



Faculty of Technology and Science  
Chemical Engineering

---

Robert Olsson

# Some aspects on flexographic ink-paper and paperboard coating interaction

---

DISSERTATION  
Karlstad University Studies  
2007:23

Robert Olsson

Some aspects on  
flexographic ink-paper  
and paperboard coating  
interaction

Robert Olsson. *Some aspects on flexographic ink-paper and paperboard coating interaction*

DISSERTATION

Karlstad University Studies 2007:23

ISSN 1403-8099

ISBN 978-91-7063-126-9

© Författaren

Distribution:

Karlstad University

Faculty of Technology and Science

SE-651 87 Karlstad

SWEDEN

forlag@kau.se

+46 54-700 10 00

[www.kau.se](http://www.kau.se)

Printed at: Universitetstryckeriet, Karlstad 2007

## Abstract

Flexographic printing is a process that employs a flexible printing form and low viscous ink, often water-based. The flexible printing form is favourable for printing on rough surfaces, but the high surface tension of the ink may cause printability problems.

This work has focused on the interaction between paper/paperboard coating and water-based flexographic ink, aimed at increasing the knowledge about the printing process in form of physical/chemical parameters that are important for ink setting. The effects of printing conditions on print quality, such as printing pressure and temperature, have also been in focus.

The work has shown that fluids of different polarities, i.e. different dipole moments, behave differently when being absorbed by a coating layer. Due to their chemical compatibility to the coating layer, fluids with large dipole moment fill the pore matrix of the coating to a lesser extent but penetrate further into the coating than fluids with small dipole moments. On the other hand, polarity of the coating layer also affects the print. When printing on coatings with different polarities, higher print densities was obtained on the more polar substrates. As a tentative explanation, it is proposed that the ink builds different layer structures during drying depending on the coating polarity.

Print gloss is related to the ink setting which, in turn, is affected by the solvent retaining capacity of the ink. Large water holding capacity allows the ink components to smoothen out before the structure is set, resulting in a higher print gloss. The rheology of inks is affected by temperature; at a higher temperature the viscosity is reduced. The reduction in ink viscosity at higher temperature has been shown to affect the print quality, e.g., print density and dot gain. It is suggested that a thicker layer is immobilised during impression due to the lower viscosity and that it is an explanation of the higher print density at a higher printing temperature.

The influence of impression pressure on dot gain has been experimentally evaluated and mathematically modelled with good agreement. The dot gain is shown to respond non-linearly to the applied printing pressure.

Studies based on pilot coated and printed paperboards is also reported, and it is shown that the print quality, e.g. print density, print gloss and dot gain, is largely dependent on the type of ink chosen and on the coating characteristics. Higher clay content in the coating resulted in increased dot gain and a decreased mottling.

## **Papers included in the thesis**

- I Olsson, R., van Stam, J. and Lestelius, M.; (2006): Imbibition into model calcium carbonate coatings of fluids with different dipole moments, *Appita Journal*, 59(6), 471-475,485.
- II Olsson, R., Yang, L., van Stam, J. and Lestelius, M.; (2006): Effects on ink setting in flexographic printing: coating polarity and dot gain, *Nordic Pulp and Paper Research Journal*, 21(5), 569-574.
- III Olsson, R., Yang, L. and Lestelius, M.; (2007): Water retention of flexographic inks and its influence on final print gloss, *Nordic Pulp and Paper Research Journal*, 22(3), 287-292.
- IV Olsson, R., Yang, L., van Stam, J. and Lestelius, M.; (2007): Effects of elevated temperature on flexographic printing, *Advances in Printing and Media Technology: Proceedings of the 34<sup>th</sup> Research Conference of IARIGAI, Grenoble, France, To be published.*
- V Olsson, R., Yang, L. and Lestelius M.; (2007): Flexographic print quality of pilot coated paperboards, *Manuscript.*

## **Robert Olsson's contribution to the papers**

Robert Olsson performed all the experimental work with the exception of the Hg-porosity measurements, the atomic absorption measurements in Paper II, the surface tension measurements of the inks in Papers IV and V and the pilot coating and printing in Paper V. Robert Olsson is the main author of all five papers included in this thesis.

## Table of contents

Abstract .....	i
Papers included in the thesis .....	ii
Table of contents .....	iii
<b>1 Introduction.....</b>	<b>1</b>
<b>2 Properties of paper and paperboard coating.....</b>	<b>2</b>
2:1 Coating technologies.....	3
2:1:1 <i>Application technologies</i> .....	3
2:1:2 <i>Metering technologies</i> .....	4
2:2 Coating colour .....	5
2:3 Coating properties .....	6
<b>3 Flexography .....</b>	<b>8</b>
3:1 The flexographic process .....	9
3:2 Flexographic inks .....	10
3:2:1 <i>Colorants</i> .....	11
3:2:2 <i>Binders</i> .....	11
3:2:3 <i>Additives</i> .....	12
<b>4 Print quality parameters .....</b>	<b>13</b>
4:1 Print density .....	13
4:2 Gloss .....	14
4:3 Mottling .....	15
4:4 Dot gain.....	16
4:4:1 <i>Physical dot gain</i> .....	16
4:4:2 <i>Optical dot gain</i> .....	17
<b>5 Basic rheology.....</b>	<b>19</b>
5:1 Viscosity.....	19
5:2 Ink rheology.....	21
<b>6 Ink transfer, ink setting and surface properties.....</b>	<b>24</b>
6:1 Ink transfer.....	24
6:2 Ink setting.....	26
6:2:1 <i>Fluid absorption</i> .....	26
6:2:2 <i>Print quality effects</i> .....	29
6:3 Surface tension.....	31
6:4 Fluid spreading .....	32
6:5 Polarity.....	34
6:5:1 <i>Polarity effects on printing</i> .....	35
6:6 Surface topography .....	36
<b>7 Summary of the papers .....</b>	<b>39</b>
7:1 Imbibition into model calcium carbonate coatings of fluids with different dipole moments (Paper I) .....	39
7:2 Effects on ink setting in flexographic printing: Coating polarity and dot gain (Paper II) .....	40

7:3	Water retention of flexographic inks and its influence on final print gloss (Paper III) .....	42
7:4	Effects of elevated temperature on flexographic printing (Paper IV) .....	43
7:5	Flexographic print quality of pilot coated paperboards (Paper V) .....	44
<b>8</b>	<b>Conclusions.....</b>	<b>46</b>
<b>9</b>	<b>Suggestions for future work.....</b>	<b>47</b>
<b>10</b>	<b>Acknowledgements .....</b>	<b>48</b>
<b>11</b>	<b>References.....</b>	<b>49</b>

# 1 Introduction

The ink-substrate interaction during printing is a complex process which depends on the physical and chemical properties of both ink and substrate, as well as on the conditions of printing. An ideal printing ink has to dry at a suitable rate, fast enough so that the printing press can be run at a profitable speed but slow enough for the ink to form a continuous smooth film on the substrate and give good print quality. The solidification of the ink on the surface is called “ink setting”. This process is highly dependent on ink-paper interaction. An ink that is suitable for one type of substrate may experience difficulties during printing on other substrates due to a less favourable ink-paper interaction. The printing press itself will also influence the ink-setting process. For example, the force employed in the printing nip affects the removal of solvent from the ink and thereby the drying of the ink. The interplay between different components in the printing process, such as the printing form, the ink and the paper, is very complex where further research is needed in order to understand the process.

The overall objective of this study has been to increase the knowledge of how certain physical/chemical parameters influence the interaction between flexographic ink and the coating on paper and paperboard. The effects of ink transfer and ink setting in the coating on print quality and runnability in printing operations have also been an important aspect of this work.

The thesis work began with studying separately the ink and paper by varying either the ink-formulation or the coating-composition and how their physical/chemical properties affect the ink-paper interaction (Papers 1 and 2). This was followed by studies (Paper 3) on the joint effects of both ink and paper coating. The investigations were further extended from lab scale to pilot machines (Paper 5). While the impact of the operation setting and print condition, such as nip pressure and ink temperature, were presented in Papers 3 and 4. As the understanding of ink-coating interaction is a key to understanding ink-transfer and ink setting, the studies may therefore generate knowledge of how to optimize the print presses, the inks and the paper substrate to improve the runnability, print quality, and profitability.



## 2 Properties of paper and paperboard coating

The properties of paper and paperboard vary greatly for different grades. The most obvious characteristics of paperboard which differentiates it from paper are its thickness and stiffness. Most products up to 225 g/m<sup>2</sup> are called paper while those above 225 g/m<sup>2</sup> are usually called paperboard, but there is a considerable overlap (Tillmann 2006). Paperboard serves primarily as a protective physical barrier to the product it contains, and is also an important substrate for advertising the product. Paper on the other hand serves primarily as an information carrier.

A characteristic feature of paper and paperboard is that the fibres form a three dimensional network through chemical bonds between the fibres, in a layered structure. In addition, all paper grades are characterised by inhomogeneity, hygroscopicity, anisotropy and viscoelasticity (Tillmann 2006). The magnitude of these features is dependent on the type of fibre used, the fibre raw material, the pulping process and the process techniques used in the stock preparation and papermaking. The homogeneity of paper extends over a few micrometres to millimetres, i.e., the lengths of fibres, fillers and air-filled pores, and if the distance is greater than that, the paper is considered to be inhomogeneous. Hygroscopicity is ranked by Tillmann (2006) as the most important characteristics of paper: paper's ability to absorb or release water affects properties such as the paper's dimension, weight, tensile strength, etc.

Another common feature of paper and paperboard is that they are mostly used as information carriers. Apart from the other functions that the paper or paperboard needs to fulfil, such as gas- and light-barrier, mechanical protection, etc., it usually needs to be printed to convey information to the recipient. Whether in the transportation chain, with the end consumer, or elsewhere along the life cycle, information is needed.

Although the base paper is the key of producing high quality paper for printing, adding a coating to the base paper enhances the printing properties. The coating is applied to the paper or board as a wet coating colour, consisting of pigments, binder, thickener, additives and water, by different techniques, e.g., roll application, see section 2:1. Nevertheless, a base paper can only be improved to a certain extent by a coating. A coating gives the paper surface

greater smoothness and higher gloss, and prevents the ink from penetrating deep into the paper structure so that the ink demand is reduced.

To further enhance the smoothness and gloss of the paper surface, the paper may be calendered. The main purpose of calendering is to modify the surface by pressure and temperature to increase the printability. Disadvantages of calendering are that the density of the paper is increased, i.e. the bulk is decreased, and also that the strength properties, brightness and opacity of the paper are reduced (Feldmann 2006).

## **2:1 Coating technologies**

Several different technologies are available to apply a coating to the paper, both on-line coating and off-line coating. In general three steps are involved, first, the application of the coating colour, second the metering of the coating to achieve the desired coat weight and the third the drying of the wet coating. Some of the application and metering are described briefly here. For the interested reader there are several books on this topic (Linnonmaa and Trefz 2000, Kogler and Auhorn 2006).

### ***2:1:1 Application technologies***

Examples of application technologies are the applicator roll and the free-jet applicator. The applicator roll, *Figure 2:1*, is the application technology most often applied within the paper industry (Linnonmaa and Trefz 2000). It consists basically of two rubber-covered rolls of different diameters. The larger backing roll provides stability to the paper during the coating process. The smaller roll, 30-40 % smaller than the backing roll, picks up the coating colour from an applicator pan containing coating colour. The coating colour is then taken by the applicator roll and transferred to the paper in a nip. The amount of coating transferred is determined by the gap between the two rolls, the speed of the applicator roll and the viscosity of the coating colour. After application, the wet coating travels a certain distance, which defines the dwell time, before being metered, e.g., with a blade (Kogler and Auhorn 2006).

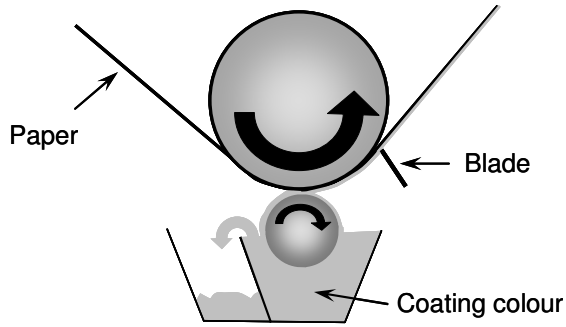


Figure 2.1: A schematic illustration of the applicator roll technique.

The free jet applicator applies the coating colour through a nozzle, with a slit opening of 0.6-2.0 mm, situated 5-20 mm beneath the backing roll (Linnonmaa and Trefz 2000). The nozzle forms a jet of coating colour which impinges on the paper on the backing roll, as in the applicator roll case. Important parameters for the transfer of coating are the slit width, the rate of flow of the coating colour and the impingement angle.

### ***2.1:2 Metering technologies***

Examples of metering technologies are blade metering and rod metering. The principle of the blade metering technology is that the blade removes the excess coating colour and fills in voids in the structure to create a smooth surface. There are mainly two main techniques, stiff blade and bent blade. A bent blade gives a smoother surface than a stiff blade, but is more prone to cause surface defects, such as blade scratches, and is more difficult to operate (Kogler and Auhorn 2006).

To ensure good coverage rather than good smoothness, the rod metering technology, *Figure 2.2*, is preferred instead of the blade-metering technology (Kogler and Auhorn 2006). The rod removes the excessive coating colour by rotating against the moving direction of the paper, producing a backflow which washes away any dirt which might possibly cause streaks in the dry coating (Linnonmaa and Trefz 2000).

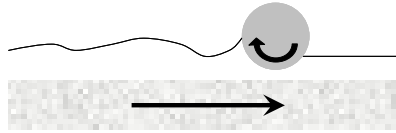


Figure 2:2: An illustration of the rod metering technology.

## 2:2 Coating colour

A paper coating usually consists of pigments, binders, thickeners and additives. The coating is usually applied to the base paper as a wet coating colour, with a solids content of 50-70 % (Linnonmaa and Trefz 2000).

The pigment of a coating colour is normally calcium carbonate, clay or talc; the pigment is available in different shapes and different particle size distributions. Coating pigments have particle sizes from coarse (60-80 wt% <2  $\mu\text{m}$ ) to ultra fine (>90 wt% <1  $\mu\text{m}$ ) (Nutbeem et al. 2005). The pigment is the most abundant component of a coating colour and therefore determines the coating properties. Calcium carbonate gives a more porous and brighter coating than clay, but clay gives a glossier coating because of its platy particle structure. To obtain synergy effects, it is possible to blend pigments of different particle sizes as well as of different types. Blending the pigments affects the porosity and average pore size of the dry coating layer (Vidal et al. 2004, Larsson et al. 2007b), making it possible to achieve coating properties which are not achievable using a single pigment type.

The second most abundant component in a coating colour is the binder, which includes a wide group of both synthetic and natural substances. Synthetic binders are the most widely used and are usually a styrene butadiene, a styrene acrylate or a polyvinyl acetate. Proteins (casein and soy protein) are natural binders, and soy protein is frequently used in North America (Lehtinen 2000). The main task of the binder is to bind the coating pigment to the base paper surface, and also to bind the coating pigment particles together and to fill out voids between the coating pigments as the coating has been dewatered. An additional task is to work as a viscosity and water-retention modifier while the coating is still fluid.

