Updated Understanding of Print Gloss

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Abstract

Print gloss is one of the most important attributes of a printed product. While is it well known that gloss mainly depends on the surface smoothness, it is less well understood how paper, inks and varnishes interact to generate a specific gloss. Ink films are known to start from a highly textured structure after the splitting of the ink film, but need to level to a smooth surface before the ink solidifies.

A model is developed that predicts the surface tension driven leveling of an ink film. The model inputs are the ink rheology, the surface tension of the ink, and the solids of the ink. In addition, the pore structure of the paper is taken into account to predict the setting of the ink on the paper. The model includes the formation of a filtercake that grows during setting, but then limits the leveling of the ink film. Other predictions, based on other ink setting models are compared.

The model results are compared to experimental results. The low gloss that can be obtained with certain inks and ink film thicknesses is linked to the ability of the ink films to level. As ink oil are absorbed into the coating layers, the filtercake thickness increases decreasing the ability of the ink film to completely level.

Introduction

Print gloss is one of the most important attributes of printed matter. High gloss is known to be the major indicator of a high quality print production. Studies have shown that print gloss variation is more detrimental for the perceived print quality than a low average gloss value. Print gloss variation is believed to be strongly affected by variation in paper surface structure (MacGregor *et al*, 1994; Beland et al, 2000). Gloss is a function of refractive index and the surface roughness of the material.

Gloss and roughness relationships for coating colors are known (Lee, 1974). Since most inks have similar refractive indices, differences in ink gloss are caused in

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large part by the degree of surface roughness. The degree of roughness, in turn, depends on a number of parameters such as the amount of ink, the speed of printing, the rheology of the ink, the roughness of the substrate, and the porosity of the substrate. There have been studies on the effects of these different parameters on print gloss, but a good understanding of how ink setting mechanisms influence the prediction of print gloss is not reported in the literature.

Fetsko and Zettlemoyer (1962) reviewed several aspects of printing and print gloss and pointed out the importance of ink film thickness. Ink gloss generally increases with increasing ink film thickness. With regard to high-gloss coated grades, ink gloss increases with substrate gloss at low ink levels but does not depend on substrate gloss at high ink levels (Zang and Aspler, 1994).

Oittinen (1983) suggested that the surface of a coated paper has two roughness components: microroughness, determined primarily by parameters related to the coating; and macroroughness determined primarily by the base stock. High gloss requires the complete disappearance of both scales of roughness. As ink thickness increased, surface voids caused by microroughness are filled, resulting in a higher gloss print, unless the roughness of the ink is greater than the microroughness of the paper.

The importance of the ink-paper interactions on print gloss was first described by Desjumaux *et al.* (1998): rapid setting papers lead to low gloss because ink filaments do not have time to level. The print gloss has been shown to depend on the pore size of the coating and pore volume; large pore sizes and small pore volumes lead to slow setting and high gloss (Micale *et al.*, 1983; Cummings, 1996; Suzuki, 1996; Arai and Nojima, 1997; Donigian *et al.*, 1997). Preston *et al.* (2001-2003) also reported the influence of pore size and volume on the rate of ink setting. They showed a nice relationship between pore size and the setting rate. The leveling of ink filament remnants on the ink surface was found to be one important factor that determines the final print gloss. The protrusion of ink pigments from the ink film was proposed to decrease ink gloss at long times.

Desjumaux *et al.* (1998) also monitored the effect of different latex types and concentration and pigment size on the wet ink gloss development. Depending on the pigment volume concentration (PVC), different mechanisms were proposed. At low PVC, the diffusion of ink solvents into the latex binder can increase the ink viscosity and stop the leveling of the surface. The interactivity of the latex with ink solvents is the key parameter that determines ink gloss. At high PVC, the capillary penetration of ink solvents may stop leveling and result in low print gloss. A mathematical model supporting these mechanisms was further developed to describe the surface-tension-driven leveling of an ink film when some ink mobile phase, e.g. solvent and low molecular weight fraction of polymer, was removed into the coated layer. Theoretical data were compared to the ink gloss development of printed model pigmented latex coatings and pure latex coatings and verified qualitatively the effect of PVC, the pigment size and the latex type.

The leveling of liquid defects has been extensively analyzed. Orchard (1962) presented a linear analysis to describe the surface-tension-driven leveling of Newtonian fluids. Kheshgi and Scriven gave a long-wave analysis and a finite element analysis of the same problem: predictions of the complete problem follow the simple linear analysis for most parameters. The leveling of coating defects was studied with regard to shear thinning rheology and modeled as the liquid phase is pulled from the coating layer by Iyer and Bousfield (1991, 1996).

Glatter and Bousfield (1997) performed experiments and proposed a model to describe the leveling of an ink film on a rough substrate using the long-wave analysis for the leveling of a fluid layer. Print gloss of ink films on plastic Mylar surfaces was continuously recorded using a laser detector mounted on a laboratory print tester. They found that both variables of printing speed and the thickness of the ink film had a strong influence on print gloss, with high speeds and thick layers of ink producing a film that levels rapidly and then slows down, ultimately producing a lower print gloss than that obtained at lower speeds and ink levels. The wavelength of defects in the printed surface was a critical parameter, with long-wavelength defects having slower leveling rates. These experimental results were compared with calculated results from a model that predicts the extent of ink leveling for a given substrate roughness, initial thickness of the ink layer, ink surface tension, and ink viscosity, but the predictions did not include the effect of ink setting.

