Air entrainment in Dip coating under vacuum

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Abstract

Air entrainment studies in dip coating have formed over many years the essential experimental tool to understand[1-5] dynamic wetting in coating flows. Although limited (no hydrodynamic assistance) in its representation of all coating flows, dip coating captures the essential feature of dynamic wetting and air entrainment. It is also a convenient simple basis for formulating theories on dynamic wetting and its failure. In this study, dynamic wetting failures have been observed and corresponding air entrainment velocities measured in dip coating at atmospheric conditions as well as under vacuum with a series of substrates and silicone oil of various viscosities to see the effect of air viscosity on air entrainment velocity. A vacuum chamber was designed and built for the purpose of these experiments and will be described in this paper. Silicone oils were used due to their low vapour pressure to prevent boiling under vacuum. Throughout the experiments, temperature changes in the vacuum chamber were closely monitored and we observed that the temperature remained constant with all test liquids. When we compared the air entrainment speeds at atmospheric conditions and also at low pressure, we found that air entrainment speed is delayed significantly as the pressure in the vacuum chamber is increased. When the results were plotted as air entrainment velocity against pressure, an exponential relation was observed. The data from this study have significant implication to the fundamental understanding of dynamic wetting. Indeed they form the *missing data link* to fully understand this phenomenon.

1 Introduction

The main objective of a coating process is to lay a thin layer of coating liquid onto a solid surface. Many coating operations involve high-speed contact between a liquid and a solid substrate. Examples of such processes may be found in the production of photographic film, coating, dyeing, printing etc. In these and most other coating applications, the main requirement of the coating flow is that it must produce a perfectly flat film of a uniform thickness (5 – 100 μm) and avoid any defects. The whole operation must also be carried out at reasonably high speed (> 1 m/s) to be economical. However, these operations are speed restricted because above a certain critical speed air is entrained at the three-phase contact line and trapped between the solid and the coating liquid. As a result, the quality of the product is affected and the processing speeds are limited. Dynamic wetting and air entrainment has been extensively studied by many including Deryagin and Levi (1964), who were the first to observe that when the critical velocity is reached, the dynamic wetting line that is originally straight and horizontal becomes unstable and breaks into straight line segments that are inclined from the horizontal. At any instant, the wetting adapts a sawteeth shape and air gets entrained at the trailing vertices where two straight-line segments seem to intersect. Burley and Kennedy (1976), Gutoff and Kendrick (1982), Burley and Jolly (1984) investigated air entrainment and produced correlations

for air entrainment velocity as a function fluid physical property but mainly fluid viscosity. A full description of the actual mechanism of air entrainment may be found in O'Connell (1989), Burley (1992), Veverka (1995) and Benkreira (2004).

Many attempts have been made to correlate the air entrainment velocity with the fluid properties and the solid substrate involved. Burley and Kennedy (1976) carried out experiments using smooth substrates and derived the following empirical correlation:

$$V_{ae} \approx 67.7\left[\mu\left(\frac{g}{\rho\sigma}\right)^{0.5}\right]^{-0.67} \tag{1}$$

Burley and Jolly (1984) derived the following empirical correlation for predicting the onset of air entrainment velocity from fluid properties:

$$V_{ae} \approx 50.5\left[\mu\left(\frac{g}{\rho\sigma}\right)^{0.5}\right]^{-0.77} \tag{2}$$

Gutoff and Kendrick (1982) experimentally found that viscosity was the predominant fluid property that controlled the air entrainment velocity and proposed the following correlation:

$$V_{ae} \approx 5.11\mu^{-0.67} \tag{3}$$

However, the purpose of this work is to produce experimental data to see the effect of air viscosity on air entrainment velocity. The effect of liquid viscosity of air entrainment velocity has been extensively studied however, the effects of air viscosity has mainly been neglected in coating flows.

2 Experimental

The dip coater used consists of a 60 mm wide vertical tape that was drawn downwards into and through a transparent tank containing the test liquid to a depth of 150 mm. To cancel the edge effects, the tank cross section was 135 mm × 90 mm. The test liquids used were silicone oils of various viscosities ranging from 20 – 500 mPa.s and their physical properties are given in Table 1. The tape was fed from a spool, plunged into the liquid, emerged through a sealed slit at the bottom of the tank and was finally wound around a cylinder driven from outside (through a special seal) by a variable speed motor. The tape velocities were measured with an optically triggered digital tachometer mounted on one of the rollers. This tachometer was also calibrated a number of times with the normal potable tachometer to check its consistency. The onset of the air entrainment was determined by slowly increasing the speed of the substrate until the break-up of the wetting line into a saw-teeth pattern could be observed with the naked eye under proper

illumination. With high viscosity liquids, it is difficult to observe the saw-teeth pattern with the naked eye and therefore had to rely on the use of a digital video camera with microscopic lenses was used to provide a better picture of the breaking of the wetting line. In some cases, (with liquids of very low viscosity), one large V in the order of up to 3cm was observed. Figure 1 shows the dynamic wetting line at break up point with its V segment.

