Low Flow Limits of Coatability on a Slide Coater

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In any given coating system the maximum coating speed occurs at that point when, for a slight increase in web speed, a coating can no longer be made, or when ribs (evenly spaced downweb lines) start occurring in the coated web. Similarly, at a given speed, the minimum wet thickness is that below which a coating cannot be made, or ribs start occurring. These two limitations are really one and the same and are known as the low flow limit of coatability. In slide coating one or more coating solutions are metered and fed through slots onto an inclined plane, where they flow down in laminar motion and then jump across a small gap onto an upward-moving web. Pulling a vacuum under the coating bead, as suggested by Beguin (1954), increases the ease and range of coatability. Deryagin and Levi (1964) were the first to point out that when one exceeds the maximum coating speed air is entrained, and the dynamic contact angle reaches 180°.

Garin and Vachagin (1972) studied the minimum coating thickness on a slide coater. Their results can be expressed as

$$t > \frac{2.19\sigma^{0.25}\mu V^{0.5}}{\rho^{0.25}\Delta P G} \qquad \frac{\Delta P}{\rho V^2} \leq 3.32 \tag{1}$$

or

$$t > \frac{0.00202\sigma^{0.1}\Delta P^{0.3}\mu^{0.7}V}{g^{1.25}\rho^{1.2}G^{1.05}} \qquad \frac{\Delta P}{\rho V^2} > 3.32 \tag{2}$$

Tallmadge et al. (1979) also studied the limits of coatability, and their results can be given as

$$t > k\,\frac{\mu^{0.5}V^b}{G^a} \tag{3}$$

where $a = 0.13$–0.17, and $b = 0.3$–0.4.

Ruschak (1976) did a theoretical study for an extrusion coater in which the coating solution is forced out of a narrow slot onto the web. His results may possibly be applicable to a slide coater. His low flow limits of coatability can be written as

$$t > 1.338\,\frac{\sigma^{1/3}G\mu^{2/3}V^{2/3}}{[G\Delta P + (1 + \cos\zeta)\sigma]} \tag{4}$$

$$t > \frac{1.338}{2}\left(\frac{\mu V}{\sigma}\right)^{2/3} G \tag{5}$$

Higgins and Scriven (1980) modified Ruschak's theory to take into account viscous pressure drop, but the general conclusions are much the same.

Experimental

The Newtonian liquids tested and their properties are listed in Table 1. The stainless steel slide coating head was inclined 30° to the horizontal, and formed an included angle with the base of 70°. In all cases the base was polyester with a surface layer of gelatin. All the coatings were made at room temperature, approximately 24°C. The coated width was 11.4 cm.

In each test the liquid flow rate of the coating was fixed at a given value, the web speed at which the base moved was adjusted down to obtain a good coating, and then the speed was increased until a good coating could no longer be maintained. The highest speed at which there was good coating with no ribbing was the maximum coating speed. As the web (base) speed increased the upstream meniscus, pinned to the lip of the slide at one end, became more and more extended. Ribs would sometimes form before the onset of air entrainment. At times, one or both edges would neck in to give a thicker, narrower coating. In other cases the bead would break because the liquid could not bridge the gap uniformly, and one or more rivulets would be coated. And in some cases air entrainment showed up as dry patches interspersed with coated areas. Chatter marks were sometimes observed and were disregarded. With the higher surface tension liquids—the aqueous solutions—many of the coatings de-wet shortly beyond the bead. This type of breakdown after the bead region was disregarded in determining the limits

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Table 1. Liquids Tested and Maximum Web Velocities

Liquid	Dens. kg/m³	Surf. Tens. mN/m	Visc. mPa · s	V_{max}, m/s $\Delta P = 0$ Pa	500 Pa	1,000 Pa	Plunging Tape V_{180}, m/s
Water	998	72	0.98	5.6	5.6	5.6	4.6–6.8
54% Corn syrup	1,231	72	21	0.94	1.1	1.2	0.98
70% Glycerin	1,191	65	25	0.85	0.90	0.93	0.83
Corn Oil	923	34	59	0.24	—	—	0.24
70% Corn syrup	1,297	72	120	0.24	0.30	0.30	0.19
88% Glycerin	1,234	65	150	0.20	0.33	0.36	0.19
Mineral oil	870	32	170	0.105	0.14	0.15	0.12
95% Glycerin	1,249	65	520	0.10	0.12	0.13	0.12
100% Glycerin	1,259	63	1,110	0.038	0.035	0.041	0.076

of coatability. With water good coatings could not be obtained because the water flowed down the slide as a rivulet.

