A Study on Drying Process of Ink at the Inkjet Nozzle Using a Laser Doppler Vibrometer

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Abstract

In drop-on-demand inkjet systems, the nozzle clogging due to evaporation is our great concern. We have developed a novel method for measuring the change of ink viscosity at the nozzle. To estimate the ink viscosity, meniscus vibration states are measured by a laser Doppler vibrometer and the results are verified by numerical simulation results using an equivalent circuit model of inkjet head.

Using our method, the change of the ink viscosity have been measured with changing idle time (non-jetting time). The results show the ink viscosity at the nozzle increases by two steps via a quasi-equilibrium state, and they are qualitatively consistent with a theoretical prediction. We have also measured the change of the ink viscosity with jetting actions after some idle time. The results indicate the existence of two step recovery process about the ink viscosity. In short term, ink viscosity recovers by refreshing the ink at the nozzle. In long term, that recovers by refreshing the ink in the pressure chamber. As a result, it was found that ink viscosity at the nozzle and that in the pressure chamber can be separately estimated by measuring the recovery process using our method.

Introduction

In inkjet printing systems, evaporation of solvent at the inkjet nozzle is a big problem because it leads nozzle clogging and jetting speed degradation. To understand drying process of ink at the nozzle, several methods have been reported. For example, there is a method that measures the drop speed against the idle time [1, 2], and a method that estimates ink viscosity from the vibration that occurred due to the collision of inkjet droplets [3]. These methods are useful for measuring the ink properties, but it is difficult to study the evaporation process over a long period of time, because the methods need ejection of ink from the nozzle and it is difficult to eject droplets after a long idle time.

This report describes a novel method to estimate ink viscosity around the nozzle by measuring a free vibration of ink meniscus. In this method, the ink viscosity has estimated by three steps. First of all meniscus vibration is measured by a laser Doppler vibrometer (LDV). Secondly a damping coefficient of free vibration, which is proportional to the fluid resistance around the nozzle, is analyzed. Finally, the ink viscosity is estimated by comparing measured damping coefficients with numerical calculation results using equivalent circuit analysis of ink fluid in the nozzle.

Measurement and analysis of meniscus vibration

Figure 1 shows the experimental setup. A laser Doppler vibrometer (LV-1710, Onosokki) is used for measuring meniscus vibrations. Measured position is precisely controlled to be set in the center of the nozzle by monitoring the laser spot position with a microscopic system. The LDV signals are acquired by a data logger (Kyence, NR-HA08), or an oscilloscope (Tektronics, TDS2004B). A laser shutter is used to minimize an influence of laser heating of ink. In our experiments, an inkjet head using stacked piezoelectric devices and water based black pigment ink are used.

