The benefits and limitations of using electrostatic assist for bead stabilisation in slide bead coating systems

J.B.Ikin, H.M.Thompson and P.H.Gaskell
Engineering Fluid Mechanics Research Group, School of Mechanical Engineering, University of Leeds,UK.

Abstract

The conventional application of suction to stabilise the bead in an industrial slide bead coating process is prone to producing streaks associated with the generation of vortices as the static wetting line migrates down the lip face [1]. It is known that electrostatic assist benefits slide bead and curtain coating by postponing air entrainment to higher coating speeds [2,3]. Flow visualisation studies have demonstrated how the dynamic contact angle is reduced and the wetting line forced upstream for the electrostatically assisted slot and curtain coating processes [3,4].

In this study, a unique method for visualising the bead through the coating gap [5] for an industrial slide bead process confirms, for example, that the dynamic contact angle reduces from typically 142° to 131° on increasing the electrostatic potential on a paper web to +507 volts. Results moreover demonstrate that the static wetting line then remains pinned to the lip corner. Finite element calculations have shown there is consequently less propensity for streaks [1]. Images of the upper free surface, however, confirm that the curvature in the bead forming zone increases with charge level resulting in an increased risk of ribbing instability [2,6].

1 Introduction

It is general practice within the industries using the slide bead coating process to plot a "coating feasibility window" depicting suction pressure as a function of coating speed [7] - Figure 1.

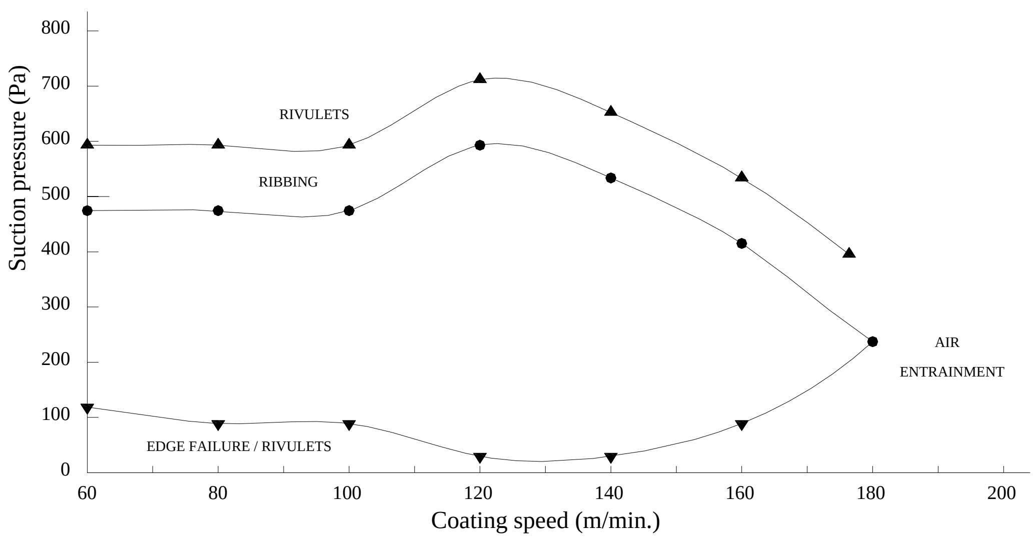


Figure 1: A typical feasibility coating window

The upper limit to suction is generally caused by ribbing flow [6,7] and the lower limit by edge bead break [7]. The lower and upper limits for suction converge at a point representative of the maximum coating speed – usually dictated by the onset of air entrainment. These limits form the feasibility "window".

The “coating quality window” lies within the feasibility window and takes into account subtle defects such as streak-lines and mottle. The multi-layer slide coating process is especially prone to generating streak-lines. In extreme cases, foreign matter can get caught in the nip between the termination of the slide and locally break the bead. In the general case, however, the fluids become disturbed and redistribute by flowing sideways to form regions of non-uniform coating thickness [8]. The free surface, when thus disturbed, tends to heal due to the levelling action of surface tension [9]. Healing is minimal at an interface between adjacent layers, however, due to the lack of interfacial tension [10]. This results in visible defects on the final dried coating – Figure 2.

