Impact of an Ink Drop on Paper

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Abstract

Dynamical spreading of an ink drop impacting on paper has been investigated experimentally. Ink drops of various sizes and velocities, impacting on paper, were observed by a microscope with stroboscopic lighting. Experimental data are explained well by a simple correlation formula, which predicts the ratio of spreading as a function of the Weber number and the Reynolds number. This experimental formula can be conveniently used in the design of ink jet printers.

Introduction

The size of a printed dot in inkjet printing, which greatly affects the print quality,[1] is determined by the spreading of an ink drop impacting on paper. The spreading phenomenon consists of two consecutive physical processes: dynamical spreading and penetration into paper. The dynamical spreading process is important in that it gives the starting condition of the penetration process. In this study, the former process is considered. Special attention is paid to the *ratio of spreading*, because it greatly affects the penetration time and the final dot size.

The dynamical spreading of a liquid drop has been investigated in various fields of engineering. Engel[2] observed the impact of a water drop on solid surfaces, in connection with the cavitation damage. He proposed an empirical formula based on the maximum radius of the drop, including the time of spreading as a parameter. The time of spreading, however, cannot be determined *a priori*. Cheng[3] proposed a simple formula that predicts the ratio of spreading as a function of the Weber number. Although this formula is easy to use, the validity is lost if the drop size is so small that the effect of viscosity is important, as in inkjet printing. Furthermore, the effect of paper surface on the dynamical spreading is not clear.

Numerical simulation methods to predict the behavior of the drop have been developed by several authors. Bechtel et al.[4] presented an assumed flow pattern method based on a truncated sphere model. Takahashi et al.[5] presented an improved MAC method to solve the Navier-Stokes equation. Although these methods may reproduce the phenomenon precisely, they are not easy to use, because of their complexity. Thus a simple formula for the ratio of spreading is desired.

In this study, ink drops of various sizes and velocities, impacting on paper, are observed by a microscope with stroboscopic lighting. A simple correlation formula, which predicts the ratio of spreading as a function of the Weber number and the Reynolds number, is proposed on the basis of the experimental data. This formula can be conveniently used in the design of inkjet printers.

Experimental

Figure 1 shows a schematic diagram of the experimental arrangement. Ink drops were periodically generated by a piezoelectric inkjet printing head and hit the paper perpendicularly. The size and the velocity of ink drops were controlled by the electric pulse applied to the head. Behavior of ink drops was observed by a microscope and a CCD camera, with stroboscopic lighting synchronized to the driving pulse, and were recorded on a VTR. Because the spreading phenomenon was faster than the framing rate of the CCD camera (1/60 sec), different stages of the phenomenon were observed by changing the delay of lighting. The paper surface was kept fresh for the impact of each drop by using a paper feeder.

The drop diameter and the impacting velocity were varied in the ranges 44-81 μm and 2.5-20 m/sec, respectively. Three types of water-based ink were used, with viscosity and surface tension ranges 2.0-7.5 cP and 50-54 dyne/cm, respectively. Two types of plain paper, four types of coated paper, and a transparent film for ink-jet printing were used.

Results and Discussion

Behavior of an Ink Drop

Figure 2 shows the behavior of an ink drop impacting on paper. The reproducibility of the spreading phenomenon under constant conditions was good. Ink drops began to spread in several microseconds and reached their maximum radius in 10-20 μsec after they touched the paper surface. The shape of a drop at its maximum radius was a flat disk, as shown in Figure 2. The behavior of drops was similar under all experimental conditions.

Parameters Affecting the Ratio of Spreading

The maximum drop diameter, D^*, is very important, because it gives the starting condition of the ink pen-

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etration process and greatly affects the penetration time and the final dot size. Because of the dynamical similarity, the ratio of spreading, D^*/d, should be determined by the Weber number, the Reynolds number, the contact angle of ink to the paper, and the roughness of the paper surface. Here the Weber number, *We*, and the Reynolds number, *Re*, are nondimensional numbers defined by

$$We = \frac{\rho d u^2}{\sigma}, \quad \mathrm{Re} = \frac{\rho d u}{\mu}, \tag{1}$$

where d, u, ρ, μ, and σ are diameter, velocity, density, viscosity, and surface tension of the ink drop, respectively.

