The effect of Rheological Property of Ink on the Generation of Inkjet Droplet

Hansol Yoo and Chongyoup Kim*

Department of Chemical and Biological Engineering, Korea University
Anam-dong, Sungbuk-ku, Seoul 136-713, Korea
*cykimku@korea.ac.kr

ABSTRACT

In inkjet printing the ink is usually a suspension of particles in liquid. Suspensions usually show shear-thinning characteristics. To understand the jetting and drop generation mechanism of suspensions we investigated similar systems for which the rheological properties are well characterized. As “inks,” Newtonian fluids (water-glycerin mixture) and shear-thinning fluids (xanthan gum solutions in the Newtonian fluid) were prepared. The diameter and velocity of droplet were measured while varying waveform of bipolar shape to the piezoelectric inkjet head and the effects of the rheological properties were examined. The result shows that the impinging velocity is strongly affected by zero-shear and extensional viscosities while the drop size is dependent on infinite shear viscosity.

Keywords: shear thinning, zero-shear viscosity, infinite shear viscosity, extensional viscosity

1 INTRODUCTION

As the inkjet printing technology is widen its application to bio- and electronic- industries beyond household or office inkjet printers, many different kinds of inks have to be handled. However, inks have not been characterized properly and the processing conditions have been determined mostly through trial and error basis. Considering the importance of the inkjet technology, in the present research, we investigated the generation of inkjet droplets to give an insight into the processing of non-Newtonian fluids for various applications by using a drop-on-demand (DOD) inkjet printing system.

2 EXPERIMENT

To investigate the generation of inkjet drops we set up an inkjet system which is the same as the one the authors used for the previous studies on spreading of inkjet drop [1, 2]. In the present case, there is no such part as solid surface. The system consists of an inkjet nozzle, a jetting driver (pulse generating system), a high-speed camera and an illumination source.

The inkjet droplet was generated by a piezo-type nozzle purchased from MicroFab Co. (Model # MJ-AT). The nozzle diameter was 50μm. In Fig. 1 the inside geometry of the nozzle is shown. In taking the picture the nozzle filled with air was immersed in a square box containing decalin. Since decalin has the same refractive index as the nozzle, the refraction at the curved nozzle surface can be avoided. To generate droplets a bipolar waveform was used. During the rise period the piezo element expands for fluid intake from the reservoir and this state continues during the dwell period. During the fall period the piezo element shrinks and fluid is ejected out of the nozzle. This state continues during the echo period. Finally, the piezo element expands to return to the initial state. Depending on the time-intervals and the voltages imposed on the piezo element a drop or drops of different sizes and velocities are generated. In the present research, the rise time and decay time in the voltage pulse to the nozzle were set at 2μs. The dwell and echo times were varied between 4 – 32μs and the dwell and echo voltages were set at 12 – 90V. We performed drop generation experiments by varying operating conditions and measured the drop size and velocity. We also examined the formation of satellite drops. All the experimental runs were performed at 309K. This higher temperature than the normal room temperature was caused by the illumination system. At this condition Ohnesorge number of the droplet was 0.055 ~ 0.060. The high speed camera (IDT, XS-4) was triggered by the jetting driver as a droplet was ejected from the inkjet nozzle. The camera was equipped with a microscopic objective lens (Mitutoyo, M plan Apo 10x, 20x) with the magnification of 5X. As the illumination source a back-lighting system (Stocker Yale, # 21AC, 180W) was installed.

The CCD camera can capture 50,000 frames per second and the pictures were taken at this mode. The exposure time was 1μs. When this fast mode was used the number of pixels per frame has to be small (512 x 48 pixels), hence the quality of picture is not satisfactorily good. One may use the flash videography method to get the better quality as demonstrated by van Dam and Le Clerc [3] and Dong et al [4]. But in the case of non-Newtonian drops the reproducibility of drop generation was not as good as in the case of Newtonian fluid, hence it was virtually impossible to use the flash videography method used in the literatures.

Three Newtonian fluids were prepared with different viscosities by mixing deionized water and glycerin (Junsei Co.). Shear thinning fluids were prepared by dissolving xanthan gum (Sigma Aldrich Co.) in deionized water or one of the water-glycerin mixtures. Table 1 shows the composition of the fluids tested here. The shear viscosity of liquid was measured by a rotational rheometer (ARES, TA Instrument). The extensional characteristics were examined by using a capillary break-up apparatus (CaBER, Thermo-Haake).

Fig. 1. Internal shape of the nozzle

Table 1. Newtonian base fluids

Sample name	1cp	4.5cp	10cp	16.5cp
DI water, wt.%	100	55	40	32
Glycerin, wt.%	0	45	60	68
Viscosity, cP	1	4.5	10	16.5

Table2. Xanthan gum solutions studied here and their Carreau model parameters.