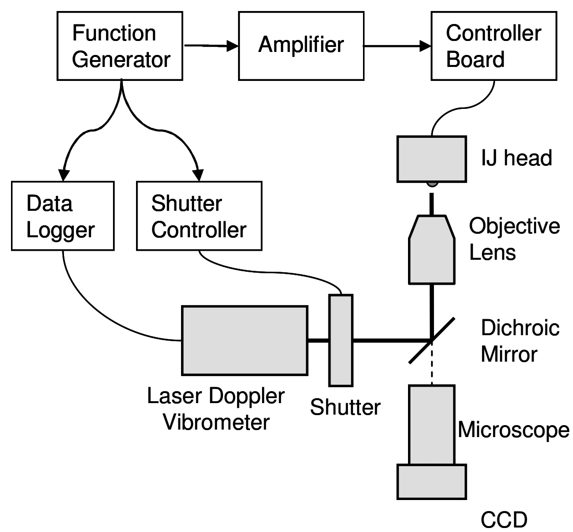

***Figure 1** Experimental setup for measuring meniscus vibration.*

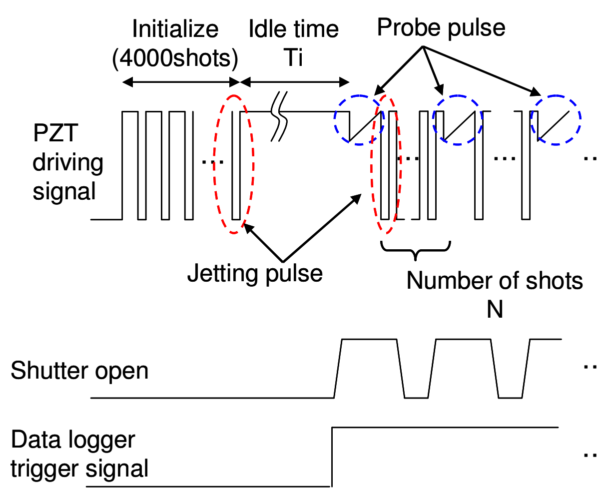

***Figure 2** Typical time sequence of function generator (FG).*

Three different signals are generated by a function generator (FG): driving waves of inkjet head, trigger pulses for the data logger or the oscilloscope, and shutter control signals. Figure 2 shows the time-sequence diagram of the signals. The driving waves are composed of two types of waveform: jetting pulses and probe pulses. At the beginning of the sequence, many jetting pulses are applied for ejecting droplets to refresh the ink inside the nozzle. Then after some idle time (Ti), the probe pulse is applied for oscillating the free vibration of the meniscus. The jetting pulse forms a trapezoidal waveform which is generally used for piezoelectric inkjet heads. On the other hand, probe pulse has a form of saw tooth in order to expand the chamber rapidly and restore it slowly to its initial position. It is also possible to observe the changes of vibration states with the number of jetting pulses (N) by applying the probe pulses between the jetting pulses.

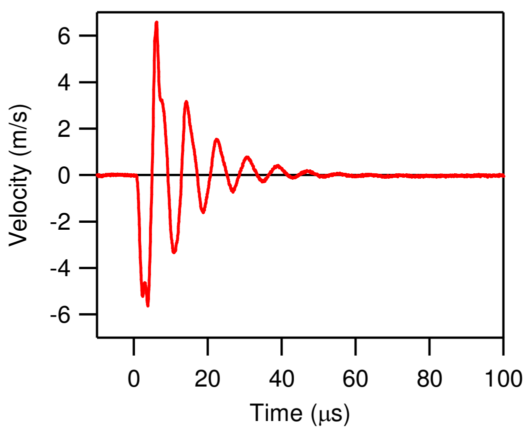

***Figure 3** An example of meniscus vibration measurement result.*

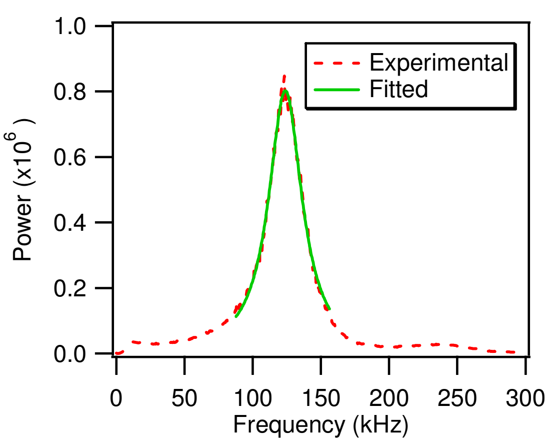

***Figure 4** Power spectrum of meniscus vibration.*

Figure 3 shows the example of the measured meniscus vibration oscillated by the probe pulse. The acoustic natural vibration mode of the meniscus is clearly observed. This natural vibration can be expressed as a damped vibration equation as

$$g(t) = B\exp(-2\pi\cdot\frac{\gamma}{2}t)\cdot\cos(2\pi\cdot f_d t)\,, \qquad (1)$$

where γ and f_d represent the damping coefficient and the damped natural frequency, respectively. The equation of power spectrum of the damped vibration, which means squared magnitude of the time Fourier transformation of equation (1), is given below.

$$|G(f)|^2 = \frac{B^2}{\gamma^2}\frac{\gamma^2/4}{(f-f_d)^2+\gamma^2/4}\,, \qquad (2)$$

The power spectrum of the measured vibration is fitted by equation (2), and γ is derived from the fitted parameter. In Fig. 4 an experimental power spectrum and a fitted spectrum are shown as an example.

