Effects of Particles on Drop Impingement

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Abstract

In traditional ink-jet-printing technology, dye-based inks are primarily used. To satisfy the demands of printing on textiles, there is a need for inks containing binder and pigment particles. While progress has been made in developing particle-laden inks for use in inkjet printers, little effort has been made to understand in detail the role of particles in the overall process. In fact there is little in the refereed literature about drop formation, impaction, and spreading phenomena for particle-laden liquids although these processes have been studied extensively in the past for pure liquids. A study of the spreading dynamics of a particle-laden drop impacting a surface will be presented.

Introduction

Pure liquid drop impaction on solid surfaces has been studied for over 100 years.[1-19] In contrast to the situation for pure liquids, drop impaction of particle-laden drops on surfaces have received little attention despite their importance in a variety of applications such ink jet printing. In fact, we have found only one publication[20] in the refereed literature on drop impaction of particle-laden drops on surfaces.

In traditional ink-jet-printing technology, dye-based inks are primarily used. To satisfy the demands of printing on textiles, there is a need for inks containing binder and pigment particles. While progress has been made in developing particle-laden inks for use in inkjet printers, little effort has been made to understand in detail the role of particles in the overall process. This study addresses the spreading dynamics of a particle-laden drop impacting a surface. The goal of the study is to develop understanding of how and why solid particles at a range of concentration affect the drop impaction process in order to support improved engineering of textile inkjet printing. The effects of the following parameters will be presented: volume fraction of particles (ϕ), particle size, and ratio of particle size to drop size.

Impact Process

When a drop impinges on a surface, several things can happen. At high impact speeds, the drop may break up or flow out radially in what is referred to as crown shape (the axisymmetric flow is not stable and thus the flow is not uniform in all directions).[6,14] If the spreading drop does not break up, the drop/substrate interaction can be separated into three stages: spread, retract, and equilibrium.

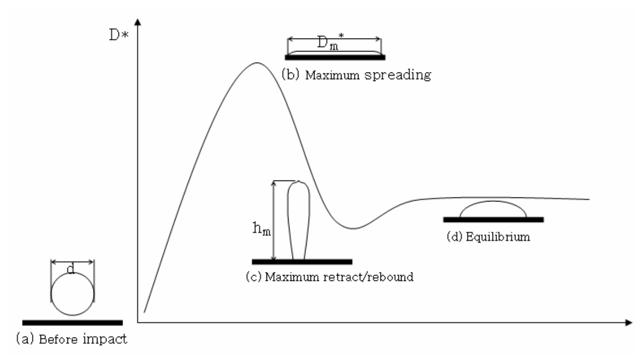


Figure 1. Impacting and spreading process: (a) before impact, (b) the maximum spreading, (c) the maximum retract/rebound, and (d) equilibrium.

These processes are illustrated in Figure 1. Before the drop impacts on the surface, the drop has kinetic energy, surface energy, and potential energy. When the drop impacts on the surface, it spreads over the surface until it reaches a maximum spreading diameter, D_m, where the surface energy of the drop is at a maximum while its kinetic energy is zero. Due surface energy, the liquid flow changes its direction and recoils inward. The amount of retraction depends on several factors including the initial kinetic energy of the impacting drop, the surface energy of the liquid, and the interaction energy between the liquid and the surface. In some cases, the liquid will retract to the equilibrium position and stop. In other cases, the liquid will retract beyond the equilibrium position and rise in the region of the initial impact. Sometimes rebounding will occur where the liquid will separate from the surface, rise a short distance and return to the surface.

Experimental

Apparatus

The experimental setup for studying the drop impaction process is shown in Figure 2. Drops are produced using a syringe pump (KD Scientific Model 230) which forces the suspension out of a flat-tipped needle (gauge 23) to produce 2.9mm diameter drops. A high speed CCD camera (Kodak MotionCorder Analyzer) was used to record continuous images of the impaction of a single drop. A series of pictures was recorded from one drop impingement event using a camera speed of 5000 frames per second. Other settings of the camera were 50 µs exposure time, 128 × 80 pixels spatial resolution, and 8 bit gray scale in black and white. Drop impaction speed was calculated from droplet displacement, which was measured using two different frames and a calibrated scale, and time between frames.

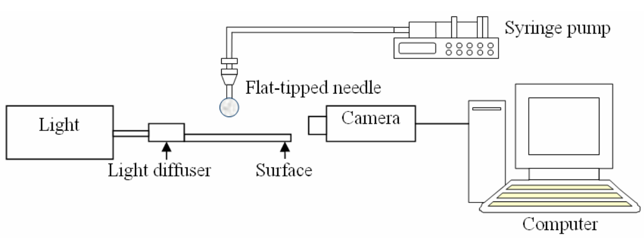


Figure 2. Schematic of experimental apparatus.

