Study of Ink Mileage Curve of Gravure Printing

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Abstract: Ink mileage curves have been studied for many years. Several models for curve fitting have been reported by different researchers. The regression coefficients derived from curve fitting were found to be very useful for comparing different inks, and were related to some properties of ink and paper. However, these models were based on the experimental data of prints made on IGT and/or Prufbau printability tester using offset inks. The quantity of transferred ink and hence the amount of ink on paper was determined by the weight difference of the printing disc before and after printing. Therefore, these models may not be applied to the ink mileage behavior of other ink types, nor on commercial printing presses.

In this study, five coated papers for rotogravure were used as testing substrates, and printed on a Cerutti rotogravure web press. Commercial toluene based gravure coated inks were marked with a selected tracer, which can be detected after printing by means of Inductively Coupled Argon Plasma (ICAP/ICP) Atomic Emission Spectroscopy (AES). The amount of ink transferred was calculated from the ICP analyses of both wet ink and printed samples. The optical densities at different tone areas were measured with reference to the optical density of unprinted paper. The ink film thickness and optical density data were fitted using different models with OriginPro 7.5 software. The degree of fit was determined by the sum of the square of residuals and the distribution of residuals around zero point. Both Oittinen and Calabro-Savagnone models fitted the experimental data equally well. The regression coefficients derived from curve fitting were related to paper properties, such as surface roughness, gloss, porosity, and pore size. It was found that the D_s, m, and n parameters were correlated with porosity and pore size.

Introduction

In a color-reproduction process, the purpose of the ink is to absorb light of various colors selectively, and the function of the paper is to reflect the incident light diffusely. The incident light passes through the ink layer, is reflected in all

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directions by the paper, passes through the ink layer again, and emerges from the surface of the ink. The observer sees that portion of it in the direction of his eyes. During the two passages through the ink film, some of the light is absorbed, depending on the absorption coefficient at each wavelength and on the thickness of the ink layer. There are, however, other factors to be taken into account, such as first-surface reflection and multiple internal reflections. With an angle of incidence of 45°, the first-surface reflection is about 4%. When the layer is glossy, this will be reflected at 45° and will not reach the eye. With a matte surface, some of this specular reflection will reach the eye and lower the apparent reflection density. Multiple internal reflections cause an increase in reflection density, since some of the light is absorbed each time it passes through the ink film. Reflection density increases with increasing ink film thickness until the saturation density is achieved. The saturation density results from the minimum reflectance, which comes from the first-surface reflection. (Yule, 1967)

An ink mileage curve (Figure 1) is a plot of the printed optical density of an ink on a substrate as a function of ink film thickness. The optical density of a print increases from zero to a saturation value if the ink layer thickness on the paper is increased. This curve provides only qualitative information about the ink mileage characteristics of the ink. In order to describe quantitatively, it is essential to fit an equation to the experimental data. The regression coefficients derived from curve fitting are very useful to compare different inks. The coefficients can also be related to some basic properties of ink and paper (Chou and Harbin, 1991). However, the empirical model must fit the experimental data well so the regression coefficients can be useful in characterizing the interactions.

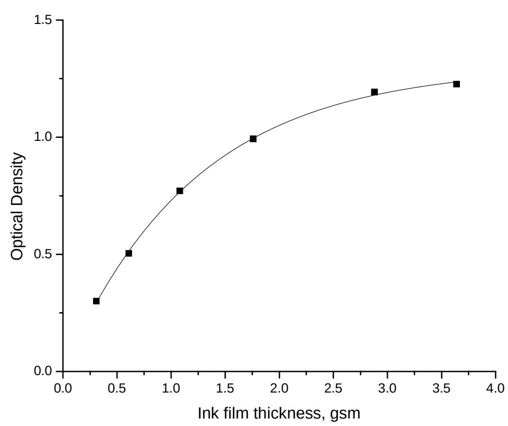


Figure 1. Ink mileage curve of cyan ink on coated paper

Several models for curve fitting have been reported by different researchers, among them Tollenaar and Ernst (1962), Kornerup et al. (1964), Oittinen (1972), Calabro and Mercatucci (1974), Calabro and Savagnone (1983), Blom and Conner (1990), MacPhee and Lind (2002). Six of the models were reviewed and compared by Chou and Harbin (1991), as listed below:

