric properties of the dielectric fluid. A computational fluid dynamics (CFD) approach has been used to analyse the resultant effect of fluid viscosity on EHD flows. This study looks at the unique effect of fluid viscosity on the flow profile, velocity magnitude and the electric field distribution. It is very difficult to experimentally study these relationships, but CFD provides insights that can open the world of Electrohydrodynamics to new levels of applications; as this will give an idea of how to manipulate the jet formation. Viscosity has been highlighted as one of the key parameters that aid jet elongation and stability. Therefore, the necessity to study its role. Most studies have been carried out experimentally, but this paper provides computation insights. To solve the multiphase problem, a finite volume method using the Volume of Fluid approach for capturing the shape of the interface was used for the investigation. The leaky dielectric model which describes the process solves the combination of the Charge Transport Model and Navier-Stokes equations simultaneously. The transient liquid-gas interface tracking was achieved using the VOF technique. Among many other features observed, the results showed that it takes more time for the electric field to overcome the opposing surface tension of the solution at higher viscosity than at lower viscosity. Higher electric field magnitudes/strength were observed for the fluid of lower viscosity than that of the higher viscosity. Also, an increase in the viscosity reduces the droplet size/jet diameter.

1. Introduction

There has been growing interest in the phenomena that arise during fluid flow and electric field interactions. Manipulation of the flow and operating parameters gives rise to unique flow patterns that can be adapted in fields like microfluidics, electrospraying, electrospinning etc. "Theoretically, the process is influenced by electrical forces on the free positive charges at either the peripheral or inside the polymer solution" [1]. In-between the polymeric solution and the collector, a high electric field is generated. The polymeric solution- in the form of pendant droplets, is initially held at the capillary tube through the mechanism of surface tension. Once the charge is induced, a mutual charge repulsion is generated, and this exerts a force that is opposite to the surface tension. At a certain critical value in which the surface tension force is overcome by the electric force, there is a discharge of the jet. Where the voltage is not high enough the jet might break up into tiny droplets; whereas if high enough a



stable jet formation is observed at the tip. As the jet flows towards the collector, the diameter is altered [2]–[4].

Several parameters are interwoven to affect the EHD flow. These are the solution parameters, process parameters and ambient factors [5], [6]. There is a strong effect of the viscosity on the jet, but to what extent? This study reveals the unique effect of viscosity on the fluid flow, by investigating the flow characteristic over time. More importantly, is the effect on the interaction of the fluid and the electric field.

2. General Momentum Balance Equation for the Dielectric Fluid

The differential equations describing EHD arise from a combination of equations describing the conservation of mass and momentum for a continuum phase and Maxwell's equations [7]. The Maxwell stress tensor is what couples the electrostatic and hydrodynamics equations [8]. The forces acting on the system account for the liquid deformation and charge distribution [9]. The EHD equation for a dielectric fluid provides insight into the role of viscosity in droplet formation; expressed as:

$$\rho \frac{\partial \vec{u}}{\partial t} = -\nabla P + \mu \nabla^2 \vec{u} + \rho g + f_e \quad (1)$$

Where ρ is the fluid density, μ is the viscosity of the solution, P is the pressure, u is flow velocity, g , is the gravitational constant, and f_e is the electromechanical force.

The left-hand side of the expression describes the fluid acceleration and the right-hand side gives the summation of several forces acting on the system. The second term on the right-hand side is the viscous force caused by the viscosity of the solution, the force opposes jet formation and movement [10], [11].

The Volume of Fluid technique was used to track the free surface. The basic idea of the VOF, developed by Hirt [12] was to introduce a fraction F assigned to each cell. This fraction represents the portion that is occupied by the liquid phase. Descriptively,

$$F(x, y, z, t) = \begin{cases} 0 & \text{the gas cell} \\ 1 & \text{the liquid cell} \\ 0 < F < 1 & \text{two phase cell / free surface interface} \end{cases} \quad (2)$$

A similar solution procedure used in [13] was adopted; the electric body forces were calculated from the electrostatic equation and then included in the Navier-Stokes equation to predict the velocity field and other fluid properties. No initial shape was assumed for the fluid shape and charge distribution.

