

Measurement and Modeling of Drop Absorption Time for Various Ink-Receiver Systems

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Abstract

An inkjet visualization setup was used to measure the drop absorption time of various ink-receiver systems. The drop absorption time is defined as the time required for the receiver to completely absorb the impinging ink drop (i.e., the drop totally penetrates into the receiver and disappears from the receiver surface). The inkjet visualization setup consists of a piezo printhead with drive electronics, an aluminum drum for receiver support, a strobe light, a CCD camera, imaging optics, and image capture system. The drops ejected from the printhead have a volume of about 25 pL and a velocity of about 5 m/s. The receivers used in the measurements include both non-porous and porous receivers. Results indicate that non-porous receivers with swellable polymeric coatings have a much longer drop absorption time (>30 s) than those receivers with porous coatings (~33.3-100 ms). The difference in drop absorption time between non-porous and porous receivers can be ascribed to the basic difference in the physical mechanisms of ink penetration into the receiver, i.e., diffusion of ink in the polymeric receiver versus capillary flow of ink in the porous receiver. Based on these physical phenomena, simple one-dimensional models have been developed to describe the drop absorption process in the non-porous and porous receivers. The dependence of drop absorption time on the volume of ink drop and physical properties of ink (such as viscosity and surface tension) and receiver (such as diffusion coefficient and porosity) was also derived. Comparison of model results with experimental data will be presented and discussed.

Introduction

An inkjet visualization setup was developed to measure the drop absorption time of various ink-receiver systems. In the literature, the drop absorption time is also called the penetration time, adsorption time, wicking time, or dry time. The drop absorption time is defined as the time required for the receiver to completely absorb the impinging ink drop (i.e., the drop totally penetrates into the receiver and disappears from the receiver surface). In comparison, the drop absorption time is much shorter than the actual dry

time of the printed receiver, which is the time required for the printed receiver to return to its equilibrium moisture content through the evaporation of ink vehicle into the air. In designing an inkjet printing system, the drop absorption time is an important parameter with regard to printer speed, image transfer, and image quality. Ink receivers can broadly be classified into porous and non-porous receivers. In the former, capillary action is the mechanism for absorption of the ink drop whereas diffusion accounts for the absorption in the latter. Typically, the drop absorption time of a porous receiver is faster than a non-porous receiver by 2-4 orders of magnitude. We have developed simple models for both types of receivers. Comparison of model results with experimental data will be given and discussed.

Apparatus and Operation

Figure 1 shows the inkjet visualization setup. It consists of a piezo printhead with drive electronics, an aluminum drum for receiver support, a strobe light, a CCD camera, imaging optics, and image acquisition hardware and software, to support both still and video rate image capture. The drops ejected from the printhead have a velocity of about 5 m/s and a volume of about 25 pL.

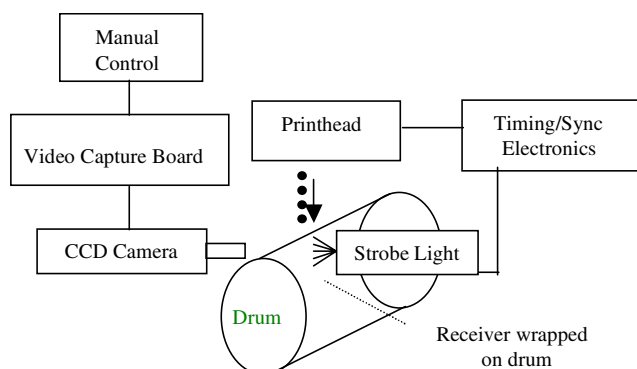


Figure 1. Experiment setup for studying ink-media interaction

In operation, the receiver is placed on the stationary drum and the camera takes a movie of the drop-receiver interaction (impact, lateral spreading, and penetration) at a rate of 30 frames/s. By observing the time at which the drop touches the receiver and the time at which the drop disappears from the receiver surface, we can determine the drop absorption time of the receiver. The accuracy in our measurements is about ± 33.3 ms.

