Flexographic ink film's resistance to inkjet ink's solvent flow in Hybrid Printing

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Abstract

Through Darcy's permeability coefficient, K, one can evaluate the resistance of a flexographic ink film to the solvent penetration of an inkjet ink through a paper substrate. This resistance plays an important role for the print quality in hybrid printing applications where flexography and inkjet printing are combined. If this resistance is too high, K→0, the inkjet ink's solvent would not penetrate into the substrate and ink smearing would occur resulting in poor printability.

Paper substrates were printed in a flexographic laboratory printing press. The flexographic printing dot area was varied to evaluate the influence of the full tone and halftone areas on K. These print outs were employed as filters for pigmented inkjet water based inks in a filtration setup. The inks had different pigment's mean particle size which allowed us to address the influence of this parameter on the filter cake build up and consequently, its impact on K. The dot area had indeed an impact in the ink's solvent penetration as we observed that the higher the dot area, the lower the K value, meaning that the resistance for ink´s solvent flow was higher. The pigment's mean particle size also showed influence on K, as we observed that the bigger the pigment particles, the higher the K.

The substrates were selected after a screening based on inkjet ink absorption speed evaluated through a print rub off test and line width measurements of printed lines.

We also printed the pre-printed flexography images using a KM 512 piezoelectric printing head and one of the inks used during filtration to evaluate the inkjet printing quality for this hybrid printing approach. We observed wider, less blurry and ragged lines with increased dot area. No ink smearing was observed for the print outs.

Introduction

According to Xiang et al. [1] the penetration of an ink's solvent is driven by capillary pressure of the substrate's surface and resisted by a filter cake during the printing process suggesting that the pore structure changes after printing. The impact of the filter cake on the ink's solvent penetration during the inkjet printing process was also discussed elsewhere [2,3,4]. An additional resistance to fluid penetration through the substrate is created when a flexographic ink film is present.

We aimed to study the resistance that a flexographic ink film and the pigmented inkjet ink's filter cake build up offered for an inkjet ink's solvent penetration into a paper substrate in hybrid printing. We also aimed to evaluate the impact of the flexography dot area on the inkjet printing quality where inkjet inks using water as solvent were printed on paper substrates pre-printed with water based flexography inks.

To study the flexography ink film resistance we employed Darcy's law [5] which uses a single parameter K to account for the characteristics of a porous medium regarding its effect on fluid flow through it. It is a simple proportional relationship between the instantaneous discharge rate through a porous medium, the viscosity of the fluid and the pressure drop over a given distance. We used a modified Darcy equation (1), where: Δp is the pressure difference between the atmospheric and vacuum pump pressure, L is the filter thickness, μ is the fluid's viscosity, A is the filtration area, t is the filtration time and K is Darcy's permeability coefficient, m is the filtrate mass.

$$\frac{dm\ (t)}{dt} = \frac{K.\Delta p.\rho.A}{L.\mu} \qquad (1)$$

The magnitude of the permeability is determined by the degree of 'openness' of the medium, which is described by the porosity of the medium and the size of the pores present in its internal structure [6]. Its value in the same porous sample may vary with the properties of the permeation fluid and the mechanism of permeation [7]. According to Gane et al. [8] K→∞ represents no resistance to fluid flow and K→0 complete blocking of the flow.

The key assumption which underlies Darcy's law is that the Reynolds number is considered to be sufficiently small. Wakeman, and Tarleton [6] reported that the Reynolds number rarely becomes large enough to lead to a turbulent flow inside the pores. Hence, we can assume that fluid inertia will only have a very small effect on the dynamics of flow.

The understanding of the flexographic ink film resistance through K together with the filter cake build up when using pigmented inks in inkjet printing, can address the threats and opportunities when inkjet and flexography printing are combined in one printing job at the same time. Evaluating inks with different mean pigment particles sizes, different paper substrates and varied flexography dot areas, one can identify the effect of these variables on the ink's solvent penetration speed, which is important for good inkjet printability. Besides it can provide support in finding combinations of inkjet inks and substrates suitable for hybrid printing.

Material and Methods

Substrate selection

In order to select the substrates for the filtration experimental designs, we did a screening of the substrates by printing different papers in a desktop inkjet printer using pigmented water based inks.

