Simulation study of droplet formation in inkjet printing using ANSYS FLUENT

Neha Thakur¹ and Hari Murthy¹
¹Department of Electronics and Communication Engineering, CHRIST (Deemed to be University), Kumbalgodu, Bengaluru - 560074, Karnataka, India

Corresponding Author: neha.thakur@res.christuniversity.in

Abstract

Flow simulations of jetting of inkjet drops are presented for water and ethylene glycol. In the inkjet printing process, droplet jetting behaviour is the deciding parameter for print quality. The multiphase volume of fluid (VOF) method is used because the interaction between two phases (air and liquid) is involved in the drop formation process. The commercial inkjet printer has a nozzle diameter of ~73.2μm. In this work, a simulation model of inkjet printer nozzles with different diameters 40μm, 60μm, and 80μm are developed using ANSYS FLUENT software. It is observed that when water is taken as solvent then the stable droplets are generated at 60μm nozzle diameter till 9μs because of its low viscosity. For higher diameter, the stamen formation is observed. Ethylene glycol stable droplets are achieved at 80μm nozzle diameter till 9μs because of their high viscosity (~10 times that of water). Along with the droplet formation, the sustainability of the droplet in the air before reaching the substrate is also important. The simulation model is an inexpensive, fast, and flexible alternative to study the ink characteristics of the real-world system without wasting resources.

Keywords: Drop formation, Inkjet Printing, Computational Fluid Dynamics, Ink formulation.

Introduction

1. Inkjet printing

Inkjet printing (IJP) is an additive manufacturing technique widely used for material deposition onto a flexible substrate. Unlike other deposition techniques, IJP is a maskless technique requiring minimum resources, making it more cost-effective and easier to use. The essential requirement of IJP is the successful ejection of droplets from the nozzle, which can take place in two ways: Continuous Inkjet (CIJ) and Drop-on-demand (DOD) [1]. Ink properties have to be properly optimized to eliminate Coffee Ring Effect (CRE), and nozzle clogging due to particle agglomeration. To avoid nozzle clogging, particle size should be 1/10th the nozzle diameter [2]. The most important step for inkjet printing is to formulate the ink that is jettable in nature.

The IJP process can be broadly classified into two stages.
(i) Droplet formation
(ii) Interaction of the droplet with the substrate

The stages (A to F) involved in the droplet formation are shown in Figure 1 [3]. In the initial condition, when no pressure pulse is applied then the nozzle is in equilibrium. When the
A pressure pulse is applied through the actuator then the transfer of kinetic energy takes place. A thin liquid filament is observed behind the droplet. At last, the droplet will escape from the attached liquid filament because of surface tension. All the stages are observed from Table 3 to Table 5 in section 3.

Figure 1: Stages of droplet generation

Droplet formation in IJP is driven by fluid properties, nozzle size, and driving waveform [4].

(i) Fluid properties: The jettability of the ink is decided by its rheological properties like viscosity (µ), surface tension (σ), and ohnesorge number (Oh). For the ideal (or jettable) ink the viscosity should be in the range of 2 to 20mPa.s, surface tension from 30 to 60mN/m, and ohnesorge number from 0 to 0.1. The combination of these three properties leads to an important dimensionless quantity that is used to determine the exact behaviour of the jetted droplet [4].

Reynolds’s Number (Re): It decides the shape of the droplet.

\[
Re = \frac{\rho vd}{\mu} \tag{1}
\]

Weber number (We): It is responsible for the type of jet breakup.

\[
We = \frac{\rho dv^2}{\sigma} \tag{2}
\]

where, \( \rho \): density, \( \sigma \): surface tension, \( \mu \): viscosity, \( v \): velocity, \( d \): nozzle diameter

\( Z \) Number (Z): It is responsible for the jettability of the ink or fluid used as given in Table 1 [5]. For the jettable ink, the \( Z \) number and ohnesorge number value should be 1 to 10, and 0.1 to 1 respectively.
Table 1: Effect of Z number on ink jettability

| Z (Oh^{-1}) | Effect on jettability       |
|-------------|-----------------------------|
| ~1          | Not jettable                |
| 1-10        | Jettable                    |
| 10<Z<14     | Satellite droplet formation |

(ii) Nozzle Size: Nozzle size decides the size of the generated droplet, which influences the quality of the printed structure. For effective printing, the particle size should be less than 1/10th the size of the nozzle diameter. The nozzle diameters considered are 40μm, 60μm, and 80μm.

(iii) Driving waveform: The waveform of the control signal plays a vital role in drop generation. If the control pulse is high, it indicates the drop will be ejected from the nozzle, else the droplet will remain inside the nozzle. In the simulation process, it can be given by choosing the suitable boundary condition like velocity-inlet, pressure-inlet, etc.

