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The Simulation Study of Fluid Physical Properties on Drop Formation of Drop-on-demand Inkjet Printing

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ABSTRACT: Inkjet printing is a method for directly patterning and fabricating patterns without the need for masks. However, the physical phenomenon in inkjet printing process is very complicated with the coupling of piezoelectricity, elasticity, and free surface fluid dynamics. The authors use the volume of fluid (VOF) method as implemented in the commercial code FLUENT to model the details of the drop formation process. The influence of viscosity and surface tension of the liquid on the droplet formation process is investigated. Consequently, we find that the speed of liquid plays an important role for the jet stability. The viscosity of liquid greatly influences the final speed of droplet. However, the surface tension of liquid does not much affect the speed of droplet. It changes the shape of the liquid thread and final droplet.

Keywords: drop-on-demand; inkjet; volume of fluid; pressure waveform

1 INTRODUCTION

Inkjet printing is an emerging technology with many applications being explored beyond its image transfer capability, including micro-dispensing and material-assembling [1-5]. It is because the inkjet printing has the advantage of making patterns without any additional lithographic processes. Inkjet printing can reduce the number of processing steps compared with conventional patterning processes, and it finally results in a lower production cost in manufacturing. For this reason, many approaches to substitute the conventional coating method with inkjet printing are in progress. Examples include color filter coating in flat panel display (FPD), electric wire coating on printed circuit board(PCB), UV-curable resins for the fabrication of micro-optical parts, organic light emitting diode (OLED) displays and so on [6-9].

The generation of inkjet droplets is a complex process, and the precise physics and fluid mechanics of the process are still the subject of much research [10]. To understand the jetting behavior of the liquids with pressure waveform, numerical analysis has also been employed [11-16]. For most of applications, it is very important that only a single drop is generated. However, occasionally, extra drops are also generated. These drops are called satellite drops. These satellites can easily lose directionality and deteriorate printing quality. This becomes critical when a very fine pattern is required. The mechanism of satellites that result from the liquid thread breakup is well known as the Rayleigh instability. The drop formation of a liquid thread has been studied in the drip and continuous modes and in surrounding viscous liquids, especially for the dripping and continuous jetting processes. Thorough reviews of related literature can be found in Bogy [17], Eggers [18], Lin and Reitz [19], Furbank and Morris [20], and Subramani et al [21]. However, for drop-on-demand inkjet process, the liquid thread breakup is along with the perturbation of the acoustic wave. Therefore, the linear analysis of Rayleigh does not predict the formation of satellites at all. Subsequent theories have predicted satellites but do not explain their detailed behavior.

In this study, we use the volume of fluid (VOF) method [22] as implemented in the commercial code FLUENT to model the details of the drop formation process. The drop-on-demand pressure waveform as an inlet pressure distribution applies to the ink channel. We study the effect of viscosity and surface tension on the droplet formation process.

2 MATHEMATICAL METHODS

The earliest significant work attempting to understand the mechanisms of drop generation was by Fromm [14]. He identified the Ohnesorge number. Oh is regarded as the appropriate grouping of physical constants to characterize drop formation. He used the parameter Z =1/Oh and proposed that Z > 2 for stable drop generation. This analysis was further refined by Reis &Derby [1], who used numerical simulation of drop formation to propose the following range,10> Z > 1, for stable drop formation. At low values of Z, viscous dissipation prevents drop ejection, whereas at high values the primary drop is accompanied by a large number of satellite droplets.

$$Z = \frac{(\alpha\rho\gamma)^{1/2}}{\eta}$$

Where v, ρ, γ, and η are respectively the average travel velocity, the density, the surface tension, and the viscosity of the fluid, and α is a characteristic dimension (the diameter of the printing nozzle).

Another limiting factor for drop generation is the influence of the fluid/air surface tension at the nozzle. A drop must have sufficient energy to overcome this barrier for ejection. Duineveld et al. [23] suggested that this leads to a minimum velocity for drop ejection.

$$V_{\min} = \left(\frac{4\gamma}{\rho d_n}\right)^{1/2}$$

Where d_n is the nozzle diameter.

