碩士學位論文

Numerical Simulation of Droplet Based on Electrostatic Hydrodynamics

濟州大學校 大學院

메 카 트 로 닉 스 공 학 과

카리드래만

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Numerical Simulation of Droplet Based on Electrostatic Hydrodynamics

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2009 . 7.

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GRADUATE SCHOOL
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Dedicated to

My Parents, My Family and Teachers

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NOMENCLATURES

ρ	Density of the fluid
u	Velocity of the fluid
t	Time
P	Pressure
μ	Dynamic viscosity
g	Acceleration due to gravity
T^m	Mechanical stresses of the fluid
T^e	Electric stresses of the fluid
q	Charge density
E	Electric field
ε	Dielectric constant
ϕ	Level set function

ABSTRACT

인쇄전자는 프린팅 공정기법으로 만들어진 전자 소자 혹은 전자 제품을 의미하며, 이러한 인쇄전자 제품으로는 2 차원 3 차원 형상의 프린팅 패턴과 구조체, 이를 기능성 잉크로 프린팅한 도선, 저항, 캐패시터, 인덕터 등의 수동소자, TFT 등의 능동 소자가 있으며, 이들의 집합체로 이루어진, RFID Tag, E paper, Solar Cell, Printed Sensor 등이 있다.

잉크젯 프린팅의 응용 범위가 인쇄전자의 출현으로 상당히 확장되었으며, 잉크젯 프린팅은 전자 부품 제조산업에서 비용의 효율성과 함께 높은 유연성을 선도하는 새로운 전망을 가능하게 한다. 잉크젯은 유일한 비접촉 프린팅 방식이며 따라서 다양한 기판의 사용이 가능하게 한다.

잉크젯 프린팅의 기본적인 원리는 미세한 잉크의 액적을 프린트 헤드 노즐을 통하여 기판에 전달하고 원하는 이미지를 형성하는것이다. 최종적으로 프린트의 특성은 잉크, 기판, 프린터 헤드 성질 및 이들간의 상호작용에 달려있다.

잉크젯 기술은 연속적인 방식과 DOD 방식으로 분류가 되며, DOD 방식에서는 잉크 액적이 필요할때마다 생성이 되는 방식으로 일반적으로 열과 압전으로 구동이 되는 방식이 있다.

그러나, 최근의 연구는 기계적인 운동 제한 때문에 정전기력 접근법으로 변화하고 추세이다. 정전기력 시스템은 기계적인 작용력을 줄이며, 높은 주파수에서도 더욱더정밀한 시스템을 만들수 있다. 또한, 작은 노즐 크기에서도 미세하고 집중화 된 액적을 얻을 수 있다.

정전기력 접근법에서는 전극에 가하는 전기 포텐셜에 의한 전기장이 형성되기 때문에 액적의 생성은 정전기력에만 좌우되며, 이러한 포텐셜에 의하여 노즐로부터 잉크를 분리하기 위한 당기는 힘이 시스템에 가해진다.

또한, 정전기력을 통한 액적 생성은 공급 전압, 전극과 그라운드와의 간격, 노즐 직경 등에 좌우되며, 정전기력 잉크젯 프린트 헤드 설계를 위해서는 이러한 변수에 대한 철저한 이해가 연구되어야한다.

본 논문에서는 정전기력 잉크젯 시스템을 설계하기 위하여 노즐 직경, 공급 전압 및 주파수 등 변수들에 대한 다양한 수치 시뮬레이션을 수행하였으며, 미세하고 우수한 액적을 생성하기 위하여 다양한 노즐 형태의 헤드 시뮬레이션을 구현 하였다.

또한, 멀티 노즐 잉크젯 시스템을 설계하기 위한 중요한 고려사항은 인접한 노즐간의 정전기력 간섭(cross talk)인데, 이러한 정전기력 간섭 문제를 분석하기 위한 시뮬레이션을 수행하였으며, 간섭 영향을 최소화하는 방법론을 제안하였다.

1. INTRODUCTION

Inkjet printing is an important technology in color document production and in recent years printed electronics. The rapid development of inkjet technology started off around the late fifties. Since then, many inkjet devices have seen the light of day. At present, two classes of inkjet technologies are available: continuous jet and drop-on-demand. The classification of the inkjet system can be shown in figure 1.1.

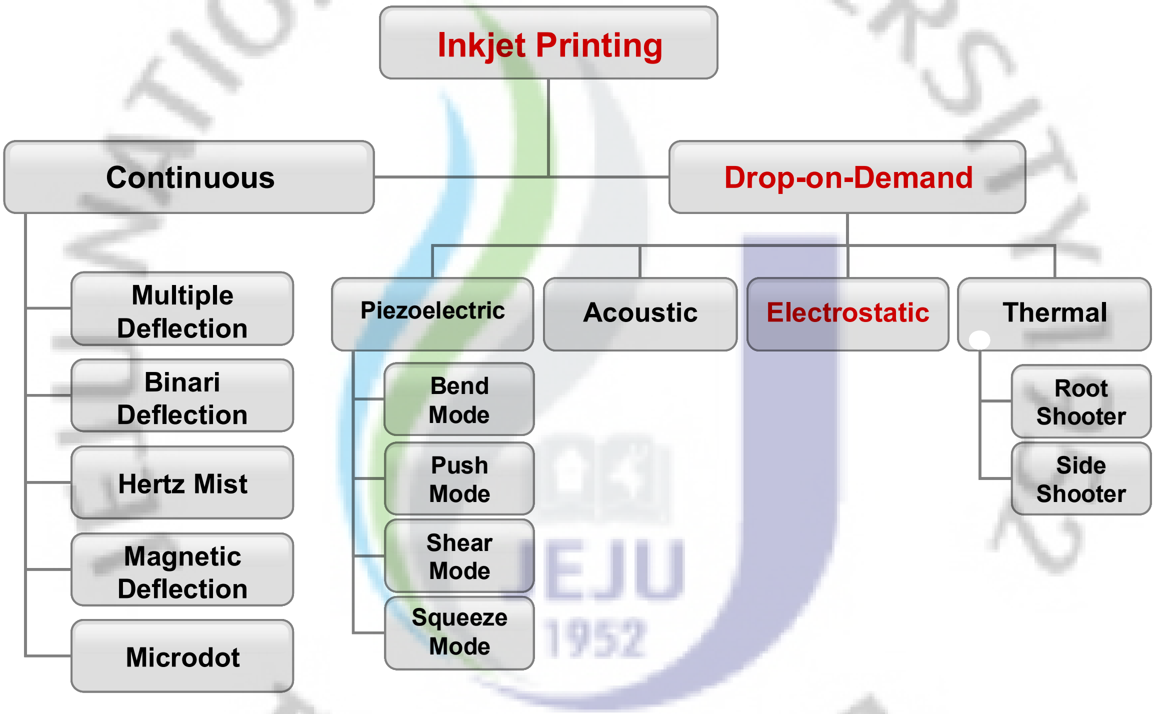


Figure 1.1. Classification of inkjet Technology

1.1. Continuous Inkjet

Continuous inkjet technology permits very high-rate drop generation, one million drops per second or faster, but is expensive to manufacture and to operate. Two classes of continuous inkjet printers are available today. High-speed industrial printers are used for applications such as carton and product marking and addressing and personalizing direct mail. Proofing printers on the other hand offer the best print quality among non-photographic devices, but they are much slower. Although the resolutions are not that high, the variable-sized dots make photographic quality possible.

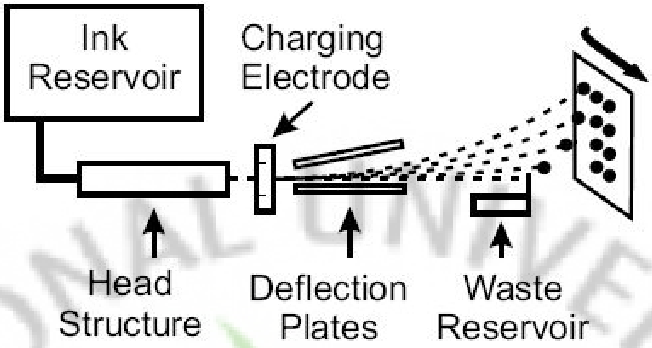


Figure 1.2. Functional Principle of a Continuous Inkjet system

A simplified sketch of a typical continuous jet printing system is shown in Figure 1.2. Ink under pressure is delivered from an ink reservoir via an input line to a head structure. The head structure, containing a piezoelectric driver plate, is periodically constricted at its mechanical resonance frequency by means of an applied electric field. By this method, an ink stream discharged from it breaks up into a plurality of individual drops. A charging electrode applies charge to each of the drops. The magnitude of the charge placed on individual drops is variable and determines the drops' ultimate paths. After the drops have exited the charging electrode, they pass between a pair of deflection plates, to which a fixed potential is applied. Drops that are utilized for printing are deflected to a media to form characters while excess drops are directed to a gutter, which in turn directs the drops to a waste reservoir

1.2. Drop-on-Demand Inkjet

For drop-on-demand systems, which are microelectromechanical systems (MEMS) that deliver droplets only when needed, several methods of actuating are proposed. Most common is thermoelectric actuation (Thermal Inkjet) followed by the piezoelectrically driven actuators (Piezo Inkjet). Especially the piezoelectric inkjet technology with its ability to print a variety of fluids is developing in many different directions. Besides printing ink on paper, new applications can be found in very specific fields such as e.g. biochemistry (DNA printing) or printing of organic polymers, solid particles, adhesives, electronic devices, circuits and display technology.

1.2.1 Thermal Inkjet

Thermal inkjet, sometimes referred to as bubble jet, is a drop-on-demand technology that uses electrical pulses applied to heating elements in contact with the fluid near the ejection aperture nozzle in order to vaporize a small amount of liquid to produce pressure impulses by the formation and collapse of gas bubbles, schematic of thermal inkjet system is shown in Figure 1.3. The conversion of the electrical drive pulses to localized heating of the fluid is mediated by thin film resistors in intimate contact with the fluid. No direct electrical contact with the fluid itself is needed. This pressure pulse is used to eject a jet of fluid from a small orifice that, given correct drive levels, will form into a single drop. This technique has the advantage of ease of integration into a dense print array inkjet print head, since the drive mechanism is simply a resistor placed in contact with the fluid to be ejected. The two forms in common use are classified by their fabrication technology as roof shooters and edge shooters. Roof shooters are fabricated by bonding an ejection orifice plate structure over the top of a wafer on which the fluid flow and heating elements are fabricated. Edge shooters, in contrast, form their ejection apertures from channels etched longitudinally into the wafer.

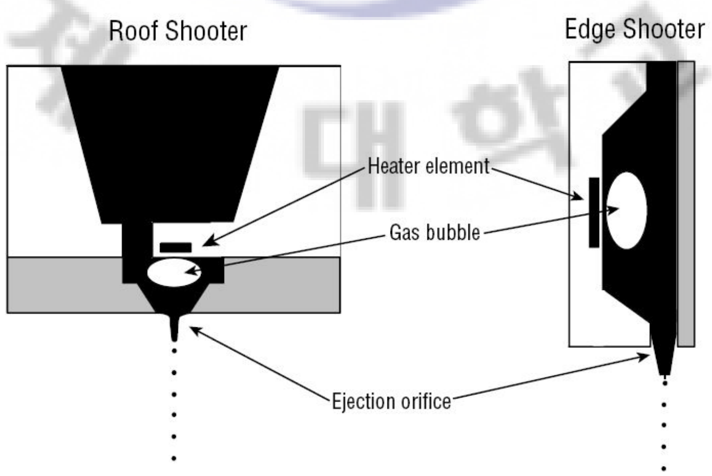


Figure 1.3. Schematic of Roof Shooter and Edge Shooter Thermal Inkjet Printer

The drawbacks are the requirement of a nonkoagating (thermal reactant forming) fluid, the lack of flexibility in tailoring the rise and fall time of the pressure pulse for optimizing control over the ejected fluid jet, and most importantly for scientific applications, the local chemical reactions that will take place during each vaporization and cooling cycle that can change the chemical composition of the fluid over time. On balance though, for commercial inkjet image printers, the advantages vastly outweigh the disadvantages.

1.2.2 Piezoelectric inkjet

Piezoelectric inkjet printers harness the inverse piezoelectric effect, which causes certain crystalline materials to change shape when a voltage is applied across them. A small electrical pulse makes the crystal contract slightly, squeezing ink out of the nozzle onto the media. Depending on the piezoelectric ceramics' deformation mode, the technology can be classified into four main types: squeeze, bend, push, and shear. For squeeze mode, radially polarized ceramic tubes are used. In both, bend- and push-mode design, the electric field is generated between the electrodes parallel to the polarization of the piezo-material. In a shear mode print-head, the electric field is designed to be perpendicular to the polarization of the piezo-ceramics.

1.2.2.1 Squeeze mode actuator

The actuator of a print-head working in a squeeze mode, as displayed in Figure 1.4. The tube, which is polarized radially, is provided with electrodes on its inner and outer surface. When it is desired to have a droplet expelled from the orifice, a short rise time voltage pulse is applied to the transducer, the polarity being selected to cause a contraction of the transducer. The resulting sudden decrease in the enclosed volume causes a small amount of liquid to be expelled from the orifice. Due to the pressure pulse, some of the ink is also forced back into the tube, but the amount is relatively small due to the high acoustic impedance created by the length and small bore of the tube. The voltage pulse is allowed to decay relatively slowly and the transducer, therefore, expands slowly to its initial volume. Due to the small rate of change of volume during the decay, the accompanying pressure reduction is too small to overcome the surface tension at the orifice. Consequently, liquid flows into the transducer to replace the liquid previously expelled without drawing in air through the orifice.

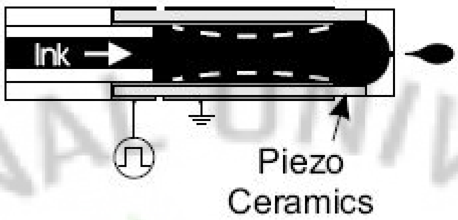


Figure 1.4. Squeeze Mode Actuator Design

1.2.2.2 Bend mode actuator

Figure 1.5 shows a piezoelectric inkjet print-head operating in bend mode. It consists of a pressure chamber including an ink inlet and an outlet passage terminated in an orifice. A conductive diaphragm forms one side of the chamber with a deflection plate made of piezoelectric ceramic attached. The outer surface of the plate is covered by a conductive coating, which provides an electrical connection to the plate. Applying a voltage to the piezoelectric plate, results in a contraction of the plate thereby causing the diaphragm to flex inwardly into the pressure-chamber. This, of course, applies pressure to the printing fluid in the chamber, which forces a droplet to be expelled from the orifice. The size of the droplets is defined by the voltage applied to the deflection plate, the pulse duration, and the diameter of the orifice.

