Modelling and Analysis of Tri-Helical Gravure Roll Coating

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Tri-helical gravure roll coating is a process which is used widely for depositing a thin liquid film onto a moving substrate. An analytic model of a simplified form of the process, that of rectangular grooves at 0° mesh angle, is presented together with supporting experimental results which confirm the validity of the model. Included also are interesting flow visualisations of the coating process, which for the first time shows the underlying physics of the process.

Experimental Setup

A schematic of the coating rig used to carry out the experiments is shown in figure 1. The apparatus utilises gravure coating rolls, of length 200mm and diameter 100mm, which can reach a maximum speed of $U_{Roll} = 100m/s$; together with controls for web tension, velocity and wrap angle. The gravure rolls are comprised of an acrylic sleeve mounted with grub screws on a central steel core. This facilitates study of a range of groove geometries and aids the illumination of the fluid bead for flow visualisation purposes achieved by the injection of a small volume of coloured dye. Film thickness measurements were made by scraping fluid from the web over a known time interval. The residual fluid remaining after scraping was found to be negligible. The fluid used in the experiments is a Newtonian water-glycerol mixture with a small volume of surfactant to reduce surface tension. The viscosities used were in the range of $\mu = 0.002$ to $0.0075 Pas$ and with surface tensions of $\sigma = 0.033$ to $0.065 N/m$.

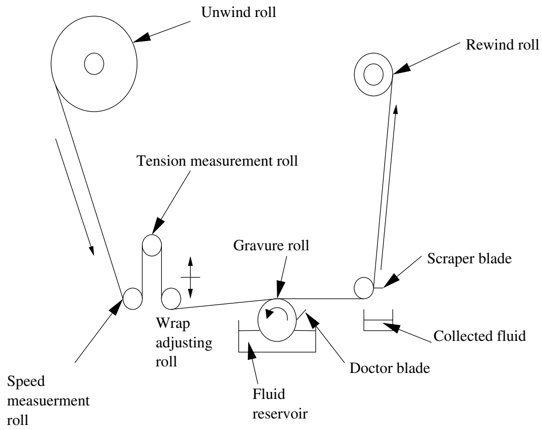

Figure 1: Cross sectional schematic of the experimental coating apparatus

Analytical Model

Hydrodynamic pressure equations and meniscus models are used to locate the menisci and determine the pressures at the interfaces. The associated flux is determined as that value for which the pressures are consistent throughout the flow domain.

Hydrodynamic Pressure Equations

For fluids with constant properties lubrication theory has long been used to model the flow in the nip region of roll coating systems [1, 2, 3, 4, 5, 6] due to the associated unidirectional nature of the flow. However, in the case of tri-helical gravure roll coating the groove height is of the same order as its width. A simplifying assumption that inertial forces are negligible (arising from the slowly changing geometry in the x-direction compared to the y- and z-directions) is made and the momentum equation can then be simplified to render the hydrodynamic pressure as the dependent variable of a Poisson's equation. Two general solutions of this equation are required; one when there is web-to-roll contact, the other when there is separation between them. These two situations are illustrated in figure 2. When the web is in contact with the roll the domain of interest is rectangular and an exact solution can be obtained. The solution where the web is not in contact with the roll is more complex due to the non-rectangular nature of the domain. A solution is obtained by subdividing the domain into three zones as shown in figure 2(b). Within zones one and two Poisson's equation is solved using finite Fourier sine transforms with the velocity between these two zones obtained by matching the velocity gradients in the z-direction. The flow above the land is assumed to be Poiseuille-Couette like. The validity of this assumption was verified by solving Poisson's equation using the finite element method.

