Theoretical aspects and practical experiences for film coated offset grades

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ABSTRACT: *Film coated offset grades are an important component of the paper industry. They are the result of the need for high quality with minimum investment costs. Pilot and commercial tests show best results using high solids levels and low viscosities. Highest quality requires optimization of base paper and coating color properties. Film coating now provides a successful and economical alternative to blade coating.*

KEYWORDS: *Coated papers, film coated papers, offset papers, paper grades, printing papers, process variables, theories, variables.*

Film coated offset (FCO) grades of paper have grown in importance recently *(1–3)*. Production of FCO grades began in Germany in 1992 due to the recession in the paper industry. Some mills needed a way to improve paper quality with minimum investment costs. The easiest way was to rebuild an old size press into a metering type size press. These could then apply the necessary coating weight for improvement of paper quality. Depending on base paper properties and desired quality, the minimum coating weight for sufficient fiber coverage and satisfactory printability was 6–8 g/m^2.

Table I shows data from two mills that started FCO production in 1992. Both mills rebuilt old size presses. The width of both paper machines is 3.1 m. Mill A produces a coated, wood-containing paper with approximately 20% bleached kraft pulp at a maximum speed of 900 m/min using 40 g/m^2 base paper. The coating weight is 9 g/m^2 per side applied at 60% solids with chrome-plated, grooved rods. Dull grades undergo calendering on-line with a soft nip calender.

Mill B specializes in recycled base using 100% deinked pulp. They run at 450–650 m/min and apply 9 g/m^2 per side premetered with chrome-plated, grooved rods using 55% solids.

Both mills started their product development using pilot trials to test different coating formulations and to determine the optimum coating weight. Various European and U.S. mills were also conducting trials on the coating process using soft nip calendering for finishing.

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Base paper and coating trial results

Figures 1 and 2 show typical results from a trial series. A 30 g/m^2 wood-containing base paper received 7 g/m^2 coating per side using 56% solids at a speed of 900 m/min. The most important quality targets are gloss and smoothness. It is also very important to attain similar values on both the wire and the top sides. The results shown in these figures used a soft nip calender operated at 160°C steel roll temperature and various line loads expressed as specific nip pressures. At these conditions, the smoother top side reached a gloss of 50% (Gardner 75°) and a Parker Print Surf (PPS) roughness of 1.9 µm. The wire side had lower gloss and was also rougher. The difference between both sides remained constant at all trial conditions.

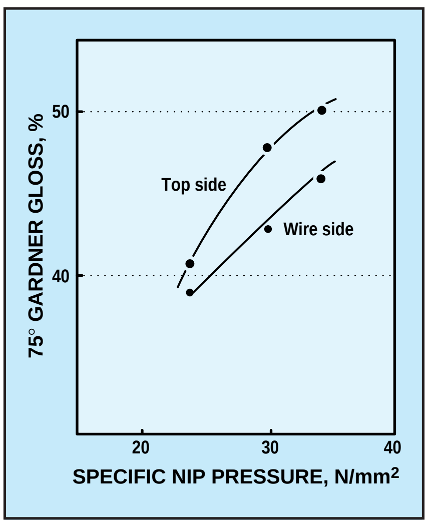
Wet pressing is the primary cause of two-sidedness. The coating process and calendering conditions can also influence it *(3–5)*. For example, different line loads or temperatures can compensate for two-sidedness almost completely provided the soft nip calender does not operate at maximum pressure. **Figure 3** shows a schematic diagram for this.

Another way to reduce two-sidedness is to apply different coating weights to each side. **Figures 4 and 5** shows gloss and smoothness results for coating weights of 8 g/m^2 and 10 g/m^2 on a 45 g/m^2 lightweight coated (LWC) base paper. With 8 g/m^2, the gloss values were 51% and 48.4% for top and wire sides, respec-

