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SORPTION AND WEB EXPANSION MECHANISMS

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ABSTRACT

The application of water to the surface of a paper or board web (in printing, coating, surface sizing etc.) causes a decrease in MD tension and a rapid increase in web width. Both processes have complex time-dependences whose details have direct practical relevance. For example, in color offset printing the amount of CD expansion between printing units determines fan-out and other misregister problems.

No single traditional measurement can predict the amount of expansion or reveal its causes. We use KCL Vesikko and supplementary paper transmittance analysis to study the CD expansion and sorption dynamics for different papers and experimental conditions. With a new sorption model we can predict the experimentally observed movements of water inside paper.

INTRODUCTION

Moisture-induced dimensional changes and tension losses in a paper web can cause problems in printing, coating, surface sizing and on-line calendering processes. Expansion in the cross-machine direction (CD) is the main reason for misregister in multicolor printing. Softening of a paper web and expansion in the machine direction (MD) can lead to web tension variations and web breaks. In this paper, we report experimental methods and theoretical models designed to characterize the dimensional changes occurring after application of water to a paper surface. The objective is to resolve the essential moisture sorption and web expansion mechanisms and their characteristic time scales in experimental conditions typical of offset printing.

The modeling consists of two parts. Firstly, we develop a macroscopic model for liquid sorption that enables us to predict the time-dependent moisture profile within fiber layers after the application of liquid. Secondly, we feed this moisture profile into an expansion model that takes into account both fiber swelling and changes in the elastic modulus.

We concentrate on the expansion in the cross-machine direction that is relevant to fan-out in offset printing. In the machine direction, the hygroexpansive behavior of paper is more complex due to water-induced relaxation of the dried-in stresses.

EXPERIMENTAL

The experiments were conducted using the KCL Vesikko device [1,2], which provides direct information on rapid in-plane dimensional changes in paper. In KCL Vesikko, water is applied to a stationary paper web by a wetting roller attached to a moving sledge. Images of the bottom surface of the paper are taken through a glass table with a high-speed CCD camera. From the series of images obtained, the time-dependent expansion in cross-machine and machine directions can be determined by image correlation analysis. In addition to expansion, we measure the moisture penetration rates independently using optical methods.

The previous experimental studies using KCL Vesikko [2] have focused on general qualitative observations on the moisture-induced expansion. We now aim at quantitative analysis by restricting ourselves to papers with similar stock compositions (mainly mechanical pulp). This helps us to tie up the model parameters with real paper properties. Moreover, with combined paper transmittance analysis we can detect the amount of capillary water as a function of time. Knowing the total water intake, we get indirect information about the amount of absorbed water in the fibers.

The dynamic dimensional changes were measured in a climate-controlled room (23°C, 50% RH) with KCL Vesikko. The measurement time was 3.2 seconds (160 readings/second). The nip pressure was constant. Ten parallel tests were carried out for each trial point. The water intake by the papers was checked using a lithium tracer. Two water application levels were used, i.e., high (0 µm) and low (–40 µm) for newsprint and book paper, high (0 µm) and extra high (+60 µm) for wallpaper. The readings in parenthesis refer to the gap between the spreading and wetting rollers in KCL Vesikko that controls the film thickness. A trial point without water addition was also measured for each paper. All the results presented here are averages of the measurements done with three different web tensions. This is to smooth out the expansion curves and to facilitate interpretation of the results.

Our optical moisture penetration measurement is based on the gray levels of CCD camera images taken immediately after the water application process in KCL Vesikko. We take advantage of the fact that variations in the paper transmittance are mainly due to changes in the amount of pore water [3]. The shadows and reflections of the sledge also affect the gray levels. This is taken into account by subtracting the reference run performed without water and nip pressure.

