Reflection Density Control Characteristics of Electro-Rheological Fluid Inkjet

Noriaki Kiyohiro and Yukihiro Hayakawa
Faculty of Engineering, Yamanashi University, Yamanashi, Japan

Introduction

Electro-rheological fluids (ERF) that respond to direct application of an electric field were first described by W. M. Winslow in 1947. The resistance to flow of this fluid can be increased extremely by applied electric fields. This means that a flow of ERF ink can be controlled by electric fields, so the jets expelled through a nozzle forced by an ink pressure can be generated at any time electrically. This type of drop on demand inkjet system was first described by Uezima in 1980. A print head structure of this type inkjet system is so very simple that a multinozzle print head can be manufactured easily. Moreover the composition of this fluid is similar to that of paint or lithographic printing ink, as ER fluid is composed of substantial particles, oily liquid and some active agents. Therefore, an ink jet system using high quality ink will be expected, so that this inkjet system will be applied to paintings on building walls or marking any characters on the card board boxes, because of using ink with color pigments and having relatively large nozzle diameter.

This paper shows theoretically that the ink volume ejected from the nozzle is varied linearly according to the off time of the voltage applied between the electrodes. This characteristic is capable of reflection density modulation by this inkjet system.

Theoretical Model of the Ink Flow

Figure l shows the schematic diagram of the print head. The plane figure of the print head is similar to that of Kyser type print head. The printing nozzle is connected to the ink supply by a hollow passage, which consists of a channel of rectangular cross-section. A couple of electrodes is placed to both upper and lower sides of the main channel.

The operation of the ERF ink jet breaks into two phases.

1. When a high voltage is applied between the electrodes, the sharing stress increases so that the ink is capable of sustaining a certain amount of pressure with no flow occurring.
2. If this applied voltage is zero, the ERF ink flows through the ink chamber because of decreased viscosity. Then the ink is ejected from the nozzle.

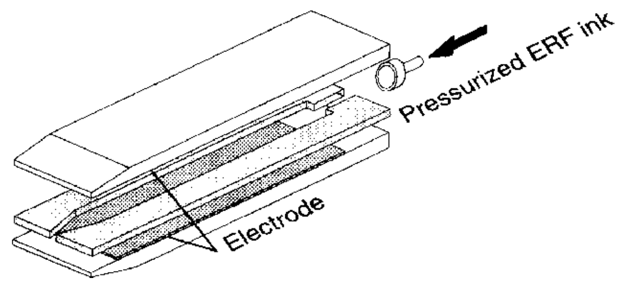

Figure 1. Schematic diagram of the print head

Conditions and assumptions in the model are as follows:

a. The fluid is incompressible.
b. A material of the print head is rigid, so the volume in the print head does not change.
c. Since Reynold's number is small, a flow in the print head is always laminar flow.
d. Viscosity and specific gravity of the ERF ink do not change for ejecting jet process, and equal spa tially in the print head.

Effect of the Shearing Stress Change

Figure 2 shows an example of the measured sharing stresses as a function of the share rates when the various static electric fields are applied to electrodes. When the electric field is not applied, the ERF has nature of ordinary Newtonian fluid and the slope of the tangent equals to a static coefficient of viscosity. As the applied electric field increases, the curve moves parallel upward.

As a shear rate is slippage between adjacent layers in fluid, and shearing stress is force exerted between those layers, an effective pressure exerted on the fluid decreases by the increased shearing stress at the same share rate. A force exerted on the fluid in the channel *ft* is

$$f_\tau = 2(l_0 + d_2) l_v \tau(t) \quad (1)$$

where, lc is a geometrical mean length of the print head. The other variables are shown in Figure 3.

Originally published in *Proc. of IS&T's Ninth International Congress on Advances in Non-Impact Printing Technologies,* October 4-8, 1993, Yokohama, Japan.

