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

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An ink jet instrument 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 instrument consists of a piezo printhead with drive electronics, a stage 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/sec. The receivers used in the measurements include both non-porous and porous receivers. Results indicate that nonporous receivers with swellable polymeric coatings have much longer drop absorption time (>30 sec) than those receivers with porous coatings (~33-100 msec). 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 are presented and discussed.

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Introduction

An ink jet instrument was developed 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. 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 ink jet printing system, the drop absorption time is an important parameter with regard to printer speed, image transfer, and image quality. Ink receivers can be classified broadly to 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.

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Supplemental Materials—Apppendix can be found on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.

Apparatus and Operation

Figure 1 shows the schematic of the instrument. It consists of a piezo printhead with drive electronics, a stage 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/sec and a volume of about 25 pL. The technique used to measure the drop velocity has been described in the literature.[1]

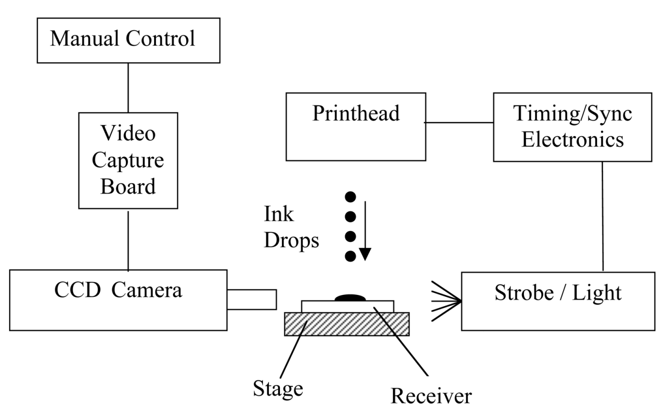

Figure 1. Instrument used for studying ink-media interaction.

TABLE I. 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 (dynes/cm)	34	33	38

TABLE II. Receivers Used in Measurements of Drop Absorption Time

Receiver	Coating Structure	Coating Composition
A	Non-porous	Gelatin/PVP
B	Non-porous	Methyl cellulose
C	Porous	Colloidal silica/PVA
D	Porous	Amorphous silica chunks of irregular sizes/PVA
E	Porous	Alumina sol-gel/PVA
F	Porous	Colloidal silica + silica/PVAc
G	Porous	Fumed alumina/PVA

Abbreviations: PVA = Polyvinylalcohol; PVAc = Polyvinylacetate; PVP = Polyvinylpyrrolidone

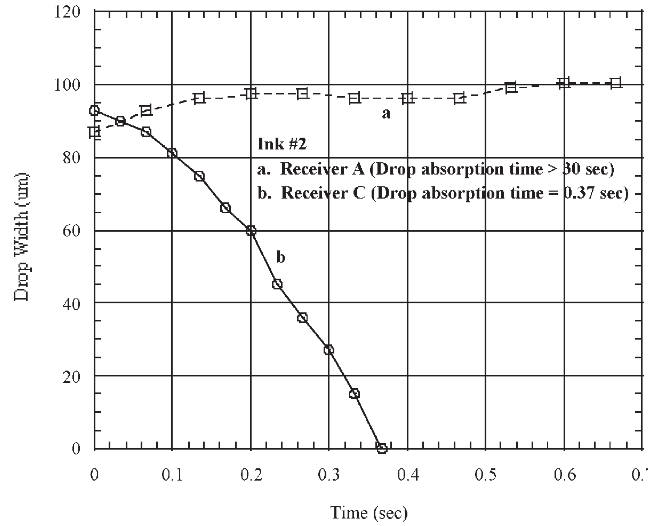

Figure 2. Drop width measured along the contact line with the paper versus time.

TABLE III. Drop Absorption Times for Various Ink-receiver Systems

Receiver	Drop Absorption Time (sec) Ink #1	Ink #2
A	> 30	> 30
B	> 30	> 30
C	0.0667	0.367
D	0.0333	0.167
E	0.0333	—
F	0.0667	—
G	0.1000	—

In operation, the receiver is placed on the stationary stage and the camera takes a movie of the drop-receiver interaction (impact, lateral spreading, and penetration) at a rate of 30 frames/sec. 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 was about ± 33 msec.