MODELLING

Sorption model

The sorption model is macroscopic and one-dimensional. As compared for example to the Lucas–Washburn Equation [4], the main extensions of our new model are sorption into the fibers, inertial effects, and diffusion along the fibers (see Figure 1). The model gives the local fluid velocity, pressure, and

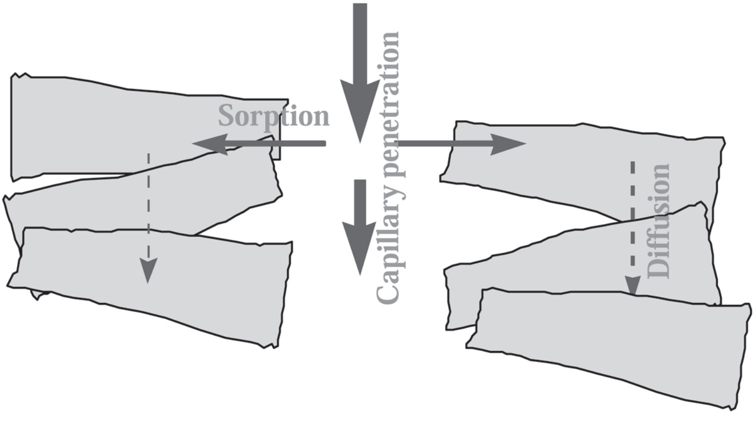

Figure 1 Moisture transport mechanisms included in the sorption model.

liquid density in fibers as a function of time. The details of the model are presented in Appendix.

There are various simplifications in the model: First, we assume that the liquid intake is given as a parameter and the paper surface roughness affects the intake but not the penetration. Moreover, the dynamic capillary pressure is assumed to be constant during the penetration. In the model, the capillary penetration stops when all liquid is within paper. This is a reasonable assumption in the case where the structural inhomogeneities of paper in the thickness direction can be neglected. Finally, the changes in the porosity or permeability due to the fiber swelling are not considered. In other words, we assume that the swelling is much slower than capillary penetration.

As only a small amount of water is applied in offset printing, capillary penetration stops very soon after the application. After that, moisture penetration takes place mainly by diffusion through fiber layers. As to the capillary flow, we modify the normal viscous force of the Navier-Stokes Equation [5] by taking it to be directly proportional to the product of viscosity and velocity. In this way, the equation is more appropriate for flow in a porous medium. The mass conservation is described by a continuity equation in which we include a sorption term that depends on the local moisture content within fibers. The dynamics of the moisture content inside fibrous matter is described by the standard diffusion equation coupled with a sorption term to the capillary water. Due to the sorption dynamics, neither the capillary liquid velocity nor the pressure gradient is constant over the paper thickness. The continuity equation can be used to derive an equation from which the pressure and velocity distributions can be obtained.

The model also includes a finite liquid layer on the sheet surface in which velocity and pressure gradient are constant. In the course of the simulation, it is necessary to follow the movements of both the top surface of liquid and the penetration front. After all liquid is within paper, the absorption of the pore water into fibers continues until the pores become empty. Simultaneously, the moisture is allowed to even out through the paper via diffusion.

Expansion model

In the expansion model, we divide the paper sheet into horizontal layers. Within each layer, the moisture content of fibers is obtained from the sorption model. The hydroexpansions and elastic moduli of the layers determine the total expansion.

Let us assume that for the *i*'th layer with local moisture content mc_i of fibers, the equilibrium expansion is $\varepsilon_h(mc_i)$. The moisture expansion of the whole sheet ε_{tot} would then correspond to the stress

$$\sigma_i = E_i(\varepsilon_{\mathrm{tot}} - \varepsilon_h(mc_i)) \tag{1}$$

within the i'th layer, where E_i is the elastic modulus. On the other hand, the sum of all layer stresses has to be equal to the external stress σ_{ext} applied to the paper in the corresponding direction:

$$\sigma_{ext} = \sum_i \sigma_i = \sum_i E_i(\varepsilon_{tot} - \varepsilon_h(mc_i)). \tag{2}$$

Experimental work [4] suggests roughly an exponential dependence of the elastic modulus on the local moisture content:

$$E = E_0 e^{-\gamma mc}. \tag{3}$$

Here the exponential factor γ is determined by the literature results [4]. In the cross machine direction, where there is no external stress, the above equations lead to the very simple form for the total expansion

$$\varepsilon_{tot} = \frac{\sum_i \varepsilon_h(mc_i) e^{-\gamma mc_i}}{\sum_i e^{-\gamma mc_i}}. \tag{4}$$

Note that the absolute value of the elastic modulus does not appear here.

