Springer

KSME

Journal of Mechanical Science and Technology 24 (2010) 307~310
www.springerlink.com/content/1738-494x
DOI 10. 1007/s12206-009-1149-y

Simulation of droplet generation through electrostatic forces †

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(Manuscript Received May 2, 2009; Revised September 10, 2009; Accepted October 16, 2009)

Abstract

This paper represents the multiphysics simulation of droplet generation of ink containing conductive nano-particles through electrostatic forces on substrate. The main focus is to investigate the phenomena by generating the drops through a nozzle with the help of electrostatic forces. The electrostatic based deposition system has vast application in printed electronics and biotechnology. In electrostatic deposition mechanism for droplet generation, a strong electric potential is applied at the tip of the nozzle; due this electric potential, the liquid containing the nano-particles experience strong electrostatic static forces at the interface with the air (at the tip of the nozzle). When these electrostatic forces exceed the internal (viscous forces) and external forces (surface tension), a deformation takes place which results in the flow of the liquid in the form of droplets. The size of the droplet is dependent on different parameters like applied voltage, properties of the ink, dimension of the nozzle. To have better understanding of this, a numerical simulation was performed based on multi-physics approach. Multiple simulations were performed by changing the position of electrode in nozzle and varying the applied voltage. Droplet size with respect to applied voltage was evaluated; electric field with respect to applied voltage and time for the droplet generation was also evaluated through these simulations. This study will help in better understanding the parameters of droplet generation phenomena and optimal design of the nozzle for the electrostatic inkjet system.

Keywords: Droplet generation; Electrostatic forces; Inkjet; Multiphysics phenomena; Numerical simulation

1. Introduction

Inkjet systems based on thermal and piezoelectric system have been employed successfully in commercial application especially with regard to digital printing. But these types of conventional jetting systems have limitations, such as thermal problems, ejection frequency and limitation in ejection frequency and clogging etc. For the development of a new kind of printing technology for printed electronics, much research is being done in the field of electrostatic inkjet printing (EIJ). The main benefit of the EIJ Printing system is generation of small droplet size at high frequency and overcoming the discrepancies that conventional inkjet systems have. Because of these added advantage, the EIJ system has immense potential in applications such as making of sensors, RIFD, flat panel display, biotechnology and drug delivery.

In the past most of the research work on droplet formation has been done after assuming the shape of the fluid meniscus, whereas the numerical simulation of drop formation has been done by assuming the initial shape at the tip of the nozzle [1]. However, the complete simulation of the electrostatic inkjet mechanism is also performed on different type of electrostatic inkjet system but the volume of fluid (VOF) technique was used [2, 3]. In the case of capillary nozzle type, many researchers have performed simulation on the electrohydrodynamics by using VOF method [4-6] using commercialized software and as well as using the level set method [7].

In this paper, simulation has been performed to investigate the complete multiphysics phenomena through commercialized software. Initially electrostatic analysis is performed then it is coupled with fluid analysis. The interface between ink and air is determined through volume of fluid (VOF). Parameters affecting the droplet generation are also evaluated through this simulation.

2. Mechanism of electrostatic inkjet system

Most of the conventional inkjet systems use thermal or piezo-actuators to generate droplets. But in recent a great deal of research has been going on regarding the electrostatic inkjet system. Fig. 1 shows the basic configuration of the electrostatic inkjet system along with the forces during the droplet

† This paper was presented at the ICMDT 2009, Jeju, Korea, June 2009. This paper was recommended for publication in revised form by Guest Editors Sung-Lim Ko, Keiichi Watanuki.