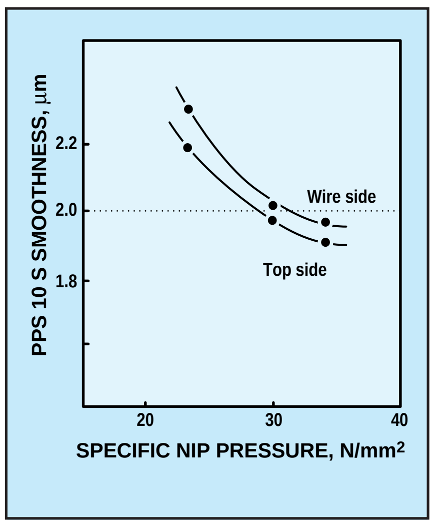
I. FCO production data for 1994

	Mill A: Wood-containing base (20% kraft), 40 g/m²	*Mill B.: Recycled base (100% deinked pulp), 60-90 g/m²*
Width, m	3.05	3.1
Speed, m/min	900	450–650
Coating weight, g/m² per side	9	9
Solids, %	60	55
Viscosity, mPa·s	800–1200	200–400
Premetering element	Chrome-plated grooved rod	Chrome-plated grooved rod
Brightness	74.8 → 78.8 coated	62–64 → 74.5 coated
Opacity	88.9 → 93.0	97.2 after calendering
Gloss	Dull grades, 2 nip soft calender nip, on-line	9 nip supercalender, 50°C

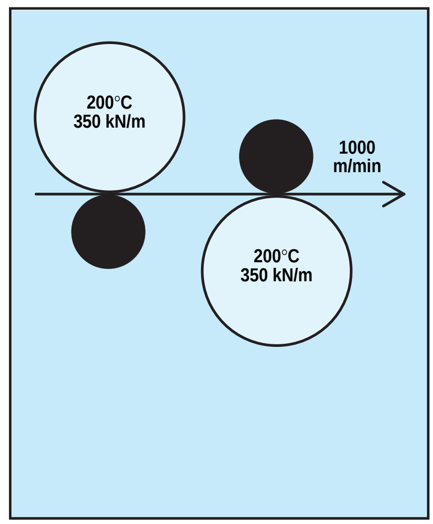
1. Gloss variation with specific nip pressure



2. Smoothness variation with specific nip pressure



3. Schematic diagram of soft nip showing maximum temperature and load



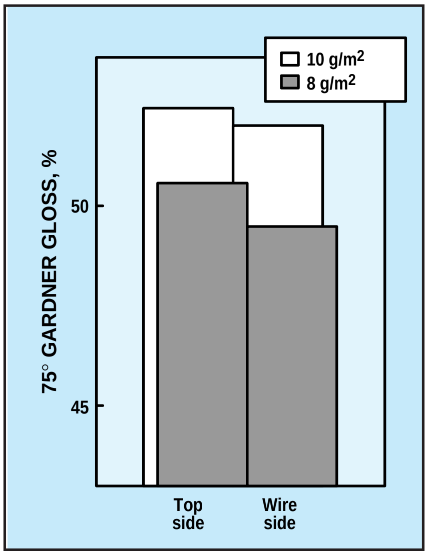
tively. Increasing the coating weight to 10 g/m² increased gloss for both sides to 54%.

It was more difficult to obtain similar smoothness levels on both sides. Improvements were possible on the smoother top side, but the wire side showed almost no difference. Even with varying calendering conditions, it was not possible to reduce the roughness difference generated in the press section between the two sides.

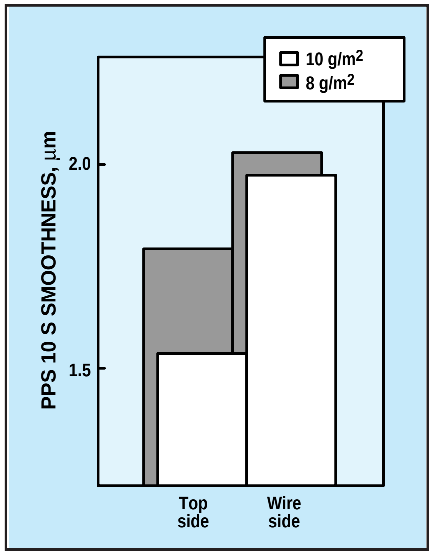
The results from Figs. 4 and 5 indicate it is possible to attain gloss values as high as 55% and PPS values of 1.5 µm with film coating technology combined with on-line soft nip calendering. To reduce two sidedness to a minimum, a base paper as evensided as evensided as necessary, since base paper properties definitely influence the final sheet quality.

