Effect of Substrate Entry Angle on Air Entrainment in Liquid Coating

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Many industrial processes depend largely on the wetting phenomenon. Coating solid substrates with thin layers of liquids is an important step, such as in the manufacturing of photoproducts, magnetic disk, galvanized steel, and paper products. In these coating processes, the wetting phenomenon is manifested in the importance of the wetting line, which is a three-phase solid-liquid-air interface. One of the basic requirements of most coating processes is the complete wetting of the solid substrates. Complete wetting is usually achieved when coating speeds do not exceed certain limits. Processes operating at speeds higher than this limit do not achieve complete wetting, primarily due to the entrainment of air inside the coating layer through the wetting line. When the coating speed increases, the wetting line is first broken into V-shaped formations, and then air bubbles are entrained from the tips of these formations.

Recent work investigated the relationships among liquid physical properties, the critical coating speed, and the nature of the solid surface. Buonopane and coworkers (1986) concluded that roughness leads to higher critical speeds of air entrainment. They also concluded that surface wettability has little or no effect on air entrainment velocities. They operated a plunging tape experimental system, using a number of plastic and paper tapes. Earlier, Perry (1967) reported that the nature of the solid surface influenced the dynamic contact angles, achieved at speeds prior to the onset of air entrainment. The parameters of air entrainment have been experimentally studied for different operating systems. Wilkinson (1975) used a roll-coating system with a scraper to remove the liquid from the roller prior to reentry. Bolton and Middleman (1980) used a similar system to study coating on a prewet substrate. They operated a roll-coating system without liquid removal. Burley and Kennedy (1976), Burley and Jolly (1984), and Gutoff and Kendrick (1982) studied air entrainment and the dynamic contact angles using a plunging dry tape into a liquid pool.

Recent work confirmed that liquid viscosity is the most important factor, influencing the critical speed of air entrainment. There is agreement that the wetting process depends on capillary and intermolecular forces at creeping and low speeds of wetting. Hydrodynamic forces play a dominant role in wetting at higher speeds. Blake and Ruschak (1979) presented a theory based on an adsorption/desorption model of the wetting phenomenon. The theory predicted the existence of a maximum speed, at which a wetting line can advance normal to itself. The theory also predicted that in the case of tapes entering the liquid surface at inclined angles, the breakup of the wetting line leading to air entrainment will be postponed to coating speeds greater than the critical speed of vertical coating. Burley and Jolly (1984) concluded from their experiments with plunging tapes that the critical velocities of air entrainment do not change with the angle of entry of the continuous flat surface into liquid. However, they observed that liquid adjacent to the lower tape surface tended to slip slightly ahead of the liquid above. Gutoff and Kendrick (1982) studied the dynamic contact angles using an apparatus based on the tilting plate method. Their air entrainment measurements, however, were taken for tapes entering vertically. Wilkinson (1975) concluded that air entrainment occurred at a critical value of the dimensionless capillary number Ca, which was approximately equal to 1.2 and was not greatly affected by the angle of entry in the range $60 < \alpha < 102°$.

It has already been established by several authors (Bolton and Middleman, 1980; Burley and Jolly, 1984; Gutoff and Kendrick, 1982) that Wilkinson's results were inaccurate. The critical capillary number of air entrainment was not a constant, but a function of the physical properties of the entrained liquid, particularly viscosity. The purpose of this work was to consider the effect of the angle of entry on the dynamic contact angle, the depth of interfacial displacement, and the critical parameters of air entrainment. The experimental system consisted of a continuously rotating liquid roller which was submerged in a liquid pool. The results showed that the angle of entry influenced the critical speed of air entrainment in the roll-coating system.

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Meanwhile, the angle of entry had little or no effect on the dynamic contact angles, measured at speeds lower than the critical speed. Measurements of the depth of interfacial displacement x_d showed significant variation with the angle of entry. These results contrast with Burley and Jolly (1984) experiments, which showed that the critical speeds do not change with the angle of entry for dry continuous tapes. The results also disagreed with Wilkinson's (1975) conclusion that the critical capillary number of air entrainment is $Ca = 1.2$ and that this value was not greatly affected by the angle of entry. However, our results were consistent with the theoretical prediction made by Blake and Ruschak (1979) for the effect of the entry angle.

