Flow Stability in Liquid Inkjets Printers

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Abstract

The production of ink-jet inks is a two stage process. First, the pigment is dispersed in an appropriate mobile phase using a mechanical stirrer. This ensures that any lumps of pigment powder are dispersed. This "pre-mix" sample is then milled using a ball-mill in order to reduce the particle size and cause the break-up of any strongly bound aggregates.

Dilute polymer solutions at flow rates corresponding to a transition from dripping to jetting. Thermal inkjet process can be analyzed by considering dynamics of capillary flow, capillary thinning and break-up process in low viscous and low viscosity elastic fluids such as dilute polymer solutions. The relative importance of three time scales inertial, viscous and elastic processes and length scales, initial sample size and the total stretch imposed on the sample govern stability of inkjets. Viscosity, relaxation modulus and surface tension are used to analyze stability of inkjet flows of viscous and viscoelasic fluids from glycol, polyethylene oxide, carbon black and borate esters.

Introduction

Inkjet printing is increasingly considered a cost-effective

and flexible method for the structuring of functional materials such as conducting polymers for applications in polymer light-emitting diodes, polymer electronics

and three-dimensional printing. Rapid prototyping capability, high precision dispensing, non-contact multi-material deposition, low material waste and 3D patterning are the key advantages of inkjet technology. In the field of micro-electro-mechanical systems (MEMS), the negative epoxy based resist SU-8 has contributed largely to the advances in high aspect ratio microdevices. Moreover, the material itself has very interesting properties, e. g. chemical inertness and elasticity module for mechanical applications in polymer MEMS. In addition, its transparency makes it an interesting candidate for microoptical applications.

In inkjet printers, ink is ejected from a nozzle by applying a pulse of pressure to the fluid ink in the supply tube, upstream of that nozzle. There are two common methods of creating this pressure pulse: thermal bubble and piezoelectric. In the thermal bubble technique, ink channels are formed on the surface of a planar substrate using a photoimageable polymer. A small heater is formed using a thin film resistive metallic layer less than 1 micrometer thick in the wall of the ink channel leading to each nozzle. Typically, such a heater is square in shape, about 10 to 20 micrometers on each side. Low resistance thin film metallic conductor. connections are attached to two opposing sides of the heater resistor, and a pulse of electrical current is flowed through the heater resistor for about 1 microsecond in duration. The amplitude of this electrical current is designed to heat the resistor enough to boil the ink. A thin layer of ink (about 0.01 micrometer of ink) closest to the resistor explosively boils, forming a vapor bubble and expanding about one thousand times in volume. This volume expansion creates a pressure pulse in the fluid, causing ink in the nozzle (downstream of the heater) to be ejected toward the paper. After several microseconds, the vapor bubble cools and collapses. Then the surface tension of the ink meniscus in the nozzle pulls in more ink from the reservoir to refill the nozzle in preparation for the next drop to be ejected.

The second pressure pulse technique uses piezoelectric materials, which are crystalline materials having the property of deforming when high electric fields are applied across them. Two configurations are commonly used: piezoelectric rods which elongate under applied fields, or bimorphs which bend (in a geometry similar to a drum head). In either case, these materials are configured so that they deform one of the walls of the ink channel leading to each nozzle. This deformation squeezes the channel, creating a pressure pulse and ejecting ink from the nozzle. An elastic diaphragm typically isolates the crystalline piezoelectric materials from the ink. The electrical pulses that energize these piezoelectric elements are once again in the microsecond range. The ink channels in a piezoelectric ink jet printhead can be formed using a variety of techniques, but one common method is lamination of a stack of metal plates, each of which includes precision micro-fabricated features of various shapes [1].

The mechanism by which a liquid stream breaks up into droplets has been investigated for some time. Dirt in the nozzle or air in the droplet can significantly affect the image. When a liquid ink droplet contacts the surface of paper, it tends to spread along paper fiber lines as well as penetrate into paper sizing and voids. The spreading of ink droplets is often too excessive and too irregular to maintain the resolution required. The penetration of ink into the paper is often too slow to absorb multiple ink drops on the same spot within very short time intervals. The poor color image quality due to ink spreading and inter-color bleeding is recognized as the critical issue in the development of ink-jet technology[2].

Special ink-jet-coated media must balance between many design parameters such as drop volume, evaporation rate, penetration rate, coating thickness, porosity, etc. Aqueous- or water-based inks are commonly used in home and small-office ink-jet printers such as in the Hewlett-Packard DeskJet series, Canon BJC series, and Epson Color Stylus series ink-jet printers. In the case of thermal ink-jet, due to the basic vapor bubble formation process, water seems the material of choice for the method. Viscosity of water-based ink-jet inks range from 2 to 8 cps or mPa.s [3].