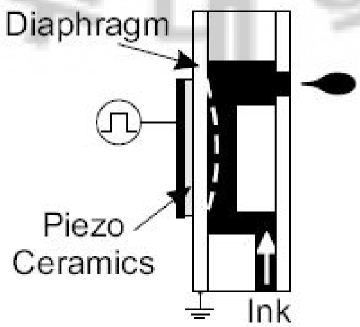


Figure 1.5. Principle of the Bend Mode Technique

1.2.2.3 Push mode actuator

In a push mode print-head design as shown in Figure 1.6, the piezoelectric ceramic rod expands; it pushes against a diaphragm to eject the droplets from an orifice. In theory, the piezoelectric actuators can directly contact and push against the ink. However, in practical implementation, a thin diaphragm between the piezoelectric actuators and the ink is incorporated to prevent the undesirable interaction between ink and actuator materials

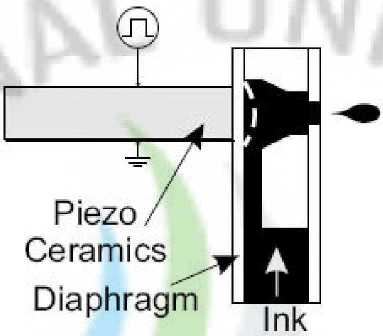


Figure 1.6. Functional Principle of a Push mode Inkjet Actuator

1.2.2.4 Share mode actuator

The shear-mode inkjet shown in Figure 1.7, has electrodes deposited on the upper half of both sides of the channel walls. The applied field is thus perpendicular to the direction of polarization, and causes the walls to shear sideways, and squeeze out an ink drop (shearing is one of the modes of displacement of a piezoelectric element). The actuator is typically manufactured from a solid block of PZT by sawing the grooves, and then depositing electrodes, with a nozzle at the end of each groove.

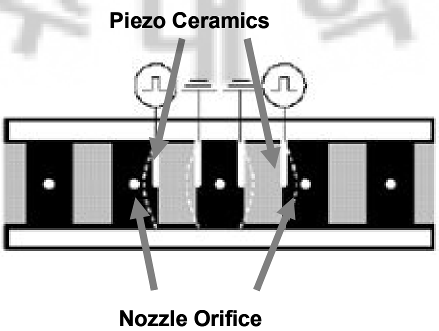


Figure 1.7. Functional Principle of a Share Mode Inkjet Actuator

1.2.3. Electrostatic Inkjet

Electrostatic jetting of liquids is a physical process caused by an electric force applied to the surface of a liquid. The electrical shear stress elongates the liquid meniscus formed at the opening of the nozzle and generates a tiny droplet as a result of the balance between electrical and surface tension forces. The electric voltage signal applied allows for a strong electric field to be concentrated in the vicinity of the apex of the liquid meniscus and thus micro-dripping ejection of droplet takes place. That is, a tiny droplet is removed from the peak of the dome-shaped liquid meniscus. Optimal conditions are introduced for applied voltage, electric conductivity, and flow rate for generating a stable drop-on-demand droplet using the micro-dripping mode. Schematic of electrostatic inkjet is shown in figure 1.8.

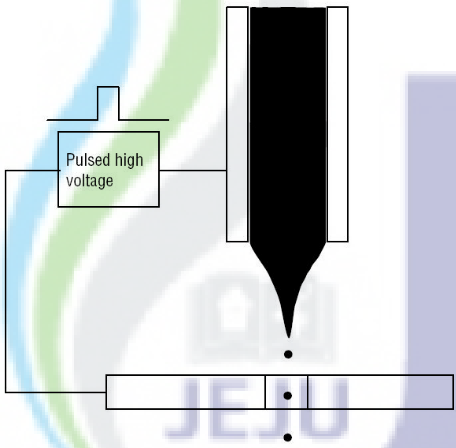


Figure 1.8. Schematic of Electrostatic Inkjet

The conventional jetting devices based on thermal bubble or piezoelectric pumping, however, have some fundamental limitations to overcome to meet the aforementioned requirements for the future generation of jetting devices: 1) Thermal bubble jetting is under a fundamental limitation on the size and density of nozzle array, as well as the ejection frequency. 2) Piezo-electric jetting in general has a fundamental limitation on the density of nozzle array, as well as the ejection frequency. However in electrostatic inkjet system these problems can be overcome, because droplet is generated by applying the high voltage to the fluid.

1.3. Overview of the Thesis

However, the behavior of the fluid under the electrostatic forces is very complex phenomena. The droplet generation depends on the applied voltage, applied frequency, nozzle diameter, position of electro and distance between electrode and ground. In this thesis a number numerical simulation has been performed to have better understanding of the electrostatic droplet phenomena. The main idea of this thesis is to investigate the electrostatic droplet generation through commercial software for better deign of the electrostatic inkjet system. Following have been investigated through the numerical simulation and has been presented in this thesis:

- Droplet ejection on different nozzle diameter
- Droplet ejection on different configuration of nozzle
- Comparison between integrated and non-integrated nozzle
- Cross-talk between multi-nozzles

The organization of the thesis is as follow:

Chapter 2 provides the over view of the CFD model for the electrostatic behavior of the fluid.

Chapter 3 will provide the numerical simulation performed in order to investigate the droplet generation phenomena by catering different parameters as mentioned earlier.

Chapter 4 presents the summary of the numerical simulation, conclusion on the out-come of these simulations and the future work.

2. CFD MODELING

The simulation of electrostatic droplet generation behavior is complex and multi-physical behavior, in which electrostatic analysis as well as fluid dynamics behavior has to be simulated. Early theoretical works focused on situations in which departures from spherical, cylindrical, or planar base states were either (a) arbitrary but infinitesimal in amplitude, as in Rayleigh's pioneering study of the stability of an isolated, perfectly conducting, charged drop, or (b) finite in amplitude but entailed assumptions made *a priori* about the symmetry of those deformations, as in the cleversurmize made by Taylor in the now celebrated spheroidal approximation he used to determine the deformation and stability of a perfectly conducting, uncharged drop immersed in a uniform external electric field. A century after Rayleigh's stability analysis which inaugurated the birth of the science of electrohydrodynamics (EHD), Miksis, Joffre, and Basaran and Scriven developed numerical methods to systematically calculate without any simplifying assumptions the equilibrium shapes and stability of electrified drops. Miksis theoretically determined the equilibrium shapes of free drops of a dielectric liquid surrounded by a dielectric medium that are subjected to an electric field. Joffre theoretically determined the equilibrium shapes of conducting drops that are pendant from a capillary and surrounded by a dielectric fluid in the presence of an. These authors also carried out experiments and showed that their theoretical predictions were in good agreement with their experiments.

Basaran and Scriven theoretically determined the equilibrium shapes of conducting drops and soap bubbles that are either pendant from the top plate or sessile on the bottom plate of a parallel plate capacitor. These authors also determined stability limits with respect to field strength beyond which stable equilibrium shapes would no longer exist and the drops would presumably go unstable by issuing jets from their pointed tips. Harris and Basaran extended these works by carrying out a systematic study of the shapes and stability of both conducting and nonconducting electrified drops that are pendant from either the top plate of a parallel plate capacitor or a metal capillary. In a series of papers, Wohlhuter and Basaran and Basaran and Wohlhuter theoretically studied the effect of linear and nonlinear polarization on the shapes and stability of pendant and sessile dielectric drops that are surrounded by a dielectric fluid in an electric field. Sherwood theoretically studied in the creeping flow limit the transient deformation and breakup of insulating and semi-insulating, or leaky dielectric, free drops in an electric field and identified different modes of breakup that depend on the physical properties of the drop and host fluids. Haywood studied without the creeping flow approximation the transient deformation of electrified drops for both liquid–liquid and liquid– gas systems. Although these investigators were not able to follow the drops to breakup, they showed that good agreement exists between their computations and previous experimental and theoretical results. Feng and Scott used finite element analysis to theoretically determine finite amplitude prolate and oblate deformations suffered by semi-insulating drops surrounded by a semi-insulating ambient fluid in an electric field. Basaran and Feng and Leal studied the large-amplitude oscillations of inviscid, conducting drops that are set into motion by a step change in velocity potential and/or electric field strength. Basaran showed that when the field strength is sufficiently large, the drops can go unstable by issuing jets from their conical tips, in accord with experiments.

In recent years, there have been a number of studies aimed at understanding the physics of drop formation from a capillary in the absence of electric fields. Zhang and Basaran experimentally studied the effects of the inner and outer capillary radii, surface tension, liquid viscosity, flow rate and surfactants on dynamics of formation of drops of Newtonian liquids into air. Among other things, these authors reported that for low viscosity liquids, the thread which connects the about to detach primary drop to the liquid remaining in the capillary always breaks at its bottom first. For high viscosity liquids, the liquid thread becomes quite long and thin before breaking. Shi showed that the threads formed when high-viscosity fluid drips from a capillary can spawn a cascade of so-called microthreads with each subsequent microthread’s radius being smaller by an order of magnitude compared to that of the previous one. Schulkes used the boundary integral method to solve for the potential flow inside a growing drop to theoretically predict the dynamics of formation and breakup of inviscid liquid drops from a capillary. Brenner did both experiments and solved a set of one-dimensional slenderjet equations to study the dynamics of formation of drops of low viscosity liquids and focused primarily on the dynamics for times approaching and after breakup. A thorough review of drop formation can be found in the recent paper by Eggers.

Whereas the theoretical understanding of the dynamics of drop formation has advanced a great deal in the past decade thanks in part to studies cited in the previous paragraph, this has not been the case for drop formation in the presence of an electric field despite the large amount of attention devoted to it in the literature. A liquid that drips from a capillary in the absence of electric field continues to do so when subjected to an electric field of low strength. If the flow rate is kept low but the field strength is increased, the mode of drop emission from the capillary can change from dripping to EHD jetting from a pendant drop that remains attached to the capillary. However, under conditions that are identical to those of EHD jetting, a regime can also be attained where droplets that are much smaller in size than the capillary radius instead of jets are emitted from the tip of a pendant drop. This mode of drop formation has been referred to as microdripping by Cloupeau and Prunet-Foch. If the field strength is kept low but the flow rate is increased, drop production occurs via the breakup of an electrified jet.

The previous discuss modeling attempts are mostly done through generating their own theoretical model. However, many researchers have performed simulation on the Electrohydrodynamics by using VOF method using commercialized CFD software and as well as using Level Set Method. The main advantage of using commercialized software is that the software handles all the complex equations in order to solve the certain type of problems.

2.1. Volume of Fluid Method

In computational fluid dynamics, the volume of fluid method (VOF) is a numerical technique for tracking and locating the free surface (or fluid-fluid interface). It belongs to the class of Eulerian methods which are characterized by a mesh that is either stationary or is moving in a certain prescribed manner to accommodate the evolving shape of the interface.

The VOF method is known for its ability to conserve the "mass" of the traced fluid, also, when fluid interface changes its topology, this change is traced easily, so the interfaces can for example join, or break apart.

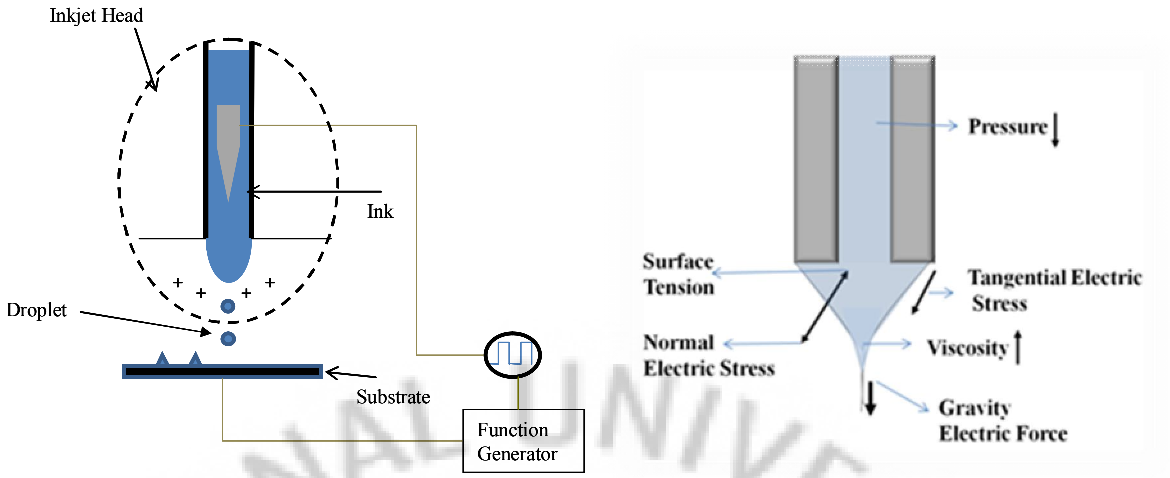
The method is based on the idea of so called fraction function C. It is defined as the integral of fluid's characteristic function in the control volume (namely volume of a computational grid cell). Basically, when the cell is empty (there's no traced fluid inside) value of C is zero, if cell is full, we have $C = 1$, and when the interphasal interface cuts the cell, then $0 < C < 1$. C is a discontinuous function, its value jumps from 0 to 1 when the argument moves into interior of traced phase.

2.2 Level Set Method

The level set method is a numerical technique for tracking interfaces and shapes. The advantage of the level set method is that one can perform numerical computations involving curves and surfaces on a fixed Cartesian grid without having to parameterize these objects (this is called the Eulerian approach). Also, the level set method makes it very easy to follow shapes that change topology, for example when a shape splits in two, develops holes, or the reverse of these operations. All these make the level set method a great tool for modeling time-varying objects.

2.3. CFD Behind the Electro Static Inkjet

A CFD model can describe the whole dynamic process of the generation of droplet generation through electrostatic forces. The CFD solution contains a wealth of information about the shape of the droplet generation, the liquid flow, electric field, charge distribution and force distribution. All the information is dynamic, which means that the changes with time during the droplet generation development can be monitored. No initial assumptions about the charge distribution or liquid shape are necessary. The schematic of Electrostatic inkjet system and forces acting on the fluid for droplet generation is shown in figure 2.1.



(a) (b)

Figure 2.1. (a) Schematic of Inkjet System (b) Forces Acting on the Liquid at Nozzle Orifice due to Electric Field

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

$$\rho\frac{du}{dt} = -\nabla P + \mu\nabla^2 u + \rho g \qquad (1)$$

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

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

Where, T^m is the mechanical stress of the fluid and T^e is the electrical stress can be written as:

$$\nabla.T^m = -\nabla P + \mu\nabla^2 u \qquad (3)$$

$$\nabla.T^e = qE - \frac{1}{2}E^2\nabla\varepsilon + \nabla P_{st} \quad (4)$$

In Equation (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 equals to zero. Here, q is the surface charge and E is the electric field. Thus, Equation (2) can be written as:

$$\rho\frac{du}{dt} = \nabla P + \mu\nabla^2 u + qE + \rho g \quad (5)$$

To determine the interface between ink and air, level set method is used. In which the density ρ and viscosity μ can be defined as following equations:

$$\rho = \rho_{air} + (\rho_{ink} - \rho_{air})\phi \quad (6)$$

$$\mu = \mu_{air} + (\mu_{ink} - \mu_{air})\phi \quad (7)$$

ϕ is the level set function defines the interface, where ϕ equals to 0 in air and 1 in ink.