There is a wide variety of thickeners, both synthetic, different types of acrylic based thickeners and PVOH (polyvinyl alcohol), and natural, CMC (carboxy

methyl cellulose), starch and soy protein. A common feature is that they all have high molecular masses. The main function of the thickener is to raise the viscosity of the coating colour and to increase the water retention. A key property of the thickener is shear thinning to ensure high runnability of the coating colour. To give high water retention, it must also interact strongly with water.

Coating additives is a large group of chemicals used for different purposes. The primary goal when using an additive is to enhance specific end properties such as the whiteness of the paper, or to improve the runnability of the coating process. The additive may be e.g. a dispersant, foam control agent, colorant or preservative.

### **2:3 Coating properties**

A typical dry coating layer (single layer) is 5-20  $\mu\text{m}$  thick, which is equivalent to a coat weight of 5-20  $\text{g}/\text{m}^2$ . If a thicker coating layer is desired, a multiple-layer procedure is the common solution. A paper or paperboard may have up to three layers of coating (Ström 2005). Usually, a coating layer of cheaper material is applied as a first pre-coating layer and the more expensive coating is applied on top, giving the desired coating property to the product. One of the most important properties of a coating (for print applications) is its pore structure, which determines the rate of ink setting, (Xiang et al. 2004). For a dry coating, the pore size ranges typically from 0.01 to 1.0  $\mu\text{m}$ , with a porosity of 20-40 % (Xiang and Bousfield 2003).

Applying, dewatering and drying the coating colour on the substrate leads to a distribution of the constituents in the thickness direction of the coating (Ström and Schulz 1993). The pigment is subject to forces in e.g. the blade coating process and, together with the distribution of pigment properties (e.g. size and shape), this gives a structure which is not always easily predicted (Vidal et al. 2004). While the wet coating layer dries, particles move closer to each other due to penetration into the base sheet and evaporation of solvents. This movement may lead to a different composition in the surface layer than in the bulk of the coating (Ström and Schulz 1993). The mechanism of binder migration to either the coating surface or the base paper during drying of the coating colour has been discussed for some time. Whether the binder migrates towards the coating surface or towards the base paper, it leads to a different chemical structure on

the surface, due either to the enrichment or the absence of binder. Raman spectroscopic studies of the coating have been conducted to find the answer to this question (Bitla et al. 2003, Vyorykka et al. 2004), and Bitla and co-workers reported that enrichment occurs at the coating surface, when the coating pigment size is large compared to the binder size. Addition of carboxymethyl cellulose (CMC) reduces binder migration due to an agglomeration of coating pigments which prevents the binders from migrating towards the coating surface. Al-Turaif and Bousfield (2005) found that the particle size distribution of coating pigments was more important than the aspect ratio, i.e., the ratio of particle length to particle thickness, for binder migration towards the coating surface. A possible cause of migration of binders is the evaporation of water from the coating surface (Engström et al. 1987). Lee and Whalen-Shaw (1993) stated that binder migration depends strongly on the quality of the base paper, on the coating colour properties, on the coating speed, and on the drying type and conditions, etc. This clearly shows the complexity of this process. Engström and Rigdahl (1992) reported that binder migration towards the coating surface during drying may affect the interaction between the ink and paper coating and thereby be a source of print mottle.

Calendering affects the structure of both the coating and the base paper of coated paper and boards. An increase in surface smoothness, closure of surface pores, reduction in pore radii and a reduction in porosity are some of the effects of calendering (Karathanasis et al. 2001, Ström 2005). Larsson et al. (2007a), found that the reduction in pore radii and porosity is affected by the binder content. The binder acts as a lubricant which makes the coating structure more easily modified by calendering.

### 3 Flexography

Since Gutenberg, around 1440, the methods of printing on different substrates, particularly paper, have evolved. The different printing methods are usually divided into groups, such as contact and non-contact methods, or alternatively analogue and digital methods. The most frequently used contact methods are offset, flexography, gravure, screen and letterpress, in which inks (colorants) are transferred through contact of printing forms (plate) with substrates. The non contact method includes ink jet and electrophotography (laser) which are also known as digital printing technologies as a printed pattern consists solely of binary ink dots (pixels). The focus of this thesis work has been flexographic printing. Hence, this technology is described more in details. For information about the other printing technologies and inks, several books have recently been published (Finely 1997, Oittinen and Saarelma 1998, Kipphan 2001).

The flexographic printing process was developed from the letterpress technology where the printing characters are slightly raised above the surface of the print form, *Figure 3:1*. Originally, flexography was called “aniline printing” but in 1952 the name was changed to “flexography” (Todd 1994). The main feature of flexographic printing is the use of a flexible print form made of polymer or rubber. This flexible print form is adapted for package printing, because it easily follows the rough surface of a paperboard, although, with increasingly improving print quality flexography is even used for newspaper printing (Wilson 2006). The improved quality of flexographic prints in recent years is mainly attributed to the developments in anilox rollers, photopolymer printing forms and inks (Moir 1994, Kipphan 2001). The substrates used for flexographic printing include paper, paperboard, corrugated board, foil, plastic films and Cellophane (Hallberg Hofstrand 2006). These substrates span over a wide range of surface and bulk characteristics and are a challenge even for the flexographic printers. When printing on a plastic film it may be necessary to increase the surface energy of the film in order to improve the ink adhesion to the surface. This is due to the large difference in surface energy between the ink and the film. The most common method for increasing the surface energy of the film is corona treatment, which oxidises the surface and thereby increases its energy. This oxidation is believed to induce polar groups on the surface (Sun et al. 1998, Park and Joong-Seong 2001)

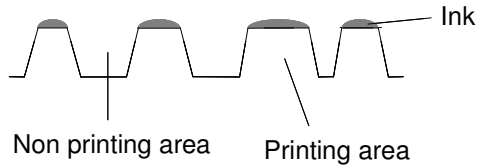


Figure 3:1: A schematic illustration of a flexographic printing plate with the printing area raised above the surface.

### 3:1 The flexographic process

The flexographic printing process consists mainly of six elements; ink, ink feeder, anilox roll, printing form cylinder, substrate and the impression cylinder. The flexographic ink is of low viscosity and it is transferred with an anilox roll from the ink chamber to the printing form and thence onto the paper substrate, *Figure 3:2*. The wet ink film has a thickness of 2-15  $\mu\text{m}$  (Liiri Brodén et al. 1996).

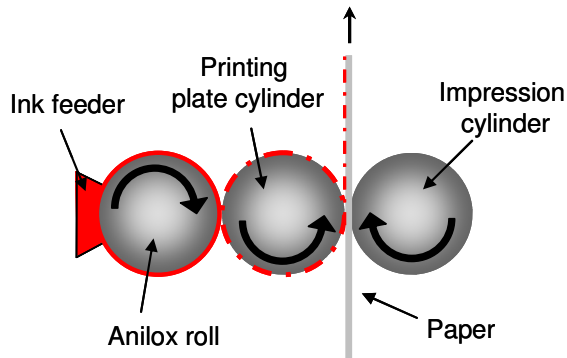


Figure 3:2: A schematic illustration of a flexographic printing press.

The primary role of the anilox roll, which has small engraved cells on its surface, is to control the ink-film thickness in the printing press (Bould et al. 2006). The engraved cells are designed for a specific volume, usually expressed in  $\text{cm}^3/\text{m}^2$ , and are distributed in a regular screen pattern over the anilox roll with defined number of lines/cm. The numbers of lines/cm together with the volume of each cell determines the ink volume that is picked up and later transferred to the substrate. To ensure a good transfer from the anilox roll to the printing form, the screen frequency of the anilox roll should be 5.5 times greater than the frequency of the printing form screen. The anilox roll is produced with a surface of ceramic or hard chromed metal (Kipphan 2001). It



was the development of the anilox roll in 1945 that made it possible to print at a higher ink level , and this is also the key to the improvement in print quality of flexographic printing (Todd 1994).

The characteristics of the flexible printing form have a large effect on the final image. Two different materials are used in printing form production, cast rubber and cross-linked photopolymer, although the latter is more frequently used (Aspler 2006). Depending on the substrate being printed, the hardness and thickness of the flexographic printing form have to be adjusted. Depending on the application, the thickness varies, from one to a few millimetres, and the hardness is a measure of the printing forms mechanical properties which are measured in degree of Shore A. For example, post-printing on corrugated board the printing form usually has a hardness of 35° Shore A whereas for reel presses 65° Shore A is a standard (Chalmers 1997). The mechanical properties of the printing form and the conditions in the printing nip strongly influence the ink transfer process, especially the contact mechanics, and also the print quality (Bohan et al. 2000, Bould et al. 2004a, Bould et al. 2004b).

### 3:2 Flexographic inks

The basic building blocks of a flexographic ink are pigment, binder, solvent and additives. A typical ink formulation for a flexographic ink is given in *Table 3:1*.

Table 3:1: Compositions of a blue water-based flexographic ink (Leach and Pierce 1999).

Ink component	Content
50 % Phthalocyanine blue (CI pigment blue 15)	24.7 %
Acrylic emulsion (water-based)	50.0 %
Water	20.0 %
Monoethylamine	2.0 %
Wax (polyethene)	3.0 %
Organic defoamer	0.3 %

Flexographic inks can be (organic) solvent-based, water-based or UV- or electron-beam-curable, although the water-based inks are the most frequently used ones and by many considered to be the ink technology of the future due to health and environmental concerns. It should also be noted that water-based inks are also used in other printing methods, e.g., gravure printing and ink jet.

The most obvious difference between water-based and solvent-based inks is probably their surface tensions (Podhajny 1990). The surface tension of ink is an important parameter for wetting both the printing form and the substrate. Surfactants are usually added to lower the surface tension of water-based inks, and thus increasing the wetting of the substrate surface. Another problem with water-based flexographic inks is that their binders have to be able to dissolve or disperse in water but yet withstand water when dry. It is not desirable for the print to start smearing only because it is raining. There are currently two possible solutions either a high-weight emulsion polymer, which has an irreversible coalescence and film formation, or a low-weight carboxylated polymer dissolved in a volatile amine, which gives an insoluble film when the amines are evaporated (Rentzhog and Fogden 2005a).

### ***3:2:1 Colorants***

The colorants in an ink may be either dye-based, soluble in the ink vehicle, or pigment-based, insoluble in the ink vehicle. Today, pigment-based inks dominate and, to be effective, the particle size of a pigment should not exceed the wavelength of visible light, i.e., should be less than ca. 0.5  $\mu\text{m}$ . A very important parameter in the final ink is the pigment's ability to disperse. The degree of ink pigment dispersion affects the rheology, colour, gloss, strength and rub resistance. To enhance the mechanical and rheological properties of the ink, slurries of ink pigment often contain a filler, calcium carbonate or clay (Todd 1994). A frequently used pigment is carbon black which is produced by burning oil and consists of soot particles of different shapes but with a small particle size (Donnet et al. 1993). Carbon black has good chemical resistance and good colour strength.

### ***3:2:2 Binders***

The main function of the binder in an ink formulation is to anchor the ink pigment to the paper surface and to produce a protective film over the pigments. The binder also affects the rheology, the ink's ability to disperse and the ink tackiness. The largest group of binders today is the styrene-acrylates which are miscible with water. These are available as both emulsion polymers and solution polymers, with different characteristics. The high molecular weight emulsion polymer binders (EPB) can be of relatively low viscosity, and they provide fast drying and good chemical resistance and adhesion. The solution polymer binders (SPB) have a higher viscosity than the EPB:s and a lower

solids content, and they are good dispersant for the ink pigment, providing high print quality and a slow drying speed. In contrast, the SPBs have poorer chemical resistance and poorer adhesion to substrates than the EPBs (Podhajny 1990, Laden 1997, Rentzhog and Fogden 2005a, 2005b). These two types of binders are usually mixed together to obtain the optimal printing ink formulation.

### ***3:2:3 Additives***

Several different types of additives are used in flexographic inks (Laden 1997). Some of the most important ones are mentioned below. Surfactants are important additives due to their ability to reduce the surface tension of the ink and to aid the dispersing of the ink pigment. Some types of surfactants also have side-effects, producing stabile foams which are a disadvantage in the printing process. To reduce the foam, a foam controller is added to the formulation. In water-based inks, pH regulators (such as amines, mentioned above) are important since their primary function is to maintain the desired pH so that no unwanted cross-linking of binders occurs already in the ink pan. Other additives for inks are waxes whose specific task is to increase the final rub resistance and water resistance of the ink film. During drying, the wax migrates towards the surface, which may lead to a longer drying time due to reduced solvent evaporation.

## 4 Print quality parameters

The assessment of print quality is in general a difficult task, depending on the purpose of the printed product and the expectations of the final customer. In business relations, the quality and acceptance of a printed product delivered from the producer to the customer is finally judged by individuals. Thus, the human perception of the print enters the equation of what quality is. From a process control point of view, i.e. the printing process, this complicates real time feedback control. However technically measurable print quality parameters exist and are used in production both on-line and off-line. Some additional parameters of particular interest for the present work are presented here, but these are not often used in production. Print density, print gloss and dot gain are frequently used as objective measures of print quality for product control and process runnability. Print mottle measurements are somewhat less frequently used by the printers due to difficulties in interpretation and as lack of links to material properties and process conditions.

The goal when measuring print quality parameters is to put numbers on how the final print is perceived. There are several arguments in favour of using different instruments to evaluate print quality because the quality assessment, if handled correctly, is then an objective correlate of the subjective in human evaluation. The assessment of the perceived image is dependent on the illumination under which the evaluation is carried out. Despite the advantages of objective assessments using different instruments for measuring print quality, the overall goal is thus to independently assess as accurately as possible the perceived assessment of a print by a person.

### 4:1 Print density

Print density is an important parameter for every print, too low a print density results in a pale print. Print density,  $D$ , is related to the reflectance as follows:

$$D = \log_{10} \frac{R_0}{R_1} \quad (4:1)$$

where  $R_I$  is the reflectance of the printed solid tone or half tone value and  $R_0$  is the reflectance of the unprinted substrate. The perceived strength of a colour is thus not linearly related to the reflectance, but by a logarithmic relationship.

As the ink layer on the substrate increases, the density increases from zero, with no ink on the substrate, to a saturation value,  $D_\infty$ , *Figure 4:1*, (Tollenaar and Ernst 1961). The relationship describing this is:

$$D = D_\infty (1 - e^{-mz}) \quad (4:2)$$

where  $m$  represents the slope of the density curve [ $(dD/D_\infty)/dz$ ] in the region of a very thin ink film and  $z$  the ink layer thickness. This equation is closely linked to the ink transfer character which will be described in section 6:1, e.g., the Walker-Fetsko equation (Eq. 6:1).

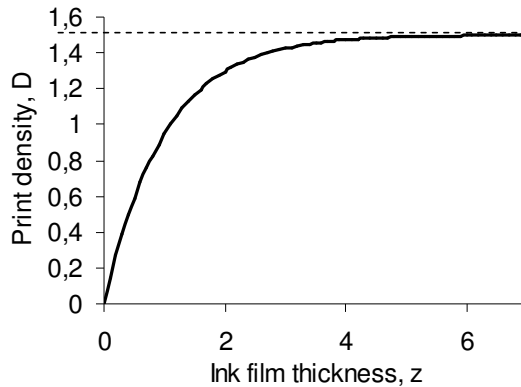


Figure 4:1: Print density dependency on the ink film thickness on the substrate, according to equation 4:2, with  $m = 1$  and  $D_\infty = 1.5$ .

