Ink film splitting acoustics and tack on paper in offset printing

A laboratory and theoretical study

JOAKIM VOLTAIRE

Licentiate Thesis
Stockholm, Sweden 2004
TRITA YTK-0403
ISSN 1650-0490
ISBN 91-7283-817-5

YKI, Ytkemiska Institutet AB
Institute for Surface Chemistry
Box 5607
SE-114 86 Stockholm

Akademisk avhandling som med tillstånd av Kungl Tekniska högskolan framlägges till offentlig granskning för avläggande av teknologie licentiatexamen måndagen den 14 juni 2004 i Konferanssal Maxi, Ytkemiska Institutet AB, Drottning Kristinas väg 51, Plan 4, Stockholm.

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Tryck: Universitetsservice US AB
Abstract

This licentiate thesis comprises two complementary studies dealing with the sheet-fed offset printing of paper. The first study addresses the further development of a practical method to acoustically monitor and analyse the film splitting of offset inks. This method was tested on laboratory printing equipment, specifically monitoring the continuous ink splitting in the nip of an IGT ink distribution unit and the short-time ink splitting in the inked print disc-paper nip of the printing unit of an ISIT instrument. The study verified that the ink splitting component of the acoustic signal contributes to the higher frequency range (10-20 kHz) of the audible spectrum, and can thus be separated from the lower frequency machine noise. Furthermore, the film splitting component is sensitive to changes in the ink and printing conditions, thus enabling its use in probing the fundamental mechanisms occurring during ink transfer and also suggesting its applicability for non-intrusive monitoring of industrial printing presses. An increase in film thickness during ink distribution corresponds to an increased acoustic power, with the exception of very low ink amounts, which give reduced acoustic emission due to a lubricating effect. The effect of the presence of fountain solution was simulated by adding emulsion-forming, but non-evaporative, ethylene glycol. This produces an increase in acoustic power at low amounts, due to resistance to glycol drop deformation, followed by a decrease at higher amounts owing to excess glycol lining the rolls. During test printing on paper, increasing ink amounts also display an increased acoustic response.

The second study further developed a theoretical model to explain and predict the evolution of ink tack in terms of ink setting directly after offset printing on coated paper. As measured by the ISIT, the tack of the printed ink rises during shorter time periods, attains a maximum, and then falls at longer times. The proposed model described how the ink tack, characterised by the impulse during disc pull-off, depends dynamically on the viscoelastic properties of the ink, the contact with paper and disc, and the flow geometry. The ink setting was modelled as a diffusion-limited transport of the oil vehicle through the ink film and into the pores of the coated paper. The coupling of the tack and setting models, compared to the ISIT experimental measurements, then provided a diffusion coefficient for ink setting during the tack rise period. This coefficient decreases with time, and increasingly rapidly with decreasing ink amounts due to the concentration-dependent diffusion. For an accurate description the elasticity and adhesion effects also have to considered, at least for explaining the tack fall period.
Sammanfattning


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I: Acoustic technique for investigation of offset ink splitting, transfer and setting
Voltaire, J., Fogden, A., Rentzhog, M., Craig, V.
Submitted to Nordic Pulp. Paper Res. J.

II: Modelling setting and tack of a sheet-fed offset ink printed on a coated paper
Voltaire, J., Fogden, A.
Submitted to J. Pulp Paper Sci.
Acknowledgements

The work was performed as a part of the PrintTech Research (T2F) Program. The Foundation for Knowledge and Competence Development (KK-stiftelsen), The Swedish Pulp and Paper Research Foundation and Stiftelsen Grafisk Forskning are thanked for partly financing this work.

A special thanks to my YKI supervisor Andrew Fogden for his contribution to this work.

Further, I would like to thank all my colleagues at YKI for giving me help and inspiration.

Finally, all my love to Ingrid, Tora and Emmy for your love and support.
1 Introduction

1.1 Physical phenomena in lithographic offset printing

Lithographic offset printing, being the most successful printing technique since the early 1900’s, is still a fascinating subject for scientific research, much due to the complex phenomena involved in the interactions between the printing press, ink and print media.

The offset principle

The principle of offset printing is schematically illustrated in Figure 1.1. The ink is transported from the ink fountain, via a train of inking roller nips until finally reaching the form rollers, plate cylinder, blanket cylinder and print media. On its way through the distribution train, the ink film is sandwiched between the contacting roller surfaces and becomes progressively thinner by film splitting. The ink is then transferred from the form roller to the image holding plate cylinder, which then transfers the image to the print media, e.g. paper, via the blanket cylinder. The fountain solution plays a central role in keeping the non-image area of the plate clean from ink through the lithographic principle, i.e. by means of a hydrophilic non-image area and a lipophilic image area in the same plane on the plate. The printing is possible due to establishment of a dynamic balance with fountain solution both as free water and partly emulsified in the ink. The ink-fount balance is thus crucial for the flow behaviour of the ink and its ability to transfer to the substrate via the blanket.
Film splitting