According to the experiment, D^*/d was the same for different types of paper if *We* and *Re* were approximately the same. Table I shows an example of results. It was observed that D^*/d was determined only by *We* and *Re* for other pairs of *We* and *Re* and for other types of paper. The surface of the ink drop at its maximum radius was uneven if the paper surface was rough.

Correlation Formula for the Ratio of Spreading

In order to construct a correlation formula, we consider a simple theoretical model of drop impact. We assume that the shape of the drop at its maximum spreading is a disk of diameter D^* and height h^*, that the paper surface is perfectly flat, and that the contact angle of ink to paper is 90°. These assumptions are justified by the results of the preceding subsections.

From the consideration of energy and volume, we obtain

$$\frac{\pi\rho d^3 u^2}{12} + \pi\sigma d^2 = E_k + F_k + \sigma S^*, \quad \frac{\pi d^3}{6} = \frac{\pi D^{*2} h^*}{4}, \tag{2}$$

where E_k is the kinetic energy, F_k is the energy dissipation, and S^* is the surface area of the drop at its maximum spreading:

$$S^* = \frac{\pi D^{*2}}{4} + \pi D^* h^*. \tag{3}$$

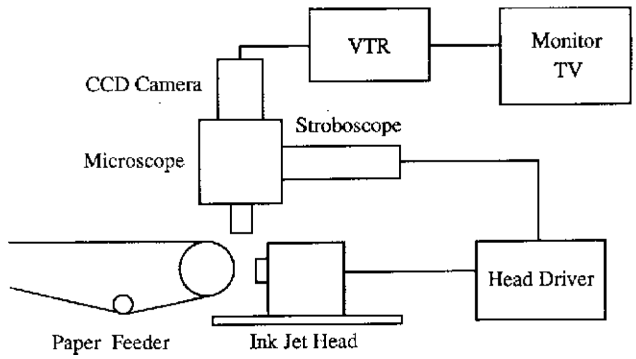

Figure 1. Schematic diagram of the experimental arrangement

Table I. Ratio of spreading, *D* / d*, for Various Papers

Type of paper	*We*	*Re*	*D*/d*
Copy paper	5.3	56.8	1.42
Bond paper	5.6	59.6	1.43
Transparent film	5.5	58.7	1.42

The left-hand side and the right-hand side of Eq. 2 correspond to the ink drop before impact and at its maximum spreading, respectively. Because

$$\frac{S^*}{\pi d^2} \approx 1 + 0.36\left(\frac{D^*}{d} - 1\right)^2, \tag{4}$$

