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Effects of shear thinning on forward roll coating

R.W. Hewson*, N. Kapur

School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, UK

ABSTRACT

This paper described the forward mode roll coating process of generalised non-Newtonian fluids characterised by the Ellis model. The fluid in the coating bead and the free surface formation are described by the lubrication approximation and the stability is also considered using a perturbation analysis of the downstream meniscus. Results highlight the complex behaviour of this coating process and volume flow rate and film thickness results are obtained for a range of operating conditions. The stability of the downstream meniscus is observed to improve with increasing level of shear thinning when $\tau_{1/2}$ (the shear stress at which the viscosity is half that of the zero shear stress viscosity) is small, however as $\tau_{1/2}$ increases the meniscus stability decreases with increasing levels of shear thinning.

Keywords: Roll coating; Generalised Newtonian fluid; Ellis viscosity model; Fluid mechanics; Mathematical modelling

1. Introduction

The application of liquid layers onto a solid substrate is a commonly encountered industrial process. The long list of coated products includes packaging material, printed media, photographic film, magnetic media such as video and audio cassettes and optical media such as compact discs. As such, an almost equally wide range of equipment is used to manufacture these coated products, including roll coaters, where the transfer of fluid to the substrate is via a series of fluid coated rollers. The simplest geometry is a two roll coater of which there are two modes of operation of roll coaters – forward or reverse roll coating, these modes are shown in Fig. 1. In forward roll coating the two rolls pass through the coating bead in the same direction (i.e. the rolls are counter-rotating), in the reverse case the opposite is true with the two rolls passing through the coating bead in the same direction (i.e. co-rotating). Both forward and reverse roll coating may be operated with a flooded or starved inlet (Summers et al., 2004). These definitions correspond to the film thickness entering the coating bead relative to the minimum gap between the rolls. When the thickness of the liquid film entering the coating bead is of the same order or greater than the gap between the rolls a rolling bank of fluid may form and be returned to the coating pool (Coyle, 1997). When the liquid film is significantly thinner than the roll separation, the upstream meniscus plays an important part in determining the pressures throughout the coating pool and on the entire coating process in general (Benkreira et al., 1982; Gaskell, 1995; Gostling et al., 2001; Gaskell et al., 2001). In the current work the flooded forward roll coating case is examined, a problem encountered in a range of coating processes, for example the transfer of fluid from a metering to applicator roll. Invoking the lubrication approximation forward roll coating has been analysed by numerous authors (Banks and Mill, 1954; Hopkins, 1957; Greener and Middleman, 1983; Schneider, 1962; Coyle et al., 1986). As part of these analyses a range of pressure boundary conditions were applied at the upstream and downstream menisci. These conditions vary in complexity and their ability to describe surface tension effects. The propensity of coating fluids that exhibit shear thinning behaviour has led to the analysis of the forward roll coating process when operated with such fluids. Coyle et al. (1987) analysed the lubrication problem for shear thinning fluids obeying the power law and compared the lubrication theory derived solutions to a full two dimensional finite element formulation of the problem for shear thinning fluids obeying the more general Carreau–Yassuda fluid model. Applying the lubrication approximation and the Prandtl–Hopkins condition (Prandtl, 1928; Hopkins, 1957) they obtained an elegant relationship for

* Corresponding author.
E-mail address: r.w.hewson@leeds.ac.uk (R.W. Hewson).
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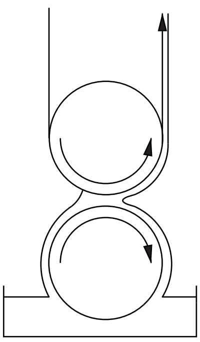

Fig. 1 – Schematic of roll coaters: (a) forward and (b) reverse.