In this thesis the ink film splitting in such offset nips is studied using an acoustic method. The acoustic method is grounded on the fact that an ink film, like many adhesive films, is not split homogeneously but is influenced by cavitation and the formation of a fibrillar or filament structure, filamentation. A schematic illustration of the ink behaviour during and after printing is given in Figure 1.2. Owing to the cavitation, the splitting emits a characteristic high frequency sound, partly audible, which is easy to detect by a microphone placed near the printing nip exit. The power of the sound is intimately associated with resistance, e.g. energy or force, of film splitting, which is commonly termed tack, tackiness or stickiness.
1.1. PHYSICAL PHENOMENA IN LITHOGRAPHIC OFFSET PRINTING

Figure 1.2 Phenomena in offset printing. Cavitation is due to an under pressurized region after the nip center. Filamentation is the formation of separate filaments prior to film splitting. Levelling is the smoothening of surface. Setting is the solvent absorption at the beginning of ink drying, which opposes levelling.

Definition of tack

A tacky material is intuitively understood as a one that sticks to a surface, which means that it is easy to attach and difficult to detach. Tackiness is often provided by so called tackifiers that are added to the material. A tackifier is a resin molecule, the task of which is to increase the wetting strength and side branch entanglement of the material. In general, the procedure for measuring tack is a two-stage process of bond formation and bond separation (46). During bond formation, contact in molecular dimensions between the material and the adherend is established by deformation and flow as well as by wetting. The second step, the bond separation with a certain rate, is connected with deformation and crack propagation or cohesive flow, i.e. split within the material. In other words, tack is not a single material property such as viscosity or density, but depends on a variety of parameters including surface properties, wetting and adhesion properties, rheology of the sample, and mechanical and environmental properties that are strongly coupled to the application and the instrument that measures it.

While tack is usually defined as the resistance to separate a sample sand-
wighed between two adherend surfaces, and has a unit depending on the measuring device, e.g. energy, force, torque, pressure etc., most often an application-specific definition is required. For example, tack of a pressure sensitive adhesive (PSA) is defined as the ability of the adhesive to form a bond of measurable strength to another material under conditions of low contact pressure and short contact time. Implicit is the assumption that the adhesive separates cleanly from the surface, without any macroscopic residue.

For an ink film on the other hand, the splitting occurs cohesively in the bulk material and the PSA tack definition does not apply. Instead, other requirements are important, such as the need for fast and strong adhesion to an already printed surface (in multi-colour printing). This is often supported by printing with inks in decreasing tack order, *tack sequencing* or *tack grading*.

**Ink film splitting and print quality**

Regarding the nature of splitting, the direct consequence of filamentation at the exit is the wavy appearance of the free split ink film (see Figure 1.2) sometimes referred to as *orange peel effect*. This orange peel texture must be allowed time to level prior to immobilisation in order to attain a high print gloss.

Inks that produce long filaments are sometimes classified as *long* and otherwise *short*. Very long inks are not desirable because of the problems with the filament residues and the increased levelling time. Long inks are often too tacky and hence may cause other printability problems. A too short ink on the other hand, results in too low a tack and smearing of the image, typically due to an over-emulsification of fount.

**Ink setting**

Strongly coupled to the levelling is the *setting*, which for a sheet-fed offset ink means the absorption of the ink oil solvent into the paper and a resulting increase in ink viscosity and tack rise. Actually, in so-called uni-tack inks, which are not tack sequenced, one utilises solely the effect of tack rise directly after print. As the ink mobility decreases at higher ink viscosity, the levelling and print gloss is affected by the means and rate of setting (32), which motivates the study of this phenomena.
1.2. OBJECTIVE AND SCOPE

The tack on paper tests described here are an indirect way to measure the setting, but clearly show the complexity of tack. Although having said that tack increases with viscosity, it is by no means a general fact. As mentioned previously the added tackifier in inks also increases the wetting strength, which effectively means that they lower the viscosity. In other words the viscosity has to be low enough to allow the tackifier to function, and this effect is actually seen in the tack on paper tests, giving a reduced tack after a certain time duration.

1.2 Objective and Scope

The primary objective with this thesis was to demonstrate, by the preliminary results obtained from laboratory scale, the potential of the acoustic technique as a relatively simple and inexpensive method to monitor film splitting in printing presses. Another objective was to increase the understanding of ink-paper interaction and the interpretation of tack on paper tests, by experiments and testing of hypothetical models.

The thesis includes two articles. The first, *Acoustic technique for investigation of offset ink splitting, transfer and setting*, is the result of monitoring and analysing the film splitting sound during inking in an IGT\textsuperscript{1}-inking device and printing with the Ink Surface Interaction Tester (ISIT)\textsuperscript{2}. The article shows that the variance of the acoustic signal is sensitive to factors that influence the ink tack, e.g. ink load and paper type. The acoustic method is believed to find its usefulness directly in the real press room, which is motivated by the fact that human hearing is already a part of a printer’s skill.