In order to apply Equation 4, one still needs to define how the equilibrium expansion ε_h depends on the moisture content. In the cross-machine direction, we assume the linear dependence

$$\varepsilon_h(mc) = \varepsilon_{wet} \frac{mc - mc_{init}}{mc_{sat} - mc_{init}}, \tag{5}$$

where ε_{wet} is the standard wet expansion at the saturation moisture content mc_{sat} (mc_{init} is the initial moisture content).

The use of the standard hygroexpansivity obtained at low moisture contents [4] instead of Equation 5 would lead to an overestimate of the dynamic expansion. This means that the swelling caused by water vapor under equilibrium conditions differs from the one caused by liquid water under dynamical conditions. In the former case, all fiber material swells roughly at the same time whereas in the dynamical situation, the swelling is very inhomogeneous in the thickness direction. The standard wet expansion measurement captures better the dynamic response of the network.

COMPARISON WITH EXPERIMENTS

In addition to the liquid density and viscosity, the sorption model contains many parameters that characterize the paper properties. We determined all except one by independent measurements or literature estimates before the actual comparison of the model with paper transmittance analysis. Only the value of the diffusion constant $D = 2 \cdot 10^{-10}\ m^2/s$ for moisture within fibers was obtained as a part of this comparison. As explained previously, the transmittance analysis enabled us to follow the amount of inter-fiber pore water as a function of time.

Figure 2 shows the change in paper transmittance and the simulated amounts of pore water for newsprint. Not only the time-scales but also the shapes of the curves and how they depend on the water intake are very similar between the experiments and simulations. The final paper transmittance remains at a higher level mainly due to the absorbed water in the micropores of fiber cell walls. This explains the small deviations between the shapes of experimental and simulated curves.

Similar plots were obtained for book paper and wallpaper as well. The model predicted quite well the time it took for the fibers to absorb all inter-fiber pore water as shown in Figure 3. Therefore, the good agreement for all papers indicates that the model describes well the relevant sorption mechanisms.

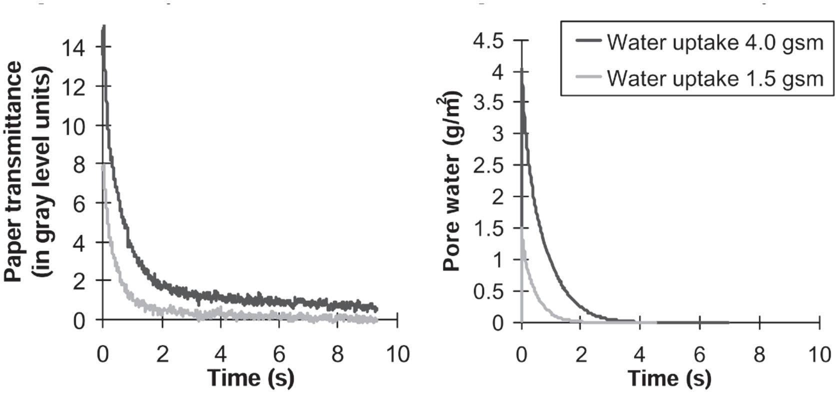

Figure 2 Paper transmittance measurements (left) and the amount of pore water according to the model (right) for newsprint (45 g/m^2) at high and low water intake levels.

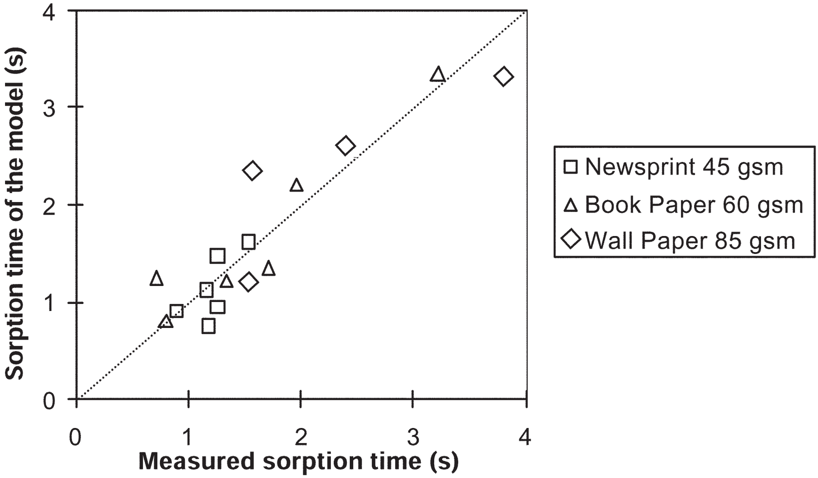

Figure 3 Comparison of the measured sorption time and that of the model. Sorption time is the time when the paper transmittance or the amount of pore water has decreased to one tenth of the maximum value. The data points include both uncalendered and calendered papers.