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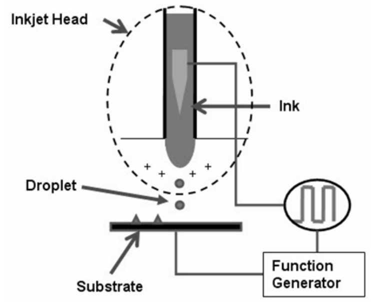
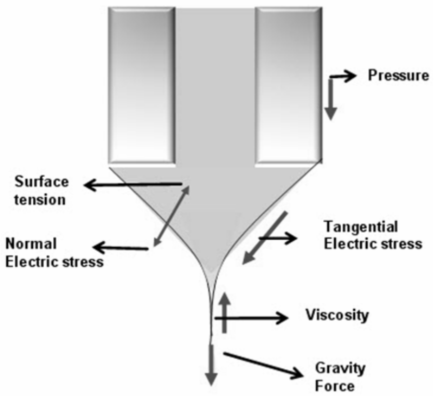


(a)



(b)

Fig. 1. (a) General Schematic of Electrostatic inkjet printing system (b) Forces acting on the ink at the tip of the nozzle.

generation process.

The electric voltage is applied in the form of a signal between two electrodes. Due to the applied voltage, an intense electric field is generated between the two electrodes which induce the liquid meniscus at the interface. When this electrostatic force is greater than the surface tension at the liquid meniscus, the liquid breaks up and droplets are ejected. The size of the droplet depends on the applied voltage, distance between the electrodes, shape and size of nozzle and physical properties of the fluid.

3. Numerical simulation

For the fluid mechanics problem, CFD software uses the Navier-Stokes equation. The Navier-Stokes equation [8] for the incompressible flow can be defined as:

$$\rho \frac{du}{dt} = -\nabla P + \eta \nabla^2 u + \rho g \tag{1}$$

To solve the complete behavior of electrostatic inkjet system the fluid dynamic and electric equation must be combined. After combining both terms Eq. (1) in terms of mechanical stress including the electric stress along with the gravitational forces can be expressed as:

$$\rho \frac{du}{dt} = \nabla.\left(T^m + T^e\right)\rho g \tag{2}$$

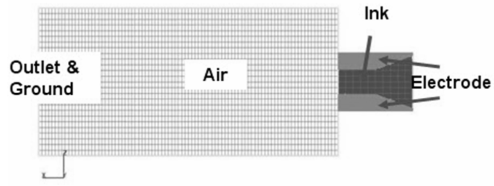


Fig. 1. Capillary Nozzle with boundary condition.

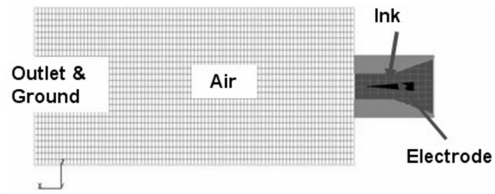


Fig. 2. Pole Type Nozzle with boundary condition.

Where, Tm is the mechanical stress of the fluid and Te is the electrical stress [9] can be written as:

$$\nabla.T^m = -\nabla P + \eta \nabla^2 u \tag{3}$$

$$\nabla.T^e = qE \tag{4}$$

In Eq. (4) the effect of the polarization forces are neglected because in isotropic and incompressible fluid the permittivity has no gradient and the dielectric force is also equal to zero [10]. Here, q is the surface charge and E is the electric field. Thus, Eq. (2) can be written as:

$$\rho \frac{du}{dt} = \nabla P + \eta \nabla^2 u + qE + \rho g \tag{5}$$

For simulation purpose commercialized CFD software (Flow3D) is used which is based on VOF. The main advantage of VOF over level set method for these kinds of problems is tracking of sharp interfaces moving through grid between two fluids and applying boundary condition on the fluid interfaces.

4. CFD model

To develop an electrostatic inkjet nozzle, it is necessary to investigate the behavior of the droplet generation through different configuration of nozzle. For this simulations were conducted on capillary type and pole type nozzle. In both the cases, different voltage is applied with 50 kHz frequency in the step function. Optimal mesh parameters are evaluated and used for these simulations for droplet diameter calculations, which also not that much computationally expensive.

