Simulation Experiments to Model the Inkjet Printing Behavior of Functional Inks

Adarsh Anand, Paul D. Fleming III and Margaret K. Joyce; Department of Chemical and Paper Engineering, Western Michigan University; Kalamazoo, MI/USA

Abstract

Flow simulations of jetting of ink jet drops are presented. The Z number of Fromm is used to characterize jettability. Simulation results are comparable to jetting behavior observed by the drop watcher on a Dimatix 2800 Materials Printer.

Introduction

With the advent of the inkjet printing process, versatility to the printing industry came about. The inkjet printing technology has allowed for more complex designs to be changed and printed and nowadays, at increasingly high speeds and greater resolutions than previously conceived [1]. More and more conventional printing methods are being found to be useful in other industries like food product manufacturing and printed electronics. From the conception of DOD (Drop on Demand) for inkjet printing, ink costs are brought down as it only jets ink when and where needed. This is important from an economic and technical standpoint when printing printed electronics, as the inks used in printing conductive circuits are expensive and waste must be reduced as much as possible [2].

The objective of this paper is to study the drop formation, and properties of functional ink jet inks through the use of CFD simulation software and cataloging and using only Z-number to describe future jetting models for other liquids and inks. This work draws reference from previous works done by Wolfgang Ohnesorge, on the properties of a jetting stream and it's breaking into droplets [3]. Ohnesorge was able to create a relationship between the internal inertia in a fluid over the fluid flow properties between two different fluids leading to creating the Ohnesorge number. The relation between the Ohnesorge number and jetting will be explored in detail and derived to better understand their relation to drop formation and their use a measure of printability. The Z number, will then be derived from the Ohnesorge number, and be used in the model [4].

The Z-number was introduced by Fromm and takes a similar approach to the Ohnesorge number [5]. The Z-number uses a range from one to fourteen to describe effective drop formation. At Z-number greater than ten, satellite drops may be formed. A simulation of the jetting process of different liquids and inks will be studied and their representative Z-numbers will be cataloged. Important characteristics of a jet that are looked for are the drop size, drop volume, drop shape and drop spacing [6]. These properties can and should be portrayed virtually, and with accuracy through a simulation to better understand the jetting of a previously unused ink by using its Z-number alone. The model, while being inspired by a previous model, however it has been and will be built completely from the ground up and be different from the previous model. This is taken as an initiative by the researchers to become more intimate with the fluid dynamic properties of the model and will allow for easier changes to be made due to familiarity with its working.

Simulation results will be compared to experimental results obtained from real time tests performed on a Dimatix 2800 series printer. The Dimatix Materials Printer is a piezo electric printer, which is versatile and has an easy-to-use interface. It has a DOD printing head and this allows for controlling the drop volume which determines the size and amount of ink jetted out. This allows for more accurate results and corrections that can be used on the simulation to further enhance it [7].

Inkjet printing is a commonly used non-impact printing process, NIP, in digital printing. The inkjet process is a computer-to-print technology in which ink is sprayed via a nozzle straight to the substrate, which takes away the need for an image carrier. The data of the digital print job image is directly transferred to the inkjet system. The functional units, the imaging system, the image carrier and inking unit are all combined in one module. This means that inkjet printing has the shortest route from image to substrate and this drives the demand and need for further enhancements in this technology.

Inkjet technologies can be divided into two main processing types, *Continuous Inkjet* and *Drop on Demand Inkjet* [8]. With drop on demand inkjet, the ink drops are generated only if the image requires them to be created. Drop on demand inkjet can be further subdivided into three categories depending on how the drop of ink is created. These are the *thermal inkjet process*, *piezo inkjet process*, and *electrostatic inkjet process*. With *thermal*, a portion of the ink is heated up to the point it vaporizes, which leads to the creation of a vapor bubble [8]. This bubble then exerts the necessary pressure on the remaining ink to squeeze out the required drop size of ink. This process is also referred to as *"bubble jet"*. In *piezo inkjet* systems, the piezoelectric ceramics change the volume of the ink chamber when electricity is applied to them [6]. This generates a pressure in the chamber forcing the ink drop to come out of the nozzle. For *electrostatic inkjet systems*, by means of an image-dependent switching element, the ink drop is released when needed and to where it needs to be placed [8].

