Angling the Wetting Line Retards Air Entrainment in Premetered Coating Flows

Hadj Benkreira and Olivier Cohu
Dept. of Chemical Engineering, University of Bradford, BD7 1DP, Bradford, U.K.

Air entrainment is a major limitation to many coating processes where one or several thin layers of liquid are deposited onto a continuous substrate. At low substrate speeds, a uniform film is formed however, as the speed is increased above a certain threshold, air is entrained between the coating and the substrate and spoils the quality of the coating. The study of air entrainment in coating flows has largely been based on dip coating experiments where a smooth flat substrate is plunged into a large pool of stagnant liquid (for a review, see Burley, 1992). These investigations pointed out the major role of the fluid properties in determining the air entrainment velocity. Recently, experiments were carried out by the present authors (Cohu and Benkreira, 1998) in an original dip coating arrangement (labeled "angled dip coating") where the wetting line was not perpendicular to the substrate speed. It was established experimentally that air entrainment in dip coating begins only when *the component of the substrate speed normal to the wetting line* exceeds a critical velocity which depends only on the properties of the liquid used. In other words, having the angle formed by the wetting line and the substrate velocity vector differ from 90° by an angle β increased the air entrainment velocity by a factor $1/\cos\beta$. This result had been anticipated earlier by Blake and Ruschak (1979) who, however, did not show conclusive experimental data. In this article, the application of the same principle to another class of coating flows, referred to as premetered coating processes, is investigated for the first time.

Premetered coating processes are coating operations where all the liquid fed to the coating head is applied to the substrate. This includes slot or extrusion coating, curtain coating, and slide coating. In slide coating, one or several premetered layers of liquid flow over an inclined plane bridge the narrow gap between the edge of the plane and the web, wet the web and get entrained by it to form a film. Even though this coating method is flexible, its range of applicability is not unlimited. In particular, when the flow rate of liquid is too low and/or the substrate speed is too fast, the coating bead becomes unstable. This has been termed the low-flow limit of coatability (Gutoff and Kendrick, 1987). As long as moderate coating thicknesses are required, the most serious limitation of slide coating operations is air entrainment. Gutoff and Kendrick (1987) found that the air entrainment velocities in slide coating with no bead vacuum are identical to those in plunging tape experiments and depend very little on the flow rate of liquid and on the width of the gap between the edge of the slide and the web. In contrast, air entrainment velocities in slot coating (Lee et al., 1992) and curtain coating (Blake et al., 1994) are usually higher than in dip coating and depend strongly on flow parameters such as flow rate, slot gap, or curtain height. The reason is that the flow in slot coating and curtain coating provides a significant "hydrodynamic assist" of dynamic wetting (Blake et al., 1994), which is apparently not the case in slide coating. This additional complexity of slot and curtain coating motivated the choice of slide coating in the present investigation.

Experimental Studies

An angled slide coating apparatus was designed in which the angle formed by the dynamic wetting line and the substrate motion could differ from its standard value of 90° (Figure 1). Although slide coating is usually operated to coat a substrate arranged (nearly) vertically at the point of application (Hens and Van Abbenyen, 1997), angled slide coating is more easily operated to coat a horizontal substrate. The reason is that the edge of the slide must remain horizontal; otherwise, the liquid on the slide would no longer flow towards the substrate. The path of a nonhorizontal substrate should therefore extend in all three dimensions, which, although feasible, poses problems. Also, the substrate cannot be wrapped around a backing roller. The experimental setup used in the experiments is shown in Figure 2. The tensioned, unsupported web (a 110-mm-wide Melinex film) was running horizontally beneath the coating head, which consisted of a single-cavity die and a slide 60-mm long inclined 30° from the horizontal. The sharp edge of the slide formed, with the substrate, a gap 0.6-mm wide. The coating head was suspended by a frame above the web and could rotate in the horizontal plane, so that the angle formed by the wetting line and the substrate velocity vector could be changed. Four values of this angle corresponding to $\beta = 0$, 30, 45 and 60° (see Figure

Correspondence concerning this article should be addressed to H. Benkreira.

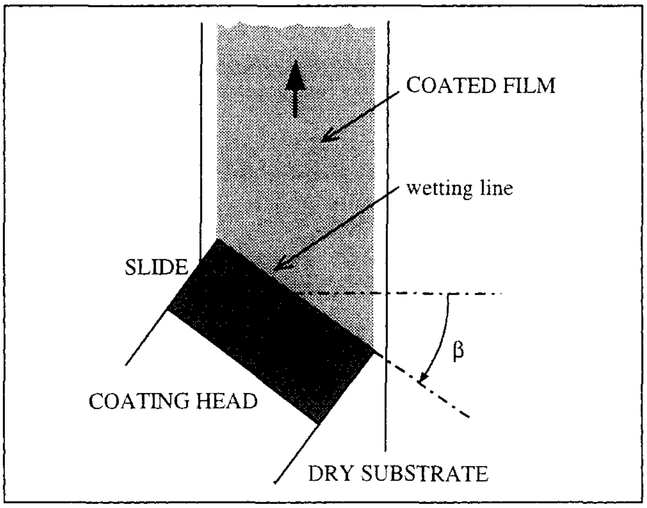

Figure 1. Angled slide coating (top view).