Drop-on-demand (DOD) ink jet printing is considered to be an efficient approach for depositing picoliter drops on various targets. It is compatible with various liquids and need not contact the substrate. Drop formation and

impaction on the substrate are important because they significantly affect the final state of the material on the substrate.

A typical process of DOD drop formation is composed of the following stages [4]:

a) Ejection and stretch of liquid – When a pressure wave travels through the liquid in the nozzle, liquid is accelerated and pushed out of the nozzle. At the beginning, the shape of the liquid meniscus at the exit

of the nozzle is parabolic. The meniscus then quickly extends outward until a liquid column with a round

leading edge is formed. After short time, the internal

pressure at the exit of the nozzle falls below the pressure inside the liquid column, and the liquid flow rate from the nozzle decreases. The velocity difference between the head of the column and the liquid at the nozzle exit causes the liquid column to begin to stretch. The velocity of the liquid at the nozzle exit continues to fall until no additional liquid flows into the column and possibly even some of liquid is

sucked back to the nozzle. Then the volume of liquid column remains constant, but the inertia of the liquid continues to extend the column. The rate of extension decreases as new surface is created with corresponding increase in surface energy.

b) Necking and Pinch-off of liquid thread from nozzle During the stretching of the liquid column, the liquid at the tail (at the nozzle exit) necks, i.e. the location with minimum radius in the liquid thread. This necking point stays at the nozzle exit, and the radius of the liquid thread here keeps thinning A second necking point begins to appear towards the head of the column, eventually producing a bulbous head. Thus, a long transitional liquid column is created, reaching from the nozzle to the bulbous head. Finally, the tail of the liquid thread pinches off from the nozzle, creating a free liquid thread with a bulbous head.

c) Recoil of free liquid thread – Recoil occurs because pressure is high in the tip of the tail at pinch off

due to the small radius of curvature, causing the liquid in the tail to flow toward the bulbous end. Instantaneously, a spherical tip at the tail develops, but its radius of curvature is much smaller than that of the head. Therefore, the internal pressure at the tail is greater than that at the bulbous end, and liquid is squeezed toward the bulbous head. Since the two ends attached to the liquid thread are not symmetrical, the head and tail behave differently. The tail recoils (moves toward the head) while the velocity of the head is almost constant.

d) End-pinching or multiple breakup(s) of liquid thread – During the shrinkage of liquid thread, a second neck near the bulbous head evolves. The radius of the neck continuously decreases until the liquid thread breaks up into two parts, a primary drop and a free secondary unsymmetrical liquid thread The lower end of the secondary liquid thread moves up while the shape of the upper end becomes bulbous. Depending on its length, the secondary liquid thread may shrink into a smaller drop or satellite , or break up into two or more parts. Contraction of the satellite towards a spherical shape transforms surplus surface energy into kinetic energy of the satellite and causes the satellite to oscillate.

e) Recombination of primary drop and satellite – The drag exerted by the surround air on the primary drop is different from that on the satellite because of differences in size and velocity. If the primary drop and satellite are sufficiently separated, the deceleration of the larger droplet due to the drag force is smaller than that of the small droplet. For this case, if the velocity of the primary drop is faster that of the satellites, they will not combine. On the other hand, if the satellite is close enough to the primary drop, the lower pressure in the wake region behind the primary drop can suck the satellite toward the primary drop, and the satellite will merge with it.

f) Oscillation to equilibrium state – When the satellite and the primary drop merge, excess surface energy is transformed into kinetic energy in the liquid inside the drop. The drop will oscillate as excess energy is converted back and forth between kinetic energy and surface energy. As the oscillations occur, energy will be viscously dissipated until an equilibrium state is reached. During the drop formation process, the oscillation of the pressure wave inside the liquid chamber leads to liquid alternately being forced out of and being sucked back into the chamber. For most cases, the weak reflection of pressure wave is not strong enough to cause the liquid to detach from the nozzle exit, so it oscillates with smaller and smaller amplitude until the pressure wave inside the chamber disappears due to the viscous dissipation inside the chamber.

g) Satellite formation –In the description given above, satellite formation occurs because two pinch offs

occur. If the second pinch-off does not happen before the liquid thread contracts into a spherical profile, then the satellite will not appear which is ideal for ink jet printing. Satellite formation is depended on three factors: a) length of free liquid thread, b) velocity of contraction of liquid thread and c) time of liquid thread pinch-off. Thus, parameters related to these three factors, such as geometry of drop generator, waveform, amplitude of voltage, viscosity and surface tension of liquid, can be expected to affect satellite formation.