Tollenaar and Ernst (1962)	$D = D_s(1 - e^{-mw})$	(1)
Oittinen (1972)	$D = D_s(1 - e^{-mw^n})$	(2)
Calabro and Mercatucci (1974)	$\frac{1}{D} = \frac{1}{D_s} + \frac{m}{w}$	(3)
Calabro and Savagnone (1983)	$\frac{1}{D} = \frac{1}{D_s} + (\frac{m}{w})^n$	(4)
Blom and Conner (1990)	$\frac{R}{R_p} = \frac{R_s}{R_p} + \frac{m}{w}$	(5)
Kornerup et al. (1969)	$\frac{R_p - R_s}{R - R_s} = 1 + (mw)^n$	(6)

where w is the thickness of ink film on the substrate. D_s, m, and n are regression coefficients. D and R are respectively the optical density and reflectance of a print. The subscripts p and s represent paper and saturation. The equations 1 and 3 result from the shape of ink mileage curves. Equations 2 and 4 are their modifications by introducing a power index to the ink film thickness. It is a common practice in mathematics to add an exponent to independent variable in order to get a better curve fitting. Equation 6 originates from Bouguer's law with some assumptions and simplifications (Kornerup et al., 1969). Equation 5 is a simplified version of equation 6. Chou and Harbin (1991) found that three-parameter equations fitted the experimental data much better than their two-parameter correspondents.

The saturation density D_s results from first-surface reflection, which is affected by the smoothness of the ink film surface. Surface roughness of an ink film is related to the ink's leveling property, which is determined by its rheological properties (Chou et al., 1990). The parameter m determines how fast the ink mileage curve approaches the saturation density by the increase in ink film thickness. It has been reported that m correlates with the degree of contact between the ink film and the paper (Tollenaar and Ernst, 1962). It was also found that m was related to ink's absorption of light and its value decreased with decreasing pigment concentration (Kornerup et al., 1969). The ink film thickness exponent n was found to be affected by ink's rheological variables (Calabro and Savagnone, 1983), and the spectral properties of the pigment (Kornerup et al., 1969).

The major disadvantage of these models is that they were based on the experimental data of prints made on IGT and/or Prufbau printability tester using offset inks. The quantity of transferred ink and hence the amount of ink on paper was determined by the weight difference of the printing disc before and after printing. Therefore, these models may not be applied to the ink mileage behavior of other ink types, nor on commercial printer. A new method has been studied to measure ink mileage (Xu et al., 2005). The inks were doped with a tracer, which were used to calculate the mass of the ink transfer, and hence the ink mileage. This internal tracer method can be used in all kinds of ink types including solvent-based gravure and flexo inks. It can also be applied to commercial printing presses.

The objectives of this work were to use the internal tracer method to measure ink mileage on a commercial printer, to find a best model to fit the experimental data, and to study the regression coefficients.

Experimental

Five coated papers for rotogravure, of about the same grammage, were used in this experiment. The characteristics of the papers are reported in Table 1. Grammage, Print-Surf (PPS) roughness, Gloss, and PPS porosity were measured according to TAPPI standards (TAPPI, 1999, 2002). A PPS Model 90 (Messmer Instrument) was used for roughness and porosity measurements. A Gardco® Novo-Gloss™ Glossmeter was used for gloss measurements. Pore sizes were determined by mercury porosimetry. Measurements were carried out using an Autopore IV 9500 (Micromeritics Instrument). More details can be found in a previous paper (Xu et al., 2005).

Table 1. Characteristics of papers

Sample No	Grammage (g/m^2)	PPS Roughness 500KPa (micron)	Gloss 75° (%)	PPS Porosity (ml/min)	Pore Size (nm)
1	50.05	1.69	58.0	10.58	101.5
2	48.95	1.60	51.8	10.67	113.0
3	50.06	1.57	61.4	7.97	100.3
4	49.58	1.52	53.5	11.93	233.1
5	50.62	1.54	52.9	10.46	146.5

The papers were printed on a Cerutti rotogravure web press (Cerutti Model 118, Italy), located at Western Michigan University (WMU) Printing Pilot Plant.

Commercial toluene-based coated yellow, magenta, and cyan inks for rotogravure (Flint Ink) were used. All inks were doped with a selected tracer. The ink efflux time with Shell cup #2 was kept at 21 ± 0.5 seconds for all inks. Printing was done at 1000 ft/min with electrostatic assist (ESA) on. The magenta cylinder has elongated cells, while the cyan cylinder has compressed cells. The print layout contains different magenta and cyan tone areas from 25% to 100 %.

