The absorption mechanism of aqueous and solvent inks into synthetic nonwoven fabrics

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Abstract

To obtain high quality printing result with aqueous inks, it is important to understand the mechanisms of ink absorption and setting on various substrates. The final position of ink pigments determines the ink density and the resolution of the printed product. Recently, it has become desirable to develop higher quality printing results on nonwoven fabrics and synthetic fiber sheets.

Absorption rates of aqueous and solvent inks into nonwoven fabrics were characterized with a Bristow absorption wheel. Several nonwoven fabrics, made with polyvinyl alcohol fibers or polypropylene fibers, were tested with aqueous and solvent inks. A model based on Darcy`s law was applied to predict the ink absorption rate into the nonwoven fabrics. The model links the void fraction, pore size, contact angle and the Darcy permeability coefficients to the absorption rate. The results showed a high correlation between the experimental data and the predicted results for most combinations of substrates and inks, but in a few cases, the absorption rates were different than expected.

The micro-scale distribution of aqueous and solvent inks on the nonwoven fabrics was evaluated with a confocal laser scanning microscope (CLSM) in order to characterize the deposition uniformity of the nonwoven fabrics. A clear difference of micro-scale distributions between aqueous and solvent inks could be obtained by CLSM.

Introduction

The mechanisms of ink absorption and setting on porous materials such as paper for all kinds of printing methods determine the rate of printing and influence the final quality of the print. Recently, not only coated and uncoated papers but also nonwoven fabrics, synthetic fiber paper and film have been used as materials for printing. The surface characteristics of these substrates influence the ink setting rate and quality of printing, but the relationship between the final pigment deposition and the rate of absorption has not been quantified.

The liquid flow in a porous substrate has been shown, in many cases, to follow Darcy`s law which states that the rate of flow is proportional to the pressure gradient and inversely proportional to viscosity. Much work has been done in the area of modeling fluid motion in porous media. If the pressure driving force is given by the Laplace equation, and the resistance to flow is described by the flow in a capillary, the Lucas-Washburn equation is found to describe the behavior; this equation is based on a series of parallel capillaries all of the same radius [1]. Often, various correction terms are used to fit the results to experimental data. A three dimensional model that describes the flow in layered porous media has been described [2]. The model could predict some sets of experimental data for a coating layer on a paper, measuring the properties of each separately. A model by Bousfield and Karles [3] is based on the pore connectivity and pore size was proposed that seems to give good comparison with experiments.

CLSM has been shown to be a powerful tool to characterize ink penetration into coated and uncoated papers utilizing a fluorescence stain technique [4, 5]. The process of ink-jet ink setting on non-cellulose fibers using CLSM was investigated [6]. It was confirmed that the ink-setting behavior of the pigment type ink-jet ink differed by the particle size of the pigment. Furthermore, they succeeded in detecting the fluorescence of the cyan ink, which did not emit fluorescence by a visible laser, using a UV laser equipped with the CLSM. The micro scale distribution of dye type and pigment type ink-jet inks on corona-treated nonwoven fabrics was evaluated by CLSM [7]. It was shown that not only chemical but also micro structural changes of the sheet surface had an influence on the behavior of setting and the micro scale distribution of the ink on the sheets.

In this study, the ink absorption rates into nonwoven fabrics were characterized with a common absorption test method. The absorption rate was predicted using Darcy's law with the pressure gradient given by the Laplace equation. The micro scale distribution of inks on nonwoven fabrics was investigated by CLSM. Clear differences in rates and pigment deposition were seen for the different substrates between aqueous and solvent inks.

Material and Methods

Samples

Three kinds of synthetic nonwoven fabrics were used. The sheet named PVA (12 g/m^2) was made from polyvinyl alcohol (PVA) fibers by a wet process. Another sheet named PP-A (15 g/m^2) was made from polypropylene (PP) fibers and polyvinyl alcohol fibers mixed. The sheet named PP-AC (18 g/m^2) was coated with an acrylic latex (Nippon Zeon, Japan) on the PP-A sheet.

