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Study on Jet Breakup Dynamics of Inkjet Printing Fluids

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ABSTRACT

Continuous Inkjet (CIJ) printing is a common 2-Dimensional printing technique that creates jets of ink that breakup into drops as they are propelled towards a substrate to create a print. Inkjet printing has been used not only to print on paper, but to manufacture a variety of devices including OLEDs, solar cells and microfluidic devices. In many cases, the 'ink' consists of a polymer dissolved in a volatile solvent. As this ink is sprayed on to the substrate, the solvent evaporates, leaving the polymer behind as the print. The addition of the polymer alters the physics of the problem significantly enough that it varies greatly from jetting only a fluid with nothing dissolved in it. Polymers impart viscoelasticity to the solution, creating ink jets that are long-lived and difficult to break into droplets. In order to maintain the formation of drops in a repeatable, uniform fashion, a disturbance of known magnitude is imposed upon the jet. While jetting a liquid with no additives in it, this disturbance governed jet breakup leads to the formation of satellite drops, smaller drops of fluid in-between the main jet drops. Satellite drops are an undesirable occurrence in inkjet printing because of their unpredictable behavior and potential to affect the quality of the print. However, the addition of polymers to the liquid can control and potentially suppress the formation of these satellite drops, greatly improving the print quality. The elasticity of the polymer and its ability to influence the jet behavior and formation of satellite drops is highly dependent on multiple factors including the backbone rigidity, molecular weight and the concentration in which it is present in the fluid. Strongly viscoelastic effects have a marked effect on the jet and their presence can be quantified quite easily. However, some polymers show weak viscoelastic behavior while present in the ink fluids and may or may not affect the jetting process. The objective of this study is to examine such a class of polymeric fluids that are weakly viscoelastic in the context of inkjet printing and satellite drop formation. Firstly, the fluids are tested in an extensional rheology setup called Capillary Breakup Extensional Rheometric – Drop-on-Substrate (Caber-DoS) to quantify their extensional properties. Then, they are tested in an emulated inkjet printing setup. The goal is to quantify the impact of the aforementioned factors on jetting and using satellite drop behavior as a guiding metric to understanding viscoelastic behavior in inkjet printing fluids.

INTRODUCTION

Non-Newtonian Fluids:

Non-Newtonian fluids make up a significant portion of the fluids we encounter in our day-to-day-life. The main difference between a Newtonian and a Non-Newtonian fluid is that the non-Newtonianfluid displays a non-linear response to a force exerted on it. This response may be in the form of a varying viscosity (the fluid thickens or thins in response to the applied force) or in the form of elasticity. This behavior of non-Newtonian fluids arises from the physical components of the fluid in the form of dissolved high-molecular weight polymers or suspended micro/nano sized particles. A polymer molecule dissolved in a fluid exists in a coiled random equilibrium state. However, when the fluid is subjected to a deforming force, the coil is stretched out of its deformed state. A restoring, spring-like elastic force acts on the polymer, returning it to the earlier equilibrium state.

Jet Breakup:

Jet breakup is a classical problem in the field of fluid mechanics, dating back to the 19th century. It is a well-known phenomenon that a cylindrical jet of fluid decays into drops under the influence of surface tension. Experiments by Savart showed thatdisturbances on the surface of fluid jets grew to break the jet into drops. Jet breakups occur independent of gravity, viscosity of the fluid, and the velocity and radius of the jet, and the instability that breaks the jet up originates from disturbances at the nozzle of the jet. Subsequently, Plateau3 and Rayleigh4 independently found that disturbances that resulted in a decrease in the surface area were favored and grew because of surface tension. Rayleigh found that for the disturbance to grow on the jet, the wavelength of the disturbance had to be greater than the circumference of the jet, and the most unstable mode of disturbance corresponded to 1.4 times the jet circumference.