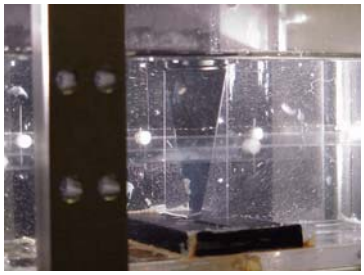


Figure 1. One large V roughly 3 – 4 cm observed with polyester substrate 53818 (transparent) and glycerin/water solution of viscosity 84 mPa.s.

In these experiments, the dip coater used was the same as that used by Benkreira (2004) but in this case, it was placed inside a vacuum chamber. The vacuum chamber has a rectangular shape with dimensions 400mm x 800mm and was constructed from 10 mm thick steel. The chamber has three viewing ports, two on the sides and the third one at the front through which the air entrainment process is usually observed. Pressure gauges were fitted to the chamber in order to monitor the pressure of the chamber. A normal thermometer is placed in the liquid inside the chamber and the temperature inside the chamber was closely monitored. In order to reduce experimental errors, each experiment was repeated at least three times. However, the discrepancies between individual and averaged data were always found to be in the range of ±5 – 10%. All coating experiments were conducted at room temperature (20 – 25°C) with silicone oils. The viscosities of all coating liquids were measured using Bohlin CVO 120 viscometer. Surface tension and contact angle measurements of the fluids were carried out using FTA 188 video tensiometer as shown in Table 1. In total, six substrates were used, which include three paper substrates and three polyester substrates. Their surface roughness data and corresponding contact angles are given in Table2. Surface roughness analysis was carried out using a picoforce multimode atomic force microscope and a Taylor Hobson Talysurf 4 instrument.

Sample	Viscosity (mPa.s)	Surface Tension (mN/m)	Density (kg/m^3)
1	8.86	≈19.00	≈900
2	18.12	≈19.00	≈930
3	49.59	18.71	951
4	86.94	19.53	958
5	181.47	19.02	962
6	459.48	18.98	963

Table 1 shows the measured physical properties of silicone oil samples at 25 °C.

Substrate	R_a (μm)	R_z (μm)	$\theta_{t = 0s}$	$\theta_{t = 3s}$
10908F (Paper)	0.73	3.22	78.40	11.97
10908B (Paper)	0.10	0.55	57.28	5.65
10929F (Paper)	0.63	2.90	63.31	12.90
10929B (Paper)	0.32	1.58	56.76	8.40
R725F (Paper)	0.44	1.75	59.77	14.68
R725B (Paper)	2.12	9.35	64.11	9.27
NSFM F (PE)	0.31	1.52	64.78	12.99
NSFM B (PE)	0.28	1.32	56.97	13.39
53818F (PE)	0.03	0.185	56.50	12.38
53818B (PE)	0.03	0.178	60.18	12.18
53281F (PE)	0.03	0.115	59.60	13.71
53281B (PE)	0.07	0.230	56.71	10.95

Table 2 shows roughness of the substrates used and corresponding contact angles with silicone oil sample 1 of viscosity approximately 50 mPa.s.

A vacuum pump with some valves fitted on was used to create the vacuum inside the chamber. Once the pressure was built up in the chamber, the liquid was left in the chamber for about an hour to be degassed. A needle valve was fitted on to the vacuum line to control the pressure more accurately.

Figure 3.Experimental set-up.

3 Results and Discussions

The important result here is the effect of air viscosity on air entrainment velocity. When we compare the results of air entrainment velocity at atmospheric conditions with the results obtained at low pressure, there is a significant difference between the two. Air entrainment velocity is significantly delayed by lower the pressure in the vacuum

chamber i.e. reducing the viscosity of the air inside the chamber. We have observed that the speed at which air is entrained is almost an exponential function of the pressure especially in the low-pressure region, as it is a function of viscosity.