The second article, *Modelling setting and tack of a sheet-fed offset ink printed on a coated paper*, is a presentation of a rather general and macroscopic model of the ink setting in relation to tack. The model is as such a guideline for better interpretation of tack tests that presently serve as a qualitative characterisation of ink-paper interactions. Specifically, the article deals with two hypothetical models: a linear viscoelastic lubrication model describing the ISIT tack force, and a diffusion model describing the solvent concentration profile in the ink film. These models were combined to explain the effect of tack build followed by tack loss after printing.

\textsuperscript{1}IGT Testing Systems
\textsuperscript{2}Ink Surface Interaction Tester, SeGan Ltd
1.3 Literature review

Acoustics applied to film splitting

In the context of materials science and materials testing, acoustic emission (AE) has long been used as a method to detect and localise development of damage, leaks, friction movements etc. The technique is based on the fact that transient acoustic waves are generated by a sudden change in the local stress field in a material (2).

A few publications exist regarding the acoustical monitoring or AE of offset printing, principally by one research group in Japan. Hayashi and Amari (19) and Hayashi et al. (20) showed that an increasing level of fountain solution decreased the acoustic power along with ink tack and filament length. Amari et al. (1) showed that a varnish with a chemical gelling bond structure gave louder film splitting noise than one with physical bonds and lower tack. The power spectrum originating from the film splitting showed a broad band distribution between $10 - 30 kHz$ with its highest intensity between $10 - 20 kHz$. The sound emitted by the paper release in a sheet-fed offset press was also studied by Iwasaki et al. (21).

Theoretical tack models

Regarding the modelling of tack, probably the most famous work originates from Stefan (1874), see (eg 4) who studied squeeze flow of Newtonian fluids between immersed circular discs. The squeezing as well as the pulling of the plates (reverse squeeze) will work against a shearing (lubrication) force due to the flow parallel to the plates and the resulting pressure gradient.

Later improvements of Stefan’s model introduced viscoelastic properties. For example, Oittinen (31) showed that more elastic inks were less tacky, which could be explained by the Scott model, see (eg 4). Tanner (40) gave a derivation of a squeeze-film model coupled to a linear viscoelastic (Maxwell) constitutive model.

Coating processes such as roll coating and printing, in which a liquid passes between two rotating rollers, can be classified into two important flow regions Taylor (41), namely a lubrication region located around the nip-center and a free meniscus flow region at the nip-exit. Both hydrodynamic lubrication and elasto-hydrodynamic models have been considered (30, 26, 8, 3, 24) based on Taylor’s theory. Ruschak (34) and Kheshgi et al. (22)
contributed by giving explicit boundary conditions for the free flow. The cavitation is mostly driven by the external load at higher printing speeds, but as discussed by Coyle (9, p.543), cavitation in coating processes is governed by an interfacial force balance between meniscus-stabilising surface tension opposed by a pressure gradient induced by either inertial forces at higher speeds and or viscous (lubrication) forces at moderate speeds. However, the modelling of cavitation has been restricted to analysis that only predicts its onset. No model so far predicts the fate of the further filament elongation in a printing nip (18, p.157).

Besides the lubrication theory, quite a deal of work has been carried out in the area of extensional rheology applied to adhesives with strong fibrillation during extension (27, 38). A work by Lakrout et al. (23) discusses the different failure criteria of an adhesive, including bulk cavitation and crack propagation either within the bulk or at the contact surface. The cavitation and filamentation and viscoelastic elongation of large molecules is also considered as a key factor for ink tack; see for example Voet and Geffken (43), Oittinen (31) and Lyne and Aspler (25).

Gay and Liebler (17) discuss the interplay between surface roughness on a micron scale and air suction that can yield tack energies much higher than thermodynamic surface energies. They determined that surface roughness and true area of contact are crucial to determine the quality of contact and thereby the intensity of adhesion.

The Shull group (e.g. 37, 12, 13) have studied adhesives and tack using a contact mechanical approach originating from the Hertz and JKR theory. Their findings may also have some qualitative relevance for printing including effects of surface roughness on adhesion.

**Tack on paper**

Gane and Seyler (15) developed and described the Ink Surface Interaction Tester (ISIT) for the study of ink tack development after printing. In a conceptual model they stated that the splitting most probably occurs at the weakest link, which could be either cohesive (in the ink or in the paper coating), or adhesive at any of the interfaces. The time for tack rise could be seen as a measure of the imbibition rate and the ink cohesive build-up. At the maximum, the split was considered as a combination of cohesive and adhesive failure including the possibility of crack-like failure in the coating layer or in the ink. The maximum was suggested to be a qualitative measure
of the coating strength, depending on the surface voidage; for higher voidage the ink-coating contact area increases, which favours a cohesive ink split closer to the tack disc. Eventually the tack falls as the adhesion between the ink surface and the tack disc decreases. The time for tack decay was believed to be a measure of the pore volume capacity.