3. Model Description and Boundary Condition

To solve the multiphase problem, a finite volume based CFD package, CFD-ACE+ (ESI Group, Paris, France) was used for the investigation. The transient liquid-gas interface tracking was achieved using the VOF technique. Central differencing scheme with second-order piecewise linear interface technique construction (PLIC) scheme was used to explore the interface shape from the value of fluid fraction in each cell. The surface tension effect along the liquid-gas interface was modelled using the continuous surface force (CSF) scheme. The properties of fluid adapted are given as density of 1000 kg m^{-3} , the surface tension of 0.075 N m^{-1} , the dielectric constant of 78, Electrical conductivity of $5.5 \times 10^{-7} \text{ S m}^{-1}$. A constant voltage of 10KV was applied on the emitter wall. The collector was modelled as a wall with zero voltage. Neumann conditions were used on the symmetry boundaries and Dirichlet conditions were used on the remaining boundaries.

4. Results and Discussion

This paper offers insight into how fluid viscosity affects EHD flow, by observing the flow profile, velocity magnitude, electric field and electric potential distribution. For the discussion, 3 liquids have

been defined with viscosities, μ_1 , μ_2 and μ_3 in increasing order of magnitude; μ_2 has the same property as water, while μ_1 was assigned a viscosity $0.1\mu_2$ and μ_3 assigned a viscosity of $10\mu_2$.

4.1. Flow profile

The jet diameter, length and contact angle differ with the viscosity. It was observed that jetting occurs earlier with the fluid with lower viscosity. Also, the liquid wets the needle wall at higher viscosity and after few seconds, it builds up around the wall. The less viscous fluids do not wet the needle external walls at all. Figure 1 shows the VOF distribution of the EHD flows for the 3 different samples. The length of the jet increases with an increase in viscosity. Also, an increase in the viscosity reduces the droplet size/jet diameter just as reported in [10], [14].

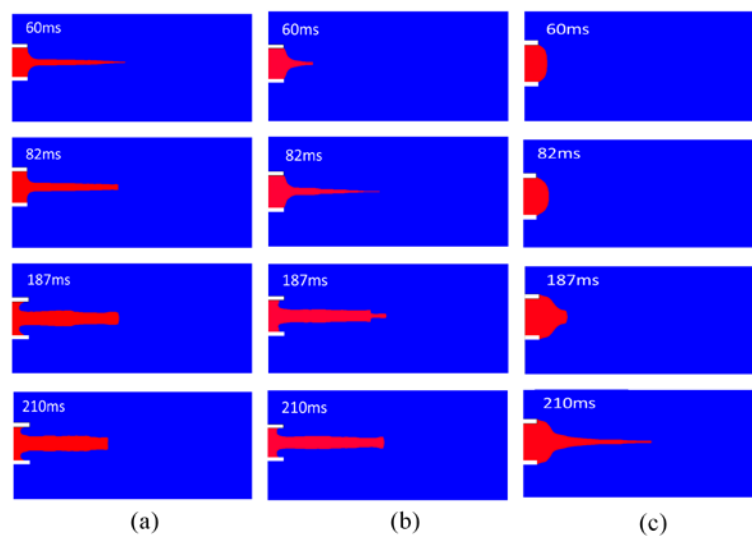


Figure 1- VOF distribution for different solutions (a) viscosity, μ_1 (b) viscosity, μ_2 and (c) viscosity, μ_3

4.2. Velocity Magnitude

A very significant difference was observed in the velocity magnitudes of the three different solutions. After 11ms, for the μ_1 solution, the peak velocity was about 130m/s, for μ_2 , approximately 33m/s and for the most viscous solution, μ_3 , a maximum velocity of 0.8m/s was reached. Also, it took a longer time for these peak velocities to be reached as the viscosity increases.