Figure 6 shows the oil absorption for two 45 g/m² LWC base papers. **Figure 7** shows the gloss of the coated and calendered sheets made from these base sheets using a coating weight of 10 g/m², 62% solids, a soft nip calender at 180°C and 350 kN/m, and 1000 m/min speed for both cases. Base A was much more two-sided than Base B for oil absorption. The higher absorption caused a deeper penetration of the coating color (10 g/m²) with concomitant lower gloss. The two-sidedness in oil absorption relates to two-sidedness in paper gloss. The amount of coating material on the paper surface influences gloss very much. Flat clay pigments give more gloss then cubic carbonate pigments. For a highly efficient coating process, it is necessary to deposit all applied coating

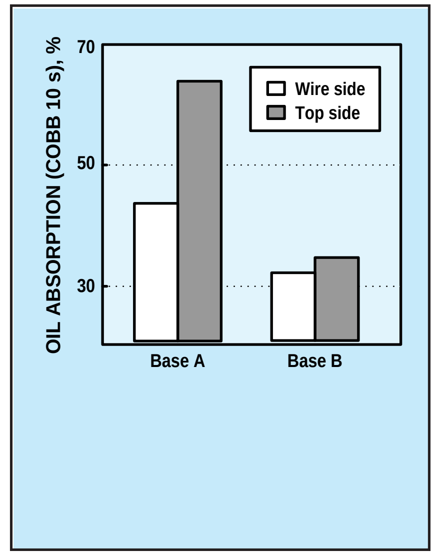
4. Gloss values for varying coating weights



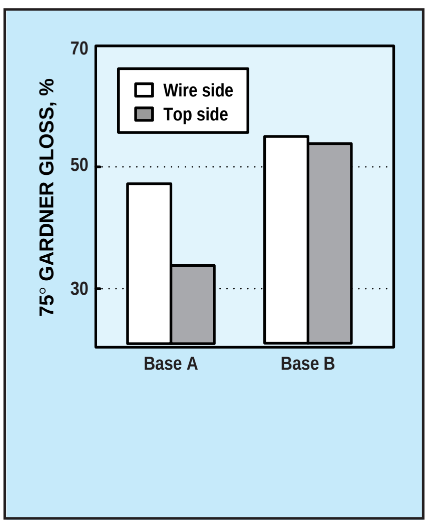
5. Smoothness values for varying coating weights



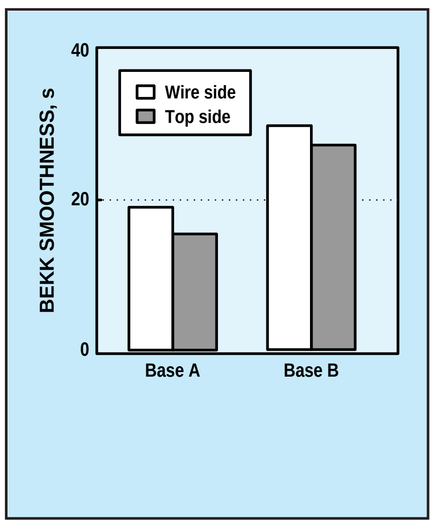
6. Base paper oil absorption in percentage of basis weight (45 g/m²)



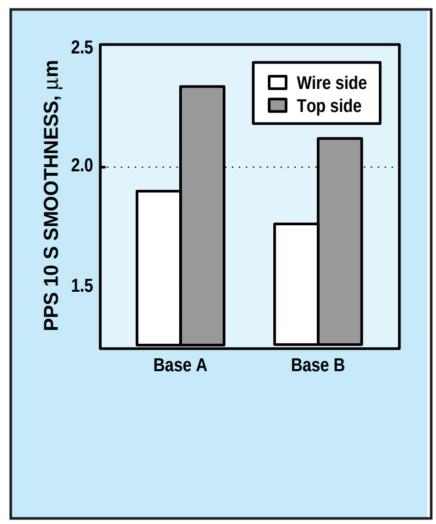
7. Coated and calendered sheet gloss



8. Base paper roughness



9. Coated and calendered sheet smoothness



pigments on the surface and to minimize penetration of pigments into the depth of the paper.

Pigments penetrating into the fibers of the sheet obviously do not contribute to the gloss on the surface. A low nip pressure from low nip loads and soft roll covers reduces the penetration of solids into the sheet. Base B was almost even-sided for oil absorption and final gloss.

Figure 8 shows the roughness (Bekk) of LWC base sheet, coated two sides with 8 g/m² and 10 g/m² coating applied at 62% solids with 1000 m/min speed. **Figure 9** indicates the smoothness values after coating and calendering the sheets. The smoother base paper was also smoother after coating and calendering. It was not possible to eliminate the two-sidedness.