The models proposed here describe the leveling of an ink film on a porous substrate, considering oil phase removal during the ink setting process. The models are different from past work in that the change in the ink film layer during the removal of oil is taken into account. Three different ink setting mechanisms are compared call the thickening, two-phase and filtercake mechanisms. These mechanisms are based on different physical phenomena. The goal of the work is to determine if one of these ink setting mechanisms describe the gloss dynamics better than the other mechanisms. These model predictions are compared with the dynamics of print gloss measured on slow and fast setting papers.

Experiments

An ink-oil solution was formulated using a typical offset cyan ink (NSP 2205A1, Sun Chemical) with different component levels of mineral oil (60 SUS, Sun Chemical). The ink and oil were blended by hand using a spatula, then under ultrasonic mixing for five minutes and final homogenization with a DynaMix stirrer (11-498-7SH, Fisher Scientific). The viscosity of the ink and various dilutions of the ink with oil were obtained by a controlled stress rheometer (Bohlin CVO, Malvern Instruments Ltd.), using parallel plate geometry, a PP 40 (40mm diameter plate). The gap between the upper and the lower plates was adjusted 1 mm and temperature was held constant at 25 °C during the measurements. Typical slow and fast setting papers were used for substrate and were supplied by Sappi North America. Printed samples were obtained using a laboratory printability tester (model MPT8000, KRK Co. Ltd.). Model inks were applied to the inking rolls and a substrate sample was then mounted on the moving member with double sided tape to fix it and printed with a layer of ink. The printing conditions are summarized in Table 1.

Parameters	Values
Nip load, kg/cm	100
Speed, m/s	2
Printing roll type (Width, cm)	Metal (4)
Inking on roll (g)	0.4

Table 1. *Experimental printing conditions.*

The gloss of the ink film printed on a paper sample was measured immediately after printing by a specially designed glossmeter, shown in Figure 1 described by Glatter and Bousfield (1997). A laser light source (675 nm, 1.0mW, M38920, Edmund Scientific) and detector are mounted at a 75° angle from the vertical at the end of a laboratory print tester (model MPT8000, KRK Co. Ltd.). The laser sends a beam of light that reflects off the mirror and then off the sample to the detector. The voltage signal from the light detector is collected and stored in a computer. The illumination area on the sample is adjustable. The sample moves through the nip and stops 100 mm from the nip, where gloss is recorded continuously every tenth of a second.

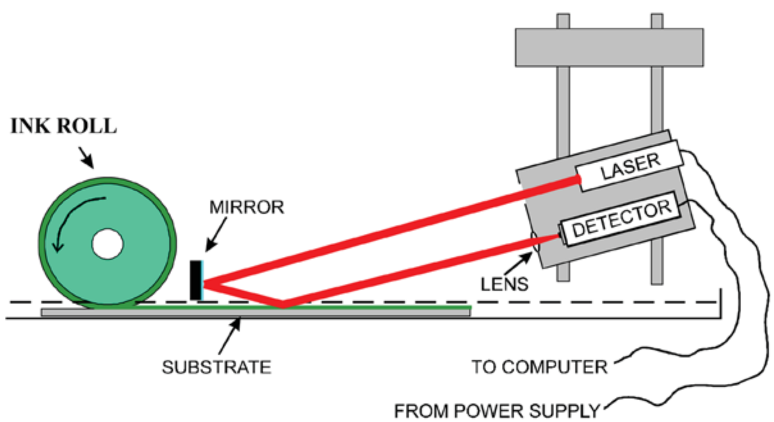

Figure 1. *Dynamic gloss tester schematic from Glatter and Bousfield.*

Model of gloss development

The leveling of a Newtonian fluid is described in the linear limit with the long wave approximation by Orchard (1962). The film profile *h*, is described as

$$h(x,t) = h_o + \varepsilon_0 \cdot \sin\left(\frac{2\pi x}{\lambda}\right) \cdot e^{-\alpha \cdot t}$$
$$\alpha = \frac{\sigma}{3\mu} \cdot \frac{16\pi^4}{\lambda^4} \cdot h_0^3 \qquad (1)$$

Where h_o is the leveled film thickness, ε_o is the initial disturbance, λ is the wavelength of the disturbance, σ is surface tension, and μ is the fluid viscosity.

If roughness is defined as the difference between the highest and lowest points of the ink profile, a prediction for surface roughness as a function of time is obtained and expressed as

$$R(t) = 2\varepsilon_0 \cdot \exp(-\frac{\sigma}{3\mu}\frac{16\pi^4}{\lambda^4}h_0^3 t) \qquad (2)$$

Ma et al. (2008) give an expression that links the roughness of a surface to the 75º gloss '*G*' value where *R(t)* is the roughness change in microns as a function of time.

$$G = 100exp(-2.5R(t)) \qquad (3)$$

Now, when a fluid phase is removed from the ink, the viscosity of the film may increase. In addition, a filtercake of particles may form at the substrate surface, reducing the effective film thickness. In the literature, it is not clear what mechanism actually occurs for an ink. One goal of this work is to test if one model of ink setting better predicts the gloss dynamics results.