	1.0cP			4.5cP		
	50ppm	100ppm	200ppm	50ppm	100ppm	200ppm
η_0(cP)	2.261	3.872	7.041	6.842	12.6	28.76
η_∞(cP)	1.169	1.372	1.627	4.658	4.016	4.349
λ	0.2474	0.22	0.2434	0.2833	0.4665	0.6789
n	0.6283	0.3839	0.5242	0.6078	0.7107	0.4151
	10cP			16.5cP		
	50ppm	100ppm	200ppm	50ppm	100ppm	200ppm
η_0(cP)	17.18	29.43	71.81	29.3	48.72	136.2
η_∞(cP)	9.333	8.692	10.65	16.02	16.54	14.04
λ	0.7652	1.299	1.847	1.657	0.9476	10.3
n	0.7331	0.7188	0.6117	0.7453	0.638	0.6862

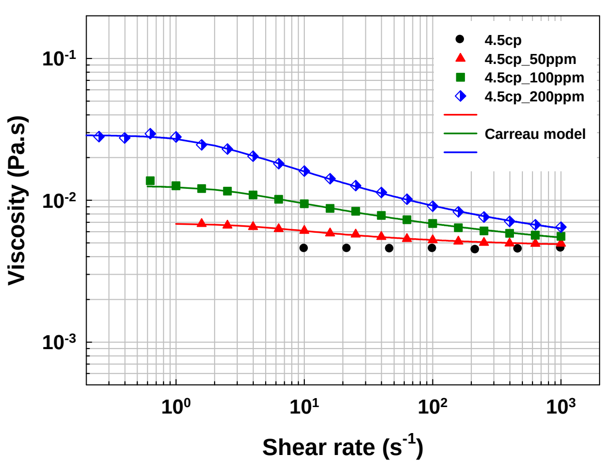

Fig. 2. Viscosities of xanthan gum solutions in a water-glycerin mixture when the base fluid viscosity is 4.5cp. Other fluids show similar shear-thinning behavior.

3 RESULTS AND DISCUSSION

Fig. 2 shows the viscosities of 4.5cp solvent base fluids. The mixture of DI water and glycerin has a shear independent viscosity while all xanthan solutions have shear thinning viscosities. The viscosity of xanthan solution is fitted to the Carreau model [5]

$$\frac{\eta-\eta_\infty}{\eta_0-\eta_\infty}=\frac{1}{\left[1+(\lambda\dot{\gamma})^2\right]^{\frac{1-n}{2}}} \tag{1}$$

and the parameters are listed in Table 2. In the Table we note that the infinite shear viscosities of xanthan solutions of the same base solvent are virtually the same as the viscosity of the solvent. In the following we will compare the drop generation characteristics of the fluids with the same infinite shear viscosities.

Since it is very difficult to measure the velocity at the exit accurately, we estimated it by numerical simulation using Fluent^{TM}, a commercial software package based on the finite volume method. We used 6320 elements and 6657 nodes in the simulation. The operating condition was obtained by the following method. From the two consecutive images on jetting of a Newtonian fluid, the flow rate through the nozzle is obtained for a given pressure waveform. From the numerical simulation results we imposed the pressure drop between the manifold and the exit of the nozzle that gives the same flow rate as the experimentally observed flow rate value. We assumed that the acoustic velocity of a dilute polymer solution is the same as the solvent. Then the pressure drop between the manifold and the exit should be the same regardless of fluid at a given waveform. Using the same pressure drop we calculated the velocity profile while varying fluid viscosity. Fig. 3 shows the velocity profiles of Newtonian fluids of differing viscosities when the pressure drop is 20000Pa. When viscosity is 1cp, the exit velocity is severely blunted. The blunting of velocity profile is caused by the inertial effect: In the blunted region, the inertial term $\rho v_r \partial v_r / \partial r$ is dominating over the viscous term and is balancing with the pressure term while near the solid boundary the viscous term is dominating over the inertial term. As viscosity increases the velocity profile becomes close to the parabolic profile. In Fig. 4 we have plotted the velocity profiles for fluids with the same infinite shear viscosity. It is seen that the velocity profiles are the same regardless of zero shear viscosity. This is because at the central region the inertial term is dominant while shear rate is extremely large near the boundary as in the case of Newtonian fluid and the shear rates at which viscosity changes appreciably occur for a very narrow region away from the boundary. This result means that the exit velocity is the same regardless of zero shear viscosity as long as infinite shear viscosities are the same for differing fluids. This means that the flow rate will be the same when the waveform is the same as long as the infinite shear viscosities are the same. Fig. 5 actually shows this trend. Drop size increases with increase in applied voltage. Since we have plotted the drop size when only one drop is generated, the data points appear to be scattered. The reason why only a narrow voltage region is plotted for each fluid is that only the region at which a single drop is generated is considered in this case. It is seen that all the data points can be drawn on a single curve with some overlaps for differing fluids. This means that the flow rate is the same for the same driving voltage, and hence the numerical prediction is verified. One exception is that the drop volume suddenly decreases with the increase in driving voltage for 4.5cP Newtonian fluid at 24V. This is caused by the break-off of satellite drops from the ejected thread caused by the capillary instability, and hence it does not represent the actual flow rate.

