Original Article

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Numerical Investigation of Electrospray Working Performance on Ethanol

Andam D. Refino[a*#], Hadi T. Yudistira[b*#], Denny H. Tri Nugroho[c], Deska L. Puspitarum[d]

[a] *Engineering Physics Program, Institut Teknologi Sumatera (ITERA), Lampung Selatan, Lampung*

[b] *Mechanical Engineering Program, Institut Teknologi Sumatera (ITERA), Lampung Selatan, Lampung*

[c] *Electrical Engineering Program, Institut Teknologi Sumatera (ITERA), Lampung Selatan, Lampung*

[d] *Physics Program, Institut Teknologi Sumatera (ITERA), Lampung Selatan, Lampung*

**Equal contribution*

[#] *Corresponding author: andam.refino@tf.itera.ac.id, yudistira@me.itera.ac.id*

Abstract: Electrospray as an alternative method to fabricate thin film is studied. High voltage is required by the electrospray system. The requirement of high voltage is different for various liquid depending on the surface tension property. Ethanol was used to resemble the solvent used in thin film deposition. From the experimental work, jetting performance did not occur despite of the high applied voltage which is around 1 KV. In this work, numerical calculation is carried out to find the reason behind of unsuccessful jetting at 1 KV applied voltage. The percentage of Rayleigh limit is around 0.4. Electrospray performance at walking distance 5 mm using ethanol is predicted to be stable when the applied high voltage is approximately 1.1 KV. The numerical investigation indicates that the jetting performance will occur if the applied voltage is more than 1.1 KV.

Keywords: *electrospray, electric field, voltage, meniscus*

Introduction

The fabrication of thin film has been given attention by many people. Thin film is needed for several applications such as solar cells [1] and sensors [2]. Currently, many peoples have considered thin film solar cell. The second generation of solar cell until the current generation of solar cell has been using thin film. Several popular methods were applied to fabricate thin film such as chemical vapor deposition [3], atomic layer deposition [4], electron beam evaporators [5], and sputtering [6]. However, these methods need a lot of costly equipment as well as high maintenance. Many people consider an alternative method to reduce the cost of the fabrication process.

Electrohydrodynamic phenomenon has been considered for alternative methods on microfabrication [7-9]. It has the possibility to decrease production cost and has the possibility of mass production. Electrospray is one of many techniques that use electrohydrodynamic phenomenon. Thin film can be fabricated using electrospray technique. However, it requires high voltages and special solvent to make stable of electrospray process. One of good solvents for electrospray is ethanol. Refino *et al.* [10] has simulated electric field distribution and stability of electrospray performance. However, the walking distance between nozzle and ground plate is too close which is around 0.5-1 mm. The fluid is easily contact the ground plate in this walking distance condition; thus, it results in electrical short circuit that could be dangerous to the user.

In this work, we investigate the electrospray working performance. Ethanol electrical properties is used as parameters. The walking distance between nozzle and ground plate was set up at a high distance. The experimental work is considered until 1 KV applied high voltage. The simulation is performed to investigate the reason of unsuccessful jetting in the experimental work at 1 KV applied a high voltage as well as to find the

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optimal and stable performance of electrospray in high voltage condition.

Experiment Result

Figure 1 shows the electrospray experiment set up that was used in this work. The high voltage system has a limit voltage until 1 KV. The ethanol liquid flowed to the nozzle using pressure system. A high differential pressure system controls the flow rate of ethanol. A CCD camera was used and connected to a computer for capturing the image of electrospray process. Control of walking distance has been done by watching nozzle on a CCD camera system. The inner and outer diameter of the nozzle are 170 µm and 300 µm, respectively. The walking distance between nozzle and ground plate was around 5 mm.

Figure 2 presents time step of electrospray performance at 1 KV. The 1 KV voltage is the maximum voltage of high voltage system that was used on this work. The high voltage system did not yield any jetting performance although the maximum voltage has already been applied. The meniscus was slightly oscillated, but the jetting was not existed. This indicates that the electric force is not high enough to break the surface tension on the tip of the meniscus. This condition suggests that the experimental set up system need more than 1 KV high voltage system. Most of previous works on electrohydrodynamic jetting mode for ethanol were required high voltage at specific experiment condition such as Sohbatzadeh et al. [11] (require 10 KV), Gan *et al.* [12, 13] (require 4.5 KV), Wang *et al.* [14] (require at least 3.2 KV), and Marinov *et al.* [15] (require 9.5 KV). The following numerical and analytical work would investigate how much minimum voltage is needed to produce successful jetting.