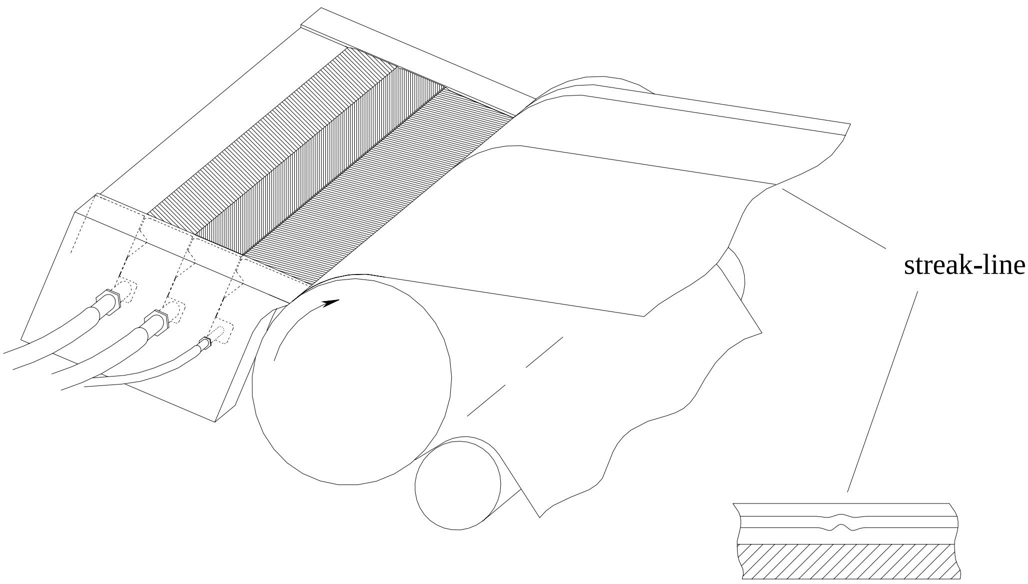


Figure 2: Narrow width coating showing a single streak-line

It is now well established that recirculations in the coating flow are a major cause of streak-line defects [7]. The vortices can trap particles or bubbles, which then disturb the flow. Solutions of unstable chemistry will generate solid deposits at the walls due to the long residence time associated with the vortex. Pieces of the solid deposit, being often fragile in nature, can subsequently become dislodged to form a ragged wetting line, which has been shown experimentally to lead to streak-lines. Noakes et al [1] showed evidence that the occurrence of streak-lines is directly linked to deposit growth, which in turn, closely relates to the strength of the vortex.

Vortices tend to occur where there is a sudden change in the direction of the flow. They can thus be found at the exits of the slots or in the bead forming zone [11,12,13]. Figure 3 illustrates what happens as suction is increased thereby causing the static wetting line to migrate down the lip face. The illustration shows two of a whole family of counter-rotating vortices as initially described by Moffatt [14]. Pinning the static wetting line to a sharp corner significantly enhances the robustness against streak-lines [1]. One method of accomplishing this is to use a thin low viscosity carrier layer while increasing the average viscosity of the complete assembly [1].

The need for stabilisation suction can be partially offset using electrostatic assist – a technique well established in the coating industry [15]. Dipoles bound within the surface of the uncoated substrate can be favourably orientated to yield a net surface charge. This can be accomplished by setting up grid ionisers [16,17], using a bristle brush electrode [15] or a corona discharge opposite a grounded metal roller bearing the web [15]. Alternatively, a high voltage can be applied to the coating roller thereby generating an electrostatic field between the roller and the coating applicator [18].

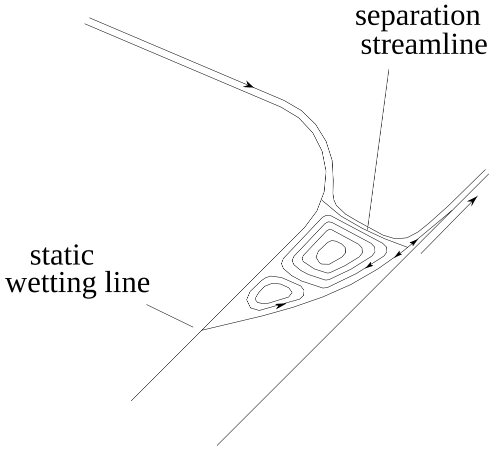


Figure 3: Typical counter-rotating vortices in the coating gap

Blake et al [3] explain that the electrostatic field at the dynamic wetting line generates a force which acts normally to the lower free surface where the liquid is conductive. The result is an effective change in local pressure, which enhances wetting by reducing the dynamic contact angle and postpones the onset of air entrainment and can thus lead to an increase in the maximum coating speed

Vandaela and Vancoppenolle [2] and Quiel et al [18] have demonstrated that whereas charge assist resist the onset of air entrainment, it also leads to increased susceptibility to ribbing. Vandaela and Vancoppenolle [2] suggest that the ribbing is induced by an increase in curvature of the upper meniscus while not showing any experimental evidence for this. Quiel et al [18] show that combining the addition of a shear thinning thickener to the bottom layer with charge assist tends to resist both ribbing and the onset of air entrainment leading to an overall significant improvement in the coating window.