One set of experiments was run with an aqueous polyvinyl alcohol solution, in order to compare the behavior of a polymer solution, which is inherently both non-Newtonian and viscoelastic, with that of the Newtonian liquids.

Viscosities were measured in capillary viscometers, surface tensions with a duNouy ring balance, and densities with a pycnometer.

Results and Discussion

Figure 1 is a typical curve of minimum wet coverage vs. web velocity, with and without bead vacuum. (Other graphs similar to Figure 1 can be found in the supplementary material deposited with the National Auxiliary Publications Service as indicated in the end footnote at the end of the text.) Figures 2–4 give curves from all the date at no bead vacuum and at 500 and 1,000 Pa bead vacuum.

From curves such as Figure 1 the maximum web velocities

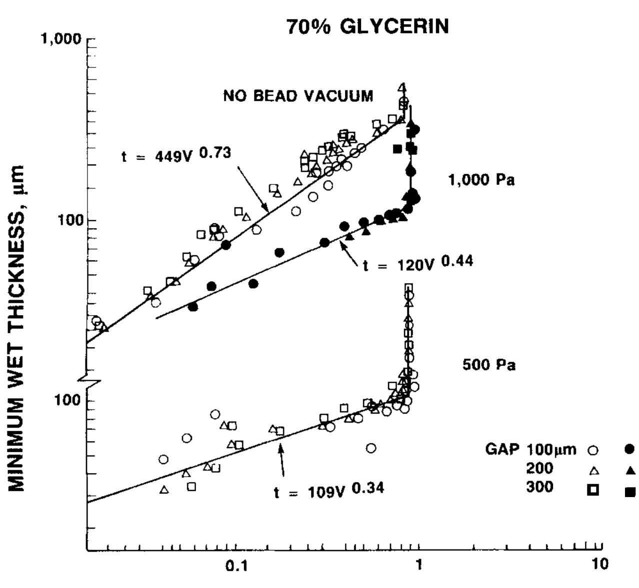

Figure 1. Minimum wet thickness vs. web velocity for slide coating a 70% glycerin solution.
500 Pa bead vacuum curve is displaced one decade for clarity.

(the vertical lines at the highest coverages) were read off and recorded in Table 1. These maximum velocities are independent of gap; they depend only on the liquid and the bead vacuum. We would expect them to be independent of the wettability of the film base, as shown to be the case of air entrainment velocities for tapes plunging into a pool of liquid (Buonopane et al., 1986). These maximum velocities with no bead vacuum are identical to the plunging tape, air entrainment velocities taken from Gutoff and Kendrick (1982), as shown in Table 1. Only with one material, pure glycerin, is there a significant discrepancy. This could be due to the hygroscopic nature of glycerin and the large changes in viscosity with small additions of water. Gutoff and Kendrick (1982), and earlier Burley and Kennedy (1976), showed that viscosity is the main factor in determining air entrainment velocity. Table 1 also shows that while bead vacuum does increase the maximum velocity, the increase is relatively small.

In some of the cases shown in Figures 3 and 4 (pure glycerin and mineral oil with bead vacuum, 54% corn syrup at 500 Pa vacuum, and 70% corn syrup at 1,000 Pa vacuum), the web velocity increases further with large increases in coating thickness. We suspect that in these cases we had not reached the true air entrainment velocity, only the onset of ribbing. Coating speeds might still be increased before the coating broke down into rivulets. Thus in these cases we probably are comparing two different mechanisms. In these cases the reported maximum velocities are measured at the intersection of the two straight line sections, and are fairly close to the values with no bead vacuum and to the plunging tape, air entrainment velocities.

The low flow limits from the main portions of all the curves can be expressed as

$$t = aV^b \tag{6}$$

All the values of constants a and b are tabulated in Table 2. Although two significant figures are reported, the constants are probably good to only one significant figure. If the form of Eqs. 1–3 from Garin and Vachagin (1972) and from Tallmadge et al. (1979) is correct, then the constant a will vary with the physical properties of the liquids coated as well as with the bead vacuum, and b should be a true constant and not vary. We see from Table 2 that b does vary from liquid to liquid as well as with bead vacuum. With bead vacuum the minimum thickness increases less with web velocity than with no bead vacuum; b is always less with bead vacuum.