Ink setting

A sheet-fed offset ink contains non-drying oil (high boiling distillate of mineral or vegetable type), drying oil (linseed oil), pigments, binder including tackifying resins, and additives (6). Ström et al. (39) studied the setting mechanism on a coated paper through a chemical analysis of the ink film after printing. The result was that the non-drying oil imbibed first, although some of the drying oil left the ink film as well. It was also found that non-drying mineral oil absorbed faster than non-drying vegetable oil. Moreover, they noted an absorption delay after several minutes and pointed to a combined effect of increased drainage resistance and osmotic pressure due to the consolidation of the ink film. The influence of swelling of paper coating latex can in addition support further setting at longer times (33, 42).

The tack on paper test with ISIT is in fact a relative measure of the ink setting dynamics. In an attempt to quantify the tack rise in terms of ink composition, Gane et al. (16) used the measured impulse and a constitutive ink viscosity model. The model predicted a mass rate that was linear with time, which contradicts the expected square root time dependence often observed in flow systems, e.g. steady diffusion, capillary flow, filtration etc.

Problems similar to ink setting, may be found in the huge literature of moving boundary problems with non-linear diffusion, generally termed Stefan problems, (see, e.g Crank (10, 11)). For the sheet-fed offset ink film the moving boundary is the air interface that moves along with the shrinking ink film and the non-linearity results from the solidification with a decreasing diffusivity. Saure et al. (35) formulated and solved numerically the diffusion problem of an evaporating paint film, which is similar to ink setting except for the different boundary conditions. B.W. van de Fliert (7) proved the existence of a classical solution to the film drying problem, if limited to fast evaporation. Pressure filtration is also a quite similar process, despite being on a much larger scale.
2 Instrumental methods

2.1 Acoustic technique to monitor ink film splitting

Measured quantities

An acoustic signal is a wave consisting of pressure variations with time, which usually has been converted to a voltage variation by a transducer (microphone). As for all types of wave signals, it can be represented in the time domain or in the frequency domain. The time domain is the original time record, i.e. amplitude as a function of time, whereas the frequency domain can be given as the power, or power spectral density (PSD), as a function of frequency. The PSD-function can be calculated by the Fast Fourier Transform (FFT) algorithm, which is included as standard in many software packages.

Alternatively, one may calculate the average power for a specified time interval of a signal regardless of the frequency distribution. This is possible to obtain directly from the time record as the average (total) power is equal to the AC-power (dynamic power or variance) plus the DC-power. The DC is the stagnant level at zero frequency and is often zero unless the record signal is floating due to ungrounded instrumentation. If DC is zero or filtered away, the relation between the total power (then AC-power) and the PSD-function can be written

$$\text{Average Power} = \sigma^2 = \frac{1}{T} \int_0^T [\mu - s(t)]^2 dt = \int_0^{f_s/2} \text{PSD}df \quad (2.1)$$

where $\sigma^2$ is the variance, $\sigma$ is the standard deviation, $T$ is the observed time period, $\mu$ is the average or DC level (here zero), $s$ is the signal value at time $t$ and $f_s$ is the sampling frequency.
If the signal is non-stationary, one can instead look at the time-frequency data, by calculating the PSD in a sliding time window with a certain duration and overlap. Alternatively, by using Eq.(2.1) for each window, one has a measure of the power as a function of time.

**Equipment**

The acoustic signal was detected by a commercially available computer desktop microphone. The maximum sample rate was 44.1kHz, giving a maximum detectable frequency of 22.05kHz. The data collection was carried out with a sound card on a Mac computer, by using a commercial (Shareware) software (SndSampler®) to record into .wav format.

The IGT ink distribution unit was equipped as shown in Figure 2.1 with a microphone and CCD camera to both acoustically and visually monitor the ink splitting behaviour in the nip between the steel and polymer rolls.

![Figure 2.1](image)  
*Figure 2.1* Positioning of the microphone and CCD camera for monitoring ink film splitting.
2.1. ACOUSTIC TECHNIQUE TO MONITOR INK FILM SPLITTING

On the IGT inking device the microphone was clamped in close proximity to the nip, central and parallel to its axis. The CCD camera was mounted either beside (i.e. looking along) the nip axis, to image filament formation and rupture, or vertically above (looking down on) the roll directly after the nip to image relaxation of the broken filaments. The study only focused on the acoustic data, although the images help to visualize the system.

On the ISIT-device two positions of the microphone were considered as depicted in Figure 2.2. The first was in the nip between print disc and paper-bearing cylinder, to record the sound during the ink splitting and transfer. The second position was in the nip between the tack disc and the printed paper, to monitor the acoustic signal during the rapid separation ("spring back") of tack disc from printed surface. In the latter case, reliable and significant results proved difficult to obtain, partly owing to the short duration of the event. As an alternative means for acoustic monitoring of tack forces, the microphone was returned to the first position, and used to monitor not only the signal on first rotation of the print disc against the paper (i.e. during printing), but also on continued rotation of the disc against the printed paper, as a function of time.
2.2 Tack on paper measurements

Equipment and measured quantities

The tack on paper tests were conducted using the ISIT, see Figure 2.2, which is a standard technique to follow the tack force or impulse of a sheet-fed offset ink film as a function of time after printing on a given substrate (15, 14).