The expression for the absorption rate of fluid on a porous substrate driven by capillary pressure

$$V / A = \sqrt{\frac{4K\varepsilon\sigma \cos\theta t}{\mu_o R_p}} \qquad (4)$$

Where V/A is the volume per unit area, *K* is permeability or Darcy coefficient of the porous media, ε is the void fraction, σ is surface tension, θ is the contact angle, R_p is the pore radius, and μ_0 is oil phase viscosity. The Darcy coefficient of the paper, the void fraction and the parameters that determine the capillary pressure all work to determine the absorption rate. These parameters are set to give a reasonable rate that causes the model results to deviate from the no setting case.

As oil is removed from the ink film, the solid volume fraction will increase. From a mass balance, an expression is obtained that links the loss of oil per unit area *V/A* with the current concentration of pigments and resins as

$$\phi = \frac{\phi_0 h_0}{h_0 - \frac{V}{A}} \qquad (5)$$

Where ϕ_0 is the initial volume fraction of solids in the ink and ho is the ink film thickness. *V/A* is found from Eq (4).

With the absorption rate behavior of the system and the viscosity-oil content data, we can estimate the increase in viscosity of the ink film as a function of time. For suspensions, an approximate expression is

$$\mu = K(1 - \phi / \phi_m)^{-2} \qquad (6)$$

Where ϕ and ϕ_m are the solids volume fraction in the ink and the maximum value, respectively. For this ink, the value of K is adjusted to match the current viscosity level compared to the current solids level. The maximum solids ϕ_m is assumed to be 0.6, a value close to the maximum packing of spheres. Figure 6.2 shows the viscosity oil content behavior. Eq. (6) gives a reasonable way to estimate the ink viscosity as the concentration of solids increases.

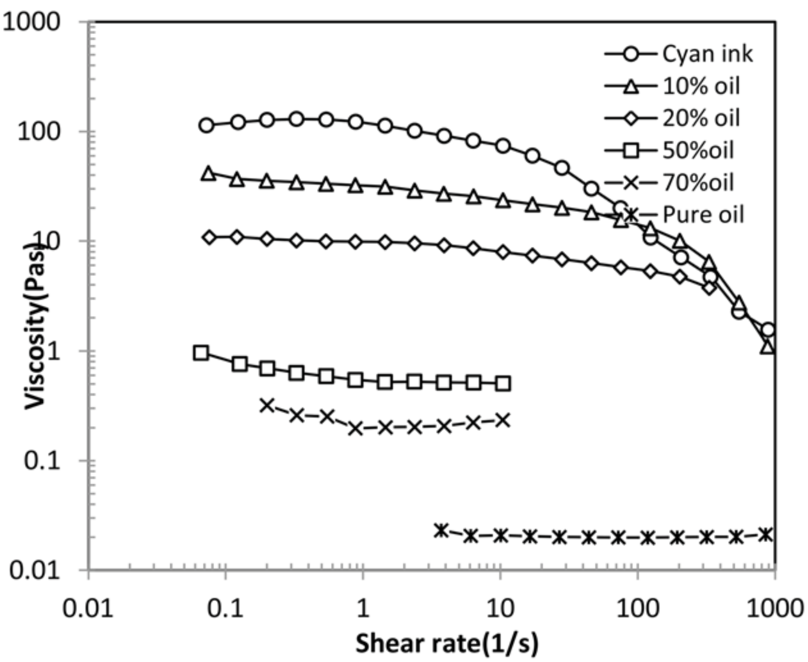

Figure 2. *Ink-oil viscosity results for different oil content.*

According to the two phase mechanism, there are two phases that contain ink resins and solvent oils, a phase with higher oil concentration and one with high resin concentration. The viscosity of this mechanism is explained by the increased viscosity of the diluted solid phase and the concentrated solid phase. At short times, the latter contributes significantly to the buildup of viscosity and is expressed as

$$\mu = Mexp(\alpha\phi^{\nu}) \tag{7}$$

Where ϕ is the solids volume fraction in the ink, α and ν are fitting parameters, 12 and 1.7, respectively, for suspensions. As in Eq. (6), the value of M is adjusted to match the current viscosity level compared to the current solids level. The only difference here between the two phase model and the thickening model is the form of the viscosity-solids relationship because in the limit of short times, the two phase mechanism behaves in this manner. For longer time predictions, the two phase model predicts that oil can be replenished into the ink layer from the resin rich regions to lower viscosity.

By inserting the viscosities acquired from Eq. (6) or (7) into the roughness expression Eq. (2), roughness as a function of time is obtained. Using Eq. (3), this roughness variation is converted to the gloss. Therefore, the film profile in combination with expressions for viscosity increase can be used to predict gloss dynamics of the system. These predictions will be labeled “thickening” or “two phase”, depending on if Eq. (6) or Eq. (7) is used.

If a filtercake is forming on the substrate as oil is removed, the viscosity of the bulk ink layer does not change, but the effective film thickness h_o does. The expression for the volume absorbed, based on this filtercake model as

$$V/A = \sqrt{\frac{4\sigma\cos(\theta)t}{\mu_0 R_p\left(\frac{\phi_0}{(\phi_m-\phi_0)K_f}+\frac{1}{\varepsilon K_p}\right)}} \tag{8}$$

Where V/A is the volume of oil removed per unit area, μ_0 is the oil phase viscosity, K_f and K_p are the permeabilities of the filtercake and the substrate, respectively. If the solid volume fraction goes to zero, the equation reduces to the no filtercake case in Eq. (4). This equation links to the filtercake thickness through a mass balance given as

$$h_f = \frac{V}{A}\frac{\phi_0}{(\phi_m-\phi_0)} \tag{9}$$

The effective value of ho to use in Eq. (2), therefore, is the initial value of h_o minus the filtercake thickness(h_o-h_f). As the filtercake thickness grows, the predicted rate of leveling decreases because the effective thickness of the ink film that can flow decreases. This decrease in leveling rate is quite a different mechanism compared to the other two mechanisms: the viscosity of the ink film is assumed to be constant.