In order to simulate the droplet generation axi-symmetric model, the density of the mesh is greater at the symmetry axis near the nozzle, because the change in fluid will start at the middle of the nozzle and also the electric field singularity will be at that point. Whereas, the model for analyzing the electric field in case of different nozzle configuration and multi-nozzle simulation 2D models are constructed taking as plane symmetry.

The computational cycle to simulate the droplet generation phenomena is shown in Figure 2.2. First the electrostatic potential is calculated in the whole computational domain i.e. for both liquid and air. By computing the electric potential, the electric body force is calculated. After calculating the electric body forces, the electric body force and gravitational forces are then induced in Navier-Stokes equation. The equation then used to simulate the liquid deformation due to the stresses from the body forces. The flow field of the surrounding is also solved. The calculation can have many shapes of the liquid as initial condition, butt in all result mentioned in this thesis is from the flat surface between the interface of liquid and air.

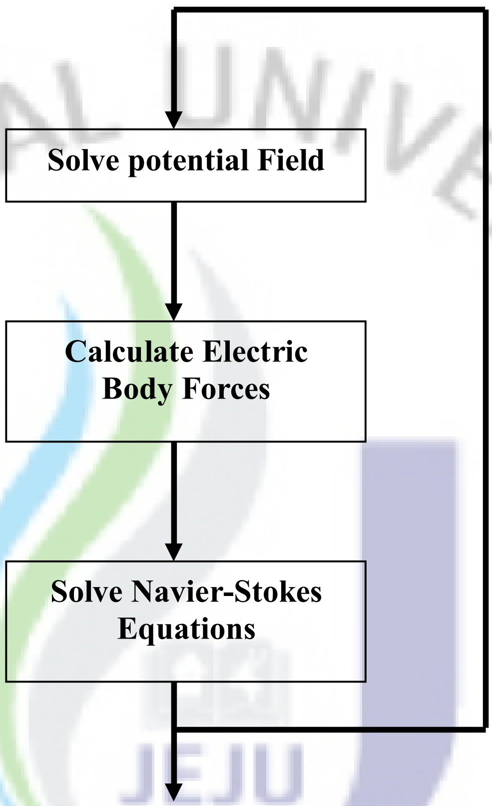


Figure 2.2. Computational Cycle

2.4. Simulated Model

In order to better understand the phenomena, simulations are performed on different size and shape. Following models were analyzed:

2.4.1 Capillary Nozzle

In order to investigate the effect of the nozzle diameter on the generation of droplet through electrostatic forces, two models were created by changing the diameter only and keeping the other parameters constant. The FEA model for capillary nozzle with applied boundary conditions is shown in figure 2.3.

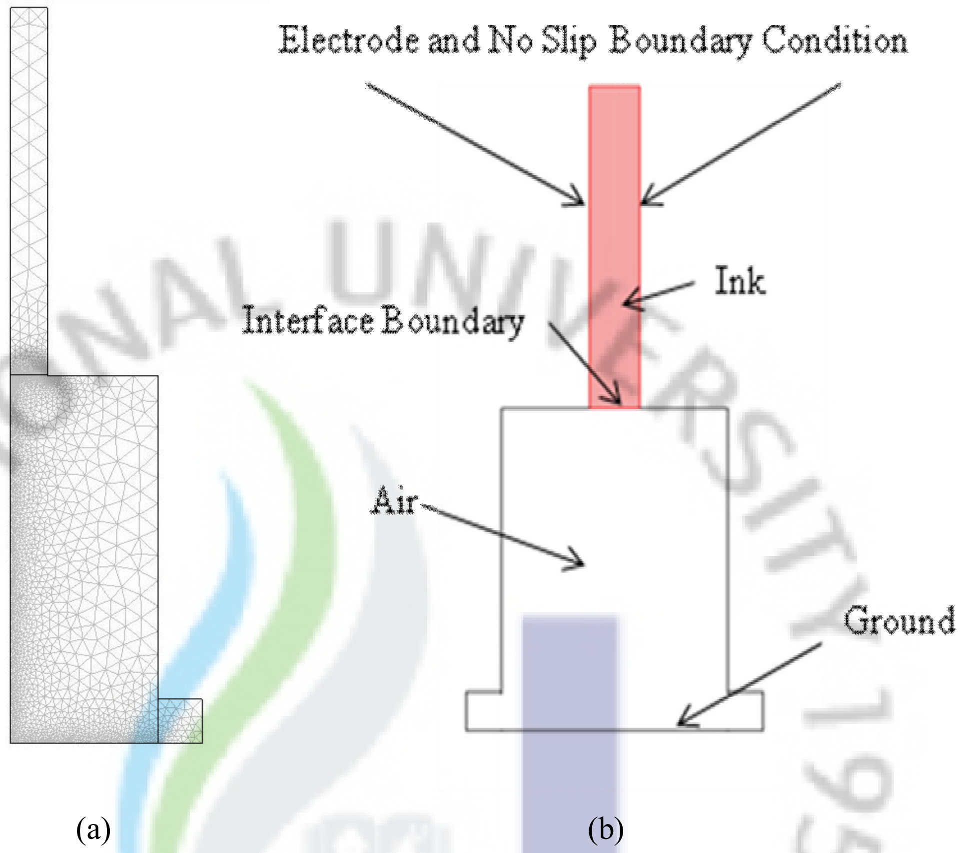


Figure 2.3. (a) Axi-symmetric Meshed Mode, (b) complete model with applied boundary condition

At the symmetry axis, axi-symmetric boundary condition is defined. Remaining boundaries are taken as zero charge. For the Level Set Two Phase Flow at symmetry axis, axi-symmetric condition is defined. Whereas, the adjoining boundary of the liquid and air interface boundary condition is defined. The rest of the boundaries are defined as no-slip condition. The geometric parameters of the models used for the droplet generation is mentioned in table 2.1.

Table 2.1. Geometric parameter for the Simulation of Capillary Nozzle

Parameters	100 μm nozzle	160 μm nozzle
Nozzle length	500 μm	500 μm
Distance between the electrode and Ground	500 μm	500 μm

For electrostatic analysis the Voltage is applied to the nozzle and the ground is defined at the base of the model. The voltage with 100 μsec as a step function simulating as 10 kHz frequency was applied at the nozzle as shown in Figure 2.4.

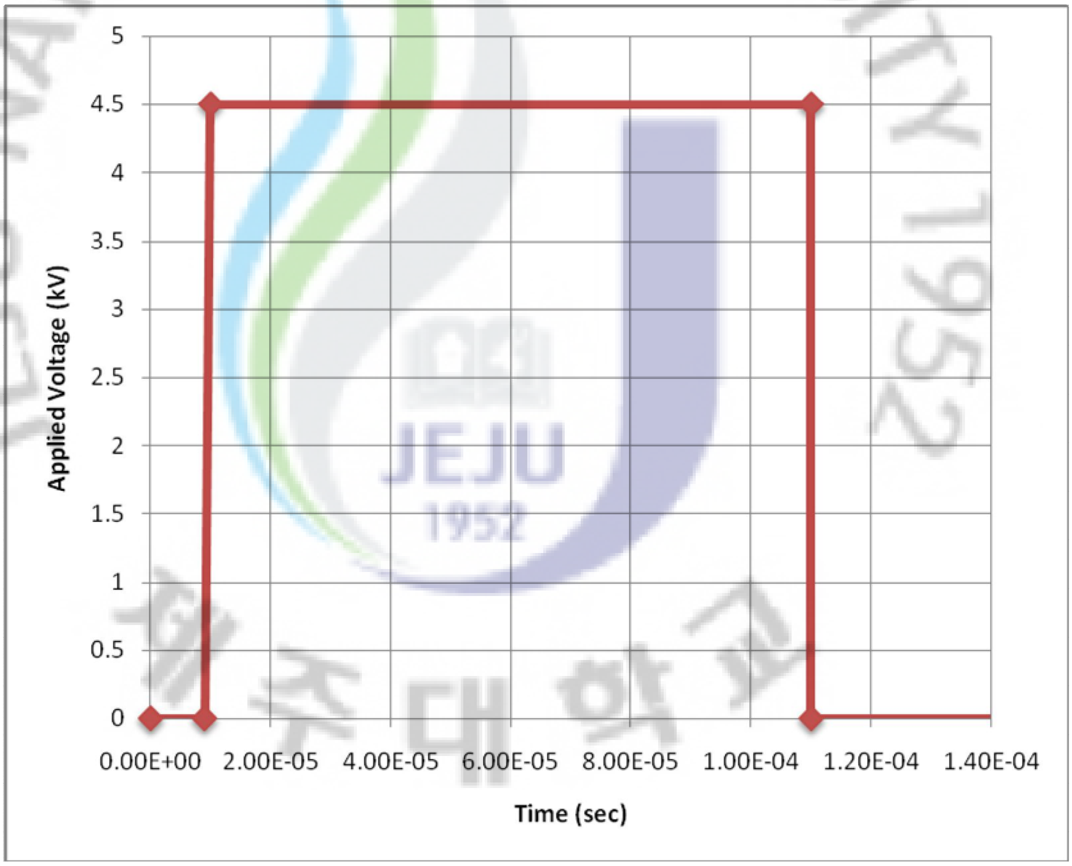


Fig. 2.4: Applied Voltage function

2.4.2 Pole Type Nozzle

For pole type nozzle configuration the model is also made by using axi-symmetric technique. In pole type nozzle case the effect of the position of the electrode for droplet generation is also analyzed. In first case the electrode is kept 15 μm inside of the nozzle, whereas, in second case the electrode is kept 15 μm out side of the nozzle. The simulation model along with the applied boundary condition is in figure 2.5.

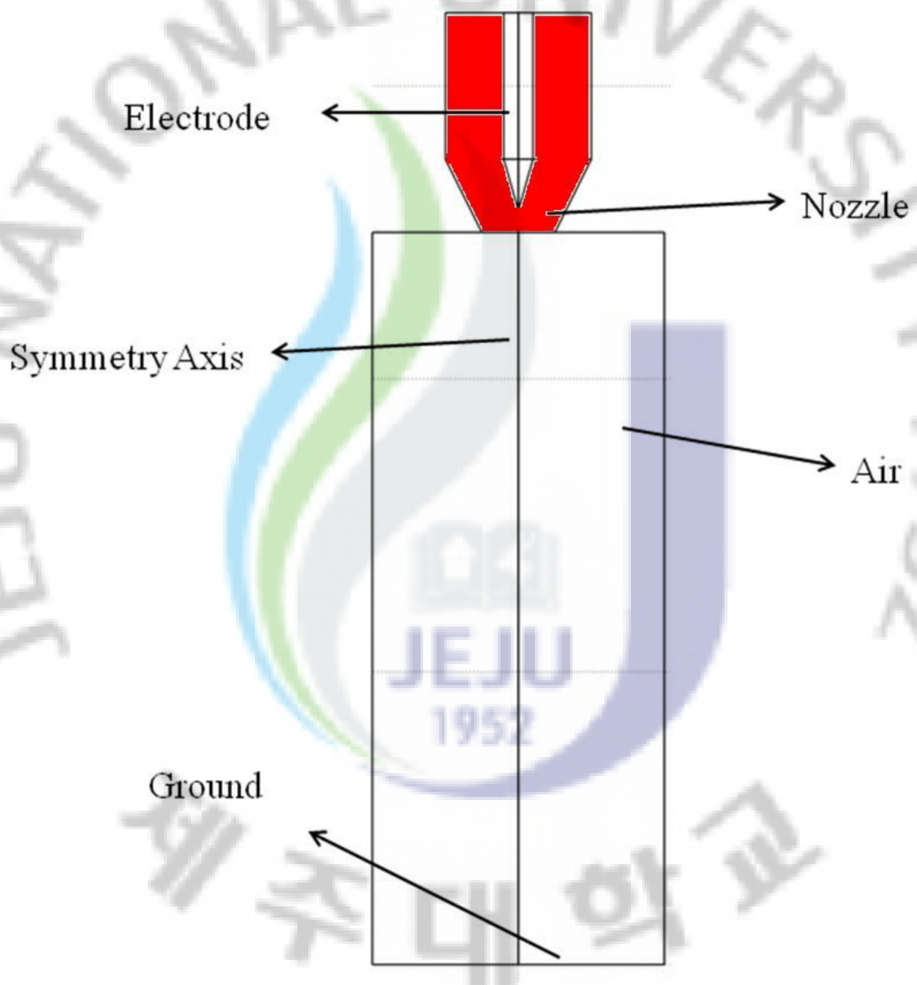


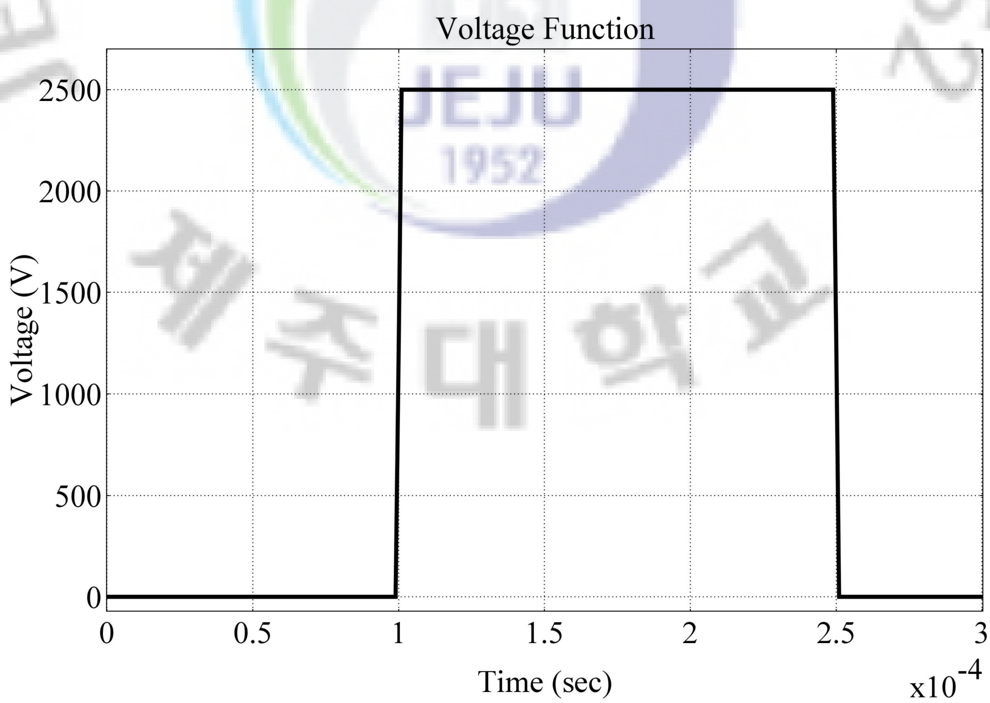
Figure 2.5. Complete model with applied boundary condition

The boundary condition this simulation is same as of capillary type nozzle, where as different frequencies were applied. The rest of the boundaries are defined as no-slip condition. The geometric parameters of the pole type nozzle are shown in Table 2.2.

