MULTIPHYSICS SIMULATION ANALYSIS OF NOZZLE CHARGED JET IN ELECTROSTATIC JET PRINTING

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Understanding the influence of various parameters in electrostatic jet printing is crucial for optimizing the inkjet process. This study utilizes a multiphysics simulation numerical model based on electro-hydraulic coupling dynamics to examine the effects of contact angle between the inkjet working medium and the wall, as well as the working voltage, on droplet movement. The findings reveal that both the voltage intensity and contact angle significantly influence droplet velocity and surface field strength, without affecting droplet trajectory. Upon separation from the nozzle, the droplet achieves maximum velocity before gradually decaying. When the voltage increases by 2.5 times, the maximum droplet velocity decreases by about 30%. The higher the voltage, the easier it is for the ink droplet at the nozzle to form a cone shape, and the longer the length of the cone shape, The larger the voltage value, the later the droplet separation time. The research results are helpful to further understand the jet dynamics mechanism in the electrohy drodynamic printing process, and can provide a reference for improving the nozzle structure.

Keywords: EHD, electrostatic inkjet, Taylor cone, Multiphysics simulation, phase field method

1 Introduction

Electrostatic inkjet is an important inkjet technology that has been widely used in fields such as printing and manufacturing [1-3]. This spray printing technology has no special restrictions on ink viscosity, and the generated jet diameter is much smaller than the nozzle size, which is not easy to cause nozzle blockage [4], the dot-line feature size of 1-2 μm can be achieved, which is almost impossible to achieve by traditional inkjet printing.. At the same time, it can also achieve ideal printing effects in areas such as flexible printing electronics, display devices, optical devices, and microstructures that require strict resolution requirements. Compared with traditional inkjet printing technology, the ink droplets in electrostatic inkjet technology move under the action of electric field force, replacing the roles of thermal bubbles, piezoelectric, acoustic waves, and static electricity in traditional inkjet printing. Under the action of the electric field, the liquid ions in the nozzle are attracted, and the meniscus deforms to form a

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cone [5]. When the electric field force on the ink surface is greater than other forces (such as surface tension), causing the balance to be broken, a jet will be ejected from the nozzle. In recent decades, many scholars have conducted in-depth research on the numerical simulation of current body dynamics [6-10]. Hirt [11], Morteza [12] and Wei Wei [13] studied the deformation and dynamic characteristics of neutral and charged droplets under uniform and non-uniform electric fields used the volume of fluid (VOF) theory, the distribution law of surface charge of droplets under the action of electric field is expounded. Qian [14] and Lan Hongbo [15] used two printing modes, pulse conical jet and continuous conical jet, simulated the electric field intensity distribution near the inkjet mouth and the ejection process of the conical jet. Karim [16] simulated the changes in droplet shape during electrodeposition using the VOF method and calculated the potential and current density of the electrolyte. Rudolf [17] established a numerical model for the coupling of two-dimensional electric field and flow field, simulating the motion process of charged droplets between plates and plates, and studied the relationship between droplet oscillation frequency, droplet properties, and electric field strength. Subhamoy [18] numerically simulated the collision phenomenon between droplets and substrates based on the VOF method, and analyzed the wetting properties and collision velocity of droplets by changing parameters such as potential. Gaute [19] used the Phase-field model to conduct dynamic simulation of droplet electrowetting, and obtained an effective expression of contact angle.

In conclusion, although great progress has been made in the numerical simulation of electrohydrodynamic printing, few studies have considered the influence of ink and micro nozzle wettability on electrohydrodynamic printing. This factor directly affects the formation and movement trajectory of inkjet droplets, which is crucial to improving the efficiency and quality of inkjet. Based on the principle of electrohydraulic coupling dynamics, this paper establishes the electric field a numerical model for the coupling of flow field and droplet dynamics was developed to study the effects of contact angle between inkjet working medium and wall and working voltage on droplet motion. This can help to better understand the inkjet process and mechanism, achieve better results and quality in practice, and lay the foundation for further optimizing inkjet printing technology in the future.

