

REVIEW OF SURFACE APPLICATION

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ABSTRACT

Surface application has gained more and more popularity as a means of increasing the quality of paper and board. In its broadest sense, surface application covers everything from surface sizing to extrusion coating, but this review will concentrate on surface sizing and pigment coating, i.e. processes taking place as an integrated part of the paper manufacture. Because the goals of the surface treatment are different and depending on the quality of the paper desired, the review will cover our present fundamental understanding of the processes themselves. The presentation will start with a description of the water or liquid penetration in paper. Then the mechanics of various blade coating processes and the liquid transport in blade coaters will be explained. Last will come a presentation of the size press and new equipment for surface sizing.

INTRODUCTION

Surface application has traditionally been a way of increasing the quality of the paper. The term quality is however as broad as the area of surface application, and the type of surface applicator used. Traditionally surface application can be divided into at least three different areas, surface sizing, pigment coating, and non-pigmented coatings.

In surface sizing, the main goal is to increase the surface strength, and sometimes also the internal strength of the paper. This has traditionally been done with starch, on-machine with a size-press. The development of the paper-machines towards higher speeds has however shown the limitations of the size presses and other developments has come into use during the last decade.

The main reason for making pigment coating is generally to improve the printing characteristics of the paper, and/or to improve its appearance by enhancing optical properties as for example gloss, whiteness, and opacity. The printing properties is enhanced through the smaller and more even pore structure which results from the coating layer. Pigment coating can be carried out on-machine or off-machine. In both cases the most popular equipment are the blade coaters.

In this context, non-pigmented coating describes varying converting processes like extrusion coating, siliconization, laminating and other processes aimed at giving functional properties, i.e. barriers for gases and liquids, non-adhesion, resistance towards grease and so on. These converting processes are carried out with roll coaters, air knife coaters, and specialized equipment like extruders and laminators.

Surface application is thus a very extensive subject. In this context, however, will only be dealt with the first two of the concepts described above, i.e. surface sizing and pigment coating. An attempt will be made to give an fundamental understanding of the processes, and a division between sizing and coating will not be made. For all kinds of surface applications, regardless of equipment, it is essential to have knowledge of the transport of liquid into paper, and how it is influenced by the characteristics of the liquid and of the paper itself. The time in the process as well as the pressure differs from process to process, and is also of importance for

the transport of liquid. This review will therefore start with a presentation of the liquid transport into paper, how it is dependent on the time, pressure, paper characteristics, and liquid characteristics. The fundamental mechanics for the blade coating and size-press coating processes will then be described. The liquid transport in the different processes will also be pointed out.

THE WATER TRANSPORT IN PAPER

In order for a liquid transport to take place, there must be a driving potential. Examples of driving potentials are capillary pressure, external pressure, vapour pressure, concentration gradients, and temperature gradients. Several of these can be present at the same time, which makes the transport mechanism complex.

The classical liquid transport model is based on the work by Lucas (1) and Washburn (2). In the model is assumed that the liquid penetrates in an open pore with a constant pore radius. The capillary pressure is expressed with the Young-Laplace equation, and is opposed by the pressure drop due to liquid flow, as expressed by the Poisseulles equation. If these are combined, and the external pressure is taken into account, the result is the classical capillary transport model of Washburn:

$$l = \sqrt{\frac{2r\gamma\cos\theta + p_E r^2}{4\eta}} \sqrt{t} \quad (1)$$

where r is the capillary radius, γ the surface tension of the liquid, θ the contact angle between the liquid and the solid, p_E the external pressure, and η the viscosity.

However, there is also a vapour phase above the liquid surface. The concentration gradient of the vapour phase can also be the cause of liquid transport. The relationship between the rate of concentration change and the concentration gradient is given by Fick's second law. If the diffusion coefficient is constant the following expression is obtained (3):

$$\frac{M_t}{M_\infty} = E \sim \sqrt{\frac{Dt}{L_{1/2}^2}} \quad (2)$$

In the equation, M_t denotes the total amount of diffusing substance at time t , M_∞ the corresponding quantity after infinite time, E the fractional degree of saturation, D the diffusion coefficient and $L_{1/2}$ the half-thickness of the specimen.

In paper, the following four transport mechanisms has been suggested by Nissan (4):

- Diffusion transport of vapour in the pores.
- Capillary transport of water in the pores
- Surface diffusion in the pores
- Water transport through the fibres.

Different authors (5-7) have had different opinions of which of these are the most important. Bristow (8) was able to measure the water penetration at short times. He obtained a non-linearity between the sorption values and the square-root of time, which does not correspond to the Washburn equation (eq. 1). This was explained by the concept wetting delay, i.e. a wetting time exists before the liquid starts to penetrate. After this the water sorption takes place according to the Washburn equation. Several authors (9-16) have accepted the concept wetting delay, and tried to explain it. However, sorption curves on a linear scale (17) did not support the wetting delay theory. It was also shown by Eklund and Salminen (18) that the concept wetting delay was misleading. This also seems to agree with the present opinion of other researchers (19-21). The non-linearity found thus points to that the Washburn equation does not explain the water penetration in paper in an adequate way.

In an extensive work by Salminen (22) the differences between the classical capillary transport model and the actual water penetration model was suggested to be due to the omission of the following factors:

- Dynamic character of the capillary pressure
- Counter pressure of air
- Expansion of the fibre network
- Liquid transport through the vapour phase
- External pressure

In the classical theory, it is assumed that the contact angle is independent of time and penetration velocity. However, the dynamic capillary pressure is probably influenced by molecular processes at the wetting zone and ahead of the liquid front, Fig. 1.

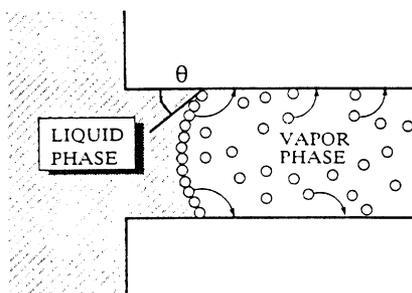


Fig. 1. Schematic view of the liquid front in a paper pore.

This means that we can have an effect of penetration velocity on the advancing liquid front and/or we have interactions between water vapour molecules and fibre wall ahead of the front. The different situations has been discussed by several authors (7, 16, 18, 23-27).

During dynamic wetting, air could be trapped in the system. This air could either be compressed or it is removed. Salminen (22) concluded that compression of the air was unimportant for capillary penetration but that the pressure penetration rate could be influenced by the counter pressure of air. The most probable situation, however was that air is transported away. For this situation an equation was derived:

$$l = \frac{\sqrt{k_p^2 r^8 + 16\eta(p_E r^2 + 2\gamma \cos\theta)t - k_p r^4}}{8\eta} \quad (3)$$

where k_T is a constant characterizing the pressure drop due to air transport in the system. If the pressure drop is low this equation transforms to the Washburn equation.

When the paper comes into contact with water it expands. This expansion has been studied by for example Skowronski, Bichard and Lepoutre (28-31) who has showed that this swelling is closely linked with the redistribution of internal stresses originating from the preceding papermaking stages. The expansion of the fibre network will however influence the water transport rate in two different ways; it will have an effect on the transport velocity of the liquid front, and it will have an effect on the cross section of the penetrating water front.

Liquid transport through vapour phase is another possible transport mechanism. A review of the studies made on steady state water vapor transport in paper has been presented by Corte (32) It is generally recognized that surface diffusion plays an important role in this process. The adsorption of water vapour on cellulose is the main mechanism that controls the movement of water vapour through paper. Osmotic pressure induced water transport has also been discussed in the literature (33-37). Scallan concluded in a review (36) that the osmotic pressure differential between the fibre wall and the external medium may be overcome only by additional water being drawn into the cell wall.