Results of Drop Absorption Time Measurements Non-porous versus Porous Receivers

Table 1 shows the chemical compositions and physical properties of the inks used in the measurements. A number of popular OEM inkjet receivers having either non-porous or porous coatings were tested for their drop absorption times. The coating structure and formulation of these receivers are shown in Table 2. The measured drop absorption time for some selected ink-receiver systems are shown in Table 3. It is noted that non-porous receivers with polymeric coatings (Receiver A and B) have much longer drop absorption time (>30 s) than those receivers with porous coatings. The drop absorption times for the porous receivers range from 33.3 to 100 ms. The difference in drop absorption time between the polymer-coated receiver and the receiver with porous coating can be ascribed to the basic difference in the physical mechanisms of ink penetration into the receiver, i.e., diffusion of ink in the non-porous polymeric receiver versus capillary flow of ink in the porous receiver. Physically, the capillary flow process is much faster than the diffusion process by 2 to 4 orders of magnitude.¹

Table 1. Inks Used in Measurements of Drop Absorption Time

	Ink #1	Ink #2	Ink #3
Colorant	Dye	Dye	Dye
Viscosity (cP)	4.6	8.4	3.0
Surface tension (dyne/cm)	34	33	38

Table 2. Receivers Used in Measurements of Drop Absorption Time

Receiver	Coating Structure	Coating Composition
A	Non-porous	Gelatin/PVP
B	Non-porous	Cellulose
C	Porous	Colloidal silica/PVA
D	Porous	Silica chunks/PVA
E	Porous	Alumina sol-gel/PVA
F	Porous	Colloidal silica + silica/PVAc
G	Porous	Fumed alumina/PVA

Abbreviations: PVA = Polyvinyl alcohol; PVAc = Polyvinyl acetate; PVP = Polyvinylpyrrolidone

Table 3. Drop Absorption Time for Various Ink-Receiver Systems

Receiver	Drop Absorption Time (s)	
	Ink #1	Ink #2
A	>30	>30
B	>30	>30
C	0.667	0.367
D	0.0333	0.167
E	0.0333	---
F	0.0667	---

High-Viscosity Ink

A high-viscosity ink (Ink #2) was also tested with several receivers. Figure 2 shows the drop base width measured along the contact line with the receiver as a function of time for Receivers A and C. As the drop penetrates into the porous Receiver C, the base width of the drop decreases. When the base width reduces to zero, the time elapsed corresponds to the drop absorption time for the ink-receiver system. The measured drop absorption time for Receiver C is 0.367 s. On the other hand, the drop stays on the surface of the non-porous Receiver A for a long time and the drop absorption time is >30 s. As expected, these dry times are longer than those for Ink #1 because Ink #2 is more viscous than Ink #1.

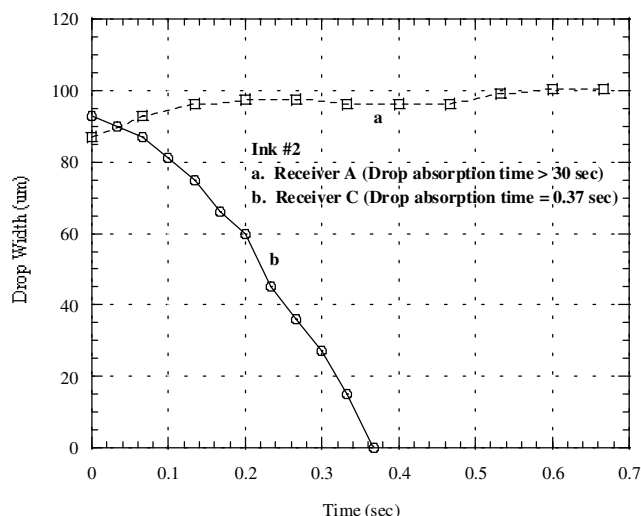


Figure 2. Drop width (measured along the contact line with the paper) vs time

Drop Absorption Time in Multidrop Printing

So far, we have measured the drop absorption time for only one ink drop applied to a given location (pixel) on the receiver. In high-quality inkjet printers, multidrop printing (at the same pixel) with multiple passes is commonly used to produce multiple tone (density) levels. To observe the effect of saturation of the receiver because of previously printed drops on the drop absorption time for the subsequent

drops, the receiver is bombarded with drops at the same pixel at a rate of 0.4 Hz. This corresponds to the ejection of one drop from the printhead every 2.5 s. In this experiment, Ink #2 was used to print on porous Receivers C and D. Results are shown in Fig. 3. For Receiver C, the drop absorption time for the n^{th} drop increases almost linearly with n . With Receiver D, while the first three drops dry faster than Receiver C the subsequent drops dry slower than Receiver C. This may be due to the difference in ink-absorption capacity between the two receivers.