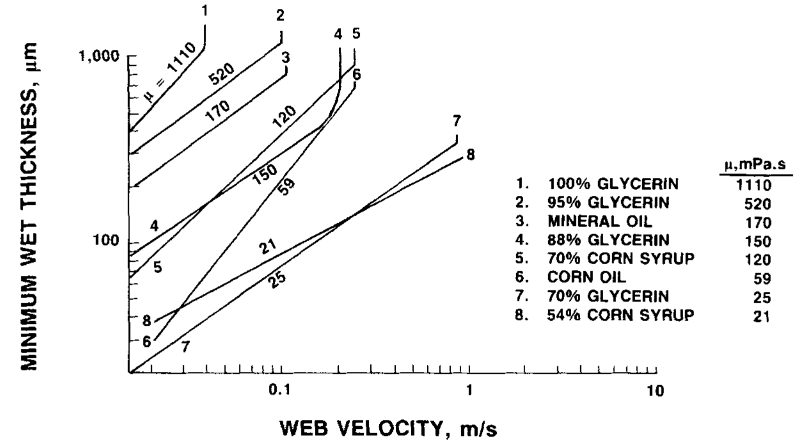

Figure 2. Minimum wet thickness vs. web velocity for slide coating various Newtonian liquids.
No bead vacuum

From Figures 2–4 we see that the minimum coated thickness increases with liquid viscosity and with web speed, and decreases with bead vacuum. A regression analysis of all the data shows that the scatter is too great to show any significance for the gap effect. From the individual graphs, such as Figure 1, one can see in some cases that at wider gaps the minimum thickness increases slightly, in other cases the opposite occurs or there is no gap effect.

A further point should be made about the coating gap. An examination of all the data shows that at wide gaps one could not form a bead at low speeds, especially with bead vacuum. The liquid was just sucked into the vacuum pan. In Figure 1 one sees that where bead vacuum is used, at the wider gaps the points start at higher speeds than at the narrow gap. When the conclusion is drawn that gap width has little or no effect on the minimum coating thickness, a qualification must be added that this assumes that a coating can be made at the wider gaps.

The minimum wet thickness increases with viscosity to the 0.8–0.6 power, as can be seen from Figure 5, a cross plot of the data in Figure 2, and similar figures with vacuum. We believe that the different solutions fall on different lines, and that some other property of these liquids is important.

Table 3 shows that the present study agrees well with the earlier studies for the effect of viscosity and velocity. The differences in the exponent on the velocity effect, b, can be ascribed to some property of the liquid that we do not measure. Table 3 also validates, at least in part, the use for a slide coater of Ruschak's theoretical study of an extrusion coater.

We found no significant effect of gap. Tallmadge et al. (1979) found that with no bead vacuum the minimum coating thickness is inversely proportional to the gap to the 0.2 power. At low bead vacuums Garin and Vachagin found the same, but at higher bead vacuums the thickness was inversely proportional to the gap to the 1.05 power. We are in reasonable agreement with

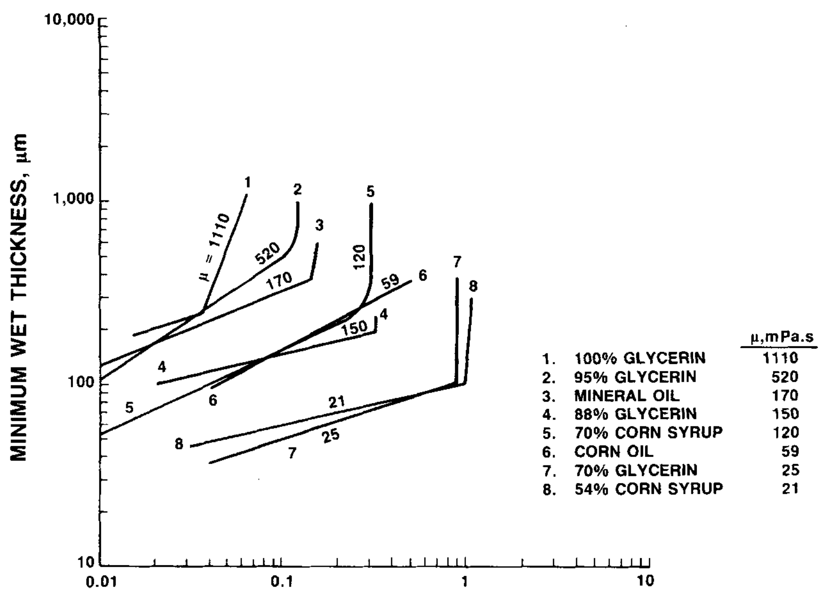

Figure 3. Minimum wet thickness vs. web velocity for slide coating various Newtonian liquids.
500 Pa bead vacuum