The development of methods for visualising the effect of electrostatic assist presents a formidable challenge due to the fact that substrates of practical significance are generally opaque and visual access to the dynamic wetting line severely limited. Zwan et al [19] used a needle coater to demonstrate how the dynamic contact angle decreases with increasing polar charge for a cylindrical jet of fluid impinging on a substrate. Fermin and Scriven [4] developed a technique for quantifying the influence of electrostatic fields on a falling curtain by coating onto a scraped hollow glass roller.

In this paper, we present the application of a unique method [5] for visualising the bead through the coating gap for a slide bead process in the presence of industrially relevant paper webs. The results serve to highlight the advantages and disadvantages of using electrostatic assist to augment suction stabilisation.

2 Experimental Set-up

A brief summary of the experimental set-up is given here. The interested reader can find more detail in Ikin [20]. A narrow width pilot coating machine fitted with a slide bead coater was used for studying charge assist effects. The specialised ancillary equipment necessary for carrying out this work include the apparatus for controlling and monitoring polar charge and for profiling the free surfaces of the coating bead.

2.1 Charge Control Apparatus

The orientation of captive dipoles was controlled using an array of grid ionisers [16,17] – Figure 4.

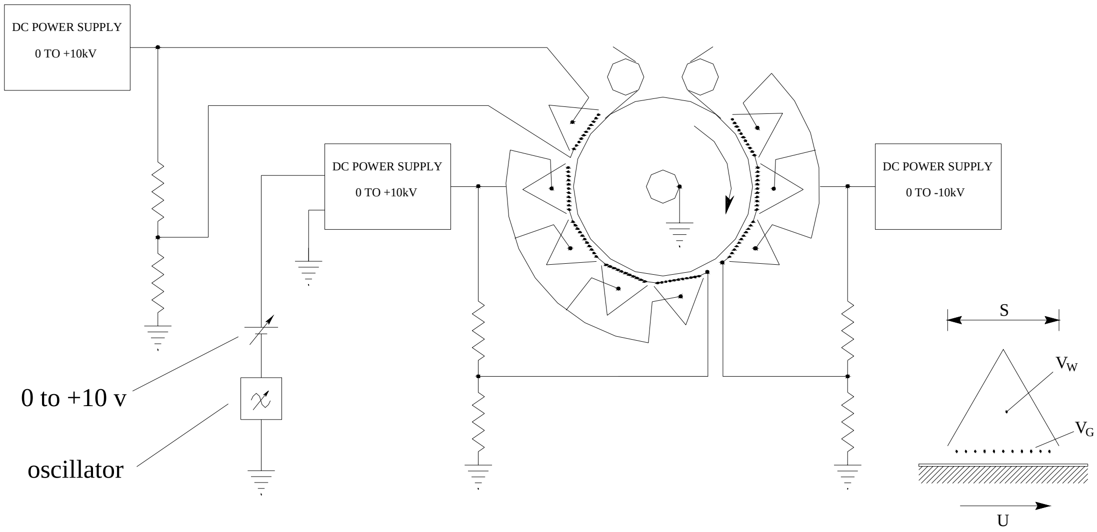


Figure 4: Charge control apparatus

Each charging device comprised an earthed electrode of width S at the centre of which was suspended a thin tungsten wire connected to a DC power source supplying a potential V_W – typically a few thousand volts. The electrode was mounted close to an earthed roller carrying the web – where the surface to be coated faced outwards. A grid or screen of closely spaced wires was mounted in close proximity to the web as shown and maintained at a potential V_G. The voltage V acquired by the web when at an initial voltage V_0 depends on web speed U and is given by:

$$V = V_G - (V_G - V_0) \exp\left[\frac{-kNS(a_0 + a_1V_W + a_2V_W^2)}{CU}\right]$$

where N is the number of electrodes, C is the capacitance of the web per unit area and a_0, a_1 and a_2 are constants. A typical response characteristic for an array of positive grid ionisers is shown in Figure 5.