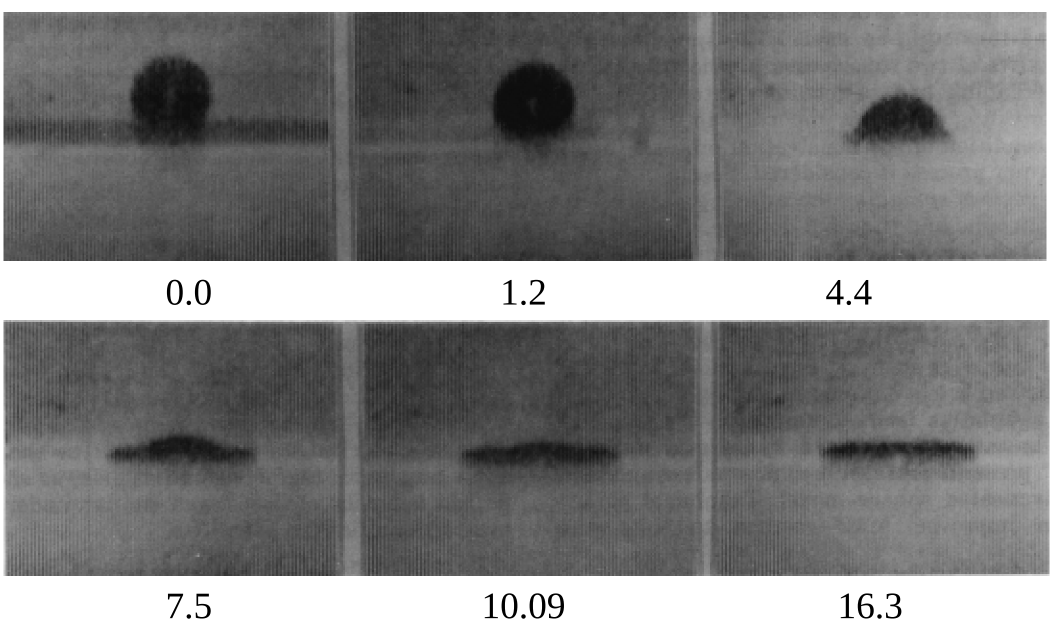

Figure 2. Behavior of a drop impacting on paper. Digits indicate the time (μsec) after the contact.

for $1 < D^*/d < 3$, we obtain

$$\frac{D^*}{d} \approx 1 + 0.48 We^{0.5} X,$$
$$X \equiv \left[1 - \frac{E_k + F_k}{\pi \rho d^3 u^2 / 12}\right]^{0.5}. \quad (5)$$

If we assume that the nondimensional number X has the following form:

$$X = \exp[- aWe^b Re^c] \quad (6)$$

and determine the values of a, b, and c by matching to the experimental data, we obtain the following correlation formula:

$$\frac{D^*}{d} = 1 + 0.48 We^{0.5} \exp[-1.48 We^{0.22} \mathrm{Re}^{-0.21}]. \quad (7)$$

Figure 3 shows a graphical representation of Eq. 7. Figure 4 shows the comparison of Eq. 7 and the experimental data. The agreement of the correlation formula and the experimental data is very good. This correlation formula can be conveniently used to predict the ratio of spreading, D^*/d, which is important in the design of inkjet printers.

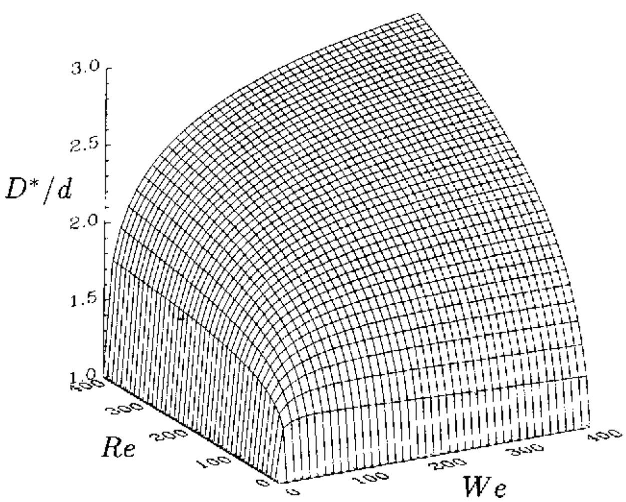

Figure 3. Graph of Eq. 7

Conclusions

It was observed that the ratio of spreading was determined only by the Reynolds number and the Weber number, independently of paper characteristics. Experimental data, in which the ratio of spreading ranged 1-3, were explained well by a simple correlation formula. This correlation formula can be conveniently used in the design of inkjet printers.

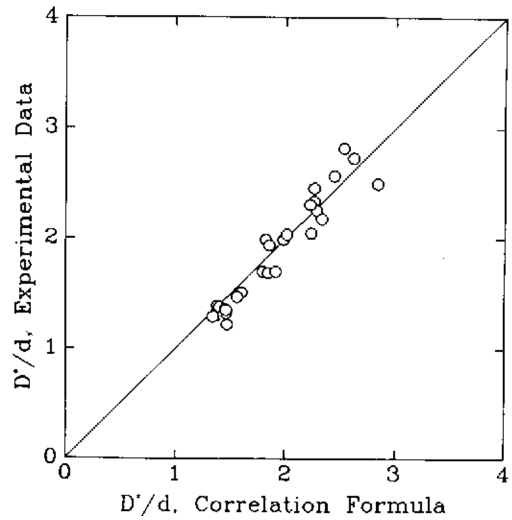

Figure 4. Comparison of the correlation formula and the experimental data for the ratio of spreading

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