Materials

Polystyrene particles having mean diameters of approximately 20 µm and 40 µm were used to produce the particle-laden liquids. The density of particle is 1.06 g/cm^3. The particles were dispersed in water and glycerin mixture (Mixture 1), which had a density matching that of the particles. Apparent viscosities of the fluids were measured using a Brookfield Viscometer. As volume fraction of particles in the liquid increased, the apparent viscosity of suspension increased as expected.[21]

Three different surfaces were used: glass slide, silicon wafer, and Teflon® film. Contact angles of liquids on the surfaces were measured using a VCA2500KE Contact Angle Surface Analysis System (AST Products Inc.). Contact angles of fluids did not vary with volume fraction of particles. The contact angles on these five surfaces are summarized in Table 1.

Table 1. Contact Angles of Liquids on Surfaces

Surfaces	Contact angle (^{o})
Glass slide	17
Silicon wafer	47
Teflon® film	112

Tests Conducted

Experiments were conducted to show the effect of particle volume fraction on spreading ratio (D*), which is an important parameter that affects printing quality. Spreading ratio is the ratio of spreading diameter (D) to the initial drop diameter (d). Two sets of tests were performed. In the first set, the impact speed and surface were held constant, and the particle volume fraction was varied; therefore, the Weber number (We) remained nearly constant and the Reynolds number (Re) changed with particle volume fraction since Re is based on the apparent viscosity of the suspension.

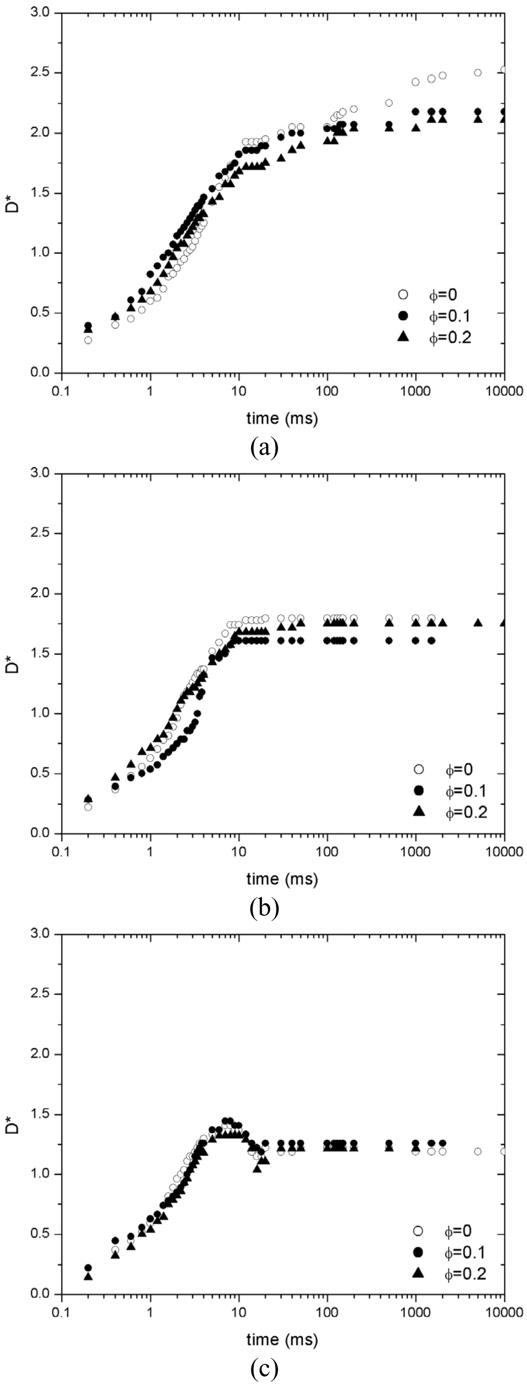
A second set of tests were conducted to determine if the effects were due solely to the increase in apparent viscosity associated with the addition of particles. The apparent viscosities of the particle-laden fluid having particle volume fractions of 0.10 and 0.20 were matched with a pure fluid produced by mixing water and glycerin (Mixtures 2 and 3). Thus it is meaningful to compare the impact process of particle-laden fluid with that of pure fluid having the same Re and We.

Results and Discussion

Effects of Impact Speed on Spreading

The effect of particles on the spreading process depends on impact speed. At low impact speed, particles do not have much effect on the spreading. As shown in Figure 3, spreading ratio, D*, is plotted as a function of time for drops impacting the three types of surfaces at impact speed of about 0.1 m/s. The liquid spreads to the equilibrium spreading ratio with almost no overshoot for the glass slide and silicon wafer, and with little overshoot for the Teflon® film. The maximum spreading ratio, D^*_m, is greatest for the glass slide because the liquid-surface interactions are strongest. Varying particle fraction from 0 to 0.2 has little effect on D^*_m, except for the glass slide. The pure liquid spread to a value of D^*_m of about 2.5 which is close to the theoretical value of 2.6.[7] The particle-laden drops do not spread as far (D^*_m of about 2.2).