Results of Drop Absorption Time Measurements

Non-Porous Versus Porous receivers

Table I shows the chemical compositions and physical properties of the inks used in the measurements. While the viscosity of the inks was measured with a Brookfield viscometer, the static surface tension was measured with a Kruss tensiometer. Both the viscosity and the surface tension of the ink are important factors in determining the drop absorption time of a receiver. A number of popular OEM ink jet receivers having either non-porous or porous coating were tested for their drop absorption times. The coating structure and formulation of these receivers are shown in Table II. The measured drop absorption times for some selected ink-receiver systems are shown in Table III. It is noted that non-porous receivers with polymeric coatings (receivers A and B) have much longer drop absorption time (>30 sec) than those receivers with porous coatings (≤ 0.1 sec for receivers C, D, E, F, and G). The drop absorption times for the porous receivers are range from 33 to 100 msec. However, it is possible that the absorption time for the porous receivers could be shorter than the accuracy of the measurement, i.e., 33 msec. 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.[2]

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 0.37 sec. 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 sec. As expected, these dry times are longer than those for the ink #1 since the ink #2 is more viscous than ink #1.

Drop Absorption Time in Multi-Drop 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 ink jet printers, multi-drop 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, due to 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 in every 2.5 sec. In this experiment, ink #2 was used to print on porous receivers C and D having ink absorption capacities of 25 and 22 mL/m^2, respectively. Results are shown in Fig. 3. For receiver C, the

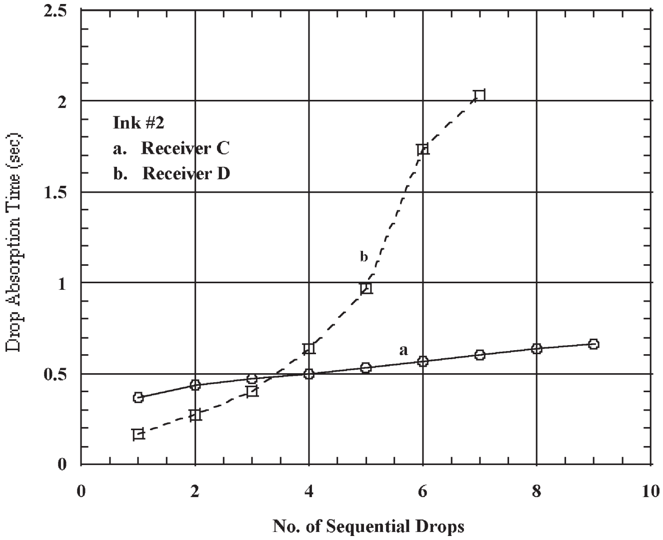

Figure 3. Drop absorption time versus number of sequential drops applied to the same location at a drop frequency of 0.4 Hz.

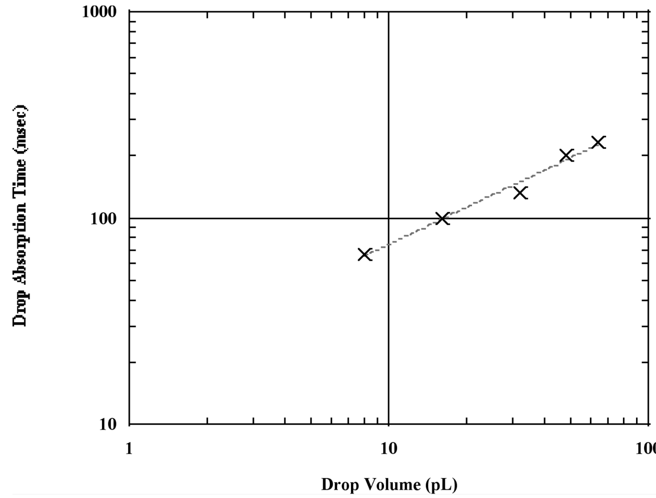

Figure 4. Drop absorption time versus drop volume.

drop absorption time for the n-th drop increases almost linearly with n. With receiver D, while the first three drops dry faster than on receiver C, the subsequent drops dry slower than on receiver C. This may be due to the difference in ink absorption capacity between the two receivers.

Dependence of Drop Absorption Time on Drop Volume

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

Theoretical Models

As discussed above, with 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 below.