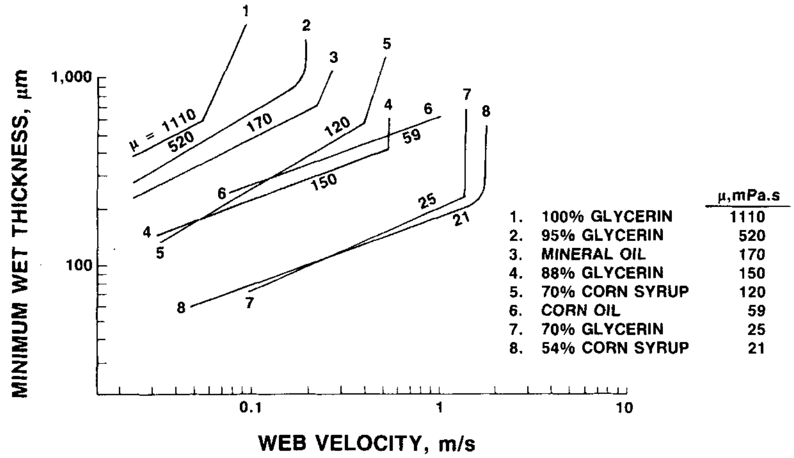

Figure 4. Minimum wet thickness vs. web velocity for slide coating various Newtonian liquids.
1,000 Pa bead vacuum

Tallmadge et al. on the effect of gap and with Garin and Vachagin on the effect of gap at low vacuum, but not with their results at high vacuum. Perhaps their strong gap effects at high bead vacuum are due to the very small included angle of 15° they have between their slide and the web. On the other hand, perhaps these effects represent a need to have a high flow rate in order to get any coating at all at high bead vacuums.

Ruschak's theory for extrusion coaters predicts that the minimum coating thickness is directly proportional to the gap. This obviously does not apply to any of the slide coating results.

We found no effect of surface tension even though it plays a major role in determining the shape of the coating bead (Galehouse and Colt, 1986). Garin and Vachagin found only a small effect: the minimum coating thickness increases with surface tension to the 0.1–0.25 power. Ruschak's theory, Eqs. 4 and 5, predicts strong surface tension effects, and so obviously do not apply to the slide coater.

The use of bead vacuum, as we have seen from Table 1, increases the maximum coating speed. It also allows one to coat more thinly, as shown by comparing Figures 4, 5, and 6, or by examining the intercepts a in Table 2. Qualitatively, our results for the effect of bead vacuum agree with Garin and Vachagin's results at low bead vacuum and with Ruschak's predictions, in that the minimum coating thickness decreases with increasing bead vacuum. We find that the major decrease in minimum thickness occurs on going from no bead vacuum to 500 Pa. A further increase in bead vacuum decreases the minimum thickness only slightly. It is obvious that Garin and Vachagin's Eq. 2 for low bead vacuum (low Euler number) cannot be applied with no bead vacuum.

Figure 6 shows the results for a polyvinyl alcohol solution. As with the other liquids, the maximum coating speed irrespective of thickness occurs at the air entrainment velocity for a tape plunging vertically into the same liquid. And this maximum coating speed is higher by a factor of eight than would be expected from its viscosity, as shown by a comparison with the data for a glycerin solution of the same viscosity.

The much broader limits of coatability for the polyvinyl alcohol solution must be due to its polymeric nature. The long polymer molecules, at the high elongation rates that exist in the coating bead, would be expected to greatly increase the resistance to breakdown of the bead. This property of the solution is called the elongational viscosity, and is discussed in detail by Bird et al. (1977). They show that the elongational viscosity for a number of polymer solutions and melts increases rapidly with elongation rate as the polymer molecules become aligned. We therefore would expect the data of Garin and Vachagin, who worked with

Table 2. Empirical Minimum Wet Thickness Relations*

	Bead Vacuum					
	0 Pa		500 Pa		1,000 Pa	
	a	b	a	b	a	b
54% Corn syrup	350	0.51	100	0.24	110	0.37
70% Glycerin	450	0.73	110	0.34	120	0.44
Corn oil	4,200	1.27	560	0.56	350	0.36
70% Corn syrup	3,600	0.95	470	0.48	640	0.59
88% Glycerin	1,500	0.69	250	0.23	310	0.37
Mineral oil	4,400	0.75	860	0.42	1,100	0.54
95% Glycerin	7,100	0.77	2,000	0.65	1,700	0.60
100% Glycerin	47,000	1.15	630	0.29	1,200	0.43
Avg. values	—	0.85	—	0.40	—	0.46

*$t > aV^b$ where t is minimum wet thickness, m V is web velocity, m/s.