At the higher impact speed (2 m/s), inertial forces dominate at impact, and initial spreading is similar on all three surfaces. For pure fluid, D^*_m is similar for the three surfaces. The effect of particles during spreading depends on the surface. For the glass slide, retraction does not occur. As particle volume fraction is increased, D_m^* is decreased. For the silicon wafer, D_m^* was about 15% lower than for the pure liquid. The retraction for the particle-laden drops was slower than for the pure liquid drop. For Teflon® film, the particles had little effect on spreading ratio.



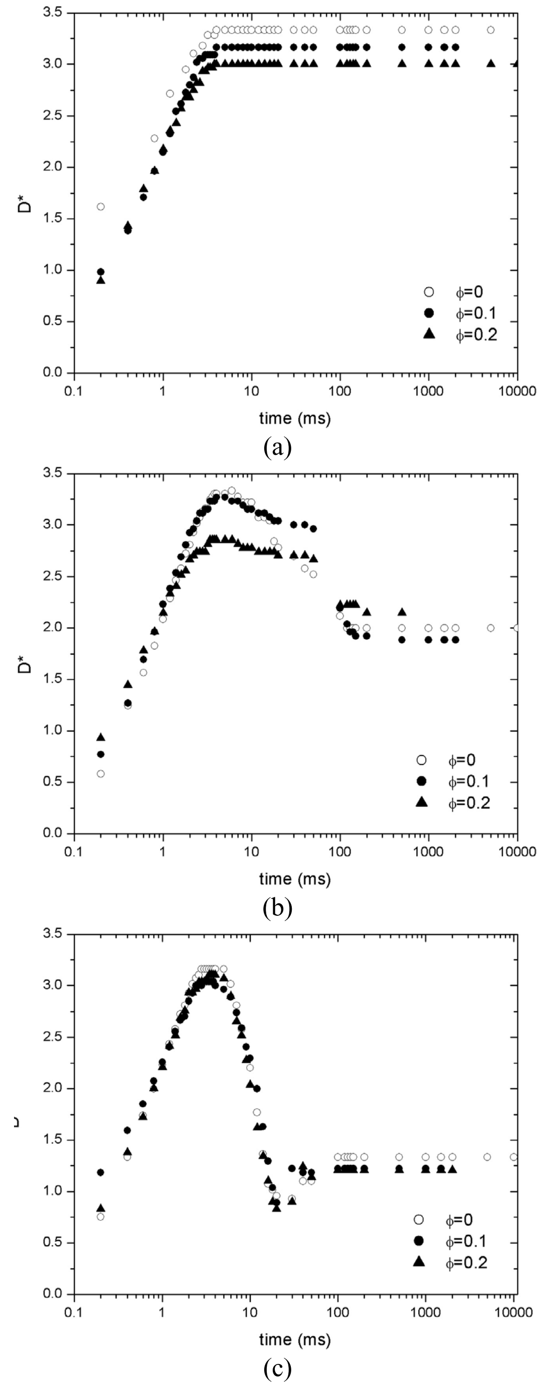


Figure 3. Impact process of particle-laden fluid at impact speed of 0. 1 m/s: (a) Glass slide, (b) Silicon wafer, and (d) Teflon® film. Liquid is water/glycerin (77/23) mixture with 40μm polystyrene particles.

Figure 4. Impact process of particle-laden fluid at impact speed of 2 m/s: (a) Glass slide, (b) Silicon wafer, and (d) Teflon® film. Liquid is water/glycerin (77/23) mixture with 40μm polystyrene particles.

Effects of Viscosity

Figure 5 illustrates that the effect of the addition of particles on the impacting process can not be solely accounted for by the change in apparent viscosity. The apparent viscosities of the particle-laden liquids with ϕ of 0.10 and 0.20 were matched with pure liquids produced by mixing water and glycerin (Mixtures 2 and 3, respectively). Thus, Reynolds number (based on apparent viscosity) and Weber number of Mixtures 2 and 3 match those of the particle-laden fluid having particle volume fractions of 0.10 and 0.20, respectively. In Figure 5, D* versus time is shown for these liquids. The results are compared with those for the liquid used to produce the particle-laden liquids. D^*_m for Mixture 2 is much lower than for the particle-laden liquid with ϕ of 0.1 even though they have the same apparent viscosity. Similar results are seen for ϕ of 0.2. This suggests that the fluid viscosity, not apparent viscosity, is the controlling viscosity parameter during spreading.