At preset time intervals, the rubber tack disc is placed in contact with the printed area, and the force necessary to separate the tack disc and printed paper is measured. The force acting through the separation is described through a pull-off curve as illustrated in Figure 2.3. The tack force, is usually referred to the maximum of the pull-off curve during the duration of contact, while the impulse is defined as the total time force integral over this duration. A tack development curve, on the other hand, as exemplified in Figure 2.4, consists of impulse or force data from several consecutive pull-offs.

![Figure 2.3](image)

**Figure 2.3** The pull-off experiment; the force increases from zero and reaches a maximum at the film split and final spring back of the tack disc.
2.3. MATERIALS

Figure 2.4 An example of tack force development (ink amount 1.2 g/m²) with a mineral oil-based ink. $F_s$ is the splitting force or maximum of $F$ in Figure 2.3

2.3 Materials

The test liquids used in the acoustic measurements were two commercial cyan sheet-fed offset inks (Akzo Nobel Inks), based on mineral and vegetable oil, and an unpigmented resin blend of higher tack than the inks. The detailed ink formula were not given, but a typical formulation of a mineral oil-based sheet-fed offset ink is according to (39) 15-22% pigment; 20-30% hard resin; 8-12% alkyd resin; 10-25% linseed oil (drying oil); 15-25% high boiling mineral or vegetable oil (non drying oil); 3-5% additives (e.g. wax, driers, antioxidants). An oil distillate was used to lower the tack of the mineral oil-based ink. In addition, one test was aimed to mimic the effect of fountain solution, which was carried out by adding non-evaporative ethylene glycol on the IGT-roller during ink distribution. A matte-coated paper was used for testing the effect of ink load and a glossy-coated paper was used in the ink setting experiments. The same mineral oil-based ink was used in the tack on paper tests as in the acoustic measurements, and the paper was a glossy-coated commercial paper. To validate the tack development model, the film thickness was varied.
3 Modelling

3.1 Modelling tack on paper

The tack development is explained here by means of two hypothetical models, one for the ink tack and one for the ink setting. The simplest interpretation is given by only considering the increase of viscosity and the tack rise. This is done by linking the viscosity with the volumetric fraction of solvent in the ink layer.

Ink tack described by a linear viscoelastic lubrication model

Figure 3.1 shows the four principal stages in a pull-off experiment, such as with the ISIT instrument described in Section 2.2, and Figure 3.2 shows a hypothetical true geometry versus a model geometry for the adhesive contact between the tack disc and the ink film during the pulling action.
3.1. MODELLING TACK ON PAPER

The tack model is based on a number of assumptions:

- The rectangular contact area is divided into a number of discretely circular contact spots that together determine the effective contact area according to Figure 3.2
- The lubrication approximation holds; the ink film is very thin compared to the characteristic contact length, resulting in negligible normal stresses compared to shear lubrication stresses
- The ink rheology is governed by a Maxwell fluid (linear viscoelastic) constitutive model
- Mass conservation and incompressibility holds
- The pull-off speed is constant; inertial forces are absent

The assumptions given above can be formulated by a reverse squeeze film lubrication model, see (40). After variable substitution adopted to the ISIT-experiments the model expressing the impulse at split \( I_s \) can be written

\[
I_s = \frac{3A_0 \eta}{512 \beta_0^2} g_1(D\epsilon, \epsilon_s)
\]  

(3.1)

where \( A_0 \) is the contact area, \( \beta_0 \) the aspect ratio (defined as the film thickness over the contact radius \( (h_0/R_0) \)), \( \eta \) the ink viscosity, \( D\epsilon \) the Deborah number

![Figure 3.1](image_url)  

**Figure 3.1** Ink and paper are in four different states during a pull-off experiment with ISIT. The picture shows schematically how cavitation, filamentation and partial adhesion may be important factors though, not visually detectable
Figure 3.2 A hypothetical “true” tack disc-ink contact geometry compared with a circular model geometry, both viewed from above. Black indicates contact areas while white areas are due to cavitation, surface irregularities or adhesion losses.

(defined as the relaxation time over the time to split ($\lambda/\tau_s$)), and $\epsilon_s$ is the elongation (defined as the stretching of the ink film divided by its initial thickness). Finally, $g_I$ is a short hand notation for a double integral, (see paper II). Eq.(3.1) summarises several effects of the tack impulse that can be used in explaining the tack development.

Ink setting described as a diffusion problem

The ink is here effectively simplified as a two component system, with the solvent phase separating from the ink into the paper via the ink-paper boundary. Note that this is only true in a macroscopic sense whereas ink is a multi-component system on a microscopic level. A schematic view of the ink setting is given in Figure 3.3.