2. Research Object and Theoretical Basis

The EHD spray printing structure is shown in Figure 1. Set the flow rate of the ink inlet at the top inlet to 0.5m/s. The supply speed of charged liquid at the position of the capillary nozzle is not high, therefore, hanging droplets are first formed at the top of the nozzle. Due to the high voltage applied between the inkjet tube and the substrate, the droplet at the top of the nozzle is subjected to not only surface tension but also electric field force. When the force balance of the droplets is broken, the droplets at the top of the nozzle will stretch from a spherical crown to a hyperboloid, finally, a stable cone will be formed at the top of the nozzle.

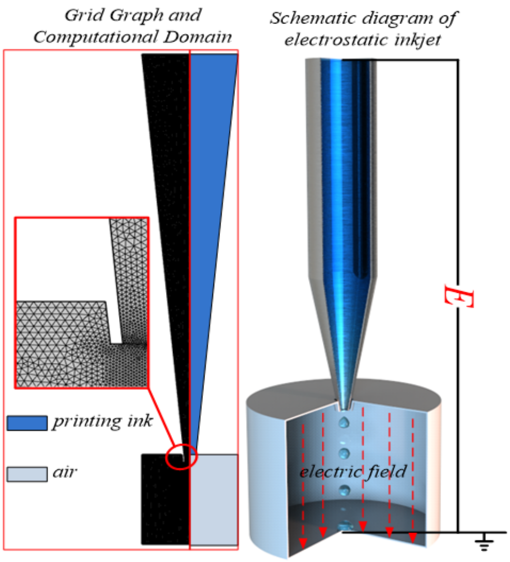


Fig. 1. Grid diagram and structural diagram of the research object

The electrostatic inkjet process is a very complex process, where ink is affected by multiple physical fields, and the effects of viscous, electric, and inertial forces all affect fluid motion. In this paper, ink is considered as an incompressible fluid, the ink movement process can be described as [20]:

$$\rho\frac{\partial u}{\partial t}+\nabla\cdot(\rho uu)=-\nabla p+\nabla\bullet\left(\sigma^{\mathrm{f}}+\sigma^{\mathrm{e}}\right)+F \tag{1}$$

$$\nabla\bullet u=0 \tag{2}$$

In the above equation, u represents the ink velocity vector, m/s; ρ represents the ink density, kg/m^3; P represents the ink pressure, Pa; σ^f represents the viscous stress tensor, N/m^2; σ^e represents the Maxwell stress tensor, N/m; F represents the total force exerted on the fluid, unit is N, including gravity and electric field force in this model. σ^f and σ^e can be expressed as:

$$\sigma^{\mathrm{f}}=\mu\left[\nabla u+(\nabla u)^{\mathrm{T}}\right]-\frac{2}{3}\mu(\nabla\bullet u)I \tag{3}$$

$$\sigma^{\mathrm{e}}=\varepsilon\varepsilon_0 EE-\frac{1}{2}\varepsilon\varepsilon_0 E\bullet E\left(1-\frac{\partial\varepsilon\varepsilon_0}{\partial\rho}\frac{\rho}{\varepsilon\varepsilon_0}\right)I \tag{4}$$

Among them: μ represents the dynamic viscosity of the ink, N.s/m^2 I represents the unit tensor; ε represents the relative dielectric coefficient of the ink;

ε_0 represents the dielectric constant under vacuum conditions, ε_0=8.85 × 10^{-12} F/m; E is the electric field strength，V/m; q_v represents the volume charge density of the fluid, C/m^3. According to Maxwell equation, the characteristic time of the electric field is $\tau_e=\varepsilon\varepsilon_0/K$. Assuming the time of fluid motion is $\tau_{i.}$ for non-electrolyte continuous fluids, the motion of charges is significantly faster than that of fluids(τ_e <<$\tau_{i.}$), therefore, the variation of charge over time can be ignored. The charge conservation equation is expressed as:

$$\tau \bullet \| E \| = 0 \tag{5}$$

$$n \bullet \| E \| = q_s \tag{6}$$

$$q_v = q_s \nabla \gamma \tag{7}$$

Where q_s represents the Surface charge density, C/m^2; n represents the unit normal vector of the two-phase interface; τ represents the unit tangent vector of the two-phase interface, $\|E\|$ represents the difference of electric displacement field at the interface of two phases.