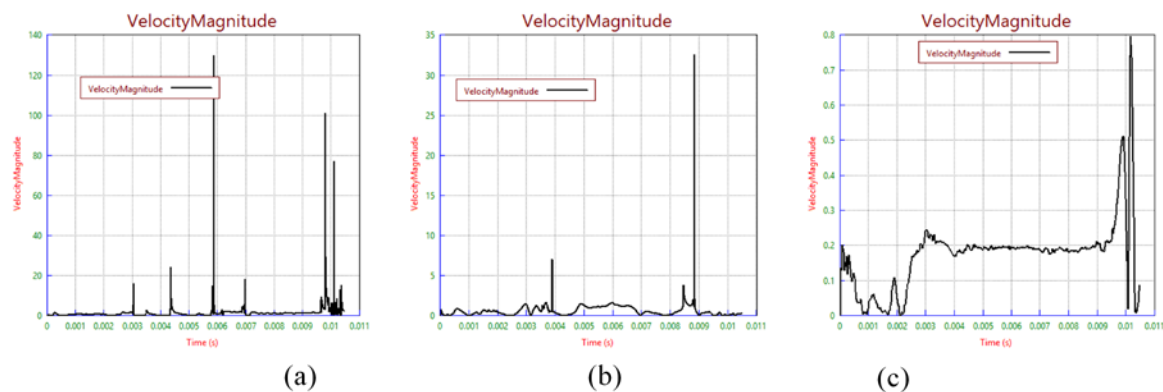


Figure 2- Velocity Magnitude for different solutions (a) viscosity, μ_1 (b) viscosity, μ_2 and (c) viscosity, μ_3

4.3. Electric Field Distribution

Leaky dielectric fluid accumulates charge on the drop-fluid interface and allows charge relaxation. The fluid also allows ohmic currents to jump from bulk and charge convection through the interfacial fluid flow. For all the solutions, the electric field strengths were in the magnitude of 10^6 V/m , as seen in Figure 3. Higher electric field magnitudes/strength were observed for the fluid of lower viscosity than that of the higher viscosity. This implies that higher field strength is required to produce jetting and overcome the fluid surface tension for highly viscous liquids.

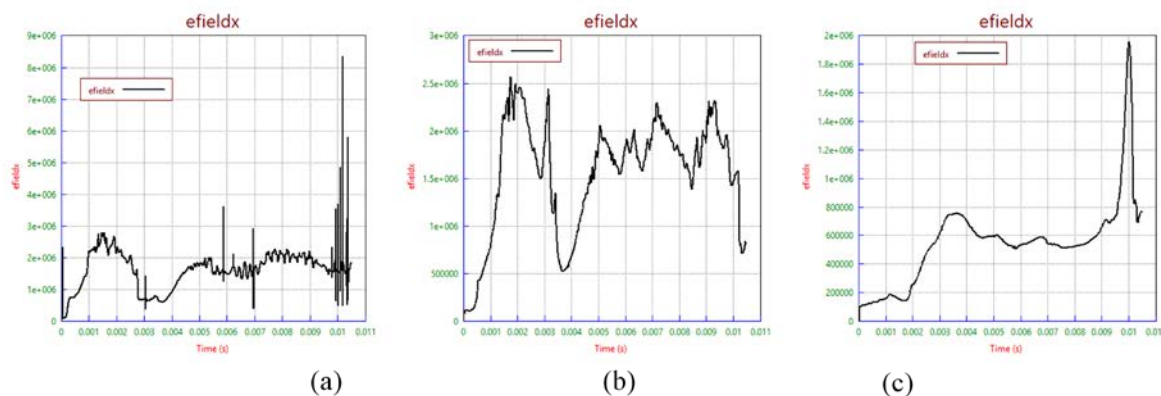


Figure 3- Electric field (V/m) for different solutions (a) viscosity, μ_1 (b) viscosity, μ_2 and (c) viscosity, μ_3

5. Conclusions

The results from this study help to establish the resultant effect of solution viscosity in EHD applications. At higher viscosity, the solution resistance to flow is higher, and at certain magnitudes, the fluid wets the needle wall and droplet build up to clog the capillary. The diameter of the jet decreases with viscosity. As observed for the velocity distribution, for faster throughput of the jets in EHD, a less viscous solution will be advantageous. Also, jetting occurs earlier in less viscous solutions. This study offers great potential for control of emerging features of EHD flows by manipulating the viscosity.

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