Prediction of Emulsification Drop Size in a Printing Nip

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Abstract

The fountain solution balance on the press is an important issue in terms of operation and quality of the printed product. Fountain solution is emulsified into the ink during the printing process. While a number publications reporting the amount of fountain solution that is emulsified for various conditions have been published, less is understood with regard to the size of the fountain solution drops.

In this study, a known amount of fountain solution is applied to a rotating ink film. The rheology of the inks is characterized with a controlled stress rheometer. The size of the fountain solution drops is characterized via light microscope images. A finite element based model is used to predict the drop breakup in a shear field and the shear flow in the printing nip. The shear rates generated in the nip are used to predict the size of drops that would be generated. The model results are compared to the experiments.

Introduction

The emulsification of ink during printing is important. Ink emulsification is the process by which the fountain solution is mixed into the process ink. The fountain solution is evenly distributed within the ink in small droplets, forming a stable emulsion. Instability of this emulsion is a reason for several print related problems both in terms of print quality and runnability of the press. The instability can be caused by incorrect feed of fountain solution and the interaction with ink. Ink-water-paper interactions are reviewed by Aspler (2006). Thus the focus of this study was to investigate the fountain solution distribution within the ink and the traces of it in the final print.

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The stability of droplets of fountain solution in the ink are influenced by the shear stresses experienced by the ink and fountain solution, the temperature, the emulsification time and the supply of fountain solution to the ink [Massolt and Hohtari, 2002]. The degree of emulsification affects the process runnability/stability and print quality. Ink can carry a certain amount of liquid water (30-50 %) within itself [Aspler, 2006]. The ink-water balance is critical in order to have a stable process. If the fountain solution feed volume is too low in the printing process, ink is transferred to the non-image areas (toning) and if the fountain solution feed is too high, the print density drops, halftone dots become ragged and fountain solution partly stays on the ink surface as surface water and interferes with ink transfer (water marking) [Kipphan, 2001]. If the pickup of fountain solution in ink, despite the best control of fountain solution volume delivery, leads to an undesirable excessive fountain solution emulsification in the ink problems such as changes in the rheological properties of the ink, toning and ink pigment flocculation can occur. Research has shown that the degree of emulsification of ink and fountain solution results in different penetration depths into uncoated paper, and higher emulsification resulting in deeper penetration due to lower viscosity of the emulsion [Liu et al., 2006]. Another study showed that emulsified inks had a faster gloss development than pure inks, probably due to the change in viscosity for emulsified inks [Xiang and Bousfield, 2002]. Research on ink-fountain solution balance, shows that the most important effect of emulsified fountain solution on ink-fountain solution-paper interactions following offset printing is the decrease of ink cohesion [Fröberg et al., 2000]. Hence, this effect is primarily due to the introduction of defects in the ink film, which lowers the cohesive force due to the generation of free surface within the ink film. Some of our basic understanding of the emulsification process are in need of improvement.

The breakup of a bubble or drop in a flow field has been studied for a number of years. Some initial work was described by G.I. Taylor (1932, 1934) where he described a critical shear rate value that will cause a drop to break up. This shear rate can be put in terms of a critical Capillary number, where above this combination of parameters, drops will break into smaller drops. A number of other researchers have refined these conditions (Acrivos, 1983, Flumerfelt, 1972, Stroeve et al. 1983, Bentley and Leal, 1986, Stone et al. 1986). Bousfield et al. (1988) report on the deformation of a bubble in a viscoelastic fluid. A review of the literature is given by Stone (1994).

The critical Capillary number Cc for breakup of a drop was given as

$$Cc = \frac{0.145}{\lambda^{1/6}\alpha^{1/2}} \quad (1)$$

Where the capillary number is defined as

$$Cc = \frac{G\mu a}{\gamma} \tag{2}$$

Where G is the shear rate, μ is viscosity, a is the drop radius and γ is the surface tension. The parameter λ is the viscosity ratio between the fluid of the drop and the suspending fluid. The parameter α is the type of shear field and for simple shear, this takes the value of one.

What is of interest here is the prediction of the value of the drop radius. For a viscosity ratio of λ=0.001, the critical capillary number should be on the order of Cc = 0.45. Therefore, if the shear rate that is generated in the nip is understood, the size of the drop could be estimated. Re-arranging Eq. (2), the drop diameter may be predicted by

$$d = \frac{2\gamma Cc}{\mu G} \tag{3}$$

The surface tension between a water drop and an ink oil should be on the order of 0.03 N/m. Methods to measure this value are available, but for our purposes, we will use this as an estimate. What is left to understand is the shear rate that is generated in the nip during the printing process.