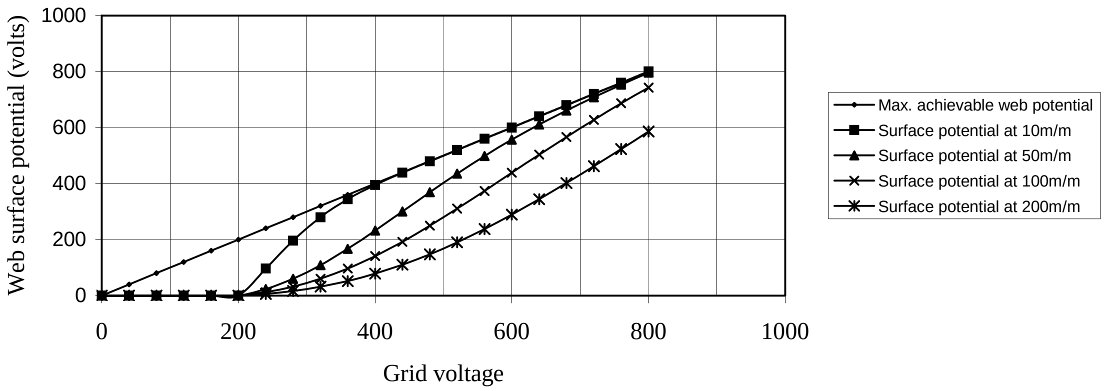
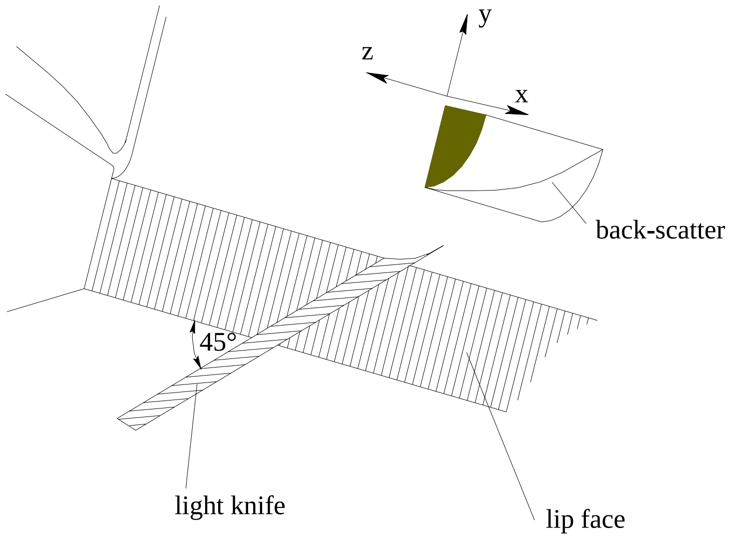


Figure 5: Response of positive grid ionisers for four different web speeds

In practice, the charge distribution was firstly smoothed by subjecting the surface to negative ions and then charged positively to achieve a desired web potential. The charge was monitored using a TREK Model 366 non-contacting electrostatic voltmeter probe mounted immediately below the coating roller.

2.2 Apparatus for profiling the free surfaces

The method used for monitoring the lower meniscus was to illuminate the flow with a sharply focused light knife. The beam was aimed through the gap between the cascade lip and web in a direction within the plane of the lip face. The beam axis was inclined at an angle at 45° as shown in Figure 6. The coating comprised a single layer of photo-emulsion containing scattering particles of silver halide and back scatter viewed along direction y.



bead profile: $y = f(x)$

laser path: $y = -z$

hence image is: $z = -f(x)$

Figure 6: Principle used for profiling lower meniscus

The method used for viewing was to mount a right angle prism within a specially designed miniature probe, which was inserted into the suction box through the side wall after initially establishing the coating bead – Figure 7.

A 5mW Lasiris MFL Micro-Focus laser operating at a wavelength of 635nm and focused to form a light knife of width 13µm at the e^{-2} points at a working distance of 65 mm was used as light source. The image of the free surface profile was recorded using a Cohu model 6712 monochrome camera fitted with Bausch and Lomb Monozoom-7E optics. The camera operated at ½" format with sensitivity down to 0.005 lux and resolution 4×10^5 pixels. The magnification range of the monozoom assembly was between 13.4 and 93.6 and the working distance of the order of 80 mm. The laser, monozoom optics and camera were mounted on translation tables assembled on a swing frame as shown in Figure 8. This enabled the optics to be moved away from the side of the machine when not being used for recording the lower meniscus profile. Risk of fouling or splashing the optics while preparing the coating head or finally washing up was thereby minimised. It also allowed convenient access to the probe when the frame was withdrawn - thereby ensuring this could be rapidly inserted after making the bead and removed prior to opening up the gap at the end of recording.

A stable optical reference point – Figure 9 - was provided by machining a step in the face of the coater lip in an area considered by prior experience unlikely to affect the flow field for the range of suction pressures of industrial interest. The cavity formed by the step was partly filled with a wedge of epoxy resin to provide adequate drainage of solutions when initially starting the coating. The resin was pre-mixed with white oil based household paint in order to enhance optical contrast.