To select the suitable desktop printer for this test we printed full tone images of cyan, yellow, magenta and black in six different printers which used water based pigmented and dye inkjet inks. From the analysis of these print outs' micrographs we observed that two of the printers were suitable to be use in our tests, those used pure colors to print the full tone images. We selected one of them. **Figure 1** illustrate a full tone image printed in two of the six printers, in the right side is the micrograph of the printer we selected.

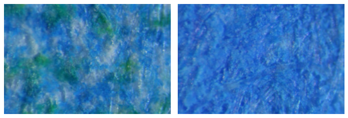

***Figure 1:** Full tone cyan image printed in two different desktop printers. In the left side, the micrograph showed dots of yellow ink on the cyan full tone image. In the right side, pure colors are observed.*

We printed all the substrates selected for the screening in the desktop printer. We performed an ink rub-off test [9] five seconds after printing each page. These results are presented in Table 1. Those papers that passed this test were then printed in flexography.

Table 1: Paper screening for experimental designs.

ID	Surface Treatment		Grammage	Suitable for	Ink Rub
#	Coating	Salt	(g/m^2)		Off Test
1	No	No	100	Multipurpose	Fail
2	No	No	100	Laser	Fail
4	Yes	No	130	Multipurpose	Fail
5	No	No	75	Multipurpose	Fail
6	No	No	80	Multipurpose	Fail
7	No	No	80	Multipurpose	Pass
8	No	Yes	80	Multipurpose	Fail
9	No	Yes	120	Inkjet	Pass
13	Yes	No	100	Offset	Fail
14	No	No	100	Inkjet	Pass
15	No	Yes	80	Multipurpose	Fail
16	No	Yes	100	Multipurpose	Fail
17	Yes	No	80	Flexography	Fail
18	Yes	No	130	Flexography	Fail
19	Yes	No	130	Flexography	Fail
20	No	No	120	Flexography	Fail
21	Yes	No	130	Flexography	Fail
22	Yes	No	140	Flexography	Fail
23	Yes	No	160	Flexography	Fail
24	Yes	No	180	Flexography	Fail
27	Yes	No	120	Rotogravure	Fail
28	No	No	120	Inkjet	Pass
29	Yes	No	120	Inkjet	Pass
32	No	Yes	80	Multipurpose	Pass
33	No	No	80	Multipurpose	Pass
34	No	No	120	Multipurpose	Pass

The test chart we used for the inkjet printing at the desktop printer and the one used at the flexography press are illustrated on the left and right side of Figure 2, respectively.

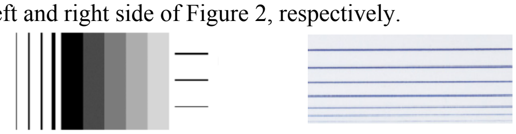

Figure 2: Test chart used for the inkjet printing on the left side and area of the test chart used for measurements in the flexography printing on the right side.

The flexography printing we did at the Flexiproof 100, a flexography laboratory press, at a printing speed of 25 m/min. The press was equipped with a 13 cm^3/m^2 anilox roll and an 80 L/cm cliché mounted on the roll with a 0.5 mm thick cushion tape.

The selection of the papers for the screening was based on the printing technology that they were suitable for, the grammage and the surface treatment. The surface treatments that we referred were pigment coating or application of salt solutions.

Each set of papers (15 and 16), (17 and 18) and (21 to 24) were the same papers but with different grammages. Paper 29 was paper 28 after the calendering step. Papers 28 and 29 were precipitated silica matt coated papers. All these papers were available commercially except papers 13 and 28.

We did line width measurements on the papers printed in flexography and inkjet. These measurements were carried out according to the ISO 13660 print quality standard [10] for the inkjet printed samples. For the flexography print outs, we applied the same method although we used a blue ink instead of a black one. These results are presented in Figure 3 for the measurements done for the inkjet printed samples and in Figure 4 for the flexography printed ones.

The selection was based on the samples that showed the thinner and wider line width. We selected Paper 28 and 29 for the inkjet printed samples, and Paper 32 and 34 for the flexography printed ones. The correct choice based on the results would have been Paper 28 and Paper 33 for the first set of measurements but due to the fact that papers 28 and 29 were the same except for the additional calendering step for paper 29, we selected those instead.