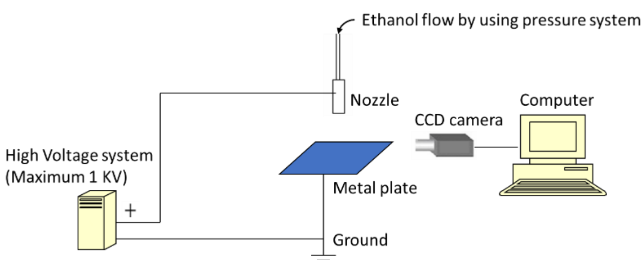

Figure 1. Electrospray experimental set up.

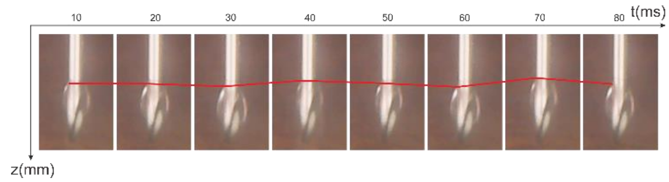

Figure 2. Time step of electrospray performance at the tip of the nozzle at 1 KV

Numerical and Analytical Simulation Results

The geometry and simulation modeling was presented in figure 3. CST microwave studio, commercial software, was used on this simulation work. Nozzle material was modeled as steel material. Its inner diameter and outer diameter are 170 µm and 300 µm, respectively. The walking distance between nozzle and ground plate is similar to the experiment condition (5 mm). The ground plate material was modeled as steel material. The nozzle was applied a high voltage (1-1.4 KV), and the ground plate was applied zero voltage on simulation work. ϴ is the angle of the axis on cylindrical coordinate. Cylindrical coordinate was used to calculate the electric force along the curve of the meniscus. The tip of meniscus location and the edge of the nozzle are at ϴ= 180^0 and 90^0, respectively.

The surface tension force was estimated in this work. Equation 1 presents the Laplace pressure equation of the liquid droplet

$$\Delta p = \sigma\left(\frac{1}{R_x} + \frac{1}{R_y}\right) \qquad (1)$$

where, Δp , σ , R_x , R_y are pressure difference (Pa), surface tension (N/m), radius of the droplet at x axis (m) and radius of the droplet at y axis (m), respectively. The surface tension of ethanol is 0.0214 N/m. Meniscus at the nozzle was modelled as a half sphere with the radius of 150 µm. The R_x and R_y values are similar, 150 µm, due to symmetry of the meniscus shape at the nozzle. The surface tension force was estimated by multiplying the Laplace pressure and the meniscus area (1.41×10^{-7} m^2). This force was 4.03×10^{-5} Newton.

The maximum meniscus charge is estimated by the Rayleigh limit model [9]. When the surface charge on the meniscus is higher than the Rayleigh limit model, the Coulomb fission can be generated at the edge of the meniscus; thus, the jetting phenomenon could be occurred. The Rayleigh limit model presented as

$$Q_{ray} = 8\pi N\sqrt{\varepsilon_0 \sigma r^3} \qquad (2)$$

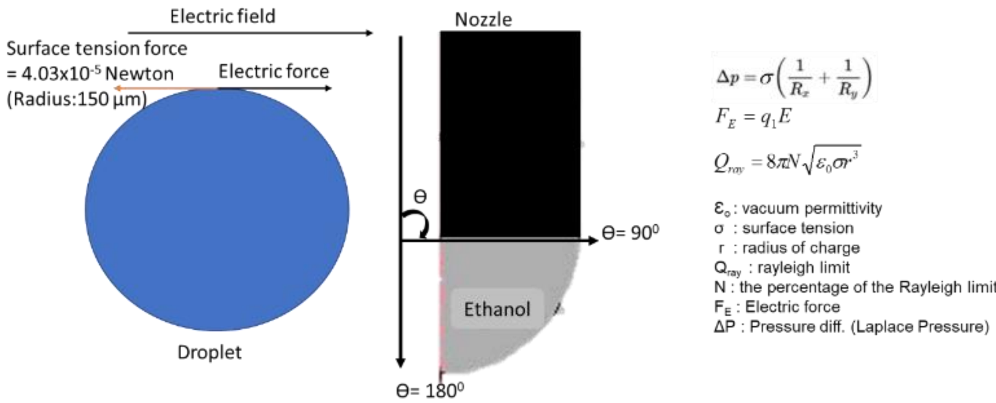

Figure 3. The geometry and simulation modelling.