Both wet ink samples and tone areas of printed samples were analyzed at Chemisar Laboratories. By knowing the amount of tracer metal in both the wet ink and printed ink film, the ink film thickness can be calculated by using:

Ink film thickness (gsm) = Tracer in print sample (gsm) / Tracer in ink (wt%) (7)

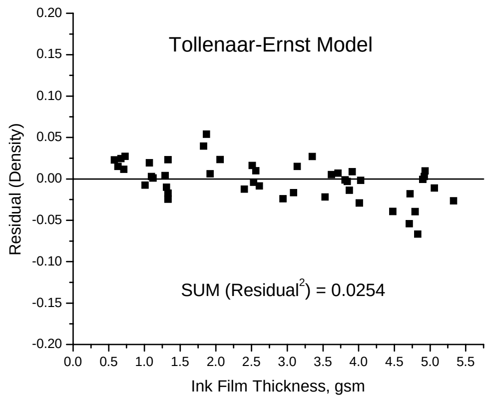
The optical densities at different tone areas were measured with reference to the optical density of unprinted paper using an X-Rite 530 densitometer.

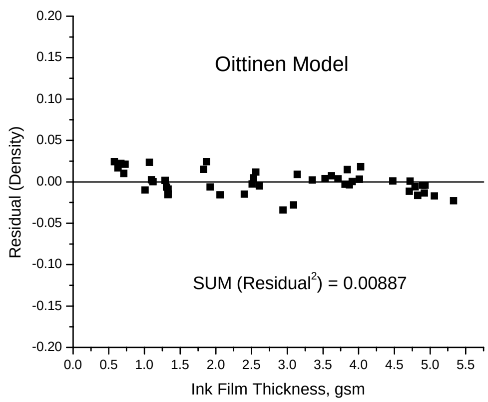
Results and Discussion

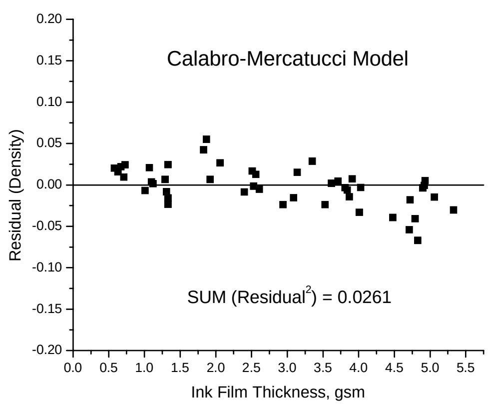
The ink film thickness and optical density data was analyzed using appropriate OriginPro 7.5 nonlinear fitting routines. Equations 1 to 6 were examined. D_s or R_s, m, and n were treated as regression variables.

The degree of fit of an equation to the experimental data can be determined by the sum of the square of residuals and the distribution of residuals around zero point. Figure 2 shows respectively the residuals of equations 1 to 6 for ten ink mileage curves of the cyan and magenta colors. The results indicate that three-parameter equations 2 and 4 fit, as expected, the experimental data much better than their two-parameter equations 1 and 3. Both equation 2 and 4 have minimal sum of the square of residuals (0.00887 and 0.00768, respectively) and even distribution of residuals around zero point. The Oittinen model (Equation 2) was found not good enough in previous studies (Chou and Harbin, 1991), but it appears a good fit in this study.

The Oittinen model and Calabro-Savagnone model were used to study the effect of paper characteristics on ink mileage behaviors. The regression coefficients, D_s, m, n, derived from curve fitting for each model are listed in Table 2 and Table 3. Saturation density D_s values derived from Calabro-Savagnone model are higher than those from Oittinen model. D_s values of cyan ink films are, as unexpected, higher than those of magenta ink films. Since these two inks have different rheological and other properties, as well as different cell geometries on gravure cylinders (compressed and elongated), it is not practical to conclude based on one printing trial. More experimental results are needed to compare these two inks.


Tollenaar-Ernst Model
SUM (Residual²) = 0.0254
Residual (Density)
Ink Film Thickness, gsm


Oittinen Model
SUM (Residual²) = 0.00887
Residual (Density)
Ink Film Thickness, gsm


Calabro-Mercatucci Model
SUM (Residual²) = 0.0261
Residual (Density)
Ink Film Thickness, gsm