Print density is usually measured with a densitometer which is designed to select light of the wavelength mostly absorbed by the colour used, cyan, magenta, yellow and black (Leach and Pierce 1999).

## 4:2 Gloss

Gloss is an important parameter for both the paper substrate and the final print. Gloss is defined as the intensity of the reflected light at a defined incidence and viewing angle ( $75^\circ$  for TAPPI gloss). The angle of  $75^\circ$  is

generally adopted within the paper industry, but it may be useful to consider other angles such as 20° for highly glossy materials (Vaarasalo 1999). Relatively speaking, a high print gloss (rather than substrate gloss) is very often greatly appreciated by ordinary consumers, which makes print gloss an important component of print quality.

Conventional wisdom says that a smoother substrate or print surface leads to higher gloss, yet the mathematical expression for this relationship is unknown (Pauler 2002). The gloss of coated paper is governed by the smoothness of the coating, both on a basepaper fibre scale, 50-100 µm, and on a coating pigment scale, <2 µm, (Nutbeem et al. 2005). The print gloss depends not only on the substrate being printed but is also related to the ink holdout and the ink setting, described in section 6:2, fast ink setting reduces the print gloss.

In printing, a term referred to as “delta gloss” or “print snap” is used. This term describes the difference in gloss between the print and the unprinted substrate. The delta gloss is of interest for the readability of a printed paper. If the delta gloss is too small it may be difficult to read the paper at a certain angle due to the shiny (glossy) surfaces. A high value of delta gloss is obtained when the substrate is matt and the roughness is on a small scale. On such a substrate, the ink fills in the small-scale roughness leading to a large difference in gloss between printed and unprinted positions (Oittinen and Saarelma 1998).

### **4:3 Mottling**

Mottling is a visible heterogeneity in a print and is closely related to an unevenness in ink transfer and ink absorption (Johansson and Norman 1996). Ink transfer and absorption are, on the other hand, affected by the substrate, ink and printing conditions. The origin of mottling may be an unevenly coated paper or board, resulting in uneven ink absorbency by the substrate. Another possible cause is a poor printing press setting that causes a variation in thickness of the transferred ink layer. The ink also needs to exhibit good flow properties so that it may level out after the printing nip. It may, otherwise, be a source of mottle. Ink transparency may also display mottling effects (Todd 1994). Mottling is usually evaluated by image analysis methods based on an analysis where the optical signal is divided into various spatial frequencies.

#### 4:4 Dot gain

During flexographic printing, the printed screen dots expand as a consequence of the pressure in the printing nip. Not only the substrate but also the flexographic print form is compressed in the nip and this leads to an expansion of the dot on the print form and produces a larger printed dot. This dot gain may be enhanced by ink spreading on the substrate after the print nip. The combined effect of print form expansion and ink spreading is the physical “dot gain”, which is a measure of the difference between the size of the printed dot and that on the original printing form. Besides the physical dot gain, there is often an optical dot gain, due to lateral light scattering in the paper substrate. Optical dot gain is always present when the print is viewed (perceived or measured) under reflected light. The optical and physical dot gain of a printed dot are illustrated in *Figure 4:2*.

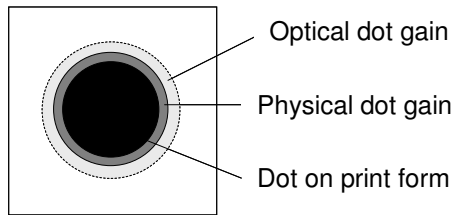


Figure 4:2: The enlargement of a printed dot (top view). Both physical and optical dot gain contribute to enlarging the visual appearance of the dot.

The combined physical and optical dot gain may be estimated from measured reflectance values, applying the Murray-Davies equation (Murray 1936):

$$R = fR_i + (1 - f)R_0 \quad (4 : 3)$$

where  $R$  is the reflectance of the image and  $R_i$  and  $R_0$  are the reflectance values of the solid print and the substrate, respectively, and  $f$  is the fractional dot area,  $0 \leq f \leq 1$ . A further description and possible mechanisms of the physical and optical dot gain are presented in the following sections.

##### 4:4:1 Physical dot gain

In flexographic printing there are two main causes of physical dot gain, the print form deformation due to the pressure in the printing nip during ink-transfer and ink spreading on the surface during the ink setting stage. Ink spreading has been found to have a large effect on the final dot size when printing in flexography (Bould et al. 2004a). The wettability is an important

factor affecting the ink spreading together with the force applied in the printing nip, leading to lateral expansion of the ink on the substrate. The physical dot gain, defined as the difference between the size of a printed dot and that on the printing form (without pressure), is a direct consequence of the ink-substrate interaction and the printing press settings. Results of an offset printing study presented by DePaoli (1981) indicate that the dot gain depends primarily on the ink thickness, the physical and chemical characteristics of the ink and the paper. According to DePaoli, the “length” of the ink, i.e. its ability to be drawn or stretched into a filament before snapping (Finely 1997) and paper absorption may be critical parameters affecting dot gain. Bohan et al. (2000) investigated the effect of printing pressure, viscosity and ink film thickness on dot gain, and they found that a higher printing pressure led to a greater dot gain, whereas a higher ink viscosity leads to a smaller dot gain. A third conclusion from their study was that a thicker ink film generated a larger dot gain, as a consequence of the fact that more ink was transferred. In offset, a significant tone dependency of physical dot gain is a well-known phenomenon: there is a little or even negative physical dot gain in light tones but a significant dot gain in the middle and dark tones. The phenomenon was explained by Yang and Lundström (2007) in the light of the differences in ink-transfer and ink-setting between the prints which consists of well isolated dots in the light tones and overlapping dots in the middle and dark tones

Bould et al. (2004b) investigated printing plate deformation as one possible cause of physical dot gain. They concluded that there are two main mechanisms of plate deformation in flexographic printing which leads to dot gain, i.e., dot expansion and side collapsing. The first is a lateral expansion of the dot surface under compression which depends on the material’s Poisson’s Ratio. The second is a “barrelling” effect where a part of the dot side comes in touch with the substrate. The Young’s modulus of the material determines to what extent “barrelling” occurs.

#### ***4:4:2 Optical dot gain***

Optical dot gain is due to the scattering of light inside the substrate. As a consequence of light scattering, some of the light is trapped under the printed dot and absorbed by the ink, and this leads to a perceptual increase in the area of the dot, as illustrated in *Figure 4:2*. Parameters affecting the optical dot gain are the lateral light scattering and spectral transmittance of the ink, *Figure 4:3*. Surface reflection may indirectly affect the optical dot gain.



Light scattering is a very complex process and several researchers have tried to elucidate its effect on optical dot gain. Yule and Nielsen (1951) were among the first to study optical dot gain. They found that the Murray-Davies equation, equation 4:3, missed the optical dot gain and they suggested a new model with the optical dot gain included.

$$R_{tot} = [fR_i^{1/n} + (1-f)R_\infty^{1/n}]^n \quad (4:4)$$

where  $n$  is an experimental variable determined by fitting to experimental spectra or densities. Theoretically, the value of  $n$  is between 1 and 2 to account for the pure optical dot gain effect. When physical dot gain is also included in the data fitting, a kind of misuse of the Y-N model, the value may be significantly larger than 2 (Yang 2003).

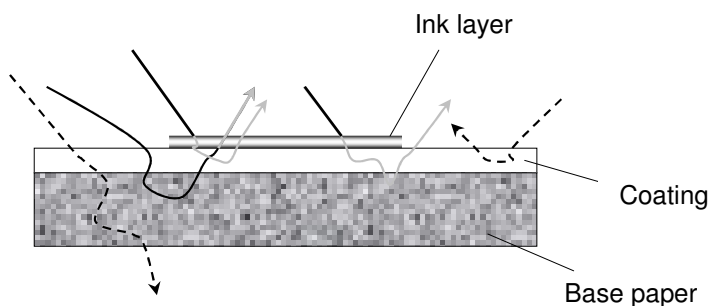


Figure 4:3: A schematic picture illustrating optical dot gain. The path of the solid arrows, illustrating light, affects the optical expansion of the dot, optical dot gain. The dashed arrows are not affected by the ink layer and hence do not contribute to the optical dot gain

Employing a nuclear microprobe device, Kristiansson et al. (1997) were able to determine the physical dot areas and thus the optical dot gain. They found that a thicker paper resulted in a larger optical dot gain and that the homogeneity of the paper is also important as well as the quality of the surface. The degree of ink penetration also affects the dot gain; a greater ink penetration decreases the optical dot gain (Yang et al. 2001).

## 5 Basic rheology

Rheology is the science of how matter deforms and flows, and it is concerned with both fluids and solid material since solids flow when the force acting upon them is large enough. In this thesis, however, rheology is discussed in relation to fluids and, in particular, flexographic inks.

### 5:1 Viscosity

Viscosity is a measure of the resistance of matter to flow. It is usually pictured as in *Figure 5:1*, which illustrates medium trapped between two plates of a given area. The fluid is considered to consist of several thin layers parallel to the plates. When a force,  $F$ , is applied to one of the plates, i.e., the top plate, while the other plate is stationary, a velocity gradient,  $v(h)$ , arises because the layer closest to the moving plate travels with almost the same velocity,  $v$ , as the plate. This layer will, in turn, drag the layer next to it along, thereby propagating the velocity further down into material with some losses, mainly due to friction, until the layer next to the stationary plate is reached where the velocity is practically zero. Hence, the velocity of any given layer is dependent on its distance from the moving plate. This requires, however, a laminar flow of the material and also a reasonably small gap between the plates. The internal “friction” of the layers between the plates is the force resisting flow and this is called the viscosity of the material.

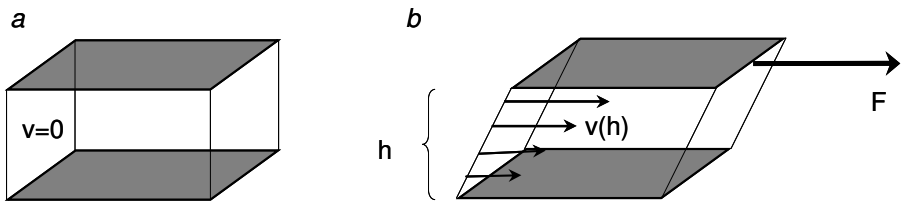


Figure 5:1: An illustration of the velocity gradient that arises in a gap in a viscometer, measuring viscosity. When zero force is applied (a), there is no gradient. When a force is applied to one of the plates (b), a velocity gradient arises; the velocity depends on the distance from the stationary plate.

Viscosity is related to the “shear stress” and “shear rate”. The shear stress ( $\sigma$ ) is defined as the force per unit area needed to achieve a given deformation (or force needed to keep the plate moving at a constant velocity):

$$\sigma = \frac{F}{A} \quad (5:1)$$

where  $F$  is the force applied to the plate and  $A$  is the area of the plates. The shear rate ( $\dot{\gamma}$ ), on the other hand, is defined as the velocity ( $dv$ ) across the gap ( $dh$ ),

$$\dot{\gamma} = \frac{dv}{dh} \quad (5:2)$$

Viscosity ( $\eta$ ) is defined as the ratio of the shear stress ( $\sigma$ ) to the shear rate ( $\dot{\gamma}$ ),

$$\eta = \frac{\sigma}{\dot{\gamma}} \quad (5:3)$$

Viscosity is usually presented as a function of shear rate, *Figure 5:2*, i.e., a viscosity curve. Different types of fluids exhibit different viscosity curves. A fluid displaying a viscosity which is independent of shear rate is said to be Newtonian. This group includes, among others, water and silicone oil. Many solutions prepared for industrial use display “shear-thinning” behaviour, where the viscosity decreases with increasing shear rate, *Figure 5:2*. Here the structure between the molecules within the solution is successively being broken down more rapidly than it is rebuilt during shearing and this leads to the drop in viscosity. When, in contrast, the viscosity increases with increasing shear rate, i.e., the structure is being built up, the phenomenon is called “shear-thickening” which is less common in industrial applications. Another important character of some fluids is that they exhibit a yield stress or yield point, where a certain amount of force must be applied to the fluid before it starts to flow. If a fluid is sheared at a constant rate and the viscosity decreases with time, the fluid is said to be thixotropic. This means that the structure in the fluid is broken down faster than it is rebuilt when a constant shear rate is applied, which leads to a net loss in structure and a decrease in viscosity with time.

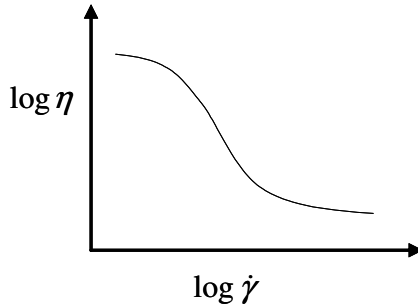


Figure 5.2: An example of a viscosity curve of a shear-thinning fluid.

Several methods are available for measuring the viscosity or the rheology of inks. One of the simplest yet very commonly applied is the flow cup. This consists of a cup with a certain volume and a hole of a specific diameter at the bottom. The time for the ink to empty the cup through the hole is measured and the viscosity is reported as seconds to empty the cup. Other methods are rotational viscometers, which measure the viscosity at a controlled shear rate, and the controlled stress rheometer. With the latter system, one can make measurements at very small stresses, which is impossible with the rotational viscometer. Textbooks are available which provide further information about measuring systems and procedures for obtaining rheological data (e.g. Barnes et al. 1989, Leach and Pierce 1999).

## 5.2 Ink rheology

When the flexographic ink is delivered from the ink maker it has a higher viscosity than is appropriate for printing. There are two reasons for this. Firstly, it overcomes a tendency for the ink pigments to settle at the bottom of the container, and secondly it allows the printer to adjust the ink viscosity to be suitable for his/her specific press and printing job (Leach and Pierce 1999). An ink that passes from the ink reservoir to the substrate is subjected to a variety of rheological parameters, *Table 5.1*, and experiences numerous shear rates where a typical shear rate lies between 1000-100000 s<sup>-1</sup> (Barnes et al. 1989). The importance of ink rheology to the printing result cannot be overestimated.

Table 5:1: The different rheological processes which an ink experiences during printing, redrawn from the course "Process rheology" given by Hudson, N.E., and co-workers, 11-15 November, 2002 in Glasgow, UK.

<i>Stage</i>	<i>Deformation</i>	<i>Time Scale</i>	<i>Rheological Test</i>	<i>Parameter Obtained</i>
Reservoir	Rest	Large	Creep, rotational shear flow	Yield stress or zero shear rate viscosity; structure at rest
Flow into cells	Low rate shear flow	~20 ms	Creep, rotational shear flow	Yield stress; low shear rate viscosity as a function of shear rate
Wiping	High rate shear flow	~180 $\mu$ s	Capillary shear flow	High shear rate viscosity as a function of shear rate
Ink on anilox roller	Relaxation from shear flow	~60 ms	Creep, oscillatory shear flow	Yield stress; relaxation time; elastic modulus; loss modulus; structure at rest
Transfer to plate cylinder	Plug flow	~5 ms	Creep	Yield stress or zero shear rate viscosity
Ink on plate cylinder	Rest	~300 ms	Creep	Yield stress or zero shear rate viscosity; structure at rest
Nip before paper and plate cylinder	Planar extension (squeeze)	~600 $\mu$ s	Squeeze film	Biaxial extensional viscosity
Nip after paper and plate cylinder	Uniaxial extension	~800 $\mu$ s	Extensional flow	Uniaxial extensional flow

Despite the importance of rheology for the printing process, there are very few repeated investigations into the rheological properties of flexographic inks. The results presented here therefore relate to both flexographic inks and inks for other contact printing methods.