One of the most overlooked potentials for water transport is the external pressure. This is surprising, because the wetting of paper in surface application as well as in printing, takes more often than not place under an external pressure. In this case the driving potential is the sum of the dynamic capillary pressure and external pressure. An increased penetration velocity caused by an increased external pressure will increase the dynamic contact angle between the fibre wall and liquid, and hence cause a decrease in the dynamic capillary pressure. The importance of the molecular interactions ahead of the liquid front is also likely to be reduced during rapid pressure penetration. At high external pressure, the transport

between external pressure, a comparatively constant capillary pressure and the pressure drop due to liquid flow. When the external pressure increases, the importance of surface chemistry related forces diminishes. It can be suggested that the importance of the factors which complicates the capillary transport theory and which are described above, are diminished when the external pressure is increased. The effect of the expansion of the fibre network is lower during the rapid pressure penetration. Water is primarily transported through the pores, and the effect of fibre sorption and diffusion is diminished. Consequently, the power of the rate function is determined by the pressure drop due to liquid flow, and the penetration volume will be proportional to the square root of contact time. At a high enough external pressure, the velocity controlling variables are the viscosity of the liquid and the pore structure of the paper.

Liquid characteristics of importance for the transport rate

The transport rate of liquid in paper under conditions which are prevailing in the actual processes has been very little studied. Typical for these processes is a short contact time and elevated pressure. The influence of external pressure is very clearly shown in a study by Eklund and Salminen (38). From Fig. 2 can clearly be seen that predictions made at zero external pres-

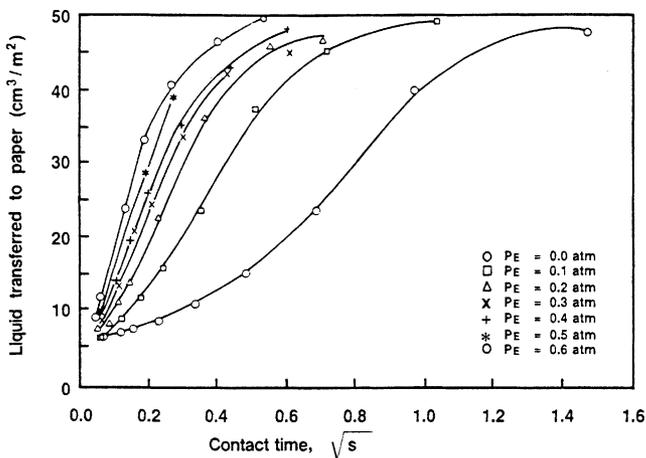


Fig. 2. The influence of external pressure on water transport.

sure has very little to do with the real conditions. It can be seen, as also was indicated above, that the influence of surface chemical characteristics are decreased when the pressure is increased. The transport rate is primarily determined by the pressure balance between the relatively constant driving forces and the pressure drop due to liquid flow. This corresponds to a straight line on a square root scale.

It can also be seen that the penetration at low or zero external pressure is parabolic on a square root of time scale, i.e. it does not fullfil the Washburn equation. Instead, results from measurements of different papers indicate that the zero pressure liquid transport is linearly dependent on contact time, Fig. 3.

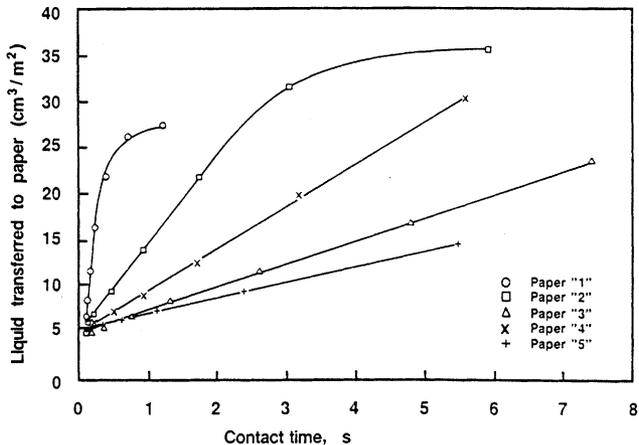


Fig. 3. Zero pressure water transport in five different papers.

In Fig. 4 is the influence of temperature on the zero pressure penetration seen. The great influence of temperature can only be explained by the increased vapour pressure on the capillary pressure determining processes ahead of the liquid front, and on the rate of diffusion. If the hydrophobicity is decreased, the influence of the temperature is diminished as can clearly be seen from Fig. 5, It is obvious that the capillary pressure determining factors are of less importance in this case.

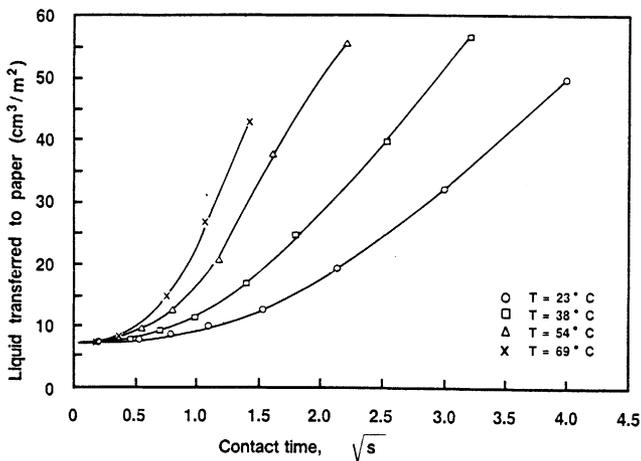


Fig. 4. Influence of water temperature on zero pressure water transport in hydrophobic groundwater containing paper.

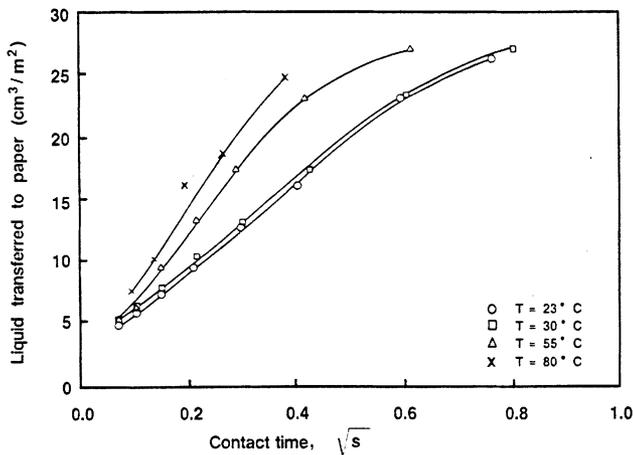


Fig. 5. Influence of water temperature on zero pressure water transport in hydrophilic groundwater containing paper

If the pressure is increased to 0,5 atm. the influence of temperature is minor, and can be explained by the influence of temperature on the viscosity.

Studies of the influence of viscosity on the penetration (5, 7, 22) have indicated that viscosity has no influence on the penetration rate at atmospheric pressure, whereas at elevated pressures it was found (22) that the penetration rate is approximately proportional to the square root of the inverse viscosity:

$$K \sim \sqrt{\frac{1}{\eta}} \quad (4)$$

An addition of surfactant to the liquid did not affect the sorption rate at zero or elevated pressures, if the amount of the surfactant (sodium dodecyl sulphate) was below the critical micelle concentration. This could be explained by the only minor influence of the surfactants on the dynamic surface tension (surface tension measured at 2,5 ms).

If a liquid (isopropanol) was blended with the water the dynamic and the equilibrium surface tension was equal, indicating that there was no aging effects in this case. In this case the transport rate was increased with increasing amount of isopropanol, Fig. 6.