Theoretical aspects of the coating process

To understand the process of film coating and to study the most important parameters, this work modeled coating color dewatering and film immobilization. The proposed model uses filtration theory. **Figure 10** shows a cross section through the press roll nip. This study used a coating level of 10–25 mL/m² premetered onto a roll cover for transport to the nip. The nip was 0–50 mm in length depending on line load applied, cover hardness, and roll diameter. Nip length and line load determine the specific nip pressure on the coating color in the nip. Machine speed and nip length determine the residence time in the nip. Under these assumptions, the coating color dewatering is a filtration process with constant specific pressure for a very short time.

Equation 1 *(6, 7)* gives the amount of fluid penetrating into the paper expressed as volume per area (V/A):

$$V/A = [2 \cdot \Delta p \cdot \Delta t / \alpha \cdot \eta \cdot k_m]^{1/2} \quad (1)$$

where

Δp = applied pressure differential

Δt = time interval

α = specific filtration resistance of the filter cake or immobilized layer

η = viscosity in Pa·s

k_m = factor comprising volumetric concentration and void fraction.

If the shear rate in a nip between two rolls without speed difference does not strongly influence viscosity, it is possible to calculate the dewatering of the coating color film using Brookfield viscosity values. The pressure and the interval both depend on the nip length. Nip impression paper allows easy measurement of a static nip length. It is also possible to calculate nip length by the finite element method. Many rubber cover manufacturers use computer programs to calculate nip lengths for varying material parameters, speed, temperature, and nip load.

The filtration resistance of a porous filter cake varies with the void fraction and the specific surface of the solid particles—clay or calcium carbonate pigments *(6, 7)*. Equation 2 shows this relationship:

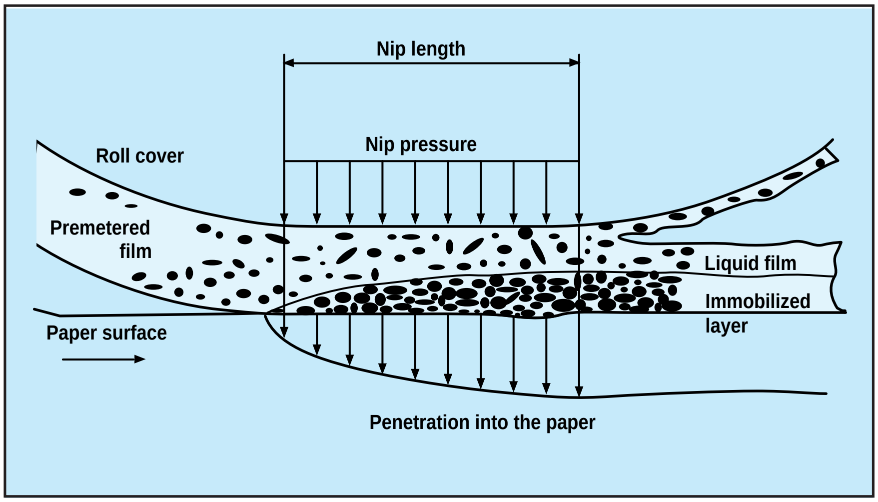
$$\alpha = [(1 - \varepsilon)^2 (S_{spec})^2 / \varepsilon^3] \quad (2)$$

where

ε = void fraction

S_{spec} = specific surface.

10. Cross section through press roll nip during film transfer from roll to paper



The specific surface depends on particle size *(7)* according to Eq. 3:

$$S_{spec} = 6/d \quad (3)$$

where

d = particle size.

Since many pigments do not have a spherical shape, their specific surface is higher than the surface of a spherical particle with the same volume. A particle shape factor, K, can compensate for this *(6)*. Equation 4 then gives the filtration resistance:

$$\alpha = [36/(d/K)^2][(1 - \varepsilon)^2/\varepsilon^3] \quad (4)$$

The literature provides values for void fractions *(6)*. Values for typical coating pigments like clay and calcium carbonate are 0.38 and 0.42, respectively.

When the fluid phase penetrates into the paper, **Fig. 11** shows that the thickness, X_i, of the immobilized layer grows. To balance the solid and the fluid phases, it is helpful to calculate in volume units. Equation 5 gives the volumetric concentration of the color:

$$C_v = 1/\{1 - [\rho_s/\rho_L] + [\rho_s/(C_m \cdot \rho_L)]\} \quad (5)$$

where

C_v = volumetric solids concentration

ρ_s = density of the solid phase

ρ_L = density of the fluid phase

C_m = mass concentration.