For a good quality printed product, the jettability of the ink is the primary requirement. Once the ink becomes jettable, it is observed how long the droplet can remain in the air without further breakup [6]. To observe the jettability of the ink ANSYS FLUENT is used to implement the multiphase volume of fluid (VOF) model of the inkjet’s nozzle with diameters 40μm, 60μm, and 80μm. These diameters are used because usually, the nozzle diameter of commercially available inkjet printers is 73.2μm, and it is seen that the best results are obtained at 60μm for low viscosity solvent (water), and at 80μm for high viscosity solvent (ethylene glycol) [7]. In this paper, the study and simulation of the droplet formation process are divided into 4 sections- 1. Introduction, 2. Materials and methods, 3. Results and discussion, 4. Conclusion.

2. Materials and Methods

Water and ethylene glycol (EG) is taken as sample solvents for ink because their viscosities are almost the same as the minimum and maximum viscosity value of the jettable ink (2 to 20mPa.s). The rheological properties used for simulation are mentioned in Table 2.

Table 2: Rheological properties of the materials used

| Property            | Air          | Water | Ethylene Glycol (EG) |
|---------------------|--------------|-------|----------------------|
| Viscosity (Pa.s)    | 1.793x 10^{-5} | 0.002 | 0.0157               |
| Surface Tension (N/m)| 0.07         | 0.07  |                      |
Density (kg/m$^3$) | 1.225 | 999.8 | 1111.4

The computational fluid dynamics (CFD) model implementation using ANSYS FLUENT requires the following steps as shown in Figure 2 [8].

**Figure 2: Flowchart of CFD modelling process using ANSYS FLUENT**

The following assumptions are made to simplify the process:

1. The fluid and surrounding air are incompressible.
2. Heat transfer will be neglected, and the ink will be assumed to have constant properties throughout the problem. No liquid evaporation takes place.
3. Laminar flow
4. Axisymmetric geometry is used.
5. The liquid properties are constant with time.

The nozzle diameter (d) considered are 40μm, 60μm, and 80μm. An area of air chamber of 10000μm x 800μm is created outside the nozzle to follow the formation of the drop in the surrounding air. A mesh is generated having 69602 cells. Multiphase Volume of Fluid (VOF) with viscous laminar flow is considered because two phases (liquid and gas) are present. The VOF uses the principle of conservation of volume fraction. The VOF method requires only one storage word for each mesh cell, which is consistent with the storage requirements for all other dependent variables [9]. The 2D, transient simulation with a pressure-based solver is used while considering the effects of gravity as well. The boundary conditions for inlet and outlet are taken as velocity-inlet and pressure-outlet respectively. The velocity of 5m/s is provided to the inlet. As the problem is time-dependent, a time step of 0.01μs is considered for running the simulation.

3. Result and Discussion

Upon the application of a pressure-inlet of 1Pa to the nozzle, the fluid starts flowing out of the nozzle. In this section, the influence of nozzle diameter (40μm, 60μm, 80μm) on the droplet ejection process is discussed keeping in mind the ohnesorge number range (0.1 to 1). The output is observed at 3μs, 6μs, and 9μs.

Table 3 shows the simulation results of both solvents (water and EG) for 40μm nozzle diameter. At 0μs two phases (liquid and gas) are represented by red color used for the solvent-filled nozzle and blue color for the air-filled chamber. The nozzle is in an equilibrium state.
state as no pressure-inlet is applied to it. When the pressure-inlet of 1Pa is applied at 3μs, both solvents have created a droplet. At 6μs the water droplet starts breaking up and by 9μs, complete drop bag breakup occurs. No droplet survives after 6μs, which indicates that a 40μm diameter nozzle is too small for ejecting even low viscosity solvents.

Table 3: Simulation results of solvents at 40μm nozzle diameter

| d   | Time | Water (Oh=0.142) | EG (Oh = 0.94) |
|-----|------|-------------------|----------------|
| 40μm| 0μs  | ![Image](image1)   | ![Image](image2) |
|     | 3μs  | ![Image](image3)   | ![Image](image4) |
|     | 6μs  | ![Image](image5)   | ![Image](image6) |
|     | 9μs  | ![Image](image7)   | ![Image](image8) |

For the 60μm nozzle, it is observed that due to the higher viscosity of ethylene glycol the solvent flow from the nozzle is less as compared to water upto 3μs. At 6μs, the droplets are successfully detached from the tail for both the solvents. At 9μs it can be seen that the water droplet is still in the air chamber whereas the ethylene glycol droplet starts getting stamen formation as shown in Table 4.