Equivalent circuit analysis

In order to establish the relationship between measured damping coefficient and the ink viscosity, equivalent circuit analysis, which is often used for analyzing acoustic properties of inkjet head, are carried out.

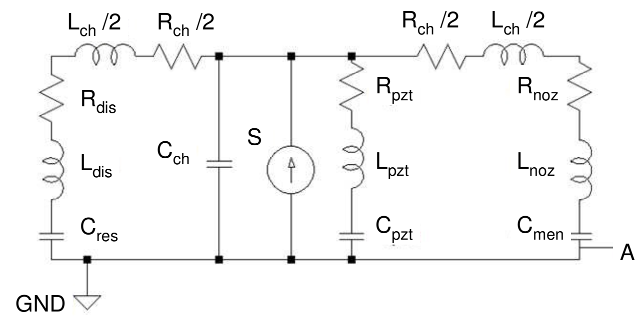

***Figure 5** An equivalent circuit model of the pressure chamber.*

In the equivalent circuit analysis, acoustic parameters such as compliances (C), inertances (L), and flow resistances (R) are represented by lumped circuit elements as shown in Fig. 5. Subscripts "men", "noz", "ch", "pzt", "dis", and "res" indicate meniscus, nozzle, pressure chamber, piezoelectric element, distributor, and reservoir, respectively. The numerical calculations are carried out by inputting the current at point S, which corresponds the probe pulse, and measuring the change of current at point A which corresponds the change of volume velocity of meniscus. In this analysis, some lumped parameters has been corrected by the experimental vibration data of a solvent (Momentive performance materials, TSF45-10) which properties are known.

Using this model, the dependence of the damping coefficient on the ink viscosity is calculated. The calculations are performed with changing the ink viscosity at the nozzle η_{noz} and that in the chamber η_{ch}, separately. Figure 6 shows the results of calculations. It is notable that γ depends strongly on η_{noz} but little on η_{ch}. When η_{noz} becomes more than 60 (mPa s), the linear relationship between γ and η_{noz} disappears since the sufficient vibration can not be obtained under such strong damping conditions. It seems that 60 (mPa s) at η_{noz} is the upper limit of this measurement method.

As a result of these numerical simulations, it is possible to derive the local viscosity at the nozzle η_{noz} from the damping coefficient measured by LDV.

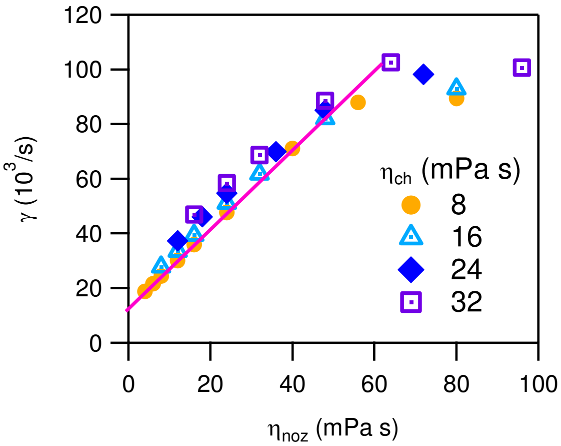

Figure 6 *Relationship between the damping coefficient and the viscosity.*

Results and discussions

Changes of ink viscosity with idle time

Figure 7 shows the results of the measured viscosity of water-based black pigment ink with changing the idle time (Ti). Figure 7 indicates the existence of the two-step evaporation process: first, η_{noz} increases rapidly, then it becomes stable around hundred seconds, and finally η_{noz} increases again after several hundreds seconds. Our speculation of this process will be discussed later.