Therefore, there are two key approaches that can be used to predict gloss: 1) adjust the viscosity using Eq. (6) and (7) as a function of time by predicting the oil content using Eqs. (4) and (5) or 2) adjust the ink film thickness in Eq. (2) by the predicted thickness of the filtercake in Eqs. (8) and (9). These models are referred to here as the thickening, two phase, and filtercake models, respectively. They will lead to a decrease in leveling rates, but describe different physical reasons.

The value of the wavelength and the initial roughness in Eq. (2) are found by matching the "non-setting" case to the initial gloss curve. All of these methods that include absorption in the leveling rate equation are approximate and may not hold for all situations and throughout the consolidation process, but they lead to simple expressions that can be compared to the experimental results.

There is a disadvantage of using the simple linear equations. At some point, the equations predict a filtercake thickness larger than the ink film thickness or a prediction of the solids of the ink larger than the maximum physically possible. When this occurs, the model predictions are meaningless; the point at which this takes place would indicate the final gloss that is predicted. In the case of the thickening and the two phase models, viscosity is increased to an extremely high value. At that point, the exponent in Eq. (1) does not grow anymore but rather drops because the effect of viscosity becomes stronger than the time increase; physically this does not make sense. Therefore, the gloss at that point is considered a final gloss. A non-linear model, not discussed here, does not have this problem, but it also predicts similar final gloss.

The fact that none of these models predict the exact shape of the gloss curve is not a serious concern. The model is based on a single sinusoidal disturbance but the experiment must have a distribution of filament sizes. The long wavelength filaments must dominate the gloss response at longer times, giving a lower value than the models. In addition, the base paper has a finite roughness that is not included in the model. Even though a few of the parameters had to be estimated, the general trends in the predictions of gloss is reasonable.

Model parameters

Tables 2 and 3 record the model parameters. The parameters in Table 2 are fixed for all the cases whereas the ones on Table 3 are different for each case. The initial film thickness was measured from gravimetric methods, the amount of ink transferred determined by weighing the inking roll before and after being divided by the printed area. The initial disturbance ε_o and the wavelength of the disturbance λ are adjusted to match the non-setting case at short time; this wavelength value did correlate to the same lengthscale that is normally seen with ink filaments. The permeability of the substrate K is also adjusted to give reasonable setting rate and values are differentiated for fast and slow setting paper substrate. The capillary pressure which is the combination of surface tension σ, contact angle θ, average pore radius R_p, and void fraction of substrate ε controls the setting rate. Fluid viscosity μ is the shear viscosity of model inks selected at a shear rate of 10 s^{-1}.

An attempt to establish the maximum solids volume fraction was made by scraping the sample from a filter and weighing at moderate and long times. The concept was that at moderate times, the filtercake would contain oil, but the oil could continue to be removed from the filtercake at long times. These results were not repeatable and at times gave obviously incorrect results. Therefore, an estimate of $\phi_m = 0.6$ was used. The solids fraction of the initial ink is estimated to be 0.5 for pure ink and reduced for the rest of the cases based on dilution by oil. In theory, these values can be measured exactly, but in the laboratory, it is not easy to measure these solids because all of the oil does not evaporate. The initial ink film viscosity is known from the rheology measurements.

Two different Darcy coefficient for filtercake are used. One is the case where the permeabilities of the filtercake and the substrate K_f and K_p are close to the paper value. The reason this value was employed was that the value from the experiments were high compared to literature values of Gros *et al.* (2002). The other case is when Darcy coefficient of filtercake is much larger; this value is measured with high diluted ink (more than 70% oil) through filtration test. When the ink filtercake Darcy coefficient is much larger than the paper, it becomes unimportant as to its exact value because the paper Darcy coefficient controls the absorption.

Parameters	**Value**
Leveled film thickness (μm), h_0	2.8
Initial disturbance (μm), ε_o	1.1
Surface tension (N/m), σ	0.04
Max.volume fraction of solids, ϕ_m	0.6
Contact angle(°), θ	0
Void fraction of substrate, ε	0.25
Average pore radius (μm), R_p	0.5
Oil viscosity (Pa s), μ_L	0.5

Table 2. *Constant model parameters.*

Parameters	Pure ink	10%oil diluted ink	20%oil diluted ink	Pure ink	10%oil diluted ink	20%oil diluted ink
	Slow setting paper			Fast setting paper		
Disturbance wavelength(μm), λ	29	36	55	29	36	55
Initial viscosity (Pa s), μ	150	50	10	150	50	10
Volume fraction of solids, ϕ_0	0.5	0.46	0.42	0.5	0.46	0.42
Permeability of substrate (m^2), K_p	1.5×10^{-19}			3.0×10^{-19}		
Permeability of filtercake (m^2), K_f	2.0×10^{-19}(low), 1.0×10^{-16}(high)					