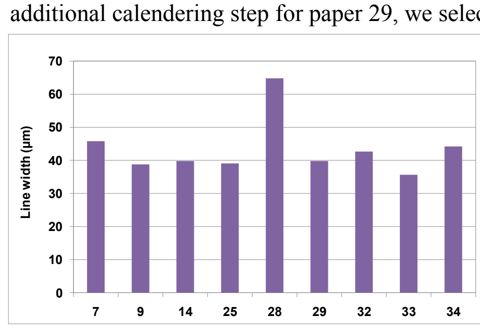

***Figure 3**: Line width measurement for inkjet printed samples.*

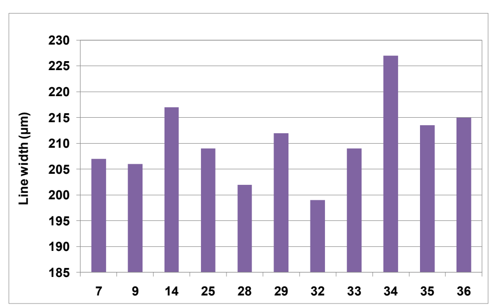

***Figure 4**: Line width measurement for inkjet printed samples.*

Experimental designs

We did two experimental designs; both were full factor factorial ones varying three factors between two levels with three center points for the error estimation which leaded in 11 experimental runs for each design in total.

The factors that were common to each design were the inks and the flexography clichés' dot areas. The third factor, which was the paper substrates, was papers 28 and 29 for Design 1 and 32 and 34 for Design 2. The experimental designs are presented in Table 2 were DA stands for printed dot area. The full factorial designs experimental run's order were fully randomized.

The clichés we used had 20% halftone and 100% full tone areas. An additional one with 60% halftone was used for the center points print outs.

Table 2: Full factorial experimental designs

Run	Design 1			Design 2		
	DA	Ink	Paper	DA	Ink	Paper
#	%	-	ID #	%	-	ID #
1	60	A	28	100	A	34
2	60	A	28	60	A	32
3	100	A	29	20	B	32
4	100	B	28	20	A	32
5	20	A	29	20	B	34
6	20	B	29	60	A	32
7	100	B	29	20	A	34
8	100	A	28	60	A	32
9	20	B	28	100	B	34
10	60	A	28	100	A	32
11	20	A	28	100	B	32

The two inks used during the experiments were water based pigmented inkjet inks from different suppliers. We measured the surface tension of the inks using the Krüss Easy Dyne viscometer employing the Wilhelmy plate method at 23°C [11]. The viscosity was measured with a Brookfield rotational viscometer at 20°C and the mean particle size distribution (MPS), was measured using the Zetasizer instrument [12]. We calculated the density. The properties of the inks are presented in Table 3.

Table 3: Properties of the inkjet inks

Ink	Surface Tension	Viscosity	Density	MPS
	mN/m	mPas	g/cm^3	nm
A	28.1	5.8	0.97	131
B	31.6	7.8	1.08	260

Samples preparation for the filtration

We printed the paper substrates using the Flexiproof 100 at a printing speed of 40 m/min using a water based flexography yellow ink supplied by Sun Chemicals. The screen of the clichés was selected to be 38 L/cm in order to be suitable for both uncoated and coated grades. The clichés were mounted on the roll using a 0.5 mm cushion tape. We used a 13 cm^3/m^2 anilox roll.

Optical measurements

We measured the apparent dot area and dot gain for each of the four papers and respective halftone areas using an X-Rite 530 spectrodensimeter. We selected the Murray Davis equation (2) [13,14,15] in the instrument's software for the calculation of dot area and dot gain . Df is the density of the full tone area, Dp is the density of the paper and Dh is the density of the halftone area in equation (2).

$$\text{Dot area} = \left[(1 - 10^{-(\text{Df}-\text{Dp})})/(1 - 10^{-(\text{Dh}-\text{Dp})})\right].100 \qquad (2)$$

We did this to verify that the printed dot area was correct and has not changed during printing. The measurements for Dp are presented in Table 4. The ones for Df and Dh are presented in Table 5. The apparent dot area and dot gain values are presented in Table 6.

Df was also used to verify the thickness of the ink film optically. The higher the density of the full tone area (less light reflected), the thicker the ink film. The lower the density (more light reflected), the thinner the ink film. We also measured the density of the halftone areas to check for deviations from the target that we set. We changed the clichés when the target values set by us were not reached.