Non-Porous Receivers

Let us consider a drop sitting on a receiver that 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. Assuming that the diffusion process is Fickian with a constant diffusion constant D, we have

$$\frac{\partial c(z,t)}{\partial t} = D\frac{\partial^2 c(z,t)}{\partial z^2} \tag{1}$$

where $c(z,t)$ is the concentration of the fluid at time t and position z in the receiver. The boundary conditions are

$$c(0,t) = c_0$$
$$c(\infty,t) = 0$$
$$c(z > 0,0) = 0$$

where $c_0 = \rho/M_w$ is the concentration of fluid in the drop with density ρ and molecular weight M_w. The solution of this problem is given by[3]

$$c(t) = c_0 - c_0 erf\left(\frac{z}{2\sqrt{Dt}}\right) \tag{2}$$

where $erf(\cdot)$ is the error function. The time-dependent flux of fluid diffusing into the receiver can be shown to be

$$F(t) = \sqrt{\frac{D}{\pi t}} \tag{3}$$

The rate of change of the drop volume is simply

$$\frac{\partial V}{\partial t} = -\pi R^2 F(t) \tag{4}$$

By integrating Eq. (4) over time, we obtain

$$V(t) - V_0 = -2\pi R^2\sqrt{\frac{Dt}{\pi}} \tag{5}$$

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

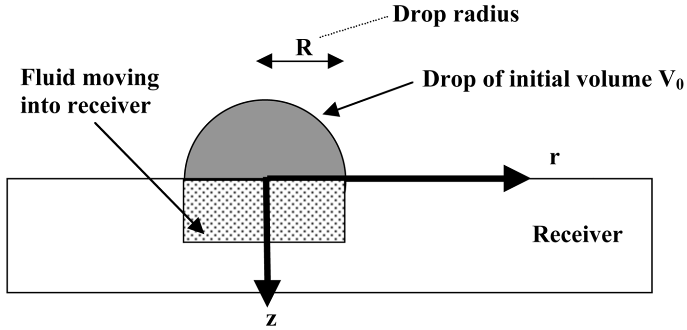

Figure 5. Geometry of drop absorption by a receiver.

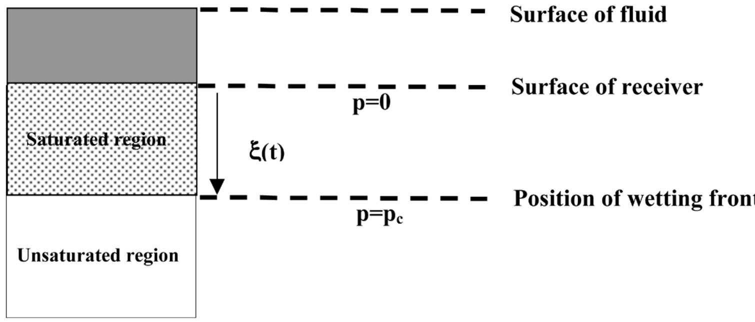

Figure 6. Wetting front of fluid penetration into porous receiver.

$$t_d = \frac{V_0^2}{4\pi R^4 D} \tag{6}$$

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 as shown in Fig. 6. 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 **q** can be described by Darcy's law[4]

$$\mathbf{q} = \frac{k}{\mu}\nabla p \tag{7}$$

Here, k is the permeability of the receiver with units of length-squared, μ the fluid viscosity, and p the pressure. Also for an incompressible fluid, the conservation of mass yields that the divergence of the fluid velocity is zero,

$$\nabla \bullet \mathbf{q} = 0 \tag{8}$$

Combing this with Darcy's law we have,

$$\nabla^2 p = 0 \tag{9}$$

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:

$$p(z,t) = \frac{p_c}{\xi} z \quad \text{for} \quad 0 \le z \le \xi \tag{10}$$

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

$$V_f = \frac{q}{\phi} = \frac{d\xi}{dt} = \frac{k}{\phi\mu}\frac{dp}{dz}\bigg|_{z=\xi} = \frac{k}{\phi\mu}\frac{p_c}{\xi} = \frac{2\lambda}{\xi} \tag{11}$$