The comparison of the sorption rates for a fixed water intake showed clear differences between the papers. The main reason for these differences was the variation in the paper density. The sorption rate was highest for the dense newsprint and lowest for the bulky book paper.

According to the simulations, the capillary penetration is very fast. For the newsprint, the model predicts that a film of 4 g/m^2 of water penetrates into the inter-fiber pores within 20 ms. Figure 4 shows for the newsprint how the moisture evens out through the sheet after the capillary penetration has stopped. The moisture content profile in the fiber material immediately after the capillary penetration ($t = 19$ ms) is almost equal to the initial equilibrium distribution. According to Figure 2, the water absorption into fibers continues till about 3 seconds. However, the evening out of moisture through diffusion along fibers takes a longer time, roughly 10 seconds for the newsprint, as seen in Figure 4.

In Figure 5 we show the CD expansions obtained for the book paper. The model expansions include a constant factor 0.03% added to the moisture-induced expansion of Equation 4 representing the mechanical expansion

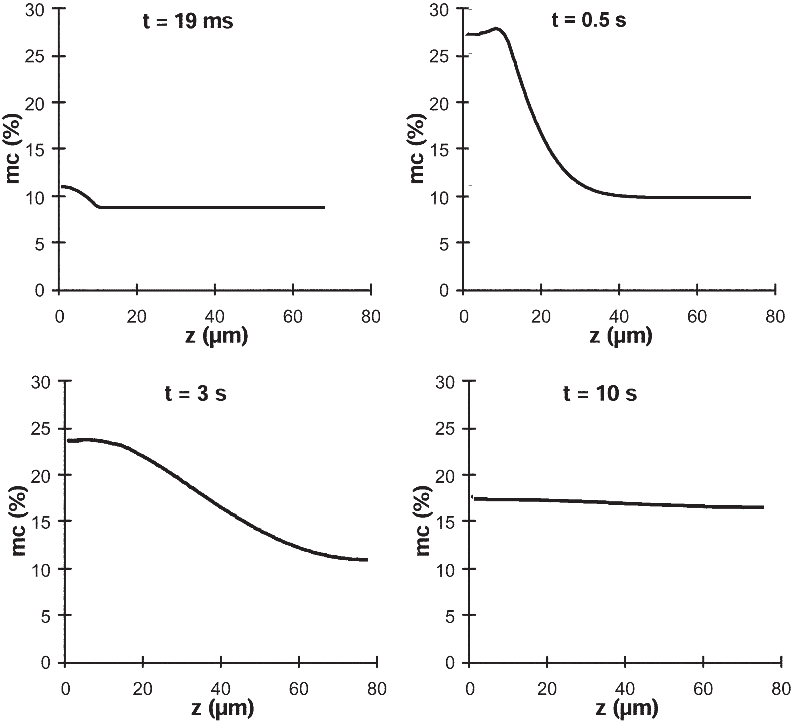

Figure 4 Predicted moisture content profiles in fiber material for newsprint (thickness direction) when the water intake is 4 g/m^2.

under the nip. We assume that the water application makes this mechanical expansion permanent.

For newsprint and wallpaper, the CD expansion is slightly overestimated by the model for large amounts of the applied water. This is not surprising as we assume the expansion dynamics to be equivalent for top and bottom paper layers. In reality, the tension from dry paper layers probably somewhat diminishes the expansivity of the wet layers during the swelling process. This reduces the final expansion level. Even with this shortcoming of the model, the simulations show that the whole CD expansion curve reflects the interplay of fiber sorption and moisture diffusion rather than any ongoing capillary transport of liquid.