Table 3. *Different parameters for each case.*

Results and Discussion

Figure 3 shows the measured and predicted gloss behavior for the ink mixed with 20% oil printed on a slow setting paper at the high value of the ink Darcy coefficient. The initial ink solids fraction is 0.42. The Darcy coefficient of the paper, the void fraction and the parameters that determine the capillary pressure all work to determine the absorption rate. In this case, these parameters are set to give a reasonable rate that causes all the models to deviate from the no-setting case a small amount. As expected, due to the low viscosity and low solids, the gloss of this oil-ink mixture increases to a high value. The no-setting case is expected to predict 100 gloss because there is nothing to stop the leveling of the defect. All three of the models predict a lower gloss than the no-setting case, but these values are higher than the measured value: the measured value actually involves a distribution of wavelengths and is also influenced by the paper roughness that is not included in these simple expressions. All three models predict the final gloss to be high. The difference between the models for the final gloss is minimal. If the parameters that control oil absorption into the paper are changed to increase the setting rate, then predictions for the 10% oil case and the pure ink case become poor in later figures. These parameters for this slow setting paper are held for all cases on the slow setting paper.

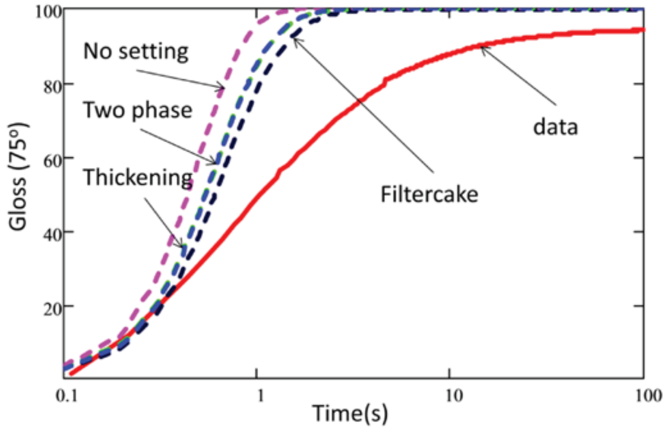

Figure 3. *Experimental gloss value and model results of 20% oil diluted ink on a slow setting paper. Model results are predicted for filtercake* K_f *= 1.0 x* $10^{-16}m^2$*.*

The results for the 10% oil and 90% ink case on a slow setting paper at the high value of Darcy coefficient of the ink are shown in Figure 4. The final gloss is not predicted to be as high as the 20% case, but the difference is not large; this result is caused by the higher viscosity that slows down leveling that gives an earlier stoppage of leveling than 20% oil case. The differences in predictions are minimal, but they do agree with the experimental gloss to a first order.

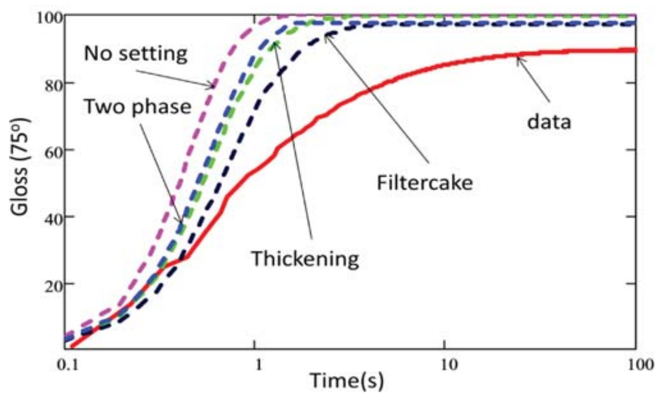

Figure 4. E*xperimental gloss value and model results of 10% oil diluted ink on a slow setting paper. Model results are predictedfor filtercake* K_f *= 1.0 x* $10^{-16}m^2$*.*

Figure 5 shows the results for the pure ink case on a slow setting paper at a high value of Darcy coefficient of the ink. The thickening model prediction is good at early times, but the final gloss is lower than the experimental data because the viscosity is predicted to increase rapidly. The filtercake model under predicts overall due to the rapid increase in the filtercake thickness; this increase is more rapid than what others may have predicted in the past because of the improved accuracy represented by Eq. (9). The initial solids of the pure ink was estimated to be 0.5. If this value was lower, then the model would give better predictions. In the case of the two phase model, not much difference is observed in the predictions of all cases because the increase in viscosity is weaker than the thickening mechanism.

Figures 6 shows the theoretical and experimental results of dynamic gloss on a fast setting paper for the ink mixed with 20% ink-oil mixture with a high ink Darcy coefficient. The major difference from the first three results is that the substrate is changed from a slow setting paper to a fast setting paper by increasing the paper Darcy coefficient by a factor of two. The no-setting case is not affected by this, but all models are expected to predict a lower gloss than the slow setting paper because the oil removal rate is higher: the leveling event is stopped sooner than the slow setting case because the viscosity or filtercake thickness increases more rapidly. Although the filtercake model prediction is closest to the experiment, all the mechanisms predict little reduction of gloss due to rapid ink setting.