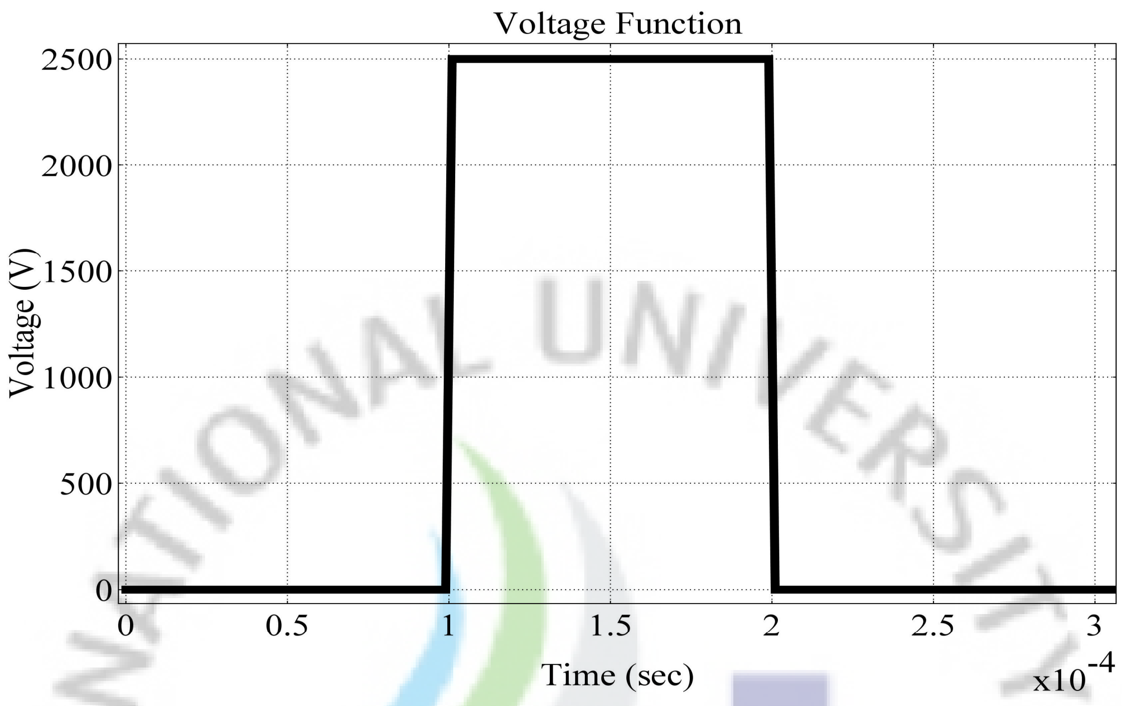
Table 2.2. Geometric parameter for the Simulation of Pole Type Nozzle

Parameter	Value
Case 1 (Position of electrode w.r.t nozzle)	15 μm inside
Case 1 (Position of electrode w.r.t nozzle)	15 μm outside
Diameter of nozzle	50 μm
Diameter of the electrode	10 μm
Nozzle length	100 μm
Distance between nozzle and ground	500 μm

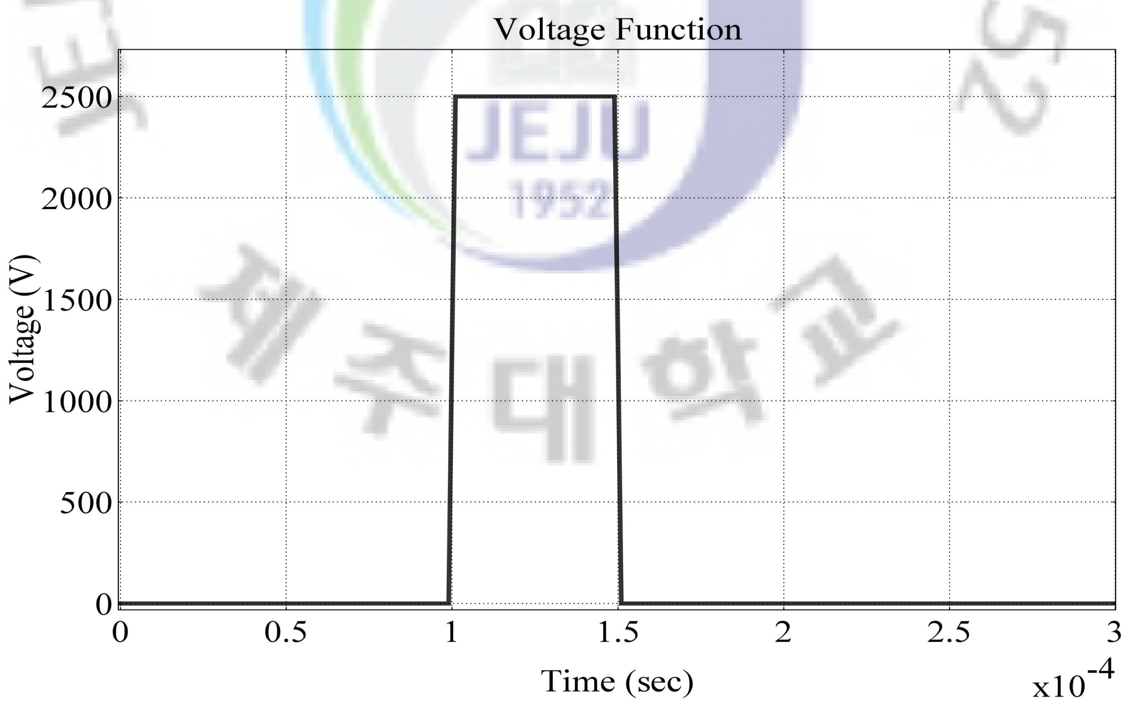
In order to investigate the effect of the voltage and frequency on the droplet generation, different voltages are applied by keeping the frequencies 2 kHz, 5 kHz, 10 kHz and Multi-step function are applied. In Multi-step function the initial 500V is applied for the period of 75 μsec and for the ejection peak of different voltages are applied for 25 μsec. The applied voltage step functions are shown in Figure 2.6.



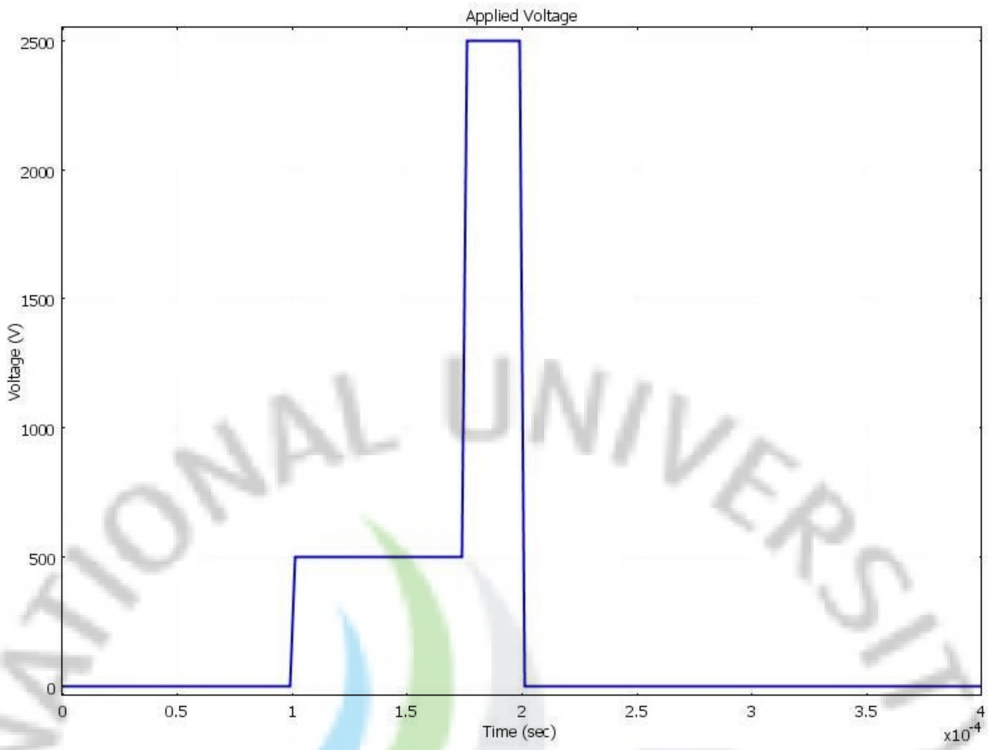
(a)


Voltage Function
Voltage (V)
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
2.5
3
Time (sec)
x10^-4

(b)


Voltage Function
Voltage (V)
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
2.5
3
Time (sec)
x10^-4

(c)



(d)

Figure 2.6. Voltage function (a) 2 kHz (b) 5 kHz (c) 10 kHz and (d) Multi-step function

2.4.3 *Electric field on different types of nozzles*

In order to design a nozzle for optimal operating parameter 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. The examples of different types of nozzles are shown in figure 2.7.

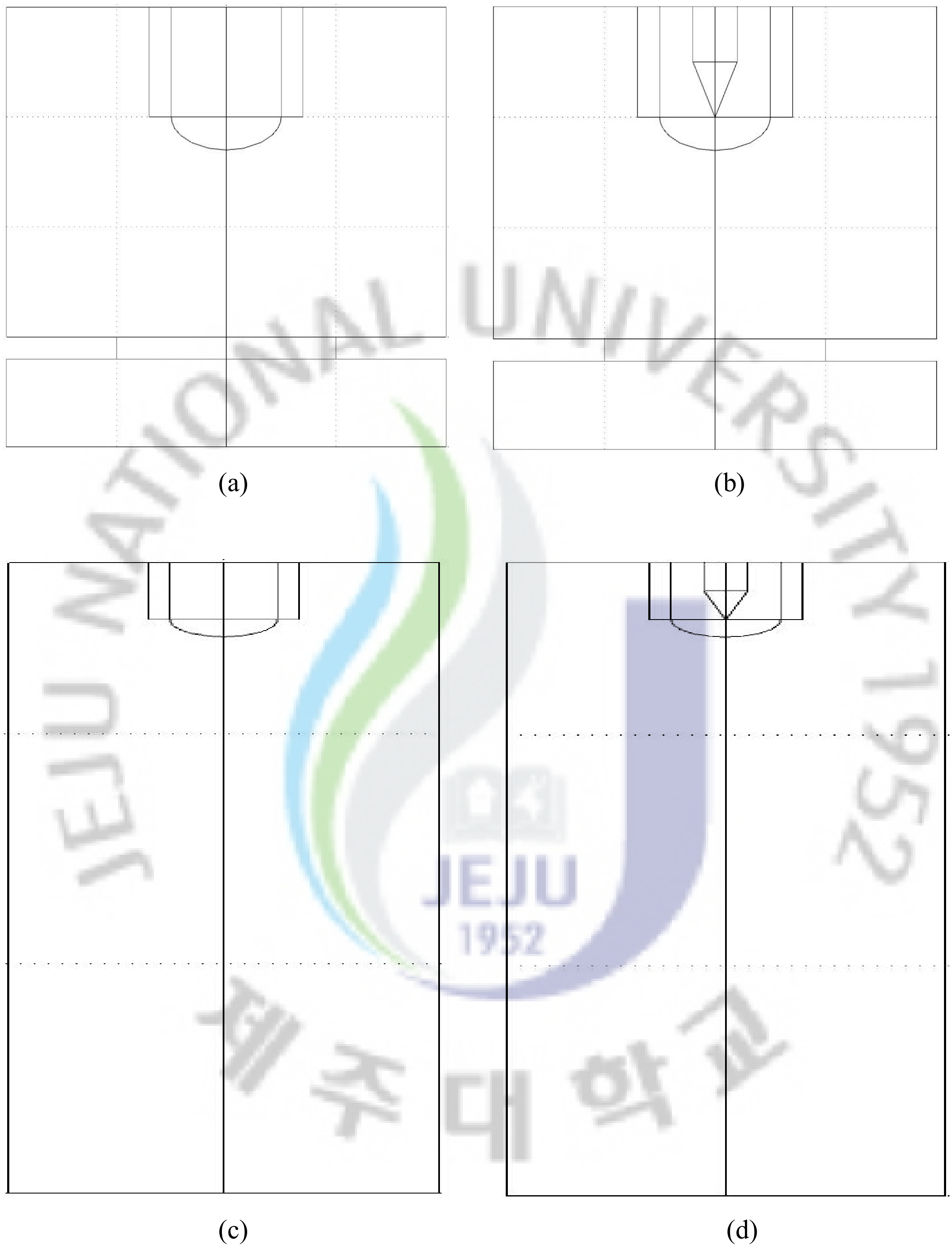


Figure 2.7. Different nozzle (a) Integrated Hole type (b) Integrated pole type (c) Non-integrated Hole Type (d) Non-integrated Pole Type

In integrated type the distance between nozzle and ground electrode is at 100µm, where as in non-integrated type nozzle the distance between nozzle and ground electrode is 500µm. The main concepts behind the integrated type nozzles are to have ground with the nozzles head in inkjet system. The diameters of the nozzles are kept 50µm. The pole type nozzle configuration is further divided in 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 general configuration of each type of nozzle is mentioned in table 3.

Table 2.3. General configuration for nozzles' comparison analysis

Type	Remarks
Model 1	Hole type integrated nozzle
Model 2	Hole type non-integrated nozzle
Model 3	Pole type integrated nozzle with electrode at the tip of the nozzle
Model 4	Pole type non-grated nozzle with electrode at the tip of the nozzle
Model 5	Pole type integrated nozzle with electrode 15 µm inside the nozzle
Model 6	Pole type non-integrated nozzle with electrode 15 µm inside the nozzle
Model 7	Pole type integrated nozzle with electrode 15 µm outside the nozzle
Model 8	Pole type non-integrated nozzle with electrode 15 µm outside the nozzle

2.4.4 Multi-nozzle cross talk

The main hurdle in designing the multi-nozzle is the electric interfering or cross-talking between the nozzles. In order to simulate the electric field interface, multi-nozzle model is generated as shown in figure 2.8. The two models are compare in which nozzle to nozzle distance is 110µm and 200µm. The voltage is applied as step function in both cases and the effect of the applied voltage analyzed. To check the effect of one nozzle on other, the voltage is applied on nozzle 1 and effect of the electric field is calculated on nozzle 2 and 3, then voltage is applied on nozzle 2 for cross talking the effect is calculated on nozzle 1 and 3 and so on. Initially the voltage is applied with 0 offset value, for better understanding and operational condition voltage with 500V offset is also applied and phenomena is studied. Moreover, for model with nozzle to nozzle distance is 110µm, simulation is also performed with offset voltage of 500V in step function as shown in figure 2.9. The number on the peaks is corresponding to the nozzle number as shown in the fig 2.9.