When filtration decreases the fluid phase of a suspension or coating color, the solids concentration increases. The distance between pigment particles decreases until they touch each other. This is the immobilization point.

Equation 6 gives the growth of the immobilized layer:

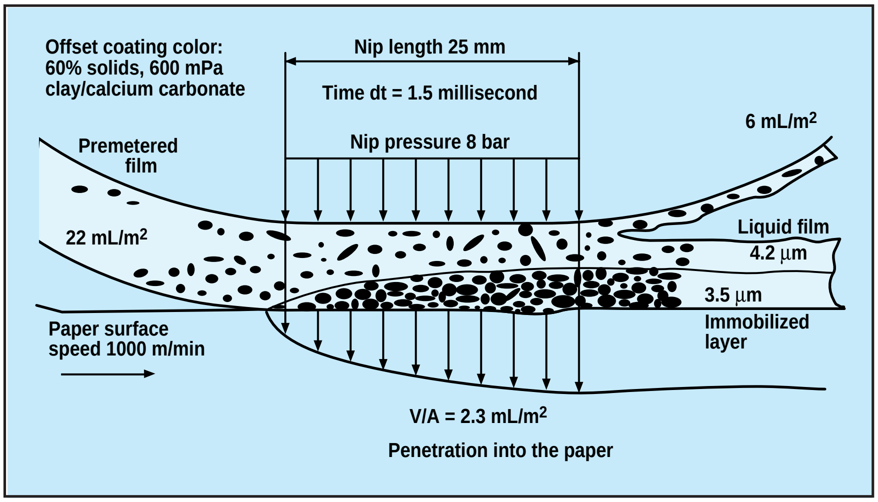
$$X_i(t) = \{1/[(1/C_v) - 1][1 - \varepsilon] - \varepsilon\}[V(t)/A] = k_m[V(t)]/A \quad (6)$$

This equation results from a volume balance between original coating color (volumetric concentration, C_v), the void fraction of the filter cake, ε, and the penetrated volume V(t) per area in square meters. Using this calculation, it is possible to determine the penetrated volume per square meter and the growth of the immobilized layer.

This assumes the dewatering process is a laminar flow through a growing porous layer of pigments. The viscosity of the liquid phase and the pore volume of the immobilized layer therefore have very strong influences on the dewatering process.

Figure 11 shows how this dewatering process may influence the structure of the coated paper. The figure shows calculated values for a clay and calcium carbonate coating at 60% solids and a coating weight of 10 g/m^2. The thickness of the premetered film is adapted to the 10

11. Cross section through press roll nip for 10–11 g/m² coating weight at 1000 m/min



g/m². The immobilized layer depends only on pressure, time, and coating properties such as viscosity, pigment shape, and size, however. Now the thickness of the immobilized layer is 3.5 µm. This is equivalent to a coating weight of 5.5 g/m². This means that an additional layer of original liquid coating color is necessary to give a total coating weight of 10 g/m². Using a volume balance, one can calculate the thickness of the film layer above the immobilized layer as 4.2 µm.

For lower coating weights, this layer would be thinner. Thicker liquid films obviously will have more pronounced film splitting effects. In pilot trials, it was possible to scrape and collect the coating film remaining on the roll after the nip. Examination showed that for typical offset coatings containing starch and latex as binders the solids concentration was the same as that of the applied coating color. Figure 11 shows that in this trial the remaining film had a thickness of 6 mL/m².

This work assumes that film splitting of the liquid layer occurs at the point of new surface generation with the lowest energy consumption. Measurements of surface tension of rubber covers showed values higher than 48 mN/m. In addition, these covers undergo optimization for maximum wetting properties to form a thin, even coating film.

Pilot trials and production results never showed that the roll cover was completely dry after the nip. It might be possible that the film splits directly between the fluid and the immobilized layer.

The following discussion of calculated results assumes that the film splits in the fluid layer as Fig. 11 shows. This figure also shows why the so-called “orange peel” pattern occurs at higher coating weight. The dewatering capacity of the press nip is not sufficient. The thickness of the immobilized layer is small compared to the liquid layer.

Figure 12 shows the ratio of the immobilized layer thickness, X_i, to the total coating thickness, X, as a function of coating weight for a typical offset coating color at three different solids levels. Conditions were 1000-m/min speed, 25-mm nip length, 8-bar pressure, 1.5-millisecond dwell, 600-mPa·s viscosity, and clay and calcium carbonate mixture.