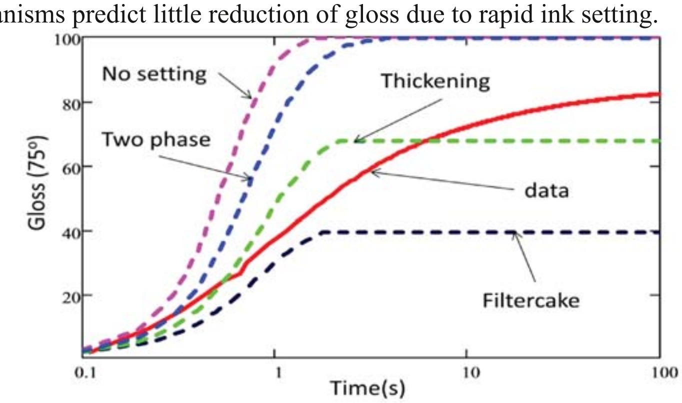

Figure 5. *Experimental gloss value and model results of original ink on a slow setting paper. Model results are predicted for filtercake K_f= 1.0 x $10^{-16}m^2$.*

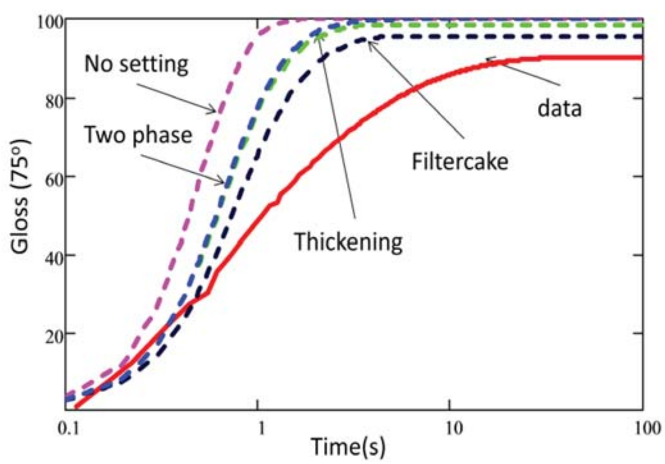

Figure 6. *Experimental gloss value and model results of 20% oil diluted ink on a fast setting paper. Model results are predicted for filtercake K_f= 1.0 x $10^{-16}m^2$.*

The results for the 10% oil and 90% ink case on a fast setting paper at the high value of Darcy coefficient of the ink are shown in Figure 7. The thickening and filtercake models predict a remarkable stoppage of leveling. The final print gloss of the thickening model shows the best prediction. The filtercake model predicts well until first two seconds, but its final gloss is significantly under predicted. This under prediction is caused by the rapid increase in the filtercake thickness. The two phase model shows some difference from the data but reaches to 100% gloss predictions.

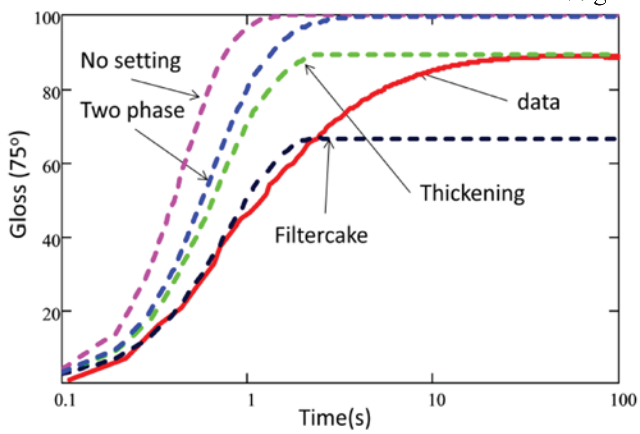

Figure 7. *Experimental gloss value and model results of 10% oil diluted ink on a fast setting paper. Model results are predicted for filtercake K_f= 1.0 x 10^{-16}m^2.*

Figure 8 shows the results for the pure ink case on a fast setting paper at a high value of Darcy coefficient of the ink. Both the thickening and the filtercake model significantly under predict gloss due to the rapid viscosity increase or filtercake thickness increase. The data does show a decrease in final gloss compared to the slow setting cases and the 20% oil case, but the difference is not as large as the models would predict. A small reduction of final gloss in the two phase model is observed, but there is quite a difference from the experimental data.

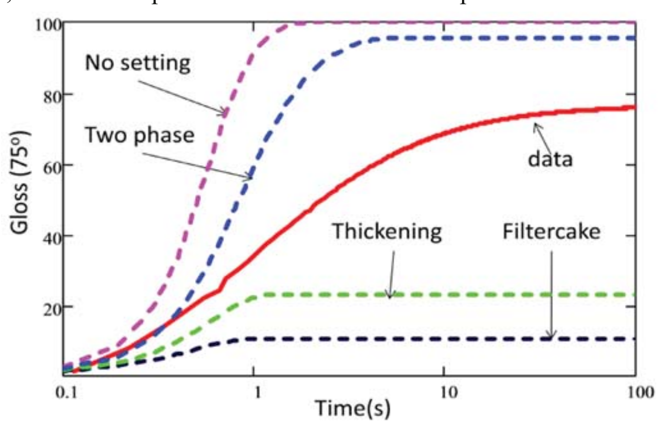

Figure 8. *Experimental gloss value and model results of the pureink on a fast setting paper. Model results are predicted for filtercake K_f= 1.0 x 10^{-16}m^2.*

The filtercake model under predicts the gloss response when the ink Darcy coefficient is at a high value. If it is set to a value similar to that of the paper, then good predictions are obtained: this is caused by the ability of the filtercake to slow down the absorption. Conversely, the predicted results of the thickening and the two phase model are the same as the previous ones since they are not affected by filtercake formation and absorption rates are not changing.

