Applied Rheology | DOI: 10.3933/APPLRHEOL-24-34188 | WWW.APPLIEDRHEOLOGY.ORG

Numerical Computation of Extrusion and Draw-extrusion Cable-coating Flows with Polymer Melts

A. Al-Muslimawi[1,2], H.R. Tamaddon-Jahromi[3] and M.F. Webster[3*]

[1] Swansea University, College of Science, Mathematics, Singleton Park, Swansea SA2 8PP, United Kingdom
[2] Basra University, College of Science, Mathematics, Baghdad Street, AL-Basra, 61004, Iraq
[3] Swansea University, Institute of Non-Newtonian Fluid Mechanics, Singleton Park, Swansea SA2 8PP, United Kingdom

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

Received: 31.7.2013, Final version: 15.12.2013

Abstract:

This paper is concerned with the numerical solution of polymer melt flows of both extrudate-swell and tube-tooling die-extrusion coatings, using a hybrid finite element/finite volume discretisation *fe/fv*. Extrudate-swell presents a single dynamic free-surface, whilst the complex polymer melt coating flow exhibit two separate free-surface draw-down sections to model, an inner and outer conduit surface of the melt. The interest lies in determining efficient windows for process control over variation in material properties, stressing levels generated and pressure drop. In this respect, major rheological influences are evaluated on the numerical predictions generated of the extensional viscosity and Trouton ratio, when comparing solution response for an exponential Phan-Thien Tanner (EPTT, network-based) model to that for a single extended Pom-Pom (SXPP, kinematic-based) model. The impact of shear-thinning is also considered. Attention is paid to the influence and variation in Weissenberg number *We*, solvent-fraction β (polymeric concentration), and second normal stress difference N_2 (ξ parameter for both EPTT, and α anisotropy parameter for SXPP). The influence of model choice and parameters upon field response is described in situ through, pressure, shear and strain-rates and stress. The numerical scheme solves the momentum-continuity-surface equations by a semi-implicit time-stepping incremental Taylor-Galerkin/pressure-correction finite element method, whilst invoking a cell-vertex fluctuation distribution/median-dual-cell finite volume approximation for the first-order space-time hyperbolic-type stress evolution equation.

Key words:

Taylor-Galerkin, tube-tooling, cable-coating, die-extrusion, free-surface, exponential Phan-Thien Tanner model, single extended Pom-Pom model

1 INTRODUCTION

The modelling of annular extrudate-swell and cable-coating flows, with dynamic free-surfaces, remains a popular topic which has motivated many studies over recent years. In this context, extrudate- or die-swell has been adopted as a benchmark viscoelastic flow problem [1], characterised by specific features of: the presence of a sharp separation point at the exit of the die, the location and shape of the free-surface spawned, and the impact of viscoelastisty upon flow response (see for example [2–5]).

Moreover, there have been a number of studies that have addressed the modeling of cable-wire coating for tube-tooling (see for example [6–8]). These have provided some progress within the inelastic, non-isothermal and viscoelastic regimes. In their work, viscoelastic coating flows were simulated with a Phan-Thien/Tanner (PTT) model and solved with a finite element technique. Based on, a time-stepping Taylor-Galerkin/pressure-correction finite element framework [9], tube-tooling extrusion coating with a low-density polymer melt has been analysed by Mutlu et al. [10]. In this study, and whilst addressing the coupling in the system between velocity and stress, both decoupled and coupled numerical approaches were adopted. The strain-hardening/softening, shear-thinning properties of the polymeric coatings were approximated with the exponential form of the Phan-Thien/Tanner (EPTT) model. There, the decoupled scheme was advocated to handle numerical solution instabilities at low-solvent concentrations representative for polymer melt response ($\beta \leq 10^{-3}$). Building upon this success, Matallah et al. [11] used the finite element method to simulate high-speed viscoelastic wire-coating, again employing coupled and decoupled schemes. There, predictions for a