4.1 Capillary nozzle

A simple capillary with diameter of 50μm is modeled in order to investigate the behavior of the droplet generation. A nFEA model is shown in Fig. 2. The voltage is applied on the

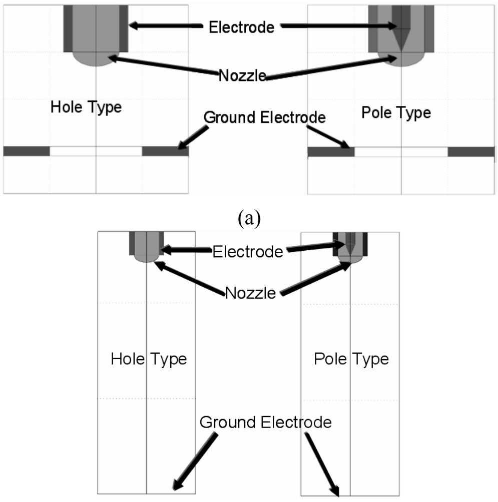


Fig. 4. (a) Integrated type (b) Non-integrated type.

nozzle, which is considered as a conductive part. The distance between the Nozzle and ground is kept at 500μm.

4.2 Pole type nozzle

The difference between the capillary type and pole type nozzle configuration is that an electrode is introduced between the capillary and capillary is considered as a non-conductive part. The ground is kept at the same distance i.e. 500μm, in order to compare the results. The FEA model of the pole type nozzle configuration is shown in Fig. 3.

4.3 Electric field on different types of nozzles

Electric field simulation on different configuration of nozzle was also performed in order to understand the electric field by applying voltage for better understanding of the nozzle design. The integrated nozzles and non-integrated nozzles were also modeled.

In the integrated type the distance between nozzle and ground electrode is at 100μm, whereas in non-integrated type nozzle the distance between nozzle and ground electrode is 500μm. The main concept behind the integrated type nozzles is to have ground with the nozzle head in inkjet system. The diameters of the nozzles are kept at 50μm. The pole type nozle configuration is further divided into three types. First type is at which the electrode is at the level of the nozzle tip. In second part the electrode is 15μm above the level of the nozzle tip and in third part the electrode is 15μm below the level of the nozzle. The model of the integrated and non integrated type nozzles are shown in Fig. 5.

The detail of the different models generated for the electric field simulation is shown in Table 1.

For the simulation purpose a commercial ink data was used as a fluid the properties of the ink are shown in Table 2.

Table 1. Data of different nozzle configuration of nozzles for electric field simulation.

Model number	Type	Electrode position with respect to nozzle tip (μm)	Ground distance (μm)
1	Capillary	N/A	100
2	Capillary	N/A	500
3	Pole type	0	100
4	Pole type	0	500
5	Pole type	15 inside nozzle	100
6	Pole type	15 inside nozzle	500
7	Pole type	15 outside nozzle	100
8	Pole type	15 outside nozzle	500

Table 2. Properties of ink used.

Properties	Values
Density	1070 kg/m^3
Viscosity	15cps
Surface Tension	32 dynes/cm
Particles	Silver - 20wt %

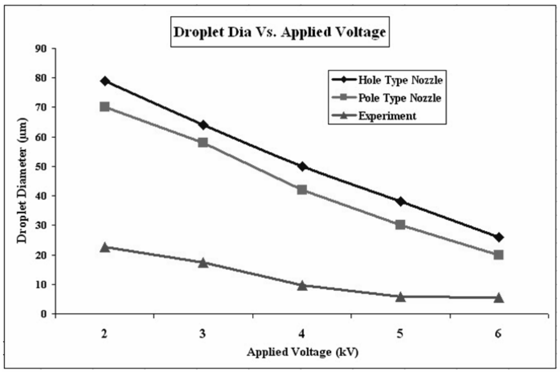


Fig. 5. Droplet Diameter against applied voltage.

5. Results and discussion

5.1 Capillary & pole type nozzle

Different voltages at 50 kHz frequency were applied to check the droplet behavior. The diameter of the droplet corresponding to the applied voltage is shown in the graph at Fig. 5.