Figures 9-11 shows the measured and predicted gloss behavior for the three cases again on a slow setting paper at a low value of Darcy coefficient of the ink. As before, the 10 and 20% oil cases, all of the models do not predict much setting and high gloss response. For the pure ink case, the filtercake model yields a much improved prediction of ink gloss. This improvement is believed to be caused by the decrease in absorption rate caused by the filtercake itself. The good prediction could be discounted, however, because the Darcy coefficient was not measured, just selected to be similar to the paper. However, this value of the Darcy coefficient is reasonable for porous media composed of packed particles of this length scale. Desjumaux *et al.* (1998) used a value of 10^{-17} m^2 for the Darcy coefficient of a coating to model the leveling of ink filaments. This is a converted value from the "structure" coefficient for a wet coating formulation provided by Letzeltzer and Eklund (1993). In our work, an even smaller Darcy law constant is expected for slow setting paper.

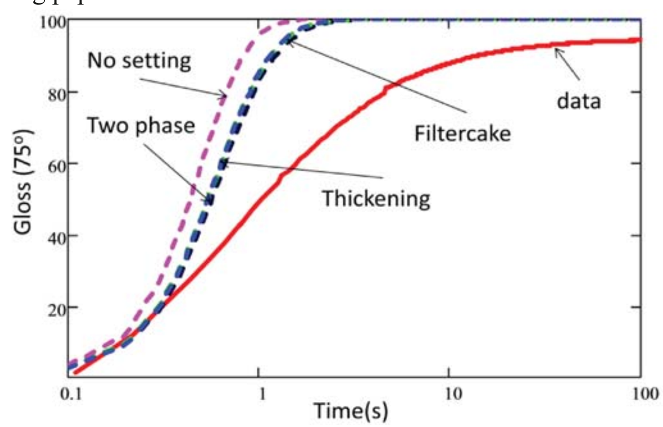

Figure 9. *Experimental gloss value and model results of 20% oil diluted ink on a slow setting paper. Model results are predicted for filtercake* $K_f = 1.0 \times 10^{-19} m^2$.

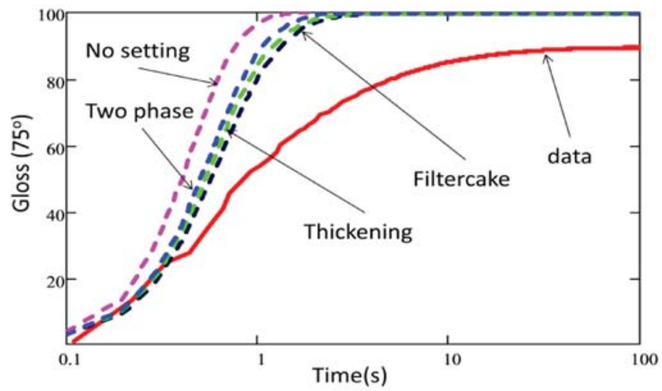

Figure 10. *Experimental gloss value and model results of 10% oil diluted ink on a slow setting paper. Model results are predicted for filtercake* K_f*=1.0 x* 10^{-19} m^2*.*

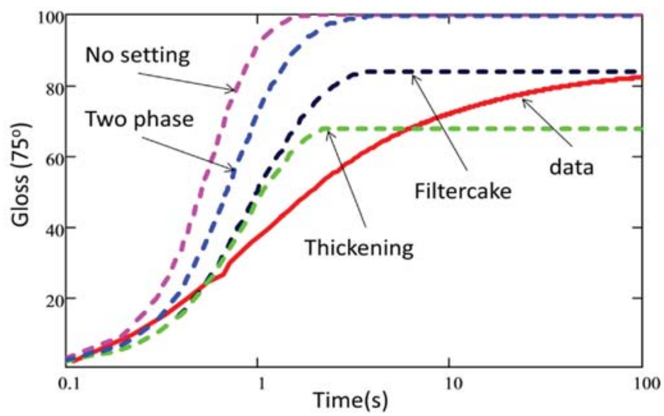

Figure 11. *Experimental gloss value and model results of the original ink on a slow setting paper. Model results are predicted for filtercake* K_f*= 1.0 x* $10^{-19}m^2$*.*

Figures 12-14 shows the theoretical and experimental results of dynamic gloss on a fast setting paper for a low ink Darcy coefficient. Again, for the 20% oil cases, the model predictions are higher than the data and almost overlapped showing some difference from no-setting case; the filtercake predictions are moved closer to the other models. For the 10% case, the filtercake model predictions of gloss increased, due to slower absorption caused by the low ink Darcy coefficient, compared to the result in Figure 6.7. For the pure ink case, the prediction from the thickening model is quite low, as before, but the filtercake model predictions are again close to the experimental data using the same value of the ink Darcy coefficient for the slow paper case. These results suggest that the small value of the Darcy coefficient is correct and that the filtercake model does a reasonable job at describing the gloss dynamics.