Table 4: Absolute density for the substrates printed in flexography (Dp)

Paper	Density			
ID #	V	C	M	Y
28	0.06	0.06	0.06	0.02
29	0.07	0.08	0.07	0.03
32	0.07	0.07	0.07	0.02
34	0.06	0.07	0.06	0.01

Table 5: Absolute density measured for the printed flexography areas (Df and Dh)

Paper	Density	
ID #	Target	Measured
28	1.00	0.84
29	1.00	1.00
32	1.00	0.89
34	1.00	1.14
28	0.60	0.53
32	0.60	0.79
28	0.20	0.17
29	0.20	0.20
32	0.20	0.21
34	0.20	0.19

Filtration set up

We draw 45 mm circles onto the flexography printed areas and cut them. They were used as filters in the filter holder. We did this to evaluate the resistance that the ink film from the printed areas plus the substrate offered for the inkjet ink to flow through the filter, in this case, the pre-printed flexography areas. We measured the thickness of the filters using Lorentzen&Wettre paper thickness testing. These results are presented in Table 7.

We weighted samples from ink 1 and ink 2 separately in test tubes with caps. We aimed at nominal ink masses ranging from 1.5

to 4.0 g with 6 ink samples per experiment. We recorded the ink's filtration time with a chronometer and fitted the data to the Darcy equation. The filter holder was a stainless steel vacuum filter produced by Sartorius Stedim Biotech.

The vacuum pump pressure measured using a manometer was 200 hPa. The atmospheric pressure was 1110 hPa.

Table 6: Dot gain and dot area measurements according to Murray Davis equation

Paper ID #	Halftone area %	Dot gain %	Dot Area %
28	20	18	38
28	60	23	83
29	20	21	41
32	20	24	44
32	70	26	96
34	20	18	38

Table 7: Thickness measurements for the printed areas

Paper ID #	DA %	Thickness μm
28	100	114
29	100	112
32	100	95
34	100	112
28	60	114
32	60	95
28	20	114
29	20	112
32	20	98
34	20	112

Printing tests

We printed on the pre-printed flexographic areas using a Konica Minolta KM512 piezoelectric printing head which employed shared wall technology to fire the ink drops [16]. The printing head had 512 nozzles divided into two rolls. We set the voltage to 17V for each roll. The drop volume was 14pL and the firing frequency 40 kHz.

The samples were glued on an endless paper web supported by two cylinders. The web velocity was set to 0.3 m/s. The printing head was installed 5 mm distant from the paper web. We used ink A, one of the inks used in the filtration, for this printing tests. The test target was a 360 dpi monochrome image illustrated in Figure 5. We did edge sharpness measurements to evaluate the impact of the dot area on inkjet printing quality. We also observed if ink smearing occurred or not.

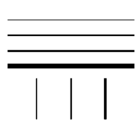

Figure 5: *Monochrome test target used at the KM 512 printing head.*

Porometer test

We did the porometer test using the ink 3809 from SunChemical [17]. This test gives an indication about the porous structure of the paper (i.e. larger or smaller pores). It was developed by SunChemical and Coater Lorilleux and consists of applying a standard ink (i.e. Porometertest farbe 3809) onto a circular rubber, transfer it to the paper and rub-off after few seconds i.e. total test time 10s. We measured the density of the ink spots using the X-rite 530 spectrodensitometer. Higher optical density means higher absorption capacity of the paper, larger pores. We tested only unprinted substrates.

Results and Discussion

Filtration

We used Modde7 to design and evaluate the filtration experiments. To analyze if the model used fit well the experimental data we used the parameters R^2, Q^2, model validity and reproducibility. The design of experiments theory can be found elsewhere [18]. For the notations used in the Modde7 software and in this publication please refer to reference [19].

The diagrams showing R^2 and Q^2 for Design and Design 2 are presented in Figure 6 and Figure 7.

