Modelling Reverse Roll Coating Flow with Dynamic Wetting Lines and Inelastic Shear Thinning Fluids

S.O.S. Echendu, H.R. Tamaddon-Jahromi and M.F. Webster*

Institute of Non-Newtonian Fluid Mechanics, Swansea University, College of Engineering, Swansea, SA28PP, U.K.

* Corresponding author: m.f.webster@swansea.ac.uk
Fax: x44.1792.295676

Received: 31.1.2013, Final version: 13.5.2013

Abstract:
This study addresses the Taylor-Galerkin/pressure-correction solution of industrial high-speed reverse roller coating flow associated with thin-film paint-coatings of strip-steel. Novel aspects lie in the inclusion of the dynamic wetting line and flow analysis due to surface tension and inelastic rheology effects, via shear-thinning and lowering high shear viscosity levels. The main aim of the study is to predict the zonal flow influences by examining viscous flow structures around the meniscus, nip and wetting line regions, conveyed via streamline and shear rate patterns, surface distributional lift and localised nip-pressures. The majority of this study focuses on the secondary nip-vortex and its influences on the contact point and dynamic wetting line. This aspect of the flow provides the driving mechanism for the onset of instabilities, which governs the entire process and tends to determine the consistency of the film thickness at the outflow. Positive peak-pressures tend to increase with decrease in nip-gap size. At low nip-gap size, negative peak pressures are observed around the substrate-wetting line contact region. At higher speed-ratios, positive peak pressures are seen to increase with less recirculation apparent around the contact zone. Significantly and upon surface tension increase, the dynamic wetting line is sucked further inwards towards the nip-gap, stimulating a localised wetting line-foil third vortex structure, which causes an apparent reduction in film-leakage thickness.

Zusammenfassung:
Diese Arbeit betrachtet die Taylor-Galerkin/Druckkorrektur-Lösung für die industrielle Hochgeschwindigkeits-Umlenkrollenbeschichtungsströmung, die beim Auftragen dünner Schichten auf einem Bandeisen verwendet wird. Die neuartigen Aspekte liegen in der Einbeziehung der dynamischen Benetzungslinie und der Strömungsanalyse aufgrund der Oberflächenspannung und inelastischer rheologischer Effekte wie Scherverdünnung und Verringerung hoher Scherviskositätsniveaus. Das Hauptziel dieser Arbeit ist, den Einfluss von Fließzonen durch die Untersuchung viskoser Fließstrukturen um den Meniskus, den Walzenspalt und den Bereich der Benetzungslinie, transportiert durch Stromlinien und Schergeschwindigkeitsmuster, Oberflächenverteilungsliften und lokalisierte Walzenspaltdrücken vorherzusagen. Der Hauptteil dieser Studie betrachtet den sekundären Walzenspalt-Vortex und seinen Einfluss auf den Kontaktpunkt und die dynamische Benetzungslinie. Dieser Aspekt der Strömung stellt den Mechanismus für den Beginn der Instabilitäten dar, die den Gesamtprozess bestimmt und dazu tendiert, die Konsistenz der Filmdicke bei der Ausströmung zu bestimmen. Positive Peakdrücke werden tendenziell mit abnehmendem Walzenspalt erhöht. Bei niedrigen Walzenspalten, werden negative Peakdrücke im Kontaktbereich der Substratbenetzungslinie beobachtet. Bei hohen Geschwindigkeitsverhältnissen treten erhöhte positive Peakdrücke mit geringerer Rezirkulation im Bereich der Kontaktzone auf. Bei Erhöhung der Oberflächenspannung wird die dynamische Benetzungslinie aufgesaugt in Richtung des Walzenspaltes, was zu einer dritten lokalisierten Benetzungslinien-Film Vortexstruktur führt, die eine scheinbare Reduktion der Dicke des Folienlecks verursacht.