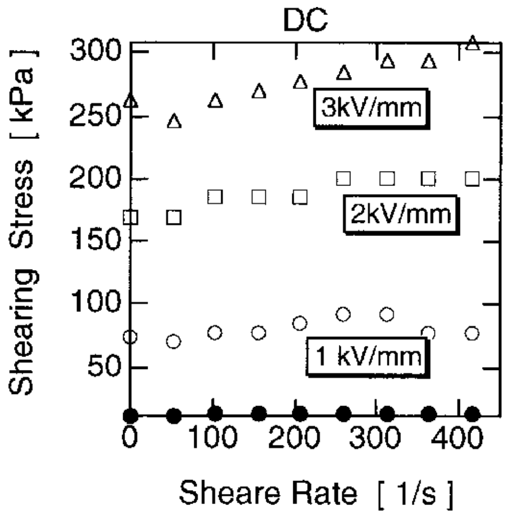

Figure 2. Shearing stress vs. shear rate for ERF with different static electrical field

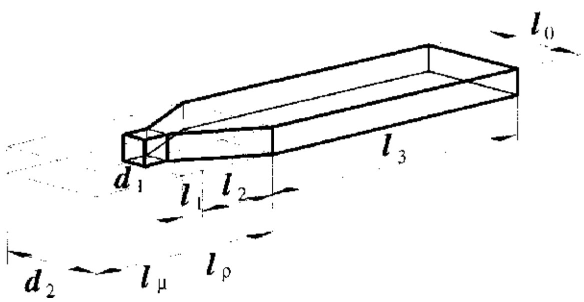

Figure 3. Shape of ink channel and variables

To solve a motion equation for the flow in the ink chamber, $p(t)$ should be estimated. The pressure exerted on the fluid is cancelled by the force due to the increased shearing stress. Then the effective pressure $p(t)$ is given

$$p(t) = p_0 - \tau(t)\frac{2(l_0 + d_2)}{l_0 d_2} \quad (2)$$

In equation (2), if the right member is negative we let $P(t)$ equal to zero.

Transaient Response of ERF

The transient response of the shearing stress of the ERF should be measured to obtain the function $p(t)$ from the equation (2). We already reported the measuring system and experimental results of the transient response of the ERF.[7] From those results, a time response caused by a step change of the electric field can be approximates by an exponential function. If we let an applied pressure to the ink p_0 equal to the maximum shearing stress, $p(t)$ is given by following two equations:

a. Time interval to when the voltage between the electrodes is zero.

$$p(t) = p_0\left\{1 - \exp\left(-\frac{t}{T_u}\right)\right\} \qquad (0 \le t < t_1) \quad (3)$$

b. After the time t_1, the voltage is applied between the electrodes again.

$$p(t) = -p_0 \exp\left(-\frac{t}{T_f}\right) \qquad (t > t_1) \quad (4)$$

where Tu and Tf are a time constant for the rising edge and falling edge respectively, and $p0$ is the pressure applied to the ERF ink. The wave form of $p(t)$ is shown in Figure 4. The time constant measured by the experiments are shown Table I.

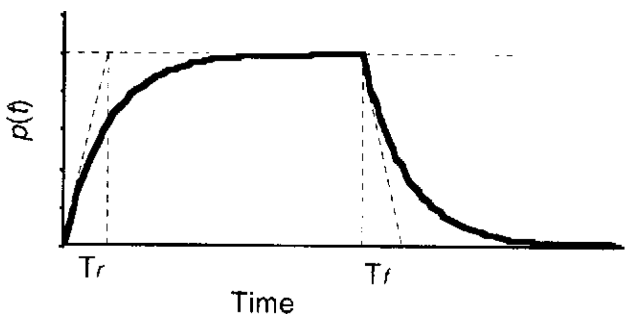

Figure 4. Effective pressure exerted to ER fluid

Table I. Measured Time Constant of ERF

Electric fields [v/mm]		2.4	2.4
Frequency [Hz]		DC	50
Time constant	raise	38.2	56.5
[ms]	fall	38.2	47.1

Equation of Motion

An equation for relating $p(t)$ to force exerted in moving fluid toward the nozzle is

$$p(t)A = \rho l_p A\frac{dv(t)}{dt} + \frac{12\mu l_\mu}{l_0^2}v(t)A \quad (5)$$

where A is a cross sectional area of the ink chamber, and v is a spatial average of the fluid velocity in the chamber. Density and viscosity of the ink are ρ and μ respectively. The factors lr and lm represent effective length of a channel having a cross sectional area A, but presenting the same inertial or viscous characteristics as the nozzle, the tapered section and parallel channel combined. The first and the second term in equation (1) represent a Newton's force of inertia and the viscous drag, respectively.