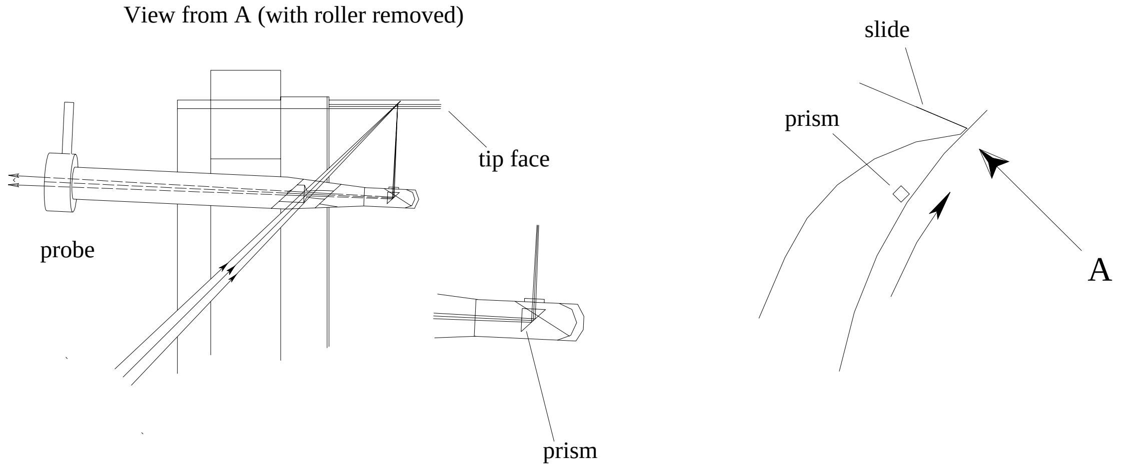


Figure 7: Receiver prism and housing

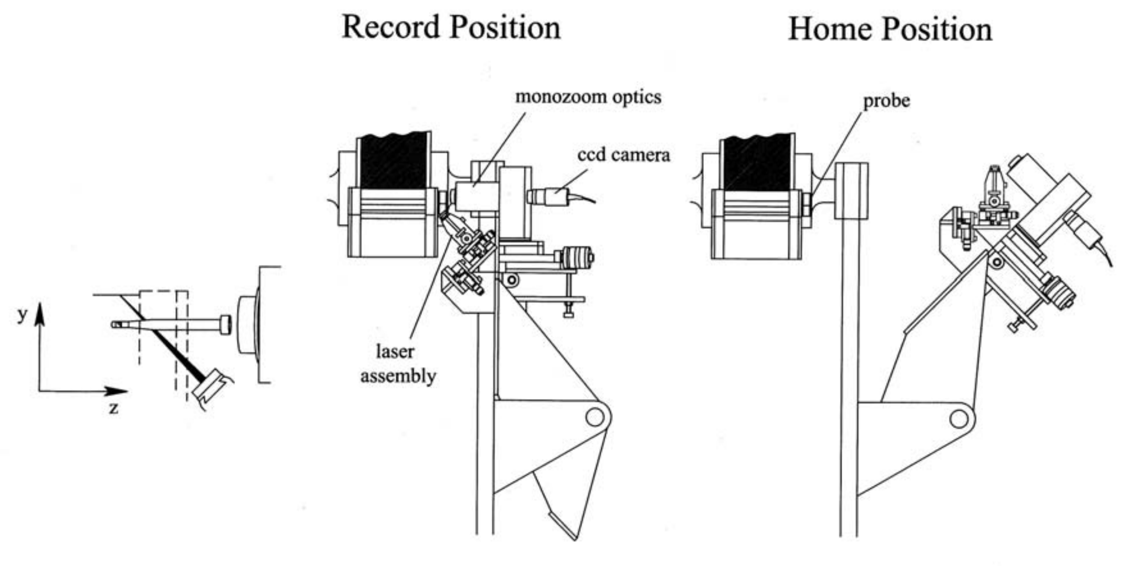


Figure 8: Lower meniscus monitor – view from behind the coater

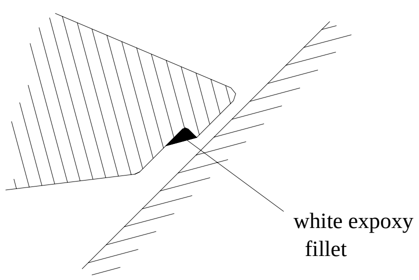


Figure 9: Method for generating a reference surface

The method used for monitoring the upper free surface was to illuminate the flow with a laser light knife and to view scatter from the side and at a glancing angle above the slide plane – Figure 10.

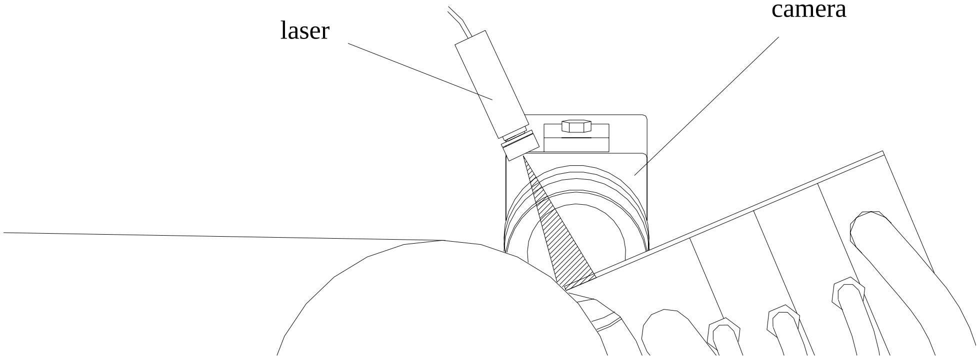


Figure 10: Upper meniscus monitor

3 Results

The dynamic response to a cyclically varying charge was determined initially with the prism housing and optics stationery and mechanically clamped as a precaution against any slight movement while recording.