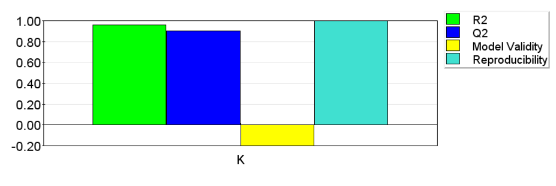

Figure 6: *Summary of fit for Design 1.*

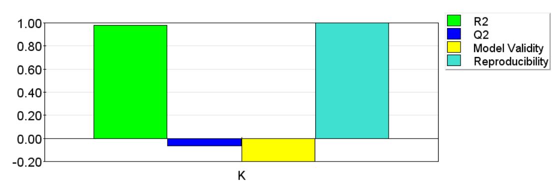

Figure 7: *Summary of fit for Design 2.*

The response variable for the design was the Darcy's permeability coefficient K, which was the angular coefficient of the filtration data curve. These values together with the coefficient of correlation R^2 for the filtration curves correspondent to each of the experimental runs are presented in Table 8 and Table 9 for Design 1 and Design 2 respectively.

The center points of the designs were done for paper 28 for Design 1 and paper 32 for Design 2, both using ink A. Due to the fact that the dot area was the only qualitative factor for these designs, it was target to 60% dot area, average between the sum 100 and 20% for the replicates or center points. As can be seen from Table 6, the measured dot gain was rather high and we did not account for this during experimentation which leaded to a significant experimental error. The actual dot areas of the flexography print outs were significant different from the target ones. We wrongly took the values of density to check for variability in the lab press where we should have measured the dot area or dot gain as a press control parameter. Refer to Table 8 and Table 9 for the actual DA of the print outs. Note that for a full tone image there is no dot gain.

Table 8: Results for the experimental design 1

Run	Design 1				
	DA	Ink	Paper	K	R^2
#	%	-	ID #	m^2	-
8	100	A	28	$1.2*10^{-16}$	0.74
4	100	B	28	$1.6*10^{-13}$	0.93
1	83	A	28	$2.8*10^{-16}$	0.90
2	83	A	28	$2.7*10^{-16}$	0.86
10	83	A	28	$2.0*10^{-16}$	0.38
11	38	A	28	$2.0*10^{-16}$	0.81
9	38	B	28	$1.1*10^{-13}$	0.52
3	100	A	29	$1.6*10^{-16}$	1.00
7	100	B	29	$1.3*10^{-13}$	0.93
5	41	A	29	$3.3*10^{-16}$	0.98
6	41	B	29	$1.9*10^{-13}$	0.99

Table 9: Results for the experimental design 2

Run	Design 2				
	DA	Ink	Paper	K	R^2
#	%	-	ID #	m^2	-
10	100	A	32	$5.5*10^{-16}$	0.96
11	100	B	32	$7.4*10^{-13}$	0.62
2	96	A	32	$5.6*10^{-16}$	0.75
6	96	A	32	$1.0*10^{-15}$	0.80
8	96	A	32	$1.2*10^{-15}$	0.97
3	44	B	32	$8.1*10^{-13}$	0.63
4	44	A	32	$1.1*10^{-15}$	0.51
1	100	A	34	$2.6*10^{-16}$	0.50
9	100	B	34	$3.5*10^{-13}$	0.61
5	38	B	34	$9.3*10^{-13}$	0.70
7	38	A	34	$8.6*10^{-16}$	1.00

The parameter R^2 indicated how well the current experimental runs can be reproduced. The value 1 indicated a perfect fit to the model. Q^2 indicated how well we could predict new experiments. Q^2 > 0.5 indicates good prediction and Q^2 >0.9 excellent prediction. For Design 1 as can be seen from Figure 6, both R^2 and Q^2 indicated good model fit and prediction, respectively. The same did not happen for Design 2, where R^2 was a good value but Q^2 was below 0.5 indicating lack of prediction to the model. Reproducibility for both designs was above 0.5 indicating that the center points or replicates had a low pure error and that we had a good control of experimental procedure. Also for both models the validity was below 0.25 which indicated that the experimental designs did not represent well the experimental data. The model validity takes into account the F-test [19] which was calculated based on the model error estimated from the center points. Especially for Design 2, the one that we actually had the worse model fit, the center point's DA was very close to the design factor's DA, respectively 96 and 100% what clearly affected the model validity. In this way, the analysis regarding the factors interaction, one of the biggest advantages of using design of experiments, was not possible to be done for the experimental data.

The K values were lower the higher the area coverage for both inks and the four papers studied as can be seen from Figure 8 and Figure 9. Paper 28 with ink B showed a different trend but the fitting of the filtration data for run #9 was rather poor, as can be seen from the R^2 for these data in Table 9.