Some simplifications have been introduced to solve the diffusion problem, as listed below:

- The model region is defined over the ink
3.1. MODELLING TACK ON PAPER

Figure 3.3 Schematic view of ink setting. A gradient in oil volume fraction $\phi$ will build up in the ink film, due to the size exclusion of larger molecules and slower solvent diffusion in the ink than in the paper. The film thickness decreases from $H_0$ to $H$ for the time $t > 0$.

- The ink consists of a solid and liquid phase, where the liquid corresponds to the absorbed solvent. Any chemical reactions are ignored, e.g. oxidative drying.

- The setting time may be divided into three parts. The first part is a fast imbibition stage, with a considerable moving boundary and possible inertial effects. The second part is a quasi-steady state with a moderately moving boundary and a moderate decreasing oil diffusivity. In the third part the ink consolidates and the diffusivity decreases further.

- The evaporation of an offset ink is nearly absent compared to its absorption and thus suggesting a boundary condition of zero evaporation. However, the bounded ink region has been extended to a semi-infinite region to simplify the mathematics.

- The ink-paper boundary value is taken as a constant concentration of oil, resulting from the balance between viscous, capillary and osmotic forces.

- The driving force is a gradient in chemical potential over the ink-paper boundary as attained by the balance between capillary, osmotic and
viscous forces. The gradient is assumed to be only a concentration gradient. Convective currents are ignored.

Mathematically, the initial fast imbibition model as given above will describe the decrease in ink film thickness as proportional to the square root of time according to

\[ H = H_0 - 2(\phi_{\infty} - \phi_i) \sqrt{\frac{Dt}{\pi}} = H_0 - \sqrt{D_a t} \]  

(3.2)

where \( \phi_{\infty} \) is a fictitious oil volume fraction at infinite distance from the ink-paper interface, \( \phi_i \) the oil fraction at the ink-paper interface, \( D \) is the diffusion coefficient of oil in the ink layer and \( D_a \) is defined as an imbibition coefficient that depends on both \( D \) and the concentration gradient. The long time limit is expected to show an exponential decrease of film thickness (7), but this case is not modelled here.

**Combining the tack and setting models**

By using a link between the volume fraction of oil and the ink viscosity it is possible to express the impulse development as a function of time, assuming that the viscosity is the only time-dependent parameter. The resulting equation is

\[ I_s = I_s(0)(D_e, \epsilon_s, A_0) \exp \left( \frac{b(1 - \phi_0)\sqrt{D_a t}}{H_0 - \sqrt{D_a t}} \right) \]  

(3.3)

where \( b \) is an empirical constant and \( \phi_0 \) the ink oil volume fraction at time zero. Eq.(3.3) can thus be used to simulate the tack development, or to fit with experimental results.

For given values of \( I_s(0) \), \( b \), \( H_0 \) and \( \phi_0 \), one can now use Eq.(3.3) to calculate \( D_a \) as a function of time from experimental data, according to

\[ D_a = \frac{H_0^2}{t} \left( \frac{\ln (I_s/I_s(0))}{b(1 - \phi_0) + \ln (I_s/I_s(0))} \right)^2 \]  

(3.4)

Eq.(3.4) reveals some interesting physical facts about the ink setting as shown later in the results.
4 Results

4.1 Acoustic measurements

The acoustic signal as obtained from the ISIT and IGT devices (Figures 4.1 and 4.2) were rather different in appearance, due to the non-stationary nature of the ISIT signal as opposed to the more or less stationary IGT signal. This is expected, as ISIT printing is a transient action involving one revolution in which only a part corresponds to ink film splitting on paper. IGT-inking on the other hand is a continuous action, though with some periodicity of the back-and-forth moving top roller. After analysing the standard deviation

![Image showing a decimated original acoustic time record during ISIT printing of 3g/m² sheet-fed offset ink (mineral oil type) on a coated paper.]

**Figure 4.1** Decimated original acoustic time record during ISIT printing of 3g/m² sheet-fed offset ink (mineral oil type) on a coated paper.
or AC component of the ISIT signal (Figure 4.3) it could be concluded that the printing or film splitting part was significantly higher than the rest of the signal. Further, by applying a high pass filter to the sound emitted from the IGT-inking, it was also found that the film splitting originated from the higher frequencies. Having identified the contribution due to film splitting, the average power or variance over the time period of film splitting was calculated for a series of ink loads, showing a considerable increase of the power with ink load. This was true for both the ISIT printing and IGT-inking experiments as shown in Figures 4.4 and 4.5, respectively. Note though from Figure 4.5 that the acoustic power from the inking components actually decreases at low ink amounts before rising for higher amounts.

By determining the specific acoustic frequencies contributing to this average power, the power spectral density was calculated. Figure 4.6 illustrates the fact that all three signals from ISIT printing are almost identical below 6kHz. Thus, contributions at these lower frequencies originate solely from the printer motor and machinery effects. The power source of film splitting thus emits sound frequencies mainly concentrated in the broad band 10 – 20kHz. The characteristic profile of the power spectra was unchanged on increasing the ink amount, but increased in level over the broad band of
4.1. ACOUSTIC MEASUREMENTS

Figure 4.3 The AC part of the signal or standard deviation $\sigma$ after applying a high pass filter at $6\text{kHz}$. The filtering reveals the increase in film splitting noise starting at approximately 0.7 s, at which time the actual printing begins.