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

$$\xi(t) = 2(\lambda t)^{1/2} \tag{12}$$

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:

$$V(t) = V_0 - \pi R^2 \phi \xi(t) \tag{13}$$

Finally, the time for the drop to disappear is

$$t_d = \frac{V_0^2}{4\pi^2 R^4 \lambda \phi^2} \tag{14}$$

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 expression relating the drop volume to the time for the drop to be absorbed by both nonporous and porous receivers can be written as:

$$t_d = \frac{V_0^2}{4\pi^2 R^4 \Lambda\alpha} \quad \Lambda = \begin{cases} \dfrac{D}{\pi} & \text{for non-porous receivers} \\ \dfrac{kp_c\phi}{2\mu} & \text{for porous receivers} \end{cases} \tag{15}$$

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. The derivation of Eq. (15) will be given in the Appendix (available as Supplemental Material on the IS&T website, http://www.imaging.org). If the drop maintains a constant wetted radius during spreading, α is equal to unity. Otherwise, α is less than one. Since πR^2 is the area of the drop on the surface, then 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, then we have the following equation for the drop absorption time:

$$t_d = \frac{V_0^{2/3}}{4\pi^2 f^4 \Lambda\alpha} \tag{16}$$

Assuming that the drop initially forms a spherical cap on the receiver surface, the geometric pre-factor f can be expressed by[5,6]

$$f^{-1} = \left\{\frac{\pi}{3\sin^3\Theta}\left(2 - 3\cos\Theta + \cos^3\Theta\right)\right\}^{\frac{1}{3}} \tag{17}$$

where Θ is the angle that the drop makes with the surface of the receiver. Based on this model the drop absorption time varies with the 2/3 power of drop volume (Eq. (16)). 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 nonporous 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 dynes/cm, and makes an angle Θ of 35 degrees with both the non-porous and porous receiver surfaces. 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[4,7]

$$k = \frac{d^2\phi^3}{180(1-\phi)^2} \qquad p_c = \frac{6\sigma(1-\phi)\cos\theta}{d\phi} \tag{18}$$

where θ is the contact angle that the fluid makes with the pore wall. We have used d = .05 microns, θ = 50 degrees, and porosity, ϕ = 0.60. Here, we also assume that the correction factor α is equal to 1.0 for the non-porous receiver. This corresponds to the observation that the wetted radius remains constant while the ink drop is absorbed. In other words, the drop is pinned to the surface during absorption. For the porous receiver, the correction factor α is assumed to be 0.50. In this case, the wetted radius shrinks as the drop penetrates into the receiver. The result is shown in Fig. 7 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 17 sec and 15 msec, respectively. These results are consistent with the experimental data of >30 sec and 67 msec for the non-porous and porous receivers, respectively (see Table III).

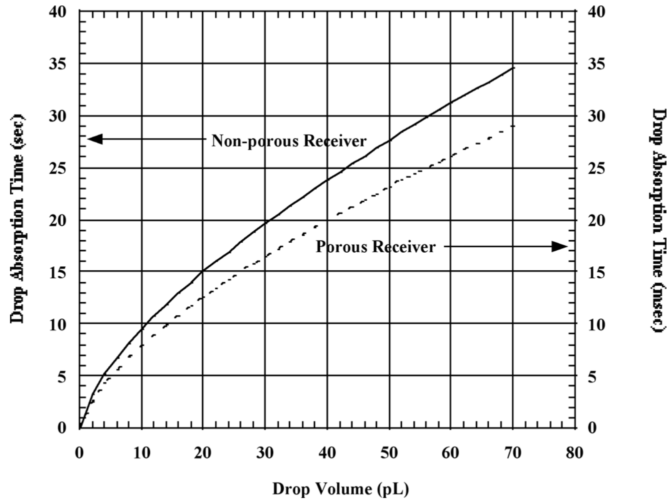

Figure 7. Calculated dependence of drop absorption time on drop volume.

The models also predict that the dependence of drop absorption time on drop volume follows the 2/3 power law (Eq. (16)). However, the above models assume that the penetration of fluid into the media is one-dimensional.

Summary

An ink jet instrument 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/sec. We have quantitatively measured the drop absorption time for various ink-receiver systems with an accuracy of ± 33 msec. Results indicate that receivers with non-porous polymeric coatings have much longer drop absorption times (> 30 sec) than receivers with porous coatings (about 33 – 100 msec). 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-re-

ceiver 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 should be very useful tools for evaluating the drop absorption time of any ink-receiver systems.

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