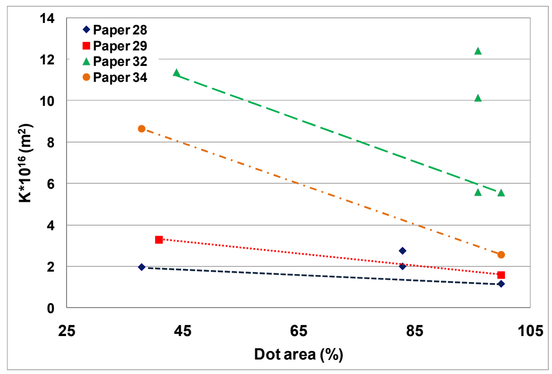

Figure 8: *K values for ink A, Designs 1 and 2*

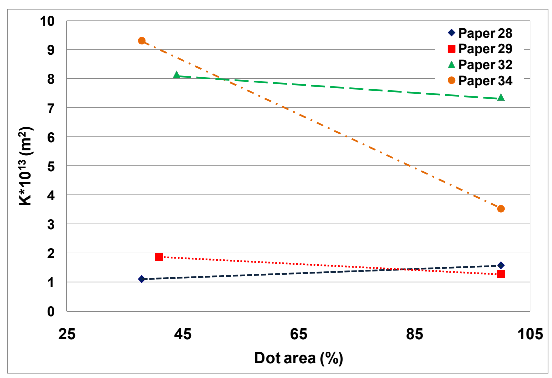

Figure 9: *K values for ink B, Designs 1 and 2*

The results from the porometer test are presented in Table 10. From these results we could assume that papers 28 and 29 have larger pores than papers 32 and 34. Larger pores indicate a faster inkjet ink penetration. But according to the filtration results we found that papers 32 and 34 were more suitable for hybrid printing as the K values were higher indicating less resistance to the inkjet ink´s solvent penetration through the paper.

Table 10: Porometer test

Paper	Density
28	1.44
29	1.31
32	1.04
34	1.00

A clear indication of the influence of the particle size of the ink's pigments was observed. Ink A had around 50% smaller MPS compared to ink B as can be seen in Table 3. The K values for ink A were three orders of magnitude smaller than for ink B for Design both designs which could be explained by a higher packing density of the ink's pigments in the filter cake formed during filtration that leaded to a higher resistance for the ink's solvent to flow through. In this way, we could suggest that inks with bigger MPS would suit hybrid printing applications better.

Printing quality for hybrid printing

The results for the edge sharpness measurements that we did on the hybrid printed images are presented in Figure 10, 11 and 12.