Figure 4.4 The average power of ISIT printing with 0, 3 and 6 g/m$^2$ ink (mineral-oil type) on a matte-coated paper, calculated from Eq.(2.1).
higher frequencies. Qualitatively similar trends were exhibited by the spectra from the IGT inking shown in Figure 4.7 The two different commercial inks based on mineral- and vegetable-oil solvent exhibited no significant difference in either their average power, (see Figure 4.4) or their PSD’s. However, a noticeable higher power was emitted from the tackier resin blend.

The addition of extra solvent (mineral oil) to the ink during distribution showed first a slight increase in average power followed by a decrease. The first increase is difficult to explain, although it can be due to a higher wetting strength of the ink and hence higher tack. At high enough solvent the decreasing viscosity becomes the dominating factor.

To simulate the effect of fountain solution, without the complication of evaporation, ethylene glycol was added to the ink under distribution. This again led to an increase in acoustic power at low addition levels, now due to the emulsified droplets, followed by a decrease at higher levels, now due to excess non-emulsified glycol lining the roll surfaces.
Figure 4.6 Power spectral density (PSD) of the acoustic signal during ISIT printing with 0, 3 and 6 g/m² ink (mineral-oil type) on a matte-coated paper.

Figure 4.7 Power spectral density (PSD) of acoustic signals corresponding to film splitting between IGT-rollers as a function of ink load. The sound level increases monotonically, although the spectral pattern shape is unchanged. Data has been decimated 100 times. The ink is of the mineral oil solvent type.
4.2 Ink tack on paper: experimental results

In the tack on paper tests the only parameter changed was the ink load. The result from a series of in total 8 ink amounts is shown in Figures 4.8 and 4.9. The result obtained on increasing the amount of ink was effectively a slower tack rise in combination with a higher tack maximum. The decrease in slope with ink amount becomes more evident at the higher ink amounts in Figure 4.9.

![Graph showing tack development over time for different ink loads.](image)

**Figure 4.8** Ink tack development for four different low ink loads. 
I is the impulse or force time integral.)
4.3 Ink tack on paper: modelling results

The imbibition coefficient as described by Eq.(3.4) was calculated as shown in Figures 4.10 and 4.11. The following estimated values of the parameters were used: $b = 13$ as in Gane et al. (16); $\phi_0 = 0.2$ typical value according to (6). It is evident that $D_a$ decreases during the tack rise, and more rapidly at smaller ink amounts. The average value of $D_a$ also increases with the ink amount.
Figure 4.10 The imbibition coefficient $D_a$ calculated by Eq.(3.4) on the bases of the ISIT impulse measurements for various low amounts of ink.

Figure 4.11 The same as in Figure 4.10, but with higher ink amounts.
5 Discussion

5.1 Acoustics of film splitting

Although the acoustic study presented here is only the first stage of an ongoing project, the results prove that the power of the signal is sensitive to parameters that affect the ink tack, specifically the ink load, oil dilution, fountain solution emulsification, tackifier concentration and setting time. It was also found that the origin of the power was in a broad band, with the film splitting mostly concentrated in the high frequency region $10 - 15kHz$. The machinery sound could therefore be filtered without considerably disturbing the measurement.

It should be remembered that the splitting sound is not easily separated as a single event, but consists of overlapping events integrated with machinery noise in a complex manner. The relative position of the frequency peaks obtained in the power spectra were actually not significantly affected by the ink amount, ink type nor printing speed, which points to the geometrical factors having the greatest importance to the underlying sound character.

Nevertheless, the power emitted from a printing nip may be a relative measure of the energy loss during film splitting. The sound is a result of elastically stored energy, that causes a shock wave in the surrounding air at film splitting. As some of the energy may be dissipated through viscous flow, a quantitative measure of energy loss will probably not be possible. However, by changing the tack the sound power changes in the same direction, which is definitely a useful practical tool for monitoring changes on a printing press.

The difference between laboratory printing and the conditions in a press room is different, in that the sound from a printing press contains many more machinery components. This may not be a problem however, if the sound from the film splitting does not interfere with the unwanted noise. A microphone sensitive to higher frequency will also increase the possibilities
to detect small changes if there is a contributing band in the ultra frequency range. Another improvement may be to use a signal amplifier in combination with more directive microphone.