By converting the force between the Surface charge of the droplet and the electric field into the volume force, the electric field force F_e can be expressed as:

$$F_e = \nabla \bullet \sigma^e = q_s E \nabla \gamma - \frac{1}{2} E^2 \nabla \varepsilon \varepsilon_0 \tag{8}$$

The inkjet process involves two complementary immiscible fluids, ink and air. In this paper, the Cahn-Hilliard equation is used to describe the diffusion interface of the immiscible two liquids. The Cahn-Hilliard equation is as follows:

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \frac{\gamma \lambda}{\varepsilon^2} \nabla \psi \tag{9}$$

$$\psi = -\nabla \cdot \varepsilon^2 \nabla \phi + \left(\phi^2 - 1\right)\phi \tag{10}$$

Among them, u represents the ink movement speed, m/s , and γ represents the ink migration rate in air, m^3.s/kg, λ represents the mixed density, N, ε represents the thickness of two intersecting interfaces, m, and the ψ can be regarded as an auxiliary variable for solving the phase field method. The correlation between the above physical quantities and the surface tension coefficient can be expressed ast:

$$\sigma = \frac{2\sqrt{2}}{3} \frac{\lambda}{\varepsilon} \tag{11}$$

In this article, ink as medium 1, air as medium 2:

$$V_{f1} = \frac{1-\phi}{2}, \quad V_{f2} = \frac{1+\phi}{2} \tag{12}$$

Define the changes in physical parameters of the smooth interface between ink and air through formulas (14) and (15):

$$\rho = \rho_{\text{ink}} + \left(\rho_{\text{air}} - \rho_{\text{ink}}\right) V_{\text{f}2} \tag{13}$$

$$\mu = \mu_{\text{ink}} + \left(\mu_{\text{air}} - \mu_{\text{ink}}\right) V_{\text{f}2} \tag{14}$$

Due to the wetting effect between the nozzle and the wall, the boundary conditions added to the wall are as follows:

$$\mathbf{n} \cdot \varepsilon^2 \nabla \phi = \varepsilon^2 \cos\left(\theta_{\text{ink}}\right) |\nabla \phi| \tag{15}$$

$$\mathbf{n} \cdot \frac{\gamma \lambda}{\varepsilon^2} \nabla \psi = 0 \tag{16}$$

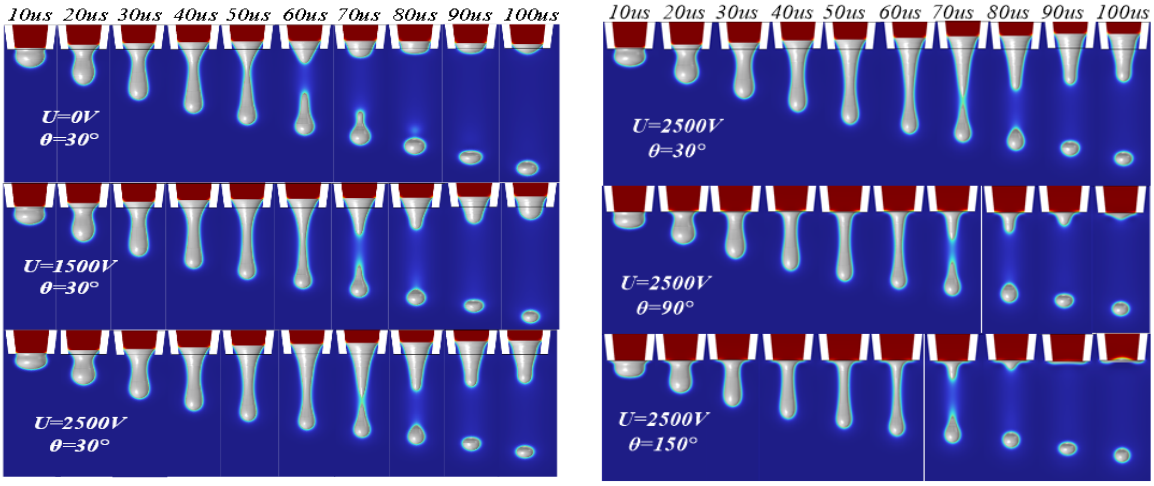
θ_{ink} is the wetting angle between the ink and the inner wall of the nozzle, deg.