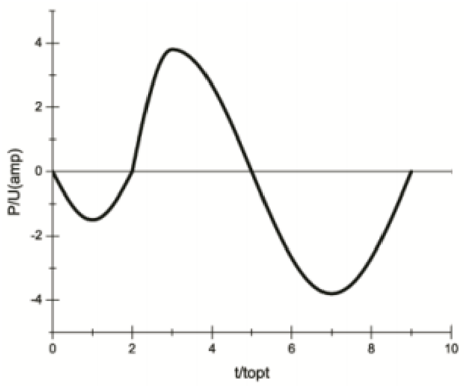

Figure 1. Pressure waveform profile at the nozzle

The physical phenomenon in an inkjet printing process is very complicated with the coupling of piezoelectricity, elasticity, and free surface fluid dynamics. In order to simplify the problem and focus on the process of droplet ejection, an inkjet printhead with a partially cone-shaped nozzle, as shown schematically in Figure 2, is considered as the simulated system. The pressure at the nozzle inlet is determined by the propagation theory of acoustic waves [24-25]. Appropriate pressure waveforms will cause fast transient increase and decrease of the channel volume. This pressure distribution acts as the initial condition for the acoustic wave propagation. The pressure waveform at the nozzle can be approximated as a sine wave as shown in Figure 1.

Ignore the viscous dissipation of ink chamber and the energy loss of pressure wave reflection, we can use the sine curve in analytic expression, as shown below:

$$P = \begin{cases} -0.5U_A \sin\dfrac{\pi}{t_{opt}} t(t < 1.0t_{opt}) \\ U_B \sin\dfrac{\pi}{t_{opt}}(t - t_{opt})\,(1.0t_{opt} < t < 1.5t_{opt}) \\ U_B \sin\dfrac{\pi}{2t_{opt}}(t - 0.5t_{opt})\,(1.5t_{opt} < t < 4.5t_{opt}) \end{cases}$$

At the beginning, the negative pressure $\boldsymbol{U}_A$ is applied on the PZT during the time t_{opt}. The liquid at the nozzle is retracted to move upward to form meniscus. During the time t_{opt} and $1.5t_{opt}$, the pressure $\boldsymbol{U}_B$ is applied and the liquid at the nozzle is accelerated to move downward through the positive pressure. The liquid thread is broken because of the negative pressure during $1.5t_{opt}$ and $4.5t_{opt}$.

The geometry and computational domain are shown in Figure 2 with the related sizes depicted. A simplified cone-shaped ink channel is employed. The nozzle is 27μm in diameter. The supply end is 70.5μm in diameter. And the ink channel length is 180μm. Because the density and viscosity of the ambient gas are so small compared to the liquid, there is less effect on the simulation results. Thus, the ambient gas is treated as a void (zero density) in the simulation system.

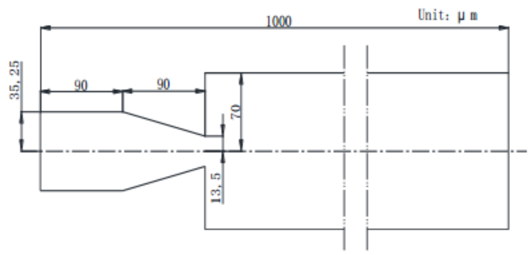

Figure 2. Schematic diagram of the inkjet printhead showing the dimensions of the modeled system

In our simulation system, the fluid is treated as laminar flow. The Froude number, Fr =υ/√gd, expressing the balance of inertia and gravity, is even with an ink speed v ≈ 1m/s in a 27μm cross-section about 60. This means that gravity is negligible with respect to inertia. So for the channel acoustics, we can neglect gravity. Moreover, the ink viscosity is a weak function of shear rate and consequently can be approximated by a Newtonian (constant viscosity) fluid. Like most of liquids, these ink are also incompressible. To model the details of the drop formation process, the volume of fluid (VOF) method [22] is implemented in the commercial code FLUENT. The volume of fluid (VOF) method is for tracking the interface location and the continuum surface force (CSF) [26] method is for modeling the effects of surface tension. To reduce the CPU time, we use a 2D rotational symmetric model with symmetry on the nozzle axis. So only the perpendicular firing jets are considered.

3 RESULT AND DISCUSSION

After simulation, a sequence of images during DOD drop formation is shown in Figure 3, revealing the main features of this process. According to the pressure waveform, first, the negative pressure $\boldsymbol{U}_A$ is applied on the PZT during the time T_{opt}. The liquid at the nozzle is retracted to move upward to form meniscus. During the time T_{opt} and $1.5T_{opt}$, the pressure $\boldsymbol{U}_A$ is applied and the liquid at the nozzle is accelerated to move downward through the positive pressure. The liquid thread is broken because of the negative pressure between $1.5T_{opt}$ and $4.5T_{opt}$.