Résumé:
Cette étude s'intéresse à la correction de pression Taylor-Galerkin pour l'écoulement de revêtement par rouleau inversé à grande vitesse, appliqué dans l'industrie de revêtement de bandes de métal par de fines couches de peinture. Les nouveaux aspects de cette étude consistent dans l'inclusion d'une ligne de mouillage dynamique et dans l'analyse de l'écoulement associé à la tension de surface et aux effets rhéologiques inélastiques, via le rhéo-amincissement et l'abaissement du niveau de viscosité à grand cisaillement. Le principal objectif de l'étude est de prédire les caractéristiques de la zone d'écoulement en examinant les structures d'écoulement visqueux autour du ménisque, les régions de pincement et de ligne de mouillage convoyées via les motifs de vitesse de cisaillement et les lignes d'écoulement, les distributions des surfaces de soulèvement et les pressions localisées de pincement. La majorité de cette étude se focalise sur le vortex de pincement secondaire et ses influences sur le point de contact et sur la ligne dynamique de mouillage. Cet aspect de l'écoulement donne accès au mécanisme conduisant à l'initiation des instabilités qui gouverne entièrement le processus et tend à déterminer la consistance de l'épaisseur

 DOI: 10.3933/ApplRheol-23-62388

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org

gap width of $s < 0.01$). As nip-gap size increases above $s = 0.5$, the variation in pressure becomes quite small with correspondingly low positive peak-pressures. At nip-gap size of $s = 0.01$ and above, no negative peak-pressures are observed around the contact region. As roll-speed is increased, positive pressure-peaks only increase at a low rate; whilst comparatively, positive peak-pressures increase rapidly with increase in foil-speed. Analysis on surface tension reveals that as the capillary number is decreased, the contact point moves in the opposite direction of foil-movement, sucking more fluid from the wetting line, with growth of a third vortex in the contact region, and apparent reduction in leakage film-width.

Findings on inelastic paint rheology representation, under which shear-thinning is taken into account, reveal that as the power-law index m is decreased, positive peak-pressures decrease linearly. Streamline flow patterns show that the primary vortex structure at the meniscus remains undisturbed due to shear-thinning, whereas the minor secondary vortex structure at the nip-zone is seen to expand into the nip-gap. When a typical industrial paint topcoat is matched with a Carreau model fit, predictions reveal two orders of magnitude reduction in localised peak-values of pressure and lift, with the same intensity of vortex transfer structures as observed for a Newtonian paint.

The study has analysed the instabilities occurring in the reverse roll coating operation and observations made offer a fresh insight on the efficient running of this process. Some dramatic rheological influences, in terms of stimulated vortices and dynamic wetting, have been revealed at the nip and wetting region. It is inferred that this can interfere with the consistent application of coating flows.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided from the Engineering and Physical Sciences Research Council (CASE studentship), Tata Steel Coated Products, UK and SPECIFIC-IKC.

REFERENCES

[1] Coyle DJ, Macosko CW, Scriven LE: Film-splitting flows in forward roll coating, J. Fluid Mech. 171 (1986) 183 – 207

[2] Coyle DJ, Macosko CW, Scriven LE: Reverse roll coating of non-Newtonian liquids, J. Rheol. 34 (1990) 615 – 636.

[3] Coyle DJ, Macosko CW, Scriven LE: The fluid dynamics of reverse roll coating. AIChE J. 36 (1990) 161 – 174.

[4] Gaskell PH, Savage MD, Summers JL, Thompson HM: Modelling and analysis of meniscus roll coating, J. Fluid Mech. 298 (1995) 113 – 137

[5] Gaskell PH, Innes GE, Savage MD: An experimental investigation of meniscus roll coating, J. Fluid Mech. 355 (2000) 17 – 44.

[6] Cohu O, Magnin A: Forward roll coating of Newtonian fluids with deformable rolls; an experimental investigation, AIChE J. 52 (1997) 1339 – 1347.

[7] Benkreira H, Edwards MF, Wilkinson WL: Roll coating of purely viscous liquids. Chem. Eng. Sci. 36 (1981) 429 – 434.

[8] Benkreira H, Edwards MF, Wilkinson WL: Mathematical modelling of the reverse and metering roll coating flow of Newtonian fluids. Chem. Eng. Sci. 37 (1982) 277 – 282.