Effective Length

Since the thickness of the ink channel l_0 is considerably smaller than the channel width of the parallel part d_2, the viscous forces on the both vertical side walls of the channel are negligible. Then, the flow through the channel whose cross sectional area is rectangular is able to treat as flow through two parallel plane plates. In the actual print head, the ink channel has the tapered and narrow parts, those parts are converted to the viscous or inertial effective length, developed by Beasley[4] of a particular parallel ink channel that gives the same viscous resistance to fluid flow as does the tapered or narrow width part.

The viscous effective length of the ink channel is

$$l_\mu = \frac{16}{3}\,\frac{l_1}{\dfrac{16}{3}-\dfrac{1024}{\pi^5}\dfrac{l_0}{d_1}\tanh\dfrac{\pi d_1}{2l_0}}\,\frac{d_2}{d_1}+\frac{l_2 d_2}{d_1-d_2}\ln\frac{d_2}{d_1}+l_3 \qquad (6)$$

In the tapered or narrow section, inertial force increases by Pascal's principle. Furthermore, velocity and acceleration increase too. Then inertial effective length is

$$l_\rho = l_3 + d_2\left(\frac{l_2}{d_1-d_2}\ln\frac{d_1}{d_2}+\frac{l_1}{d_1}\right) \qquad (7)$$

Volume Expelled from the Nozzle

We obtain the ink velocity by solving equation (5) by substituting equaiton (3) and (4) respectively:

$$(0 \le t < t_1)$$
$$v_1(t) = \frac{p_0}{\rho l_\rho}\left[\frac{1}{\alpha}\{1-\exp(-\alpha t)\} - \frac{T_r}{T_r\alpha-1}\left\{\exp\left(-\frac{t}{T_r}\right)-\exp(-\alpha t)\right\}\right] \qquad (8)$$

$$(t > t_1)$$
$$v_2(t) = \frac{p(t_1)}{\rho l_\rho}\left[\frac{T_d}{T_d\alpha-1}\left\{\exp\left(-\frac{t-t_1}{T_d}\right)-\exp\left(-\alpha(t-t_1)\right)\right\}\right] + v_1(t_1)\exp\left(-\alpha(t-t_1)\right) \qquad (9)$$

where $\alpha = \dfrac{12\mu l_\mu}{\rho l_\rho l_0^2}$

By integrating equation (8) and (9) with respect to t, the volume ejected from the nozzle is

$$(0 \le t < t_1)$$
$$Q_1(t) = \frac{l_0 d_1 p_0}{\rho l_\rho}\left[\frac{1}{\alpha}t-\frac{1}{\alpha^2}\{1-\exp(-\alpha t)\} + \frac{T_r}{T_r\alpha-1}\left[\frac{1}{\alpha}\{1-\exp(-\alpha t)\}-T_r\left\{1-\exp\left(-\frac{t}{T_r}\right)\right\}\right]\right] \qquad (10)$$

$$(t < t_1)$$
$$Q_2(t) = l_0 d_1\left[\frac{p(t_1)}{\rho l_\rho}\frac{T_d}{T_d\alpha-1}\left[T_d\left\{1-\exp\left(-\frac{t-t_1}{T_d}\right)\right\} - \frac{1}{\alpha}\left\{1-\exp\left(-\alpha(t-t_1)\right)\right\}\right] + \frac{1}{\alpha}v_1(t_1)\left\{1-\exp\left(-\alpha(t-t_1)\right)\right\}\right] \qquad (11)$$

Experimental and Calculated Results

The DOD inkjet system for measuring the droplet volume is shown in Figure 5. The ink in the reservoir is pressurized by the pressure regulated compressed air. DC and AC voltages are generated by the high voltage switching circuit, driving signal is generated with the controller using v25 micro-controller code compatible to Intel 8086 CPU. The switching intervals and pulse width of the driving signal can be set arbitrary from the ten-key board. Droplet volume is measured from a high speed motion picture, which is taken with the camera made in our laboratory. One frame of the motion picture is digitized with the scanner, and calculates the volume with the personal computer. As the motion picture represents only two dimensional images, the assumption is made that the droplets have a circular cross section. The experimental and calculated results are shown in Figure 6.