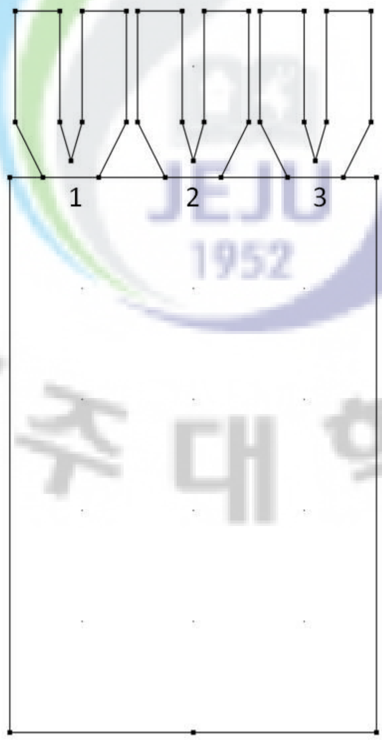


Figure 2.8. Multi-Nozzle Model

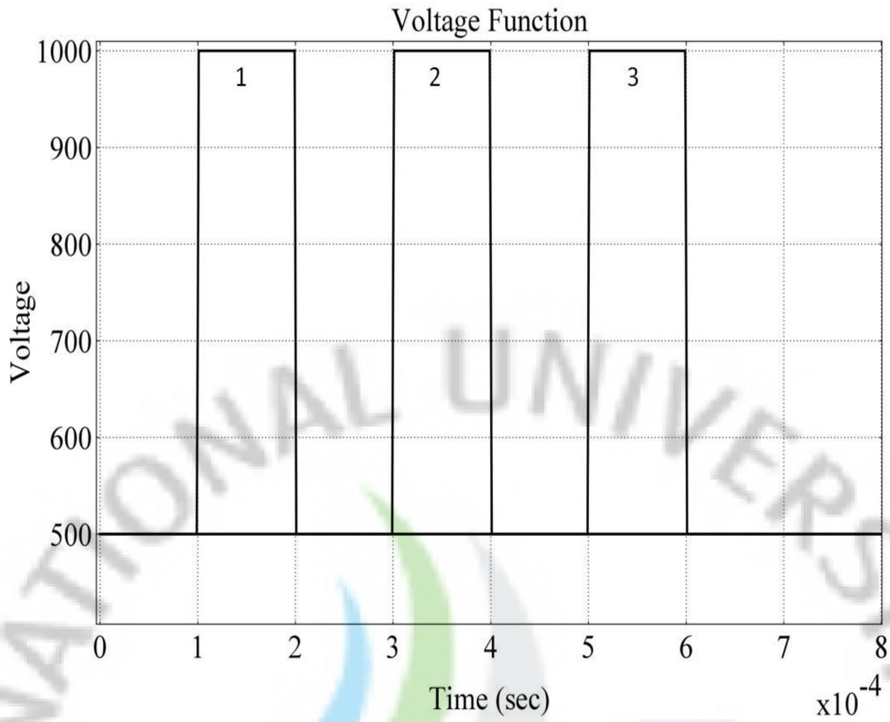


Figure 2.9. 500V Offset Voltage function

2.4.5 *Ejecting fluid*

For simulation purpose the properties of fluid used for the simulation is mentioned in table 2.4.

Properties	Value
Density	1080 kg/m3
Viscosity	0.004 N.s/m2
Surface Tension	0.07N/m
Pigments	Ag
Solvent	Water based

3. RESULTS AND INTERPRETATIONS

Different numbers of simulations were performed on the models as mentioned in chapter 2. The main focus is to observe the droplet generation phenomena and also parameters for droplet generation. In this chapter results obtain by the numerical simulation are presented. For simulation, commercial software 'COMSOL' is used. COMSOL is a multiphysics capabilities; two or more type of physics can be incorporated for the simulation purpose.

Fro the droplet generation, multiphysics problem is solved in a sequential method, first the initial conditions were determined, the interface between ink and air. After getting initial condition electrostatic analysis was done to calculate the electric field. In the end Level Set Method was solved by incorporating electric field results. For the droplet generation the mass of droplet with respect to applied voltage, magnitude of Electric field against the applied voltage and effect of different voltage step function were also evaluated.

For the electric field simulation the only the electrostatic simulations are performed in order to check the value of electric field as well as cross-talking of nozzle in multi-nozzle case. For the cross-talking of the nozzles the distance between nozzles to nozzle were changed and also the off-set voltage case were simulated.

All the simulations performed were time dependent, because the applied voltage is time dependent step function and behavior of the liquid is also a time dependent phenomena under the applied boundary conditions. The results on simulation are as follows:

3.1 Capillary Nozzle

In order to evaluate the droplet size the step function of voltage 1 kV, 2 kV, 3 kV, 4 kV and 5 kV is applied. The droplet mass is calculated for each voltage on 100㎛ and

160 μm capillary nozzle. The graph of voltage with respect to applied voltage is shown in figure 3.1.

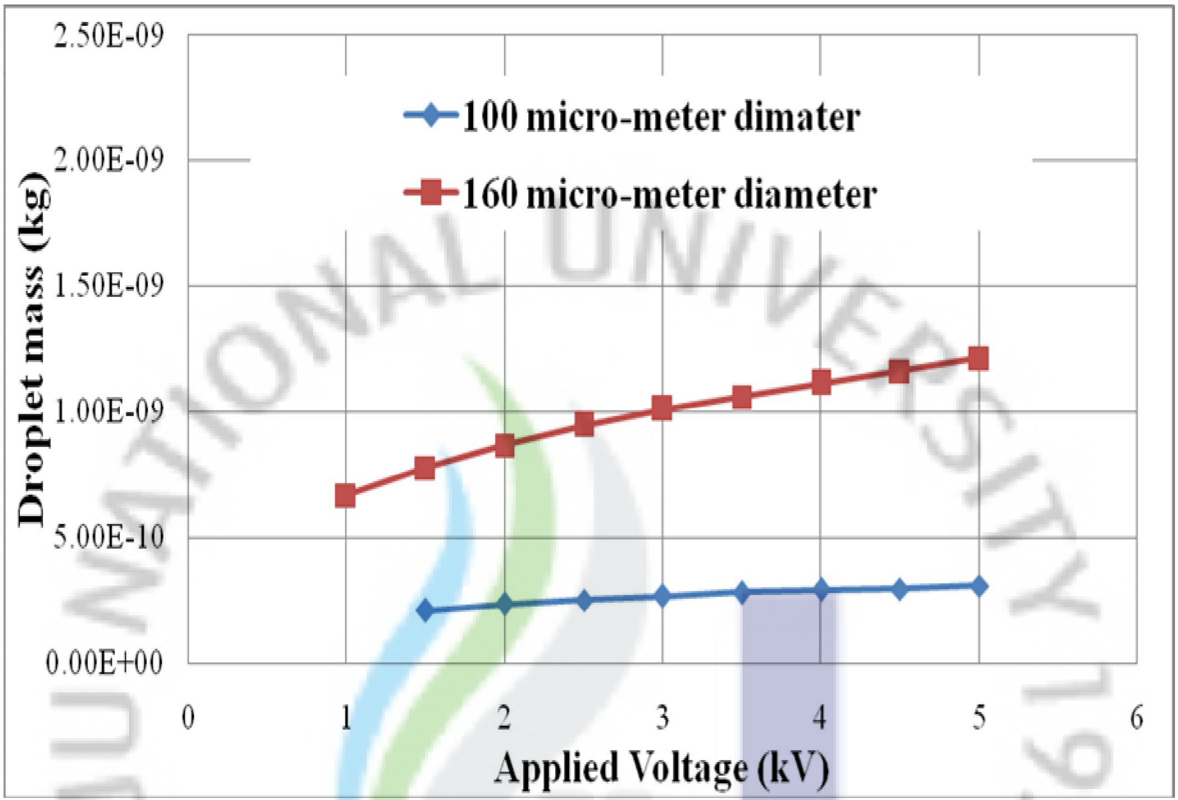


Figure 3.1. Mass of the droplet at different voltages

As shown in the graph, the mass of the droplet in 100 μm is less then the value of mass of droplet for 160 μm capillary nozzle. This shows that for smaller nozzle diameter the droplet generated for the smaller size capillary. But as shown in graph in figure 3.1, the droplet generation for 100 μm capillary nozzle is started at 1.5 kV.

The value of electric field with respect to applied voltage is shown in graph at figure 3.2. These values are calculated at the tip of the nozzle, from where the droplet generation starts to take place. For the 160 μm capillary nozzle the value of electric field is greater than of 100 μm at the same applied voltage.

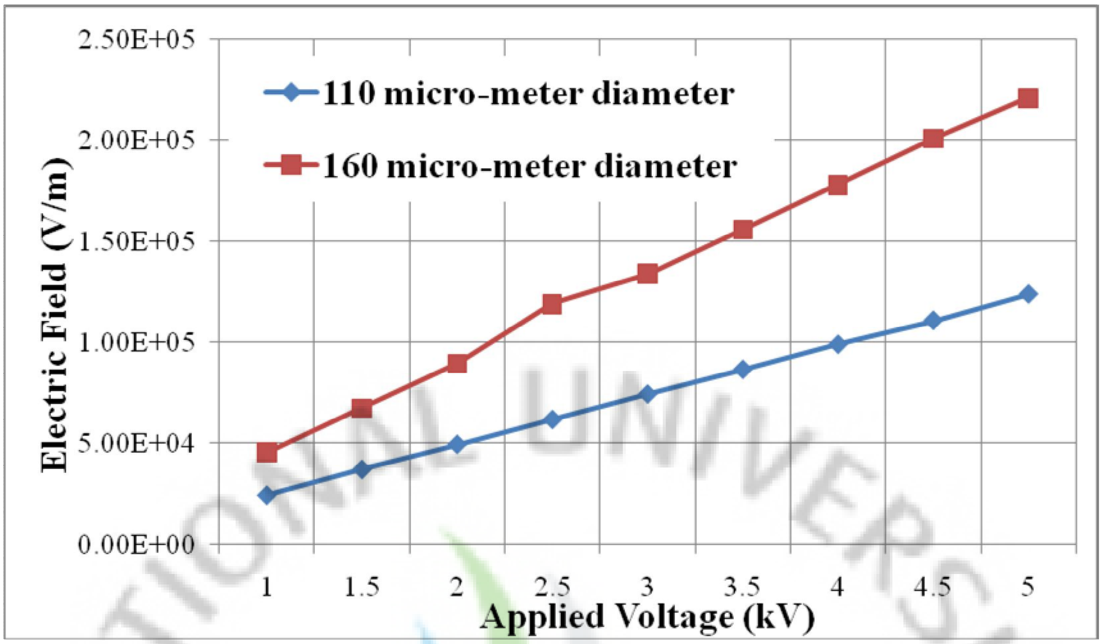


Figure 3.2. Electric Field with respect to applied voltage

Figure 3.3 and Figure 3.4 shows the distribution of the electric field from center of the nozzle (100μm diameter and 160 μm diameter respectively) to the ground electrode, the sharp decrease in the Electric Field is due the value inside of the ink

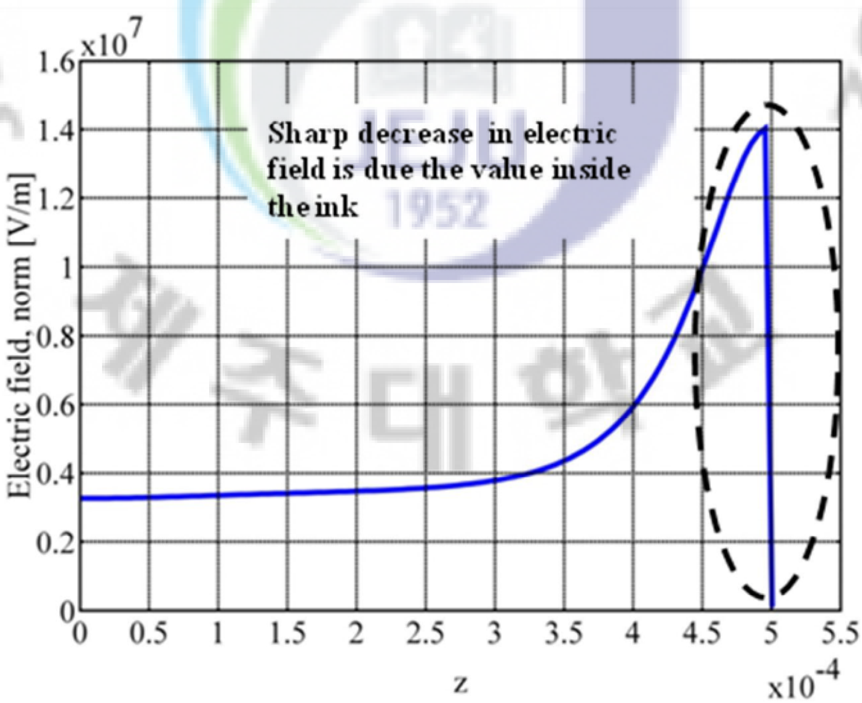


Figure 3.3. Electric Field in z-direction at 2.5kV. (100μm capillary)

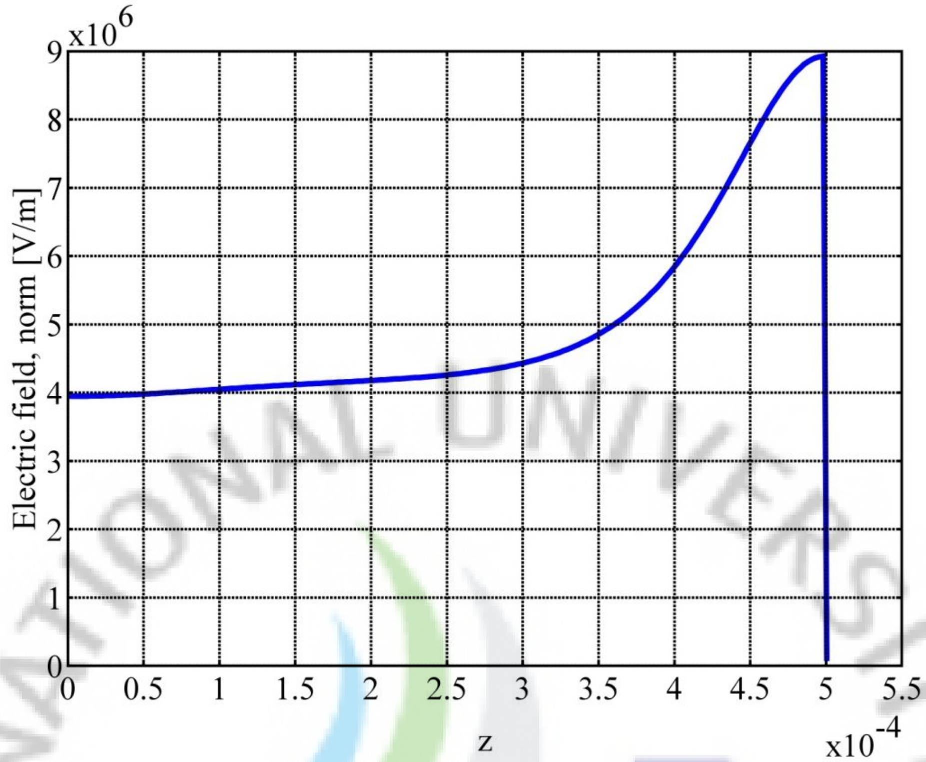


Figure 3.4. Electric Field in z-direction at 2.5kV. (160µm capillary)

Fig 3.5 shows the droplet generation through 100µm nozzle at different time when the 2.5 kV is applied to the nozzle. As shown in the figure the droplet is separated after 60 µsec.