Results and Discussions

One of the biggest applications that are a driving force for this project is the field of printed electronics. Printed electronics are a set of printing methods used to make electrical devices on different surfaces. Printing uses common printing equipment or other low-cost printing methods that suit the purpose and design of the material. The different methods used are gravure printing, flexographic printing, lithography/offset printing, ink jet printing and screen-printing. The benefits of printed electronics are that they are simpler to manufacture on both low and high volume products. Printed electronics also give the advantage of printing over large areas and flexible surfaces, as in the case for solar panels [9]. They enable roll-to-roll fabrication and the processes employed to manufacture printed electronics are also more flexible, as is the case with inkjet printing. Inkjet printing brings its own advantages to printed electronics in comparison to other printing methods. For one, the entire process is digital, enabling variable patterns to be readily printed. It is a non-contact process, so there is no worry for impurities or disturbances on the printed sheet from the printer itself. It also has low ink consumption, which is a very important benefit because the costs of the inks are very expensive and one of the disadvantages. Inkjet printing allows the designer of a circuit to add layers as they choose simultaneously. There is also the ease of transferring a prototype from the lab to the fabrication or manufacturing assembly [2].

Different inkjet printing methods were analyzed to understand their potential and drawbacks. The piezoelectric printing holds the most promise for the research into drop study formation. Unlike thermal bubble jet, piezoelectric does not require a heating medium, as it does not need to have the ink vaporized. It can be used for dispensing of polymers or metal inks, as it will not alter the chemical structure of the ink, as may be the case of polymers through heating [1]. It can be used for dispensing of polymers or metal inks, as it will not alter the chemical structure of the ink, as may be the case of polymers through heating. Figure 1 shows how a piezoelectric printing head works.

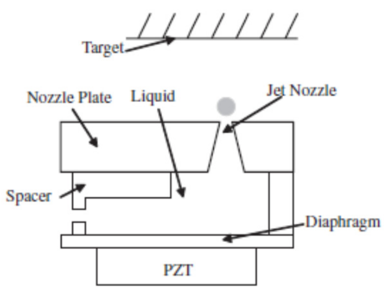

***Figure 1**. Piezoelectric diagram [11]*

The laboratory tool to be used in this study is a Dimatix 2800 piezoelectric printer, which will also be used to further study the different phenomena that occur during jetting. The Dimatix 2800 is a versatile, easy to use interface, printer that follows the principle of piezoelectric ink – jetting, where a set amount of electricity is sent through a piezoelectric crystal, which changes its shape with the current. This in turn pushes the ink out of the nozzle. An illustration is shown in Figure 2.

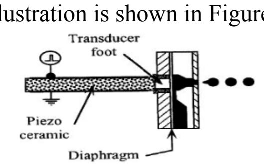

Figure 2. *Dimatix piezoelectric nozzle principle [7]*

The Dimatix printer inkjets via the manipulation of a waveform, through the GUI of the software provided, that dictates how much pressure the crystal will apply on the ink chamber of the printer head. This is very useful to someone studying the process of ink – jetting as it gives control of drop volume, which determines the size and amount of ink to be jetted out of the nozzle onto the substrate [7]. It also allows the user to control the speed by manipulating the waveform for the Dimatix printer. The drop formation and drop size are determined by the first two phases of the waveform where drop speed is determined by the third and fourth phase. To ensure continuous optimal performance, principles that allow for an ink to be jetted properly certain properties of the process must be analyzed with more scrutiny. The drop speed, drop volume, drop shape and jet straightness become vital in print quality performance [6]. The drop speed, at which a drop is jetted from the nozzle, helps reduce disturbances from the surroundings that could change the shape or trajectory of the drop. The drop volume changes or is changed on an application to application basis. The drop shape can negatively affect the print through the formation of tails or satellite drops.