When a fluid element is ejected it has to be taken apart from the nozzle because of the inertia and pull-back of the liquid from the nozzle. Before break-off the fluid element becomes elongated and becomes a thread. This also means that there is a significant change in velocity during the rearrangement of fluid elements to become a spherical droplet. Fig. 6 shows the impinging velocity of droplets for

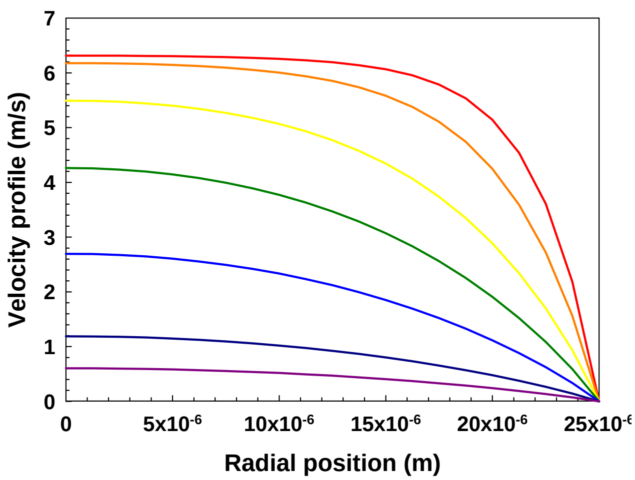

Fig. 3. Velocity profile of Newtonian fluids at a typical condition of 20000Pa pressure difference. From the top, each graph corresponds to 1, 2, 5, 10, 20, 50 or 100 cp liquid.

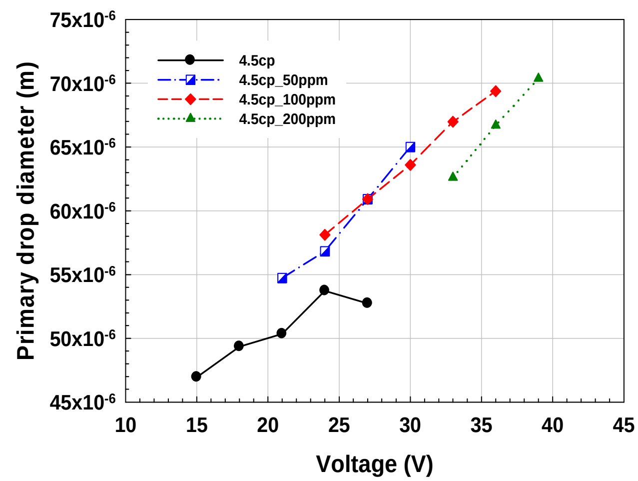

Fig. 5. Diameter of the primary drop. The sudden decrease in drop diameter for water is due to the break-off of satellite drops caused by the interfacial instability.

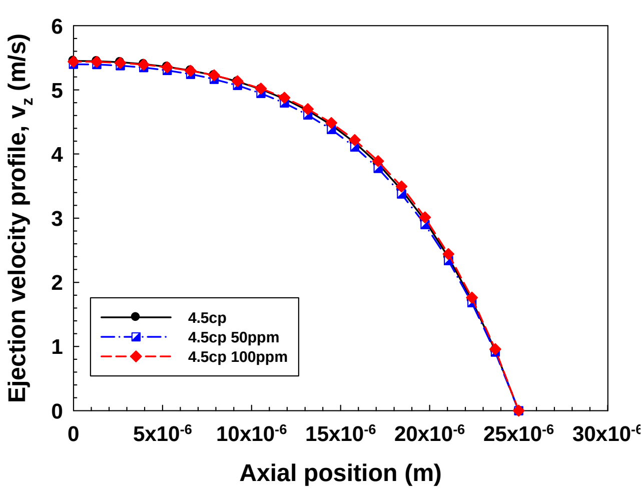

Fig. 4. Ejection velocity profile for fluids with differing zero shear viscosities but the same infinite shear viscosity.