The goal of this work is to understand the size of drops that are generated by the working of a rolling nip similar to that which occurs during printing. The shear rate that is generated in the nip is predicted using finite element methods. The results are correlated into a simple expression that others can use. This shear rate is used in Eq. (3) to predict the drop size. The predictions are compared to a set of experiments from three inks that have different tack rating, at different speeds and fountain solution applied.

Experimental

The TackOscope device is based on a set of contacting rotating rollers. This method comprises a system similar to that of an ink distribution chain on a printing press, with an additional feature for applying fountain solution in a controlled manner by using a precise ultrasonic spray dampening.

The printed samples were prepared in laboratory scale by application of an inkfountain solution emulsion onto a plastic film with the TackOscope device. The ink distribution device was run so that a defined amount of fountain solution was added to the ink prior to printing. After printing, the prints were air dried under ambient conditions.

A quantity of 4 ml printing ink was placed on the TackOscope distribution rollers. The TackOscope was set at a speed of 50 $m.min^{-1}$ and held at 30 °C during ink distribution. During the first 30 s, the ink becomes evenly distributed on the roller surfaces, after which the actual measurement is started and the speed increased to 200 $m.min^{-1}$. Depending on the desired amount of fount to be added, the machine was run for a corresponding time to apply the chosen volume from the spraying unit, which delivered fount at the rate of 10 μls^{-1}. Two plastic films were put back to back one on top of the other through the TackOscope nip, thus enabling one side printing whilst maintaining a balance contact with both roller surfaces. After reaching the desired fount concentration point, ignoring evaporation, the contacting films were passed through the nip immediately to transfer the pre-formed ink-fount emulsion onto the film and allowed to air dry under ambient conditions. The purpose of the plastic film was to be able to see the emulsified drops in the ink.

Three yellow inks were supplied by Sun Chemical that were denoted as low, medium and high tack inks. Rheological tests were performed on these inks with a controlled stress rheometer (Bohlin, CVO). The geometry was 2 mm parallel plates. The tests were only run in oscillatory mode because of issue caused by constant shear. The tack values of the inks are also obtained.

The plastic strips that were sent through the nip were analyzed under a microscope. A typical image is shown in Figure 1. While the low magnification image does not make it clear, after enlargement of the image, small spots are seen in the image. These lighter spots are the drops of the emulsified ink. The size of these faint light regions was measured after importing the image into Microsoft Viso, using a measuring tool. The values are an average of only seven spots.

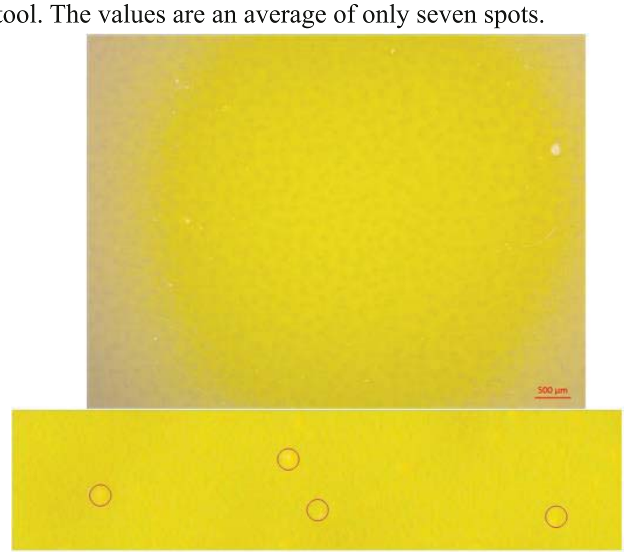

Figure 1. *Microscope images of the ink film. Faint light images are the location of fountain solution drops, circled in red in the lower image.*

Theory

The overall approach was to calculate the flow field that occurs in the nip using a finite element code. From these results the maximum shear rate was predicted for a wide range of conditions. This shear rate was correlated to the known parameters such as ink viscosity, speed and gap. From the shear rate and critical Capillary number described above, the size of an emulsified drop is predicted. These predictions are compared to the observed drop sizes.

A commercial finite element method (COMSOL Multiphysics) was used to model the flow field. A continuous film of fluid is assumed here. Figures 2 and 3 illustrate the geometry. The region of interest is the small region where the ink is in contact with both the top and bottom roll surfaces. Most will think of this as a "pressing" action, but it is understood now that due to the pressure generated in the nip, some shear flows occur. In Fig. 3, the region of interest brings out the details of the situation. The top and bottom surfaces are moving at the speed of the roll surfaces. This is a velocity boundary condition for the program. The left and right sides of the regions are inlet and outlet regions.