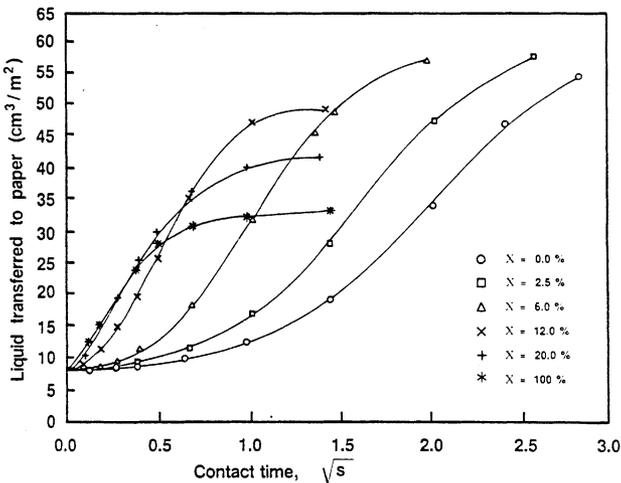


Fig. 6. Zero pressure transport of isopropanol solutions.

At increased pressures, however, there was no influence of the surface tension of the liquids on the penetration rate. The differences which occurs could be explained by differences in viscosity.

The salt concentration seems to have an influence on the zero pressure transport but its is of no importance for the pressure transport.

The influence of the liquid characteristics on the penetration rate at zero pressure and at elevated pressure could then be summarized as follows:

	0 atm	0,5 atm
Increase in temperature	++	0
Increase in viscosity	0	--
Increase in dynamic surface tension	--	0
Increase in salt concentration	--	0
Increase in pH	0	0

In this context it must be pointed out that some of the factors mentioned in the table also have an indirect influence on the pressure penetration rate because of their influence on viscosity.

The influence of paper characteristics on the water transport.

The liquid transport can be influenced by structural and chemical modifications of the fibre matrix. Factors primarily affecting the structure, and which can be of interest for the paper-maker from the point of view of surface application, is the influence of mechanical pressure on the paper, grammage, beating, and calendering. The surface chemical factors of importance are primarily the hydrofobicity of the paper and the moisture content.

An increasing mechanical pressure acting on the paper will decrease the surface smoothness of the paper, and will decrease the initial uptake of liquid, Fig 7. A compression of the paper will also decrease the apparent pore radius and thereby the transport rate. The void volume is also diminished.

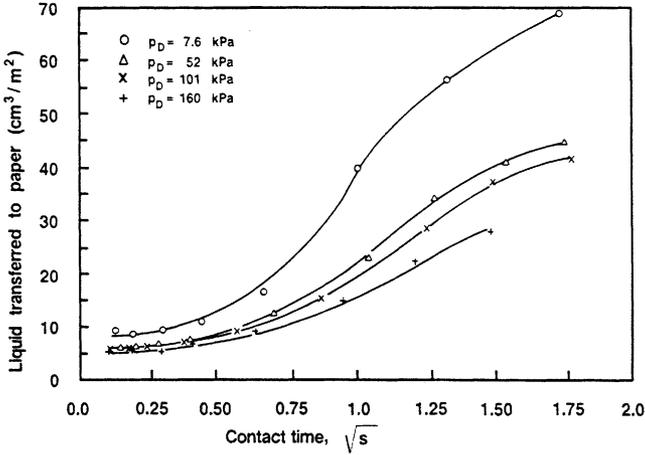


Fig. 7. Influence of mechanical pressure exerted by the liquid applicator on the zero pressure water transport in 38 g/m² paper.

The classical water transport model suggests that capillary transport of a liquid in a pore system is not dependent on the thickness of the pore system. In practice, however, the counterpressure of air ahead of the liquid front, and the response of the pore structure to mechanical pressure may be affected by the grammage of paper. The pore size distribution and the pore size fractions could also be influenced by the grammage. Experiments with papers of different grammage (22), showed however, that the water transport rate at zero and elevated pressures was not influenced by the grammage.

It has been shown (38) that the zero pressure water sorption is significantly decreased if the beating degree is increased from 25 to 69 °SR. This will probably also be the case for elevated pressures. In practice, however, the beating is changed only to a minor degree. It can be deduced from Fig. 8 that a comparatively small change in beating degree, in this case caused by changing the freeness of the groundwood fraction from 29 to 41 °CSF in a groundwood sheet containing 50% groundwood, did not affect the water transport at zero or elevated pressure.

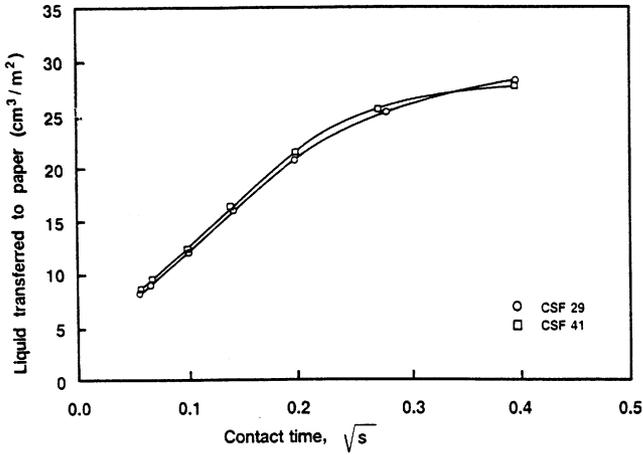


Fig. 8. Influence of the freeness of the groundwood fraction on the pressure penetration (0,5 atm)

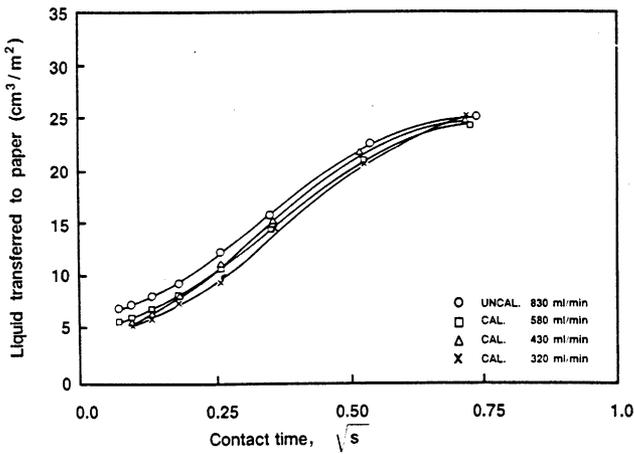


Fig. 9. Influence of calendering and surface roughness values (Bendtsen) on capillary transport.

Calendering will have a smoothing effect on the sheet and by that decrease the initial liquid uptake. The differences in the liquid transport are however significant only at contact times below 0,1 s where the liquid uptake is strongly dependent on the initial smoothness. At longer contact times, the expansion of the fibre matrix levels out the original differences in the dry pore system, Fig. 9.

In rapid pressure penetration, it seems like the pore structure differences of the dry papers are not completely eliminated by the expansion, Fig 10.