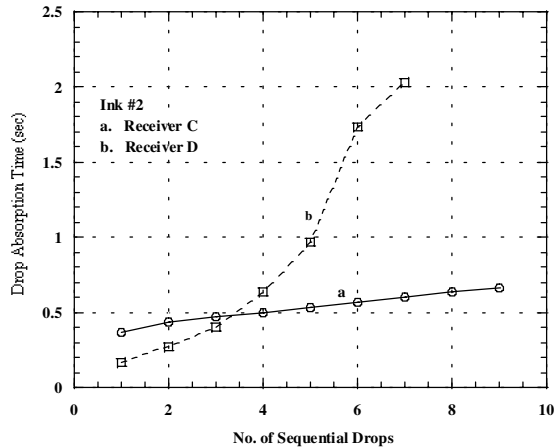


Figure 3. Drop absorption time vs number of sequential drops applied to the same location at a drop frequency of 0.4 Hz

Dependence of Drop Absorption Time On Drop Volume

In this measurement, we used a printhead that could eject drops of various volumes ranging from 8 to 64 pL. The drop absorption time for Ink #3-Receiver G system was measured for different drop volumes. Figure 4 plots the drop absorption time as a function of drop volume (in a log-log scale). The data were fitted by a linear function giving a slope of 0.6. This indicates that the drop absorption time would depend on the 0.6 power of the initial drop volume for this ink-receiver system.

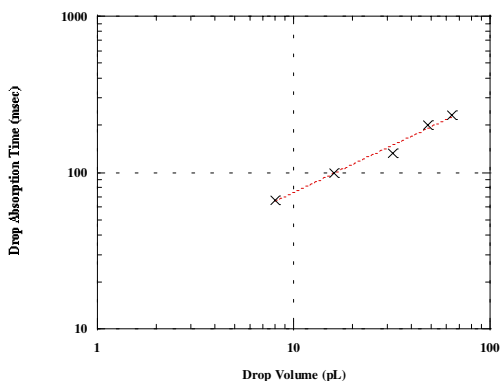


Figure 4. Drop absorption time vs drop volume

Theoretical Models

As shown in the previous section, the same ink non-porous receivers have significantly longer drop absorption times than porous receivers. This is primarily due to the difference in fluid transport mechanism between these two types of receivers, namely, the slow diffusion process for non-porous receivers versus the fast capillary flow process for porous receivers. Based on these phenomena, we develop simple models for the drop absorption time for both types of receivers. For simplicity, we assume that the wetted radius of the drop on the surface remains constant as the drop is absorbed. A general expression for the drop absorption time for non-constant wetted radius is given later.

Non-Porous Receivers

Let us consider a drop sitting on a receiver, which is infinite in the r and z directions as shown in Fig. 5. Initially, the drop has a volume V_0 and a wetted area on the receiver surface of radial extent R . Furthermore, let the drop lose volume only by diffusion in the z -direction. In this case, we have a simple one-dimensional diffusion problem. The time-dependent flux of fluid diffusing into the receiver can be shown to be²

$$F(t) = \sqrt{\frac{D}{\pi t}} \tag{1}$$

The rate of change of the drop volume is simply

$$\frac{\partial V}{\partial t} = -\pi R^2 F(t) \tag{2}$$

By integrating Eq. (2) over time, we obtain

$$V(t) - V_0 = -2\pi R^2 \sqrt{\frac{Dt}{\pi}} \tag{3}$$

where V_0 is the volume of the drop at $t = 0$. The time for the drop to disappear is given by setting $V(t) = 0$ at $t = t_d$. Thus, the drop absorption time can be expressed by