5.2 Tack on paper

The tack rise period

After inspecting Eq. (3.3) one would expect that the impulse increases slower with time at higher ink amounts (higher $H_0$). This effect is seen in the results in Figure 4.9 and slightly in Figure 4.8. However, the calculation of the imbibition coefficient $D_a$ reveals that $D_a$ is strongly dependent on the film thickness as shown in Figures 4.10 and 4.11. The result is reasonable since the diffusion coefficient $D$ of the ink is expected to decrease as this is common behaviour for polymeric materials. However, some extra concentration dependence is also included in the coefficient $D_a$ by the driving force $\phi_\infty - \phi_i$. The magnitude of the diffusion coefficient $D$, that is $\sim 10^{-9} cm^2/s$ after using Eq. (3.2) with $\phi_\infty = 0.2$ and $\phi_i = 0$, seems to be realistic, but has to be verified by, e.g. NMR.

In calculating the diffusion coefficient in this manner, is however based on a number of assumptions. If the other variables than the viscosity changes, then the theory fails in predicting the right diffusivity by this method. The other weak link is the relation between the volume fraction and viscosity, which need an independent method to verify.

The tack fall period

As the tack becomes higher and eventually falls, other factors than only viscosity has to be considered, such as the effective contact area, the elastic contribution and the geometrical factors such as aspect ratio and elongation. The question is though to what relative extent they are important. The modelling and experimental results (see paper II) indicates that the elasticity increases during this period. However, the geometrical factors are difficult to measure experimentally, which implies that geometrical factors can not be uncoupled from the rheological ones. Nevertheless, it is qualitatively seen from the experimental split marks that the effective adhesive area decreases during the tack fall though it can not be determined quantitatively.
5.2. TACK ON PAPER

Lubrication vs filament elongation

As pointed out in the introduction, cavitation and filamentation are key factors in film splitting. Filaments are certainly observed, and they definitely have an influence on the print quality. Cavitation is of course one of the causes of the splitting sound measured by the acoustic method. The elongation of thin filaments is also important in many coating processes, e.g. spin and roll coating. In this work however, filamentation was ignored in the tack model. The reason is that a question can be raised on how important the filamentation is to the ink tack of very thin ink films ($\sim 1 \mu m$). Lubrication and shear stress dominates over the normal stress if the film thickness is about 100 times smaller than the contact area (40), i.e. aspect ratio $\beta < 0.01$. Filamentation may therefore play a minor role in the overall splitting resistance if the filaments do not become too long. However, as pointed out by Miller and Myers (28) and Myers et al. (29) a considerable tack resistance possibly come from the surface tension and pressure-volume work in the formed cavities. This idea is also adopted by Gay and Liebler (17) for adhesives in general. Moreover, no filaments can neither be seen in the ISIT tack experiment or in the ISIT printing, possibly because the filaments are too small and do not get time enough to develop as in the IGT inking, where they may have relevance for the tack. This suggests that one can neglect the contribution from the filament elongation, though the cavitation can have some importance.

Flow geometry

One may argue that the circular geometry assumed in the the tack model would be more relevant for a raster print, which is interesting in general, than the full tone print of focus in this study. However, as long as the total volume of deformed ink remains the same, it is believed that the physical relevance of the circular geometry is sufficient, at least as a first approximation. If cavities are formed during the elongation, which is the natural cause of filamentation, the circular geometry might be thought of as if the cavities and filaments existed before the extension. The latter is also true if the adhesive contact is not perfect owing to the surface roughness and discrete asperity contacts between the tack disc and the ink film.
Diffusion model vs capillarity models

It is important to compare with the results obtained by equations of Lucas-Washburn (LW) (44) or Bosanquet (5) for capillary flow. The LW and Bosanquet theories are special cases of Newton’s second law of motion (45), where LW is based on a pressure balance between capillarity, viscous drag and gravity and Bosanquet instead includes inertial forces but neglects gravity. The point is that these theories assumes a limitless source of flowing media. This is not the case in ink setting, which includes a finite source that contributes to a considerable viscous drag. The LW-theory predicts, contradictory to the ink setting results, that penetration rate increases with capillary radius. The reason is that the steady flow in the LW-theory is due to the viscous drag in the capillary and not, as in the proposed model here, at the ink-paper boundary. Bosanquet equation on the other hand predicts an increasing penetration rate at decreasing radius. This is naturally the result of having a starting driving pressure following the same trend while ignoring gravity or other external fields. The Bosanquet equation can possibly explain the initial penetration before any establishment of gradients or quasi-steady flows (36).
6 Conclusions

In the thesis a macroscopic model for the tack development as obtained by the ISIT device, has been suggested, and an acoustic method has been tested for various print parameters mainly affecting the ink tack, such as ink film thickness and ink composition.

The tack modelling couples a diffusion model for the oil transport from the ink into the paper, to a linear viscoelastic reverse squeeze-film lubrication model. The model seems realistic in that it can explain the experimental trends, and may therefore assist in interpreting the results from tack development measurements.

The results from the acoustic measurements showed that an increasing ink amount, or an ink with higher tack, gave higher acoustic power. Further, the film splitting emitted a characteristic sound at higher frequencies, with its frequency distribution providing a finger print of the type of substance used. The acoustic technique as described in this preliminary work, despite the rather simple and inexpensive equipment, has been proved to be useful, and the method may be developed further for on-line application.
References