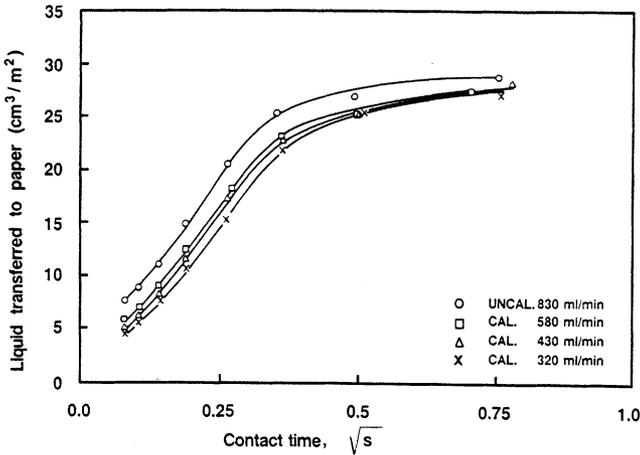


Fig. 10. Influence of calendering and surface roughness (Bendtsen) on pressure penetration (0,5 atm)

That increasing hydrophobicity of the paper decreased the water sorption under no external pressure is indicated by the several thousand references on the subject of sizing, and is common knowledge, and is also indicated in Fig. 3. for some different papers, and in Fig. 11 for the same kind of paper with different amounts of rosin size.

The influence of hydrophobicity on the penetration under pressure has however not been studied extensively. Salminen (22) shows that the transport rate is increased considerably when

the pressure is increased, but that there even at a pressure of 0,5 atm still is an influence of the hydrophobity on the liquid uptake, which could not be explained by structure differences, because all the papers in his study had virtually the same pore structure. The results are presented in Fig. 12.

A possible explanation for the differences is that the amount of pores accessible to pressure penetration will decrease with increasing hydrophobity. The reason is that the external pressure needed to overcome the capillary pressure is increased when the hydrophobity (or contact angle between the pore surface and the liquid) is increased). It is also interesting to note that the hydrophobic probably also protect the bonding areas in the paper by increasing the pressure needed to reach the bond with the distance to the bond. This is a consequence of the diminishing distance between the hydrophobic walls. The bond protection seems to be the main reason to make the sheet hydrophobic before it is surface sized. The surface size uptake will probably be influenced only to a minor degree by hydrophobic sizing because of the high pressures prevailing in the process.

An interesting factor for the water uptake is the moisture content of the web. Studies (22) of the zero pressure water transport indicate that an increasing moisture content increase the water transport in hydrophilic paper, but decrease it in hydrophobic. This indicates that the water transport is capillary pressure driven for hydrophilic paper but diffusion driven for hydrophobic. When the driving potential is diffusion it is of course diminished by a decreased difference in moisture between the fibre and the liquid. For pressure penetration, on the other hand, the influence of moisture content on the penetration rate is negligible, or can be explained by the effect of the moisture content on the structure of the paper.

The water transport in a paper is thus dependent on capillary forces and diffusion. The diffusion seems to be the main transport mechanism for the transport of water into the fibre wall. It seems also probable that diffusion is the main transport mechanism for zero pressure penetration in hydrophobic paper. In pressure penetration, and for hydrophilic sheets, capillary transport is generally the main transport mechanism, the exception being very dense sheets.

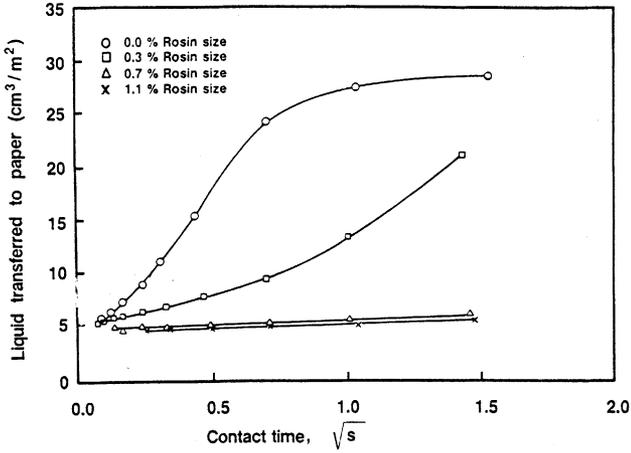


Fig. 11. Influence of rosin sizing on zero pressure water transport.

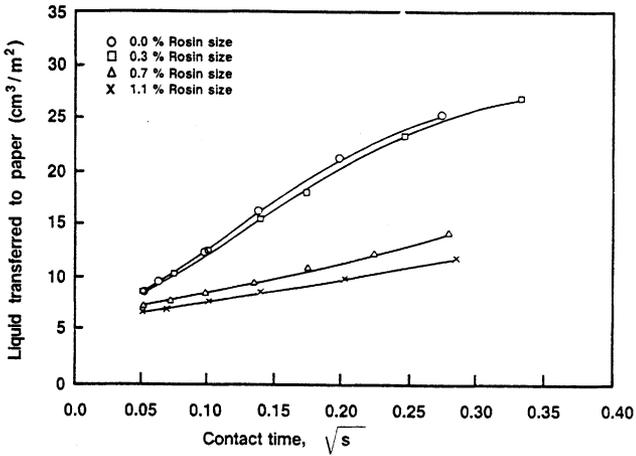


Fig. 12. Influence of rosin sizing on pressure penetration (0,5 atm) of water into base paper for coating

THE BLADE COATING PROCESS

Blade coating is today the most important method for surface application of paper and board. There are several reasons for this. The speed limit for blade coating has not been reached, and is far above the highest paper machine speeds used. The solids content of the size or coating color can be high, thus diminishing drying requirement. A high smoothness of the paper is obtained. The process is easy to control and it is easy to apply different coat weights. Blade coaters are mostly used for pigment coating, but the increased difficulties with the size presses with increased speeds has caused a shift towards blade coaters and blade coater-like developments for surface sizing as well.

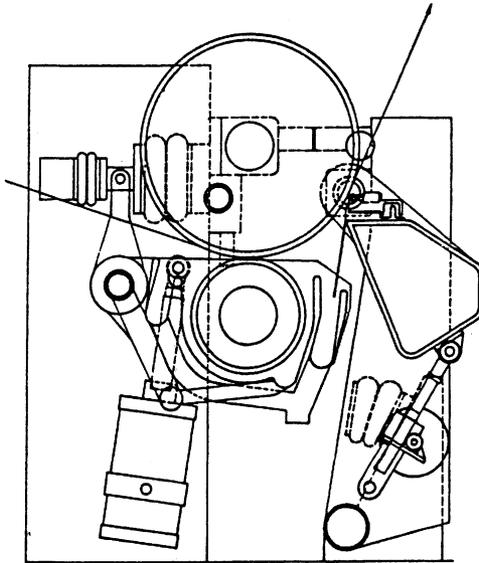


Fig. 13. Blade coater

Through the years several different blade coaters have been developed. Most of them, however, work according to the same principles; a coating color (or size) is applied with some kind of applicator, after which the coating layer is evened out and regulated with a flexible steel blade. The blade coaters can be classified according to the mode of application, the construction of the blade, and the time between application and blade.

A. Applicators

1. Roll applicators
2. Contact applicators
 - jet applicators
 - fountain applicators
 - short dwell applicators
 - puddle applicators

B. Dwell time

1. Long dwell time
2. Medium dwell time
3. Short dwell time

C. Blade configuration

1. Bevelled blades
2. Low angle blades

Different manufacturers of blade coaters have different concepts, which however from a theoretical point of view often are quite similar.

Applicators

As can be seen from the table, there are two principally different modes of application; pressure application, and contact application, or application with small or negligible pressure.

1. Pressure applicators.

The only pressure applicator with widespread use is the applicator roll. This is a rubber-covered roll which applies an excess of liquid on the paper. The distance between the applicator roll and the backing roll (paper) is usually of the magnitude 0,2 to 0,5 mm and can be adjusted. The speed of the applicator roll is usually about 15-25% of the web speed.