Experimental Apparatus

The apparatus consisted of a black acrylic cylinder, which was horizontally mounted inside a transparent acrylic tank. The cylinder could be rotated by a variable speed motor, which provided a linear velocity at the cylinder outer surface, in the range $3 < V < 160$ cm/s. A heavy scraper was used to remove liquid from the cylinder surface prior to its reentry into the tank. Three cylinders with different diameters were used in the experiment. The tank was filled with liquid to different heights, allowing the cylinder surface to enter the liquid pool at different angles of entry. The liquids used were glycerol solutions, which covered a wide range of viscosities $71.3 < \mu < 748.0$ mPa · s, and liquid properties numbers $0.0007 < N_{pp} < 8.3954$, as shown in Table 1. Liquid viscosities were measured by a Haake viscometer, and surface tension coefficients were determined by the Fisher Surface Tensiomat, which is based on the platinum-iridium ring principle of du Nouy.

The experimental system was designed to measure the static and dynamic contact angles Θ, the displacement distance x_d, and the linear velocity of the plunging acrylic surface V. The depth of interfacial displacement was measured along the solid surface between the horizontal level of the liquid-free surface and the wetting line. A high-precision tachometer measured the rotational speed of the cylinder. A still-macrophotography system was used to record the profile of the liquid surface in the wetting line region. The system consisted of a 35-mm Camera, 105-mm lens, bellows, extension bellows, and a high-intensity UV light source. The maximum reproduction ratio was 1.2× at a working distance of 16 cm. The photographic pictures were interpreted by a digitizer-microcomputer system. Prior to taking pictures, the contact line was examined by a cycloptic microscope. Dynamic contact angles were recorded only for stable contact lines. Close to critical conditions of air entrainment, the contact line was unsteady. Measurements of all parameters were reproducible.

Results and Discussion

Measurements of the dynamic contact angles and the depth of interfacial displacement were made at a wide range of speeds lower than the speed corresponding to the onset of air entrainment. The level of liquid in the pool determined the angle of entry α, which was measured from horizontal. The angle α varied in the range $30 \leq \alpha \leq 80°$. Measurements of the dynamic contact angles showed little or no change with variations in the angle of entry. Figure 1 shows a typical sample of these results for a glycerol solution with a low physical properties number $N_{pp} = 0.029$. Meanwhile, measurements of the depth of interfacial displacement showed a consistent and significant variation with the angle of entry for the entire range of physical properties numbers $0.0007 \leq N_{pp} \leq 8.3954$. Figure 2 shows a sample of these results. Since the depth was measured from the horizontal level of liquid downward, at static conditions $V = 0$, the capillary rise is assigned a negative value. The disparity in displacement depths decreased as the coating speed approached the critical value.

Observations of the wetting line revealed a pattern, consistent with the pattern known for vertical wetting. As the coating speed increased, the straight horizontal wetting line broke at some locations into V-shape patterns, and then air bubbles started to break off from the vertices of the broken line. This pattern was observed for all angles of entry. Rollers of different diameters showed the same result. Therefore, the substrate may be considered nearly flat. All rollers, however, showed consistent variations in the critical speed of air entrainment with the angle of entry. The dependence of the critical speeds on the angle of entry was also observed in the entire range of liquid properties number N_{pp} (Figure 3). All results show that the breakup of the wetting line happened at speeds lower than the critical speed of air entrainment onto vertical substrates.

Compared with experimental systems using plunging tapes, our measurements correspond to the lower side of an inclined tape. The results suggest that for a particular glycerol solution, the breakup of the wetting line is postponed to higher coating

Table 1. Liquid Pool with Various Viscosities and Properties

Glycerol Solution	Density kg/m³	Surface Tension mN/m	Viscosity mPa · s	N_{pp}
1	1,256.0	61.8	748.0	8.3954
2	1,248.0	66.2	406.5	0.7393
3	1,247.4	66.4	385.8	0.5948
4	1,246.9	66.5	365.1	0.4751
5	1,245.8	67.3	303.1	0.2180
6	1,240.2	67.5	261.1	0.1195
7	1,238.2	67.7	221.7	0.0617
8	1,237.1	62.8	173.3	0.0288
9	1,236.5	67.8	179.5	0.0264
10	1,233.4	67.9	146.8	0.0118
11	1,229.5	67.9	125.8	0.0064
12	1,225.5	68.0	104.8	0.0031
13	1,214.3	68.4	71.3	0.0007