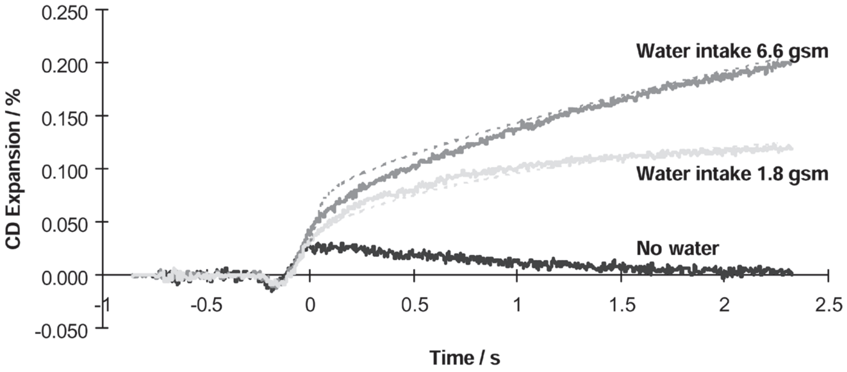

Figure 5 Expansion measurements (solid curves) and results of the model (dashed curves) for uncalendered book paper at high and low water intake levels and without water addition.

CONCLUSIONS

When applied to the typical conditions found in offset printing, our sorption model predicts that it takes only a few milliseconds for water to fill the topmost pores of an uncoated paper. This is followed by much slower water sorption into fibers, which lasts over a few seconds. Simultaneously, diffusion along the fiber material evens out the moisture through the sheet. When the fiber sorption has already ceased, the diffusion process still continues. It takes of the order of ten seconds for the moisture profile to even out in the thickness direction.

We found very good agreement between the experimental transmittance analysis and the simulated behavior of the amount of water inside inter-fiber pores. This indicates the reliability of the sorption model and gives a basis for other model predictions that cannot be tested experimentally by the present methods. Compared to the classical Lucas–Washburn Equation, the most essential extension of our sorption model is the coupling between pore water and the moisture in fiber material (together with diffusion). Inertial effects are negligible in offset printing.

The model shows that the sorption rate into fiber material increases with paper density. Thus, a given amount of water in the inter-fiber pores disappears fast if paper density is high. The total water intake may also depend on paper density.

The water intake determines the total wetted fiber surface area and thus the overall rate of water sorption into fibers. A large water intake not only leads to a high final level of CD expansion but also to a very fast initial expansion.

Our simple model for CD expansion explains quite well the effect of water intake observed experimentally with KCL Vesikko. In the model, the swelling effect is estimated by an ordinary wet expansion measurement instead of the standard hygroexpansivity for low moisture contents. The latter would lead to an overestimate of the dynamic expansion observed with KCL Vesikko. In MD direction, modeling is more difficult due to relaxation and creep.

In summary, we have a combination of experimental techniques and models that allow us to separate the various factors affecting the moisture-induced expansion of paper.

ACKNOWLEDGEMENTS

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APPENDIX: DETAILS ON THE SORPTION MODEL

Basic equations

We begin from the one-dimensional Navier–Stokes Equation [5]

$$\frac{\partial}{\partial t}\rho v = -\frac{\partial}{\partial z}\rho v^2 + \eta\frac{\partial^2 v}{\partial z^2} - \frac{\partial p}{\partial z} \tag{A1}$$

where ρ is the liquid density, η is the viscosity, v is the local fluid velocity, and p is the local pressure. Because the equation has been derived by requiring the conservation of momentum, it provides also the fundamentals for liquid in porous media. The only required modification concerns with the viscous force that in porous media is well approximated by taking it to be directly proportional to the product of viscosity and velocity. Taking this into account we obtain

$$\frac{\partial}{\partial t}\rho v = -\frac{\partial}{\partial z}\rho v^2 - \frac{\eta}{K}v - \frac{\partial p}{\partial z} \tag{A2}$$

where K is the permeability constant. Note that if the first two inertial terms were neglected, one would be left with Darcy's law [4]

$$v = -\frac{K}{\eta}\frac{\partial p}{\partial z}. \tag{A3}$$

In porous material like paper, fibers absorb liquid from capillaries which needs to be taken into account in writing the final equations. By denoting the local density of liquid in fibers by ξ, we can describe the sorption and diffusion dynamics by the equation