The theory for applicator roll application is rather complex, and will not be presented in detail here. Some fundamental things about the applicator roll can however be mentioned, as they are of importance for the understanding of the process:

a. The liquid in the gap between the paper and applicator roll is subjected to shear, the shear rate probably being in the magnitude of $1-2 \times 10^5$.(39).

b. The amount of liquid leaving the applicator is determined by the viscosity of the liquid, the machine speed, the distance between the rolls, and the geometry of the system. If the gap is flooded (as it should be) the applicator roll speed has only minor influence on the amount.(39)

c. A pressure is built up between the rolls. The pressure is dependent on the hardness of the rolls, machine speed, liquid viscosity, and the distance between the rolls. The magnitude of the pressure pulse varies, but is of the magnitude 0,5 - 1,5 kN/m. On the outgoing side of the nip, the pressure can be sub-atmospheric giving rise to cavitation phenomena.(39)

d. For a pigment coating, a filter cake is built up during the application, and the transport rate in the following steps is dependent on the structure of this layer.(40)

2. Contact applicators

These types of applicators can be divided into two groups, one where the applicator is separated from the blade, and one where there is a distance between them. Examples of the first type is the fountain applicator and the jet applicator, and examples of the second type is the puddle coater and the short-dwell coater.

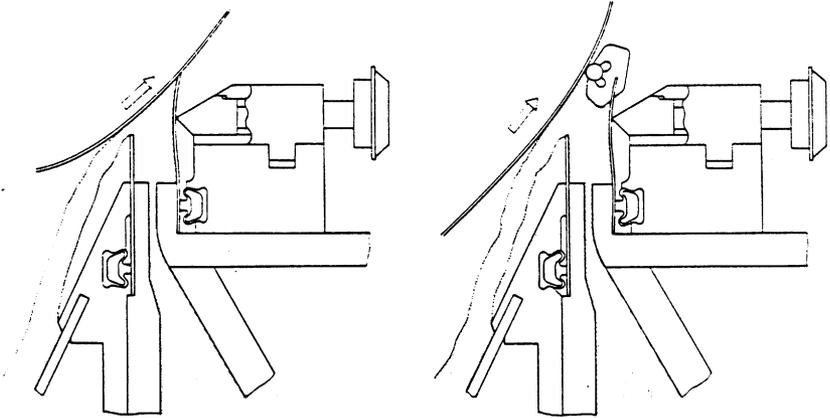


Fig. 14. Short-dwell coater with a. bevelled blade, b. rotating rod for coat weight adjustment.

Irrespective of construction, the liquid and paper is brought into contact under negligible external pressure. The amount transferred is dependent on the construction of the machine, typical for a fountain applicator is that it gives a layer of even thickness, independent of speed and liquid characteristics, whereas the jet applicator gives a constant amount per time unit, i.e. the amount on the paper decreases with machine speed. For the puddle coater and the short dwell coater the situation is more undefined, because there is no well defined borderline between application and blade metering, and the shear situation is very complex. It seems however as if the thickness of the applied layer which have an effect on the blade is of the same magnitude as for application with a roll applicator, and that the thickness of the layer is increased with increasing machine speed and high shear viscosity.

3. Time between application and blade.

In all coaters there is a time difference between the moment when the liquid is brought into contact with the paper until it reaches the blade. This time can differ from 0,5 s for a slow going coater with applicator roll, to 2 ms in a high-speed short-dwell coater.

4. The blade

There have been much written in the literature of the processes which are supposed to take place at the blade tip (41-46). We can however divide between two different systems, the bevelled blade, or stiff blade, where the angle between the paper and the blade is of the magnitude $30 - 60^\circ$ and the low angle process where the angle at the tip usually is below 10° . Of these the bevelled blade system is the more used and investigated, but both are of interest in surface applications as will be described further on.

It seems that there is a fundamental agreement on the theory for bevelled blade which was put forward by Kahila and Eklund (47) which was based on earlier assumptions (48). In this theory, the main idea is that the coat weight is determined by the surface area under the blade, and that the blade always is in contact with the fibres. An increased force from the blade decreases the surface area, thus decreasing the coat weight. When the force on the paper from the blade is decreased, the paper swells, its surface area increases and the coat weight increases. In the process, the pressure (force/blade tip area) under the tip is constant for a constant coat weight. There are some disagreement about the dynamic forces which are built up before and under the blade. Today most investigators agree that the impulse force first mentioned by Kahila and Eklund (47) is the major force in the system but there is some disagreement whether or not there is a build up of a hydrodynamic pressure under the tip of the blade.

The concept that the blade tip is parallel with the paper (49, 50) during stable running conditions may not be completely true. The pressure difference along the tip of the blade may compress the paper and cause a wedge to occur and thus also give rise to a hydrodynamic pressure (51). It also seems natural that the forces from the blade is transferred to the paper via a liquid film.

It must however be stressed that the main feature in the blade coating process is a filling of the cavities of the paper, and that the compressing effect is determining the coat weight in bevelled blade coating.

The theory of low angle blade coating is much less understood. In this process the blade has an angle of $0-10^\circ$ against the paper, and is running on the side of the blade, Fig. 15.

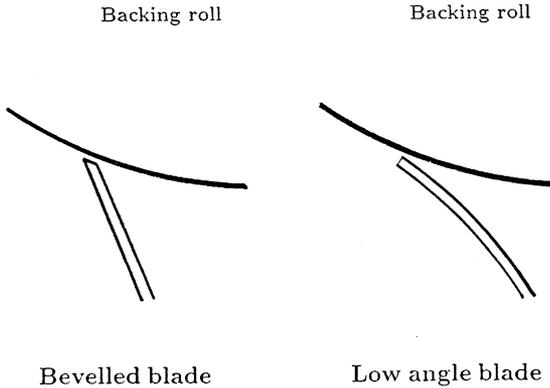


Fig. 15. The geometry in bevelled blade and low angle blade coating.

The main forces are the hydrodynamic force and the impulse force. In this process the blade is not in contact with the paper, and the coat weight is regulated with the blade angle. The mechanical force on the blade is high. If the blade angle is decreased, the hydrodynamic (and impulse) force increase, and the blade bend out from the surface until a new equilibrium is reached. The situation is stable, because there is two large forces counteracting each other. The system allows for high coat weights, as well as coating of smooth substrates, something which is impossible with the bevelled blade coater, which runs unstable when the blade no longer is in contact with the paper.

The water transport in the blade coating process

If the information above is put into its context, the following view can be put forward for the different coating processes:

a. Flooded nip inverted blade (20 m/s)

Pressure pulse 2 ms / dwell time 0,1 s / pressure pulse 25 ns

Because there is an excess of liquid present, the first pressure pulse will transfer an appreciable amount of liquid into the sheet, see Fig 16 which is a redrawing of Fig 2. Of course the amount transferred is depending on the base paper and liquid used, but the system will follow the general characteristics described above for pressure penetration of liquid. In the figure the pressure has been approximated to be 0,5 atm. An increase of the pressure will further increase the liquid transferred. There are two major factors decreasing the water transport in this case, firstly the viscosity of the liquid, and secondly the building up of a thin filter cake in the case of pigment coatings. The filter cake will be the most important factor for the pressure drop (40).

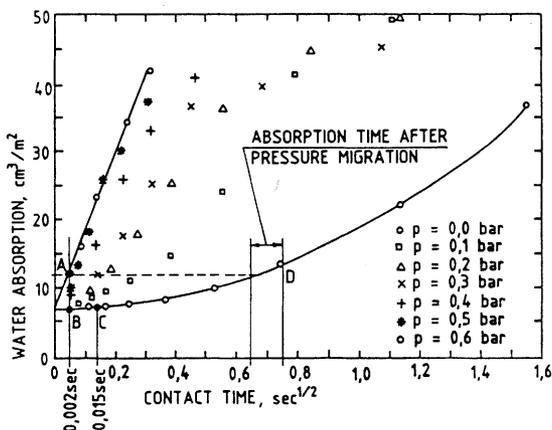


Fig. 16. Pressure penetration of water in 52 g/m² groundwood containing base paper for coating.