h) The curve of DOD drop formation - In order to discuss qualitatively the DOD drop formation process,

the position of several key points in the ejected liquid can be plotted versus time.The velocity of any point can be calculated from the slope of its position versus time curve. Initially, Point (1) is the leading edge of the liquid ejected from nozzle and later becomes the tip of primary drop or final drop. Point (2) is the tail of free liquid thread and also the first pinch off point of liquid from the nozzle exit. Points (3) and (4) are the lower and upper points produced by the second pinch-off. Later, they become the tail of the primary drop and the head of the secondary free liquid thread or satellite, respectively. Between Points (2) and (4), other pinch-off points may occur, but are not considered here. Point (5) is the tip of liquid ejected from nozzle due to the multiple reflection of pressure wave.

In analysis of inkjet process, voltage is applied and the piezoelectric ring changes its diameters and creates a pressure wave that propagates along the capillary tube and reflects at its ends. In the nozzle region, the pressure wave

accelerates the liquid and ejects a column of it that will break up into a droplet if its kinetic energy is sufficient to overcome the surface energies.

The process described above is governed by two phenomena: (1) the propagation of the pressure wave along the capillary tube and (2) the conversion of the kinetic energy of the liquid jet into surface energy. Both phenomena can be characterized by dimensionless numbers, namely the Ohnesorge number (*Oh*) and the Weber number (*We*) that allow determining whether a droplet is ejected at first place and second, if it is free of satellite drops. One considers the kinetic- surface energy conversion governed by both the speed of the jet and the surface tension. *Oh* characterizes the propagation of the pressure wave and its attenuation by viscous dissipation. In order to generate a droplet, two conditions need to be fulfilled. First, the kinetic energy must be higher than the surface energy of the drop. It is correlated with Weber number given by

$$W_e = KineticEnergy / SurfaceEnergy = d v^2 \rho \sigma^{-1} \quad (1)$$

where d is the droplet diameter, v is its velocity, ρ is the liquid density and σ is the surface tension of the liquid. The second condition is that the kinetic energy should be higher than the viscous dissipation. This is described by the Reynolds number: Re = Kinetic Energy Dissipated Energy.

Oh combines these two conditions:

$$Oh = \sqrt{We} / R_e = \mu. \quad (\rho.\sigma.d)^{-0.5} \quad (2)$$

where μ is the dynamic viscosity of the liquid. *We* must be large enough and *Oh* must be small enough to generate a drop. No breakup occurs when *We* is smaller than a critical value defined by the Equation below

$$We = 12. \left(1 + 1.077.Oh^{1.6}\right) \quad (3)$$

The critical value of *We* for water is close to 12. For We<12 no breakup occurs whereas for 12<We<18, vibration behavior dominates and the flow enhances the amplitude of drop oscillation to produce a few satellites [5]. A similar approach can be taken in which the fluid properties are described by the Z-number (*Z*) which is equivalent to the inverse of *Oh*. The drop formation in a DOD inkjet printer is only possible for *Z*>2[6]. It can be further refined to predict that, for a range of concentrated alumina wax suspensions, DOD inkjet printing takes place in the range of 1<*Z*<10. At *Z*=10 or higher, satellite-drops are formed [7].

Both the critical Ohnesorge number (*Oh*) and the critical Weber number (*We*) are dependent on temperature as shown in Figures 1 and 2, respectively

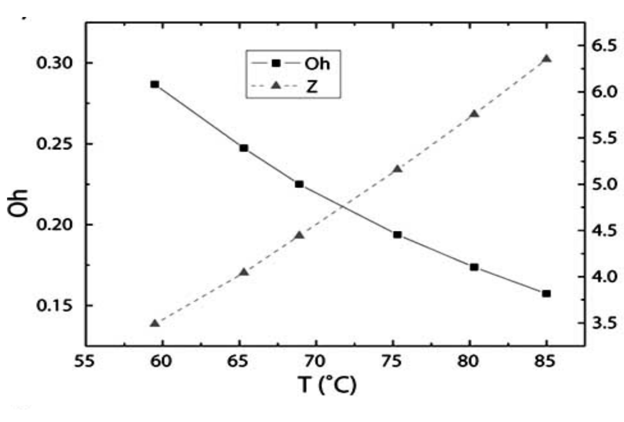

Figure 1 Oh and Z-number of SU-8 versus temperature, a viscous and non-Newtonian liquid.