Inkjet printing:

Figure 1.1 shows a sample inkjet printing setup, a 2D printing technique in which drops of ink are generated from a nozzle and propelled toward substrates to create an image. Inkjet printing has been used traditionally to print on paper and plastic based substrates, but increasingly has found use in the manufacture of multiple devices such as OLEDs, solar-cells and biosensors. 7–11 Figure 1.2 shows these devices produced with an inkjet printing process. There are two major categories – Drop-OnDemand (DOD) and Continuous Inkjet (CIJ). DOD inkjet printing has a fluid reservoir connected to the nozzle and an actuation mechanism creates a rapid change in the volume of the reservoir that acts as a pulse to eject a specific quantity of ink through the nozzle. In CIJ, a continuous stream of ink is generated and broken into droplets by

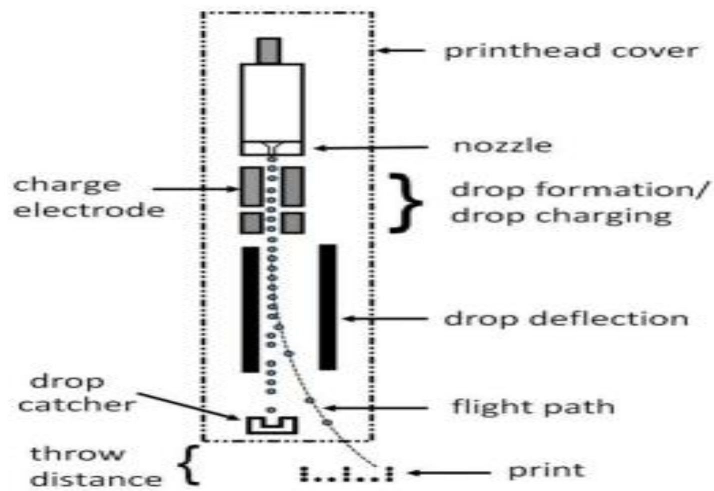
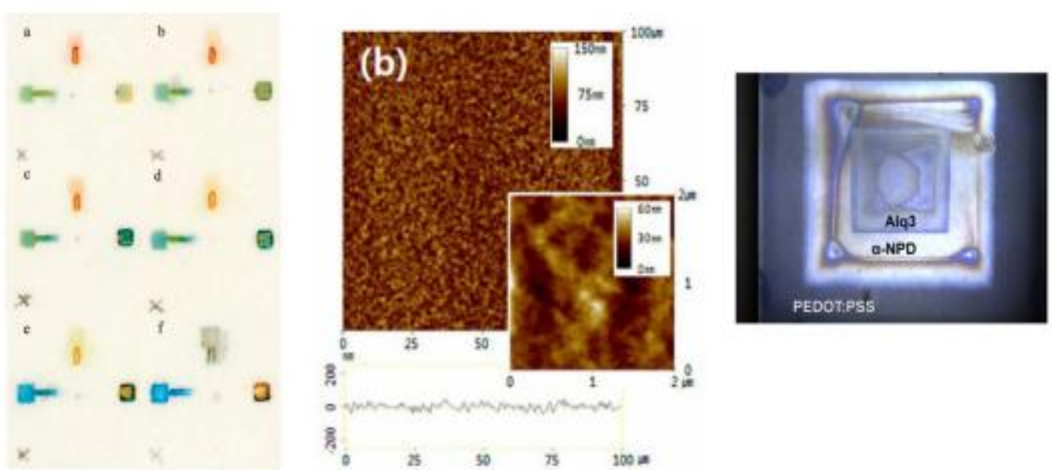


Figure 1.1: Sample Continuous InkJet Printing setup. [12]



(a) (b) (c)

Figure 1.2: (a) Microfluidic Multianalyte system, [9] (b) AFM image of a solar cell [10] and (c) Organic Light Emitting Diodes [11] made using InkJet printing