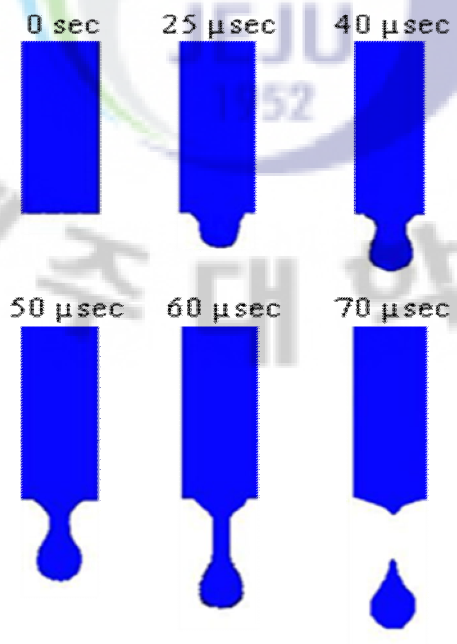


Figure 3.5. Drop formation at 2.5kV with respect to time from 100µm nozzle

The result shows that droplet size depends on the applied voltage and also the diameter of the nozzle. By increasing the voltage, droplet size is slightly increased and for the same voltage by increasing the nozzle the droplet size is increased.

3.2 Pole Type Nozzle

For the pole type nozzle the four different cases were simulated in which the diameter of the nozzle is kept constant and the voltage step function is varied as shown in figure 2.6. The droplet mass with respect to the applied voltage for each step function is shown in figure 3.6. By observing the graph the droplet size also depends on the width of the pulse (frequency) of applied voltage. As the pulse width increases the droplet size also increasing.

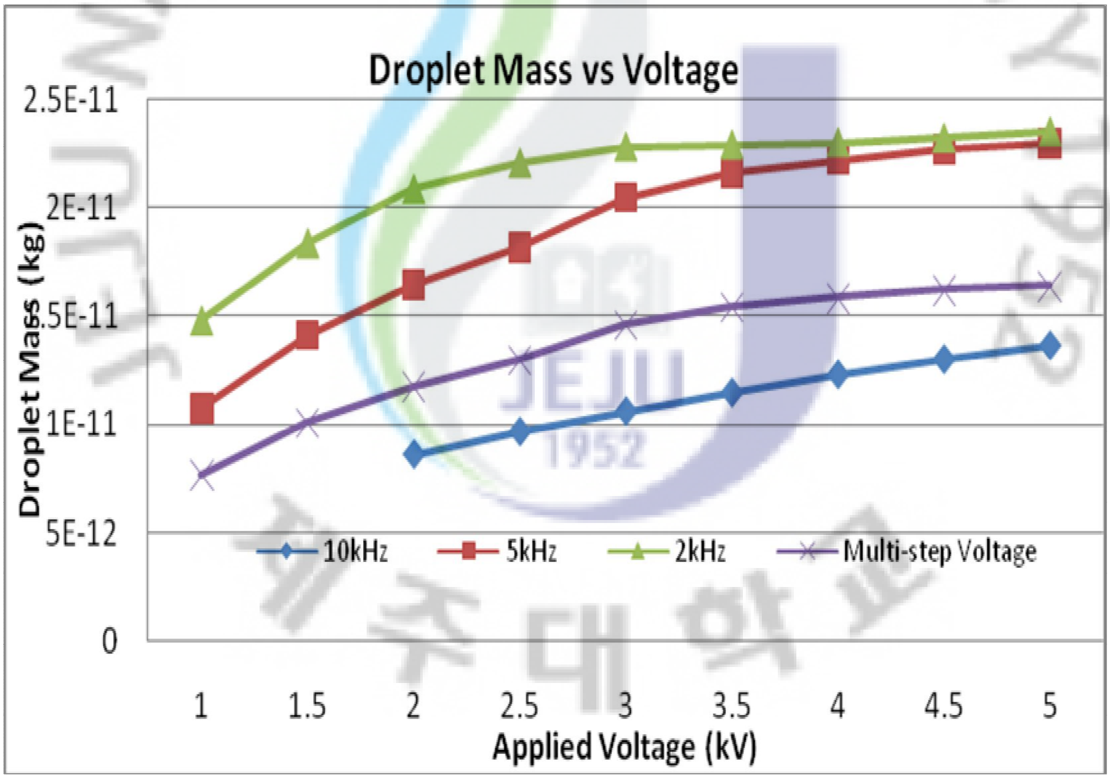
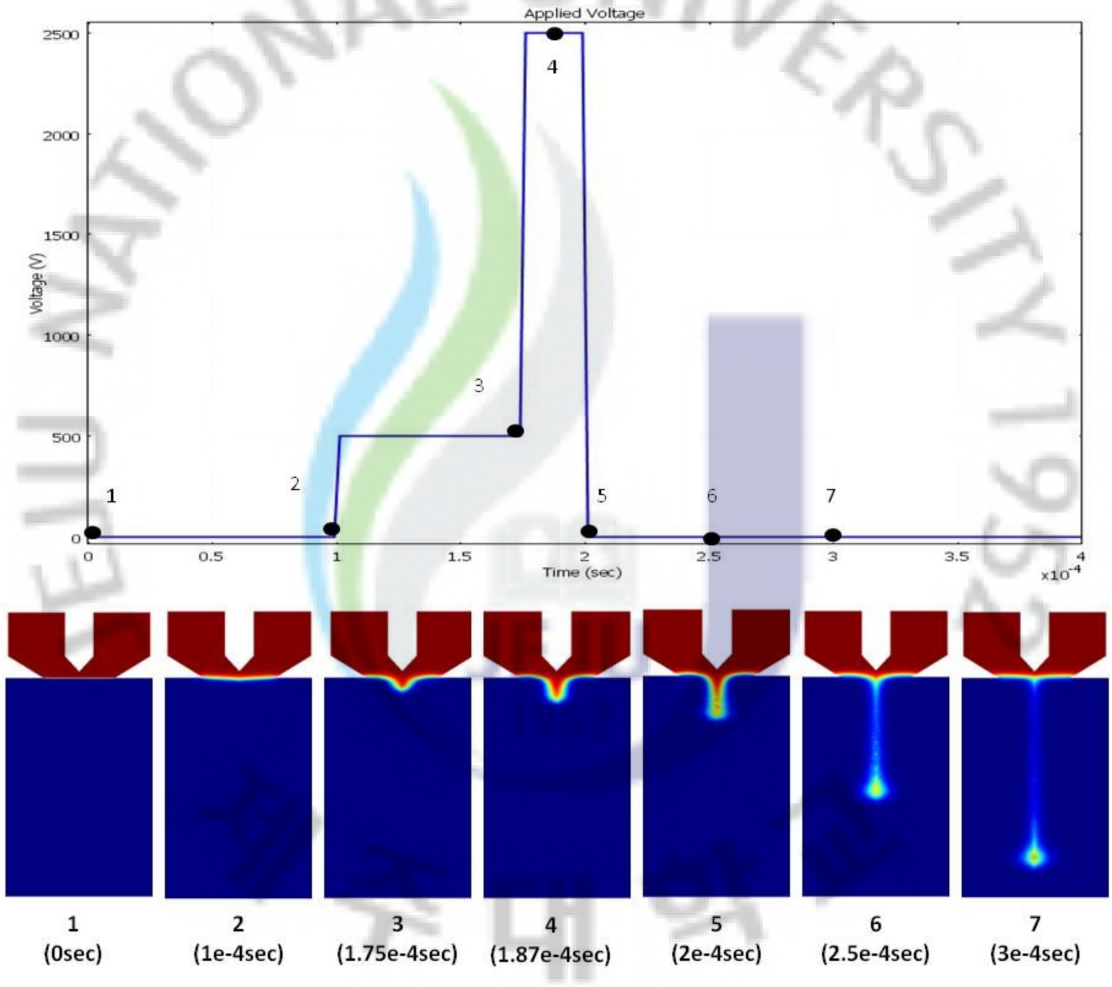
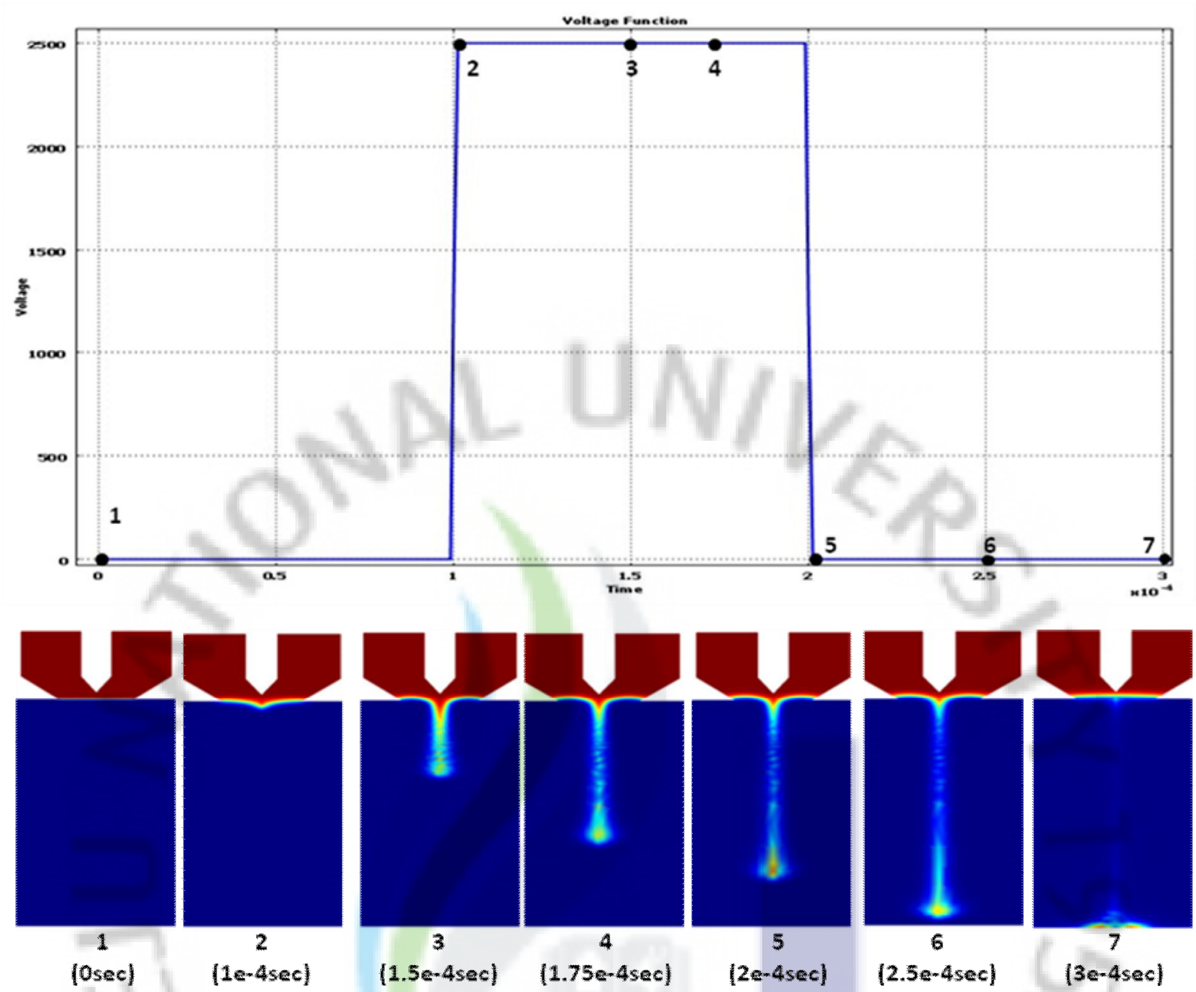


Figure 3.6. Droplet mass against applied voltage functions

In case of multi-step function the width of the pulse is same as of 5 kHz pulse width but the magnitude of the voltage is being increased in a step, by doing this the initial energy of the multi-step is used to excite the ink where as the small ejecting pulse is applied to extract the droplet. With the help of multi-step voltage the droplet size has been decreased in the simulation and this also help in designing the better Drop-on-Demand Electrostatic inkjet system. The comparison between simple voltage function and multi-step voltage function is shown in Figure 3.7.



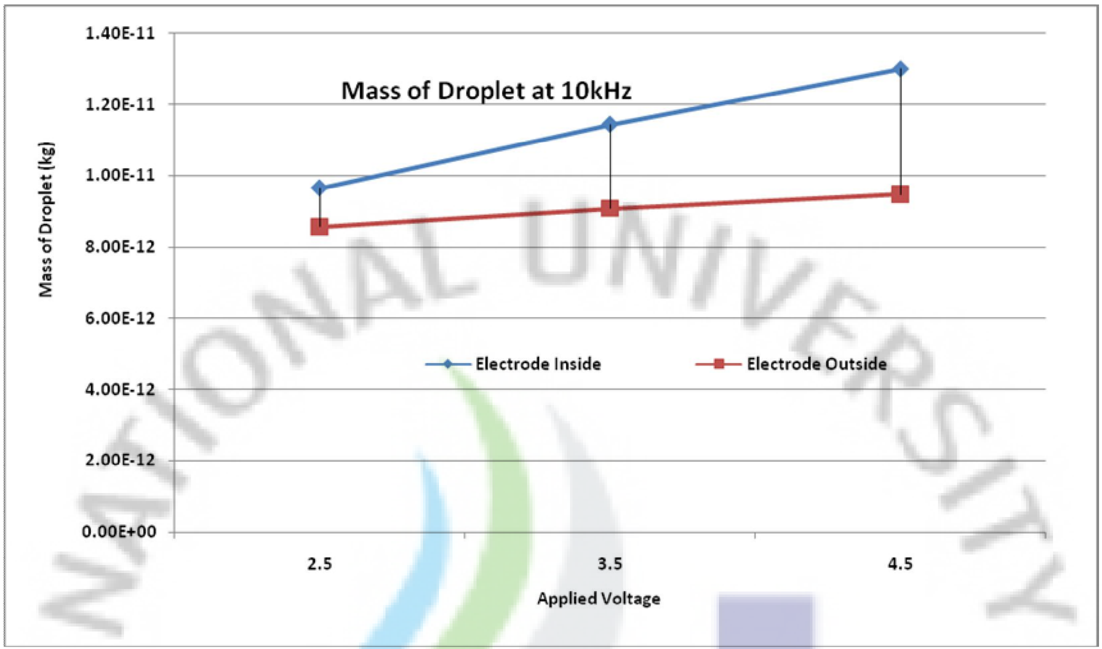
(a)