Table 4: Simulation results of solvents at 60μm nozzle diameter

| d   | Time | Water (Oh= 0.116) | EG (Oh = 1.151) |
|-----|------|-------------------|----------------|
| 60μm| 0μs  | ![Image](image9)   | ![Image](image10) |
|     | 3μs  | ![Image](image11)   | ![Image](image12) |
|     | 6μs  | ![Image](image13)   | ![Image](image14) |
|     | 9μs  | ![Image](image15)   | ![Image](image16) |
From Table 5, the results for 80μm nozzle diameter can be analyzed. At 3μs, the water droplet is detached from the other droplets but at the same time, the EG droplet is followed by a small ligament of fluid. At 6μs, the water droplet gets distorted from its spherical shape, whereas the EG droplet retains its shape. At 9μs, the water droplet gets stamen formation but the EG droplet has maintained its consistency.

Table 5: Simulation results of solvents at 80μm nozzle diameter

| d   | Time | Water (Oh =0.101) | EG (Oh= 1.329) |
|-----|------|-------------------|-----------------|
| 80μm| 0μs  | ![Water_0μs](image) | ![EG_0μs](image) |
|     | 3μs  | ![Water_3μs](image) | ![EG_3μs](image) |
|     | 6μs  | ![Water_6μs](image) | ![EG_6μs](image) |
|     | 9μs  | ![Water_9μs](image) | ![EG_9μs](image) |

For the low viscosity fluids, the nozzle diameter of the range 60μm will give the desired results and for highly viscous fluids the diameter should be ~80μm. The objective of inkjet printers is not only to generate droplets, but the flight time of the droplet from the nozzle outlet to the substrate is also important. Moreover, the sustainability of the droplet is also a major concern. If the droplet is formed but is unable to reach the substrate properly then it may result in satellite drop formation or splash formation.

4. Conclusion

The process for droplet generation from the inkjet printer’s nozzle is observed. This work is the preliminary research work, for a better understanding of the droplet generation process in inkjet printing by using water and ethylene glycol as sample ink solvents. The simulation models using ANSYS FLUENT are created for three different nozzle diameters 40μm, 60μm, and 80μm. The droplets generated by water at 60μm nozzle and by ethylene glycol at 80μm nozzle sustains till 9μs. Using the simulation model before the actual printing process will be beneficial as it involves no actual material usage. The future work would be based on selecting different solvents, such as toluene, hexane and checking for their stability. The addition of precursors to the solvent is also part of the proposed work.

Funding Information

The authors confirm that no funding was obtained to carry out the research work.
Conflict of Interest

The authors confirm that there is no conflict of interest.

Contribution of authors

Ms. Neha Thakur was involved in carrying out the research work, collecting data, analyzing the results, and writing the draft.
Dr. Hari Murthy was responsible for supervising, proofreading, and providing technical inputs.

References

[1] H. S. D, Fundamentals of Inkjet Printing: The Science of Inkjet and Droplets. NJ, USA: John Wiley & Sons, 2016.
[2] S. Khan, S. Ali, and A. Bermak, “Smart Manufacturing Technologies for Printed Electronics,” Hybrid Nanometer-Flexible Electronics Material, pp. 1–22, 2020, Doi: 10.5772/intechopen.89377.
[3] P. Wang, “Numerical Analysis of Droplet Formation and Transport of a Highly Viscous Liquid,” 2014.
[4] Rajesh PK and Aravindraj S, A Numerical Simulation and Validation Study of the Mathematical Model of Droplet Formation in Drop on Demand Inkjet Printer and the Effect of Rheological Properties of Polymerink,” International Journal Mechanical Engineering Technology, vol. 10, no. 3, pp. 1326–1338, 2019.
[5] S. Sharma, S. S. Pande, and P. Swaminathan, “Top-down synthesis of zinc oxide-based inks for inkjet printing,” RSC Advances, 2017, Doi: 10.1039/c7ra07150g.
[6] J. Wang, J. Huang, J. Zhang, and W. E. T. Al, “A Method for Calculating the Critical Velocity of Microdroplets Produced by Circular Nozzles,” Vol. 00, no. 00, pp. 1–9, 2020, Doi: 10.1089/3dp.2019.0111.
[7] H. C. Wu, H. J. Lin, Y. C. Kuo, and W. S. Hwang, “Simulation of droplet ejection for a piezoelectric inkjet printing device,” Material Trans., 2004, Doi: 10.2320/matertrans.45.893.
[8] A. D. Canonsburg, “ANSYS Fluent Tutorial Guide,” January 2017.
[9] K. F. Teng and R. W. Vest, “Mathematical models of inkjet printing in thick-film hybrid microelectronics,” Applied Mathematical Model, 1988, Doi: 10.1016/0307-904X(88)90010-8.