Droplet Formation from Particulate Suspensions

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Abstract

This work presents an experimental study of the formation of pendant droplets of a liquid suspension of non-colloidal, neutrally buoyant, solid particles from a circular orifice into a second liquid phase. The length of the liquid thread at break-off (L) and the diameter of the resulting droplet (D) are examined for various particle volume fractions (φ), ratios of spherical particle diameter to orifice diameter (D_p/d), and flow rate (Q). While no obvious trends were observed for the thread length of the forming drop as the particle concentration of the suspension was increased, structures much different from those in droplet formation from pure liquids were observed near the bifurcation point. Specifically, the particles where observed to be swept out of the necking region of the liquid thread both toward the fluid remaining at the exit of the capillary and down into the forming droplet. At higher particle concentrations this movement of the particles out of the neck created spindle-like structures near both ends of the neck and pinch-off was observed to occur much further away from the surface of the droplet than is the case for pure liquids.

Introduction

The formation of droplets from particle-laden liquids is an important phenomenon in many applications including ink-jet printing, fuel combustion, and spray drying operations. Ink-jet printing applications have typically involved the use of dye-based inks for printing on paper although there has been increasing interest in applying the technology to such novel applications as textile and fabric printing (Tincher, Hu & Li, 1998), the digital manufacture of ceramics (Blazdell *et al.,* 1995), and the deposition of organic polymers in coating operations in the semiconductor industry (Perçin, Lundgren & Khuri-Yakub, 1998). Switching from dye-based, soluble inks to solids-laden inks introduces new challenges in the process. The presence of the solid particles in the jetting fluid can lead to agglomeration and possible nozzle clogging, and may also fundamentally change the reliability of the jet break-up process. The primary goal of this work is to experimentally investigate the formation of pendant drops of a solid-liquid suspension as a first step in probing the effects solid particles have upon the jetting and droplet formation processes of these mixtures.

Droplet formation from pure liquids is an active area of research and has been extensively studied both experimentally and numerically. Peregrine, Shoker & Symon (1990) investigated the formation of droplets experimentally by direct imaging with high-speed photography and synchronized lighting. Their work provided a qualitative description of the process that elucidated the asymmetrical structure of the thread of fluid formed by the falling drop just prior to detachment. They showed that near the pinch-off point the forming drop was nearly spherical and was attached to fluid at the tip of the capillary by a long, slender needle-like thread. At pinch-off this thread broke at the surface of the drop and then retracted due to unbalanced surface tension. This work was extended by Shi, Brenner & Nagel (1994) by examining the effect of viscosity on the structure of the falling drop. They found that the length of the thread that was formed just before pinch-off became longer as the viscosity of the fluid was increased. Additional experimental work has been performed by Zhang & Basaran (1995) on the formation of pendant drops into air. Zhang (1999a, 1999b) has also investigated the formation of pendant drops into both air and viscous fluids by the numerical "volume of fluid" method.

Despite the large body of literature on pure liquid drop formation little has been published concerning the process for solid-liquid suspensions. This work is a preliminary report of our efforts to generate the information necessary to understand this process by investigating pendant drop formation from particle-laden liquids experimentally using photography and image analysis.

Experimental Setup

Experiments were performed using the apparatus depicted in Figure 1. Pendant droplets of suspension were formed into silicone oil (polydimethylsiloxane) (ρ = 0.950 g/cm^3, η = 19cP) at the tip of a 5 cm long stainless steel capillary. The suspension was driven from the drop delivery vessel using a Harvard Apparatus syringe pump. As the suspension left the capillary the break-up process was captured photographically using a Cooke SensiCam high-speed camera with a frame rate of 30 frames per second and an exposure time of 100 µs. The light source utilized was a 300 watt light bulb diffused through translucent Lexan of 1/4" thickness. The observation chamber was made of 1/4" plate glass and was 12" tall with a 6" square cross-section. The observation chamber, the drop delivery vessel, the light diffuser, and the camera were all placed on a vibration-damped table from Newport in order to isolate the apparatus from any external motions.