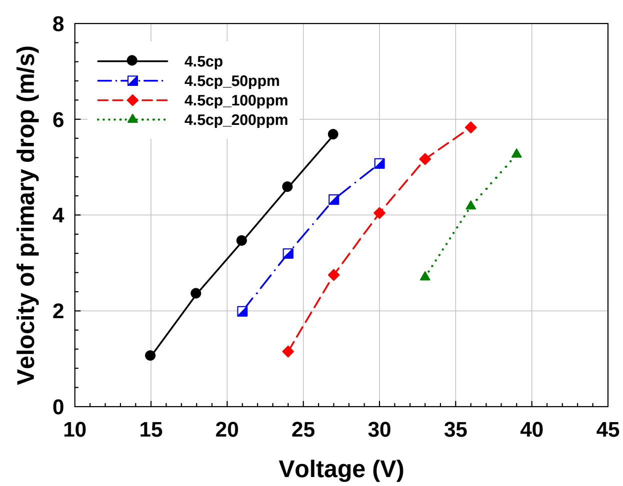

Fig. 6. Impinging velocity of primary drop. Even though drop size is the same at a given driving voltage, velocity of the drop is a strong function of xanthan gum concentration

differing zero-shear viscosities. In this case the infinite shear viscosity is the same. Unlike the case of drop volume impinging velocity is vastly different depending on zero-shear viscosity. First of all, there is a minimum driving voltage to generate a single drop for a given fluid and the minimum driving voltage increases with the increase in zero-shear viscosity. Since the same amount of fluid is ejected from the nozzle at a given waveform, the difference should be caused by the difference in other properties. Recalling that the drop is formed by the break-off from the nozzle and there is a significant extension of fluid thread before break-up due to the difference in the velocities of the head and the tail of the fluid thread, we have investigated the extensional characteristics of inks. In the case of Newtonian fluids it is a well-known fact that the extensional viscosity is three-times the shear viscosity. In the present case the extensional rate is extremely high and hence we may not apply the same principle to the inks considered here since the Newtonian behavior is not expected at this high extensional rate. Therefore, we used a capillary break-up apparatus to examine the extensional characteristics of inks. Fig. 7 shows the results of capillary break up tests. In the Figure, in the case of 50ppm solution, there is a significant delay in thinning of diameter of fluid thread compare with the Newtonian fluid and the delay becomes longer when xanthan gum concentration increases. The reason for this delay appears to be caused by the difference in zero-shear viscosity as well as the extensional thickening of xanthan gum solutions due to alignment of molecules along the thread due to extension [6]. In the above, we have considered only the representative cases due to the lack of spaces. Actually the same behavior has been observed for other sets of fluids.

4 CONCLUSION

In this presentation we have considered the effect of fluid rheology on the generation of inkjet drops using xanthan gum solutions with differing zero shear- and high shear viscosities. The result shows that the drop size is determined by the infinite shear viscosity at a given wave-form. Both the experimental and numerical studies confirm it. The impinging velocity is strongly dependent on the extensional properties. In the presentation a more detailed analysis will be given with more data.

ACKNOWLEDGEMENT

This work was partially supported by Mid-career researcher Program through NRF grant funded by the MEST (Ministry of Education, Science and Technology), Korea (No. 2010-0015186)

REFERENCES

[1] Y. Son, C. Kim, D.H. Yang and D.J. Ahn, Langmuir, 24, 2900-2907, 2008.

[2] Y. Son and C. Kim, J. Non-Newt. Fluid Mech., 162, 78-87, 2009.

[3] D. B. van Dam and C. Le Clerc, Phys. Fluids, *16*, 3403-3414, 2004.

[4] H. M. Dong, W. W. Carr and J. F. Morris, J. F. Phys. Fluids, 18, 072102, 2006.

[5] R.B. Bird, W.E. Stewart and E.N. Lightfoot, "Transport Phenomena," 2nd ed., Wiley, 2002.

[6] R.B. Bird, R.C. Armstrong and O. Hassager, "Dynamics of Polymeric Liquids: Vol. 1 Fluid Mechanics," 2nd ed., Wiley, 1987.

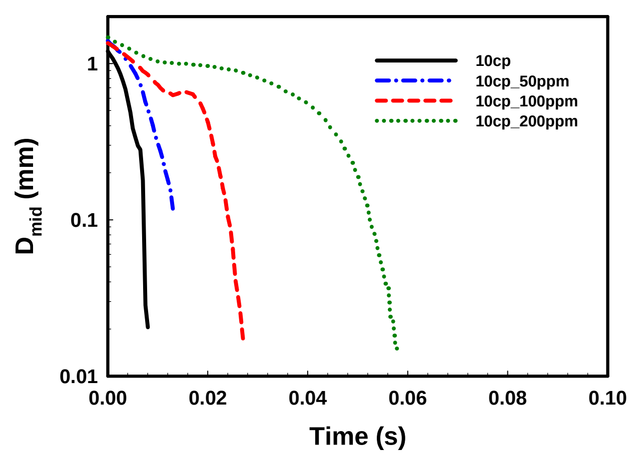

Fig. 7. The results of capillary break-up tests for fluids with the same infinite shear viscosity but differing zero shear viscosity. The solvent viscosity is 10cp.