Most of the printing inks exhibit a shear-thinning behaviour that was observed by, among others, Wang et al. (1998) when studying offset inks. However, as pointed out by Pangalos et al. (1985), to use only viscosity as a benchmark when printing with offset inks may be highly misleading. They showed that the rheology of carbon black ink formulations is strongly dependent on the shear rate and on time. Moreover, both viscosity and thixotropy increase with increasing pigment concentration. The consensus from these two studies by Wang et al. and by Pangalos et al. are that the ink properties are dependent on

the shear history; i.e. the inks exhibit thixotropic behaviour. On the other hand, rheopectic behaviour that is the opposite to thixotropic behaviour, i.e. the viscosity increases with time at constant shear rate, was observed for flexographic ink, possibly due to solvent and pH regulator evaporation (Havlíková et al. 1999). In a study by Gane and Ridgway (2000), it was found that the viscosity of the vehicle of a centrifuged flexographic ink was time-independent, i.e. no thixotropic or rheopectic behaviour, whereas for the complete ink a thixotropic behaviour was seen, indicating that the ink pigments influences the thixotropy.

Bould et al. (2006), found that the print density increased with increasing viscosity of the flexographic ink. In gravure printing, the print density is also affected by a decreasing ink viscosity, the ink transfer increases with decreasing ink viscosity but, at the same time, the colour strength is reduced so the change in print density depends more on the ink pigment (Bohan and Claypole 2004). It has also been shown that the dot gain increases significantly with decreasing ink viscosity (Bohan and Claypole 2004, Davies and Claypole 2006) as a consequence of greater ink spreading.

Rentzhog and Fogden (2005b) observed a different rheological behaviour with cyan than with black flexographic inks. This was attributed to an increased interaction between the cyan pigment and the binders due to the non-spherical shape or smaller mean particle size of the cyan pigment. They also confirmed the observation of Fernández et al. (1998) that the viscosity is exponentially linked to the temperature, following approximately an Arrhenius relationship.

$$\eta = Ce^{\frac{D}{T}} \quad (5 : 4)$$

where  $C$  and  $D$  are constants and  $T$  is the absolute temperature.

## **6 Ink transfer, ink setting and surface properties**

The amount of ink that is transferred during printing and the manner in which it is positioned on/in the paper or paper coating are dependent on the ink transfer and ink setting processes. Besides the anilox cylinder volume which has the greatest effect, the contact (area) in the printing nip and the ink behaviour also affect the ink transfer. The ink setting speed influences the time of drying and hence the speed at which the press may be run. In addition, ink setting also affects the print quality such as print gloss. These two processes, which are closely connected, are discussed in this section, together with surface properties.

In printing, the surface characteristics such as surface energy and surface tension are very important parameters. In flexographic printing, the relative difference between the surface tension of the ink and surface energy of the substrate is a crucial parameter. Because the surface tension of water-based inks is high, there is a practical risk that these inks may show poor wetting of the substrate.

### **6:1 Ink transfer**

The anilox cell volume is the single most important parameter determining the amount of ink to be transferred. Larger cell volumes result in higher ink amount on the printing form and thus a greater ink amount than a small cell volume, but the amount of ink transferred is also affected by the printing pressure, the ink viscosity and surface porosity of the substrate, to name a few parameters.

Studies of parameters affecting ink transfer have been in focus for a long period of time. One of the first studies was conducted by Walker and Fetsko (1955). The outcome of their study was an equation describing the amount of ink transferred to the substrate in the printing nip. The equation is based on the paper's possibility to immobilise a portion of the ink, the ink thickness on the printing plate and the understanding that only a certain fraction of the wet ink will be transferred:

$$y = (1 - e^{-kx}) \left[ fx + b(1 - f)(1 - e^{-x/b}) \right] \quad (6:1)$$

In this equation,  $y$  is the amount of ink transferred to the substrate per unit area,  $x$  is the amount of ink on the printing plate before impression and  $k$  a constant related to the smoothness of the paper.  $b$  is the immobilisation capacity of the substrate for the ink, i.e., the amount ink that can be immobilised before impression.  $f$  is the fraction of ink that is transferred to the paper during the film split ( $0 \leq f \leq 1$ ). At a low ink level on the printing plate, similar to that in commercial printing, Walker and Fetsko suggested that there is incomplete contact between the substrate and the ink film on the printing plate and that the immobilisation capacity of the substrate exceeds the ink amount on the printing plate. On the other hand, at a high ink level the contact is complete and the ink immobilised during impression is equal to  $b$ . The remaining wet ink film, i.e., the non-immobilised ink, then splits at the printing nip exit. Taylor and Zettlemoyer (1958) further investigated how the wet ink film splits between the printing plate and the substrate at the printing nip exit. They suggested that the ink film split is promoted by viscosity variations within the ink film. These variations are due to the fact that the higher temperature or/and higher shear rate make the ink film “weaker” closer to the substrate surface and hence less ink is transferred. Ercan and Bousfield (2000) investigated the filament size at the exit of a printing nip. Their rather unexpected conclusion was that an increasing elastic nature of the fluid reduced the filament size. One of the more recent modifications to the Walker-Fetsko equation (6:1) was proposed by Zang (1993) implementing a new splitting function,  $f_{\infty} + (0.5 - f_{\infty})e^{-2f_{\infty}x}$ :

$$y = (1 - e^{-kx}) \left( b(1 - e^{-x/b}) + [f_{\infty} + (0.5 - f_{\infty})e^{-2f_{\infty}x}] [x - b(1 - e^{-x/b})] \right) \quad (6:2)$$

Contact    Immobilisation    Free ink film split    Immobilisation

where  $f_{\infty}$  is the limiting value (at high ink thickness) of the splitting parameter. The physical implication of each term is presented underneath the mathematical term in this equation. Other studies have also attempted to link parameters of the Walker-Fetsko equation (6:1) to physical and chemical properties of ink and substrate and printing conditions (Karttunen 1973, Mangin et al. 1981).

De Grâce and Mangin (1983), studied ink transfer in relation to substrate properties and press conditions. They found that the surface roughness of the substrate influenced the ink transfer, so that a rougher surface accepts more



ink. But too rough a surface reduces the contact area and this also reduces the ink transfer. On the other hand, on newsprint the print density was relatively unaffected by surface roughness. Also, investigating the printing pressure, they found that a higher pressure forces more ink into the substrate (newsprint), but that too high a pressures closes off some of the pores, and thus reduces ink transfer. Another parameter influencing ink transfer is the surface energy of the substrate. In flexographic printing, the effect of surface energy on ink transfer is overall small, especially in full-tone areas. In the half tone areas, a clear influence may nevertheless be seen (Lagerstedt and Kolseth 1995). However, factors such printing pressure, printing speed and the roughness of the surface play a greater role for ink transfer than surface energy. The surface profile and the compressibility of coated papers also influence irregularities in both print density and print gloss due to their effect on the calendering uniformity and the thickness of the transferred ink film (Lepoutre and De Grâce 1978). Cozzens et al. (1965), studied ink penetration in uncoated papers and found that a lower viscosity of the ink increased the immobilisation under all printing conditions.

## **6:2 Ink setting**

After the printing nip exit, the ink is supposed to level out and set, i.e., to be adsorbed to the surface and dry, a process commonly referred to as ink setting. The ink-substrate interaction plays an important role in this process. The ink setting process affects the speed at which the ink dries and hence the speed at which the printing press may run. It also influences the final properties of the print, i.e., print quality. Ink setting is a complex process which has been studied by many researchers but is not yet fully understood. Ström (2005) separates the drying of offset inks into three categories: Firstly the ink sets and becomes “touch-dry”, secondly a physical drying takes place and the ink becomes “semi-dry”, and thirdly the chemical drying is completed and the ink is “completely dry”. The first two stages mainly copes with oil absorption (fast and slow absorption) after which the chemical drying starts, which involves a polymerisation of alkyd resin and drying oils (Ström and Gustafsson 2004).

### ***6:2:1 Fluid absorption***

Ink setting is dependent on fluid removal, either by evaporation or by absorption, and this is in turn affected by the paper or paper coating pore network. The size of the pores is an important factor in ink vehicle absorption. The flow of fluids in capillaries was studied by Lucas (1918) and Washburn

(1921), who independently found a relationship between capillary radius and absorption speed for horizontal cylindrical capillaries:

$$l^2 = \left( \frac{\gamma \cos \theta}{\eta} \frac{r}{2} \right) t \quad (6:3)$$

where  $l$  is the distance (depth) the fluid front has moved at time  $t$ ;  $\gamma$  is the surface tension;  $\eta$  is the viscosity;  $\theta$  is the contact angle between the fluid and the solid and  $r$  is the capillary radius. This Lucas-Washburn (L-W) equation was originally developed for horizontal capillaries, but it can be applied on a paper or paper coating to describe capillary-driven fluid flow into a porous structure. The equation works for water, oil and solvent, and a good correlation was found between spreading of aqueous, dye-based ink jet inks on uncoated paper and coefficients of the L-W equation (Breton et al. 1990). However, for pigmented inks of high viscosity and non-Newtonian fluids, the model failed. From the equation, it is evident that a large capillary ( $r$ ) promotes faster absorption of fluid than smaller ones, but the experimental results indicate the opposite (Donigian et al. 1997). The cause of the failure is the complexity of the paper structure that is beyond the assumption of the L-W model (a collection of uniform and cylindrical pores), to say nothing of the complexity of the inks. Nevertheless, this equation is still in use in the printing industry, mainly because of its simplicity, and it has been the subject of further development by many researchers.

Bosanquet (1923), was one of the first researchers who took the Lucas-Washburn equation a step further by introducing a viscous resistance term together with a term taking into account the momentum of the liquid column. The equation proposed by Bosanquet was later applied in a network model for simulating fluid imbibition by Schoelkopf et al. (2000b). They found that the wetting of the pores was initially slowed down by inertial flow and that the effect was most pronounced for larger pores. In another publication by Schoelkopf et al. (2000a), employing this network model to simulate fluid uptake of a paper coating together with experimental results, it was concluded that the imbibition proceeds to a large extent in finer pores in the network. The imbibition excludes larger pores that are retarded due to inertial effects and the absorption is mainly due to the smaller pores. The result is that some paths are more favourable for fluid flow into the pore system, i.e., there exists a preferred pathway (Schoelkopf et al. 2000a, 2003).

The dependence on pore density,  $N$ , i.e., number of openings, pores, at the surface, of the absorption of fluid into a coated paper has been investigated by Preston et al. (2001). They found that when normalized to the pore density, the Lucas-Washburn equation holds, i.e., the larger pores set ink more rapidly. However, when normalising with respect to void volume,  $N(r_A)^2$  where  $r_A$  is the average pore radius, smaller pores set ink faster, as seen experimentally. This shows the importance of both pore size and pore density for controlling the ink setting.

Different mechanisms, mainly for offset inks, have been proposed for ink setting. Schoelkopf and Gane (2003) proposed a single-phase model; where the viscosity of the deposited ink film as a whole increases while it dries (solvent loss). The increase in viscosity continues until the ink is immobilised. On the other hand, Xiang and Bousfield (1998) proposed a mechanism in which a filter cake is building up on the substrate, the of which thickness grows continuously during drying. In this model, the ink is considered to be a two-phase system, in which the ink loses solvent until it becomes immobilised. A third mechanism proposed by Donigian (2004, 2006) may be considered as a mixture of the two aforementioned. The ink is assumed to exhibit two phases of different viscosity, a low viscous phase that depletes first and then a high viscous phase which is depleted immobilising the ink structure. There is also an interplay between these two phases. When the low viscous phase is nearly depleted, the high viscous phase will transfer oil to the low viscous phase, and the high viscous phase will thereby continuously increase in viscosity. Eventually, the low viscous phase is nearly depleted and the high viscous phase containing resins begin to immobilise forming the ink surface.

Comparing a normal ink with a centrifuged ink, Gane and Ridgway (2000) found that the rate of absorption of the normal ink was higher than that of the centrifuged ink. They concluded that polymers in the centrifuged ink entered and were trapped inside the fine pores of a coating, blocking these pores off for further fluid absorption. Meanwhile, the ink forms a filtercake which binds the polymer and thereby leaves the highly absorbing fine pores open for absorption, i.e., the filtercake build-up acts as a “pump” speeding up the ink absorption rate by not clogging the finer pores. In another publication, Ridgway and Gane (2005) found that the ink filtercake build-up is different for different pigmented inkjet inks. They speculated that there may be a greater tendency for

pigment aggregation for some inks than for others, and that this may lead to different filter-cake build-ups. The filtercake build-up depends also on an initial separation mechanism, i.e., liquid is removed faster from the interface than it can be delivered from the ink bulk. The rate of absorption of ink is fastest for the highly filtercake-forming inks at first, but at longer time intervals the filtercake formation acts as a brake on further ink absorption.

For offset inks, separation of the components during absorption has been reported by several researchers (Rousu et al. 2000, Ström et al. 2001). Rousu et al., found that, in pure pigment structures, the mineral oils penetrated further than the other components of the ink. The separation was also more pronounced for clay- and silica-based structures than for calcium carbonate-based structures with a similar pore size and surface area. When latex, i.e., reducing the surface energy and increasing the polymer level in the substrate, was introduced into the coating structure, the separation of ink components was decreased significantly, which can not be solely explained by structural changes in the coating (Rousu et al. 2000). It was also found that the linseed oil was absorbed to a greater extent than mineral oil by the latex film resulting in a decreased separation. A low  $T_g$  and gel-% of the latices increased the interaction with the ink oils (Rousu et al. 2003). Ström et al. (2000), concluded that the absorption of mineral oil is faster than that of vegetable oils for which absorption may continue for several hours. Latex swelling may reduce the ink setting rate due to pore closing (Xiang et al. 2002, Rousu et al. 2003). At high binder levels in the coating, the ink setting is controlled by the ink-latex interaction, whereas at low binder levels the ink setting is controlled by the pore structure of the coating.

### ***6:2:2 Print quality effects***

A slow or fast ink setting, as a consequence of pore blocking or a favourable pore size distribution, affects the time available for levelling out ink filaments and for internally arranging the ink pigment.

Several researchers have investigated the effects of pore size and ink setting on print gloss (Donigian et al. 1997, Gros et al. 2002, Karathanasis et al. 2003, Preston et al. 2003). It has been shown that the ink gloss depends strongly on the ability of the ink filaments to level out the initial rough wet ink surface after printing and on the redistribution of the ink film components during the

consolidation of the ink film (Preston et al. 2003). In offset printing, the consolidation process may continue for up to 2 hours and thereby also affect the gloss development and the micro-roughness of the print. Gros et al. (2002), studied ink setting by measuring filtercake resistance and comparing it to the ink setting rate. It was shown that the filtercake resistance was associated with the print gloss development; a high filter cake resistance promoting print gloss. The print gloss is also affected by the coating. Both the size of the surface pores and the orientation of the pores in the coating influences the ink absorption and hence the print gloss. The study conducted by Chinga et al. (2002) demonstrated clear correlations between the pore orientation/diameter ratio and the print gloss for offset prints.