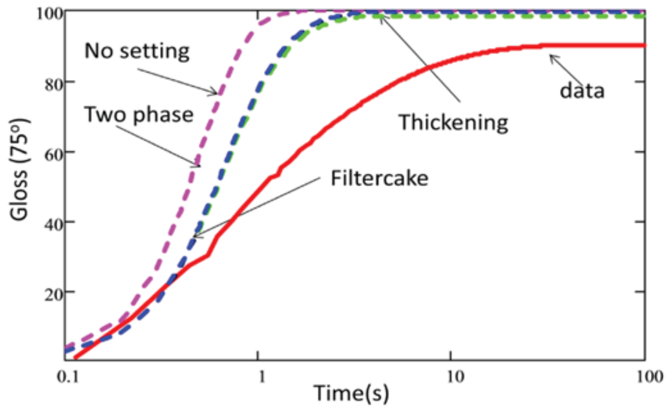

Figure 12. *Experimental gloss value and model results of 20% oil diluted ink on a fast setting paper. Model results are predicted for permeability of filtercake K_f= 1.0 x $10^{-19}m^2$.*

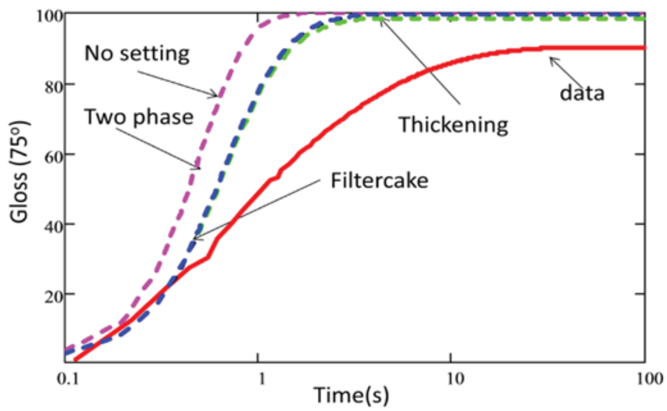

Figure 13. *Experimental gloss value and model results of 10% oil diluted ink on a fast setting paper. Model results are predicted at permeability of filtercake K_f= 1.0 x $10^{-19}m^2$.*

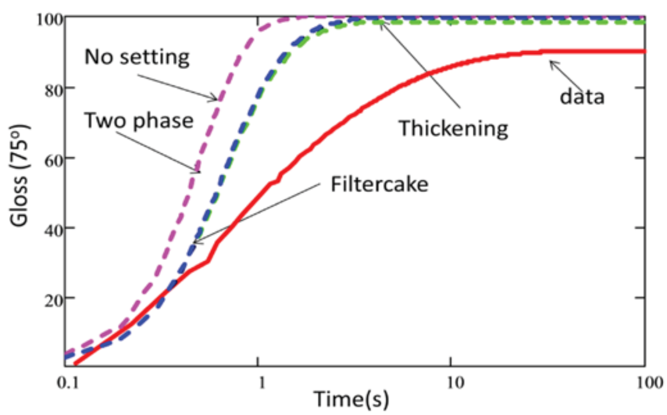

Figure 14. *Experimental gloss value and model results of pure ink on a fast setting paper. Model results are predicted at permeability of filtercake K_f= 1.0 x $10^{-19}m^2$*

Because the experimental results did not show a big difference in gloss between the paper substrates, the predictions of the models was not put under a difficult test. Some past tests, for example by Jeon and Bousfield (2004), had gloss values that changed between coatings to a larger extent than these results. In addition, a few of the model parameters had to be estimated. Therefore, a firm conclusion with regard to the predictive powers of the different models cannot be made. For the parameters studied here, the thickening model tends to over predict the decrease in gloss as the oil content decreases. This result is caused by the increase in viscosity as the oil is removed and matches the viscosity measured at steady state for inks of different oil content. The two-phase mechanism, in the form of the equation used here, shows a weaker viscosity increase as oil is removed and predicts higher gloss than the experiments. The filtercake model, when the permeability of the ink filtercake is set to close to an expected value, seems to be able to predict the change in oil content and the change in paper type better than the other models, but firm conclusions cannot be made.

More work could be done to measure the permeability again of the ink filtercake layer, the permeability of the paper, and some of the other parameters, but at this point, this work clarifies what are key issues and measurements that are needed. A significant effort was put forward to measure the solids content of the ink, but a good method to obtain this value was not found. Without this parameter, trying to obtain other parameters more accurately is not helpful. These measurements and predictions should help future studies on this topic, but a clear result in terms of model is not obtained.

Concluding Remarks

Gloss dynamics of ink immediately after printing were measured on different substrates. Experimental results reveal the effect of substrate type and ink viscosity on print gloss: the print gloss of model inks with high viscosity on a fast setting paper is low. A mathematical model was developed to describe how various ink setting mechanisms affect the leveling of the ink film. Theoretical results verify qualitatively experimental data even though both are not quantitatively comparable. High ink viscosity and high solid fraction of ink films retards the leveling event leading to low print gloss. Dynamic print gloss is greatly influenced by absorption rate of the oil phase into paper that is treated differently in terms of ink setting models. When Darcy coefficient of the ink is high, absorption process is dominated by the paper. However, with a low value of Darcy coefficient of the ink close to the paper, absorption is controlled by the combination of filtercake formation and the paper: the predictions of the filtercake model for all cases is better than the other models, but firm conclusions cannot be made because of uncertain values of some of the parameters.

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