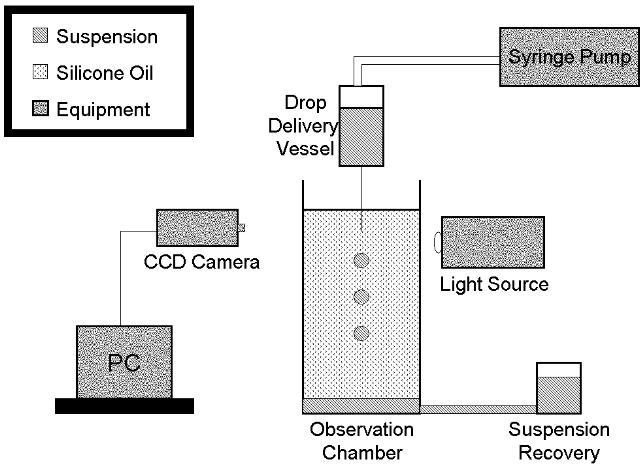

Figure 1. Schematic of the experimental apparatus.

The suspension utilized in all experiments was a mixture of 25% zinc chloride in water solution, UCON 90,000 oil (polyalkylene glycol from Union Carbide) and 250-212 μm diameter spherical poly-(methyl methacrylate) particles. The composition of the mixture was 71% zinc chloride/water solution and 29% UCON. This composition yielded a density equal to that of the particles (1.18 g/cm^3) and a viscosity of approximately 40 cP. All mixture percentages are on a mass basis.

Results

The thread length of the forming drop just prior to bifurcation and the diameter of the resulting drop were measured from photographs using Adobe Photoshop 5.0 for particle volume fractions ranging from 0 to 0.25 for three different diameter capillaries (d = 1/16", 1/8", 1/4" OD) and three different flow rates (0.382 mL/min, 1.91 mL/min, 7.64 mL/min). In all instances the capillary tip was captured in the photographs and was used as the scale in measuring the thread length and the drop diameter. Thread length was obtained by averaging the length from the capillary tip to the upper edge of the droplet just before (L_1) and just after (L_2) bifurcation and the droplet diameter by averaging the width (D_1) and the height (D_2) of the drop after detachment (see Figure 2). For concentrated suspensions the drop is relatively non-spherical and this introduces some error. Further work will examine the droplet well after breakup to allow surface tension to return it to a spherical shape

The results of these experiments are presented graphically in Figures 3-6 in which dimensionless thread length and drop diameter are plotted against particle volume fraction for the three flow rates.

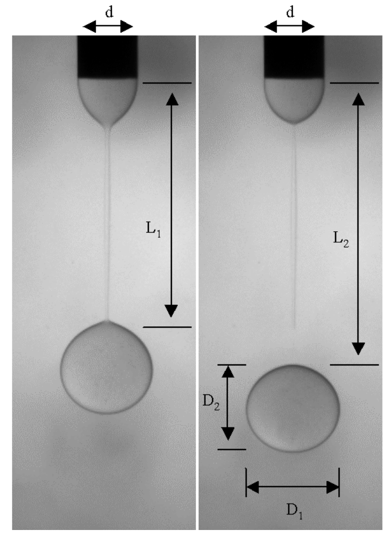

Figure 2. Sample measurement of thread length (L) and drop diameter (D) for φ = 0, d = 1/8".

