Investigation of a Spreading Model for a High Speed Spot Color Printer using Hot Melt Ink Jet Inks

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Abstract

This paper presents the major findings of a comprehensive thesis research project conducted by the author.[1] Capillary flow porometry and mercury intrusion porosimetry techniques were utilized to evaluate key paper properties of the modified spreading model for a porous medium with transverse and radial capillaries.[2] A novel technique known as transverse capillary flow porometry, useful in the evaluation of in-planar (x-,y-directional) pores, was also incorporated. Accent Color Sciences' Truecolor 400 web-fed printer with Spectra CCP-256 printheads and Sabre hot melt inks were used to generate print samples. 75 nanogram ink drops were jetted onto three different plain papers at a printing speed of 160 FPM. The resultant drop radius (R_p) was determined and used in the spreading model in relation to the radius of the ejected ink drop (R_f). An initial drop radius (R_d) at the time of impacting the paper was calculated based on the evaluated paper and printing properties.

The spreading model has been compared to the Spectra "Splat Model", developed specifically for hot melt inks.[3] The two spreading models were further simplified into three components: (1) Final Drop Spreading Coefficient [FDSC], (2) Drop Impact Spreading Coefficient [DISC], and (3) Characteristic Paper Spreading Coefficient [CPSC]. The analysis proved that the two models had very comparable CPSCs, but different DISCs and FDSCs.

Introduction

Hot melt ink jet inks are used in numerous digital printer systems. The Tektronix Phaser 300 and 500 series printers, Brother Ink Jet printers, and Polaroid DryJet printers for digital proofing use hot melt inks. Prints generated with these devices have a layer of the wax-based ink above the substrate surface. This is well known and acceptable for the specific end use application of these systems. The ACS400 Web-fed printer (Accent Color Sciences, East Hartford, CT), on the other hand, requires for the ink to be completely penetrated into the paper surface. This printer system is being sold by IBM Printing Systems (Boulder, CO) as the InfoPrint HC4000. Its intended use is for high speed spot color printing of bank statements, telephone bills, investment portfolios, and direct mailings to name a few. The black images are generated by an IBM 3900/4000 High Speed Laser document printer. The reason it is important to assure the ink has completely spread and penetrated into the paper is due to the various post processes the final print may undergo. For example, a folder/stacker system, an envelope handling system, and perhaps a paper rewinder prior to being further processed. The other factor is that the ink may also undergo mechanical abrasion within the ACS printer if not properly "fused" into the paper. At printing process speeds in excess of 230 feet per minute, this must all occur in less than 1 second. The following figure depicts the ACS printer system:

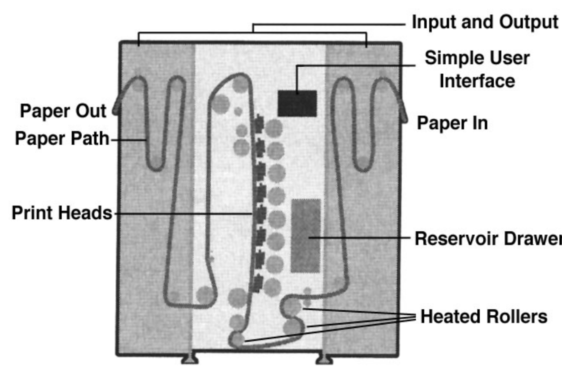

Figure 1. ACS400 Web-fed Printer System

The three heated rollers provide temperature control to effectively raise the paper temperature up to the required paper temperature depending on the paper's basis weight and surface/structural properties (i.e., Gurley Porosity and Sheffield Smoothness). Along the "printing region" a heated platen is implemented behind the paper web. In Figure 1, this is located where the printheads are positioned in the system on the backside of the paper. In order to adjust print quality in the ACS printer, there is a screen set up in the Graphic User Interface (GUI) which allows the printer operator to select "Configure Paper Type" settings. The settings have been optimized for Paper Basis Weight, Gurley Porosity, and Sheffield Smoothness. Depending on the characteristics of the paper, the printer can easily be set up to run papers with the following properties: (1) Basis weight: 16# - 28#; (2) Gurley Porosity: 5 – 30 sec/100cc of air; (3) Sheffield Smoothness: <100 – 200 Sheffield Units (SU). For more information, the author suggests contacting Accent Color Sciences directly at (860) 610-4000. As part of the proprietary internal investigation jointly conducted by ACS and IBM, it was determined that Gurley Porosity had a much greater impact on the spreading and penetration characteristics of the hot melt inks than Sheffield Smoothness.

This paper highlights the investigation of a spreading model developed in Stanley Middleman's book *Modeling of Axisymmetric Flows: Dynamics of Films, Jets, and Drops*, which incorporates both radial and traverse capillary pores into the model. The model in the literature has been modified to include the size of the ejected ink drop and is represented by the following equation:

$$R_p / R_f = (R_d / R_f) \times \{1+[(4/3\varepsilon)(R'/R)^{1/2}]\} \qquad (1)$$

The terms of the equation are defined as follows:

R_p = Final drop radius.
R_f = Radius of ejected ink drop prior to hitting the paper.
R_d = Radius of initial contact radius of ink drop.
R = Radius of radial capillaries.
R′ = Radius of transverse capillaries.
ε = Fractional open area (or volume) of pores. [Porosity]
Note: All the terms above, with the exception of ε, are in microns (μm).

Capillary flow porometry,[1,4,5] mercury intrusion porosimetry,[1,4,6] and a novel technique known as transverse capillary flow porometry[1,7] were used to determine R, R′, and ε in Equation 1. A typical image analysis system, with a frame grabber, using Global Lab software was used to measure the size of the ink drops onto the three different papers. The experimental setup will be detailed further in the following section.

The Spectra Splat Model is represented by the following equation:

$$S/D = 1.26 \times [1+0.5 \times (N_{Re})^{1/2}]^{1/3} \qquad (2)$$

The terms of the equation are defined as follows:
S = Final drop radius.
D = Radius of ejected ink drop prior to hitting the paper.
N_{Re} = Reynolds Number of the ejected ink drop (ACS Operating Parameters = 25.3 for Reynolds Number).

The author, in his thesis work, has further simplified both models into the following equation:

$$FDSC = DISC \times CPSC \qquad (3)$$

The terms are defined as follows:
FDSC = Final Drop Spreading Coefficient.
DISC = Drop Impact Spreading Coefficient.
CPSC = Characteristic Paper Spreading Coefficient.

Experimental Approach

The ACS400 Web-fed printer system was used to generate print samples at a printing speed of 160 fpm. 75 nanogram (ng) drops were jetted at 7 m/sec at a printhead operating temperature of 120°C onto print surface temperatures of 50°C, 65°C, 70°C, 75°C, and 80°C. A 75ng ink drop is equivalent to an ejected ink drop radius, R_f, of 27.7μm. Black ink was used throughout the investigation for the image analysis of the printed drops. Three papers with very different porosity characteristics were used to print onto. The papers are as follows:

Table 1. Three Commercially Available Papers

Paper Mfg	Basis Weight	Gurley Porosity (sec/100cc)	Sheffield Smoothness
Georgia Pacific (A)	20# Medium	10 Porous	145 Average
Champion Int'l (B)	18# Light	1.5 Non-Porous	180 Rough
Willamette Industries (C)	42# Out of Spec	24.4 Non-Porous	170 Rough
Bowater Inc. (D)	18# Light	100 (Non-P) Out of Spec	159 Rough

The rating of "medium", "porous", "average", and so forth correspond to the actual settings used by the ACS printer system. In the case of the Bowater paper, the Gurley porosity value would indicate that this paper would not be recommended for customer use. However, for experimental purposes, the "Non-Porous" setting would be used. The letters A, B, C, and D will be used to refer to each of the three papers. Paper C was not evaluated as part of the spreading model investigation. It was, however, used to correlate the transverse capillary flow porometery data.[1] The lighter weight papers were not able to complete the in-planar (transverse) capillary flow porometry test.