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

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

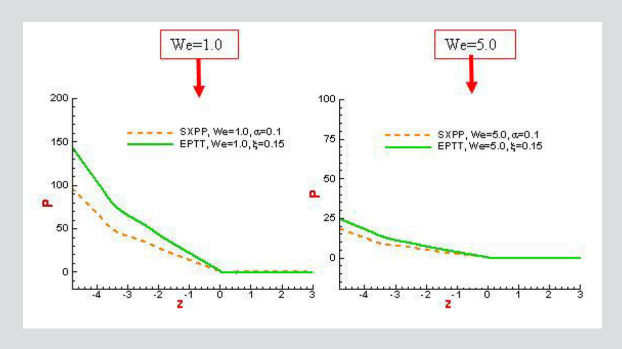

Figure 13: Pressure profiles, SXPP{$q = 2$, $\epsilon_{SXPP} = 0.1$, $\alpha = 0.1$} versus EPTT{ $\epsilon_{EPTT} = 0.5$, $\xi = 0.15$} (We variation, $\beta = 10^{-3}$).

ity property). This has been accomplished here by fixing ϵ_{SXPPP} and allowing q to vary. Here, a near-optimal least-squares fit has been extracted to experimental data, across the complete range of shear and extensional viscosity. Through the knowledge on molecular stretch, the SXPP model provides a way forward in practical applications where one seeks to take advantage of recovering structures in a complex flow.

Initially, the extrudate-swell benchmark problem with a dynamic free-surface has been studied, and then, subsequently extended into a study on the more complex industrial flow of tube-tooling cable-coating. The latter problem manifests two separate top and bottom moving free-surfaces. For the extrudate-swell problem, attention is paid to describe the impact of Weissenberg number *We* and solvent-fraction on swelling ratio. Findings reflect that, an increase in swelling occurs as *We* increases and β decreases. In addition, strain-rate stabilisation has also been investigated for this problem to interrogate the influence of singularity capturing on the die-exit solution. In this respect, it has been successfully demonstrated that such treatment can have a significant impact on the peak-level of stress exiting the die. In turn, this influences the accurate determination of free-surface profiles, where such variation has been detected in swelling-ratio at selected Weissenberg numbers. Moreover, the swelling ratio is also observed to decrease when some non-zero second-normal stress-difference is incorporated within the model representation.

Under tube-tooling flow with the EPTT and SXPP models, the respective influences of Weissenberg number *We*, solvent-fraction β, and second normal stress-difference *N2* (ξ_{EPTT} for EPTT, ξ_{SXPP} and α_{SXPP} for SXPP) have each been systematically investigated. Under shear-thinning properties, a decline in the total pressure-drop is observed as Weissenberg number *We* increases and solvent-fraction β decreases. Under *We* variation, a weak contribution of radial stress τ_{rr} arises, leading to minor adjustment in the normal stress τ_{zz} and first normal stress N_1. Comparative data are presented for SXPP and EPTT solutions, governing total pressure-drop and stress production, both with and without N_2 contributions. Generally, lower levels of pressure-drop and stress are observed in SXPP as op-

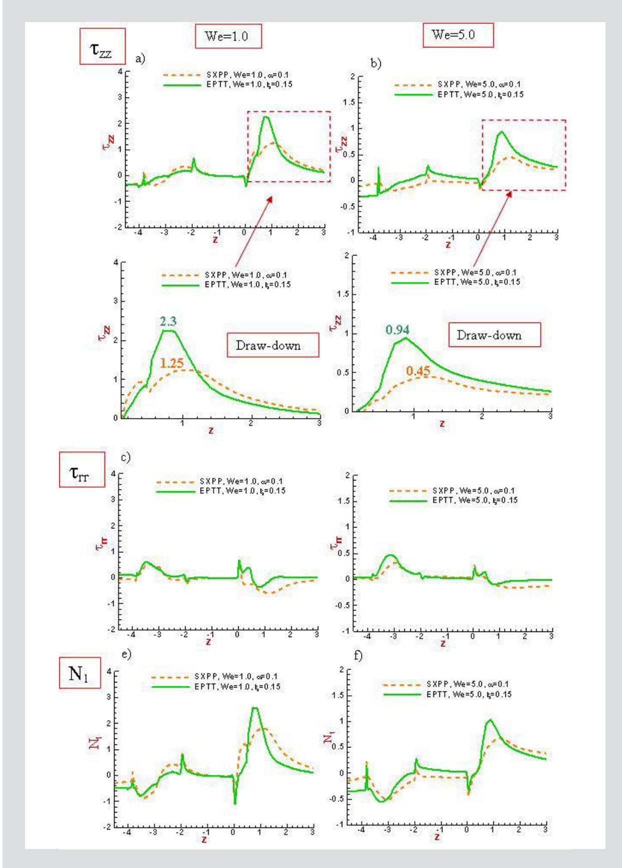

Figure 14: τ_{zz}, τ_{rr}, and N_1 profiles at centreline, SXPP-{$q = 2$, $\epsilon_{SXPP} = 0.1$, $\alpha = 0.1$} versus EPTT{$\epsilon_{EPTT} = 0.5$, $\xi = 0.15$} (We variation, $\beta = 10^{-3}$).