During the dwell time, the only driving force is the capillary pressure, and the penetration will then follow the curve for zero pressure. It can be seen that the water uptake for this relatively hydrophilic paper (a LWC base paper) is not negligible, but it is certainly lower than the penetration caused by pressure. It is also obvious from the foregoing, that the absorption from a hydrophobic paper would have been very small during the dwell time considered.

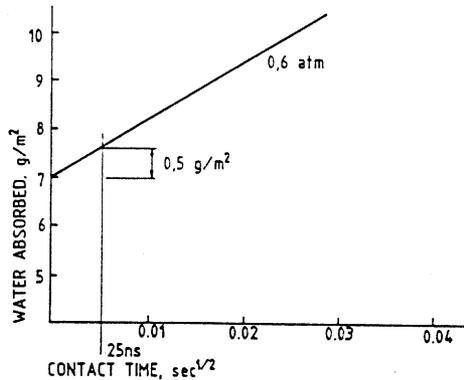


Fig. 17. Water transfer under the tip of the blade (38)

The last part of the process is the pressure pulse under the blade, Fig 17. When the liquid is under the blade, the amount is already determined by processes ahead of the blade tip, meaning that the pressure pulse under the blade has no influence on the coat weight. There is however a forced transport of the available liquid into the sheet. This is especially important for pigment coating, as it can cause a pressure filtration and an increase in solids. Because of a building up of a filter cake at the applicator roll, which determines the flow losses, the transport rate will be relatively low.

b. Flooded nip low angle blade 10 m/s

Pressure pulse 4 ms / dwell time 0,2 s / pressure pulse 0,1ms

The longer pressure pulse (but probably lower pressure) and the longer dwell time will have the same general influence as described above, only that the transferred amount will be larger. The pressure pulse at the blade is however of interest

in this case, as the coat weight is not determined at this stage. The extensive pressure during a relatively long time can cause penetration into the sheet. As described above this penetration will be diminished by increasing viscosity of the liquid and by a pigment layer built up on the paper at the applicator roll.

c. Fountain or jet application, bevelled blade (20 m/s)

Dwell time 0,2 s / pressure pulse 25 ns

In this case the process starts with a capillary transport of liquid under negligible pressure. The transport rate of liquid is low. The pressure pulse under the blade can cause some penetration, but because the coat weights are determined before the blade tip, the penetration does not cause an increase in the coat weight. It can be supposed that a thin filter cake is built up during the dwell time, which will somewhat diminish an increase in solids content for pigment coatings.

d. Puddle type coater (20 m/s)

Dwell time 25 ms / pressure pulse 25 ns

The situation is as in the previous case, only that there is less time available for building up of a filter cake.

e. Short dwell coater (20 m/min)

Dwell time 2 ms / pressure pulse 25 ns.

The situation is as for the puddle coater. There is no time for a filter cake to build up. The amount of liquid transferred to the paper is extremely low, as can be seen from Fig. 16. This low water transfer is however the major reason for the use of these units. The low water penetration implies that the bond breaking in the sheet is low, and the runnability therefore good.

THE SIZE PRESS AND OTHER ROLL APPLICATORS

The traditional way of making surface applications is with the size press. Size presses are always on-machine units. The use of the size presses has been restricted to applying starch or a natural or synthetic polymer on to the paper in order to improve the surface strength or/and the internal strength of the paper. Sometime also pigment is added to the starch solution (for example 50% starch 50% pigment). Pigment coating is seldom made in a size press, because of the low solids content which must be used in order to minimize the orange-peel effect.

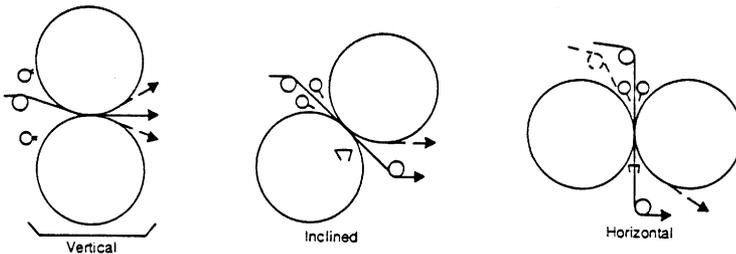


Fig 18. Different types of size-presses.

The size presses can be divided into three different types, the vertical, horizontal and inclined size presses. Of these, the inclined press is the most common. The size press is usually situated in the dryer of the paper machine at a place where about 1/3 of the drying capacity remains. The two rolls are pressed against each other. One of the rolls is covered with soft rubber, the other is covered with hard rubber or is a metal roll.

There are some characteristic problems with size presses. One of these is the film splitting effect. When the size is between the two rotating rolls, the pressure will gradually increase up to a maximum, after which it is diminished. On the outgoing side the pressure can be sub-atmospheric (compare with

applicator roll above) causing cavitation phenomena. A film splitting takes place because a part of the size follows the roll and a part follows the paper. The surface formed on the paper will be uneven (orange-peel effect), fig. 19. A prerequisite for this to happen is that a part of the size remains on the surface, which seems probable (52), even if most of the size penetrates into the paper. Film splitting occurs in all kinds of roll applicators, but its magnitude varies. The film splitting effect will of course increase with increasing viscosity and pigment content.

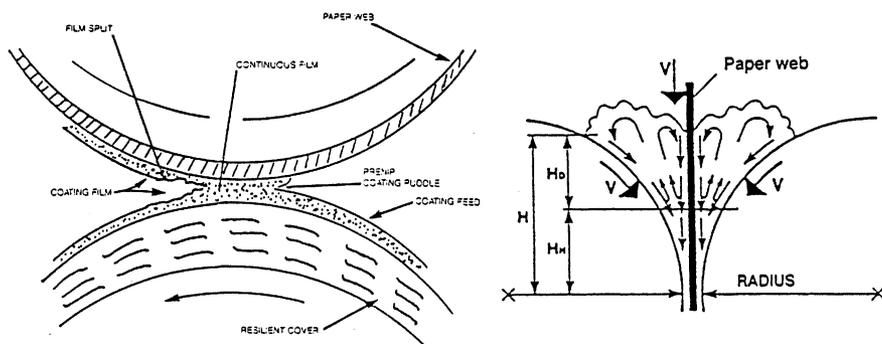


Fig. 19. Film splitting and flow pattern in a size-press.

Another typical problem for size presses is an unfavourable flow pattern in the size press, Fig. 19. When the paper goes down in the nip between the two rolls, the liquid will follow the paper. The speed of the liquid adjacent to the paper is the same as for the paper, and decreases towards the bulk of the size. The same phenomenon takes place at the two rolls. All of the liquid will however not pass through the nip; some of it must turn around and force its way up from the nip, an upward flow will result. This upward flow will be stronger with increasing speed and will result in spitting from the size pond. The problem can be diminished by increasing the diameter of the

rolls, thereby making the counteracting hydrostatic pressure in the pond higher. The size presses which today run at speeds above 13 m/s therefore have rolls with a diameter of about 1.6 m, making the unit very large.

Despite the different developments of the size press which have taken place, it seems like the upper speed limit for these units is about 16-17 m/s. Modern paper machines however run at higher speeds, and therefore the interest in other types of equipment for surface sizing has increased. Another reason is that the solids content of the starch must be decreased when the speed increases, thereby further increasing the demand for drying capacity.