Again, radial and transverse capillary flow porometry were used to evaluate the radial and transverse capillary pore sizes. Porous Materials, Incorporated (PMI) (Ithaca, NY) conducted all of the testing for the original research work conducted by the author. Porewick (PMI tradename), an inert flourinated hydrocarbon with a very low vapor pressure, was used as the wetting agent for the paper testing. Mercury intrusion porosimetry was also conducted by PMI to determine the total open pore volume (ε), or porosity, of each paper.

The printed dot sizes were measured for Papers A, B, and D at all five paper temperatures using a standard image analysis system with a frame grabber at a 75X magnification. Global Lab software (DATA Translation, Marlboro, MA) was used to evaluate 81 ink drops per paper temperature for all three papers. Based on the recommended "Configure Paper Type" settings used for each of the papers, the final ink drop size was interpolated from the spreading data. Paper A had a recommended paper temperature setting of 72°C. Papers B and D had a recommended paper temperature setting of 76°C.

Results and Discussion

Based on the radial/transverse capillary flow porometry and mercury intrusion porosimetry analysis, the following values were determined for R, R′, and ε terms from Equation 1 for Papers A, B, and D:

Table 2. Radial/Transverse Pore Sizes & Porosity (ε)

Paper	Radial (R) Capillary Pore Size (µm)	Transverse (R′) Capillary Pore Size (µm)	Paper Porosity (ε)
A	1.0848	0.0657	0.6018
B	0.7799	0.0255	0.4784
D	0.2666	0.0092	0.6134

The values in the table above are expressed as pore radii, not pore diameters. Again, mercury intrusion porosimetry was used to determine paper porosity. This was done by evaluating the total intrusion volume. The following equation was used to determine paper porosity:

$$\varepsilon = [(SW)(IV)] / [(SW)/((BW)(1/PT))] \qquad (4)$$

where,
SW = Sample Weight (g)
IV = Total Intrusion Volume (cm^3/g)
BW = Paper Basis Weight (g/cm^3)
PT = Paper Thickness (cm)

The following table depicts the ink drop spreading results from the Global Lab analysis of 81 individual ink drops. The values are stated as the mean radii, not as diameters.

Table 3. Ink Drop Spreading Results for 75ng Drops

Paper Temp (deg.C)	Paper A Rmean (microns)	Paper B Rmean (microns)	Paper D Rmean (microns)
50	43.52	42.62	46.06
65	49.43	46.30	52.32
70	60.99	53.74	55.41
75	68.27	56.95	63.83
80	68.02	72.50	59.07

Again, the value for R_p (final ink drop size) from Equation 1, which is taken as the Rmean value at the recommended paper temperature setting for each paper was interpolated based on the data in Table 3 above. Therefore, the following table shows the value of R_p for each of the three papers:

Table 4. Final Ink Drop Sizes for Spreading Models

Paper	Operating Temperature (°C)	R_p for 75ng Drops (microns)
Paper A	72	63.90
Paper B	76	60.06
Paper D	76	62.88

As stated earlier, a 75ng ink drop has an ejected drop radius, R_f, of about 27.7µm. The values stated in Tables 2 and 4 and the value for R_f was then used in Equation 1 to determine a value for R_d, the radius of the initial contact radius of the ink drop impacting the paper surface. The following table summarizes all the terms in Equation 1:

Table 5. Spreading Model Equation 1 Parameters for Papers A, B, and D

Parameter	Paper A	Paper B	Paper D
R (microns)	1.0848	0.7799	0.2666
R′ (microns)	0.0657	0.0255	0.0092
ε (porosity)	0.6018	0.4784	0.6134
R_f (microns)	27.70	27.70	27.70
R_p (microns)	63.90	60.06	62.88
R_d (microns)	41.35	39.93	44.79