Aqueous and solvent inks for flexographic printing (T&K TOKA, Japan) were compared. The aqueous ink is composed of pigment, isopropyl alcohol, resin and water. The solvent ink is composed of pigment, resin and a mixture of alcohol as a solvent. The same type of pigment is used in both inks.

Characteristics of nonwoven sheets

The pore volume of nonwoven sheets was determined by the silicon oil void test. Silicon oil was applied to the samples to ensure that they were saturated with oil, and then the oil was completely wiped from the surface. The void fraction was calculated from the area and weight of the samples before applying the oil and the weight of oil saturated samples. The void fraction was also estimated using CLSM and the oil-filled volume in the sheets was measured by image analysis. The silicon oil was stained with a fluorescent agent, Nile Red, before measuring.

A mercury porosimeter (PoreSizer 9320, Micromeritics Instrument Co.) was used to determine the pore sizes in the nonwoven sheets. Pore size distributions were also estimated from CLSM images by measuring the oil-filled area in the sheets.

The contact angle of water or oil drop on the nonwoven sheets was measured. After dropping liquid on the nonwoven sheet, a camera recorded the size change of the liquid drop on the substrate every 10 msec for 300 msec.

Ink absorption rate into nonwoven sheets

The absorption rates of aqueous and solvent inks into nonwoven sheets were characterized with a Bristow absorption wheel. A known volume of diluted ink was added to the trough. The inks had to be diluted to enable them to flow easily through the slit at the bottom of the trough. The area of the trace left on the substrate was measured. The contact time between the ink and the substrate was varied by changing the speed of the wheel. In some cases, several layers of the paper were needed to prevent the "saturation" of the sample. The volume absorbed per unit area was then calculated.

A model based on the Laplace equation and Darcy`s law was used to predict ink absorption rate into the nonwoven sheets. The model links the void fraction, pore size, contact angle and the Darcy permeability coefficients to the absorption rate. The equation is derived by replacing the pressure gradient in Darcy's law with the Laplace equation, the depth of penetration with *V/A*, and integrating with respect to time to obtain:

$$\frac{V}{A} = \sqrt{\frac{4K\varepsilon\cos(\theta)\sigma t}{\mu R}} \qquad (1)$$

where *V/A* is the ink absorption volume per unit area, *K* is the Darcy permeability coefficient, ε is the void fraction, θ is the contact angle, σ is the surface tension, μ is the viscosity and *R* is the average pore radius. The contact angle, void fraction and pore radius were obtained from experiments, while the surface tension and viscosity were assumed to be the same as water for the aqueous inks.

The permeability coefficient, *K*, was obtained by measuring the water and air permeability through the sample based on this form of Darcy's law:

$$\frac{d(V/A)}{dt} = \frac{K\Delta P}{\mu L} \qquad (2)$$

where ΔP is the pressure drop and *L* is the distance that the pressure acts in the flow direction. Water and air permeability were obtained by measuring the volume of water or air volume passing through a given area of nonwoven sheet in unit time.

Observation by CLSM

A confocal laser scanning microscope (CLSM; TCS-SP2, Leica) was used in this experiment. The laser beam was first irradiated and scanned on a sample, and then the fluorescence emitted from the sample was detected as a fluorescence image. A 3D image was reconstructed from a series of single confocal images accumulated digitally.

The selected objective lens was an x 40 oil-immersion lenses with immersion oil (Refractive Index: 1.518) supplied by Leica. The Z-resolution of the oil-immersion lens is three times better than that of a dry lens with air between the sample and the objective lens. Therefore, it is possible to reduce the optical resolution for a depth up to less than 0.6 μm using an oil-immersion lens [8]. Oil-immersion lenses have been previously used to observe pulp fibers [9, 10]. An excitation wavelength of 488 nm from an Ar laser (50 mW) was used for this analysis. Confocal images were obtained using XYZ scan modes. A sequence of XY frames (238 x 238 μm^2) was obtained at 0.5 μm intervals in the z (thickness) direction. The pixel count of each frame was 1024 x 1024 pixels.