[9] Benkreira H: Dynamic wetting in metering and pre-metered forward roll coating, Chem. Eng. Sci. 57 (2002) 3025 – 3032

[10] Benkreira H, Khan MI: Air entrainment in dip coating under reduced air pressures, Chem. Eng. Sci. 63 (2008) 448 – 459.

[11] Carvalho MS, Scriven LE: Deformable roll coating flows: steady state and linear perturbation analysis, J. Fluid Mech. 339 (1997) 143 – 172.

[12] Chandio MS, Webster MF: Numerical simulation of reverse roller-coating with free-surfaces, ECCOMAS Computational Fluid Dynamics Conference (2001).

[13] Chandio MS, Webster MF: Numerical simulation for viscous free surface flows for reverse roller-coating, Int. J Numer. Method H. 12 (2002) 434 – 457.

[14] Shiode H, Tamal H, Isaki T: Flow simulations of dynamic wetting line at a reverse roller coater using VOF Method. J. Soc. Rheol. Japan 37 (2009) 59 – 64.

[15] Jang JY, Chen PY: Reverse Roll Coating Flow with Non-Newtonian Fluids, Commun. Comp. Phys. 6 (2009) 536 – 552.

[16] Belblidia F, Tamaddon-Jahromi HR, Echendu SOS, Webster MF: Reverse roll Coating Flow: A computational investigation towards high speed defect free coating, Mech. Time-Depend. Mater. (2013) doi: 10.1007/s11043-012-9204-y.

[17] Echendu SOS, Belblidia F, Tamaddon-Jahromi HR, Webster MF: Modelling with viscous and Viscoplastic materials under mixing and separating flow configurations, Mech. Time-Depend. Mater. 15 (2011) 407 – 428.

[18] Hawken DM, Tamaddon-Jahromi HR, Townsend P, Webster MF: A Taylor-Galerkin based algorithm for viscous incompressible flow, Int. J. Num.

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org

Meth. Fluids. 10 (1990) 327–351.
[19] Webster MF, Tamaddon-Jahromi HR, Aboubacar M: Time-dependent algorithm for Viscoelastic flow-finite element/volume schemes. Num. Meth. Partial Diff. Equ. 21 (2005) 272–296.
[20] Ramaswamy B: Numerical Simulation of Unsteady Viscous Free-surface Flow, J. Comp. Phys. 90 (1990) 396–430.
[21] Carvalho MS, Scriven LE: Multiple States of a Viscous Free-surface Flow: Transition from pre-metered to a metering flow; Int. J. Num. Meth. Fluids. 24 (1997) 813–831.
[22] Keunings R: An Algorithm for the Simulation of Transient Visco-Elastic Flows with Free-Surfaces, J. Comp. Phys. 62 (1986) 199–220.
[23] Saito H, Scriven LE: Study of Coating Flow by the Finite Element Method, J. Comp. Phys. 42 (1981) 53–76.
[24] Ashmore J, Shen A, Kavehpour H, Stone H, McKinley G: Coating flows of non-Newtonian fluids; weakly and strongly elastic limits, J. Eng. Math. 60 (2008) 17–41.
[25] Chen KSA, Scriven LE: Roll Coating, Forward and Reverse: Effect of Feed Condition, AIChE Spring Meeting, New Orleans, (1988).
[26] Benjamin DF: Roll Coating Flows and Multiple Flow Systems PhD. Thesis University of Minnesota, Minneapolis, University Microfilms Int., Ann. Arbor (1994).
[27] Tiu C, Wang L, Liu TJ: Non-Newtonian effects of pre-metered reverse roll coating, J. Non-Newtonian Fluid Mech. 87 (1999) 247–261.
[28] Hao Y, Haber S: Reverse roll coating flow, Int J. Num. Meth. Fluids 30 (1999) 635–652.
[29] Benkreira H: Experimental study of dynamic wetting in reverse-roll coating, AIChE J. 48 (2002) 221–226.

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org