The results show that with increasing coating weight the liquid layer, $X – X_i$, is growing. The calculation uses constant viscosity of 600 mPa·s. The viscosity values refer to Brookfield viscosity measured at very low shear rates. Although the shear rate between premetering rod and rubber cover is in the same range as under a blade (10^5–10^6 s^{-1}), the work assumes that the shear rate in the nip is considerably lower. From the moment of premetering until the transfer to the paper in the nip, there are no speed differences that cause a high shear force like in a blade coater. Applicator rolls and paper have the same speed when going through the press nip. At lower coating weight, the ratio X_i/X reaches values near 1. This means immobilization of almost the complete film. One should avoid this by lower pressure or increased water retention of the coating—essentially an increase in viscosity.

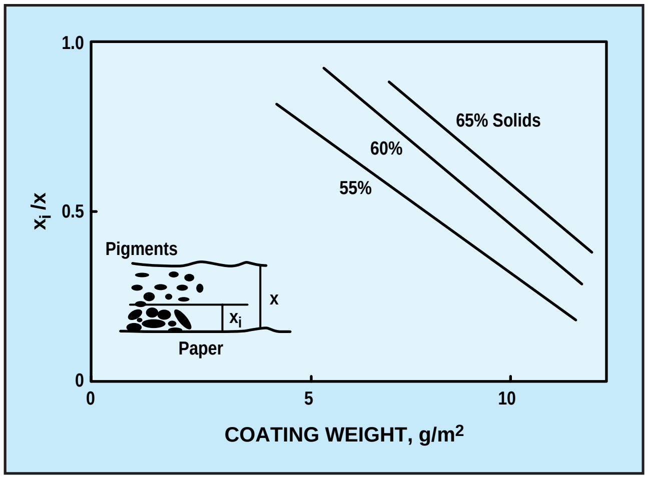
At coating weights above 10 g/m², the liquid film becomes thicker than the immobilized layer. This can lead to spraying of fine coating droplets after the nip and an uneven coating structure—the so-called “orange peel” pattern.

Another important result of these calculations is the amount of liquid as water and starch that penetrates into the paper. To keep the sheet as strong as possible, this amount should be small.

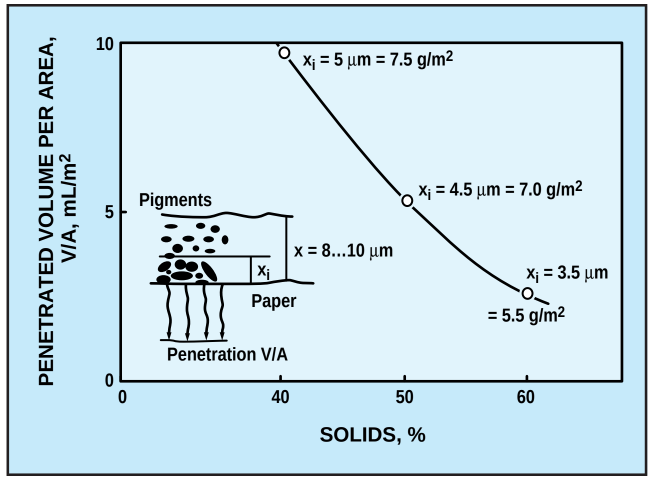
Figure 13 shows the liquid volume per unit area, V/A, that penetrates into the sheet due to immobilization of the coating in the press nip. Machine conditions were the same as in Figs. 11 and 12. The calculation considers the change in viscosity with different solids. Target coating weight was 10 g/m². Solids varied between 40% and 60% for a clay and calcium carbonate coating.

As Fig. 13 shows, the amount of liquid per unit area (mL/m²) is much higher at 40% solids than at 60% solids. Although the viscosity is very high at 60% and the immobilized layer thinner because of higher filtration resistance (pressure drop), the coating at 60% solids is much easier to apply than the coating with lower solids. Since the interval in the nip is only 1–2 milliseconds, there is a high acceleration of liquid volume and more movement between