Based on the above theory, this paper uses the comsol computing platform to construct the EHD numerical simulation model, and according to equation 3-8, uses the coefficient partial differential equation to construct the force model of the ink in the electric field environment, uses the level set method to realize the two-phase flow coupling equation under the electric field, and finally constructs the multi-physical field numerical model which is suitable for the research object of this paper.

3 Numerical Results and Analysis

3.1 Changes in various physical fields during droplet movement

Due to the fact that inkjet printing can adjust the voltage and ink properties to achieve changes in droplet motion morphology during operation, Fig.2 (a) shows the motion of droplets in the computational domain at different voltage intensities. The results show that as the voltage increases, the separation time between droplets and the nozzle is prolonged. At the same time, droplets at the nozzle outlet are more likely to form a cone, mainly due to the increase in voltage, the electric field strength also increases, made the electric field force on the droplets more significant, at the same time, the electric field can also affect the wettability of the ink and the wall surfacel. However, the size of the separated droplet does not change significantly with different voltage intensities; Fig.2 (b) shows the movement of droplets at different contact angles. The results show that the time for ink droplets to detach from the nozzle is not significantly affected by the contact angle, but it has a significant impact on the ink morphology at the nozzle mouth. In addition, as the contact angle continues to increase, the length of the conical ink hanging from the nozzle mouth will actually shorten.



(a) At different voltage intensities (b) At different contact angles

Fig. 2. Motion morphology of ink droplets

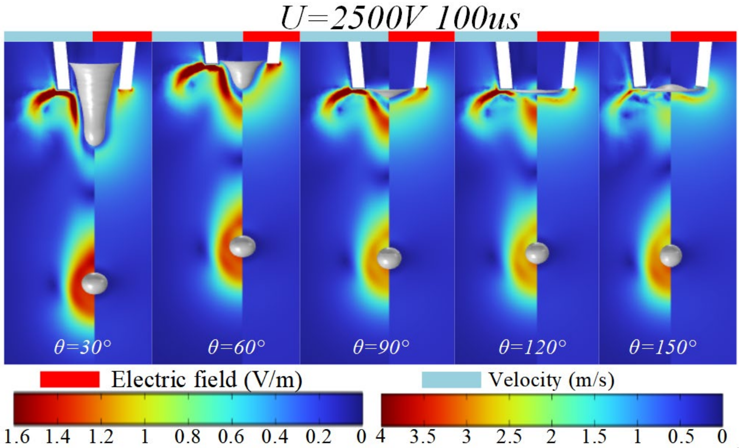


Fig. 3. Distribution of velocity and electric field during inkjet process

Fig.3 shows the distribution of velocity field and electric field during the inkjet process. The results show that there is a non-uniform field strength at the edge of the ink droplet that detaches from the nozzle during its movement. This is due to the presence of induced charges at the interface between ink droplets and air, which changes the distribution of the gas-liquid boundary electric field. The maximum field strength appears near the nozzle mouth, which is related to the curvature of the nozzle mouth edge, the above phenomenon is not affected by the wetting characteristics between the ink and the wall surface. In addition, the above velocity field distribution results show that during the droplet falling process, due to the presence of a certain field strength at the droplet boundary, made the air in the nearby area also move under the action of electric field force. During the ink falling process, it will drive the air flow, which makes the velocity field near the droplet tend to be relatively high. However, the nozzle outlet position will also increase the air velocity in high field strength areas due to the increase in field strength, this pattern is not affected by changes in contact angle.