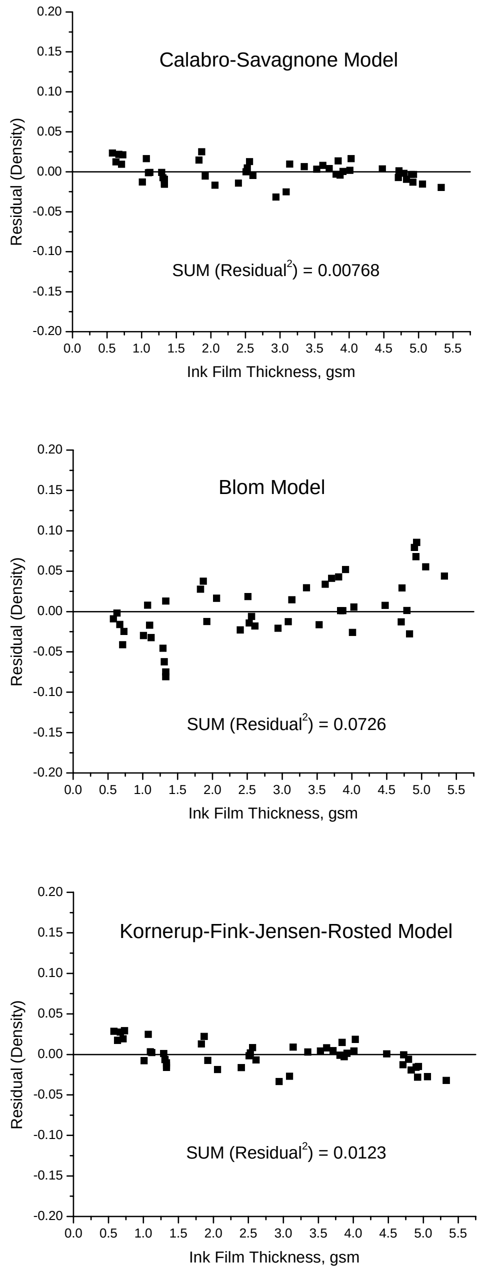


Figure 2. Sum of the square of reflection density residuals and their distribution for various models

Table 2. Regression coefficients of Oittinen model

Paper	Cyan			Magenta		
Sample No	D_s	m	n	D_s	m	n
1	1.904	0.176	0.975	1.491	0.208	1.361
2	1.872	0.177	0.952	1.478	0.233	1.271
3	2.981	0.109	0.862	1.296	0.241	1.435
4	1.524	0.218	1.029	2.075	0.138	1.179
5	2.044	0.175	0.901	1.477	0.199	1.388

Table 3. Regression coefficients of Calabro-Savagnone model

Paper	Cyan			Magenta		
Sample No	D_s	m	n	D_s	m	n
1	2.957	2.910	1.001	1.979	2.143	1.488
2	2.785	2.960	0.991	1.904	2.052	1.419
3	4.985	3.601	0.873	1.547	1.931	1.709
4	2.080	2.604	1.108	3.184	2.767	1.215
5	3.207	2.981	0.923	1.888	2.153	1.558

The correlations between paper characteristics and regression coefficients for both models are shown in Table 4 and Table 5. It is apparent that for both cyan and magenta inks, the porosity and pore size have more effect on the D_s, m, and n parameters than the roughness and gloss. Pauler (1988) pointed out the importance of ink penetration to the shape of the ink mileage curve and proposed a model to study the effect of different paper structures on ink penetration. Porosity and pore size are main factors of ink penetration, therefore, have effect on ink mileage characteristics.

Table 4. Correlation matrix of regression coefficients of Oittinen model

	Cyan			Magenta		
	D_s	m	n	D_s	m	n
Roughness	0.017	-0.156	0.061	-0.432	0.440	0.293
Gloss	0.772	-0.758	-0.466	-0.466	0.402	0.646
Porosity	-0.994	0.998	0.892	0.811	-0.780	-0.840
Pore Size	-0.617	0.738	0.652	0.945	-0.944	-0.765

Table 5. Correlation matrix of regression coefficients of Calabro-Savagnone model

	Cyan			Magenta		
	D_s	m	n	D_s	m	n
Roughness	0.049	0.079	-0.076	-0.408	-0.450	0.210
Gloss	0.780	0.731	-0.502	-0.438	-0.418	0.653
Porosity	-0.995	-0.997	0.894	0.804	0.786	-0.927
Pore Size	-0.640	-0.693	0.740	0.936	0.957	-0.784

It should be noticed that the effects of paper characteristics on ink mileage parameters of cyan and magenta inks are reverse to each other. The reason is unclear, and needs further investigation.

Conclusions

The models that were used to fit laboratory results were also found useful to fit pilot plant press results. It was found that Oittinen model and Calabro-Savagnone model fitted the experimental data much better than other four models, which was evidenced by minimal sum of the square of residuals and their even distribution around zero point. These two models were used to study ink mileage characteristics. The regression coefficients derived from curve fitting were compared and related to paper properties. Good correlations were found with porosity and pore size.

Ink characteristics and printing conditions are also important to ink mileage curves. However, they were not investigated at this step. A clearer understanding will be achieved after more studies. The ultimate goal is that an ink mileage curve can be programmed for the press to adjust ink input as the printing conditions change.

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