Breakup of the free liquid thread leads to the generation of a primary drop and satellites. The satellites drop formation mechanism results from the long liquid thread itself, because a long liquid thread will not be stable. The length and speed of liquid thread at pinch-off, surface tension and viscosity of the liquid, will direct cause for breakup of the liquid thread. This breakup process is well known as the Rayleigh instability.

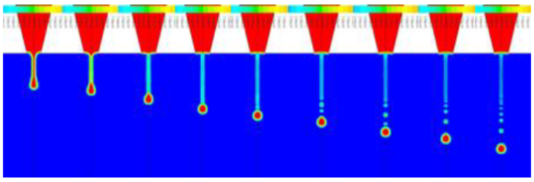

Figure 3. A sequence of images view of the simulated ejection droplets.

The pressure waveform at the nozzle inlet, as shown in Figure 1, is conducted in this study to discuss the effects of pressure parameters on the droplet ejection. The three factors, $\boldsymbol{U}_A$, $\boldsymbol{U}_B$ and T_{opt} of the pressure waveform that influence the droplet formation process, are respectively investigated.

The liquid as ink, the related density, viscosity and surface tension are respectively 1,111.4 kg/m^3, 15.7cps and 73.5dyn/cm. It is calculated that Z is 2.99 and V_{min} is 3.13m/s.

3.1 *Influence of viscosity on the droplet formation process*

As described above, the inkjet is a complicated free surface flow of two immiscible fluids of liquid and gas. Viscosity and surface tension of the liquid plays a significant role on the flow behavior. The fluids with various viscosity, the kinematic parameter and dimensionless numbers Z for each fluid are summarized in Table 1. The ejection behaviors of the various liquids are simulated under the identical waveform condition.

The ejected liquid process for the viscosity 9.1cps and 13.1cps at the instant of 10us, 15us, 20us and 25us are shown in Figure 4. It can be seen that under identical pressure conditions and surface tension, as the viscosity of the liquid increases, the ejected liquid thread becomes shorter since the resistance of viscosity increases. For viscous liquids, the viscous dissipation will slow down the dynamics of breakup. Therefore, as viscosity of the liquid increases, the speed of droplet becomes slower. As liquid thread becomes longer, the liquid is more unstable and generates more satellites.

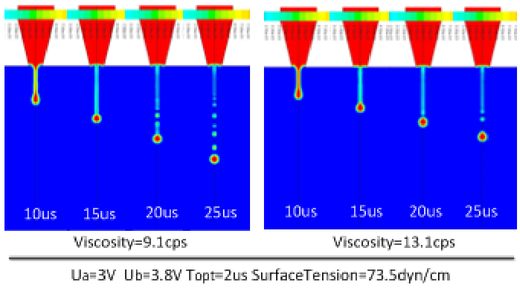

Figure 4. Phases contours of viscosity on the droplet formation

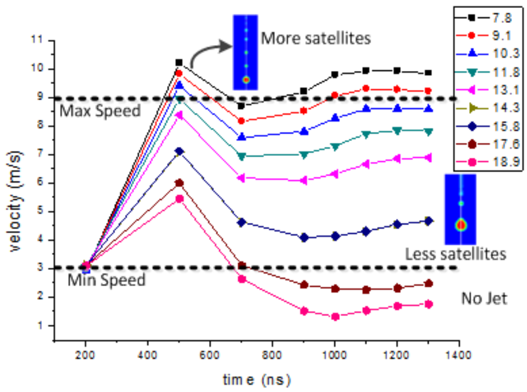

Figure 5. Relationship of the viscosity and the velocity of droplet

To investigate the jet stability, the jet speed, fly time and satellites conditions are shown in Figure 5. As the viscosity of the liquid increases, the speed of droplet becomes slower. Below the minimal jet speed 3.13m/s, the liquid thread does not jet out of the nozzle because it does not overcome viscous resistance. While upon the maximum jet speed about 9m/s, liquid thread becomes longer and more unstable. More satellites are generated, which is not desirable for the quality of the printing. We found that among the minimal and maximum jet speed, more specifically, the jet speed 8.58m/s,