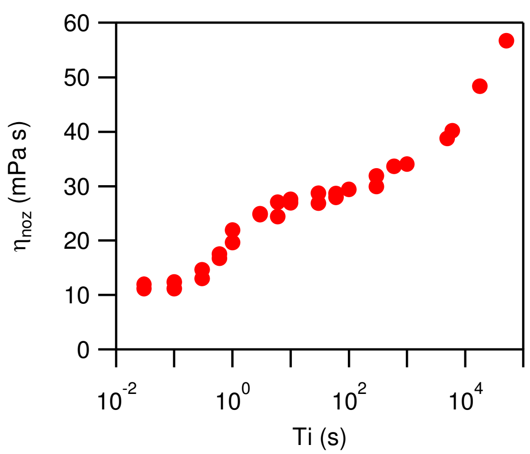

Figure 7 *Change of viscosity at the nozzle by idle time.*

Refreshing process with jetting pulses

Figure 8 shows the change of η_{noz} with the number of jetting pulses (N) after some idle time. In this experiment, several probe pulses are applied between jetting pulses, and the meniscus vibrations are measured at each probe pulses. Figure 8 indicates that refreshing process, in which the ink viscosity recovers to its initial value, has two steps. In the short term, the ink viscosity recovers by stirring and ejecting ink at the nozzle. In the long term, it recovers by refreshing ink in the pressure chamber.

This result suggests that distribution of the ink viscosity along the distance from the nozzle surface can be estimated by observing the recovery process as shown in Fig. 8. Especially, the measured viscosity after applying 30~50 pulses will be a good approximation of the viscosity in the pressure chamber η_{ch}, because it indicates the viscosity after ejecting the local viscous ink at the nozzle. Therefore, η_{noz} and η_{ch} can be separately estimated by this method.

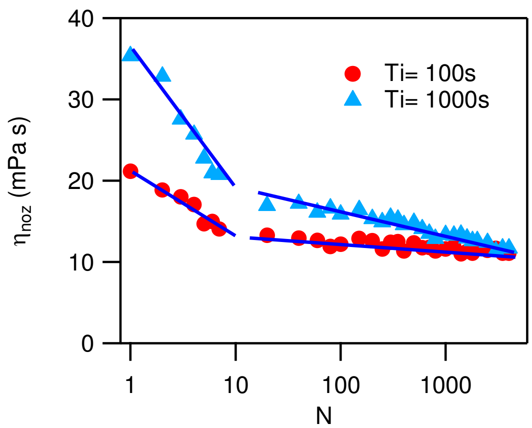

Figure 8 *Change of viscosity with the jetting pulses.*

Effect of shaking pulses

For the on-demand inkjet systems, during the idle time shaking pulses are often applied to the idle nozzles in order to prevent misfiring. We evaluated the effect of applying the shaking pulses by measuring η_{noz} and η_{ch}.

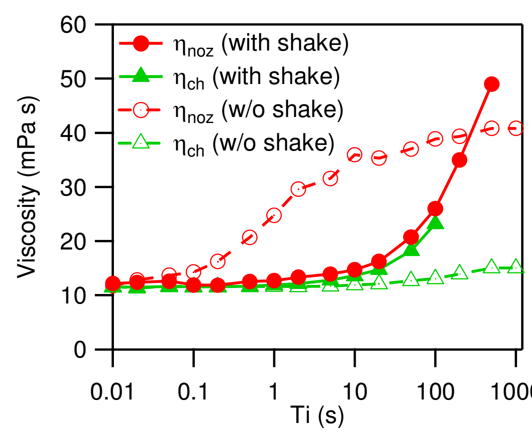

Figure 9 *Changes of viscosity by idle time with and without shaking pulses.*

Figure 9 shows the results of measured η_{noz} and η_{ch} with or without shaking pulses over the idle time. The shaking pulses have the same form as the jetting pulses but the voltage is smaller. When the shaking pulses are applied, the viscosity is kept much lower than without the shaking pulses until ten seconds. However, in the long term, the viscosity with the shaking pulses, especially η_{ch}, is higher than without the shaking pulses. Thus, the shaking pulses can keep the ink viscosity low at the nozzle, but they will promote the evaporation of the whole ink because fresh ink is always exposed on the surface of the nozzle by the shaking pulses. Figure 9 indicates that ink at the nozzle and in the pressure chamber is fully stirred by the shaking pulses since η_{noz} and η_{ch} become almost same value.