3.2 The influence of voltage intensity on the velocity of droplet motion trajectory

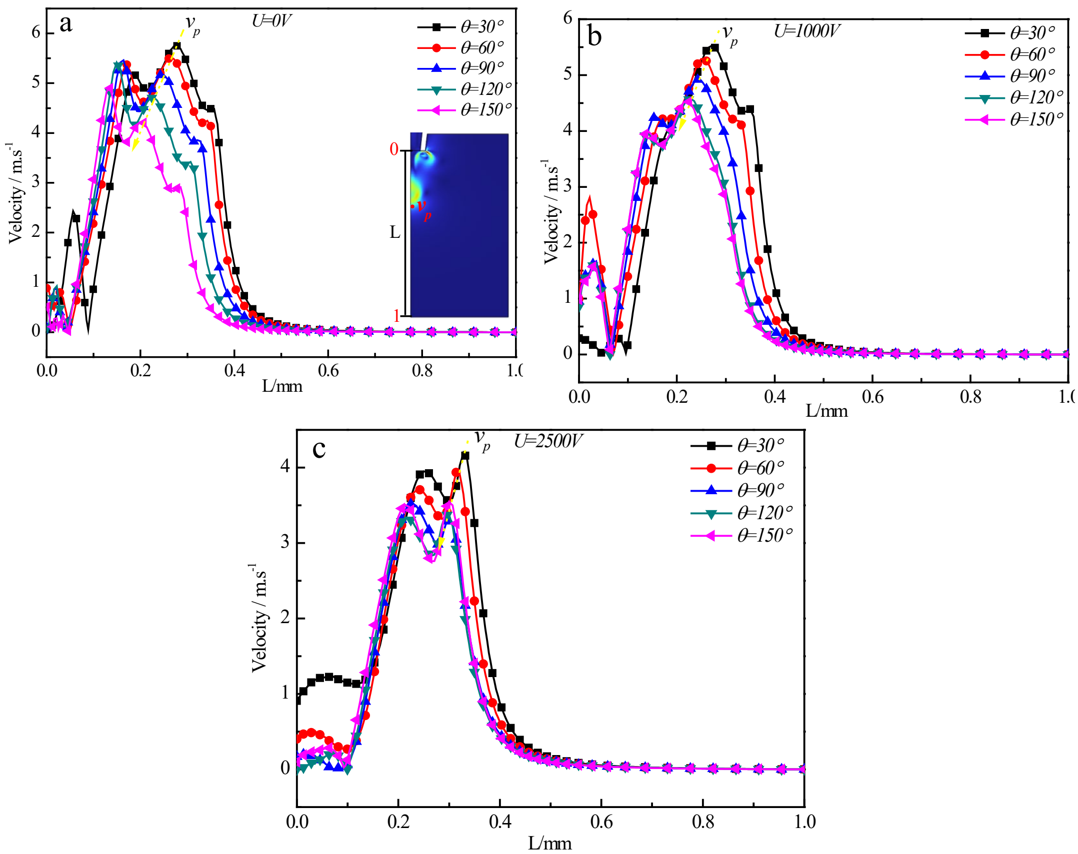


Fig. 4. The Influence of Voltage Intensity on the Velocity of Droplet Motion Trajectory

Based on the schematic diagram of the electrostatic printing structure in Fig.1, it shows the ink droplets are subjected to gravity and electric field forces in the calculation domain, both of which are in the downward direction. Therefore, the trajectory of the droplet movement is a straight line, which is the perpendicular line from the center of the ink jet outlet to the printing board below. The ink discharge velocity directly affects the printing effect, so the droplet movement speed is very important. Fig.4 shows that under different voltage intensities, the droplet movement after 100*us*, the velocity change on the trajectory is marked as v_p at the bottom of the droplet. The results show that when the voltage value is 0, the working fluid velocity on the droplet movement trajectory actually increases, and the v_p value decreases with the increase of contact angle. However, when the voltage starts to increase and the contact angle is below 120°, as the contact angle increases, the v_p value range decreases. When the voltage is 2500V and the contact angle is 150°, the phenomenon of v_p value increasing with the increase of contact angle occurs. In addition, the results in Figure 4 also show that when the voltage intensity is 1000V and the contact angle is 30°, the bottom velocity of the droplet is about 5.5m/s. When the voltage is increased to 2500V, the droplet velocity decreases to 4.2m/s, and the voltage has a significant effect on reducing the droplet velocity. This is because when the voltage is high, the separation of the droplet from the nozzle is delayed, and the initial velocity is obtained within the same time.