Here, pressure boundary conditions are imposed as zero gauge pressure. While the program can easily account for non-Newtonian fluids, for this work, only Newtonian fluids are studied. The viscosity and density of the fluid are inputs into the model.

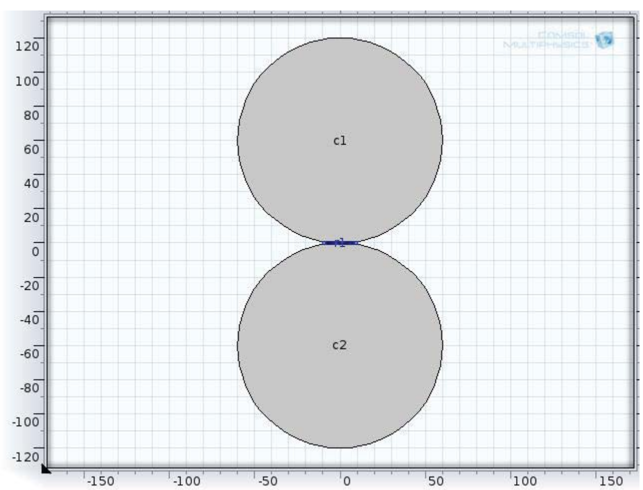

Figure 2. *Large scale view of system. Two rolls are C1 and C2. The radii are kept the same but various radii are selected.*

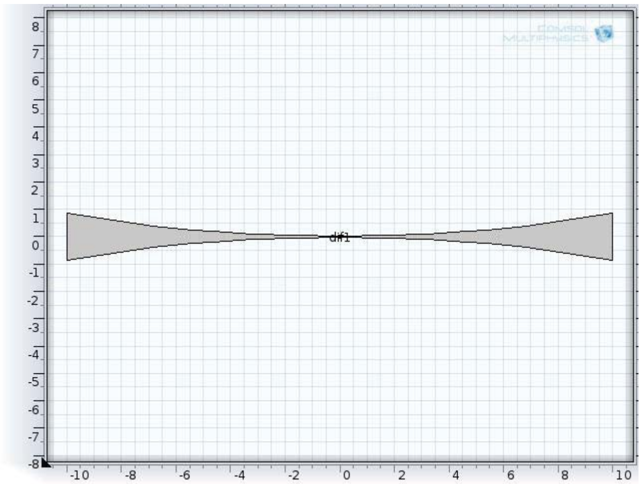

Figure 3. *Englargement of region of interest. Gap between surfaces is set and can be on the order of microns.*

Figure 4 shows a typical pressure pulse. As is typical for this geometry, as fluid is pulled into the nip, the pressure increases to some maximum value. At the exit of the nip, the pressure drops to low (sub-ambient) values before returning to atmospheric pressure. The pressure is not a function of the vertical position, only the flow direction. The pressure gradients in the flow direction cause shear flows to occur. Figure 5 shows the shear rate distribution within the nip and its dependency on the refinement of the mesh used in the calculation. Where the pressure gradients are large, the shear gradients are large as well. Because of the sharp gradients in pressure, a fine mesh was required to obtain quality results.

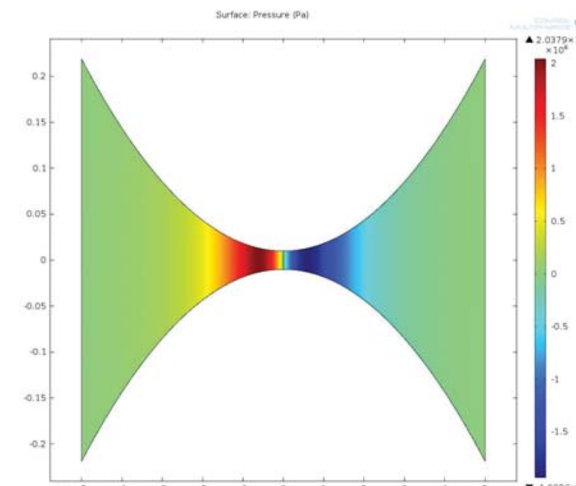

Figure 4. *Pressure distribution in nip. Wall motion is from left to right. Nip has been enlarged in the vertical direction for illustrative purposes. Red indicates high pressure and blue low pressure. Green is atmospheric pressure.*