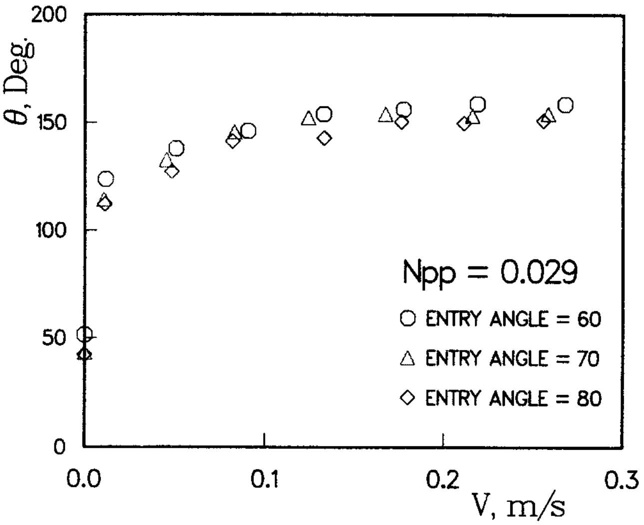

Figure 1. Variation of dynamic contact angle with velocity.

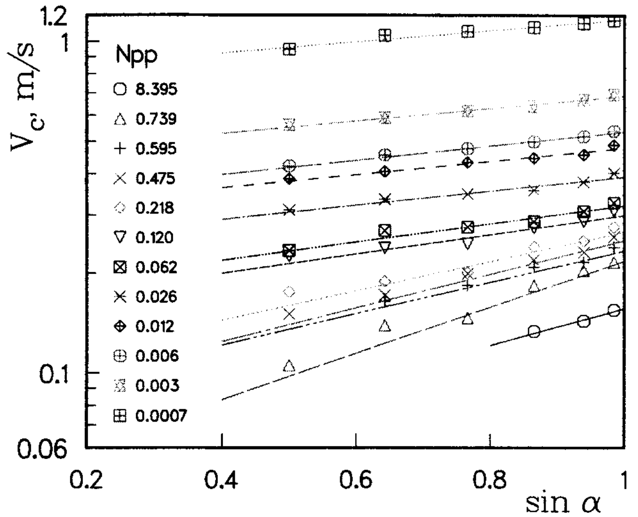

Figure 3. Variation of critical velocity for different liquid properties.

speeds, as the angle of entry α increases from a small value $\alpha = 30°$ to such higher values as 80°. This conclusion is in agreement with the predictions made by Blake and Ruschak (1979), if we compare the results of $\alpha < 90°$ in the roll-coating system to the lower and upper sides of a plunging tape, respectively.

The capillary number $Ca = \mu V/\sigma$ is the most relevant dimensionless group in the wetting phenomenon. The test liquid is most appropriately represented by the dimensionless physical properties number $N_{pp} = g\mu^4/\rho\sigma^3$ introduced by Kapitsa and Kapitsa (1949). Figure 4 shows the relationship between the critical capillary number and the physical properties number for different angles of entry. The results suggest that variations in the critical parameters are more pronounced for liquids with higher physical properties number. This in turn means a greater influence by the entry angle in the case of test liquids with high viscosity. Our experimental results can be used to develop the dimensionless correlation.

$$Ca_c = aN_{pp}^b \qquad 0.0007 \le N_{pp} < 8.4 \tag{1}$$

for different angles of entry $40 < \alpha < 80°$. The results of the regression analysis are listed in Table 2, where r is the regression coefficient. Comparison can be made with a correlation developed by Gutoff and Kendrick (1982) for $\alpha = 90°$,

$$Ca_c = 0.77\, N_{pp}^{0.088}, \qquad 10^{-10} < N_{pp} < 100 \tag{2}$$

Burley and Jolly (1984) developed another correlation for the vertical case.

$$Ca_c = 0.62\, N_{pp}^{0.06}, \qquad 10^{-6} < N_{pp} < 10 \tag{3}$$

It must also be noted that correlations 2 and 3 were developed for dry continuous tapes, while our correlations (Eq. 1) are for roll-coating systems. The reason for the discrepancy between our results for the roll-coating system and those of Burley and

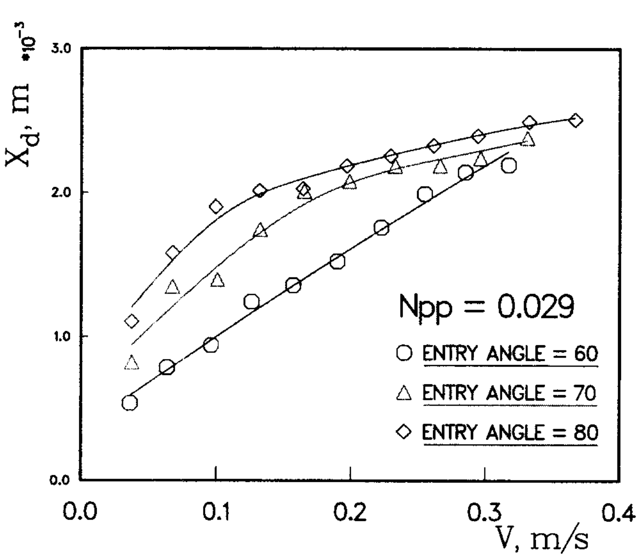

Figure 2. Variation of displacement depth with velocity.