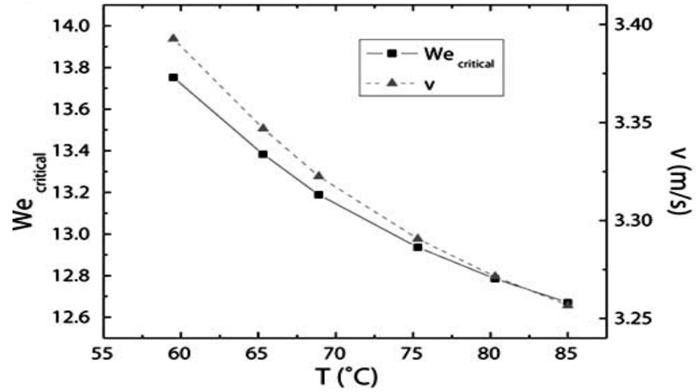

Figure 2 We and Z-number of SU-8 versus temperature.

In the field of micro-electro-mechanical systems (MEMS), the negative epoxy based resist SU-8 has contributed largely to the advances in high aspect ratio micro-devices [8,9]

In inkjet of Newtonian fluids viscosity and surface tension are the key material parameters. At higher capillary viscous flows, both shear and extension forces take place, dynamic shear and extensional viscosities are important. In viscoelastic fluids, relaxation modulus and relaxation time also affect drop formation and drop impaction.

The break-up dynamics of droplets and jets of complex fluids such as elastic solutions are governed by the extensional viscosity and surface tension of these non-Newtonian fluids. The dynamical response of complex fluids in extension is quite different than in simple shear. Whereas the shear viscosity of a typical elastic solution will heavily thin with increasing shear rate, the extensional viscosity can increase by several orders of magnitude with increasing strain. This strain hardening has been found to stabilize jets and drops of viscoelastic fluids by resisting the extensionally dominated flow leading to break-up resulting from capillary stresses. In order to understand and predict the impact dynamics of a droplet on wormlike micelle solution thin film, detailed knowledge of both the shear and extensional rheology is essential. There is no experimental or numerical data showing how elasticity and shear thinning affect the impact dynamics of droplets on thin films or deep reservoirs of elastic or visco-elastic solutions.

Method and Materials

Carbon black pigment inks were made by dispersing carbon black, dispersant and water in an attritor at high concentration,20% relative to the ink at 5%. A central composite design was used to navigate the effect of grinder time and dispersant concentrations on the rheological properties of the dispersion and the final ink. Glycol , polyethylene oxide and borate ester inks were also prepared by dispersing in water. Solid inkjet was prepared by dispersing pigment in waxes. Rheometrics Fluid Spectrometer was used in analyzing viscosity and normal stresses of aqueous inks where as solid inkjet rheology was analyzed by Ares of TA instruments.

Result and Discussion

As shown in Figure 3, inkjet printing solutions vary in their shear dependence and power law dependence is used to determine the extent of shear thinning. The shear rate used in the viscometer fall short of the shear rates present in inkjet flows. The shear rates in DOD or drop on demand have been found to be in the range of 1000 – 10,000 sec-1 by using the following calculation.

$$\bar{\dot{\gamma}} \sim O\left(\frac{\bar{V}}{R_{noz}}\right) \sim O\left(\frac{\frac{S}{A_{noz}}}{R_{noz}}\right) \qquad (4)$$

where $\bar{\dot{\gamma}}$ is the scale of shear rate, $\bar{V}$ is the averaged speed of liquid ligament being jetted out from the inkjet nozzle, S is the volumetric flow rate, A_{noz} is the cross-section area of the inkjet nozzle, and R_{noz} is the radius of the inkjet nozzle. While three inks made from glycerin, carbon black and water showed varying degree shear thinning in a capillary rheometer, DOD drop formation for all three inks was very similar[10]. The time scale for the shearing in the DOD inkjet nozzle is much shorter than that in the capillary viscometer. Depending on the concentration of a solution, a solution can show normal stresses indicative of elasticity in addition to viscosity both of which are shear rate dependent. A dimensionless analysis using Ohnesorge number (Oh) Weber number (We) are not sufficient.