Discussion about drying process of ink

According to the theoretical study of Torpey [4] and Sengun [5], evaporation process of multi-component ink is described by the balance equation of evaporation, diffusion and convection as shown in equation (3).

$$\frac{\partial c_i}{\partial t}dx = -\frac{\partial}{\partial x}\left(Uc_i - D_i\frac{\partial c_i}{\partial x}\right)dx\,, \qquad (3)$$

Where c_i is the concentration of component i, t is the time, x is the distance from the nozzle surface, U is the convective velocity, and D_i is the diffusion coefficient of component i. By the equation (3), the distribution of the concentration of the ink components can be solved with two boundary conditions. One boundary condition is obtained from the meniscus surface, and the other is obtained from the supply channel which contains fresh ink. The concentration of component i at the nozzle will reach to an equilibrium condition at some time.

As mentioned in Fig. 7, the evaporation process of our system has two-step processes. In the first step, the ink concentration in the pressure chamber can be considered as constant. Therefore the ink concentration at the nozzle increases rapidly and reaches to the quasi-equilibrium point as predicted by the equation (3). When Ti becomes more than 100 seconds, the increasing of the ink concentration in the pressure chamber can be no longer ignored as shown in Fig. 9. Thus the the ink viscosity at the nozzle increases again. This is the second step shown in Fig.7

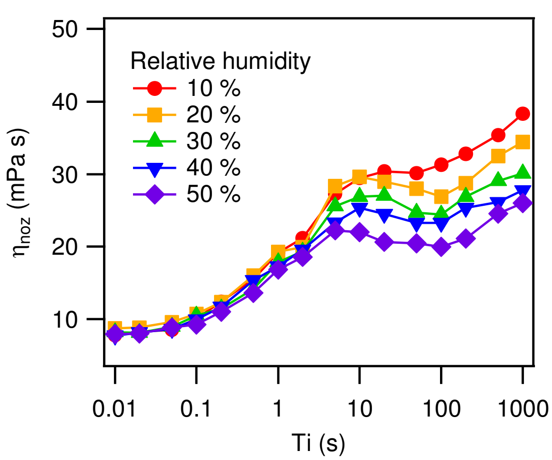

Figure 10 *Dependence of the changes of viscosity on relative humidity of surrounding air.*

Figure 10 shows the dependence of viscosity changes on relative humidity of surrounding air. Figure 10 indicates that the stable viscosity around 100s is determined by the relative humidity. This result is also qualitatively consistent with the theoretical model [4][5] in which the water concentration at the nozzles is determined by the relative humidity at the equilibrium condition.

Conclusion

In order to study the evaporation process at the inkjet nozzle, a novel method for measuring ink viscosity has been developed. In this method, the ink viscosity is derived from the meniscus vibrations measured by LDV. Furthermore, by observing the changes of the viscosity with jetting pulses, the ink viscosity at the nozzle η_{noz} and that in the chamber η_{ch} can be separately estimated.

The experimental results indicate two-step drying process about the ink viscosity. In the first step, the ink viscosity at the nozzle increases rapidly, and then reaches to the quasi-equilibrium point at around 100 seconds. In the following step, the ink viscosity at the nozzle increases again as the ink viscosity in the pressure chamber increases. The viscosity at the equilibrium point depends on relative humidity of surrounding air. These results are in a good agreement with the theoretical predictions.

References

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Author Biography

Manabu Seo received his M.S. degree in mechanical engineering from Kyoto University. In 2002, he joined Ricoh Company and has engaged in the research and development of optical measurement systems and laser processing systems. His research interests includes inkjet systems, optical measurement technologies, and color management.