Simulations provide a decent, inexpensive and more flexible alternative to studying these characteristics, as they provide quick feedback to the user from models based on imitating real world systems. This allows the user of such models to refine and test their virtual models and work out its kinks before running expensive real time tests. As the case with all simulations, they are based on previous real world tests and experiments. In the case of inkjet models, they are based on previous studies conducted to study jetting through a nozzle and the resulting analysis of the stream's properties that cause drop formation. Inkjet simulations can be divided into two categories, one being to study drop formation, and the other being to study the drop's impact on the surface of a substrate. The important physical properties that are involved in drop formation are the fluid's properties of viscosity, density, and surface tension. These properties will be the building blocks upon which the simulations will be built.

The Ohnesorge number is a dimensionless number created by Wolfgang Von Ohnesorge as a way to interconnect the four regimes of jetting and define their boundaries. In his thesis, "Application of a cinematographic high frequency apparatus with mechanical control of exposure for photographing the formation of drops and the breakup of liquid jets" [10], he studied the phenomenon of drop formation of water through a nozzle of set length and diameter [3]. Ohnesorge concluded the four regimes are 1) Slow dripping from the nozzle under gravity with no jetting 2) Breakup of a cylindrical jet by axisymmetric disturbances of the jet's surface 3) Breakup by screw-like disturbances of the jet, also known as a wavy or uneven breakup of the jet, and 4) Atomization of the jet, where the uniform cylindrical stream into droplets in the form of a diverging spray at the nozzle exit.

Given the nozzle diameter d, the Reynolds number is given by

$$\mathrm{Re} = \frac{\rho V d}{\mu}, \tag{1}$$

and Weber number given by

$$\mathrm{We} = \frac{\rho V^2 d}{\gamma}, \tag{2}$$

which leads to the Ohnesorge number being

$$\mathrm{Oh} = \frac{\sqrt{\mathrm{We}}}{\mathrm{Re}}, \tag{3}$$

which can also be written as

$$Oh = \left(\frac{\mu}{\gamma\rho d}\right)^{\frac{1}{2}}, \qquad (4)$$

where μ is the dynamic viscosity, γ is the surface tension.

The Z number, as introduced by Fromm [5], is the inverse of the Ohnesorge number

$$Z = Oh^{-1} \qquad (5)$$

Z gives a wettability factor for which $1 \leq Z \leq 14$, jetting can occur. When Z is closer to 1, the less likely it can be jetted, for Z ~ 10, where satellite drops begin to form and 10< Z <14, the satellite drops rejoin.

The current model was built through Ansys Fluent, CFD software developed and released by Ansys Inc. for building virtual simulation models needed for model flow, turbulence, heat transfer, and other applications. The model was built via the tutorial provided by Ansys for its own VOF model. The model was then recreated using ANSYS's own CAD package and meshed using the ANSY meshing software provided as part of its Workbench package. The mesh was then imported in to ANSYS Fluent standalone. A multiphase simulation model using the Volume of Fluid model as suggested by Ansys was used as this was a mathematical model that was designed for use with two immiscible fluids and uses a single set of equations to track the movement of one volume fraction through another. This model is typically used in predicting the breakup of a jet of liquid, bubble formation and the tracking any liquid-gas interface.

The solver is a pressure based solver, which deals with low speed incompressible flows as was the case in the simulation with a velocity of 5 m/s. The macro provided by the VOF ANSYS Tutorial was modified to achieve the drop formation as it follows a cosine law for applying the velocity for a limited period of time. The model used was time dependent, to track the transient behavior of the drop through the allocated period. The fluid velocity was initially set to 5 m/s for the first 10 µs and then set to 0 after. The simulation is to run for 30 µs total. Shown in Figure 3, are a series of images showing the drop behavior at a certain time.