An attempt to diminish the problems with the size press was the development of the gate-roll coater, Fig 20. In this coater there is a pond between two applicator rolls, which regulates the amount of size which is transferred (53). A size of higher viscosity or a pigment coating can be used. The film splitting effect is however characteristic also for this type of coater. The amount which is transferred is pre-metered, i.e. we have a volumetric transfer. Because the amount is restricted the penetration into the paper will be lower than for a size press.

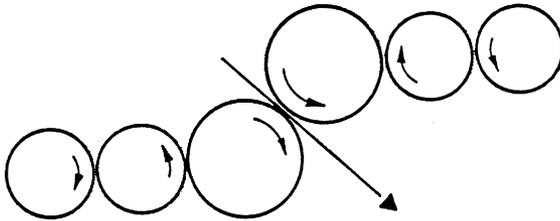


Fig. 20. Gate-roll coater

The gate roll coaters can be regarded as predecessors to the transfer size presses, which have been on the market for some years. In these units there is a pre-metering of the size on to the size-press roll from which it is transferred to the

paper. However, instead of making the premetering with rolls, like in the gate-roll process, the premetering is made with a blade unit. The general configuration can be seen from Fig. 21.

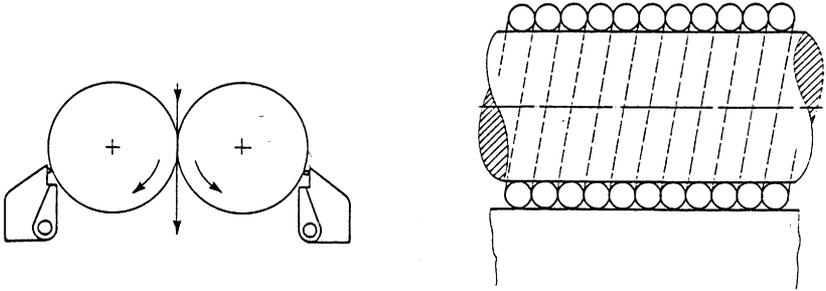


Fig. 21. A transfer size press (Speed Sizer) with a rotating rod for determining the size transferred.

It is common practice to use a short dwell coater for the application. An even film is premetered with the blade and transferred in the nip to the paper (54). The problem with this type of equipment is that debris from the paper has a tendency to follow the roll, and will be caught under the blade where it will cause streaks in the starch film. This can be avoided by installing scrapers ahead of the short dwell unit. Another possibility is to use the low-angle technique instead of the bevelled blade (see above on blade coaters). In Fig. 21 is presented a third method, i.e. the blade is changed for a wired rotating rod (55). In this case, the amount of starch which is transferred is mainly dependent on the thickness of the wires on the rod, and of the hardness of the backing roll. The pressure of the rod against the roll, the machine speed, and the viscosity has very little influence on the pick-up of the starch (56).

A third possibility to avoid the problems with size presses is to use a blade coating device working directly on the paper. These processes have been explained above. For surface sizing the almost only method which is used is the short dwell blade coaters described above. These coaters have a very good runnability, does not demand hydrophobic sizing of the paper, have no upper speed limit, and it is easy to adjust the amount of size. The drawback is that two units are needed, i.e. simultaneous sizing of both sides can not be made.

For simultaneous coating or sizing of both sides, either a system with two blades working against each other, or a blade-roll system could be used. The blade against blade system however demands very high strength of the paper, which is drawn through the nip between the blades, and is therefore not used for surface sizing. The roll-blade system is described in Fig. 22.

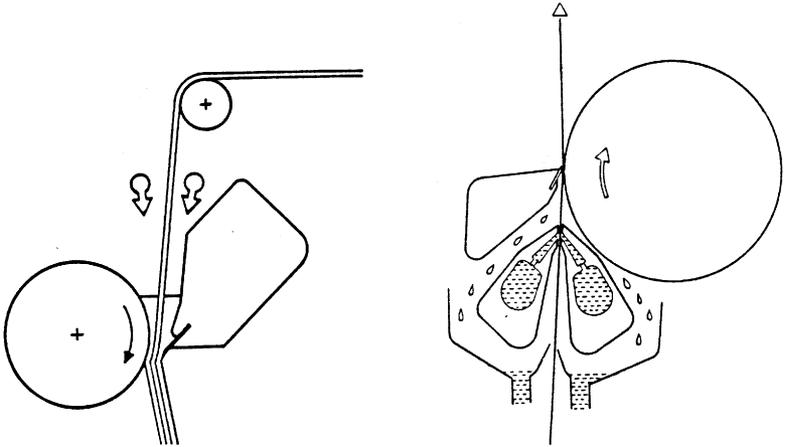


Fig. 22. Simultaneous coating of both sides in blade-roll units

These two units differ in the web threading, and in the application of the size (or coating colour). In one of them, the application is with a puddle on one side and a pond on the other, and the web threading downwards from the coating head, in the other the application is made by means of two fountains, one on each side of the sheet, and the web threading is upwards

from the coating head. In both cases the amount is regulated with a blade. The transport phenomena which takes place will therefore be comparable with the them taking place in a corresponding blade coater.

Surface size uptake in the size press

The amount of research on the mechanism of surface sizing in the size press is relatively limited (57-64). One of the most extensive studies has been made by Hoyland et al. (59, 60). They divides the size press nip into three regions, Fig. 23.

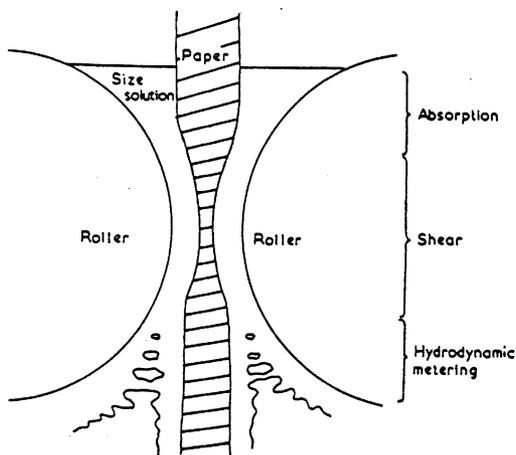


Fig. 23. The size press nip.

When the paper comes into the nip there is first an absorption of size. In the shear region, the paper is compressed and size solution is pressed into the paper because of the external pressure. In the outgoing part of the nip film splitting and cavitation phenomena dominate. On the basis of experiments on a laboratory size press, Hoyland (59) has also derived an equation to explain the pick-up in a size press:

$$PU = K_1 + \frac{K_2}{(\eta S)^n} + K_3 \eta S \quad (5)$$

where PU is the wet pick-up of surface size, K_1 , K_2 , and K_3 are constants, S is the machine speed, and n is a constant.

The three terms in the equation are called the base paper (immobilisation) term, the absorption term, and the hydrodynamic term. The base paper term determines the immobilisation of the size which takes place because of the surface roughness of the paper or effects caused by the compression and expansion of the paper when it passes the nip. This term is completely dependent on the base paper.

The absorption term is determined by the amount of surface size which is absorbed into the paper before it goes into the nip. This term was derived from the Washburn equation. The hydrodynamic term gives an expression of the amount of size which is remaining on the surface after the passing of the nip.

Hoyland et al.(60) are of the opinion that most of the surface size uptake below 2,5 m/s is dependent on the characteristics of the paper, after which the hydrodynamic term then will increase in importance. Hein, Hermann and Schuster (61) have also derived an expression for the hydrodynamic pressure, Fig. 24.