$$\frac{\partial \zeta}{\partial t} = \mu(\zeta_{\mathrm{s}} - \zeta) + \frac{\partial}{\partial z}\left(D\frac{\partial \zeta}{\partial z}\right), \tag{A4}$$

where ζ_s is the saturation density, μ is the mass transfer coefficient, and D is the diffusion constant for the moisture diffusion along fibers. Neglecting the diffusion ($D = 0$) and assuming the initial condition $\zeta(0) = 0$, Equation A4 implies an exponential increase of the fiber liquid density

$$\zeta(t) = \zeta_s(1 - e^{-\mu t}). \tag{A5}$$

In other words, the characteristic time for sorption is $1/\mu$. The exponential time-dependence agrees well with experimentally observed swelling of individual fibers [6,7].

The Navier–Stokes Equation is combined with the equation of continuity [5]

$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial z}\rho v \tag{A6}$$

which guarantees the conservation of mass for the flow within the pores. However, this equation does not take into account the sorption into fibers which requires an additional term in the equation. Neglecting the diffusion, the change $\Delta\zeta$ of the local fiber liquid density within a thin horizontal layer of volume V corresponds to the mass $V(1-\phi)\Delta\zeta$ absorbed, where ϕ is the network porosity. On the other hand, the resulting change in the pore liquid density within the same layer is $-(1-\phi)\Delta\zeta/\phi$. This implies that the sorption described by Equation A4 can be taken into account by rewriting the continuity equation as

$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial z}\rho v - \frac{(1-\phi)}{\phi}\mu(\zeta_s - \zeta). \tag{A7}$$

The important parameter ζ_s appearing in Equations A4 and A7 can be obtained by measuring the fiber saturation point (FSP):

$$\zeta_s = \frac{FSP\,\rho_{paper}}{(1-\phi)}. \tag{A8}$$

Here ρ_{paper} is the dry paper density.

Due to the fiber sorption, neither the liquid velocity nor the pressure gradient is constant over the porous material. The continuity Equation A7 can be used to derive an equation from which the pressure distribution can be obtained. First we assume that the capillaries are full of incompressible liquid with constant density ρ. In this case Equation A7 becomes

$$\rho\frac{\partial v}{\partial z} = -\frac{(1-\phi)}{\phi}\mu(\zeta_s - \zeta) \tag{A9}$$

and Equation A2 can be rewritten as

$$\rho \frac{\partial v}{\partial t} = 2v \frac{(1-\phi)}{\phi} \mu(\zeta_s - \zeta) - \frac{\eta}{K} v - \frac{\partial p}{\partial z} \cdot \tag{A10}$$

Differentiating this equation with respect to z and making again use of Equation A9 one obtains

$$\frac{\partial^2 p}{\partial z^2} = -\frac{(1-\phi)}{\phi} \mu \left[\frac{\partial \zeta}{\partial t} + \frac{2(1-\phi)}{\rho\phi} \mu(\zeta_s - \zeta)^2 + 2v \frac{\partial \zeta}{\partial z} - \frac{\eta}{K\rho} (\zeta_s - \zeta) \right] \tag{A11}$$

where the derivate of ζ with respect to the time t is obtainable from Equation A4. Equations A10 and A11 form the basis of the model so that Equation A10 is used to calculate the velocity distribution and Equation A11 the pressure distribution in the region where the capillaries are filled with liquid.

The model also includes a finite liquid layer on the paper surface whose initial thickness is a given parameter (relates to the water intake). In this layer, the velocity u and the pressure gradient are constant (refer to Equation A6) with simple coupling

$$\rho \frac{\partial u}{\partial t} = -\frac{\partial p}{\partial z} \cdot \tag{A12}$$

The boundary condition for the velocities at the paper top surface $z = 0$ reads

$$u = \phi v(z = 0) \text{ for all } t. \tag{A13}$$

In the course of the simulation, it is necessary to follow the movements of both the top surface of liquid and the penetration front. The capillary penetration stops when either the liquid top surface meets the paper surface or the penetration front comes to the bottom surface of paper.