Results and Discussion

Characteristics of nonwoven sheets

Table 1 shows the properties of the nonwoven sheets. In the silicon oil test results, the PVA sheet showed the highest void fraction (ε), while the PP-AC sheet had the lowest value because it was coated with latex. The void fraction given by CLSM measurements showed close value to the results obtained by the silicon oil test.

Table 1. Measured parameters of substrates

		PVA	PP-A	PP-AC
Thickness (μm)		40	58	66
Void fraction	ε	0.441	0.375	0.364
Pore radius (μm)	*R*	2.5	2.0	2.3
Contact angle, *water*	$\cos(\theta)$	0.28	0.0069	0.24
Contact angle, *oil*	$\cos(\theta)$	0.99	0.99	0.99
Permeability coefficient, *water* (m^2)	K_w	3.33 $\times10^{-12}$	14.8 $\times10^{-12}$	9.23 $\times10^{-12}$
Permeability coefficient, *air* (m^2)	K_a	2.73 $\times10^{-12}$	3.40 $\times10^{-12}$	3.80 $\times10^{-12}$

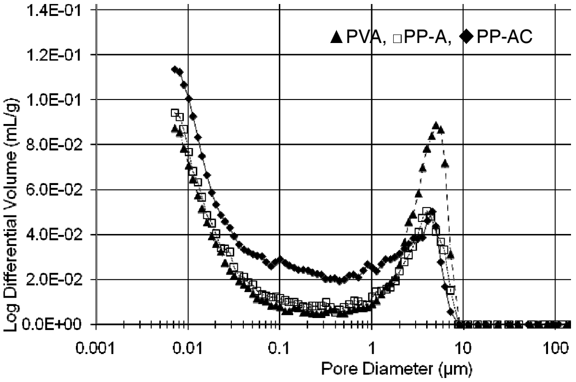

Figure 1. Pore size distributions in the nonwoven sheets

Figure 1 shows pore size distributions in the sheets measured by the mercury porosimeter. The peak values (*R*) of the log differential volume are shown in Table 1, but it is clear that all samples have a wide range of pore sizes. In the PVA sheet, there were many pores with the diameter of around 5 μm. This result corresponds with the previous result that it has higher void fraction than other sheets. In the PP-AC sheet, there were many smaller pores between 0.1 and 1 μm. This is because larger pores were filled up with the latex. The pore size given by the image analysis of CLSM showed larger values, by a factor of ten, than the porosimeter. The low pressure results of the porosimeter are suspected to not be accurate.

The contact angle (θ) measured at 10 ms is shown in Table 1. The PVA sheet showed the lowest water contact angle because the PVA fiber is hydrophilic. The PP-A sheet showed the highest water contact angle. This is because polypropylene fiber contained in the PP-A sheet is hydrophobic. Comparing the PP-A sheet with the PP-AC sheet, the water contact angle decreased after coating with acrylic latex and the surface became more hydrophilic. The oil contact angle showed very low values and was almost the same for all nonwoven sheets.

The hydrophilic PVA sheet showed the lowest water permeability (K_w) despite of its highest void fraction. This result is hard to understand but must be related to the connectivity of the pores.

Ink absorption rate into nonwoven sheets

Figures 2 and 3 show total liquid volume (TLV) transferred to the sheets per unit area by measuring with the Bristow absorption wheel and predictions using Darcy`s law; this volume is also related to the penetration depth of fluid into the sample. Solid lines represent experimental data and dotted lines are the predicted results.

The solvent ink penetrated into the sheets deeper than the aqueous ink at the same contact time for all samples. Ink penetration depth into the PP-A sheet was the lowest for the aqueous ink, but was the highest for the solvent ink. The aqueous ink seems to spread over the surface of the PVA sheet and does not penetrate deeply into the sheet because the surface is hydrophilic and permability is low. These results demonstrate that a combination of the contact angle and the permeability control penetration.

Comparing the PP-A sheet with the PP-AC sheet, the penetration depth of aqueous ink increase by coating acrylic latex. The aqueous ink may penetrate deeply into the PP-AC sheet in regions where there is latex. It was observed that the coated latex was penetrated into the bottom of the sheets by CLSM.