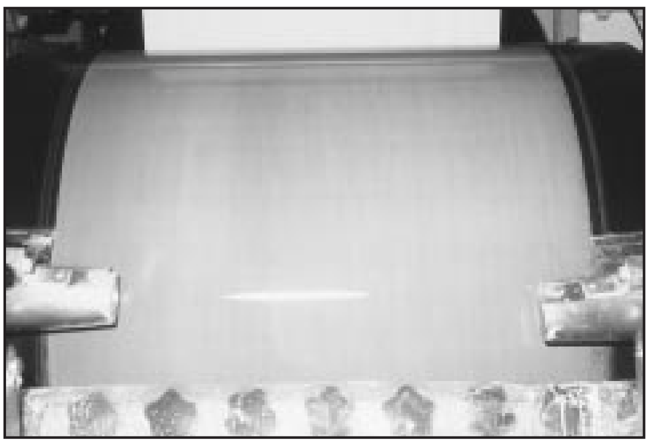
12. Ratio of immobilized pigment layer to total coating thickness



13. Penetration of fluid phase into the sheet for various solids concentrations



14. Photograph of premetered film on roll at 8 g/m² and 62% solids



15. Photograph of web release after press nip

particles inside the coating layer at low solids. This causes uneven and coarse coating structure—the so-called "orange peel" *(3)*.

The conclusion from the theoretical analysis and practical experience is that one should run the highest possible solids concentration and keep the viscosity as low as possible. To this end, newly developed starches for high solids coatings are available that allow an increase in solids content to 60% or higher.

Practical experience

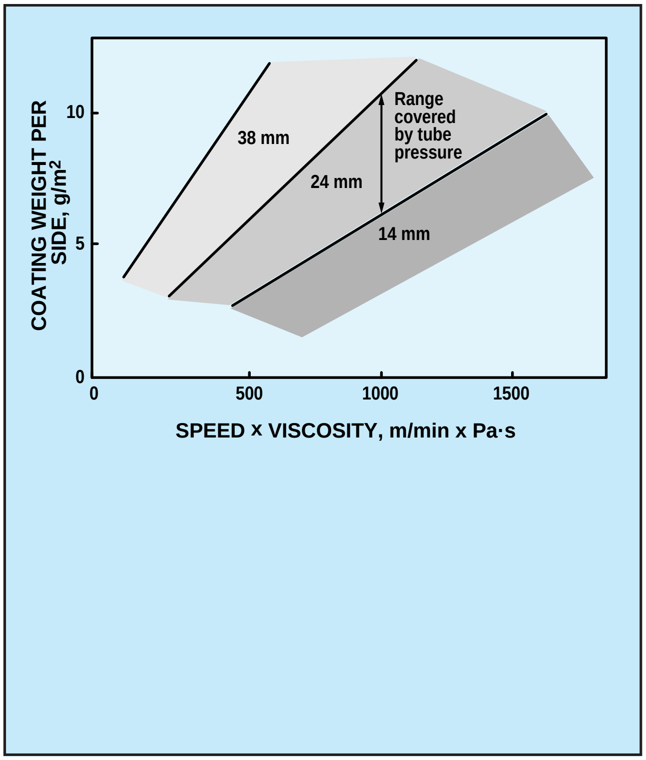
A premetering element is necessary to apply such high solids coatings on a rubber covered applicator roll. The premetering element must withstand the highly abrasive pigment slurry at speed differences of 15–25 m/s. It should also allow a very precise cross direction (CD) profile. At 60% solids, a difference in film thickness of 1 µm corresponds to 1 g/m² difference in coating weight.

Grooved rods have common use for several years for sizing with metering-type size presses. They allow a precise volumetric premetering. Under certain circumstances, their lifetime may only be a few days or hours with abrasive pigments such as titanium dioxide. Smooth rods are alternatives, since wear is not so critical *(3, 8)*. With a smooth rod, the hydrodynamic force determines the film thickness on the roll.