After the capillary penetration has stopped, we assume that the absorption of the pore water into fibers continues until the pores become empty. This means that the pore liquid density ρ does not remain everywhere constant any longer. It would be natural to expect it to vary according to equation

$$\frac{\partial \rho}{\partial t} = -\frac{(1-\phi)}{\phi} \mu(\zeta_s - \zeta) \frac{\rho}{\rho_0} \tag{A14}$$

where ρ_0 is the initial density with fully filled inter-fiber pores. Equation

A14 describes the fact that as the local pores become partly empty (i.e., ρ decreases), there is less contact area between the liquid and fiber material which retards the sorption rate. However, we take also into account the tendency of the liquid to move during sorption so that the film does not break (especially if the liquid film is thick). This is done by combining Equation A14 with adjustments of local densities so that due to the overall sorption, the pore liquid density effectively varies only near the upper film edge. Although this refinement of the model is a physical one, we found its effect to be rather small.

The decrease in the pore liquid density causes a modification in the equation for the fiber liquid density as well. The absorption and diffusion after the capillary penetration is described by the equation

$$\frac{\partial \xi}{\partial t} = \mu(\zeta_s - \zeta)\frac{\rho}{\rho_0} + \frac{\partial}{\partial \mathrm{z}}\left(D\frac{\partial \zeta}{\partial z}\right)\cdot \tag{A15}$$

Numerical techniques

Because of the nonlinearity of the equations describing the capillary penetration and sorption processes, only a numerical solution of the model dynamics is possible. For this purpose, we discretize both space (typical lattice unit 1 μm) and time and look for numerically stable iteration schemes.

During the capillary penetration, the system of equations is very complex. The time development of the local fluid velocity is obtained by the so called implicit Euler method [8] for which the iteration scheme can be obtained easily from Equation A10. Here the time step has to be very small (0.025 ms) but as pointed out previously, the capillary penetration stops quite soon and the total iteration time remains reasonable. Equation A11 is discretized with the boundary conditions that $p = 0$ at the penetration front and $p = p_{app} + p_c$ at the top of liquid, where p_{app} is the applied pressure and p_c is the dynamical capillary pressure. The calculation of the whole pressure distribution involves the solution of a linear tridiagonal matrix equation at each time step but there exist fast numerical methods for this purpose [8].

After the capillary penetration has stopped, we need to consider only Equations A14 and A15 describing the sorption and diffusion processes. As these processes continue for quite a long time, the numerical integration is speeded up by applying the so-called Crank–Nicolson iteration scheme [8] that is stable for all time steps. In practice, we take the time step to be 0.05 s so that the truncation error does not become too large.

Transcription of Discussion

SORPTION AND WEB EXPANSION MECHANISMS

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Theo van de Ven Paprican, McGill University

I have two questions, if I may. The first is related to your model. You take inertia effects into account, are they really important?

Jukka Ketoja

Not for these amounts of liquid. If you don't have any pressure peaks, the inertial effects seem not play any big role. The main contribution to inertia comes from the film above the paper, not from the liquid within the pores, because you have to get that film moving as well. If the film gets thicker, then the inertial terms become important. Or if you have a high pressure peak like in blade coating, then the inertial effects could be important, but not for offset printing.

Theo van de Ven

If your fibres were treated by internal or surface sizing agents, how would that affect the time scales of absorption?

Jukka Ketoja

Of course, that would affect the capillary penetration so that would be completely different, but I don't think the sizing would affect much the absorption into fibres or the diffusion.

Peter Herdman Arjo Wiggins R & D

I have a small question myself, in the expansion curves that you showed (Figure 5, Page 1365, Volume 2) with different applications of water there was also a further curve at the bottom with no water applied and there seemed to be a little kick in that. What was actually going on to give that bit of experimental noise, I assume it was noise?

Jukka Ketoja

It is really the artefact coming from the moving roll. Probably the paper bends and gives you a negative expansion. That is the only thing I can think of.

Peter Herdman

So you just sent the sledge and roller along dry for this. Another question if I may. For the cross correlation technique with the CCD cameras do you need an image on the paper or is it just the paper's structure itself which is seen by the camera in order to get these impressions.

Jukka Ketoja

The paper structure itself is enough and you can maybe add contrast by some colouring.

Shri Ramaswamy University of Minnesota

The way I understand it as the capillary flow is so fast you are assuming that your capillaries and pores are immediately filled with liquid, correct. So you did not simulate the distribution of moisture profile within the capillaries?

Jukka Ketoja

No, we assume there is a straight penetration front moving.