Since the latex affects the rate of absorption of inks, and thus the rate of ink setting, it will also affect the final print gloss. Latices that interact strongly with the ink oil in offset ink produce poor print gloss due to the faster ink setting rate (Karathanasis et al. 2003). Xiang et al. (2002), reported an increase in print gloss due to latex swelling closing off pore entries, thereby lowering the ink setting rate.

Investigating drying conditions when printing in offset, Xiang and Bousfield (2001) found a decrease in print gloss and an increase in ink film roughness with increasing drying temperature in the printing press. This may be because the ink dries too fast, “freezing” the structure before it has smoothed out after the printing nip exit. A slow ink setting generates a higher gloss and a smoother ink film with less ink pigments at the surface than a fast setting ink (Preston et al. 2002), *Figure 6:1*.

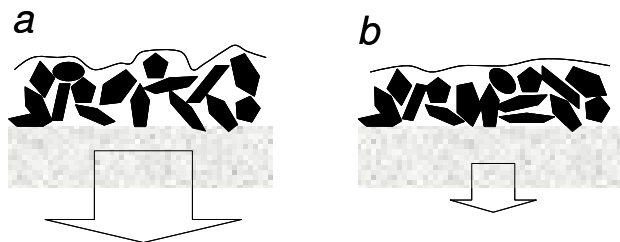


Figure 6:1: Fast ink setting produces a rougher and less glossy ink film (a) than slow ink setting (b).

### 6:3 Surface tension

Surface tension is defined as the force needed to move a particle from the (liquid) bulk to its surface due to the unbalanced forces at the interface, *Figure 6:2*. In the bulk, the liquid molecules experience attractive forces from all directions, whereas the attraction at the surface is unbalanced lacking the force in the direction perpendicular to the surface (Holmberg et al. 2003), see *Figure 6:2*. The work,  $W$ , done to overcome the unbalanced attractive force (surface tension,  $\gamma$ ) when creating a new surface, e.g., when one drop of water becomes two, is proportional to the area of the new surface,  $\Delta A$ :

$$W = \gamma \Delta A \tag{6:4}$$

where  $\gamma$  is the surface tension. It is also important to notice that the temperature of the system affects the surface tension. An increase in temperature reduces the surface tension (Cini et al. 1972) as a consequence of stronger thermodynamic motion and weaker inter-molecular attraction, so that less work is needed for creating new surfaces.

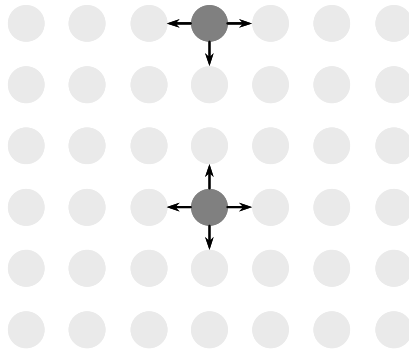


Figure 6:2: An illustration of the origin of surface tension due to the imbalance of attractive forces at the surface.

To lower a system's surface tension, and thus to reduce the work required to create a new surface, surfactants are usually added to the solution. Surfactants are a group of molecules exhibiting both hydrophilic and hydrophobic characteristics, and are therefore very interesting for industrial applications. The dual character of the surfactants means that their most favourable position in a solution is at the surface, or to be arranged in different aggregates. Since the

surfactants arrange themselves at the surface they also affect (reduce) the system's surface tension.

It is important to distinguish the dynamic from the static surface tension. Solutions consisting of different components, including surfactants, have an equilibrium state in which the system has minimised its energy. The surface tension of this state is static. When a sudden change occurs in the system, e.g., short stirring of the solution, new surfaces, or interfaces, are created. If the surface tension is measured immediately after the creation of a new surface, a different surface tension is obtained from the static value due to the disturbance to the system, since it takes time for the surface active components in the fluid to migrate towards the surface. In due course, the surface active component has found its way to the surface of the fluid and the dynamic surface tension approaches to the static value. The dynamic surface tension is often more important for industrial applications than the static, since the system is seldom in equilibrium. In flexographic printing, this is also the case. At the high speeds at which the printing press is running, the surfactants and other components do not have sufficient time to fully migrate to the surface. Hence the dynamic surface tension is more relevant for the printing process (Bassemir and Krishnan 1990, Bassemir and Krishnan 1991).

#### **6:4 Fluid spreading**

The surface tension of the ink is an important factor, but equally important for printing is the surface energy of the substrate. Actually it is the difference between the surface tension of the ink and the surface energy of the substrate that determines the ink's ability to wet the surface. The spreading of a fluid, ink, is determined by the competition between the adhesive force between the substrate and the ink (the solid and the fluid) and the cohesive force of the fluid. The interfacial tension between the fluid and the solid promotes spreading while the cohesive forces act against it. Thomas Young described this relationship with an equation known as Young's equation (Hiemenz and Rajagopalan 1997):

$$\gamma_{LV} \cos \theta = \gamma_{SV} - \gamma_{SL} \quad (6:5)$$

where  $\gamma$  is the interfacial tension of the interface indicated by the subscript indices,  $LV$  for liquid-vapour,  $SV$  for solid-vapour and  $SL$  for solid-liquid.  $\theta$  is the contact angle obtained when a liquid is placed on a solid surface, *Figure 6:3*.

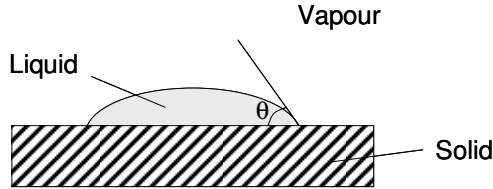


Figure 6:3: A side view of a drop on a solid surface illustrating the contact angle,  $\theta$ .

To predict whether a liquid spontaneously spreads over a surface, a spreading coefficient,  $S$ , may be calculated:

$$S = \gamma_{SV} - (\gamma_{SL} + \gamma_{LV}) \quad (6:6)$$

If  $S \geq 0$ , the liquid will spontaneously spread over the surface. Otherwise it will form a drop with a specific contact angle. By modifying the surface tension of the liquid or/and the surface energy of the substrate, the sign (positive or negative) of the spreading coefficient may be altered, turning the liquid from for example unfavourable to favourable wetting. One way of doing so is by adding a surfactant to the liquid, another is corona treatment that was described in an earlier section (section 3).

Fluid spreading on a porous material has many applications. Starov et al. (2002) studied the spreading of liquid drops on thin dry porous layers similar to a paper coating. The process that a drop of a fluid spreads over a porous substrate may be subdivided into two stages. Firstly, the drop spreads rapidly over the substrate until a maximum radius is reached. In the second stage, the imbibition of the drop begins and the diameter of the drop starts to shrink due to the removal of the fluid. It is also noted that an imbibition front inside the substrate expands slightly ahead of the spreading of the drop in the first stage. During the first stage, spreading, rapid changes in contact angle are observed, while during imbibition, the second stage, the contact angle remains almost unchanged. During absorption of a drop, the wetting front beneath the contact area is almost laterally flat leading to negligible sorption in the lateral direction (Alleborn and Raszillier 2004). Studying water-borne ink-jet printing



applications, von Bahr et al. (2001) determined that the surface tension of the ink and the substrate surface energy were the crucial parameters for wetting. The substrate roughness influenced, to some extent, the spreading of the drop. A final conclusion from the work of von Bahr et al. is that with decreasing drop size the surface effect increases.

## 6:5 Polarity

Polarity is a displacement of electrical charges, although the net charge is zero, in a molecule resulting in a bimodal character where one side is more positive and the other is more negatively charged (Israelachvili 1997), *Figure 6:4*. For a polar molecule the dipole moment is defined as:

$$u = qL \quad (6:7)$$

where  $L$  is the distance between the two charges,  $+q$  and  $-q$ .

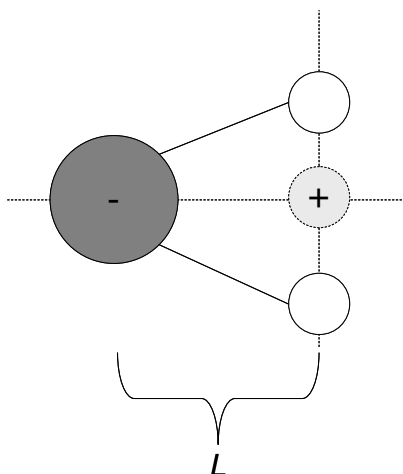


Figure 6:4: A schematic picture of a polar molecule, e.g.,  $\text{H}_2\text{O}$ . The charges are separated by a distance  $L$  where the positive charge is an average between the two positively charged atoms, shown as open circles in the picture.

Polarity is also incorporated into the surface tension. The surface tension,  $\gamma$ , consists of one apolar part,  $\gamma^{LW}$ , and one polar part,  $\gamma^{AB}$ , where the index  $LW$  represents the Lifshitz-van der Waals interaction and  $AB$  the acid-base interaction. The apolar and polar components of the surface tension are additive (van Oss 1994):

$$\gamma_i = \gamma_i^{LW} + \gamma_i^{AB} \quad (6:8)$$

where the index  $i$  represents the actual interface. From this equation it is possible to distinguish a fluid exhibiting more a polar character from an apolar fluid, although their total surface tensions may be the same. The polar components in equation 6:8 may be further broken down to:

$$\gamma_i^{AB} = 2\sqrt{\gamma_i^+ \gamma_i^-} \quad (6:9)$$

where the indices + and – represents acid and base component, respectively. To see whether a substrates surface tension components are polar or apolar, a mathematical relationship originating from Young-Dupre may be used (van Oss 1994):

$$(1 + \cos \theta)\gamma_{LV} = 2(\sqrt{\gamma_{SV}^{LW} \gamma_{LV}^{LW}} + \sqrt{\gamma_{SV}^+ \gamma_{LV}^-} + \sqrt{\gamma_{SV}^- \gamma_{LV}^+}) \quad (6:10)$$

By measuring the contact angle,  $\theta$ , with three different liquids, with completely determined  $\gamma_{LV}$ ,  $\gamma_{LV}^{LW}$ ,  $\gamma_{LV}^+$  and  $\gamma_{LV}^-$ , it is possible, with a set of three different equations, to calculate these three components of  $\gamma_{SV}$ .

### ***6:5:1 Polarity effects on printing***

The effects of different polar substrates and inks on the printing process have to some extent been covered in the literature. Van Gilder and Smith (1998) investigated waterless offset printing and found that a latex of high polarity in the coating yielded a higher print gloss. This was attributed to an interaction of the ink with the high polar latex leading to a longer levelling time for the ink. Later, van Gilder and Smith (2001) studied the effect of latex polarity in avoiding ‘carryover piling’ when printing with a six-colour waterless sheet-fed offset printer. High polarity latex again gave a higher print gloss than a substrate with a low-polarity latex. The high-polar latex also required a longer time to develop sufficiently high ink splitting forces to avoid ‘carryover piling’. These authors claimed that this was due to a lower interactivity between the latex and the ink diluents.

A non-polar offset ink penetrates deeper into the coating layer than a polar ink (Rousu et al. 2000). These authors found that mineral oil exhibited a faster absorption rate with increasing pore size, whereas linseed oil behaved in the opposite manner, with the same latex content in the coating. It was suggested that the linseed oil shows a slower absorption rate with increasing pore sizes due to a decrease in surface energy of the linseed oil and thereby a stronger interaction with the latex. The absorption of mineral oil into a latex film follows Fick's law of diffusion, but the diffusion is slowed down by an increase in polymer polarity (Fouchet et al. 2004).

The fractional polarity ( $\gamma^{AB} / \gamma^{tot}$ ), where  $\gamma^{AB}$  is the surface free energy related to Lewis acid-base interaction and  $\gamma^{tot}$  the total surface tension, differs considerably among papers of different grades (Etzler et al. 1995). Papers with a large fractional polarity may exhibit poor ink adhesion due to repulsive polar forces between the paper and the ink. Etzler et al. also concluded that a macromolecular rearrangement in the paper surface plays an important role in the wetting of paper by alkyd varnishes. The macromolecular rearrangement is responsible for a wetting delay with polar fluids, whereas non-polar fluids wet the paper well.

In the case of alkaline water-based gravure inks, the penetration rate into the base sheet is faster than that of acidic inks, mainly due to the smaller contact angle resulting in good wetting of the surface (Triantafillopoulos et al. 1992). The acidic ink results in a substantial loss of gloss and low tone density, whereas the alkaline ink gives a superior print quality.

## 6:6 Surface topography

The topography, roughness, of a paper surface affects properties and performance like the gloss, the ink spreading and the paper feed amongst other things. Surface roughness is usually measured on the substrate and not on the final print. Several roughness parameters are in use, but some of the most commonly used are  $R_a$  and  $R_q$ .  $R_a$  is the arithmetic average of the absolute values of all points of the profile, and  $R_q$  is the root mean square of the values of all points of the profile (Suontausta 1999). It is also important to remember that surface roughness can be considered on various scales; some phenomena, are best viewed on a large scale while others are best viewed on a small scale, i.e., roughness exists in different sizes. This is very important in the application

of surface topography studies to paper and paperboard, since it is formed from constituent fibres (varying in length, roughly 1 to 3 mm, and width 30-50  $\mu\text{m}$ ) that are subjected to dewatering, pressing, calendaring and drying. The production process gives a material that exhibits features from the operations, with formation, possible wire marks, shrinkage and densification. Together with the inherent structure of the fibre, these features leave contribution to the surface topography and thickness variations which are seen for all paper and paperboard grades. An illustration of this is seen in *Figure 6.5*. The coating procedure (section 2) also affects the surface topography of paper and paperboard as can be seen (*Figure 6.5*), improving it (reducing the deviation from a planar surface).

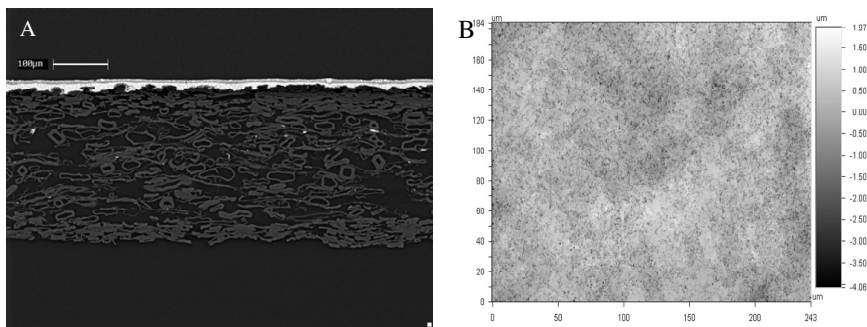


Figure 6.5: Scanning electron microscopy cross section (A), ruler is 100  $\mu\text{m}$ , of a multiply coated paperboard and surface topography image (B), using profilometry, of a pilot coated paperboard.