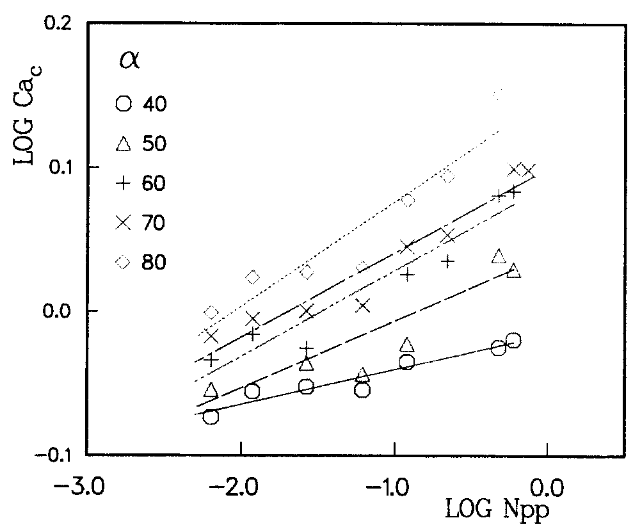

Figure 4. Dimensionless correlations of air entrainment.

Table 2. Regression Analysis

	$Ca_c = a\,N_{pp}^b$		
α	a	b	r
40	0.96	0.02	0.92
50	1.10	0.05	0.90
60	1.23	0.06	0.93
70	1.26	0.06	0.93
80	1.41	0.07	0.88

Jolly (1984) for the dry tape system is not clear to us, unless it is related to the experimental system. Burley and Jolly (1984) did notice some differences between the two sides of the tape. They reported that the initial V-shaped peaks formed were much smaller at the upper surface of the tape by comparison with those in the lower surface. They also reported that for high-viscosity liquids, the contact line on the upper side was observed to break up into small V-shaped peaks slightly ahead of the lower meniscus for a given tape velocity.

Conclusion

Consistent and significant variations in the critical speeds of air entrainment with the angle of entry were observed in a roll-coating system. This is in agreement with predictions made by Blake and Ruschak (1979).

Notation

a, b = constants
Ca = capillary number $\mu V/\sigma$
Ca_c = critical capillary number $\mu V_c/\sigma$
D = diameter of roller, m
g = acceleration of gravity, m/s^2
N_{pp} = physical properties number $g\mu^4/\rho\sigma^3$
V = coating speed, m/s
V_c = critical coating speed, m/s
x_d = depth of interfacial displacement, m

Greek letters

α = angle of entry, degrees
Θ = dynamic contact angle, degrees
μ = viscosity, Pa · s
ρ = density, kg/m^3
σ = surface tension, N/m

Literature Cited

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

Bolton, B., and S. Middleman, "Air Entrainment in a roll Coating System," *Chem. Eng. Sci.*, **35,** 597 (1980).

Buonopane, R. A., E. B. Gutoff, and M. M. T. Rimore, "Effect of Plunging Tape Surface Properties on Air Entrainment Velocity," *AIChE J.*, **32,** 682 (1986).

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).

Burley, R., and B. S. Kennedy, "An Experimental Study of Air Entrainment at a Solid/Liquid/Gas Interface," *Chem. Eng. Sci.*, **31,** 901 (1976).

Gutoff, E. B., and C. E. Kendrick, "Dynamic Contact Angles," *AIChE J.*, **28,** 459 (1982).

Kapitsa, P. L., and S. P. Kapitsa, "Wave Flow of Thin Layers of a Viscous Liquid," *Zh. Eksp. Teor. Fiz.*, **19,** 105 (1949).

Perry, R. T., "Fluid Mechanics of Entrainment Through Liquid-Liquid and Liquid-Solid Junction," PhD Thesis, Univ. of Minnesota (1967).

Wilkinson, W. L., "Entrainment of Air by a Solid Surface Entering a Liquid/Air Interface," *Chem. Eng. Sci.*, **30,** 1227 (1975).

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