EXPERIMENTAL METHODS

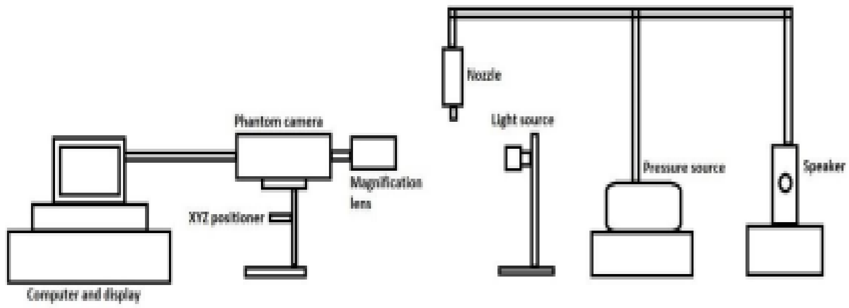


Figure 2.1: A schematic of the jetting setup and data acquisition system used in the experiments

A typical jetting setup used is shown above. A nozzle of diameter 800 um with a fluid reservoir is connected to a pressure source and speaker. The pressure source drives the fluid out of the reservoir through the nozzle at pressures of 4-6 psi (depending on the polymer used), while the speaker imposes a frequency of 800 Hz on the fluid to enable the break-up. The pressure and frequency are calibrated to ensure the growth of the maximum disturbance mode. A 5x4 light array illuminates the jet. A high-speed camera (Phantom Vision V4.2) with a Nikon 18-55mm lens is used to capture the break-up at 10000-12000 frames per second (depending on the polymer used), within a window of 400x100 pixels. This setup was inspired by Donnelly and Glaberson's jet breakup study.

Break up time is defined as the break-up distance divided by the velocity of the jet. Break up time is an excellent indicator of the different regimes present in the fluids. As the perturbations in the fluid jet become significant and the effects of surface tension are apparent, the peaks of the perturbations coalesce into the jet drops, separated by long, thin cylindrical filaments.

These filaments eventually break off and condense into satellite drops, in between the drops of the jet. When the concentration of the polymeric binder is low, the effects of elasticity are not apparent in the fluid jet. However, upon increasing the concentration of the polymer, especially in CAB, the fluid transitions from being inelastic to being weakly elastic.

This effect is seen in the break-up time, which increases as the effect of elasticity are felt. In the other Vinnol E22/48A case, as the effect of elasticity increases, the break-up time also increases. Hence a direct correlation can be observed between the presence of elasticity and increase in break up time. In the later stages of the filament breakup, the breakup process transitions from being inertia dominated to being viscosity dominated, and as the concentration increases, elasticity dominated.

As seen in Caber-DoS, viscous filaments decay slower than inertial filaments do, and elastic filaments decay slower than viscous filaments do. 34 This is also correspondingly reflected in the breakup of the Vinnol E15/45M and the Paraloid B66, the other two polymeric binders used in the study. The Paraloid data is the work of undergraduate student Samantha Bonica, who was also a member of the NNFD lab. A sharp increase in the breakup timewas observed in the Vinnol E15 binder at the 17 wt% concentration, as the elastic effects became apparent. As this binder is quite sensitive to concentration effects, it shows this trend. The Paraloid, which shows an elastic response only at the 30 wt% case, did not show a sharp response, but rather a continued increase in breakup time with the increase in concentration. Hence, viscosity in by itself proves to be a factor to slow down the growth of perturbations and increase the breakup time, but at specific concentrations, the effects of elasticity become apparent, and elasticity further delays the breakup of the filaments formed in-between the drops, thereby increasing the breakup time.