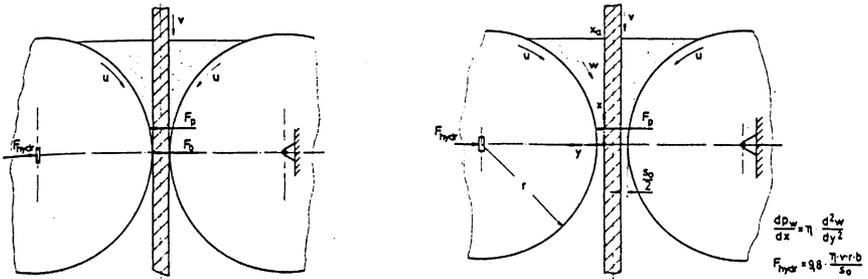


Fig. 24. The pressure balance in a size press nip (61)

The expression is comparable with that of Hoyland.

According to Dill is the surface size uptake dependent on a capillary penetration calculated according to the Washburn equation, a pressure penetration proportional to the pressure and time, and inversely proportional to the viscosity, an uptake in the surface roughness, and a free surface film which forms on the surface.

In a recent study (64) Remmer confirmed earlier findings (59-62) on the general theory for the size press uptake, and stated that the uptake can be explained by the following equation:

$$PU = K_1 + [\textit{pressure sorption}] + [\textit{hydrodynamic uptake}] \quad (6)$$

K_1 = surface roughness volume = constant

$$[\textit{Pressure sorption}] = k_1 \cdot \sqrt{\frac{t}{\eta}}$$

$$[\textit{Hydrodynamic uptake}] = k_2 \cdot \frac{R}{P} \cdot \eta \cdot \frac{1}{t}$$

where k_1 and k_2 are constants, R roll diameter and P the linear pressure

In this model there is no term for the capillary penetration. It is also quite clear from the sorption studies (22) referred to above that capillary penetration only can be a factor of importance if the speed is very low, as it was in the investigations made by Hoyland.

CONCLUDING REMARKS

In this review of surface application, the main stress has been put on the transfer of surface size or coating colour to the paper in different types of applicators. The aim has been to explain the processes which takes place in the size press and in different blade coaters. Liquid penetration and how it is dependent on the characteristics of the liquid and the paper has been described for zero external pressure, as well as for

the more common situation where pressure is applied. This has been used as a base to explain how different applicators work from a theoretical point of view.

The result of the application is however also much dependent on the stability of the process, and on the properties of the size or coating color, not to mention the properties of the paper. These factors have not been dealt with in the review. Without a proper understanding of the process, however, it is impossible to adjust the base paper, coating color or surface size in such a way that the best possible quality of paper is obtained.

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Transcription of Discussion

REVIEW OF SURFACE APPLICATION

Prof. D. E. Eklund

Dr. M.B. Lyne, International Paper Co.

I would like to take issue with the concept that liquid penetration into papers where capillary suction is the primary driving force should be described as penetration proceeding linearly with time. Surely, if capillary suction, even if preceded by vapour diffusion, does not vary through the thickness of the paper, and the total drag force (integrated over the depth of penetration) increases linearly with depth, then the penetration rate will slow as the liquid penetrates through the paper. In this case the depth of penetration will be proportional to the square root of time.

Prof. D.E. Eklund

In response to your first question about reference 19, you said this as an opponent at the doctor's disputation of Pekka Saalminen in Turku Oct 3rd. 1988. At that time, you agreed with what I said in this paper. As to the second question, if the capillary pressure is the rate determining factor, then there is also a square root of time relationship, which also can be demonstrated by the pressure curves I have shown. But if the rate determining factors are the change of contact angle with time, that is for example molecular processes taking place ahead of the water front this would be the rate determining factor through the paper. The viscous drag, will not have anything to do with the rate of penetration, because it is not the rate determining factor. Henry Kent will later show other possibilities of water penetration into paper. If these are rate determining, then the process which takes

place is independent of the position in the paper. In this case also the viscous drag will have no influence.

Dr. M.B. Lyne, International Paper Co.

If on a macro scale the driving force remains independent of location and the retarding drag force increases with depth into the paper. You must still have a slowing of penetration with time.

Prof. D.E. Eklund

I do not think so. The penetration rate will always be determined by the rate determining factors. If you take, for example, a hydrophobic paper, then it is the molecular processes ahead of the water front, or the diffusion which are the rate determining factors.

With a hydrophilic paper, the viscous drag could be the rate determining factor. However, both hydrophobicity and hydrophilicity is seldom found simultaneously in the same sheet.

Dr. A. Nissan, Westvaco

My colleague and friend George Batten (1) took the simplest case for checking the Washburn equation which was a straight circular section glass tube with zero contact angle, and worked out the theory of what would happen if you take that tube and just put it vertically touching the surface of water. In this case, many things can happen. Firstly, the velocity must be uniform at the beginning because there is no boundary layer. To reach this velocity, you need one kinetic energy head ($\rho \times v^2$) and you have to add this to the Washburn equation. But then the boundary layer begins to build up. The length of the boundary layer is an inverse function of the Reynold's number as is the time, therefore the slower the flow, the longer it will take for the Washburn equation to come into effect. You can calculate this from boundary layer theory. Furthermore, between the start and where Washburn comes in, the velocity distribution across the tube changes from uniform to parabolic. The kinetic energy average for a parabolic distribution is two heads of kinetic energy, not one, therefore you have to add another kinetic energy head before you can start to use Washburn. There are also some losses, about $0.14 v^2$, for the change of velocities and the drag in the boundary layer. Furthermore, there is something which has been observed, but never taken into account. Workers on flow in capillaries noticed that the meniscus does not change it's shape and in glass

it curves up, but a parabolic distribution should have a shape which is the opposite. The velocity should be higher in the centre. Therefore one kinetic energy head is being destroyed at the outlet as well, we have to add another kinetic energy head. The contact angle at the beginning is geometrical, i.e. 90 degrees, and it takes time for it to change from this to zero, we presume that time to be the same as the time for the boundary layer to grow, because both are molecular phenomena. If you add up all these terms, you get two things. One you can fit very accurate experiments on water in glass capillary tubes to these equations, but not to Washburn alone. In the end, it fits Washburn, but for point one or two of a second or so, there are many terms even for imbibition of water in glass tubes and we have not considered cellulose nor absorption nor swelling nor diffusion or any of the other factors that come in paper.

Only after the passage of a finite period will Washburn's equation come into its own.

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Prof. D.E. Eklund

We carried out these experiments also, not with a capillary but with paper, and I think we agree that the Washburn equation has many limitations and should not be used for explaining water penetration. This is especially true when you have a hydrophobic surface or when you use external pressures. Thank you for your comment.

Dr. L. Wagberg, SCA Teknik

Could you comment on the results which came out of diffusion theories of liquid transportation in porous media? These theories tell you that if, for example, you look at a liquid front moving in one dimension, then this movement should be proportional to the square root of time. If the liquid front is moving in two dimensions, it should be proportional to t and if there are three dimensions involved, it should be proportional to t raised to 1.5. This comes out of the diffusion theory and it has been confirmed by flow experiments in porous claybeds. Could it be that the proportionality to t in your results is an indication of water flow in two dimensions in the application which you have in your system?

Prof. D.E. Eklund

What happens is that you fill up the whole surface so that the water can only move in one direction, not in two directions as far as I can tell, at least on a macro scale. Henry Kent's paper will tell us that you have transport in two dimensions in a micro scale. I believe that molecular interactions explain the results we obtained. These molecular interactions ahead of the water front are often the rate determining factor, and they give a linear relationship between penetration and time.