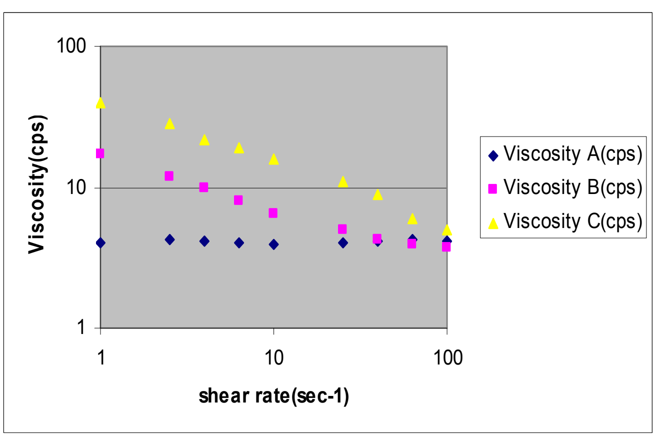

Figure 3 viscosity dependence on shear rate, A-20% glycol solution, B – Polyethylene Oxide solution and C-Borate Ester solution

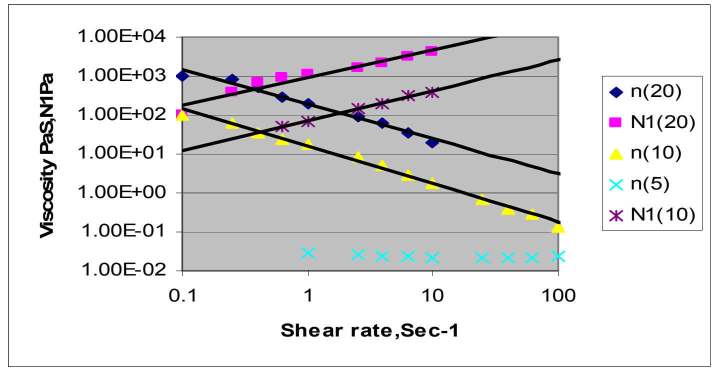

Figure 4 – dependence of viscosity and normal stresses on carbon black glycol solutions at 20%, 10% and 5% carbon black

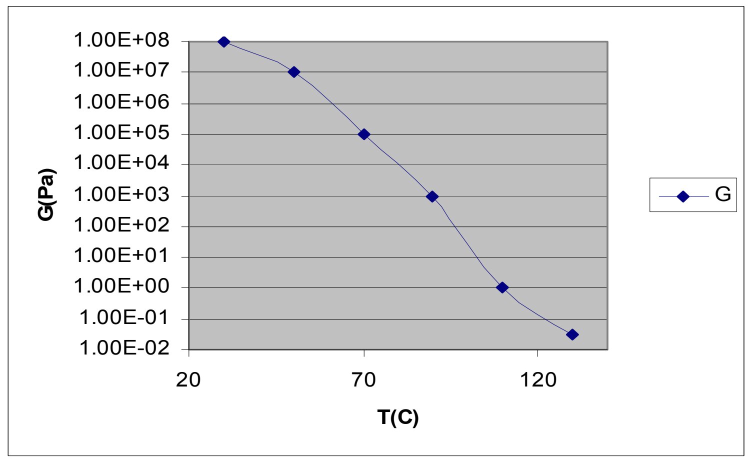

Figure 5- shear modulus of Phaser 8400 at different temperature and 1Hz.

An approach to obtaining better image quality without relying on special media is the use of solid ink (or hot melt or phase-change ink). In operation, the ink is jetted as molten liquid drops. On contact with the media, the ink material solidifies, very little spreading and absorption occurs so that brilliant color and high resolution can be realized almost independent of the substrate properties. Solid ink sticks are loaded into a hopper on top of the machine (notably free of any packaging or cartridges). The solid ink is then melted into a page-width print head, which jets the molten ink onto an intermediate drum. Once an entire image has been accumulated on the drum, it is transferred onto the receiver through a pressure nip, and the page is either ejected into the output tray or re-routed back through the machine for auto-duplex.

Solid Inkjet shows significant drop in shear modulus as the temperature is increased from 30C to 130C. Temperature at which drops are formed is in the neighborhood of 130C. The material consisting of wax and gel is visco-elastic at lower temperatures and as the temperature goes to 130C,the drop temperature, modulus is between 0.01 –0.1 Pa.

Conclusion

Analysis of Inkjet flows is reviewed. Viscoelastic experiments in standard rheometers show that inkjet fluids may be shear thinning and visco-elastic. Models and experiments offer challenges in optimizing inkjet design.

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Author Biography

Suresh Ahuja received his BS in physics and chemistry from the Punjab University (1959), his MS in Soil Physics from Indian Research Institute (1961) and his PhD in Polymer Physics from Polytechnic Institute of Brooklyn (1967). After working over 37 years at Xerox with several years as Principal Scientist he retired. He has over twenty (20) patents. He has published over 60 publications and presentations at international conferences. He is a member of APS, ASME, SOR and IST.