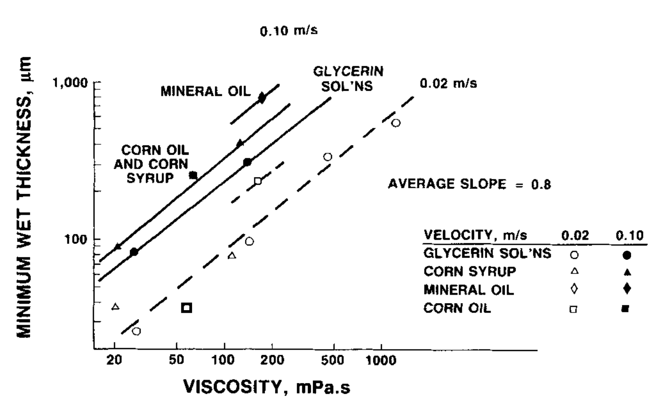

Figure 5. Minimum wet thickness vs. viscosity.
No bead vacuum; data from Fig. 2

Table 3. Comparison with Earlier Studies

	For $t > k\mu^c V^b$	
	c Exp. on μ	b Exp. on V
Present study		
No bead vac.	0.8	0.9
500 Pa bead vac.	0.7	0.4
1,000 Pa bead vac.	0.6	0.5
Garin and Vachagin (1972)		
Low ΔP	1.0	0.7
High ΔP	0.5	1.0
Tallmadge et al. (1979)		
No bead vac.	0.5	0.3–0.4
Ruschak (1976)		
For extrusion coaters	0.7	0.7

gelatin solutions, to show much broader limits than the data given here with Newtonian solutions.

Conclusions

This study confirms the results of Garin and Vachagin (1972) and of Tallmadge et al. (1979) that the minimum coating thickness increases as the viscosity or the coating speed increases. It also confirms the earlier work at low or no vacuum that this minimum coating thickness is only slightly affected by the coating gap and is reduced by bead vacuum. We found that further increases in bead vacuum give only a slight reduction in minimum thickness; Garin and Vachagin found an increase in minimum thickness at higher bead vacuums. In addition, we have shown that a polymer solution shows wider limits of coatability than Newtonian liquids. Also, the maximum speed at which a coating can be made with no bead vacuum is identical to the air entrainment velocity of a tape plunging into a pool of the same liquid; thus this maximum coating speed, like the maximum speed at any thickness, decreases with increasing viscosity. This maximum coating speed with thick coatings increases slightly with bead vacuum.

Acknowledgment

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Notation

a, b, c = constants
g = acceleration of gravity, m/s
G = coating gap, m
k = constant
ΔP = bead vacuum, Pa
t = thickness of wet coating, m
V = web velocity, m/s
V_{max} = maximum web velocity for thick coatings, m/s
V_{180} = air entrainment velocity for a plunging tape, m/s

Greek letters

ζ = static contact angle, degrees
μ = dynamic viscosity, Pa · s
ρ = density, kg/m^3
σ = surface tension, N/m

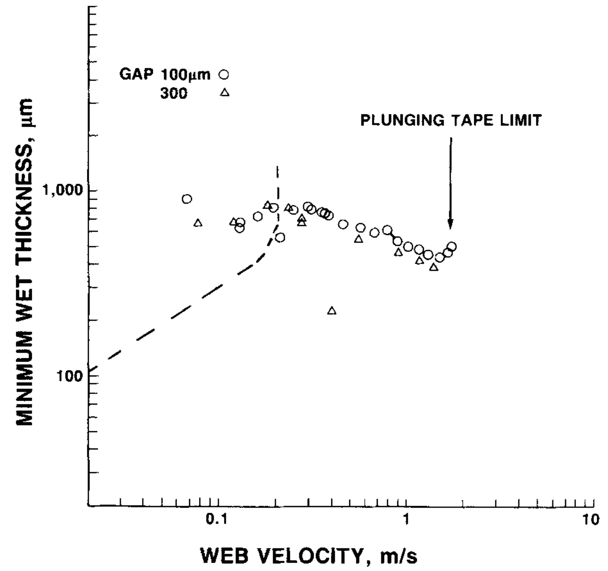

Figure 6. Minimum wet thickness vs. web velocity for slide coating a polyvinyl alcohol solution.
Viscosity 146 mPa · s, no bead vacuum.
---- Glycerin solution of the same viscosity, from Fig. 2.

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