$$t_d = \frac{V_0^2}{4\pi R^4 D} \tag{4}$$

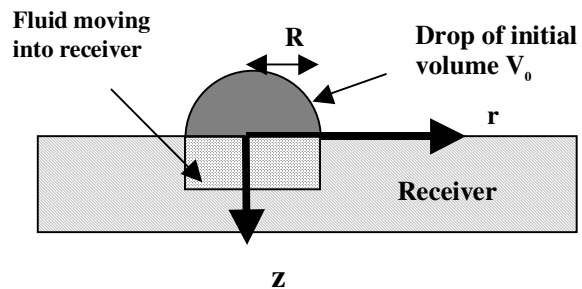


Figure 5. Geometry of drop absorption by a receiver

Porous Receivers

We again consider a drop sitting on the receiver with a wetted area of radial extent R . Let the drop lose volume by capillary action only in the z -direction. Thus, as before, we have a one-dimensional fluid transport problem. The media has porosity, ϕ , which is the ratio of void volume to total volume of the receiver.

At time t , the fluid has penetrated a distance $\xi(t)$ into the receiver forming a wetting front. We assume that behind the wetting front, the receiver is completely saturated whereas ahead of the front, the receiver is completely unsaturated. The wetting front advancing into the dry media serves as a boundary for the flow domain behind the front.³ This boundary is treated as a surface at which the pressure is equal to p_c , the capillary pressure. For an incompressible fluid, the velocity of the fluid \mathbf{q} can be described by Darcy's law³

$$\mathbf{q} = -\frac{k}{\mu} \nabla p \quad (5)$$

Here, k is the permeability of the receiver with units of length-squared, μ the fluid viscosity, and p the pressure.

Combining Darcy's law and the incompressibility of the fluid, we have

$$\nabla^2 p = 0 \quad (6)$$

for the region behind the wetting front. This equation can be solved analytically in one dimension with boundary conditions $p = 0$ at the receiver surface ($z = 0$) and $p = p_c$ at the location of the front. The solution is:

$$p(z, t) = \frac{p_c}{\xi} z \quad \text{for} \quad 0 \leq z \leq \xi \quad (7)$$

The Darcy fluid velocity, q , divided by the porosity gives the average velocity of the front through the receiver

$$V_f = \frac{q}{\phi} = \frac{d\xi}{dt} = \frac{k}{\phi\mu} \left. \frac{dp}{dz} \right|_{z=\xi} = \frac{k}{\phi\mu} \frac{p_c}{\xi} = \frac{2\lambda}{\xi} \quad (8)$$

where we have set $\lambda = kp_c/2\mu\phi$. This equation can be integrated to give

$$\xi(t) = 2(\lambda t)^{1/2} \quad (9)$$

The total volume of fluid in the drop at any time t is given by the initial volume of the drop minus the amount of fluid in the receiver:

$$V(t) = V_0 - \pi R^2 \phi \xi(t) \quad (10)$$

Finally, the time for the drop to disappear is

$$t_d = \frac{V_0^2}{4\pi^2 R^4 \lambda \phi^2} \quad (11)$$

Note that λ has units of length-squared/time as does the diffusion constant.

A General Expression

In the previous sections the expression for the drop absorption time is based on the assumption that the wetted radius is constant. For non-constant wetted radius, a general expression⁴ relating the drop volume to the time for the drop to be absorbed by both non-porous and porous receivers can be written as:

$$t_d = \frac{V_0^2}{4\pi^2 R^4 \Lambda \alpha}, \quad \Lambda = \begin{cases} \frac{D}{\pi} & \text{for non-porous receivers} \\ \frac{kp_c \phi}{2\mu} & \text{for porous receivers} \end{cases} \quad (12)$$

where V_0 is the initial drop volume, R is the maximum radius of the wetted area on the surface, Λ is defined as the transport coefficient of the receiver, and α is a correction factor that depends on how the drop spreads and is usually less than one. Because πR^2 is the area of the drop on the surface, the drop absorption time is essentially given by the square of a volume divided by an area, divided by a transport coefficient. If we further assume that R is a function of the drop volume, say $R = fV_0^{1/3}$ where f is a geometric pre-factor, we have the following equation for the drop absorption time:

$$t_d = \frac{V_0^{2/3}}{4\pi^2 f^4 \Lambda \alpha} \quad (13)$$

It is noted that based on the above model the drop absorption time varies with the 2/3 power of drop volume [Eq. (13)]. This compares well with the 0.6 power dependence obtained by experiment (see Fig. 4).