3.3 Effect of contact angle on the velocity of droplet motion trajectory

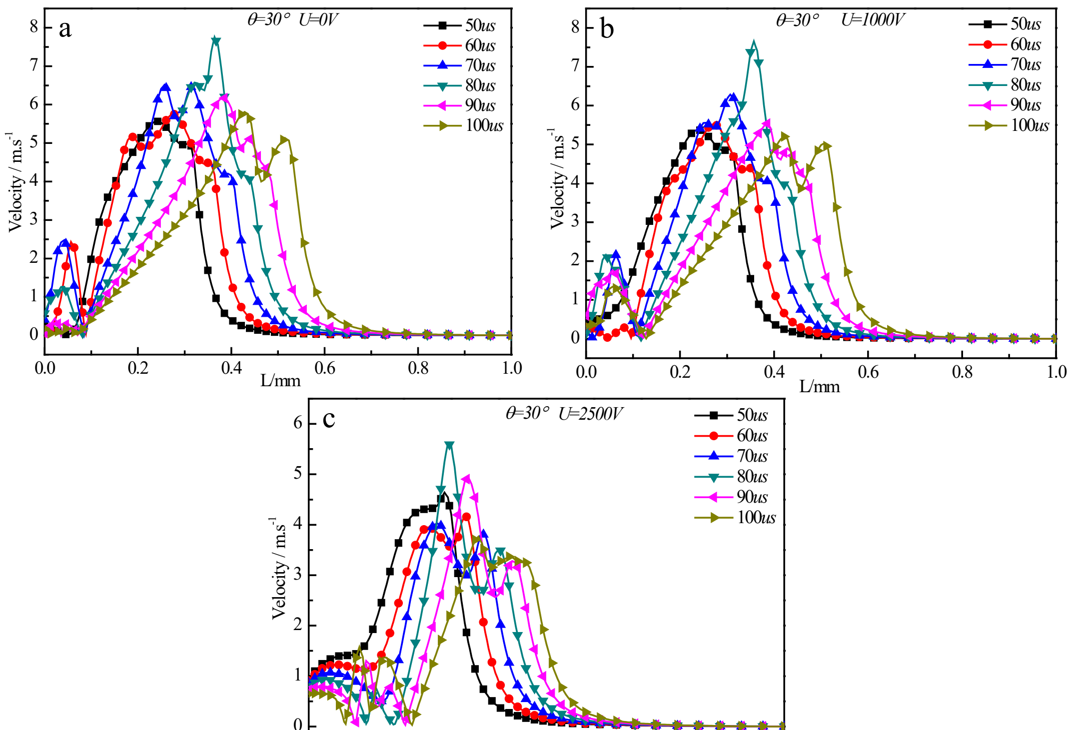


Fig. 5. The speed change from the center of the nozzle to the vertical line of the printing board

During the inkjet process, the electric field force has a significant impact on the movement of ink droplets, and the force on ink droplets varies at different times. In order to explore the differences in droplet motion speed at different times, this section will investigate the θ= 30 °, U=2500V, the velocity distribution of the ink at each time is compared, as shown in Fig. 5. The results show that when the velocity of the droplets before separation from the nozzle is relatively small, it can be seen from the droplet movement pattern in Fig. 2 that when the ink-jet time is greater than 70*us*, the ink has been separated. When it reaches 80*us*, the separated droplet velocity reaches the maximum, then the droplet velocity begins to decline, and when the voltage increases 2.5 times, the maximum velocity attenuation of droplets is about 30%, it indicates that the effect of the separated electric field on the ink is weakened, and this law is not affected by the voltage intensity. The larger the voltage value, the longer the droplet separation time. At this time, the smaller the distance between the droplets and the substrate below, the smaller the velocity of the droplets to the substrate below. However, compared to other voltage values, the time when the droplets reach the substrate is basically the same. Therefore, when working at high voltage, low speed droplets can reduce the collision and diffusion between the substrate and droplets, and improve printing quality.