A second trial allowed the charge control apparatus to be optimally configured to attain the maximum possible surface charge in order to increase sensitivity.

3.1 Dynamic response to varying polar charge

The surface charge was varied cyclically, the lowest and highest voltages being +5v and +507v respectively and the period 4.2 seconds – Figure 11.

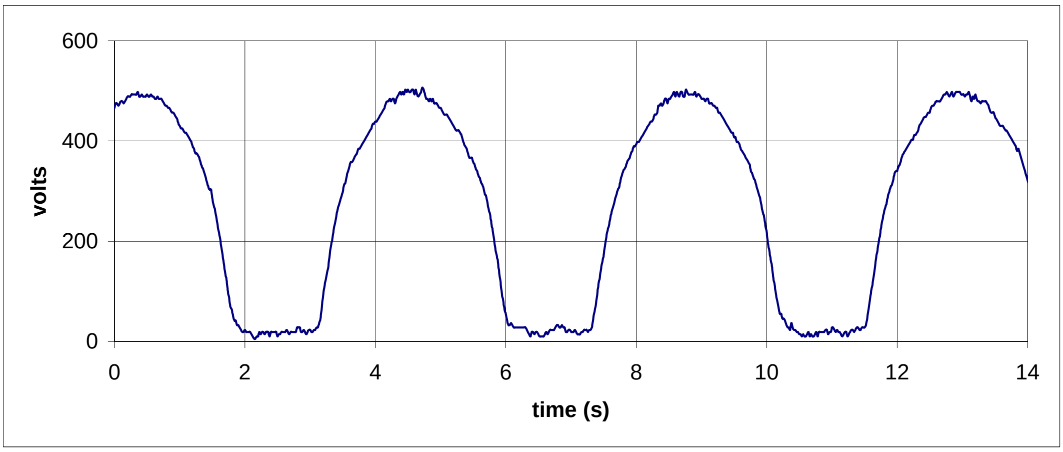


Figure 11: Charge waveform for determining dynamic response

Figure 12 shows the profiles of the lower meniscus at the instants in time when the dynamic contact angle was at the lowest and highest values of 130.8° and 141.7° respectively. The coating comprised a single layer of viscosity 24.2 mPa.s and of surface tension 28 mNm^{-1} when measured at a surface age of 1 second. The wet laydown was 65 µm and the coating speed 50 m/min. The stabilisation suction was 275 Pa and the coating gap 165 µm.

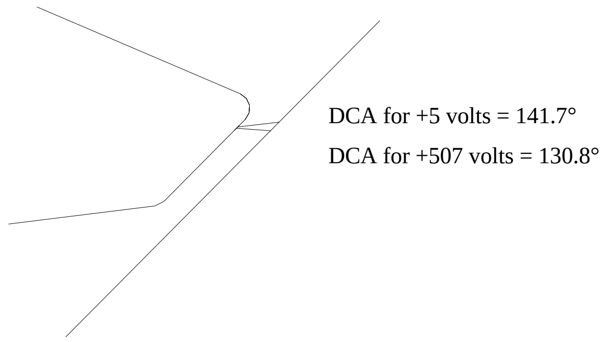


Figure 12: Response of the lower meniscus to varying charge for 165 µm gap

Figure 13 shows corresponding profiles for when the coating gap was opened up to 508 µm and the stabilisation suction maintained at 165 Pa. Here the dynamic contact angle is seen to peak at a maximum of 155.9° and a minimum of 140.7°.

These results show that the presence of electrostatic charge pulls back the dynamic wetting line thereby decreasing the dynamic contact angle. This explains why the onset of air entrainment can be postponed to higher coating speeds for the slide bead process using charge assist [2]. It is also observed that the static wetting line remains fixed. The force due to charge is thus predominantly localised at the dynamic wetting line. This contrasts with the force due to suction pressure, which acts uniformly along the entire length of the lower meniscus. Whereas charge assist serves to increase robustness against air entrainment, it also does so with less risk of downward migration of the static wetting line and the associated tendency for generating streak-lines compared with the use of suction pressure alone.