1) were tried. The width of the coating head was $w = 100$ mm and the coated width was $L = w \cos\beta$. No bead vacuum was imposed. Four mineral oils were used as Newtonian test fluids. Their properties are listed in Table 1. The liquid was pumped to the coating head using a precision gear pump (Stanhope, Bradford, U.K.). Flow rates were measured by collecting and weighing the liquid emerging from the slide throughout a known period of time. Substrate speeds were measured using a revolution counter mounted on an idler roller. All experiments were carried out at room temperature, approximately 27°C.

In each run the liquid volumetric flow rate Q was fixed at a given value, and the substrate speed V was adjusted down to obtain a continuous coating. Then, the speed was increased until either the low-flow limit of coatability or the air entrainment limit was reached. In the former case, bead instability (usually triggered by edge effects when $\beta \neq 0$) would lead to the appearance of large dry patches on the substrate. When this phenomenon was observed, the flow rate was increased until a continuous coating was again obtained and then the speed was increased further. Eventually, a speed was attained at which the dynamic wetting line (which could be viewed from underneath through the transparent substrate) would break up into a characteristic sawteeth pattern (Burley, 1992). This corresponded to the onset of air entrainment. At this point, both the speed and the flow rate were recorded. In order to terminate the test, further increases of the flow rate were imposed and the corresponding air entrainment velocities were measured.

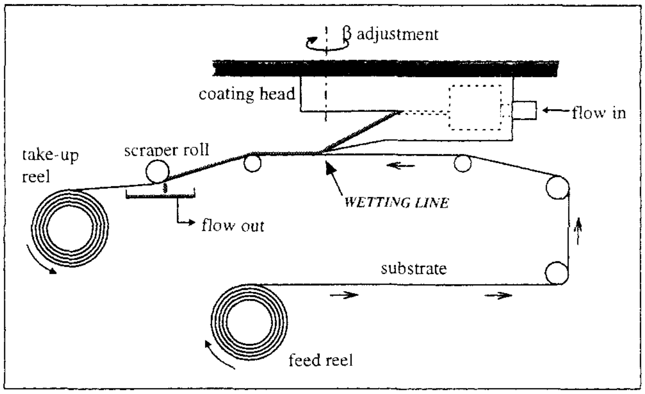

Figure 2. Experimental setup.

Results and Discussion

In plunging tape experiments, the air entrainment velocity with Newtonian liquids and smooth substrates may be correlated with the liquid viscosity μ, surface tension σ, and density ρ, as

$$V_{ae} \approx 70.5 \left[\mu \left(\frac{g}{\rho\sigma} \right)^{0.5} \right]^{-0.77} \quad \text{(in cgs units)} \qquad (1)$$

with $g = 981$ cm/s^2 (Burley and Jolly, 1984; Burley, 1992; Cohu and Benkreira, 1998). Although in the present work higher air entrainment velocities were obtained with lower fluid viscosities in agreement with Eq. 1, air entrainment velocities with $\beta = 0$ were found to be much lower than predicted by the above correlation. This is shown in Table 1. This discrepancy with plunging tape data constrasts with the findings of Gutoff and Kendrick (1987) and may be attributed to the particular geometry of the slide coater used here, which was designed to coat a horizontal web. For a given liquid at any angle β, the onset of air entrainment V_{ae} was also found to depend slightly on the flow rate of liquid supplied to the substrate. The same behavior was found by Gutoff and Kendrick (1987) in some of their experiments, and suggests a small contribution of the flow in assisting the dynamic wetting process.

In order to magnify the influence of β on the air entrainment velocity, all the data obtained are plotted in Figure 3 where the *component of the substrate speed normal to the wetting line* $V\cos\beta$ is reported for various film thicknesses, $h = Q/VL$ at the onset of air entrainment. In spite of the scattering of the data, the curves obtained for a given liquid with

Table 1. Liquids Tested and Air Entrainment Velocities at $\beta = 0$

Mineral Oil	Vis., μ (mPa·s)	Surf. Tens. σ (mN/m)	Density, ρ (kg/m^3)	Air Entrain. Vel. at $\beta = 0$ (cm/s)	
				Plunging Tape*	This Work**
1	130	32	886	15	10–11
2	74	32	881	23	12–15
3	35	31	876	40	23–30
4	14	31	872	80	40–54

*Data established after Burley and Jolly (1984) (Eq. 1).
**Depending on the flow rate of liquid.