3.4 Changes in electric field intensity on the trajectory of liquid droplets

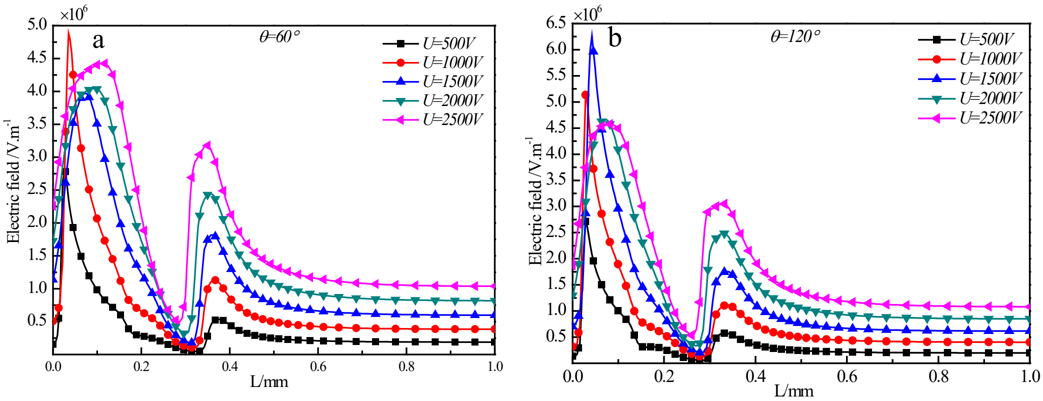


Fig. 6. Velocity variation from nozzle center to vertical line of printing board (60us)

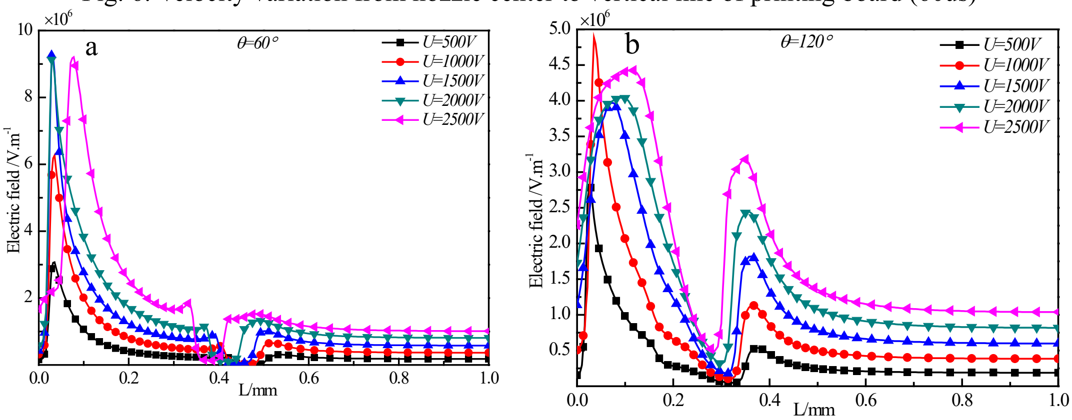


Fig. 7. Field strength variation from nozzle center to vertical line of printing board (100us)

Due to voltage differences that can cause changes in the intensity of the electric field, in order to further analyze the effect of the electric field on the movement of ink droplets, this section counts the distribution of electric field intensity on the droplet trajectory before and after separation, as shown in Fig.7. The results show that increasing the contact angle will promote an increase in the electric field intensity at the interface between air and ink, and the greater the voltage value, the greater the field intensity on the droplet surface. Based on the characteristics of droplet motion morphology, it can be inferred that this is due to the decrease in contact angle, which causes conical deformation at the bottom and top of the droplet. However, the curvature radius of conical droplets is relatively small, resulting in an increase in field strength at these positions, when the droplet is not separated from the nozzle (60us), the larger the contact angle, the slightly lower the field strength near the droplet compared to after separation. However, when the contact angle is small, the opposite pattern occurs, so the smaller the contact angle, Ink is prone to deformation during movement due to the influence of electric field forces.

4. Conclusions

Based on the principle of electro hydraulic coupling dynamics, this article establishes a numerical model for the coupling of electric field, flow field, and droplet dynamics, and studies the effects of inkjet contact angle and working voltage on droplet motion. The main conclusions are as follows:

(1) When ink droplets move in an electric field, the voltage intensity will affect the separation time between the droplets and the nozzle. The higher the voltage, the easier it is for the ink droplets at the nozzle to form a cone shape, and the longer the cone length. At the same time, the higher the voltage value, the slower the movement speed of the droplets during separation.

(2) Based on the characteristics of droplet motion morphology, it can be inferred that this is due to a decrease in contact angle, resulting in conical deformation at the bottom and top of the droplet. However, the curvature radius of conical droplets is relatively small, leading to an increase in field strength at these locations.

(3) After the ink droplet is separated from the nozzle, the separated droplet velocity reaches its maximum value, and then the droplet velocity begins to decay. When the voltage increases by 2.5 times, the maximum droplet velocity decays by about 30%, which is not affected by the voltage intensity.

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