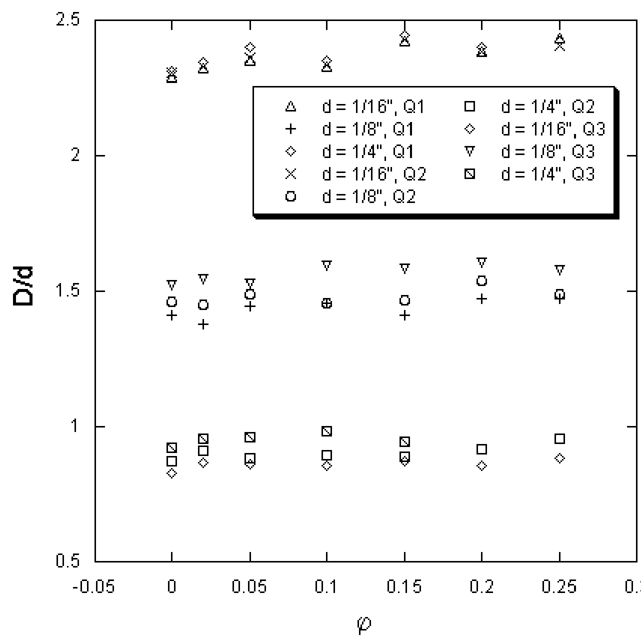

Figure 3. Dimensionless drop diameter vs. particle fraction for all three capillary diameters and all three flow rates.

Figure 3 illustrates that the drop diameter was not observed to depend significantly on the particle fraction over the range investigated in these experiments although it increased slightly with increasing flow rate. There may be a very slight increase in the size of the drops with increasing particle fraction. Additional experimentation at higher particle fractions must be performed to determine whether this trend becomes more pronounced or if the drop size remains unaffected.

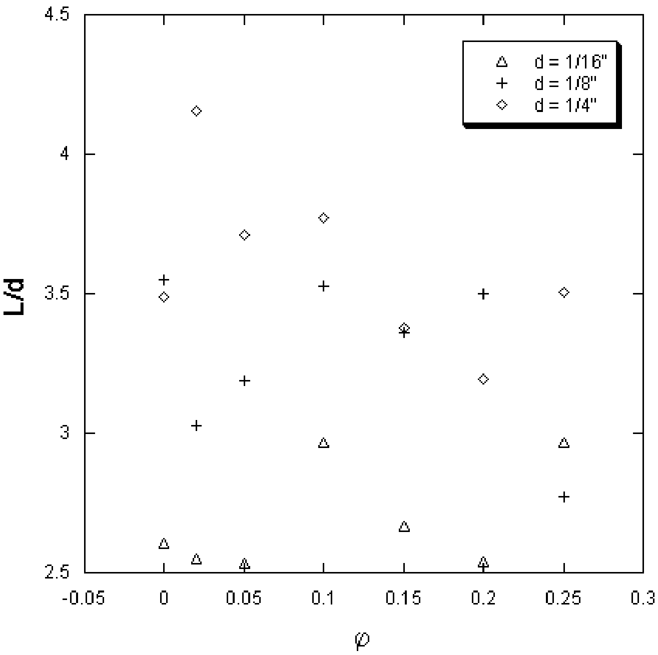

Figure 4. Dimensionless thread length vs. particle fraction for flow rate Q_1 = 0.382 mL/min.

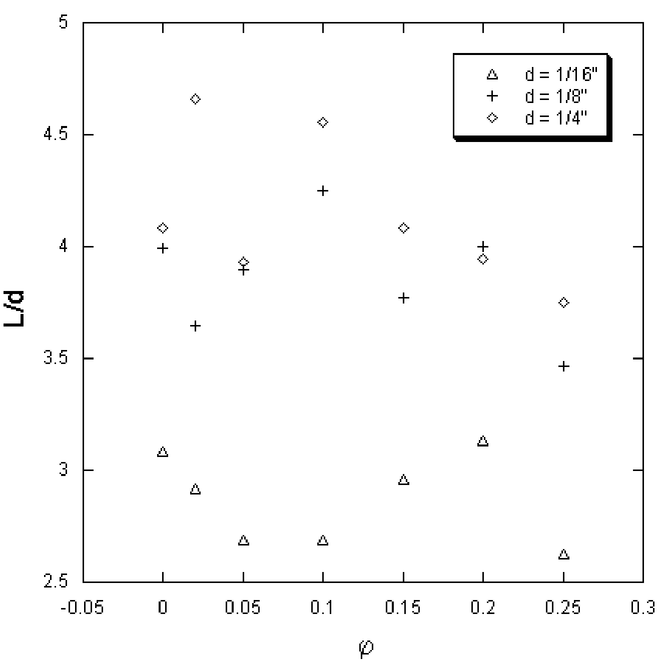

Figure 5. Dimensionless thread length vs. particle fraction for flow rate Q_2 = 1.91 mL/min.