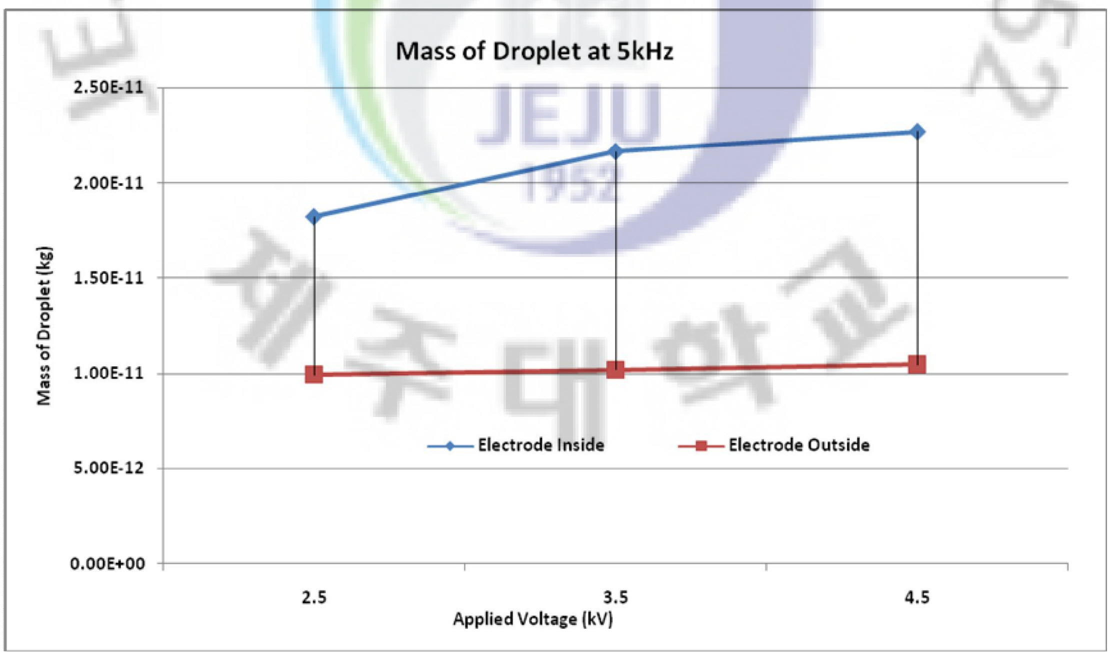
(b)

Figure 3.7. Comparison of different steps of droplet generation (a) Droplet generation phases in multi-step voltage function and applied max voltage is 2.5 kV (b) Droplet generation phases in 5kHz voltage function and applied max voltage is 2.5 kV

The important factor for generation of the small droplet is the position of the electrode. Numerical simulation was performed by moving the electrode 15μm outside of the nozzle tip. The droplet size was calculated and comparison with the simulation results as shown figure 3.6. was made. As the position of the electrode is placed outside of the nozzle tip the droplet size is decreased. The comparison graphs of the droplet size with respect to the applied voltage width are shown in figure 3.8.



(a)



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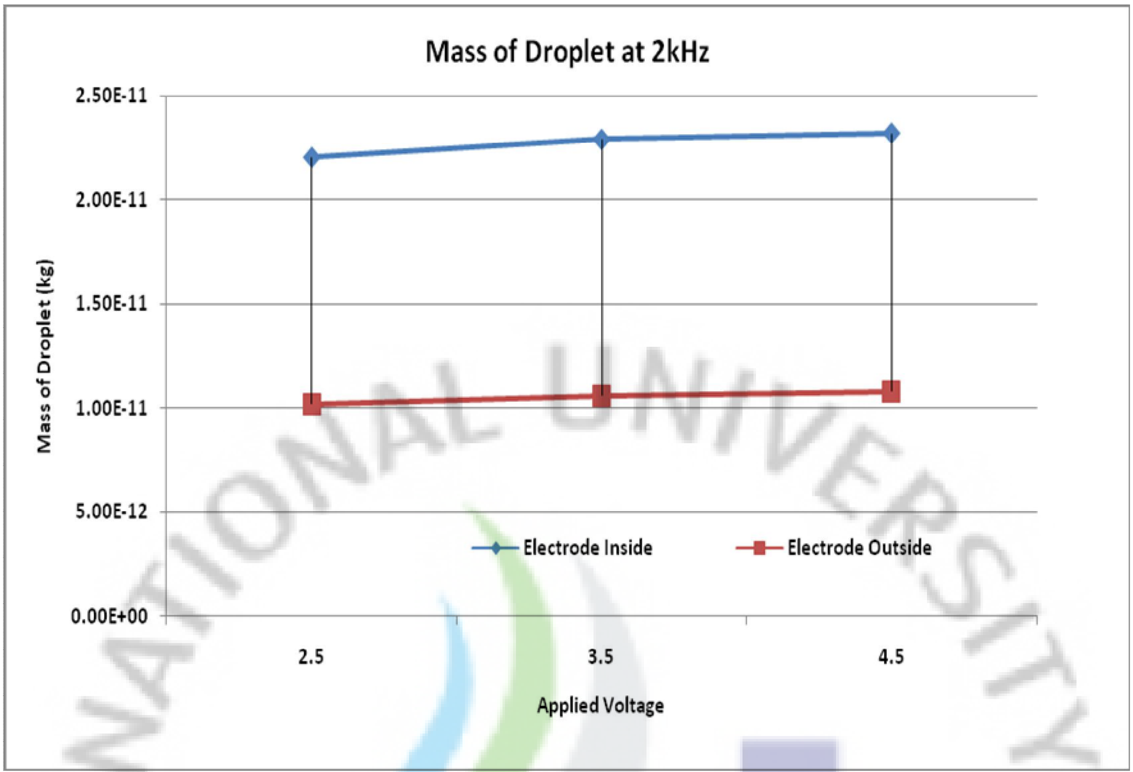

(c)

Figure 3.8.Comaprison of droplet mass on applied voltage between electrode inside and outside of nozzle (a)10 kHz (b)5 kHz (c)2 kHz

By changing the voltage step function the droplet size also varies due to time of the applied voltage the droplet generated mass increases with increase in time of applied voltage.

By comparing the results the multi-step voltage function provide better results (small droplet mass) as compared to the 5kHz voltage function. The results also show the timing of the drop generation which also helps in determining the accuracy of the droplet placement on the substrate.

The droplet size generated by putting the electrode outside the nozzle is smaller in size as compared to the electrode inside the nozzle.

3.3 Electric Field on Different Types of Nozzles

For the development of 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 figure 3.9. 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.

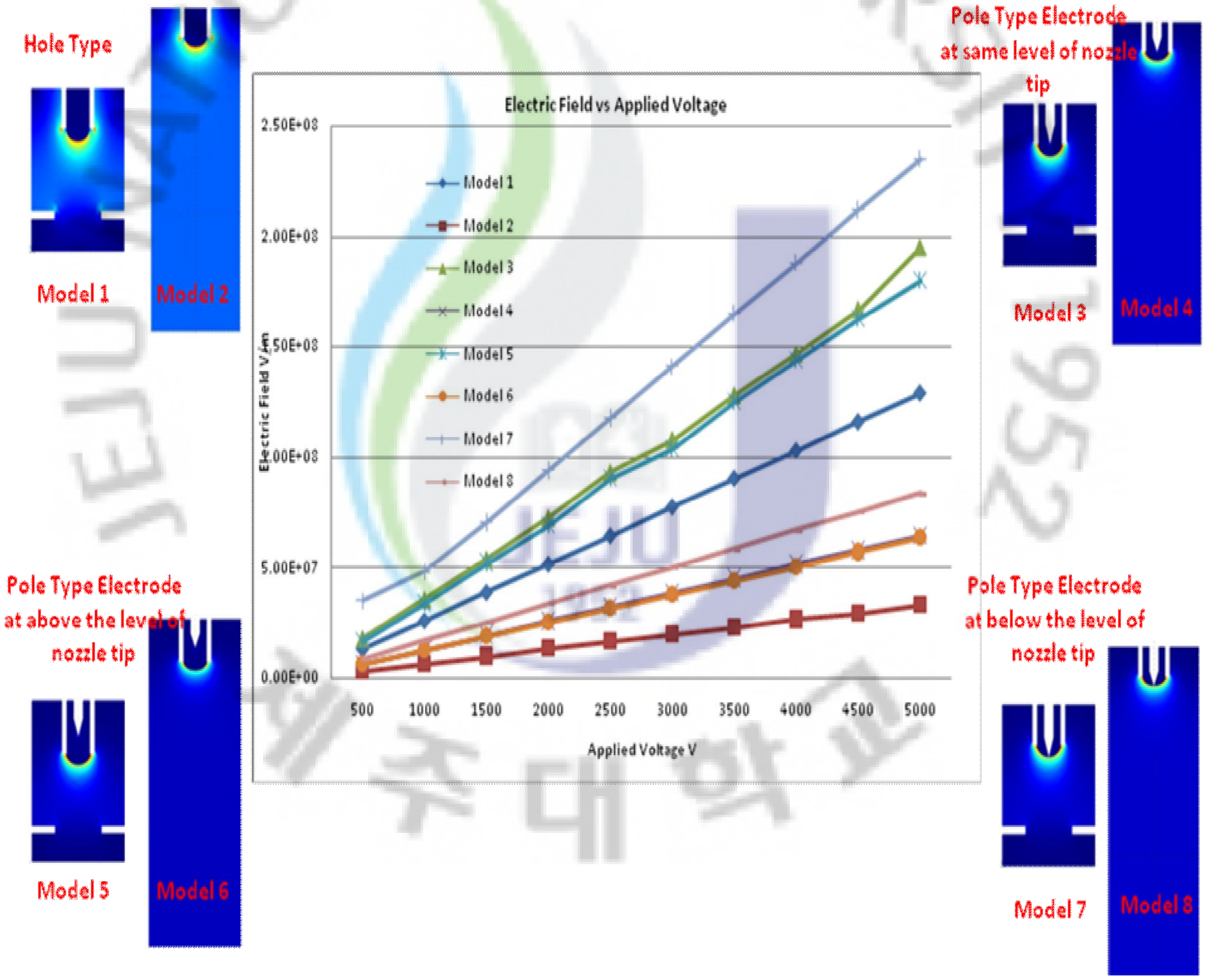

Figure 3.9. Electric field simulation on different types of nozzles configuration

Electric field simulation on different configuration, shows that the value of electric field as greater in model 7 (where electrode is outside the nozzle) as compared to other models. This shows that for better design of the electrostatic inkjet nozzle the electrode should be either at the tip or slightly outside of the nozzle. For same value of applied voltage the integrated type nozzle is greater then the non-integrated type.

3.4 Multi-Nozzle Cross Talk

In multi-nozzle initially electrostatic simulation is performed by changing the nozzle to nozzle distance. The electric field is calculated at the different nozzles as mentioned in figure 2.8 by keeping the distance between nozzle to nozzle 110µm. The figure 3.10 shows the graph of electric field at the tip of each nozzle by applied voltage at the middle nozzle. The figure 3.11 shows the graph of electric field at the tip of each nozzle by applied voltage at the middle nozzle by keeping the nozzle to nozzle distance 200µm.

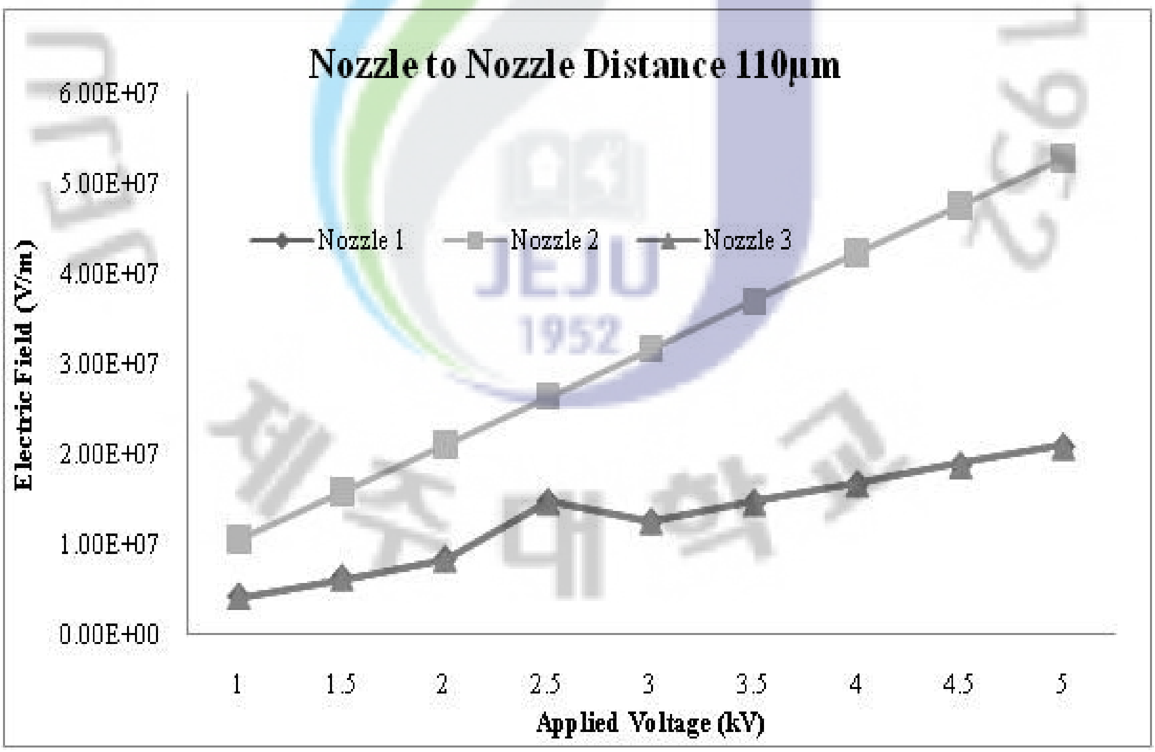

Figure 3.10. Electric Field (nozzle gap 110µm)

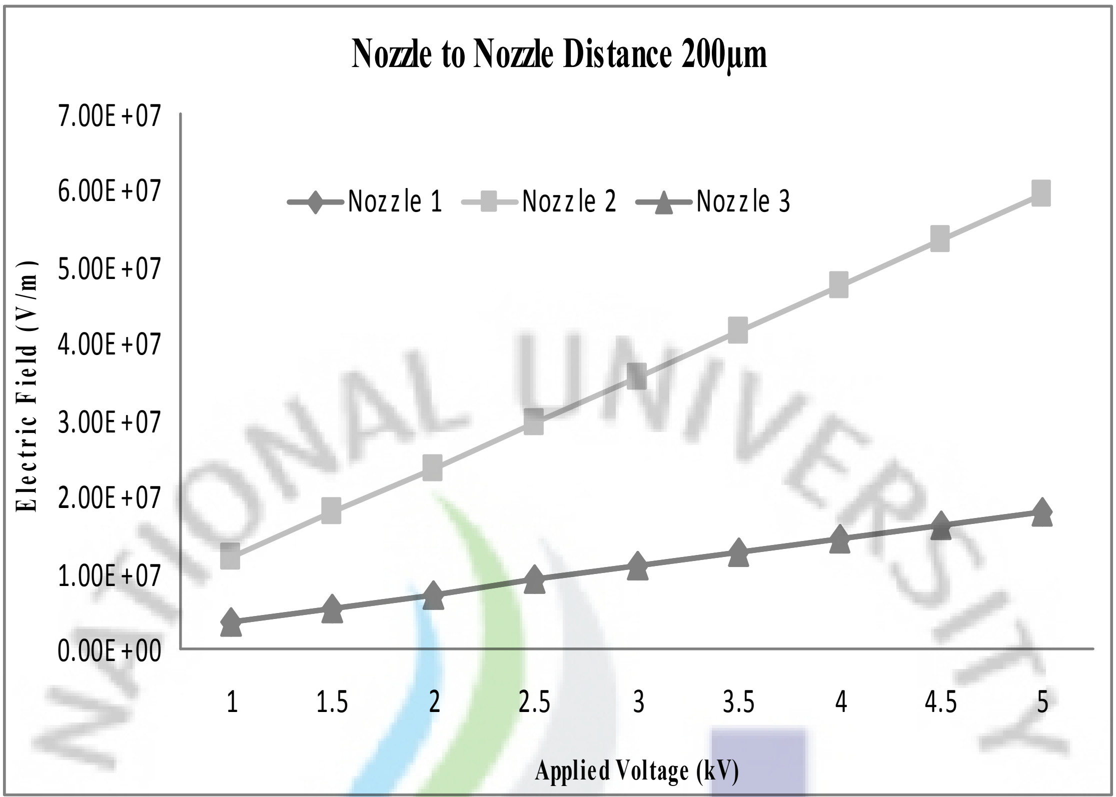

Figure 3.11. Electric Field (nozzle gap 200µm)

As shown in the above figure the data of the nozzle 1 and nozzle 3 is overlapped due to same amount of the electric field as the distance between nozzle to nozzle is equal.