There are numerous ways of measuring the surface roughness on different scales. It is appropriate to classify the methods into contact and non-contact (optical) methods. The contact methods are dependent on mechanical contact, with a probe “dragged” along the surface to measure the surface profile. Atomic Force Microscope (AFM) is one such instrument. Another type of contact method is the air-leak method, e.g., the Parker Print Surface (PPS) instrument, which determines roughness by measuring the air flow rate for a given air pressure drop over the surface. The flow of air over the surface under standardised conditions indicates the roughness of the substrate Parker (1965). Some of the non-contact methods are those using an interference microscope or a confocal microscope. Both are optical methods having a high measuring sensitivity but a common drawback is their small measurement area. Another non-contact method is the OptiTopo, which employs the variations between

shadows and highlights induced when an object is illuminated with a characterised light source to calculate the topography of the object. This method is rapid, less than 5 seconds, and it is possible to scan a fairly large area (Hansson and Johansson 1999, Gil Barros 2006).

Effects of surface topography can be found in many applications. As described earlier, a rough ink surface results in a less glossy print. On the other hand, the roughness of the print contributes to friction and a more stable paper stack when printed, preventing the paper sheets from gliding.

## 7 Summary of the papers

This section presents a short summary of the key results and a discussion of the papers included in this thesis. The first papers are focused more on the physical and chemical properties of the materials included in the printing process, i.e., ink and coating. The last papers have a focus on a larger scale and on process parameters influencing the final print quality. The full papers are attached at the end of the thesis.

### 7:1 Imbibition into model calcium carbonate coatings of fluids with different dipole moments (Paper I)

The goal for this study was to investigate the chemical parameters of the ink and their influence on imbibition into a paper coating. The first task was to develop a suitable substrate, a model coating, to study the course of imbibition into a coating layer. Model coatings with different porosities and pore sizes were prepared by vacuum dewatering a coating colour under continuous shear in a rheometer. The method showed very good reproducibility and the model coatings mimicked commercial coatings well with respect to pore size, porosity and surface roughness.

Different fluids with viscosities and surface tensions similar to those of the flexographic ink vehicle were employed for the imbibition measurements on the model coatings. From the imbibition measurements it was possible to evaluate volume changes, spreading diameter and penetration depth. These data showed that the filling of the pore system is dependent on the dipole moment (polarity) of the fluids, a fluid with larger dipole moment filled the pore matrix to a lesser extent than those with a lower dipole moment. A “preferred pathway” explanation may be applied describing the way in which different fluids prefer different flow paths. It was also seen that a fluid with a high dipole moment penetrated deeper into the pore matrix than a fluid with a low dipole moment, *Figure 7:1*.

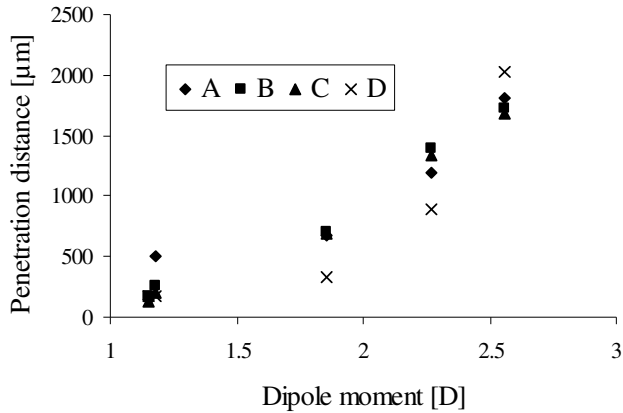


Figure 7:1: Total penetration distance versus dipole moment of the fluids. A, B, C and D represent model coatings of different porosities and different average pore sizes.

An interesting aspect of this work is that water and rapeseed oil display distinctly different behaviours on different types of substrate. This may imply that the optimization principles for the surface properties of paper are different when printing with flexographic ink (water based) and when printing with offset ink (oil based), if the absorption rate is a crucial factor.

### 7:2 Effects on ink setting in flexographic printing: Coating polarity and dot gain (Paper II)

This study focused in how the ink transfer and the subsequent ink setting processes are affected by the physical/chemical properties of the substrate (coatings) and by the nip pressure. Four coating layers were produced using calcium carbonates of different particle sizes and latices of different polarities. Upon printing, different print densities were observed, *Figure 7:2*. For a certain amount of ink transferred onto the coating layers, it is the latex character rather than the pore size of the substrates that dominates the print density. The more polar substrate resulted in a higher print density than the less polar substrate. A tentative explanation was given on the basis of different ink layer formations: the latex polarity promotes a tighter ink layer structure, reducing light scattering inside the ink layer.

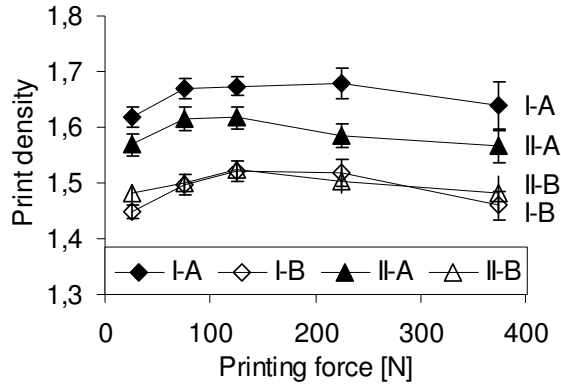


Figure 7:2: The print density of the full-tone print on the different coating layers (error bars shows the 95% confidence interval) as a function of printing force.

From interference profilometer measurements it was concluded that the dot enlargement is not a linear function of the pressure, *Figure 7:3* right. This applies for both tone values in the test prints, 40 and 60%, and in both the print direction and the cross print direction. A possible reason is the increasing deformation of the printing plate (dot) under pressure. A mathematical model based on elastic mechanics was proposed. Simulations with the model (the solid line) well reproduced the trend observed experimentally, *Figure 7:3* left. The diameter of the printed halftone dot was shown to be greater in the print direction than in the cross print direction.

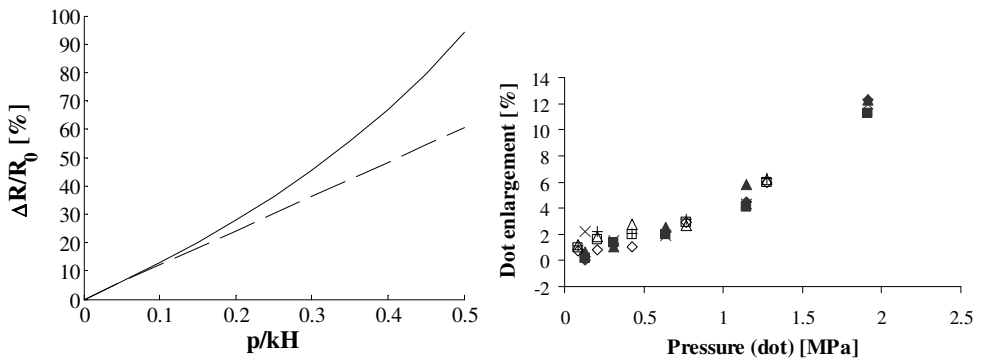


Figure 7:3: Comparison between the mathematical model (left) and experimental values (right).  $H$  is the dot height,  $p$  the pressure,  $k$  the elastic stiffness of the printing plate,  $\Delta R$  the dot enlargement ( $\Delta R = R - R_0$ ) and  $\Delta R/R_0$  the relative dot enlargement.



### 7:3 Water retention of flexographic inks and its influence on final print gloss (Paper III)

The paper describes the interplay between the water retention of flexographic inks and the final print gloss. Water-based flexographic inks containing an emulsion polymer binder (EPB) and a solution polymer binder (SPB) have been studied by means of viscosity curves and water retention measurements. Different ink pigments (pigment red and carbon black) have been used to investigate the influence of pigment-binder interaction on viscosity and water retention.

The results show that the choice of binder clearly dominates in determining the viscosity curves of the inks. The EPB-based inks display a clear shear thinning behaviour while those containing SPB show a very weak shear thinning. This is explained by their abilities to build networks through entanglement and electrostatic interaction. It was also found that the choice of pigment influenced the viscosity less than the choice of binder. Water retention, on the other hand, is influenced by the interaction between the ink components and water, together with the packing abilities of the ink components. It was shown that a high water retention value favours high print gloss, *Figure 7:4*. A long drying time, as a consequence of a large water retention, allows the ink to relax and to smoothen out the initial surface roughness produced at the printing nip exit. The printing gloss varies with respect to the ink's immobilisation time and, as a consequence, a lower dewatering rate is favourable for forming a smoother ink film.

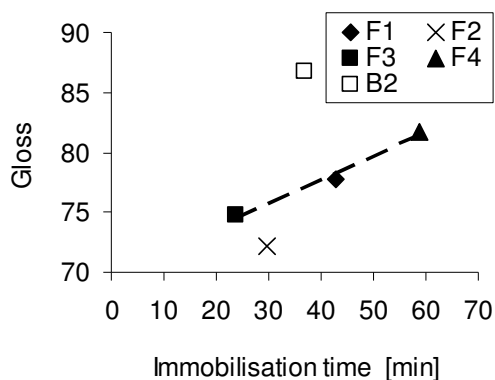


Figure 7:4: Gloss versus immobilisation time for the inks. B2 contains carbon black pigment while the other inks contain pigment red. The dashed line is added for illustrative purpose.

### 7:4 Effects of elevated temperature on flexographic printing (Paper IV)

As modern presses runs at very high speeds, a large amount of heat is generated and this leads to a higher running temperature. This requires a knowledge of how the ink performs at temperatures higher than room temperature. The aim of this study was to evaluate how the flexographic ink responds to temperature increases in the printing press and the impact of the temperature increase on print quality. Previous studies showed that the temperature in a flexographic printing press may increase up to 50 °C (Podhajny 1990). The increase in inking station temperature levels out after roughly 30 minutes, whereas in other parts of the offset press the temperature may continue to increase for several hours (Nordström 2000).

The results show that viscosity decreases with increasing shear rate and increasing temperature and that the print density increases with increasing temperature as an effect of the lower ink viscosity, *Figure 7:5*. The increase in print density at higher temperatures is believed to be a consequence of greater degree of ink immobilisation in the printing nip due to the reduction in ink viscosity. Short wavelength mottling is reduced at high temperature, possibly due to an advantageous levelling as the viscosity decreases. At long wavelengths, on the other hand, mottling increases marginally, probably due to the stronger local ink absorption (in the z direction) of the substrate and perhaps to vaporization that prevents the ink from levelling out the substrate roughness over a (relative) large area (long wavelength). This is in line with the fact that dot gain is slightly reduced at a higher temperature as a consequence of a faster immobilisation of the ink.

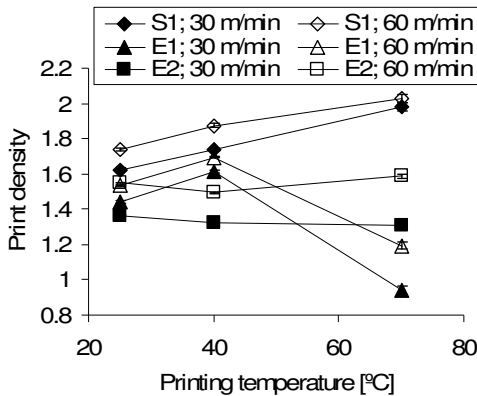


Figure 7:5: Print density (full tone) at different temperatures and different printing speeds. Error bars are the 95% confidence interval of 100 measurement points.

## 7:5 Flexographic print quality of pilot coated paperboards (Paper V)

The objective of this paper is to expand the work done in the previous studies into a more production-like situation and to investigate if the results also apply on a pilot scale. But also, at same time, investigate how different type of inks behaves at substrates of different character, porous structure, with respect to ink transfer and setting and final print quality. Pilot coated paperboard with different pigment blends, clay and calcium carbonate, and lattices, hard and soft, in the coating producing different pore sizes and roughness has been produced. These pilot coated paperboards have been printed on a pilot flexographic printing press with two inks, one solution polymer binder based and one emulsion polymer binder based.

The results have clearly shown that the importance of being familiar with the actual mechanisms of the ink-substrate interaction when choosing ink to be printed to achieve favourable performance, print quality and runnability. The choice of ink influences all measured print quality parameters within this study. When comparing the inks, it appears as the solution polymer binder based ink has a tendency to reside to a greater extent on the surface of the substrate whereas the emulsion polymer binder based ink probably penetrates more into the coating as evidenced by gloss and dot gain measurements (physical and physical/optical). The clay content of the coating has a large influence on dot gain, *Figure 7:6*, with a greater amount of clay in the coating the dot gain is increased, light scattering are given as a possible parameter contributing to this difference in dot gain seen between the coating pigments. A decrease in mottling was also seen with increasing clay content, probably as a consequence of the smoother surface produced by the clay. Generalising the results for soft versus hard lattices it is shown that the pore characteristics is slightly shifted, with a soft latex the average pore radius are slightly larger than for a hard latex. The hard latex has also a higher paper gloss and results in a higher print density.

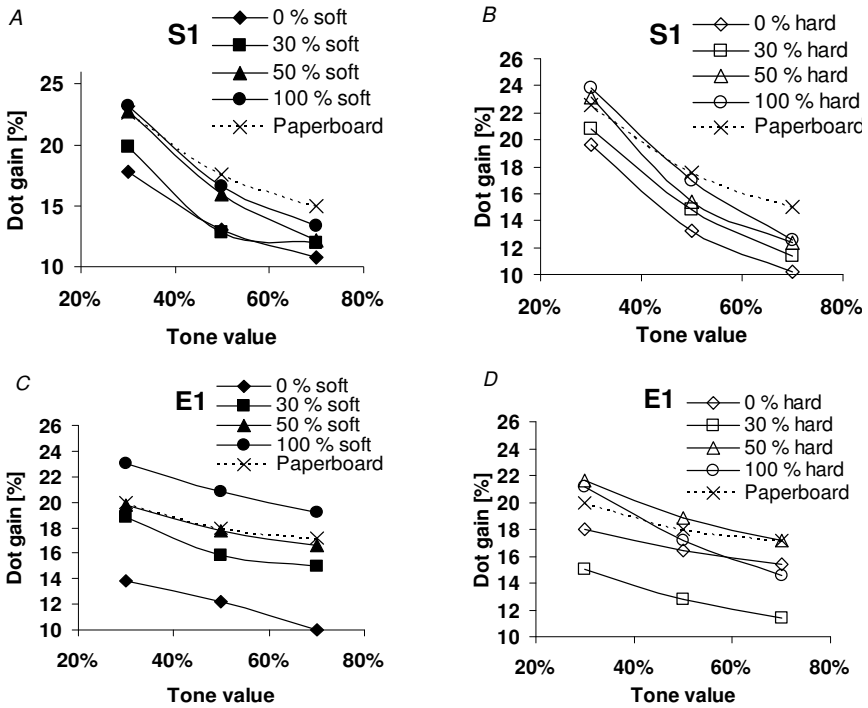


Figure 7:6: Dot gain measured with a densitometer for S1 (ink 1) and E1 (ink 2), for the various pilot coated paperboards with varying clay content (percentages values given in the figures) and the different latex types, soft A) and C), and hard B) and D).

## 8 Conclusions

The results of these studies can be summarised as followed; more detail is provided in the appended articles. The first studies have focused on the effect of ink-coating interaction on ink setting. In the later studies, the focus has turned towards the printing process and how it may affect print quality.