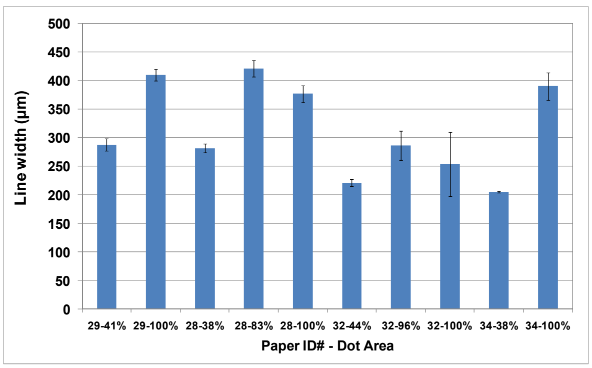

Figure 10: *Line width measurements for the hybrid printed samples.*

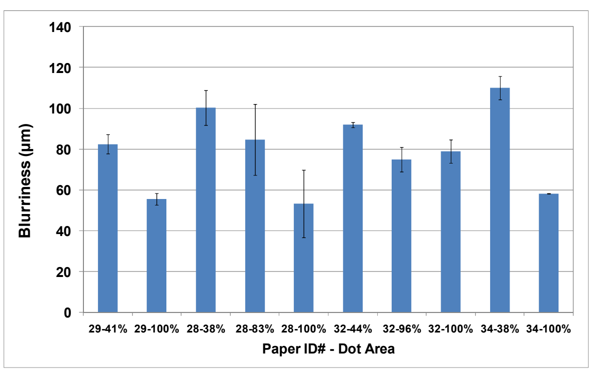

Figure 11: *Blurriness measurements for the hybrid printed samples.*

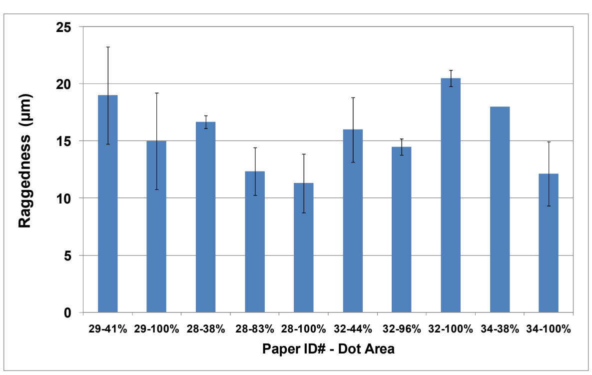

Figure 12: *Raggedness measurements for the hybrid printed samples.*

The results for the edge sharpness measurements indicate good printability of the inkjet water based ink on the pre-printed flexography surface. The measurements indicated wider, less blurry and ragged lines with increased dot area. No ink smearing was observed.

Future work improvements

We intended to re-do the experimental designs doing the measurements of the filtration time and ink mass dynamically. The K values for both designs were rather low indicating that there was no or very little ink's solvent penetration. This was not what we visualized during the filtration. Most of the ink's solvent volume penetrated the substrate within 5 to 20 seconds but until all the volume was filtered, minutes were observed for the filtration time. We need to optimize the filtration step.

We assume that better results and conclusions could be drawn if we had the same paper but with some differences in surface treatment like salt concentration, degree of surface sizing or calendering.

Pigmented inkjet inks are made of colloidal stable pigment particles. Some changes in the pH or surface treatments which affect the ionic strength of the paper surface could lead to changes in the stability of the pigments' dispersion in the ink leading to agglomeration when it gets in contact to the surface. If controlled, agglomeration is desirable to keep the ink's pigments on the surface and allow only the penetration of the ink's solvent into the substrate [20,21]. We suggest a study of the agglomeration of the ink's using substrates with different salt concentrations.

It would be interesting to have more accurate measurements regarding the porosity of the unprinted and printed flexographic areas using for example mercury porosimetry. In this way we could compare the size of the ink's pigment particles to the pore size and volume of the substrate. Thus, we could have information about the percentage of the pigment particles which have been retained during filtration. Information about the filter cake's thickness and the thickness of the flexography ink film could be measured using SEM pictures. Microtome images could be done to visualize the inkjet ink penetration into the flexography printed samples.

We should do the filtration analysis for the unprinted papers to address the resistance to ink's solvent flow of the substrate itself.

We could use the instrument penetration dynamic analyzer and compare these results with the filtration ones.

We suggested better control of the printing quality through measurements of dot gain and dot area. We shall have test charts containing 25, 50, 75 and 100% dot areas to address these parameters for each substrate before filtration.

Conclusions

We intended to evaluate the resistance to the inkjet ink's solvent flow through paper substrates using filtration experiments where the data were fit to Darcy´s equation. Even though we got very low values for the permeability coefficient, K, we could visualize some trends when the flexography printed dot area was increased and inks with different mean particle size were employed. We observed that inks with bigger mean particle size would suit hybrid printing application better as the resistance for the fluid flow would be lower. We observed that K was higher the higher the dot area of the flexographic printed image indicating that higher resistance was observed which could impose some difficulties when doing inkjet printing on top of full tone flexography images.

We observed that papers with smaller pores would be better for hybrid printing as it would lead to lower fluid flow resistance. However, the measurements we use to address the pore structure do not give as much information about it as a mercury porosimetry measurement would have given. We did not measure the porosity of the printed areas to be able to draw a better conclusion on that.

The print quality evaluation on the hybrid printed samples indicated that it is possible to do inkjet printing with pigmented inkjet inks on top of pre-printed flexography areas and get good printability with no ink smearing. We got wider, less blurry and ragged lines with increased flexography dot area based on the edge sharpness measurements.

We did not get good model validity for the experimental designs since there was an experimentation error related to the control of the flexography press. We did not use the right printing quality parameter, the dot gain or the dot area to account for variations between the clichés dot area and the actual dot area of the print out. This problem could have been easily addressed doing these measurements before the filtration. Better results could be achieved in this way and we could benefit from the advantage of doing experimental designs.

References

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