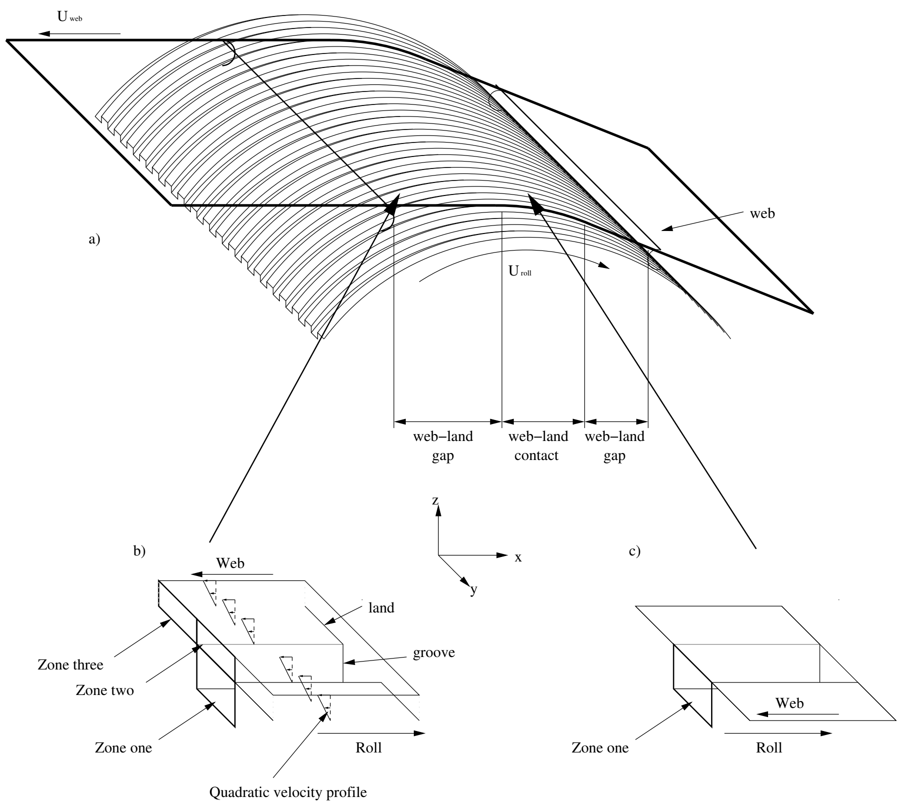

Figure 2: Schematic diagram of (a) the coating region; (b) roll-web gap geometry; (c) roll-to-web contact geometry.

Meniscus Models

The Coyne and Elrod [7] cavitation model is used to describe the upstream and downstream menisci. The dynamic contact angle was modelled using the empirical law of Jiang, Oh and Slattery [8], which relates dynamic contact angle to the static contact angle and capillary number ($\frac{\mu U_{web}}{\sigma}$). This model ensures the dynamic contact angle remains bounded between 0 and 180° and when implemented ensures the coating model remains robust. This is the only part of the model that relies on empiricism but is found to have only a small influence on the stable pickout process.

Results

Pickout and Film Thickness

Figure 3 show typical experimental and analytic results for pickout with a zero angle trihelical gravure coating arrangement. In all cases there is good agreement between the two. Typically, as the speed ratio ($S = \left|\frac{U_{web}}{U_{roll}}\right|$) is increased the pickout rises almost linearly to a maximum value at $S \approx 1.2$. It can also be seen that the pickout does not tend to zero as S decreases, this is because the volume of fluid entering the bead within the groove is

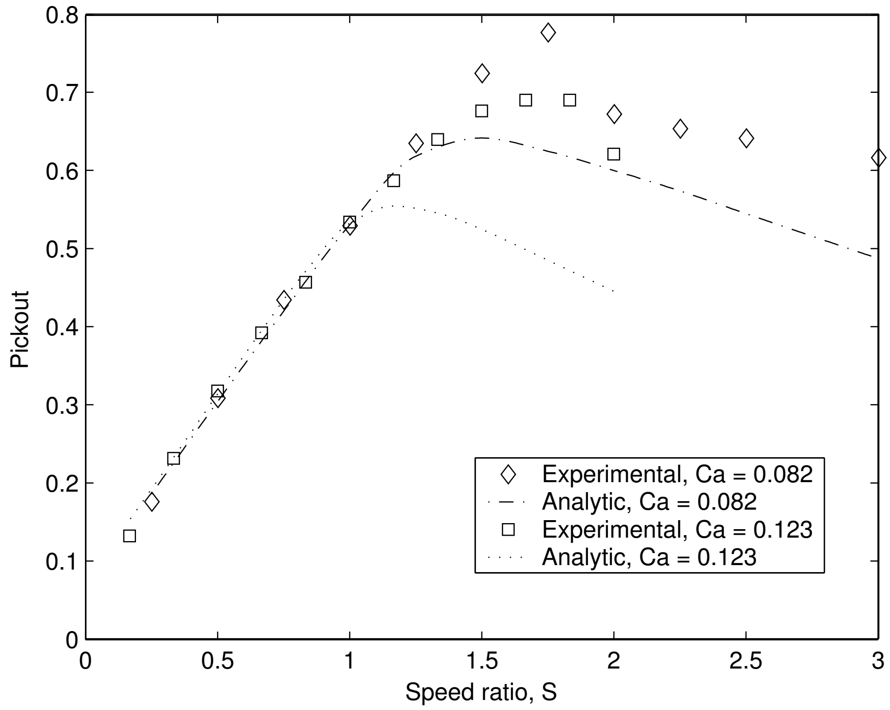

Figure 3: Groove width 0.47mm, depth 0.35mm, land width 0.54mm, angle of wrap 4.8°

unable to entirely pass though the bounded channel (where the web is wrapped over the roll), in practice this results in a build up of fluid at the downstream meniscus that either drips off the web or runs back over the approaching roll surface.

A maximum pickout is both observed experimentally and predicted by the analytical model. The decrease in pickout as S increases beyond 1.2 is due to an increase in the dynamic contact angle and therefore a larger volume of fluid moving with the roll. Streaking is observed experimentally as this large contact angle permits an unstable 'tube' of fluid to pass from the upstream to the downstream side. It is found that the intuitive relationship that the shallower the groove the greater the pickout is adhered to, with pickout being lower for deeper grooves.