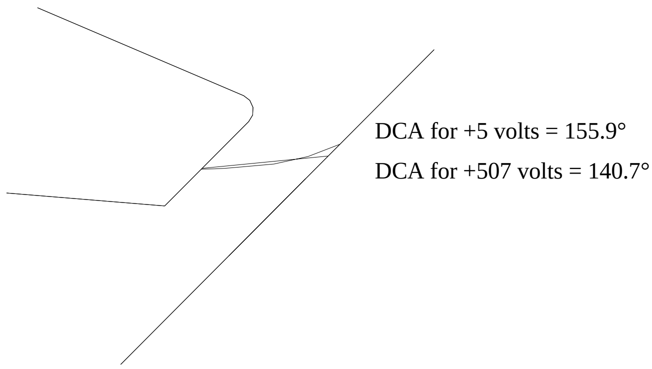


Figure 13: Response of the lower meniscus to varying charge for 508 µm gap

The corresponding profiles of the upper meniscus for a gap of 508 µm are shown in Figure 14. The curvature of the free surface is seen to increase slightly in the presence of surface charge.

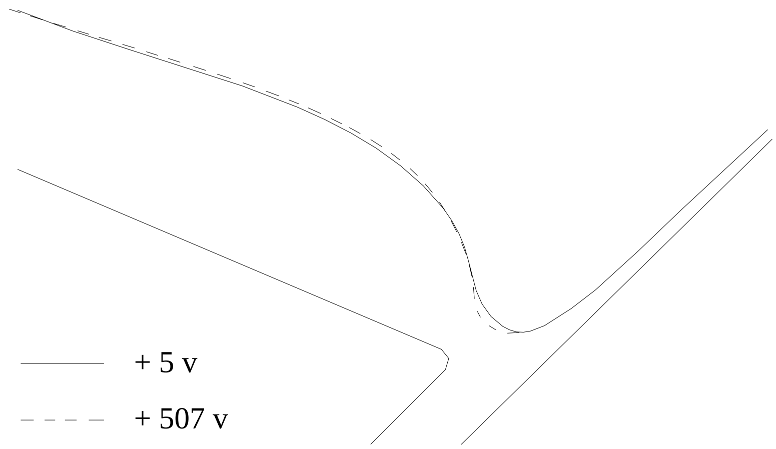


Figure 14: Response of the upper meniscus to varying charge for 508 µm gap

3.2 Response to a step change in polar charge

The charge control system was optimally configured and adjusted over two separate runs to achieve firstly 0 volts and secondly +700 volts. The properties of the solution remained unchanged. The wet laydown was set at 70.6 µm and the coating speed at 80 m/min. Raising the surface charge to achieve +700 volts opens up the coating window. For example when operating with a gap of 152 µm the minimum allowable suction pressure is reduced from 450 Pa to 300 Pa. Figure 15 shows the response of the bead with and without charge assist when operating with a gap of 495 µm and an optimised suction pressure of 292 Pa.

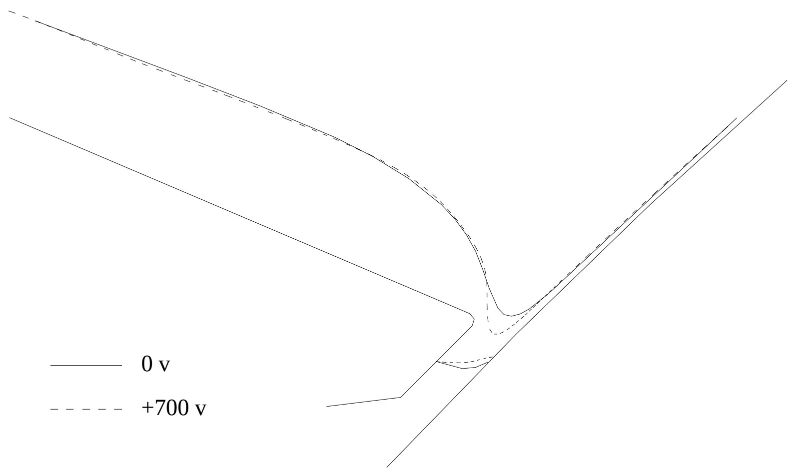


Figure 15: Response of the bead profile to a surface charge of +700 v using a gap of 508 µm

It will be seen that the bead waist now significantly deepens with increased surface charge – an effect known to be associated with an increased tendency for ribbing – Schweizer et al [6]. This confirms the hypothesis suggested by Vandaele and Vancoppenole [2] that the instability seen with charge assist is associated with increased curvature of the downstream free surface.

4 Conclusions

A unique method [5] for visualising the bead through the coating gap for a slide bead process has been applied in order to quantify the effects of bound polar charge residing on the surface of an industrially relevant paper web. Polar charges orientated to yield a net positive voltage at the surface of the substrate causes a reduction in the dynamic contact angle and results in a decrease in the minimum suction pressure required for maintaining stability and resisting air entrainment. The forces acting on the lower meniscus predominate at the dynamic wetting line in contrast to the effect of applying suction, which acts uniformly over the entire meniscus. It is thus possible to achieve stable coating while ensuring the static wetting line remains firmly locked to the corner with consequential improved robustness against the generation of streaks. The experiments confirm that the increased risk of ribbing from this mode of operation found by Vandaele et al [2] is likely to be sourced in an increase in curvature of the upper meniscus in the presence of orientated polar charge at the substrate surface.