Image 1- Time @ 10^{-8} s

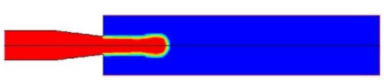

Image 2- Time @ 500×10^{-8} s

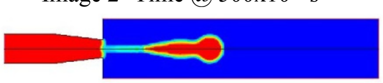

Image 3- Time @ $1001 \mathrm{xe} 10^{-8}$ s

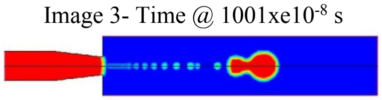

Image 4- Time @ 1501×10^{-8} s

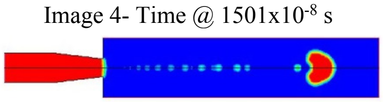

Image 5- Time @ 2001×10^{-8} s

Figure 3. *Visualization of drops.*

Future Work

The next step in the process would be to accumulate a databank of Z numbers for a range of fluids and then referencing an unknown sample's behavior only via its Z number. This would help predict the behavior process of a given sample without having to find out all its individual properties first, although the properties such as surface tension and viscosity would later be ascertained and cross referenced to ensure the accuracy of the prediction. Some other possible changes that could be is to move the inlet location to study the movement of the fluid in the ink chamber, as it moves towards the nozzle area and fluid region to become pressure based and see the drop's impact on a surface. The final goal is to predict a fluid's drop formation behavior by simply entering is given Z number to simulate its jetting behavior.

References

[1] Xiaoying Rong. "Print Quality Comparison Between Kodak Prosper and Offset Lithography" NIP 26, 2010.

[2] Fu, Ellie. "Application of Inkjet Printing in Printed Electronics." *Hong Kong Digital Printing Association*. Nano and Advanced Materials Institute Limited, 05 Mar 2012.

[3] Ohnesorge, W. v. "*Anwendung eines kinematographischen Hochfrequenzapparates mit mechanischer Regelung der Belichtung zur Aufnahme der Tropfenbildung und des Zerfalls fl¨ussiger Strahlen"*, Konrad Triltsch, Würzburg, 1937.

[4] Lim, S. (2012)."*Inkjet printability of electronic materials important to the manufacture of fully printed otfts*. (PhD Dissertation, Western Michigan University, 2012.).

[5] Fromm, Jacob. "Numerical Calculation of the Fluid Dynamics of Drop-on-Demand Jets." *IBM Journal of Research and Development*. 28. 1984.

[6] Wijshoff, H. "Structure- and fluid-dynamics in piezo inkjet printheads." Venlo, The Netherlands: 2008. <Wijshoff, H. (2008). Structure- and fluid-dynamics in piezo inkjet printheads. In Venlo, The Netherlands: Oce Technologies.

[7] Fujifilm, Dimatix. "DMP-2800 Series User Manual." *Dimatix Materials Printer*. Santa Clara: 2007. <www.dimatix.com >.

[8] Kipphan, H. (2006). *Handbook of print media, technologies and production methods.* (1st ed.). New York: Springer-Verlag New York Inc.

9] Hakola, Liisa. "Benefits of inkjet printing for printed electronics." *VTT Business from Technology*. VTT Information Technology, 15 Sep 2005. Web. 8 May 2013.

[10] McKinley, G. H., & Renardy, M. (2011). Wolfgang von Ohnesorge. In Cambridge, MA: Massachusetts Institute of Technology.

[11] Wu, Hsuan-Chung, Huey-Jiuan Lin, Yung-Chi Kuo, and Weng-Sing Hwang. "Simulation of Droplet Ejection for a Piezoelectric Inkjet Printing Device." *Materials Transactions*. 45.3 (2004): 893-899. Web. 8 May. 2013

Author Biography

Adarsh Anand received a BE in Aeronautical Engineering from Western Michigan University (2011). Adarsh is currently a Masters student in Paper and Printing Science hosted by the Department of Chemical and Paper Engineering at Western Michigan University.