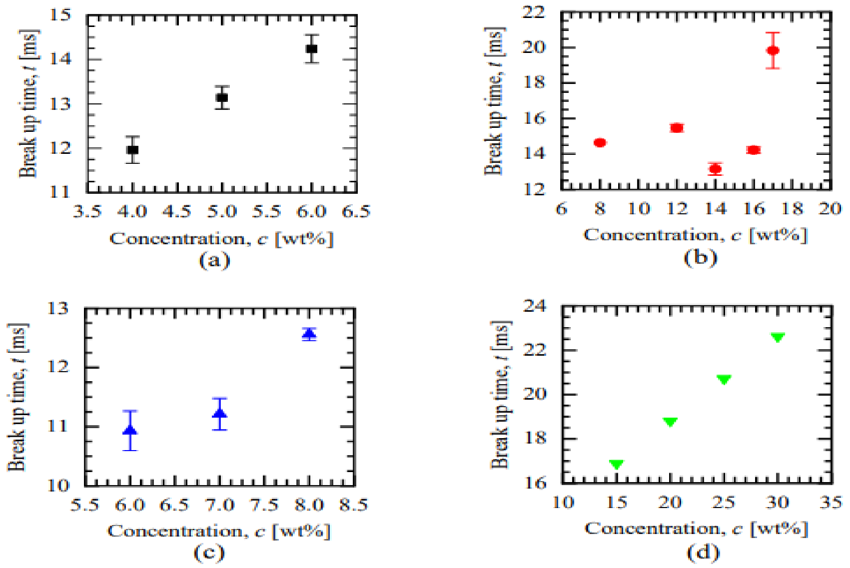


Figure 3.1: Variation of break up time with concentration for (a) CAB and (b) Vinnol E15/45M (c) Vinnol E22/48A and (d) Paraloid B66

Particle laden solutions – CaBER-DoS results:

The third and final part of this thesis focuses on studying jetting results of particle laden solutions. Since Vinnol E15 showed the most sensitivity to the jetting process, it was again chosen as the ideal candidate to continue these jetting experiments with. However, since the lab supply of Vinnol E15 was not sufficient to generate all solutions, a new sample of Vinnol E15/45M powder was obtained from Wacker Chemie. This new batch of Vinnol E15/45M has rheological properties that are different from the previous batch used, hence new measurements had to be carried out. Vinnol E15 was mixed along with 8 µm SiO2 particles in Methyl Ethyl Ketone to create the particle laden solutions. The Vinnol concentration was maintained at 16 wt%, whereas the microparticle concencentration was at 0 wt%, 0.5 wt%, 1 wt%, 2 wt% and 4 wt%. CaBER-DoS and jetting experiments were performed on all 5 samples. The final images from the breakup are shown in Figure 3.6. It was previously assumed that the 16wt% Vinnol with no particle addition would yield similar results to the 16 wt% Vinnol previously tested, but however that assumption was disproved through CaBER-DoS results. Hence, these results are treated as independent results with no correlation to the previous jetting results.

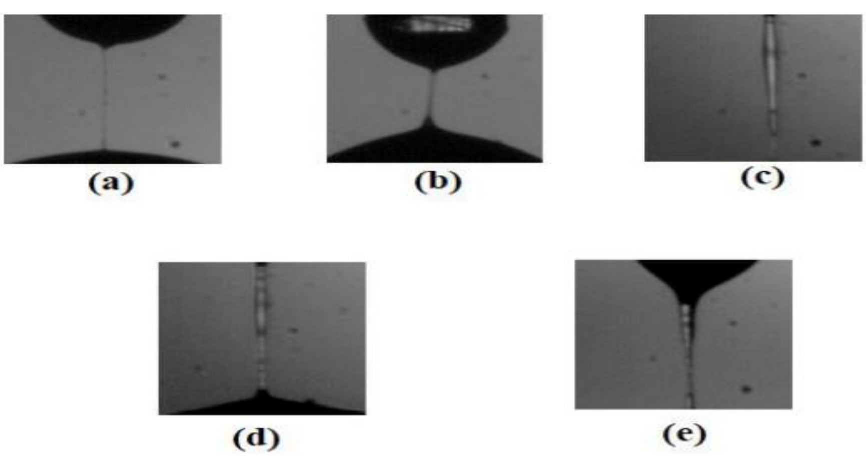


Figure 3.6: CaBER-DoS breakup images for 16 wt% Vinnol E15 with (a) 0 wt% SiO_2 (b) 0.5 wt% SiO_2 (c) 1 wt% SiO_2 (d) 2 wt% SiO_2 (e) 4 wt% SiO_2