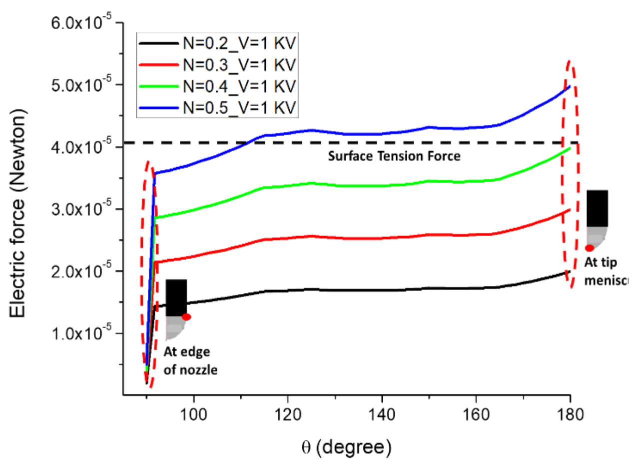

Figure 4. Electric force estimation for different Rayleigh limit percentage at 1 KV.

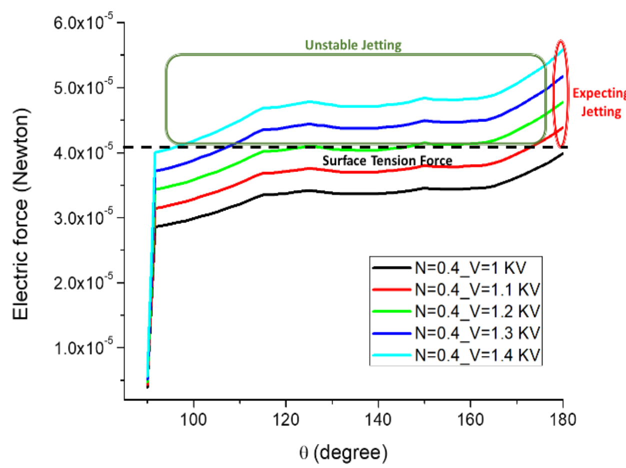

Figure 5. Electric force estimation for the difference of applied high voltage at N=0.4.

where Q_{ray}, σ, ε_0, N and r are the Rayleigh limit charge (C), the surface tension of the liquid (N/m), the vacuum permittivity (C/Vm), percentage of Rayleigh limit and the radius of the meniscus (m), respectively.

Figure 4 presents the electric force estimation for different Rayleigh Limit percentage at 1 KV. The ethanol did not break at 1 KV on a long curve of the meniscus for *N*=0.1-0.4 from this numerical simulation work. On the other hand, the ethanol has broken at 1 KV on $\theta = 110° - 180°$. Thus it indicates the unstable jetting. The stable jetting requires jetting performance only at the tip of meniscus (θ=180^0). The experimental work shows that there is no jetting performance at 1 KV; thus, it indicates that the N value is not more than 0.5. Yudistira *et al.* [9] presented that the N value for small droplet is around 0.2. The *N*=0.4 value is considered acceptable to model the maximum Rayleigh limit on the meniscus.

Figure 5 shows the electric force estimation for various applied high voltage at N=0.4. The jetting performance is predicted to occur at more than 1.1 KV applied voltage. The unstable jetting yields at more than 1.2 KV applied voltage. Electrospray performance at walking distance 5 mm using ethanol is predicted to be stable when the applied voltage is approximately 1.1 KV. The numerical investigation presents that the jetting performance will occur if the applied voltage is more

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than 1.1 KV. An experimental work is going to validate this numerical work in the future work.

Summary

The experiment shows that there is no jetting performance despite of the 1 KV applied. A numerical work was done to investigate the reason of unsuccessful jetting at 1 KV applied voltage. It is predicted that jetting performance requires at least 1.1 KV applied voltage to be occurred. From the simulation with the Rayleigh limit percentage, N=0.4, stable jetting performance requires 1.1 KV applied voltage. Further increase of applied voltage to above 1.2 KV results in unstable jetting.

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