Table 1. Fluids with various viscosity, the kinematic parameter and dimensionless number Z

Viscosity[cps]	Initial velocity[m/s]	Breakup velocity [m/s]	Length of breakup[um]	Z
7.8	10.2	9.84	100.3	6.02
9.1	9.82	9.21	97.2	5.16
10.3	9.41	8.58	90.4	4.56
11.8	8.95	7.82	81.7	3.98
13.1	8.38	6.89	74.9	3.59
14.3	7.1	4.67	65	3.28
15.8	7.11	4.67	44.9	2.97
17.6	6	2.47	36.4	2.67
18.9	5.45	1.76	23.6	2.48

Table 2. Fluids with various surface tensions and the kinematic parameter

Surface tension[dyn/cm]	Initial velocity[m/s]	Breakup velocity [m/s]	Length of breakup[um]
30	8.21	5.09	104
35	8.05	5.02	92.3
45	7.83	4.98	84.2
55	7.52	4.84	77.1
65	7.27	4.74	70.3
73.5	7.11	4.76	64
85	6.85	4.43	57.7
95	6.56	4.09	46.3
105	6.27	3.76	40.9

7.82m/s, 6.89m/s, 4.67m/s, 4.67m/s are respectively with corresponding viscosity 10.3cps, 11.8cps, 13.1cps, 14.3cps and 15.8cps , and the liquid threads are suitable and less satellites are generated. The maximal speed of fluid thread occurred at a time about 5us when liquid thread is rushing out of the nozzle tip. From time about 5us–14us, the negative pressure wave pulls the liquid thread back inside the nozzle that slows down the speed of liquid thread. When Z is in the range of 2.97–4.56, the final speed of liquid thread is in the range of 3.13–9m/s, in which range less satellites are generated.

3.2 *Influence of surface tension on the droplet formation process*

The fluids with various surface tension, the kinematic parameter, the minimal velocity properties and dimensionless numbers Z for each fluid are summarized in Table 2. The ejection behaviors of the various liquids are simulated under the identical waveform condition and viscosity.

The ejected liquid process for the surface tension 35dyn/cm and 95dyn/cm at the instant of 10us, 15us, 20us, 25us and 30us is shown in Figure 6. It can be seen that under identical pressure conditions and viscosity, the ejected liquid thread becomes shorter as the surface tension of the liquid increases. It can be reasoned out by the fact that higher surface tension results in higher downward pulling force near the nozzle. As a consequence, the jet speed correspondingly slows down and the liquid thread needs more energy to overcome the resistant of surface tension. Therefore, the minimal speed of droplet becomes faster as the surface tension of the liquid increases. For liquid of lower surface tension (35dyn/cm), the shape of the liquid thread becomes slender. For the liquid of high surface tension (95dyn/cm), the shape of the liquid thread and droplet are round.

Table 3. Fluids with various surface tensions and the kinematic parameter

Surface tension[dyn/cm]	Z	V_{min} [m/s]
30	1.91	2.00
35	2.06	2.16
45	2.34	2.45
55	2.59	2.71
65	2.81	2.94
73.5	2.99	3.13
85	3.22	3.37
95	3.40	3.56
105	3.58	3.64

To investigate the jet stability, the jet speed, fly time and satellites conditions are shown in Figure 7. As surface tension of the liquid increases, the speed of droplet becomes slower. There is a little difference with the viscosity and pressure conditions. The surface tension varies from 30dyn/cm to 105dyn/cm, and the jet speed varies a little. However, the liquid thread is obviously shorter from 104um to 49um. For liquids of high surface tension, the shapes of the liquid thread and tail droplet are round. Meanwhile, the liquid thread is short and a single droplet is formed most rapidly. This is most desirable for the printing quality.