Effects of Particle Size

Figure 6 illustrates that increasing particle size from approximately 20µm to 40µm had little effect on spreading ratio. However, rebounding on Teflon® was observed with 20µm particles, but not with 40µm. More study is required to explain this observation.

Rebounding

For the 20-micron particles with ϕ of 0 and 0.1, the drop impacting at a speed of 2 m/s on Teflon® film retracts beyond the equilibrium position and rises up as shown in Figure 7. When the drop stretches up, it shows necking which continues until a secondary drop is generated. While the secondary drop is airborne, the drop on the surface spreads, retracts, and reaches an equilibrium state until the secondary drop falls down by gravity and impacts on and combines with the drop on the surface. The recombined drop spreads and retracts to its equilibrium position.

Since rebounding did not occur for $\phi = 0.2$, further experiments were conducted using $\phi = 0.05$, 0.15, and 0.3. The secondary drop stayed airborne longest for ϕ of 0.15, but a secondary drop was not generated for either $\phi = 0.2$ or 0.3. Further work is being conducted to elucidate the role of particles in rebounding.

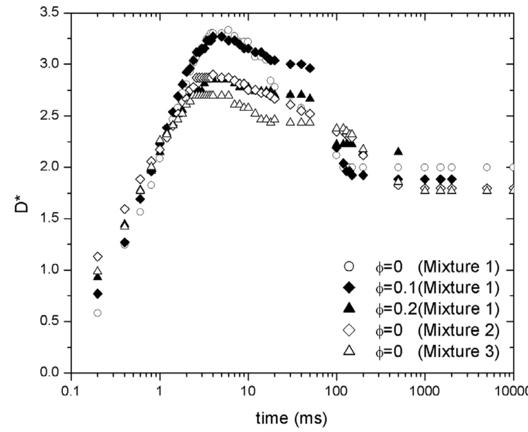


Figure 5. Impact process of 40 µm particle-laden fluid at impact speed of 2 m/s on silicon wafer.

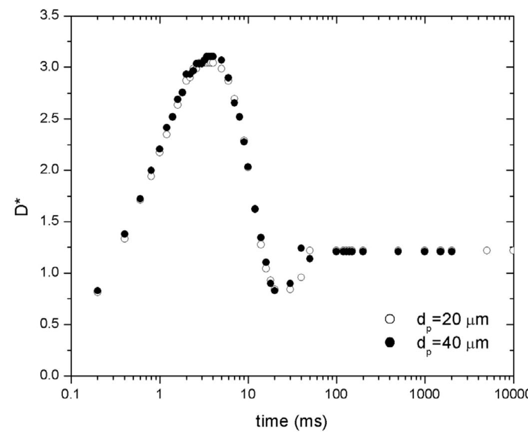


Figure 6. Effect of particle size on impact process at impact speed of 2 m/s on Teflon® film. Volume fraction of both liquids is 0.2.

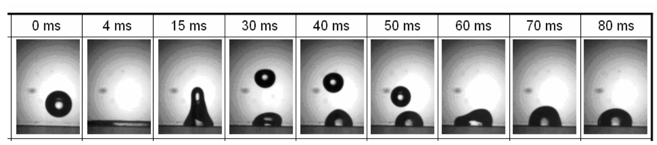


Figure 7. Images of drop impaction with a volume fractions of 0.

Conclusions

The effect of particle volume fraction on the impacting process revealed that particles can affect the impacting process. These effects can not be explained simply by change in apparent viscosity. Fluid viscosity appears to be more important than apparent viscosity during the impacting process.

The effect of particles on the spreading process depends on impact speed. At low impact speed (0.1 m/s), particles do not have much effect on the spreading. At the higher impact speed (2 m/s), the effect of particles during spreading depends on the surface. Effects were seen for the glass slide and the silicon wafer, but the particles had little effect on spreading ratio for Teflon® film.

Increasing particle size from approximately 20 µm to 40µm had little effect on spreading ratio.

At an impact speed of 2 m/s and a particle size of 20 microns, the rebound behavior on the Teflon® surface depends on particle volume fraction. At $\phi = 0$, 0.05, 0.10, and 0.15, rebounding occurred, but at $\phi = 0.20$ and 0.30, rebounding did not occur.

Acknowledgements

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Biography

Hyunyoung Ok received his B.S. degree in Textile Engineering from Pusan National University, Korea in 1995. She is currently a Ph.D. student in Department of Polymer, Textile and Fiber Engineering, Georgia Institute of Technology. Her work has primarily focused on the impact process of particle-laden drop and ink-jet printing on textiles.