Modeling ink absorption using Darcy`s law

The predicted results for aqueous ink were derived from water permeability coefficient (K_w) and water contact angle. Air permeability coefficient (K_a) also was applied to predict the absorption rate; however, the calculated data did not match the experimental data.

The results showed a high correlation between the experimental data and the predicted results for the PP-A sheet and PP-AC sheet as shown in Fig. 2. This demonstrates that the model captures the correct relationship between contact angle, pore size and permeability. However, for the case of the PVA sheet, the absorption rates were lower than expected. This difference may be caused by ink trapped in the space between the piled sheets, which led to decrease of the absorption depth. According to the results of surface profile by CLSM, the surface of PVA sheet was the roughest of the three kinds of nonwoven sheets.

For the predicted results, the low values of absorption rate in PP-A and PVA were attributed to the high contact angle and low permeability coefficient, respectively. The high values of PP-AC sheet was attributed to the low contact angle and medium permeability coefficient. This model could be applied to predict liquid absorption rate into porous media such as synthetic nonwoven sheets.

The predictions for solvent ink in Fig. 3 were obtained from water permeability coefficient (K_w) and oil contact angle. The ranks of predicted results are the same as water permeability coefficient. Predicted results are close to the experimental data, but a couple of cases were off by a factor of two. If more accurate permeability and/or contact angle or pore size are used, predicted results might get closer to experimental data.

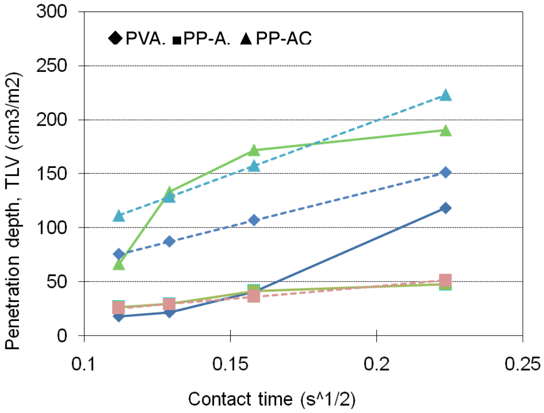

Figure 2. The absorption rates of aqueous ink Dotted lines; predicted, Solid lines; experimental

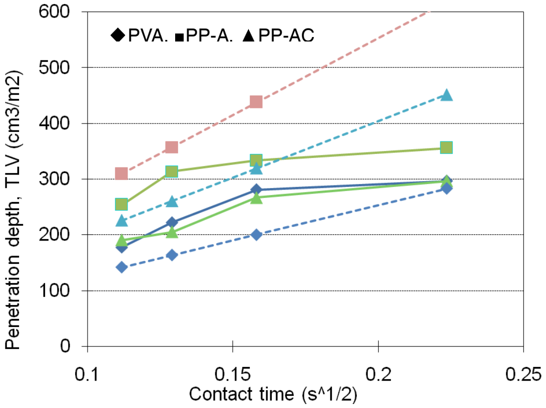

Figure 3. The absorption rates of solvent ink Dotted lines; predicted, Solid lines; experimental

Ink distribution on nonwoven sheets observed by CLSM

Figures 4-6 are the reconstructed images of the orthogonal projections for the nonwoven sheets printed with the aqueous (1) and solvent (2) inks. The bottom image is an XZ-plane which is sectioned virtually along yellow line, and the right image is an YZ-plane which is sectioned along white line. The inks were applied with the Bristow absorption wheel. The red ink emitted strong fluorescence at the excitation wavelength of 488 nm and is shown as red. The fibers did not emit any fluorescence at this wavelength.

For the hydrophilic PVA sheet, the aqueous ink spread over the surfaces of each fiber and evenly covered the PVA fibers of a concave shape as shown in Fig. 4. In contrast, for the solvent ink, the pigment particles in the ink were aggregated and were unevenly distributed on the PVA fibers. It seems that the pigment particles are not dispersed well in the solvent and the solvent evaporates rapidly, as a result the aggregate pigments are fixed on the fibers.