posed to EPTT predicted solutions, due to the exaggerated propensity of SXPP to thin at faster rate than for EPTT. Furthermore, a lower level of residual-stress N_1 is observed in the final coating at higher levels of elasticity: for example with EPTT, there is a drop of almost 30 % in peak-value from the *We* = 5 to *We* = 20 solution.

ACKNOWLEDGEMENTS

The first author acknowledges financial support from the Ministry of Higher Education, and Mathematics Department, College of Science, Basra University, Iraq during the course of this research.

REFERENCES

[1] Tanner RI: Engineering Rheology, Oxford University Press, London (1985).

[2] Al-Muslimawi A, Tamaddon-Jahromi HR, Webster MF: Simulation of viscoelastic and viscoelastoplastic die-swell flows, J. Non-Newtonian Fluid Mech. 191 (2013) 45–56.

[3] Oishi CM, Martins FP, Tomé MF, Cuminato JA, McKee S: Numerical solution of the eXtended Pom-Pom model for viscoelastic free-surface flows, J. Non-Newtonian Fluid Mech. 166 (2011) 165–179.

[4] Mitsoulis E: Extrudate swell of Boger fluids, J. Non-Newtonian Fluid Mech. 165 (2010) 812–824.

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

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

[5] Tomé MF, Grossi L, Castelo A, Cuminato JA, McKee S, Walters K: Die-swell, splashing drop and a numerical technique for solving the Oldroyd B model for axisymmetric free-surface flows, J. Non-Newtonian Fluid Mech. 141 (2007) 148–166.
[6] Gunter S, Townsend P, Webster MF: Simulation of some model viscoelastic Extensional flows, Int. J. Num. Meth. Fluids 23 (1996) 691–710.
[7] Mutlu I, Townsend P, Webster MF: Non-Newtonian flow modelling for the processing industry, in: J.R. Whiteman (ed.), Mathematics of Finite Elements and Applications, Vol. 18, Wiley, Chichester (1997) 299–312.
[8] Mutlu I, Townsend P, Webster MF: Computation of viscoelastic cable coating Flows, Int. J. Numer. Meth. Fluids 26 (1998) 697–712.
[9] Carew EOA, Townsend P, Webster MF: A Taylor-Petrov-Galerkin algorithm for viscoelastic flow, J. Non-Newtonian Fluid Mech. 50 (1993) 253–287.
[10] Mutlu I, Townsend P, Webster MF: Simulation of cable-coating viscoelastic flows with coupled and decoupled schemes, J. Non-Newtonian Fluid Mech. 74 (1998) 1–23.
[11] Matallah H, Townsend P, Webster MF: Viscoelastic multi-mode simulations of wire-coating, J. Non-Newtonian Fluid Mech. 90 (2000) 217–241.
[12] Matallah H, Townsend P, Webster MF: Viscoelastic computations of polymeric wire-coating flows, Int. J. Num. Meth. Heat Fluid Flow 12 (2002) 404–433.
[13] Baloch A, Matallah H, Ngamaramvaranggul V, Webster MF: Simulation of pressure and tube-tooling wire-coating flows through distributed computation, Int. J. Num. Meth. Heat Fluid Flow 12 (2002) 458–493.
[14] Ngamaramvaranggul V., Webster MF: Viscoelastic simulations of stick-slip and die-swell flows, Int. J. Num. Meth. Fluids 36 (2001) 539–595.
[15] Ngamaramvaranggul V., Webster MF: Simulation of pressure tooling wire-coating flow with Phan-Thien/Tanner models, Int. J. Num. Meth. Fluids 38 (2002) 677–710.
[16] McLeish TCB, Larson RG: Molecular constitutive equations for a class of branched polymers: The Pom-Pom polymer, J. Rheol. 42 (1998) 81–110.
[17] Verbeeten WMH, Peters GWM, Baaijens FTP: Differential constitutive equations for polymer melts: The extended Pom-Pom model, J. Rheol. 45 (2001) 823–843.