The first study addressed the ink properties and their relation to imbibition into a paper coating. Different fluids were used and it was found that the dipole moment of the fluid affected the filling of the coating pore system. A fluid with a larger dipole moment filled the pore matrix to a lesser extent and penetrated further into the coating than a fluid with a small dipole moment. In the second study, the coating properties, porosity and polarity, were investigated in relation to imbibition. Different polar latices resulted in different print densities although the transferred amount of ink was the roughly the same. A tentative explanation was proposed where the latex polarity affect the ink layer structure. The dewatering of the ink is an important parameter for ink setting. These aspects have been investigated by measuring the water-retention capacity of the inks and linking this to the print gloss. A larger water-retaining capacity of the ink was shown to be positive for print gloss development due to longer time for ink levelling after the impression.

In the later studies, the focus has shifted towards the impact of the printing process on the print quality. The effect of printing pressure on the printing form deformation and on the dot gain has been investigated, and a non-linear relationship between printing pressure and dot gain was observed. This relationship was also successfully modelled mathematically assuming the validity of Hooke's law. The temperature rise due to e.g. friction in the printing press affects the viscosity of the ink, and this in turn affects the print quality. It has been shown that the print density is affected by the temperature change, possibly due to a greater degree of ink immobilisation during impression. A study employing pilot-coated and pilot-printed paperboards has also been conducted. The results show that the print quality, e.g. print density, print gloss and dot gain, is largely dependent on the type of ink chosen and on the characteristics of the coating thereby showing the link between the laboratory and pilot studies.

## 9 Suggestions for future work

To understand the fundamental aspects of the flexographic process, considerable research is required due to its complicated nature. Although this work has focused on the ink setting and parameters associated with this, more research is needed within this topic.

Further studies of the ink material and the relation of the components to ink performance on the printing press are needed. More knowledge of how the pigment, binders, additives and solvents work and what factors influence their performance on a fundamental level is needed for further development of the printing inks.

As the printing presses increases in speed, ink rheology will be a key parameter to be controlled in order to permit higher speeds while maintaining a high print quality. A more detailed investigation of the ink rheology, studying both high and low shear rates is needed for this further development and understanding. An interesting aspect would be to study the extensional viscosity (rheology) of the inks in connection with the film splitting at the exit of the printing nip.

Further studies on the mechanisms controlling ink setting and ink setting rate are also needed. The theories for offset inks must be extended and, if possible, converted to other printing technologies.

## 10 Acknowledgements

First I wish to sincerely thank my supervisor, Associate Professor Magnus Lestelius, for all his support and help during my years as a PhD student, and for all the interesting conversations about the educational system.

I thank my co-supervisor, Associate Professor Jan van Stam, is gratefully acknowledged for his positivism and for always making me feel better when things did not go my way, and my second co-supervisor, Associate Professor Li Yang, is gratefully acknowledged for always structuring my thoughts and supporting me.

The financial and competence support of the Surface Treatment Programme at Karlstad University, the Swedish Pulp and Paper Research Foundation, the Knowledge Foundation and the Swedish Agency for Innovation Systems is gratefully acknowledged.

I am also thankful to the T2F programme for inviting me to join their wonderful network.

Associate Professor Anthony Bristow is acknowledged for the linguistic review of this thesis.

Thanks are extended to all former and present colleagues at the Department of Chemical Engineering at Karlstad University; it would not be the same without you. I especially address warm thanks to Erik, Jerker, Anna, Dan, Henrik and Behudin, who made it worthwhile. Mikael, thanks for all the laughs and conversations through the years, it has been a real pleasure.

I am sincerely grateful to my family and friends for all their support and for the encouragement they always give me.

Finally, I thank Marianne and Theo for all their understanding and love.

## 11 References

- Al-Turaif, H. A.; Bousfield, D. W. (2005):***The Influence of Pigment Size Distribution and Morphology on Coating Binder Migration*, Nordic Pulp and Paper Research Journal, vol 20, no 3, pp. 335-344.
- Alleborn, N.; Raszillier, H. (2004):***Spreading and Sorption of a Droplet on a Porous Substrate*, Chemical Engineering Science, vol 59, no 10, pp. 2071-2088.
- Aspler, J. (2006):***Ink-Water-Paper Interactions in Printing: An Updated Review*, Advanced Coating Fundamental Symposium, TAPPI Press, Atlanta GA: pp 117-146.
- Barnes, H. A.; Hutton, J. F.; Walters, K. (1989):***An Introduction to Rheology*, 7 ed.; Elsevier: p 199.
- Bassemir, R.; Krishnan, R. (1990):***Practical Applications of Surface Energy Measurements in Flexography*, Flexo, vol 15, no 7, pp. 31-32, 34-36, 38-40.
- Bassemir, R. W.; Krishnan, R. (1991):***Surface and Colloidal Aspects of Dynamic Ink/Paper Interactions During Printing*, Papercoating Fundamentals, Montreal, Canada, pp 69-75.
- Bitla, S.; Tripp, C. P.; Bousfield, D. W. (2003):***A Raman Spectroscopic Study of Migration in Paper Coatings*, Journal of Pulp and Paper Science, vol 29, no 11, pp. 382-385.
- Bohan, M. F. J.; Claypole, T. C. (2004):***The Influence of Viscosity in Rotogravure Reproduction*, International Printing and Graphic Arts Conference, Vancouver, Canada, pp 155-160.
- Bohan, M. F. J.; Claypole, T. C.; Gethin, D. T.; Megat Ahmed, M. M. H. (2000):***A Model for Ink Impression in Printing Contacts*, Journal of Pulp and Paper Science, vol 26, no 11, pp. 414-419.
- Bosanquet, C. H. (1923):***On the Flow of Liquids into Capillary Tubes*, Philosophical Magazine, Serie 6, vol 45, no 267, pp.
- Bould, D.; Hamblyn, S.; Claypole, T.; Bohan, M. (2006):***The Effect of Process Characteristics on Image Reproduction in Flexographic Printing*, IARIGAI, Leipzig.
- Bould, D. C.; Claypole, T. C.; Bohan, M. F. J. (2004a):***An Experimental Investigation into Flexographic Printing Plates*, Journal of Graphic Technology, vol 1, no 3, pp. 1-8.



- Bould, D. C.; Claypole, T. C.; Bohan, M. F. J.; Gethin, D. T. (2004b):***Deformation of Flexographic Printing Plates*, 56th Annual TAGA Technical Conference, San Antonio, TX, USA.
- Breton, M.; Pontes, F.; Oliver, J.; Wong, R.; Malholtra, S.; Gage, D.-M. (1990):***Wettability of Paper with Inkjet Inks; Effects of Ink and Paper*, Sixth International Congress on Advances in Non-Impact Printing Technologies, Society for Imaging Science and Technology, Springfield, VA, USA: p 517.
- Chalmers, I. R. (1997):***Flexographic Printability of Packaging Grade Papers*, Appita, vol, no, pp. 335-341.
- Chinga, G.; Helle, T.; Forseth, T. (2002):***Quantification of Structure Details of LWC Paper Coating Layers*, Nordic Pulp and Paper Research Journal, vol 17, no 3, pp. 313-318.
- Cini, R.; Loglio, G.; Ficalbi, A. (1972):***Temperature Dependence of the Surface Tension of Water by the Equilibrium Ring Method*, Journal of Colloid and Interface Science, vol 41, no 2, pp. 287-297.
- Cozzens, S. L.; Butto, A. M.; Schaeffer, W. D.; Zettlemoyer, A. C. (1965):***Ink Penetration During High-Speed Printing of Uncoated Paper*, Paper in the Printing Process, Aulanko, Finland, Banks, W. H., Ed. pp 1-24.
- Davies, G. R.; Claypole, T. C. (2006):***Effect of Viscosity on Ink Transfer in Gravure Printing*, IARIGAI, Leipzig.
- De Grâce, J. H.; Mangin, P. J. (1983):***A Mechanistic Approach to Ink Transfer Part I: -Effect of Substrate Properties and Press Conditions*, 17th International Conference of Printing Research Institutes, Saltsjöbaden, Sweden, Banks, W. H., Ed. Pentech Press, London: pp 312-332.
- DePaoli, A. (1981):***The Effect of Printing Conditions on Dot Gain*, TAGA Proceedings, pp 17-42.
- Donigian, D. W. (2004):***New Mechanism for Setting and Gloss Development of Offset Ink*, International Printing and Graphic Arts Conference, Vancouver, Canada, pp 77-94.
- Donigian, D. W. (2006):***A Multiphase Mechanism for Setting and Gloss Development of Offset Ink*, TAPPI Advanced Coating Fundamentals Symposium, Turku, Finland.
- Donigian, D. W.; Ishley, J. N.; Wise, K. J. (1997):***Coating Pore Structure and Offset Printed Gloss*, Tappi Journal, vol 80, no 5, pp. 163-172.
- Donnet, J.-B.; Bansal, R. C.; Wang, M.-J. (1993):***Carbon Black: Science and Technology*, 2nd ed.; Marcel Dekker, Inc.: New York, USA, p 461.

- Engström, G.; Rigdahl, M. (1992):***Binder Migration - Effect on Printability and Print Quality*, Nordic Pulp and Paper Research Journal, vol 7, no 2, pp. 55-74.
- Engström, G.; Ström, G.; Norrdahl, P. (1987):***Studies of the Drying Process and Its Effect on Binder Migration and Offset Mottle*, Tappi Journal, vol 70, no 12, pp. 45-49.
- Ercan, S. N.; Bousfield, D. W. (2000):***Influence of Fluid Rheology on Filament Size*, International Printing and Graphic Arts Conference, Savannah, GA, USA, TAPPI Press: pp 121-132.
- Etzler, F. M.; Buche, M.; Bobalek, J. F.; Weiss, M. A. (1995):***Surface Free Energy of Paper and Inks: Printability Issues*, Papermakers Conference, Chicago, IL, USA, TAPPI Press: pp 383-394.
- Feldmann, R. (2006):***Calendering*, In Handbook of Paper and Board, Holik, H., Ed. Wiley-VCH Verlag GmbH Co: Weinheim, Germany, pp 294-309.
- Fernández, M.; Muñoz, M. E.; Santamaría, A. (1998):***Rheological Analysis of Highly Pigmented Inks: Flocculation at High Temperatures*, Journal of Rheology, vol 42, no 2, pp. 239-253.
- Finely, C. (1997):***Printing Paper and Ink*, Delmar Publishers: p 439.
- Fouchet, B.; Noirot, P.-A.; Desjumaux, D.; van Gilder, R. L. (2004):***Diffusion Dynamics of Offset Ink Components in Very Thin Latex Films of Different Structure and Composition*, International Printing and Graphic Arts Conference, Vancouver, Canada, pp 43-57.
- Gane, P. A. C.; Ridgway, C. J. (2000):***Rate of Absorption of Flexographic Ink into Porous Structure: Relation to Dynamic Polymer Entrapment During Preferred Pathway Imbibition*, Advances in printing science and technology: proceedings of the 27th research conference of IARIGAI, Graz, Austria, Bristow, A. J., Ed. Pira International Ltd: pp 59-85.
- Gil Barros, G. (2006):***Influence of Substrate Topography on Ink Distribution in Flexography*, Dissertation, Karlstad university, Karlstad, Sweden.
- Gros, M.; Gandini, A.; Blayo, A.; Xiang, Y.; Bousfield, D. W. (2002):***The Influence of Ink Pigment Concentration and Filter Cake Resistance Coefficient on Ink Setting Rates*, 11th International printing and graphic arts conference, Bordeaux, France, p 8pp.
- Hallberg Hofstrand, E. (2006):***Flexographic Post-Printing of Corrugated Board*, Dissertation, Karlstad University, Karlstad, Sweden.

- Hansson, P.; Johansson, P.-Å. (1999):***A New Method for the Simultaneous Measurement of Surface Topography and Ink Distribution on Prints*, Nordic Pulp and Paper Research Journal, vol 14, no 4, pp. 314-319.
- Havlíková, B.; Cicák, V.; Brezová, V.; Hornáková, L. (1999):***Water-Reducible Flexographic Printing Inks-Rheological Behaviour and Interaction with Paper Substrates*, Journal of Materials Science, vol, no 34, pp. 2081-2088.
- Hiemenz, P. C.; Rajagopalan, R. (1997):***Principles of Colloid and Surface Chemistry*, 3rd ed.; Marcel Dekker, Inc.: New York, NY, USA, p 650.
- Holmberg, K.; Jönsson, B.; Kronberg, B.; Lindman, B. (2003):***Surfactants and Polymers in Aqueous Solution*, 2nd ed.; John Wiley & Sons, Ltd: Chichester, West Sussex, England, p 545.
- Israelachvili, J. (1997):***Intermolecular and Surface Forces*, Second ed.; Academic Press Limited: London, UK.
- Johansson, P.-Å.; Norman, B. (1996):***Methods for Evaluating Formation, Print Unevenness and Gloss Variations Developed at STFI*, Tappi Process & Product Quality Conference Proceedings, Cincinnati, OH, USA, TAPPI Press: pp 139-145.
- Karathanasis, M.; Carne, T.; Dahlvik, P.; Haugwitz, B.; Ström, G. (2001):***Importance of Coating Structure for Sheet-Fed Offset Print Quality*, Wochenblatt für Papierfabrikation, vol 129, no 7, pp. 426-432.
- Karathanasis, M.; Fogden, A.; Dahlvik, P. (2003):***The Concept of Critical Ink Setting Time and Its Relation to Print Gloss: Influence of Latex Binder*, Nordic Pulp and Paper Research Journal, vol 18, no 2, pp. 145-149.
- Karttunen, S. T. P. (1973):***Structure and Behaviour of a Paper's Surface in Printing*, The fundamental properties of paper related to its uses, Cambridge, UK, Bolam, F., Ed. pp 544-560.
- Kipphan, H. (2001):***Handbook of Print Media*, Springer: Heidelberg, Deutschland.
- Kogler, W.; Auhorn, W. J. (2006):***Coating of Paper and Board*, In Handbook of Paper and Board, Holik, H., Ed. Wiley-VCH Verlag GmbH & Co.: Weinheim, Germany, pp 332-382.
- Kristiansson, P.; Nilsson, C. M.; Busk, H.; Malmqvist, L.; Elfman, M.; Malmqvist, K. G.; Pallon, J.; Sjöland, K. A.; Utui, R. J.; Yang, C. (1997):***Optical Dot Gain on Newsprint Determined with the Lund Nuclear Microprobe*, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, vol 130, no 1-4, pp. 303-307.