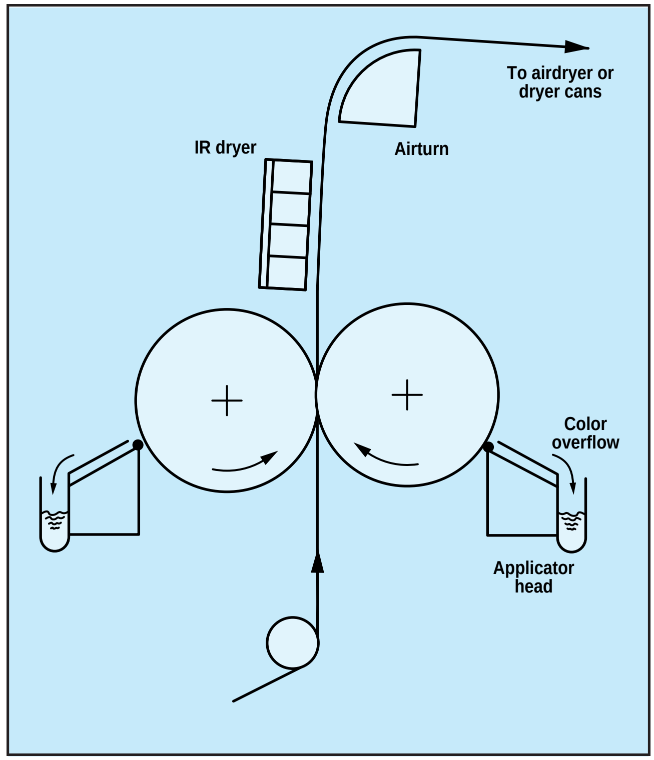
Figures 14 and 15 show the premetered film on an 800-mm diameter pilot applicator roll and the web release after the nip. The film on the roll in Fig. 14 corresponds to a coating weight of 8 g/m² premetered with a smooth rod of 24-mm diameter at a speed of 1000 m/min. Figure 15 shows the web release at the same conditions.

Speed and viscosity have the strongest influence on the premetered amount. Roll cover hardness and rheological behavior have minor influence. Viscosity adjustment is only possible within a certain range (typically between 400 and 1600 mPa·s), and the speed is fixed. The only free parameter is the diameter of the smooth rod consider-

16. Rod diameter and coating weight as a function of speed and viscosity for 60% solids coating



17. Film coating installation with coater-like web path



ing that the tube pressure applied on the rod is in a normal practical range of 1–2 bar.

To apply a coating weight of 10 g/m^2, a smaller rod diameter is sufficient when hydrodynamic forces are high. Applying the same coating weight at low speed or viscosity requires a larger rod diameter. **Figure 16** shows the relation between coating weight and hydrodynamic force expressed as a product of speed times viscosity.

Three rod diameters—38 mm, 24 mm, and 14 mm—can cover the entire range of current applications. A typical example shows that a speed of 500 m/min and a viscosity of 1.0 Pa·s requires a 38-mm diameter smooth rod to apply 10 g/m^2 of a 60% solids coating. With a 24-mm rod, a maximum of 6 g/m^2 is possible. Otherwise the tube pressure against the rod would be so low that the CD profile would be uneven.

For coatings with solids other than 60%, one can calculate the coating weight applied by the ratio of actual solids to the 60% curves in Fig. 16. If the hydrodynamic force is high (1000 m/min and 1.0 Pa·s), a 24-mm rod could also apply 10 g/m^2.

Rods of these diameters are very stiff compared to the grooved rods used for sizing. The rubber covers must be softer to allow a satisfactory CD profile. Then the rod and the cover form a small nip that is necessary for an even film distribution across the width of the machine.

As mentioned above, the first experiences with film coating occurred with rebuilt size presses. The installation of the applicator heads and additional IR dryers or air dryers required removal of several dryer cans. The space required by the film coater or size press is therefore an important consideration for any rebuild project. **Figure 17** shows a suggested installation for a film coating apparatus with minimum space demand and optimum web path. The web comes from below the machine floor, passes through the applicator roll nip, and nips immediately before IR dryers. For simultaneous coating, it is necessary to turn the web with an air turn toward the air dryers or the next dryer cans. This drying arrangement is essentially the same as with all blade coaters.

Conclusions

Mill experience in film coating since 1992 shows that this technique is a successful and economical alternative to blade coating. In combination with two single-nip, soft calenders, gloss values higher than 50% and PPS values between 1.5 µm and 2.0 µm are now possible.

To achieve this high quality level, the base paper and the coating color require optimization. The most important properties of the base paper are even-sidedness and smoothness. For the coating color, special pigment types like high brightness calcium carbonates or high gloss clays will influence the brightness and gloss.

For runnability, the solids concentration of the coating should be as high as possible. Depending on pigment and binder types used, solids levels of 55–65% have proven effective. In addition, the viscosity should be between 500–1200 mPa·s (Brookfield 100 rpm) *(8)*.

Grooved or smooth rods can do the premetering. Testing has shown that a ceramic coating will increase the wear resistance of grooved rods. An alternative is a smooth rod with larger diameter of 24 mm or 38 mm. Operation with smooth rods requires constant viscosity during production to conform to the hydrodynamic principle. TJ

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