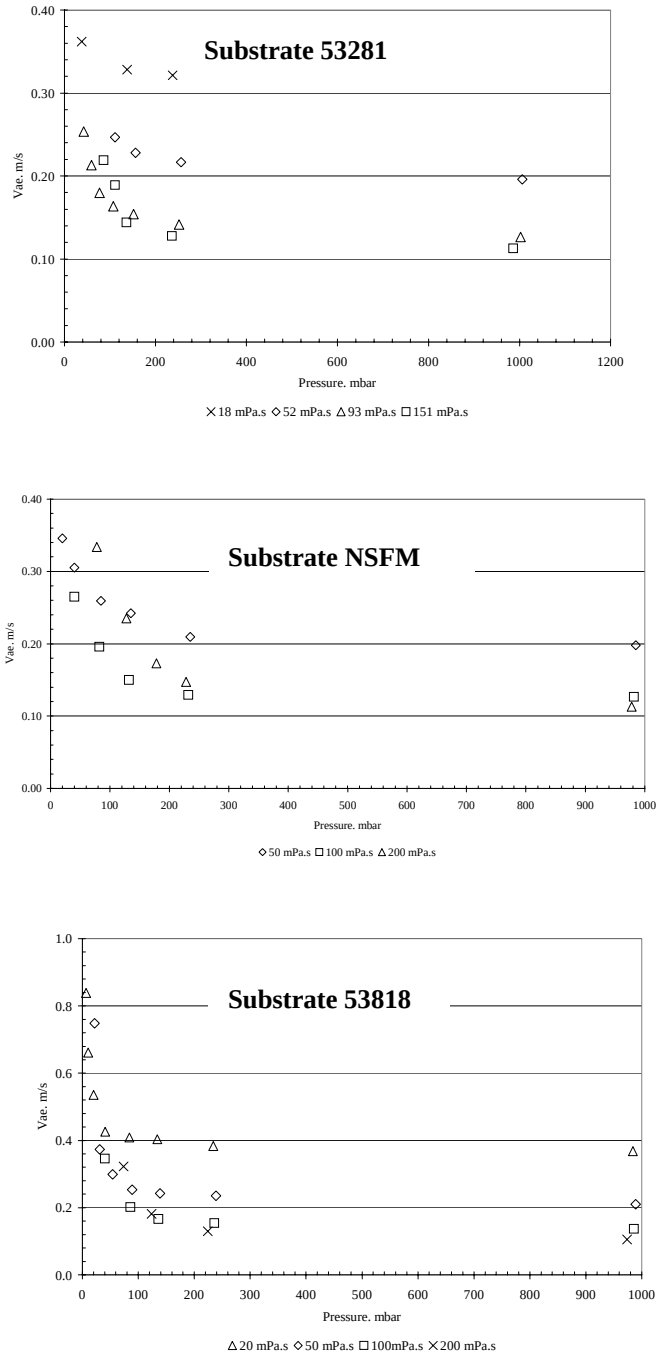
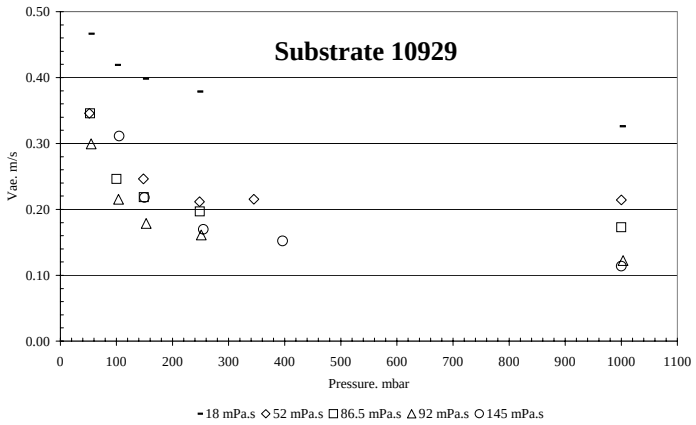
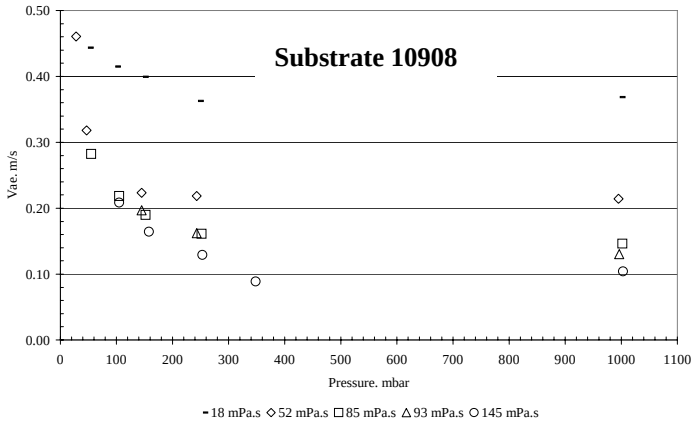


Figure 4. Air entrainment speed against pressure for the three polyester substrates.





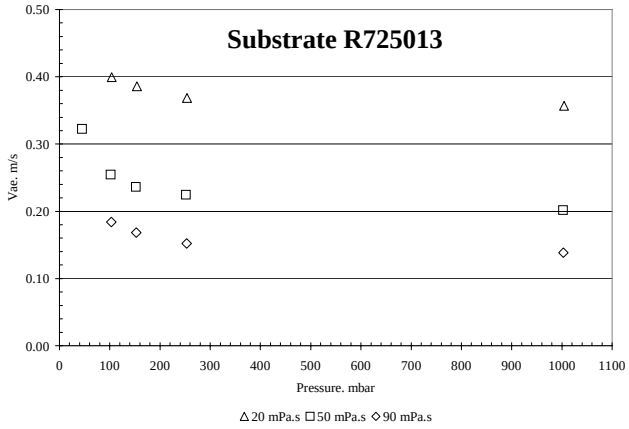


Figure 5. Air entrainment velocity against pressure for the three paper substrates

4 Conclusion

This work has provided new experimental evidence of the effect of vacuum on air entrainment in dip coating. It shows that the viscosity of air (which is normally neglected when dealing with coating flows) has a significant effect on the speed at which air is entrained. Our results show that very high coating speeds could be achieved provided that the experiment is carried out under vacuum.

5 Acknowledgement

We would like to thank the Engineering and Physical Sciences Research Council (EPSRC) for their financial support.

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