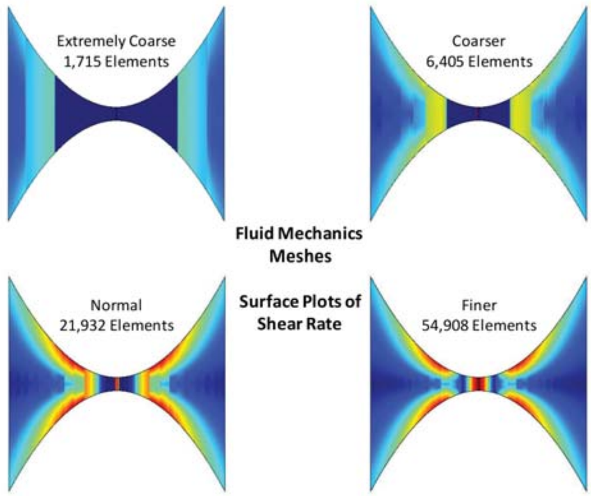

Figure 5. *Shear rate distribution in region. Red is high shear rates and blue are low shear rate regions.*

A wide range of gaps, speeds, viscosities, roll diameters where run. The maximum shear rate was recorded. Dimensionless groups are a nice tool to reduce the number of parameters and correlate maximum shear rate with other parameters.

The Reynold's number used here is based on the gap between the roll surfaces as is given as

$$\mathrm{Re} = \frac{\rho V h_g}{\mu} \tag{4}$$

Where ρ is density, V is the surface velocity of the roll, hg is the gap, and μ is viscosity.

A dimensionless gap is

$$h_g^* = h_g / R \tag{5}$$

where R is the roll radius.

Shear rate γ is made dimensionless as

$$C_f = \frac{2\mu\gamma}{V^2\rho} \tag{6}$$

Around 500 different simulations using different parameters for the various values of velocity, viscosity, roll speed, density and viscosity. These parameters should cover the normal range of press operations. A nice correlation is obtained shown in Figure 6.

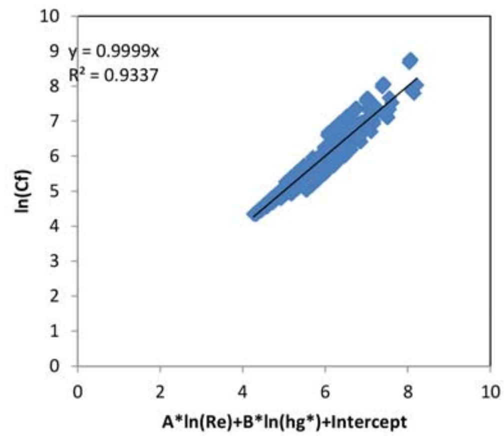

Figure 6. *Correlation of shear rate with Re and hg* . A=-0.95 B=0.085 Intercept = 2.0*

Therefore, the equation to correlate the dimensionless shear rate results would be

$$\ln(Cf) = -0.95\ln(Re)+0.085\ln(hg^*)+2.0 \quad (7)$$

Reasonable results are found with just shear rate and Reynolds number shown in Figure 7.

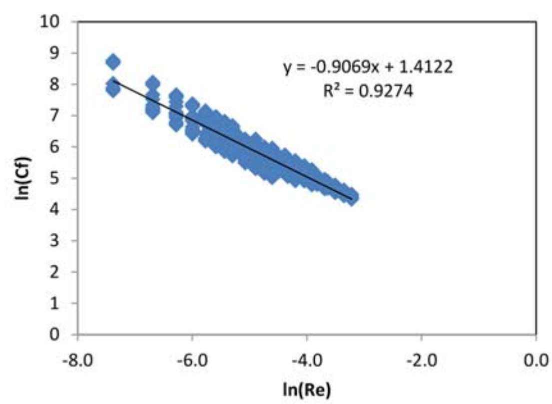

Figure 7. *Correlation of Re with Cf. ln(Cf) = -0.9lnRe+1.4122.*

For both correlations, the slope on Reynolds number is negative. This seems counter to expectations because increasing velocity would seem to increase shear rates.

However, the dimensionless shear rate has a velocity squared in the bottom. Therefore, the shear rate seems to be almost linear with velocity. Decreasing gap decreases Reynolds number but seems that again points to an increase in Cf, which makes sense.

Results and Discussion

The complex viscosity of the three inks are shown in Figure 8. One surprise is that the complex viscosity for the low and medium inks were almost identical, but the high tack ink was actually lower. The reason for this could be related to the polymers that are added to the ink or other adjustments in the ink formulation.