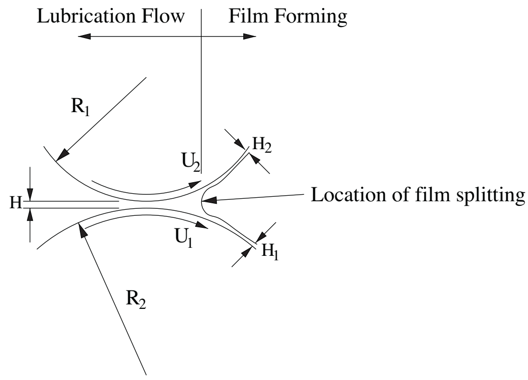

Fig. 2 – Definition of problem domain showing the two regions: (i) the lubrication flow between the two rolls and (ii) the film splitting of the fluid film onto the upper and lower rolls.

the ratio of film thicknesses leaving the bead to that of the roll speeds:

$$\frac{T_1}{T_2} = S^{(n/n+1)}, \tag{1}$$

where T_1 and T_2 are the film thicknesses on the upper and lower rolls respectively, S is the ratio of speeds of the top to bottom rolls and n is the power law index. In both the finite element analysis and lubrication model the effect of an increase in shear thinning behaviour (a decrease in n) was to increase the flow rate through the coating bead and move the film split location further from the point of minimum separation of the two rolls.

One of the major difficulties associated with assessing the effect of shear thinning on a coating process is in defining the viscosity that characterises the process. In the case of the analysis of Coyle et al. (1987) neglecting the surface tension effects, and thereby solving the problem for an infinite capillary number (ratio of viscous to surface tension forces), avoided this problem. Considering surface tension forces in addition to viscous ones, as is undertaken in the work presented here, requires a capillary number to be defined as a function of a characteristic viscosity. Consequently any assessment of shear thinning effects will depend on this relationship and the rheological model.

A number of computational studies of visco-elastic fluids have been undertaken. The visco-elastic nature of the fluid together with the requirement to establish the free surface location as part of the solution make such problems complex. In addition to the conservative equations, the general conformation tensor based constitutive equation must be solved, from which the polymeric contribution to the stress tensor is obtained (Pasquali and Scriven, 2002; Behr et al., 2005). Romero et al. (2006) and Bajaj et al. (2008) studied slot coating of visco-elastic fluids onto a moving substrate. Similarly, Quintella et al. (2007) examined both computationally and experimentally the displacement of a visco-elastic fluid filled capillary tube by a semi-infinite slug of air. The complexity of the computational models for visco-elastic fluids illustrates the need for a simplified model capable of capturing the physics of the fluid film deposition process, one such model was developed by de Ryck and Quéré (1998) who used a very elegant lubrication based asymptotic analysis – assuming a Poiseuille velocity profile – to obtain an equation describing the residual fluid film deposited on a wire withdrawn from a fluid filled gap. With only a single adjustable parameter, obtained from experimental data, the analysis provides a useful tool to enable the influence of the different parameters effecting the process to be examined. A similar analysis was undertaken by Ashmore et al. (2008) who developed a more general analysis for a range of different geometries in the limits of when the fluid rheology is either dominated by shear thinning effects or elastic effects. In common with the analysis of de Ryck and Quéré (1998) a quadratic velocity profile is assumed as the constitutive equations lacked an analytical solution. Their model showed excellent qualitative agreement with the experiments they undertook, with quantitative agreement observed for the shear-thinning dominated flows. In order to fully analyse the effects of shear thinning the current analysis is restricted to generalised Newtonian fluids only (i.e. when the Weissenburg number goes to zero), furthermore it permits a stability analysis to be undertaken.

1.1. *Scope of paper*

This paper examines the forward roll coating process of a fluid obeying the Ellis model (Reiner, 1960; Matsuhis and Bird, 1965) by means of the usual lubrication approximation. The Ellis model was chosen as it is able to describe shear thinning fluid behaviour at low shear stresses – essential if free surface flow is considered (Myers, 2005). Importantly for forward mode roll coating where meniscus stability can be an issue the stability of the coating bead is analysed by examining the restoring forces resulting from a perturbation in meniscus location (Savage, 1977).

2. Coating model

The model is divided into two components illustrated in Fig. 2: (i) the lubrication model of the flow between the two rolls together with an upstream boundary condition $p_\infty = 0$, consistent with a fully flooded inlet (Gostling et al., 2001), (ii) the film splitting model that describes the downstream meniscus.

2.1. *Lubrication flow*

By making the lubrication assumption that the flow is unidirectional (Reynolds, 1886) the balance of pressure and viscous forces is written:

$$\frac{d}{dY}\left[\bar{\eta}\frac{dU}{dY}\right] = \frac{dP}{dX}, \tag{2}$$

where $\bar{\eta}$ is the local fluid viscosity, Y is the coordinate perpendicular to the near parallel roll surfaces and X the direction