Meniscus Location

The wetting line position is a sensitive parameter that can be used to validate the model. Figure 4 shows the change in menisci location with variations in S and wrap angle (β). Agreement between the theory and experiment is once again found to be good in all cases; as S increases the bead size decreases. The model does, however, consistently over predict the bead size with the upstream and downstream menisci lying further from $x = 0$ than measured experimentally- this is more apparent at low speed ratios, especially on the downstream side.

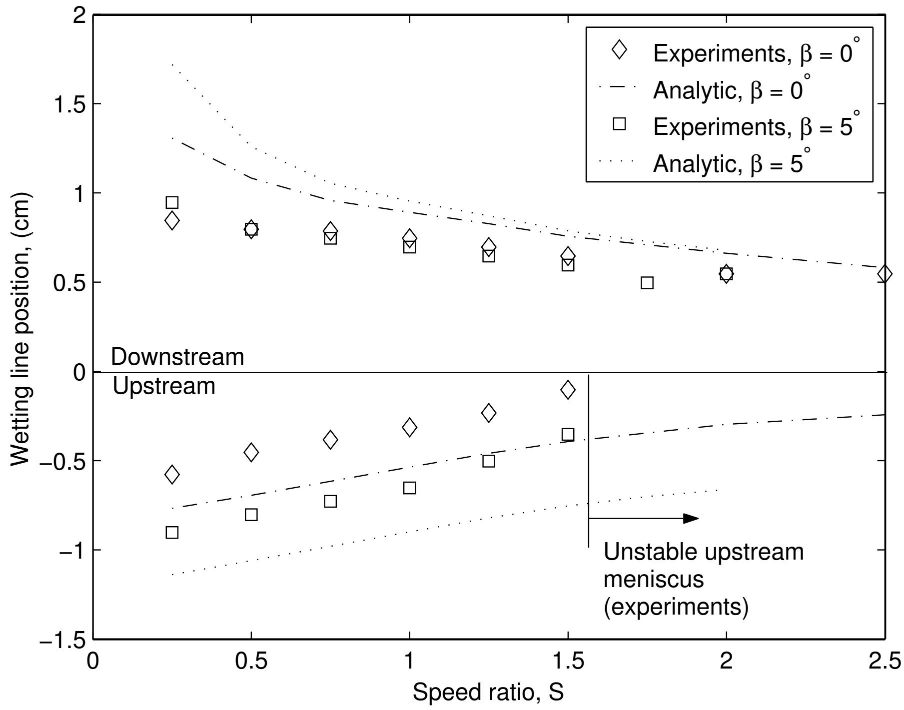

Figure 4: Groove width 0.47mm, depth 0.35mm, land width 0.54mm, capillary number 0.082

Flow Visualisation

Flow visualisations performed by injecting ink into the flow and with a camera looking along the roll axis at the meniscus reveals the main structures within the flow. It was not possible to observe the flow within the grooves in any detail but in the web-roll gap the flow was observed to have a similar topography to that encountered in smooth roll coating [9]; both upstream and downstream of the web-to-roll contact vortices can be identified. This is seen most clearly at low speed ratios (figure 5), but the vortex structures are also present at higher speed ratios, as shown schematically in figure 6.

Figure 5: Flow Visualisation, speed ratio 0.22

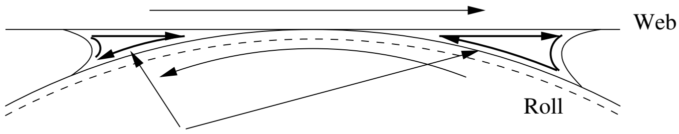

Figure 6: Diagramatic representation of flow topography

Acknowledgements

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References

[1] W. H. Banks and C. C. Mill. Some observations on the behaviour of liquids between rotating rollers. *Proceedings of the Royal Society of London A*, 223:414, 1954.

[2] M.R. Hopkins. Viscous flow between rotating cylinders and a sheet moving between them. *British Journal of Applied Physics*, 8:442–444, 1957.

[3] J. Greener and S. Middleman. Reverse roll coating of viscous and viscoelastic liquids - response. *Industrial and Engineering Chemistry Fundamentals*, 22(4):507–507, 1983.

[4] E. Pitts and J. Greiller. The flow of thin liquid films between rollers. *Journal of Fluid Mechanics*, 11:33, 1961.

[5] W. S. Ho and F. M. Holland. Between-roll metering coating technique, a theoretical and experimental study. *Tappi Journal*, 61:53, 1978.

[6] H. M. Thompson, N. Kapur, P. H. Gaskell, J. L. Summers, and S. J. Abbott. A theoretical and experimental investigation of reservoir-fed, rigid-roll coating. *Chemical Engineering Science*, 56(15):4627–4641, 2001.

[7] J.C. Coyne and H.G. Elrod. Conditions for the rupture of a lubricating film. part 1: Theoretical model. *Journal of Lubrication Technology*, 92:451, 1970.

[8] K.M. Jiang, S. Oh, and J.C. Slattery. Correlation for dynamic contact angle. *Journal of Colloid and Interface Science*, 69(1):74–77, 1979.

[9] P. H. Gaskell, G. E. Innes, and M. D. Savage. An experimental investigation of meniscus roll coating. *Journal of Fluid Mechanics*, 355:17–44, 1998.