As mentioned earlier, the modified radial and transverse capillary model and the Spectra Splat model can be further simplified into Equation 3. The following table depicts the breakdown of each of the three terms in Equation 3 for both models:

Table 6. Comparison of Spreading Model Terms for Equations 1 and 2

	FDSC	DISC	CPSC
Equation 1	R_p/R_f	R_d/R_f	$1+[(4/3\varepsilon)(R'/R)]^{1/2}$
Equation 2	S/D	1.26	$[1+0.5\times(N_{Re})^{1/2}]^{1/3}$

By plugging in the values in Table 5 into the terms for Equation 1, for each of the three papers, and the given Reynolds Number (N_{Re}) of 25.3 into the Spectra Splat model equation, the final results for this comparison are as stated in the following table:

Table 7. Comparison of Radial & Transverse Capillary Model to the Spectra Splat Model for a 75ng Drop Mass

Model	Paper	FDSC	DISC	CPSC
Spectra	N/A	1.92	1.26	1.52
R/T Cap	Paper A	2.31	1.49	1.55
R/T Cap	Paper B	2.17	1.44	1.50
R/T Cap	Paper D	2.27	1.62	1.40

The following observations are supported from the results given in Table 7 above:

1. The calculated CPSC of 1.52 for the Spectra Splat Model, using 25.3 for the Reynolds Number, is very comparable to the values for the three papers evaluated using the Radial/Transverse Capillary Model. There is a 7.9% difference between the CPSC values for the Splat Model (1.52 and for Paper D (1.40). The differences for Papers A and B are 2.0% and 1.3% respectively.
2. Spectra's value of 1.26 for the DISC is considerably different that the three papers evaluated using the Radial/Transverse Capillary Model. There is a 28.6% difference between the Splat Model and Paper D (1.62).

The differences for Papers A and B are 18.3% and 14.3% respectively.

3. The calculated FDSC for the Spectra Splat Model (1.92), using 25.3 for the Reynolds Number, is considerably different than the three papers evaluated by the Radial/Transverse Capillary Model. There is a 20.3% difference between the FDSC values for the Splat Model (1.92) and Paper A (2.31). The differences for Papers B and D are 13.0% and 18.2% respectively.

Conclusion

The comparison of the two models showed the following: (1) Both models have very similar CPSC terms. There was less than an 8.0% difference between Paper D [1.40] to the Splat Model value of 1.52. On average, the differences were less than 4.0%. (2) The main differences found were in the DISC term results. Spectra used a higher viscosity ink and a laboratory bench setup, exposed to room temperature conditions, to determine the 1.26 value for the DISC term. The ambient temperature in an ACS printer is about 50°C. (3) The resultant values of the DISC term significantly influenced the results obtained for the FDSC terms. There was a 13.0% to 20.3% difference between the Spectra Splat Model and the results found for the three papers evaluated.

References

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Biography

Nathaniel R. Schwartz is a Senior Research Chemist for Flint Ink Corporation’s Digital Ink Division at the Ann Arbor World Headquarters location. Prior to joining Flint Ink he was a Principal Chemical Engineer at Accent Color Sciences (1996-1999) working on custom color development and ink/paper printing process studies. Prior to ACS he worked at Rexam Graphics (1995-1996) and IRIS Graphics (1990-1995) where his primary responsibilities were ink formulation and process development. He has co-authored a couple of papers on the light stability characteristics of IRIS ink jet prints and holds 2 U.S. patents. He received his B.S. (1990) and M.S. (1998) in Chemical Engineering from the University of Massachusetts Lowell. He is an active member of AIChE, TAPPI, and of the ANSI standards subcommittee working on new test methods for digital printing materials.