- Laden, P. (1997):***Chemistry and Technology of Water Based Inks*, Blackie Academic and Professional: London, UK, p 345.
- Lagerstedt, P.; Kolseth, P. (1995):***Influence of Surface Energetics on Ink Transfer in Flexo Printing*, Advances in printing science and technology: proceedings of the 23rd research conference of IARIGAI, Paris, France, IARIGAI: pp 269-299.
- Larsson, M.; Engström, G.; Vidal, D.; Zou, X. (2007a):***Impact of Calendering on Coating Structures*, Nordic Pulp and Paper Research Journal, vol 22, no 2, pp. 267-274.
- Larsson, M.; Vidal, D.; Engström, G.; Zou, X. (2007b):***Paper Coating Properties as Affected by Pigment Blending and Calendering*, Tappi Journal, vol 6, no 8, pp. 16-22.
- Leach, R. H.; Pierce, R. J. (1999):***The Printing Ink Manual*, 5th ed.; Kluwer Academic Publishers: Dordrecht, Netherland, p 993.
- Lee, D. I.; Whalen-Shaw, M. (1993):***Fundamentals and Strategies*, In Binder Migration in Paper and Paperboard Coatings, Whalen-Shaw, M., Ed. Tappi Press: Atlanta, pp 19-38.
- Lehtinen, E. (2000):***Coating Binders - General*, In Pigment Coating and Surface Sizing of Paper, Lehtinen, E., Ed. Fapet Oy: Helsinki, Finland, pp 188-194.
- Lepoutre, P.; De Grâce, J. H. (1978):***Ink Transfer Characteristics and Coating Structure*, Paper Technology and Industry, vol 19, no 9, pp. 301-304.
- Liiri Brodén, E.; Wickman, M.; Ödberg, L. Tryckfärgers Kemi - En Kartläggning**, PFT-rapport nr 3 rev.; PFT-programmet: Stockholm, Sweden, 1996; p 217.
- Linnonmaa, J.; Trefz, M. (2000):***Pigment Coating Techniques*, In Pigment Coating and Surface Sizing of Paper, Lehtinen, E., Ed. Fapet Oy: Helsinki, Finland, pp 414-486.
- Lucas, V. R. (1918):***Ueber Das Zeitgesetz Des Kapillaren Aufstiegs Von Flüssigkeiten*, Kolloid-Zeitschrift, vol 23, no, pp. 15-22.
- Mangin, P. J.; Lyne, B. M.; Page, D. H.; De Grâce, J. H. (1981):***Ink Transfer Equation - Parameter Estimation and Interpretation*, Advances in Printing Science and Technology, vol 16, no, pp. 180-205.
- Moir, W. W. (1994):***Flexography - a Review*, Surface coatings international, vol 77, no 5, pp. 221-222.
- Murray, A. (1936):***Monochrome Reproduction in Photoengraving*, Journal of Franklin Institute, vol 221, no, pp. 721-744.

- Nordström, J.-E. P. (2000):***Thermal Changes in a Waterless Sheet-Fed Offset Inking Station*, International printing and graphic arts conference, Savannah, GA, USA, TAPPI Press: pp 153-165.
- Nutbeem, C.; Husband, J.; Preston, J. (2005):***The Role of Pigments in Controlling Coating Structure*, PITA 2005 Coating Conference, pp 97-102.
- Oittinen, P.; Saarelma, H. (1998):***Printing*, Fapet Oy: Helsinki, Finland, p 295.
- Pangalos, G.; Dealy, J. M.; Lyne, B. M. (1985):***Rheological Properties of News Inks*, Journal of Rheology, vol 29, no 4, pp. 471-491.
- Park, S.-J.; Joong-Seong, J. (2001):***Effect of Corona Discharge Treatment on the Dyeability of Low-Density Polyethylene Film*, Journal of Colloid and Interface Science, vol 236, no, pp. 155-160.
- Parker, J. R. (1965):***An Air Leak Instrument to Measure Printing Roughness of Paper and Board*, Paper Technology, vol 6, no 2, pp. 126-130.
- Pauler, N. (2002):***Paper Optics*, AB Lorentzen & Wettre: Kista, Sweden, p 93.
- Podhajny, R. M. (1990):***Critical Ink/Press Performance Parameters in Flexo and Gravure*, Polymers, Lamination & Coatings Conference, TAPPI Proceedings, Boston, MA, USA, pp 581-583.
- Preston, J. S.; Elton, N. J.; Husband, J. C.; Dalton, J.; Heard, P. J.; Allen, G. C. (2002):***Investigation into the Distribution of Ink Components on Printed Coated Paper: Part 1: Optical and Roughness Considerations*, Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol 205, no 3, pp. 183-198.
- Preston, J. S.; Elton, N. J.; Legrix, A.; Nutbeem, C. (2001):***The Role of Pore Density in the Setting of Offset Printing Ink on Coated Paper*, Advanced Coating Fundamentals Symposium, San Diego, CA, USA, Tappi Press: pp 19-34.
- Preston, J. S.; Husband, J. C.; Nutbeem, C.; Parsons, D. J. (2003):***Ink Gloss Development Mechanism after Printing. Part 2: The Influence of Substrate*, 8th Advanced coating fundamentals symposium, Chicago, IL, USA, p 15pp.
- Rentzhog, M.; Fogden, A. (2005a):***Influence of Formulation and Properties of Water-Based Flexographic Inks on Printing Performance for PE-Coated Board*, Nordic Pulp and Paper Research Journal, vol 20, no 4, pp. 410-417.
- Rentzhog, M.; Fogden, A. (2005b):***Rheology and Surface Tension of Water-Based Flexographic Inks and Implications for Wetting of PE-Coated Board*, Nordic Pulp and Paper Research Journal, vol 20, no 4, pp. 399-409.

- Ridgway, C. J.; Gane, P. A. C. (2005):***The Impact of Pore Network Structure on the Absorption of Pigmented Inkjet Inks*, Tappi Coating Conference, Toronto, Canada, Tappi Press, Atlanta, USA: p p.15.
- Rousu, S.; Gane, P.; Spielmann, D.; Eklund, D. (2000):***Separation of Off-Set Ink Components During Absorption into Pigment Coating Structures*, Nordic Pulp and Paper Research Journal, vol 15, no 5, pp. 527-535.
- Rousu, S.; Lindstrom, M.; Gane, P.; Pfau, A.; Schadler, V.; Wirth, T.; Eklund, D. (2003):***Influence of Latex-Oil Interactions on Offset Ink Setting and Component Distribution on Coated Paper*, Journal of Graphic Technology, vol 1, no 2, pp. 45-56.
- Schoelkopf, J.; Gane, P. A. C. (2003):***Offset Ink Concentration Profile During Vehicle Imbibition into Coated Paper, Proposing a Viscous Gradient Model*, Tappi Journal, vol 2, no 8, pp.
- Schoelkopf, J.; Gane, P. A. C.; Ridgway, C. J.; Matthews, G. P. (2000a):***Influence of Inertia on Liquid Absorption into Paper Coating Structures*, Nordic Pulp and Paper Research Journal, vol 15, no 5, pp. 422-430.
- Schoelkopf, J.; Gane, P. A. C.; Ridgway, C. J.; Spielmann, D. C.; Matthews, G. P. (2003):***Imbibition Behavior of Offset Inks Part 1: Gravimetric Determination of Oil Imbibition Rate into Pigmented Coating Structures*, Tappi Journal, vol 2, no 6, pp. 9-13.
- Schoelkopf, J.; Ridgway, C. J.; Gane, P. A. C.; Matthews, G. P.; Spielmann, D. C. (2000b):***Measurement and Network Modelling of Liquid Permeation into Compacted Mineral Blocks*, Journal of Colloid and Interface Science, vol 227, no 1, pp. 119-131.
- Starov, V. M.; Kostvintsev, S. R.; Sobolev, V. D.; Velarde, M. G.; Zhdanov, S. A. (2002):***Spreading of Liquid Drops over Dry Porous Layers: Complete Wetting Case*, Journal of Colloid and Interface Science, vol 252, no 2, pp. 397-408.
- Ström, G. (2005):***Interaction between Offset Ink and Coated Paper - a Review of the Present Understanding*, Advances in Paper Science and Technology: 13th Fundamental Research Symposium, Cambridge, UK, I'Anson, S. J., Ed. pp 1101-1137.
- Ström, G.; Gustafsson, J. (2004):***Ink Drying in Sheet-Fed Offset Printing - Effect of Temperature*, International Printing and Graphic Arts Conference, Vancouver, BC, Canada, pp 35-41.

- Ström, G.; Gustafsson, J.; Sjölin, K. (2001):***Printing Papers Separation of Ink Constituents During Ink Setting on Coated Substrates*, Coating and graphic arts conference and trade fair, San Diego, CA, USA, pp 303-313.
- Ström, G.; Schulz, A. (1993):***Chemical Composition of Coated Paper Surfaces Determined by Means of ESCA*, Nordic Pulp and Paper Research Journal, vol 8, no 1, pp. 105-112.
- Ström, G.; Sjölin, K.; Gustafsson, J. (2000):***Separation of Ink Constituents During Ink Setting on Coated Substrates*, International printing and graphic arts conference, Savannah, GA, USA, pp 89-99.
- Sun, Q. C.; Zhang, D. D.; Wadsworth, L. C. (1998):***Corona Treatment on Polyolefin Films*, Tappi Journal, vol 81, no 8, pp. 177-183.
- Suontausta, O. (1999):***End-Use Properties of Printing Papers*, In Pulp and Paper Testing, Levlin, J.-E.; Söderhjelm, L., Eds. Fapet Oy: Helsinki, Finland, pp 182-215.
- Taylor, J. H., JR; Zettlemoyer, A. C. (1958):***Hypothesis on the Mechanism of Ink Splitting During Printing*, Tappi Journal, vol 41, no 12, pp. 749-757.
- Tillmann, O. (2006):***Paper and Board Grades and Their Properties*, In Handbook of Paper and Board, Holik, H., Ed. Wiley-VCH Verlag GmbH Co: Weinheim, Germany, pp 446-466.
- Todd, R. E. (1994):***Printing Inks: Formulation Principles, Manufacture and Quality Control Testing Procedures*, Pira International: Leatherhead, Surrey, UK, p 427.
- Tollenaar, D.; Ernst, P. A. H. (1961):***Optical Density and Ink Layer Thickness*, Proceedings of the Sixth International Conference of Printing Research Institutes, Elsinore, Denmark, Banks, W. H., Ed. pp 214-234.
- Triantafillopoulos, N.; Rosinski, J.; Serafino, J. (1992):***The Role of Ink and Paper Chemistry in Water Based Publication Gravure*, International Printing and Graphic Arts Conference, Pittsburgh, PA, USA, TAPPI Press: pp 279-289.
- Vaarasalo, J. (1999):***Optical Properties of Paper*, In Pulp and Paper Testing, Levlin, J.-E.; Söderhjelm, L., Eds. Fapet Oy: Helsinki, Finland, pp 162-181.
- Walker, W. C.; Fetsko, J. M. (1955):***A Concept of Ink Transfer in Printing*, American Ink Maker, vol, no December, pp. 38-44,69-71.
- Van Gilder, R. L.; Smith, D. A. (1998):***Development of a High Polarity Latex Polymer Suitable for Waterless Sheetfed Offset Paper Coatings*, 1998 Pan-Pacific and International Printing and Graphic Arts Conference, Québec City, Québec, Canada, pp 199-206.

- van Gilder, R. L.; Smith, D. A. (2001):***Development of a High Polarity Latex Polymer for Waterless Sheetfed Offset Paper Coatings*, Paper Technology, vol 42, no 2, pp. 50-56.
- van Oss, C. J. (1994):***Interfacial Forces in Aqueous Media*, Marcel Dekker, Inc.: New York, p 440.
- Wang, Z.; Wang, X.; Fang, T. (1998):***The Rheology of the Offset Inks*, Surface Coating International, vol 81, no 5, pp. 219-222.
- Washburn, E. W. (1921):***The Dynamics of Capillary Flow*, The Physical Review, vol XVII, no 3, pp. 273-283.
- Vidal, D.; Zou, X.; Uesaka, T. (2004):***Modelling Coating Structure Development: Monte-Carlo Deposition of Particles with Irregular Shapes*, Nordic Pulp and Paper Research Journal, vol 19, no 4, pp. 420-427.
- Wilson, L. (2006):***Hot of the Press*, FLEXO, vol 31, no 9, pp. 54-56.
- von Bahr, M.; Kizling, J.; Zhmud, B.; Tiberg, F. (2001):***Spreading and Penetration of Aqueous Solutions and Water-Borne Inks in Contact with Paper and Model Substrates*, Advances in printing science and technology volume 27: advances in paper and board performance: proceedings of the 27th research conference of IARIGAI, 10-13 Sept. 2000, Graz, Austria, pp 87-101, vol, no, pp.
- Vyorykka, J.; Vuorinen, T.; Bousfield, D. W. (2004):***Confocal Raman Microscopy: A Non Destructive Method to Analyze Depth Profiles of Coated and Printed Papers*, Nordic Pulp and Paper Research Journal, vol 19, no 2, pp. 218-223.
- Xiang, Y.; Bousfield, D. W. (1998):***The Influence of Coating Structure on Ink Tack Development*, 1998 Pan-Pacific and International Printing and Graphic Arts Conference, Québec City, Québec, Canada, pp 93-101.
- Xiang, Y.; Bousfield, D. W. (2001):***Effect of Coat Weight and Drying Condition on Coating Structure and Ink Setting*, Advanced coating fundamentals symposium, San Diego, CA, USA, Tappi Press: pp 35-46.
- Xiang, Y.; Bousfield, D. W. (2003):***Coating Pore Structure Change after Printing*, 8th Advanced coating fundamentals symposium, Chicago, IL, USA.
- Xiang, Y.; Bousfield, D. W.; Hayes, P. C.; Kettle, J. (2004):***A Model to Predict Ink-Setting Rates Based on Pore Size Distributions*, Journal of Pulp and Paper Science, vol 30, no 5, pp. 117-120.



- Xiang, Y.; Bousfield, D. W.; Hayes, P. C.; Kettle, J.; Hultgren, L. (2002):***Effect of Latex Swelling on Ink Setting on Coated Paper*, Journal of Graphic Technology, vol 1, no 1, pp. 13-23.
- Yang, L. (2003):***Ink-Paper Interaction: A Study in Ink-Jet Color Reproduction*, Dissertation, Linköping University, Norrköping, Sweden.
- Yang, L.; Lenz, R.; Kruse, B. (2001):***Light Scattering and Ink Penetration Effect on Tone Reproduction*, Journal of Optical Society of America, image science and vision, vol 18, no 2, pp. 360-366.
- Yang, L.; Lundström, N. (2007):***Physical Dot Gain of Offset: Understanding and Determination*, Nordic Pulp and Paper Research Journal, vol 22, no 3, pp. 388-393.
- Yule, J. A. C.; Nielsen, W. J. (1951):***The Penetration of Light into Paper and Its Effect on Halftone Reproduction*, TAGA Proceedings, pp 65-67.
- Zang, Y.-H. (1993):***A New Approach for Modelling Ink Transfer*, Tappi Journal, vol 76, no 7, pp. 97-103.

# Some aspects on flexographic ink-paper and paperboard coating interaction

---

The overall objective of this study has been to increase the knowledge of how certain physical/chemical parameters influence the interaction between flexographic ink and the coating on paper and paperboard. The effects of ink transfer and ink setting in the coating on print quality and runnability in printing operations have also been an important aspect of this work.

The thesis work began with studying separately the ink and paper by varying either the ink-formulation or the coating-composition and how their physical/chemical properties affect the ink-paper interaction (Papers 1 and 2). This was followed by studies (Paper 3) on the joint effects of both ink and paper coating. The investigations were further extended from lab scale to pilot machines (Paper 5). While the impact of the operation setting and print condition, such as nip pressure and ink temperature, were presented in Papers 3 and 4. As the understanding of ink-coating interaction is a key to understanding ink-transfer and ink setting, the studies may therefore generate knowledge of how to optimize the print presses, the inks and the paper substrate to improve the runnability, print quality, and profitability.