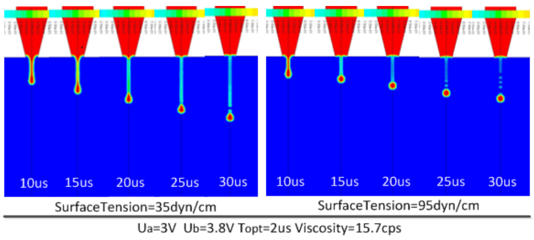

Figure 6. Phases contours of viscosity on the droplet formation

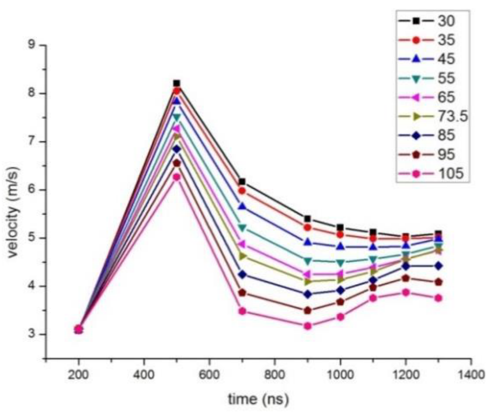

Figure 7. Relationship of the surface tension and the velocity of droplet

4 EXPERIMENT

In order to verify the correctness of the simulation results, the industrial printhead which feathering 27μm nozzle diameter is carried out for our experiment. The industrial printhead contains 512 nozzles, and the distance between nozzle and substrate is about 1 mm. The center line parallelism is guaranteed between the printhead and the substrate that make up for glossy paper. The nano silver ink for our experiment has 15.7cps viscosity, and the surface tension is 73.5 dyn/cm, the average particle size is 30 nm and the mass fraction is 30%. The experiment process is shown in Figure 8:

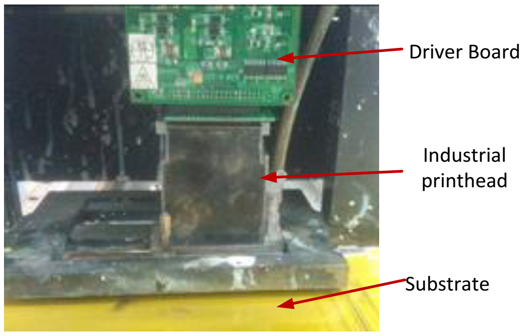

Figure 8. System of inkjet printing

The glossy paper is as substrate which temperature is 25°C. The printhead voltage is respectively 3.6 V, 3.7 V, 3.8 V, 3.9 V, 4.0 V, 4.2 V and 4.3 V. We investigate the mean diameter of 10 droplet inkjet on the substrate. Meanwhile, the quantity of the satellite droplets is also studied. Therefore, the relationship between the drive voltage of printhead and the diameter of droplet is shown in Figure 9:

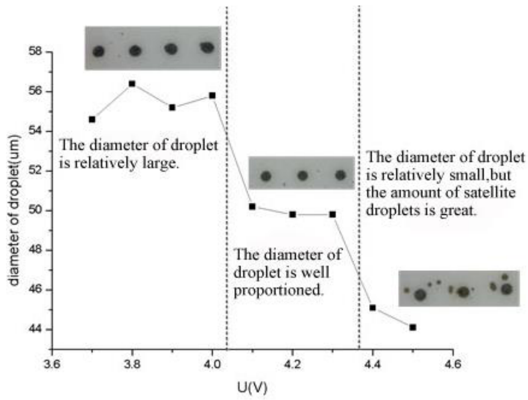

Figure 9. Observed experiment data

Within a certain range of inkjet droplet diameter with the increase of the driving voltage type steps to reduce the trend, and with the increase of the driving voltage, especially after more than 4.4 V, the satellite droplets increased obviously. This agreement with the results of numerical simulation is, when the driving pressure is small due to the effect of droplet viscous force, easy to form larger droplets. As the driving pressure, droplet speed faster, in the case of nano silver ink surface tension must be, the droplets appear more satellite droplets which reduce the droplet size. Therefore, for the nano silver ink used in this study, the driving voltage within the range (4.0 ~ 4.4 V) can form uniform droplets and greatly reduce the probability of the satellite droplets for the follow-up to lay a good foundation for industrial application.

5 CONCLUSIONS

The physical phenomenon in an inkjet printing process is very complicated with the coupling of piezoelectricity, elasticity, and free surface fluid dynamics. We use the volume of fluid (VOF) method as implemented in the commercial code Fluent to model the details of the drop formation process. Viscosity and surface tension of the liquid play significant roles on the flow behavior. What's more, we find that the speed of liquid plays important role for the jet stability. The viscosity of liquid influences the final speed of droplet greatly. It shows good jet stability when the final speed of droplet is between 3.13m/s and 9m/s. However, the surface tension of liquid does not much affect the speed of droplet. It changes the shape of the liquid thread and final droplet.

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