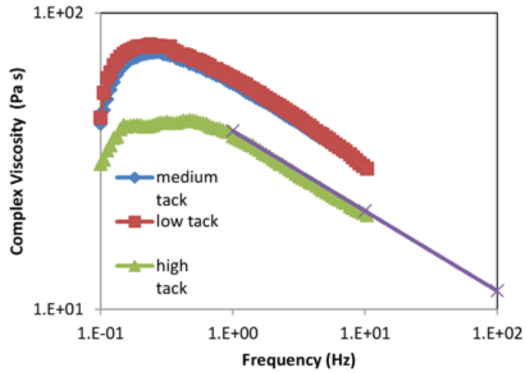

Figure 8. *Complex viscosity of the three inks. The series is a power-law fit to the high tack ink data.*

The tack curves obtained with these inks are shown in Figure 9. The high tack did have the highest tack value, but interestingly, the medium tack ink showed "medium behavior" only to a certain time after which the tack dropped. Hence, the maximum value of the low tack ink was higher than for the medium tack ink. This result may be caused by some aging of the ink or different devices used to characterize.

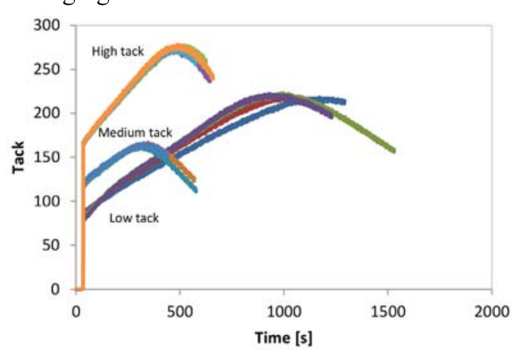

Figure 9. *Measured tack curves for the different inks*

The cases that were run, the measured drop size and predicted size are shown in Table 1. The average drop size is the average of ten drops seen in the microscopic image. The predictions are using the complex viscosity at 1 Hz, the roll speed, and the estimated density and gap (10 microns) to calculate a Reynolds number. This Reynolds number is used to calculate a shear rate with the correlation in Eq. (6). This maximum shear rate is used to estimate a drop diameter using Eq. (3). The influence of speed may be the only factor that had a clear trend with higher speeds giving smaller drops. The image analysis was difficult because the yellow ink did not offer much contrast. A number of issues lead to uncertain results. The amount of fountain solution did not influence the size of the drops but it did result in an increase number of drops.

In terms of the predictions, the amount of ink and the amount of fountain solution were not expected to influence the results. Only the ink viscosity and the speed were parameters. The amount of ink likely did influence the gap, but it was not clear how to adjust the gap in the model predictions because the gap is not measured. Therefore, the model predicts the same value for various ink amount and fountain solution levels. The model clearly does predict a decrease in drop size as the velocity increases.

Even though there are a number of issues around the experiments and the theory that could case disagreement by orders of magnitude, the results are in a similar range. In general, the model under predicts the size of the drop. This may be caused by a number of issues such as extensional shear gradients in the nip that are not accounted for in the model, other non-Newtonian effects, or some non-equilibrium issues. As the speed of the rolls increases, both the observations and the theory predicts that the drop size decreases. The model was developed with the assumption that the amount of fountain solution added to the nip should have little effect on the size of the drops.

Sample number	m/min	Ink type	ml	Spraying time [s]	Ave. drop size (micron)	Predicted drop size (micron)
1	150	Low tack	4	No fount	na	
2	150	Low tack	4	60	8.9	1.4
3	150	Low tack	4	120	5.8	1.4
4	150	Low tack	4	10	7.8	1.4
5	150	Low tack	4	30	5.8	1.4
6	150	Medium tack	4	No fount	na	
7	150	Medium tack	4	60	6.9	1.4
8	150	Medium tack	4	30	3.7	1.4
12	150	Medium tack	4	120	4.3	1.4
13	150	Low tack	2	60	6.9	1.4
14	150	Low tack	4	60	10.0	1.4
15	150	Low tack	8	60	6.9	1.4
16	150	Low tack	4	120	10.0	1.4
17	50	Low tack	4	60	16.6	9.7
18	350	Low tack	4	60	1.5	0.4
19	150	High tack	4	No fount	na	
20	150	High tack	4	30	2.7	1.5
21	150	High tack	4	60	2.2	1.5
22	150	High tack	4	120	2.5	1.5
23	150	High tack	4	120	2.0	1.5
24	150	Low tack	4	No fount	na	
25	150	High tack	2	60	2.8	1.5
26	150	High tack	8	60	2.7	1.5
27	350	High tack	4	60	1.2	0.3

Table 1. *Summary of the results.*

Concluding Remarks

The basic mechanisms that influence the emulsification of ink in a nip were explored with some experimental techniques and theoretically. The size of the drops tends to decrease with increasing speed, but other trends were not clear in this limited study. The theory predicts drops that are smaller than what is measured, but in general, the theory predicts the correct order of magnitude. More work is needed to understand the emulsification step.

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