Shri Ramaswamy

So this means that instantaneously the pores are filled with liquid it is only the fibre absorption that you are studying.

Jukka Ketoja

Of course, in the end it is only the absorption and diffusion processes that matter. However, the model also describes how the instantaneous penetration takes place. We didn't know how fast this process is. Now we know that better.

Shri Ramaswamy

The rate of absorbtion of the moisture or the absorbtion coefficient that you have determined, how does it compare with literature work on absorption rates?

Jukka Ketoja

I am not familiar with all the references as I am a newcomer into the field. Perhaps I can show you the numbers I used, you can then work out the comparison yourself. I take into account the relative bonded area which is not contacted with liquid in estimating the absorption rate.

Byron Jordan Paprican

I have a question about the way you are using the optics to measure the amount of water, because the water is decreasing the scattering coefficient and so you are getting your improved transmittance in proportion to the reduction of scattering coefficient. At the point here where the water is still propagating through the sheet, you have for example in your graph (Figure 2, Page 1362, Volume 2) at half a second roughly half of the sheet is wet and half is still more or less dry and you have a layered structure of a more translucent layer over a more opaque layer and this is quite different from the situation where you have a uniform structure that is all filled with water and I am not sure that in these transient situations the relationship you are using is as reliable or perhaps a slightly different model could be used for this.

Jukka Ketoja

Yes I understand your point and I would have shared that before actually doing these comparisons. The fact that the experimental results compare so well with the model has given us confidence that our interpretation of the experimental results is correct. In principle, the things you pointed out are real issues but probably not so critical as one might think.

Discussion

Kari Ebeling UPM-Kymmene Corporation

Could you speculate how the flocks behave at the surface of the paper when they have been wetted. They have been compressed through wet pressing and if you have a breaker stack calendering in the dryer part further densification of the flocs has occurred. As soon as these flocs see some water they pop up. How does the opening up of the surface flocs affect the frontier of the water penetration?

Jukka Ketoja

We come here to the point of how much the network inhomogeneity affects the absorption process. Of course, the inhomogeneity is there and it is real. I cannot give any wise answers to the question; we haven't really considered that at all. Perhaps it is best that I don't comment on that at the moment.

Lars Ödberg AssiDomän

The diffusion into the fibres was dependent on the density of the sheet, should that not be a fibre property really.

Jukka Ketoja

It is actually both. The density dependence is a bit hidden here due to the way we have parameterised the system, but one place where the density is hidden is the saturation density. If you have denser paper (assuming a constant fibre saturation point), then the liquid saturation density in these equations is larger. In other words, when you have more fibre material, there is more reservoir where the water can go in and that increases the saturation density.

Heinrich Baumgarten TU Dresden

According to your model I understood that you guess that if one gram of water goes into the fibre wall then you have swelling of 1 mm in fibre wall thickness. If I look at your Figure 4 (Page 1364) you find roughly an increase in thickness in the same amount as you would expect when the paper takes up 4 grams per square meter of water, so the big increase is of course in thickness in a range of up to 10%. How did you take account of this in your model? If you have calendered it and compressed it then the thickness increase would be even more.

Jukka Ketoja

We didn't consider the thickness increase. The coupling to the thickness direction was not included in the model and certainly that can lead to some deviations from the experimental result that we actually had. So that is a good point.

Jean-Marie Serra-Tosio EFPG

How can you take into account the difference in the thickness of the paper in your model, with different layers with expansions. In newspaper we have some variation due to the formation and the weight.

Jukka Ketoja

I don't take that into account at all, so in this sense it is very crude with description, but it still surprisingly well describes the qualitative features of the expansion.

Jean-Marie Serra-Tosio

We have some difference to your model because there is some difference with the orientation of the fibres inside newspaper?

Jukka Ketoja

No not really. That effect would come in through the elastic modulus.

Jean-Marie Serra-Tosio

If you try to put two real layers without bonding, a double paper, to see the influence, would your model work? I think that the division of steam, the layer of water and the tension of the evaporation, can change the diffusion and absorption.

Jukka Ketoja

We would like to develop the expansion model. At the moment, we are more pleased with the absorption model that seems to be sufficient for this type of investigations, but the expansion model has to developed from here in order to describe all the features you have described.