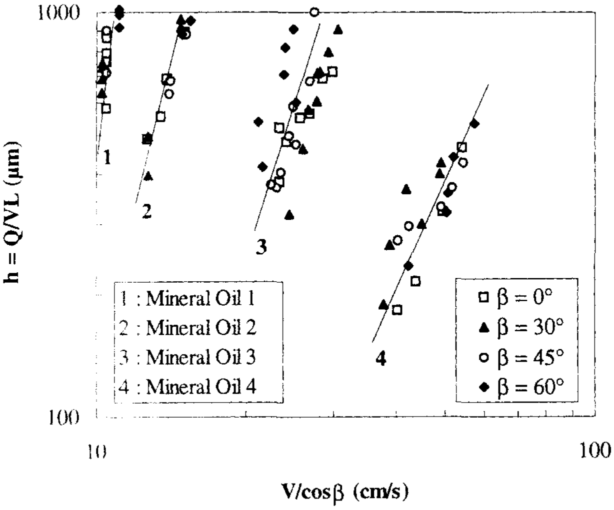

Figure 3. Film thickness vs. component normal to the wetting line of the substrate speed for four liquids and four values of angle β.

various angles β clearly superimpose. This shows that the speed which is relevant to air entrainment in slide coating is not the velocity V of the substrate itself, but its component normal to the wetting line $V\cos\beta$. Therefore, as in dip coating (Cohu and Benkreira, 1998), angling the wetting line with respect to the substrate motion (that is, increasing β) increases air entrainment velocities by a factor $1/\cos\beta$ regardless of any other parameter.

It is noteworthy that the increase in the air entrainment velocity due to changes in β (up to a factor 2 for $\beta = 60°$ compared to $\beta = 0$) is much greater that the variations of V_{ae} due to changes of the flow rate (no more than 30 or 40% for a threefold increase in the flow rate). This suggests that the influence of β on the air entrainment velocity cannot be simply explained by changes in the macroscopic hydrodynamics using the argument of hydrodynamic assist of dynamic wetting. Conversely, the results are consistent with the concept of a maximum speed of wetting (that is, under given flow conditions the speed of a wetting line normal to itself is limited) put forward by Blake and Ruschak (1979) and further explained by Cohu and Benkreira (1998). Thus, the influence of β on air entrainment is apparently of kinematic—and not of dynamic—origin, which ultimately suggests that angling the wetting line delays the onset of air entrainment in *all* coating flows.

Conclusion

This study has confirmed that having the dynamic wetting line not perpendicular to the substrate motion is an effective way to delay air entrainment in coating flows. In this investigation, slide coating was considered because this flow does not provide a significant hydrodynamic assist of the wetting process. This choice enabled us to show that the effect of angling the wetting line is purely kinematic. However, angling the wetting line in slide coating presents a number of practical drawbacks. As explained earlier, the substrate is preferably horizontal, which may favor air entrainment. Also, in the absence of a backing roller, the bead is very sensitive to fluctuations in the web movement. Such problems should not affect curtain coating, which is well designed to coat a horizontal, unsupported web. Angled curtain coating should therefore be investigated more thoroughly. In particular, it is necessary to find out how angling the wetting line in curtain coating will affect the capability of this flow to assist the dynamic wetting process. An additional challenge will be to determine the film thickness distribution across the width of the substrate, as the flow in angled curtain coating (as indeed in angled slide coating investigated here) will necessarily involve a cross-web component.

Acknowledgments

This work was supported by a Marie-Curie fellowship awarded to Dr. O. Cohu under the T.M.R. Program of the Commission of European Communities.

Literature Cited

Blake, T. D., A. Clarke, and K. J. Ruschak, "Hydrodynamic Assist of Dynamic Wetting," *AIChE J.*, **40**, 229 (1994).

Blake, T. D., and K. J. Ruschak, "A Maximum Speed of Wetting," *Nature*, **282**, 489 (1979).

Burley, R., "Air Entrainment and the Limits of Coatability," *JOCCA*, **75**(5), 192 (1992).

Burley, R., and R. P. S. Jolly, "Entrainment of Air into Liquids by a High Speed Continuous Solid Surface," *Chem. Eng. Sci.*, **39**, 1357 (1984).

Cohu, O., and H. Benkreira, "Air Entrainment in Angled Dip Coating," *Chem. Eng. Sci.*, **53**, 533 (1998).

Gutoff, E. B., and C. B. Kendrick, "Low Flow Limits of Coatability on a Slide Coater," *AIChE J.*, **33**, 141 (1987).

Hens, J., and W. Van Abbenyen, "Slide Coating," *Liquid Film Coating*, S.F. Kistler and P.M. Schweitzer, eds., Chapman and Hall, London, p. 427 (1997).

Lee, K. Y., L. D. Liu, and T. J. Liu, "Minimum Wet Thickness in Extrusion Slot Coating," *Chem. Eng. Sci.*, **47**, 1703 (1992).

Manuscript received Sept. 29, 1997, and revision received Jan. 27, 1998.