Calculated results agree fairly with the experimental one after the ink is ejected entirely and forms the droplet.

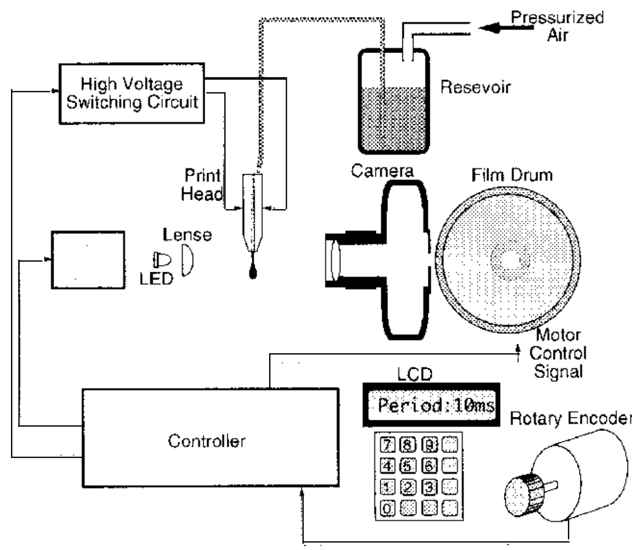

Figure 5. Experimental setup for measuring droplet volumes

Droplet Volume Modulation

A droplet volume ejected from nozzle is calculated according to the equation (8) and (9) as a function of the applied voltage off time. Figure 7 shows numerical results for several nozzle areas. Since the droplet volume is proportional to the applied voltage off time, ejected volume can be easily controlled. Therefore reflection density modulation might be realized in this inkjet system.

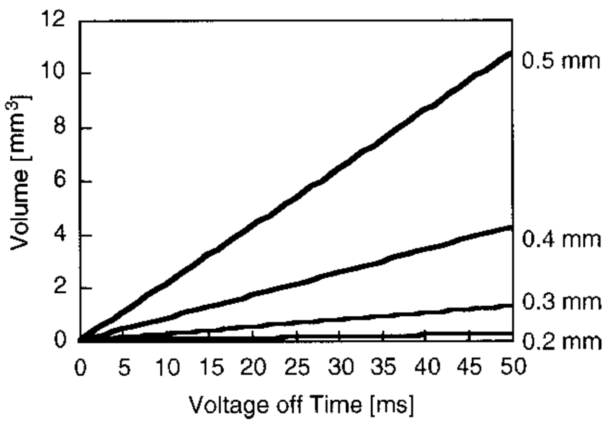

Figure 6. Ejected droplet volume vs. electric field off time with different nozzle aperture

Conclusion

Ejected volume of the ERF inkjet system is calculated using the model for a flow through the ink chamber. The results show that ejected drop volume is proportional to the electric field off time. Since it will be suitable for industrial applications that are required high printing quality and high UV lightfastness.

References

1. H. Uezima, Jap. Pat. 55-117, 663 (Sep. 10, 1980).
2. W. M. Winslow, U.S Pat. 2,417,850 (Mar. 25,1947).
3. W. M. Winslow, U.S. Pat. 2,661,596 (Dec. 8, 1953).
4. J. D. Beasley, *Photogr. Sci. Eng.*, **21**: pp. 78-82 (1977).
5. N. Kiyohiro, *Jap. Soc. Print. Sci. Tech.* **27**: pp. 21-27 (1990).
6. N. Kiyohiro, I. Sakabe, *Jap. Soc. Print Sci. Tech.* **29**: pp. 320-328 (1992).
7. N. Kiyohiro et al., *Proc. 8th International Congress on Advances in NIP Technologies*, pp. 340-342 (1992).
8. N. Kiyohiro et al., *Proc. 7th International Congress on Advances in NIP Technologies*, pp. 59-66 (1991).