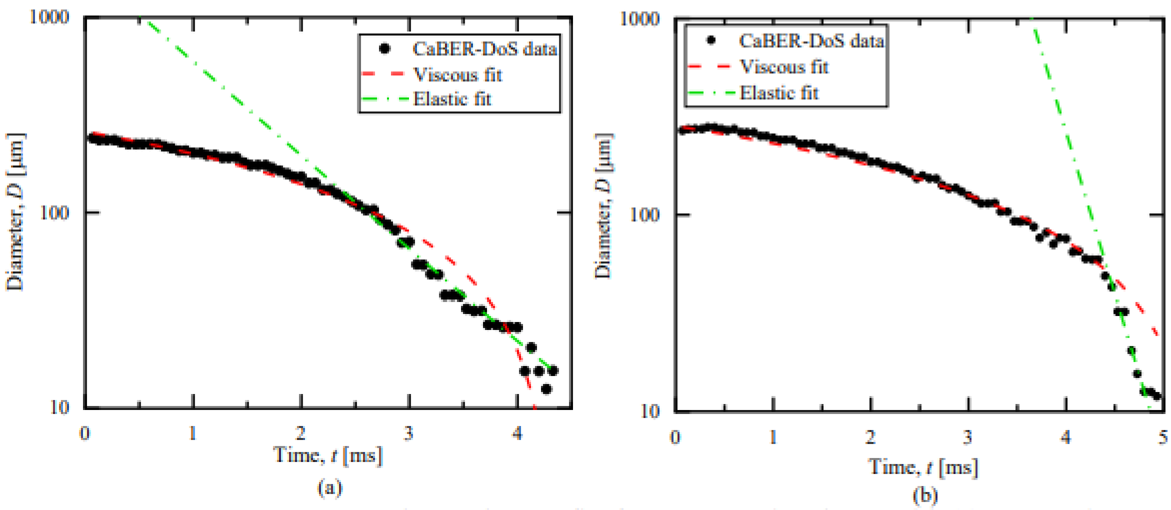


Figure 3.7: CaBER-DoS data and curve fits for 16 wt% Vinnol E15 with (a) 0 wt% SiO_2

(b) 1 wt% SiO_2

CONCLUSIONS

A parametric study was performed on a series of inkjet inks. The inks contained different polymeric binders of varying concentration and molecular weight. These inks had similar behavior in a shear flow, but displayed completely different reactions in extensional flows. The concentration of the polymeric binder was steadily increased until the effects of elasticity became significant in the flow. Jetting studies were performed on the fluids. The first effect of elasticity was seen in the results that showed increased break up time as the concentration of the polymer increased. Similar effects were seen in the jet drop formation as the size of the main jet drop increased and the size of the satellite drop decreased or tapered off to a constant value as the concentration of the polymer was increased. Both these results are also yardsticks to measure the effects of elasticity in the flow. Satellite drop velocity was also measured and was observed to increase negatively as the polymer concentration increased, suggesting that as the polymer concentration increased, the satellite drops both decreased in size and retracted faster back into the jet. Hence, a set of markers were identified to quantify elasticity in weakly viscoelastic solutions through the evaluation of satellite drop behavior. Satellite drop studies were performed in the second part of the study, focusing on the formation and motion of a single satellite drop. High speed imaging revealed that the position of the satellite drop was a linear function of time, and hence travelled with a constant velocity, which resulted in not being able to measure the elastic restoring force acting on the satellite drop. The third part of the study was on the addition of microparticles to the 16 wt% Vinnol E15 solution. While the solution was elastic with no microparticles added, the elastic effects decreased in magnitude as the concentration of the microparticles increased, disappearing completely at higher concentrations, while the viscosity of the solutions increased correspondingly with increase in concentration. This can be attributed to the adsorption of the polymer molecules onto the surface of the microparticles. Furthermore, the microparticles have a tendency to agglomerate, leading to inhomogeneous regions of particle accumulation. This irregular accumulation causes the filaments in both CaBER-DoS and jetting experiments to breakup in an asymmetric fashion. The effect of such accumulation can be seen in the main drop volume, breakup time and satellite drop retraction velocities.

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