[18] Rubio P, Wagner MH: LDPE melt rheology and the Pom-Pom model, J. Non-Newtonian Fluid Mech. 92 (2000) 245–259.
[19] Zatloukal M: Differential viscoelastic constitutive equations for polymer melts in steady shear and elongational flows, J. Non-Newtonian Fluid Mech. 113 (2003) 209–227.
[20] Bogaerds ACB, Grillet AM, Peters GWM, Baaijens FPT: Stability analysis of polymer shear flows using the extended Pom-Pom constitutive equations, J. Non-Newtonian Fluid Mech. 108 (2002) 187–208.
[21] Tanner RI, Nasseri S: Simple constitutive models for linear and branched polymers, J. Non-Newtonian Fluid Mech. 116 (2003) 1–17.
[22] Verbeeten WMH, Peters GWM, Baaijens FPT: Viscoelastic analysis of complex polymer melt flows using the extended Pom-Pom model, J. Non-Newtonian Fluid Mech. 108 (2002) 301–326.
[23] Aboubacar M, Aguayo JP, Phillips PM, Phillips TN, Tamaddon-Jahromi HR, Snigerev BA, Webster MF: Modelling Pom-Pom type models with high-order finite volume schemes, J. Non-Newtonian Fluid Mech. 126 (2005) 207–220.
[24] Aguayo JP, Tamaddon-Jahromi HR, Webster MF: Extensional response of the Pom-Pom model through planar contraction flows for branched polymer melts, J. Non-Newton. Fluid Mech. 134 (2006) 105–126.
[25] Aguayo JP, Phillips PM, Phillips TN, Tamaddon-Jahromi HR, Snigerev BA, Webster MF: The numerical prediction of planar viscoelastic flows using the Pom-Pom model and high-order finite volume schemes, J. Comput. Phys. 220 (2007) 586–611.
[26] Tamaddon-Jahromi HR, Webster MF: Transient behaviour of branched polymer melts through planar abrupt and rounded contractions using Pom–Pom models, Mech. Time-Depend. Mater. 15 (2011) 181–211.
[27] Webster MF, Tamaddon-Jahromi HR, Aboubacar M: Time-dependent algorithms for viscoelastic flow-finite element/volume schemes, Numer. Meth. Part. Diff. Eqns. 121 (2005) 272–296.
[28] Blackwell RJ, McLeish TCB, Harlen OG: Molecular drag-strain coupling in branched polymer melts, J. Rheol. 44 (2000) 121–136.
[29] Matallah H, Townsend P, Webster MF: Recovery and stress-splitting schemes for viscoelastic flows, J. Non-Newtonian Fluid Mech. 75 (1998) 139–166.
[30] Wapperom P, Webster MF: Simulation for viscoelastic flow by a finite volume/element method. Comp. Meth. Appl. Mech. Eng. 180 (1999) 281–304 .
[31] Belblidia F, Matallah H, Webster MF: Alternative subcell discretisations for viscoelastic flow: Velocity-gradient approximation, J. Non-Newtonian Fluid Mech. 151 (2008) 69–88.
[32] Wapperom P, Webster MF: A second order hybrid finite-element/volume method for viscoelastic flows, J. Non-Newtonian Fluid Mech. 79 (1998) 405–431.
[33] Bush MB: A numerical study of extrudate swell in very dilute polymer solutions represented by the Oldroyd-B model, J. Non-Newtonian Fluid Mech 34 (1990) 15–24.
[34] Tanner RI: A theory of die-swell revisited, J. Non-Newtonian Fluid Mech.129 (2005) 85–87.
[35] Georgiou GC, Schultz WW, Olson LG: Singular finite element for the sudden-expansion and the die-swell problems, Int. J. Num. Meth. Fluids 10 (1990) 357–372.
[36] Al-Muslimawi A, Tamaddon-Jahromi HR, Webster MF: Numerical simulation of tube-tooling cable-coating with polymer melts, The 13th International Symposium on Applied Rheology (ISAR), The Korean Society of Rheology (2013) 31–55.

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

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