5 Acknowledgements

The authors gratefully acknowledge the financial support provided by the EPSRC through Grant reference GR/M93291/01. Thanks is also expressed to Dr. T. Rhodes of ILFORD Imaging UK Limited for his continued support and arranging permission to use and exploit the extensive experimental facilities available within the company and for authorising the manufacture of the equipment designed specifically for this work.

6 References

1. Noakes, C.J., Gaskell, P.H., Thompson, H.M. & Ikin, J.B. ‘Streak-Line Defect Minimization in Multi-Layer Slide Coating Systems’ *Trans IchemE* 80 Part A pp 449 – 463 [2002]
2. Vandaele, F. & Vancoppenolle, G. ‘The influence of electrostatic assist on the coating window of slide and slot coating’ *Proc. 3rd Eur. Coat. Symp*. pp 247-252 [1999]
3. Blake,T.D. & Clarke, A. ‘An Investigation of Electrostatic Assist in Coating’ *Proc. 3rd Eur. Coat. Symp*. pp 279-280 [1999]
4. Fermin, R.J. & Scriven, L.E. ‘Electrostatically Assisted Coating Flows” *Proc. of 3rd European Coating Symposium, University of Erlangen-Nürnberg* pp 91-95 [1999]
5. Ikin, J.B., Gaskell, P.H., Noakes, C.J. & Thompson, H.M. ‘An Experimental Study of Instability Phenomena and Coating Limits in Industrial Carrier Layer Flows’ *Proc. 4th Eur. Coat. Symp*. pp 277 – 282 [2001]
6. Schweizer, P.M. & Rossier, P.-A. ‘High Speed Operating Range for Slide Coating’ *Proc. 5th Eur. Coat. Symp*. – Fribourg, Switzerland – 17-19 Sept. pp 182 – 189 [2003]
7. Hens, J and Van Abbenyen, W., ‘Slide coating’ in S.F.Kistler and P.M.Schweizer, (Eds), *Liquid Film Coating* London: Chapman and Hall, Chap 11b pp 427 - 462, [1997]
8. Apps, C. J. ‘Slot Exit Phenomena in Industrial Slide-Fed Coating Systems’ *PhD. Thesis*, University of Leeds [2000]
9. Orchard, S. E. ‘On surface levelling in viscous liquids and gels.’ *Appl. Sci. Res.* 11: p 451-464 [1962]
10. Tricot, Y-M. ‘Surfactants: static and dynamic surface tension’ in S.F.Kistler and P.M.Schweizer, (Eds), *Liquid Film Coating*, London: Chapman and Hall, pp 99 - 136 [1997]
11. Schweizer, P.M. ‘Visualisation of coating flows’, *J.Fluid Mech*., 193, pp 285-302 [1988]
12. Ikin, J.B., Summers, J.L. & Thompson, H.M. ‘An experimental and numerical investigation of double-layer slide bead coating’ *Proc. 2nd Eur. Coat. Symp*. pp 320-328 [1997]
13. Gaskell, P.H., Thompson, H.M., Savage, M.D. & Ikin, J.B. ‘Steady recirculating flow near contact lines’ *Chem. Eng. Sci.,* 54, pp 819-828 [1999]
14. Moffatt, H.K. ‘Viscous and Resistive Eddies near a Sharp Corner’ *J.Fluid Mech.*, 18, pp 1-18 [1964]
15. Kisler, S., Chirokas,E.A. 7 Foster,D.A. ‘Precharged web coating apparatus’ *US Patent 4,457,256* [1984]

16. Gibbons, C.B., Kerr, W.C. & Maddocks, R.H. ‘Web treatment method.’ *US Patent 3,702,258* [1972]
17. Hartman, R.L. ‘High Speed Curtain Coating Process and Apparatus’ *International Patent Application WO 89 / 05477* [1989]
18. Quiel, R.R., Gros, A.E., Finnicum, D.S.& Joos, F.M. ‘Slide Bead Coating Method’ *US 2002/0081390* [2002]
19. Zvan, G.R., Douglas,L.J. & Kistler, S.F. ‘A Novel Method for Dynamic Contact Angle Measurement’ *International symposium on Coating Process Science & Technology*. *Spring National Meeting*, *New Orleans*, *LA* [1992]
20. Ikin, J.B. ‘An Experimental Analysis of Carrier Layer Flows’ *PhD. Thesis,* University of Leeds [2005]