Model Results

As an example, we can use the above formulas to estimate drop absorption times for non-porous and porous receivers as a function of drop volume and various ink and receiver parameters.

Using Ink #1, the drop has a viscosity of 4.6 cP, surface tension of 34 dyne/cm. For the non-porous receiver A, a diffusion constant of 1.6×10^{-8} cm²/s is assumed. For porous receiver C made up of particles of diameter d , we use the following relations for the permeability and capillary pressure^{3,5}

$$k = \frac{d^2 \phi^3}{180(1-\phi)^2}, \quad p_c = \frac{6\sigma(1-\phi)\cos\theta}{d\phi}, \quad \alpha = \frac{1}{2} \quad (14)$$

where θ is the contact angle that the fluid makes with the pore wall. We have used $d = 0.05$ microns, $\theta = 50$ degrees, and porosity, $\phi = 0.60$. The result is shown in Fig. 6 where we plot the drop absorption time as a function of drop volume. (Note that the values for the porous receiver have

been multiplied by 1000.) The porous receiver has a drop absorption time about 3 orders of magnitude faster than the non-porous receiver. For a drop of 25 pL, the drop absorption time for the non-porous and porous receivers are 16 s and 27 ms, respectively. These results are consistent with the experimental data (see Table 3).

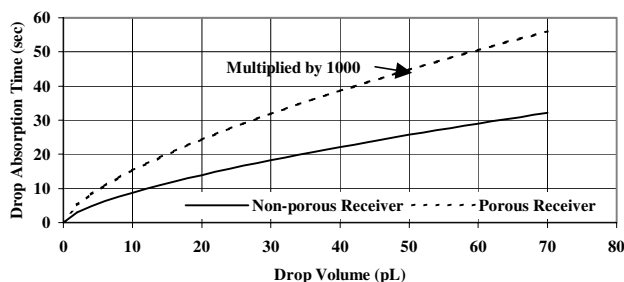


Figure 6. Drop absorption time vs drop volume

The models also predict that the dependence of drop absorption time on drop volume follows the $2/3$ power law [Eq. (13)]. However, the above models assume that the penetration of fluid into the media is one-dimensional. We have some numerical evidence from simulations using a commercial fluid dynamics code and also from solving the diffusion equation in the radial as well as the z direction that this power law relationship still holds⁴.

Summary

An inkjet visualization setup has been constructed to study the ink-receiver interaction and measure the drop absorption time. The drops from the printhead have a volume of about 25 pL, and a velocity about 5 m/s. We have quantitatively measured the drop absorption time for various ink-receiver systems with an accuracy of ± 33.3 ms. Results indicate that receivers with non-porous polymeric coatings have much longer drop absorption times (>30 s) than receivers with porous coatings (about 33.3–100 ms). This is primarily due

to the difference in fluid transport mechanism between these two types of receivers, namely, the slow diffusion process for non-porous receivers versus the fast capillary flow process for porous receivers. Based on these phenomena, simple models for both types of receivers have been developed. Although model results are consistent with experimental data, further refinements of the models are clearly needed to understand the complex ink-receiver interaction. These include the extension of the one-dimensional models into two-dimensional formulations as well as the allowance for a changing wetting radius on the surface. In summary, the experimental setup and theoretical models described in this paper could be a very useful tools to evaluate the drop absorption time of any ink-receiver systems.

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Biography

Kwok Yip received his Ph.D. degree in Physics from Lehigh University in 1973. From 1975 to 1984 he worked in the Wilson Center for Research and Technology at Xerox Corporation in Webster, NY. Since 1984, he has worked in the Kodak Research Laboratories. His recent work has focused on the physics of inkjet printing. He is a member of the IS&T and the American Physical Society.