Figure 5 shows the results of the PP-A sheet. Similarly to previous results of the PVA sheet, the aqueous ink spread over and covered the surfaces of each fiber. The pigment particles in the solvent ink were more aggregated than the PVA sheet.

The pigment particles in solvent ink were also aggregated on the PP-AC sheet as shown in Fig. 6. Most of the aqueous inks tend to be distributed on the coated latex. This result supports the hypothesis that the aqueous ink penetrates in regions where there is hydrophilic latex in the PP-AC sheet. The cross section images show that the pigments in ink are captured by latex coating near the surface, and also show that the solvent ink pigments seem to be in a distinct layer. The latex may be able to “filter” the ink pigments because of the small pore size added to the system, shown in Fig. 1. It is not clear why the solvent inks seem to produce a distinct ink layer while the aqueous inks do not on PVA and PP-A sheets.

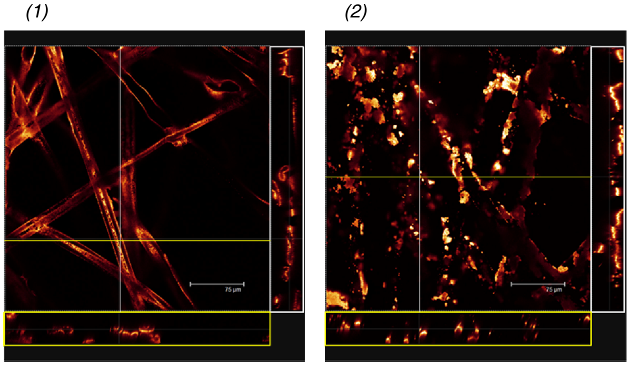

Figure 4. The reconstructed images of the orthogonal projections for the PVA sheet printed with the aqueous (1) and solvent (2) inks

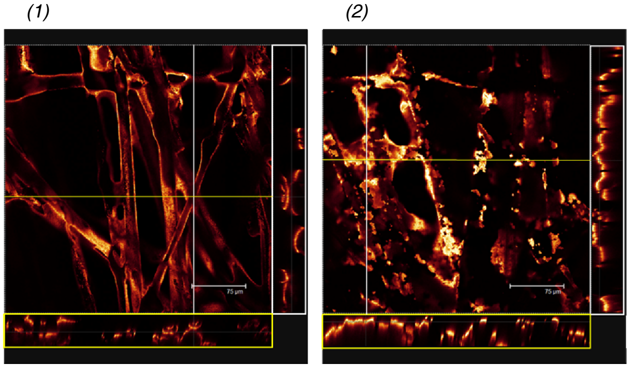

Figure 5. The reconstructed images of the orthogonal projections for the PP-A sheet printed with the aqueous (1) and solvent (2) inks

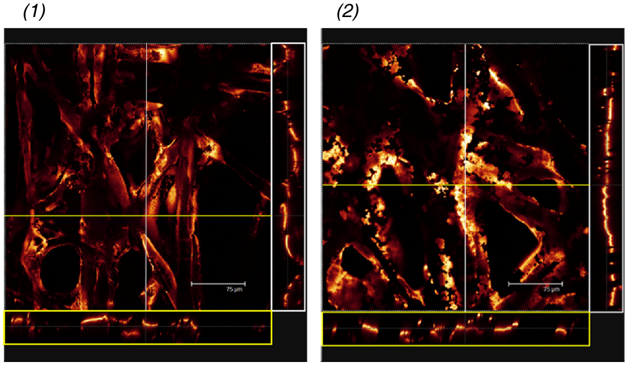

Figure 6. The reconstructed images of the orthogonal projections for the PP-AC sheet printed with the aqueous (1) and solvent (2) inks

Conclusion

The absorption rate into three substrates is predicted, within expected accuracy, by the Darcy’s law combined with the Laplace equation. A range of contact angles, permeabilies, pore sizes and void fractions are covered. The basic mechanism of capillary driven flow in porous media is confirmed. Pigments are captured in distinct layers for solvent inks. For aqueous inks, only the substrate coated with latex could capture pigments near the surface.

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