The results for the thread length (Figures 4-6) are much less clear. The length of the thread oscillates with increasing particle fraction for each of the three different flow rates and each of the three different capillary diameters. As φ increases there seems to be no definite trend towards lengthening or shortening of the thread. One example of this can be seen in Figure 4. Here L/d for both the smallest and the largest diameter capillaries increases as φ is increased from 0.2 to 0.25 but decreases drastically for the middle diameter capillary over the same concentration range. It is interesting to note that the profile for d = 1/8" is very similar in all three of the L/d graphs. In this case the trend is for L/d to initially decrease with increasing φ and then to reach a local maximum near φ = 0.1 and then taper off as φ is further increased. It should be noted that jetting was observed for the largest capillary diameter at the highest flow rate for particle fractions of 0.2 and 0.25.

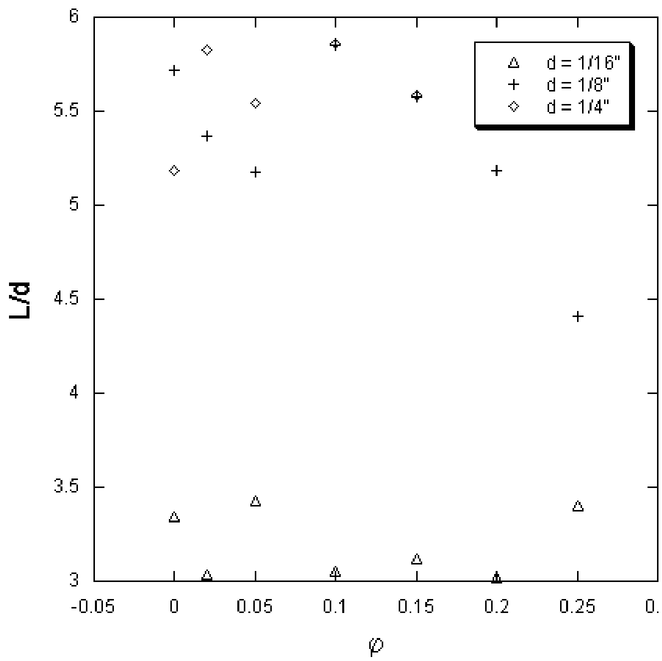

Figure 6. Dimensionless thread length vs. particle fraction for flow rate Q_3 = 7.64 mL/min.

The most interesting results of these experiments are the qualitative characteristics of the structure developed during the necking and subsequent pinch-off of the drop (Figures 7-9). For pure fluid (φ = 0) the structure developed near pinch-off is the asymmetrical "needle-sphere" combination described by Pergrine, Shoker & Symon (1990) and Shi, Brenner & Nagel (1994). This structure is observed for all three capillaries for φ = 0 and φ = 0.02. For the two larger diameter capillaries the presence of particles in the necking region was common even for low particle fractions. As the drop formed and the liquid thread was elongated the particles caught in the thread were swept back towards the remaining fluid near the capillary tip and down towards the forming drop. If pinch-off occurred between the drop or the capillary tip and the particles in the neck, smaller secondary (satellite) drops were formed that contained particles. This situation was observed often for the two larger capillaries and most frequently at larger particle fractions. Particles were rarely caught in the neck for the smallest diameter capillary.