As shown in the graph the droplet diameter is decreasing as the voltage increases. In the pole type nozzle also the diameter of the droplet is also decreasing with increase in applied voltage. Moreover, the diameter is smaller than the droplet diameter generated through the capillary type nozzle. By comparing the graph of droplet generation for both the cases, the droplet diameter in the capillary nozzle is 79, 64, 50, 38 and 26μm at 2, 3, 4, 5 and 6kV respectively, whereas the droplet diameter is 70, 58, 42, 30 and 20μm at 2, 3, 4, 5 and 6kV respectively. This shows that the droplet size changes as the configuration of electrode changes. The simulation results are also compared with the experiment results of the pole type nozzle configure-

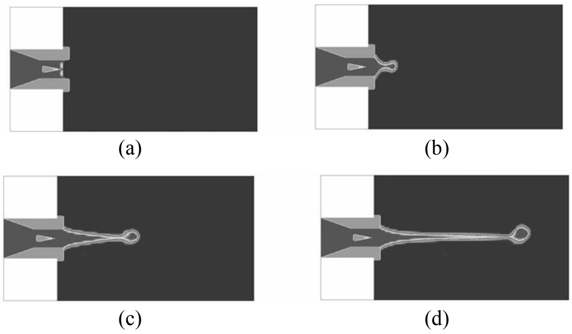


Fig. 6. Droplet generation with respect to time at 4kV (a) 1e-6sec, (b) 1e-5sec, (c) 1.5e-5sec and (d) 2.5e-5sec.

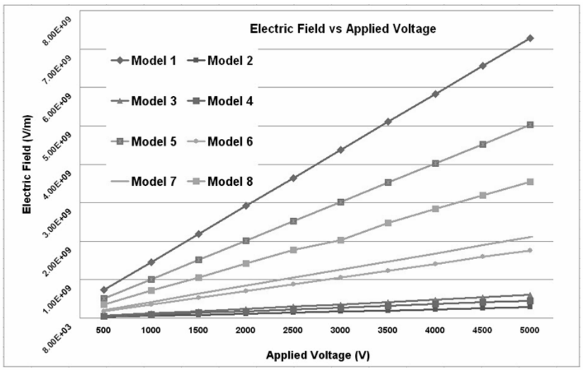


Fig. 7. Graph of Electric field simulation on different types of nozzles configuration.

tion. As shown in the graph at Fig. 5, the trend is similar as compared to simulation results, which means that by increasing the voltage, droplet diameter decreases. This difference in the experimental results and the simulation results is due to assumption that all the free charges are at the liquid surface.

Fig. 6 shows the behavior of the droplet generation with respect to given time.

5.2 Electric field on different types of nozzles

For the development of a better drop-on-demand electrostatic inkjet system, electrostatic simulation was performed on different types of nozzle designs. These simulations provide the electric field with respect to the position of the electrode as well as the distance from the ground. The simulation results are shown in Fig. 7. By looking at the result the nozzle where the electrode is outside of the nozzle tip with integrated ground has more value of electric field as compared to other types of nozzle design.

6. Conclusions

By numerical simulation of ejection mechanism with the help of electrostatic forces, the following can be concluded:

By increasing the applied voltage the droplet diameter decreases. The pole type nozzle generates small droplets at same applied voltage as compared to the capillary type due to the effect of the electric field.

The simulation results are compared with the experiment data, in both the cases the droplet diameter decreases with increase in voltage. The trend is similar but the difference in values due to assumption is taken for the simulation.

In electric field simulation, the integrated electrode will perform better than non-integrated one and with pole type configuration.

In the future, the simulation work will more evaluated in detail, and charge density and other parameter will be modeled. The results will be compared with the experiment data and also multi-nozzle will be simulated for the electrostatic inkjet system.

Acknowledgment

This study is supported by Ministry of Knowledge Economy, Korea through project “Strategy Technology development project”.

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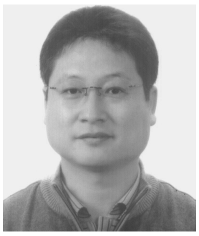

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