In order to reduce the electric interface the offset voltage of 500V as shown in figure 3.12 is applied for the geometry where nozzle to nozzle distance is 110µm. The graph of electric field with respect to applied voltage is shown in figure 3.12 the graph is taken when the step voltage is applied to nozzle 2. Figure 3.13 shows the contour of the electric field by applying 500 V offset voltage and peak voltage is applied at the nozzle 2.

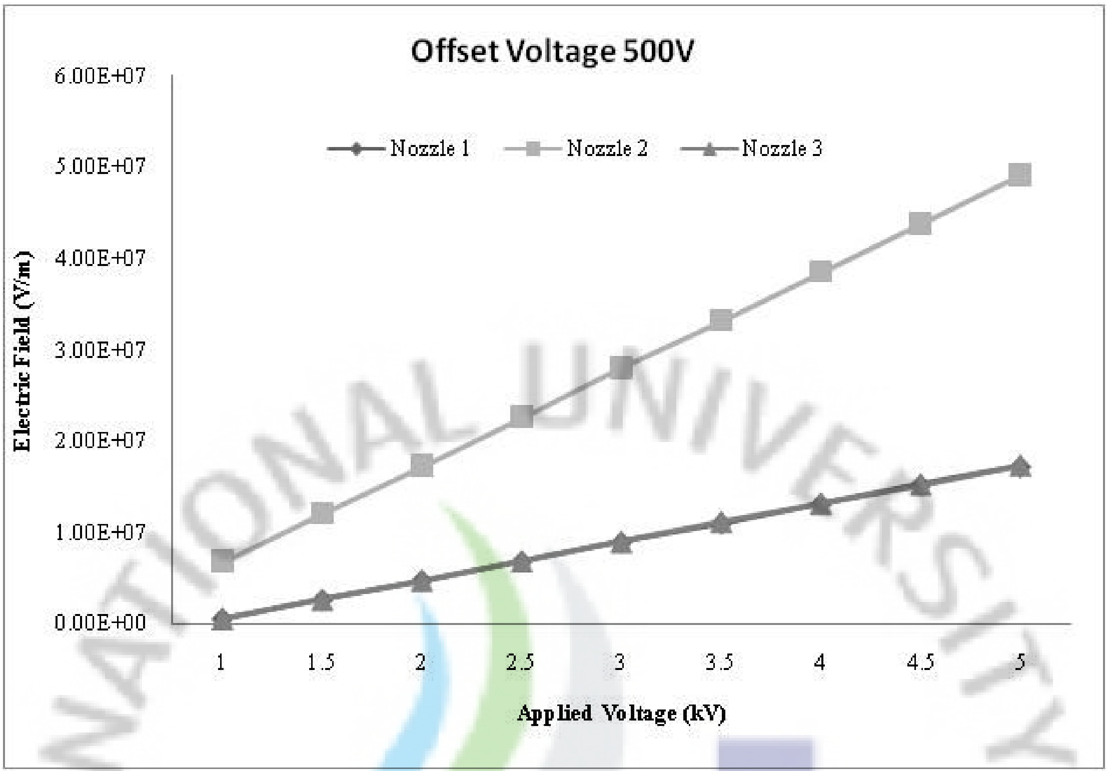

Figure 3.12. Electric Field for offset voltage (nozzle gap110μm)

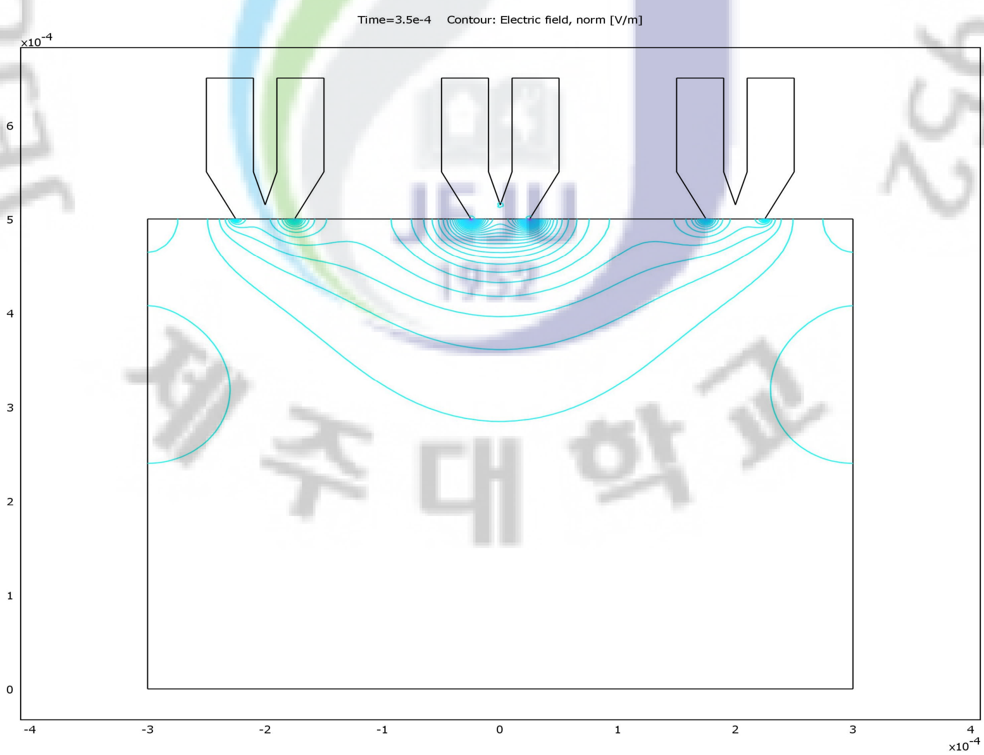

Figure 3.13. Electric Field contour with 500 V offset and peak voltage is applied at nozzle 2

The figure 3.14 shows the value of electric filed with respect to time by applying voltage at the nozzle 2 and with offset voltage of 500 V on nozzle 1 and 3. These values are taken at the center of the each nozzle's tip.

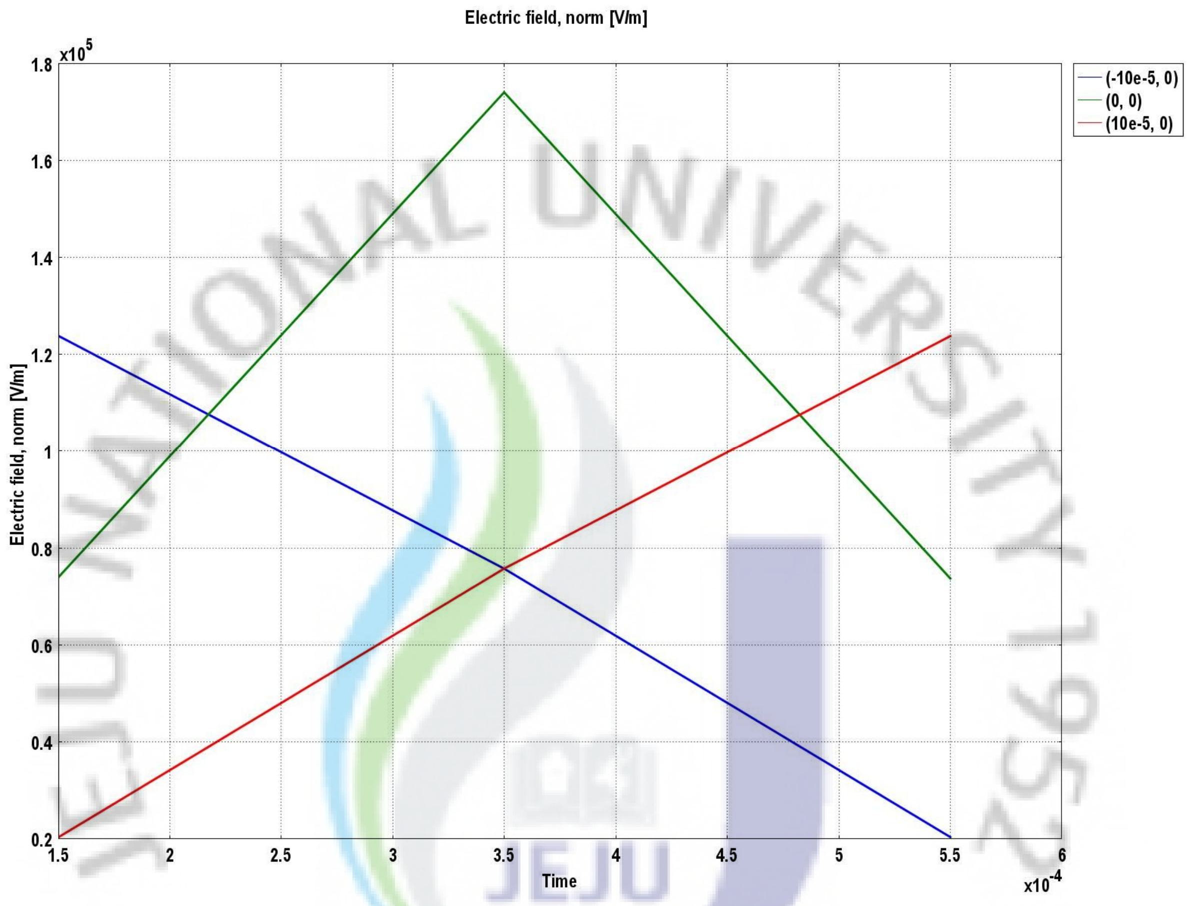

Figure 3.14. Electric field with respect to time when voltage applied on Nozzle 2

By looking at the graph it shows that by increasing the distance between nozzle to nozzle the electric interfering reducing, but it will limit the number of nozzle in array and also affect the printing density. In order to overcome this problem, other solution is to apply the offset voltage. The value of the offset voltage has to keep at the level where no ejection of the droplet took place. By applying the offset voltage the electric field will repel at the nozzle where voltage peak is not applied and also can reduce the nozzle to nozzle distance for high printing density.

4. SUMMARY

Electrostatic inkjet system has a huge application area in the field of printed electronics and also the image printing. The main advantage of Electrostatic inkjet system over thermal and piezo type inkjet, there is no moving parts to drive the droplet and also the issue of the nozzle density can be overcome through electrostatic inkjet system. In recent years lot of research is being conducted in this field to develop a novel electrostatic inkjet printing system. For design and development of electrostatic inkjet head it is necessary to understand the droplet generation behavior through electrostatic forces.

Droplet generation through electrostatic forces is a multiphysics phenomenon, in which the droplet is generated by overcoming the surface tension forces through electrostatic forces. In this thesis numerical simulation is presented to investigate the droplet generation and also the effect of different parameters. Moreover, for multi-nozzle system, electrostatic simulations are performed and reported in this thesis.

5.1 Conclusions

In this thesis droplet generating phenomena is simulated and also studied the behavior of the droplet by varying the voltage and diameter of the capillary. The result shows that droplet size depends on the applied voltage and also the diameter of the nozzle. By increasing the voltage, droplet size is slightly increased and for the same voltage by increasing the nozzle the droplet size is increased.

In case of pole type nozzle, on different applied frequencies of voltage step-function the droplet mass changes, due to the times of the applied voltage. The multi-step function also used to develop the droplet, which will also help in study of accuracy of the droplet placement on substrate. The effect of position of electrode for droplet generation is also studied. By comparing the result of the droplet generation mass, the mass of the droplet generated by electrode outside the nozzle is smaller than the droplet generated by electrode inside of the nozzle. Ion order to produced small size required droplet the electrode should be either outside of the nozzle or at the level of the tip. The droplet generation and the distance of the electrode out of the nozzle have to investigate further.

Electric field simulation of different configuration of nozzles also presents that for generation of the droplet by applying less voltage, integrated type nozzles are better option as compared to non-integrated type. Due to reduce in gap between the electrode and ground in integrated type nozzle, which results in high electric field at the same applied voltage as compared to non-integrated one.

In case of the multi-nozzle the electric interfacing can be reduced by increasing the gap between nozzles to nozzle. By applying the offset voltage it is observed that the electric interface in decreased due to repulsive force, but this offset voltage should be of lower value in order to avoid unnecessary droplet.

For designing the electrostatic inkjet multi-nozzle system at relative low voltage following has to be considered:

- Pole type nozzle performs better then the hole type nozzle
- The multi-step function for applied voltage is better option for generation of droplet, because it will generate stable meniscus and also provide the better accuracy of the droplet placement on substrate.
- For droplet generation at low voltage, integrated nozzle approach is better then the non-integrated conventional approach. Due to less distance between the electrode and ground, it will required less voltage.
- In Design of the multi-nozzle main issue is cross-talk between two nozzles. This issue can be address by increasing the gap between nozzles to nozzle, but this will affect the amount of nozzle on print-head. To overcome this problem, an

offset voltage is suggested, by applying offset voltage it will reduce the effect of one nozzle to another. The other suggestion is to introduce special insulation coating between nozzles to nozzle to decrease the nozzle to nozzle distance.

4.2 Future Work

A numerical simulation is proposed in this thesis for electrostatic droplet generation phenomena. Given below are possible future work, extensions and applications:

- Comparison between simulated results and experimental data
- Further investigation of the different shapes of the nozzles
- Number of simulation should also performed by using VOF software and the results must be compared with Level Set Method simulation
- Droplet generation simulation through multi-nozzle model and comparison of the simulated result with the experimental data.

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