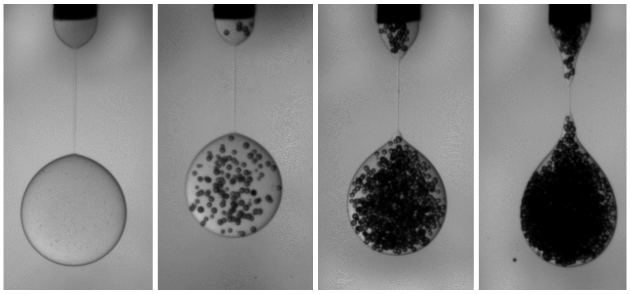

Figure 7. d = 1/16", φ = 0, 0.02, 0.1, 0.25

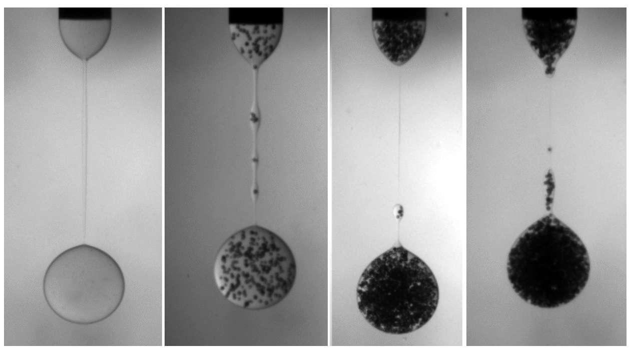

Figure 8. d = 1/8", φ = 0, 0.02, 0.1, 0.25

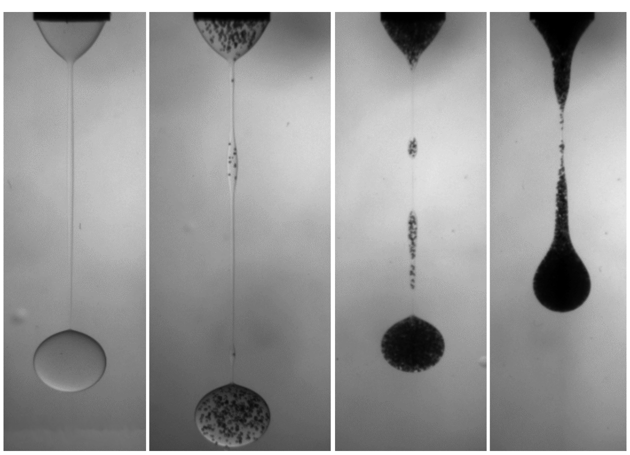

Figure 9. d = 1/4", φ = 0, 0.02, 0.1, 0.25

At larger particle fractions the structure observed near pinch-off becomes significantly different and the forming droplet has a less spherical, pear-like shape. As the particles are swept back towards the fluid near the capillary tip and down into the forming drop a new "spindle"-like structure is formed at either end of the neck. This structure becomes more pronounced for the larger diameter capillary (see Figure 9, $\varphi = 0.25$) where pinch-off actually occurs far from the leading edge of the drop. Typically the spindle is retracted into either the formed drop or the hanging fluid after break-off although at larger particle fractions, capillary diameters, and flow rates the spindle itself can undergo necking and pinch-off from the rest of the fluid to generate additional satellite drops.

Conclusion

This work has examined the pendant drop formation process for a particle-laden liquid from a circular capillary into a second liquid phase over a range of particle fractions, flow rates, and capillary diameters. It was found that the length of the liquid thread at pinch-off oscillated with increasing particle concentration and that the drop diameter was little affected. Most interestingly, as the particle fraction was increased structures very different from those reported for pure liquids were observed and the bifurcation occurred farther from the surface of the forming drop.

References

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Biography

Roy Furbank is currently a PhD candidate in the Department of Chemical Engineering at the Georgia Institute of Technology. His research is in the field of multiphase flow. Roy received a B.S. in Chemical Engineering from the University of Texas at Austin in 1995.