A Review of Deformable Roll Coating Systems

S.J. Abbott[1], N. Kapur[2], P.A. Sleigh[3], J.L Summers[2] & H.M. Thompson[2]
[1]Consultant to Rheologic Ltd., UK; [2]Institute of Engineering Thermofluids, Surfaces & Interfaces (iESTI), School of Mechanical Engineering, University of Leeds, Leeds, UK; [3]School of Civil Engineering, University of Leeds, Leeds, UK

n.kapur@leeds.ac.uk

1. Introduction

Roll coating systems are used to deposit liquid layers on continuous moving webs via the use of one or more rotating rolls. This article provides a brief review of the behavior of roll coating systems that feature a deformable gap, as opposed to a fixed gap. Deformable roll coating systems are employed throughout the manufacturing industry to coat waxes, hot melts, adhesives, silicone liquids, etc. onto paper, plastic and metals.[1] As with fixed-gap rigid-roll coating systems liquid is dragged, via the action of viscous lifting (see Fig. 1 left) or supplied directly from a reservoir (see Fig. 1 right), into the converging deformable-gap between two moving rolls, one or both of which is covered with a deformable, elastomer layer.

During operation, hydrodynamic pressures develop that are capable of deforming the elastomer layer(s) which, unlike fixed-gap, rigid-roll coating, lead to a corresponding change in the deformable-gap profile that, in turn, affects the pressure distribution, and so forth. The pressures and the deformation of the elastomer layer(s) are clearly much greater when the rolls are in contact than when they are separated by a small, pre-set distance (see Fig. 2). A deformable roll-pair can be operated in one of two modes. With the rolls at rest either:

1. A **PRE-SET GAP** is specified and the separation of the roll centers is set by the adjustment of mechanical stops.
2. A **LOAD** is specified and the separation of the roll centers is set by applying a force across the roll pair.

There are two possible outcomes:

3. A **POSITIVE** gap, that is clearance between the roll surfaces.
4. A **NEGATIVE** gap, that is the roll surfaces are in interference.

Of course, during operation the minimum gap between the rolls will be influenced by the hydrodynamic pressures generated within the liquid and the elastic restoring forces produced within the elastomer layer(s). The use of deformable roll coating systems is widespread for the following key reasons:

- They are inexpensive to build and maintain, simple to operate, and less sensitive to mechanical tolerances.
- They can be used to produce thinner, stable coatings (when operated in negative-gap mode) than are achievable with a fixed-gap, rigid-roll configuration.
- They are useful in the transference of pre-metered coatings.
- They reduce the possibility of damage due to roll clash and the risk of wear when used as an alternative to rigid-rolls alone in fixed-gap forward and reverse roll coating operations.
- Recent analyses of the flow stability suggest that deformable systems can be operated at significantly higher speeds than their rigid-roll counterparts.

A disadvantage of deformable roll coating systems, however, is that:

- They are sensitive to variations in the elastic properties of the elastomer layer, which can change with use, usually as a result of the leaching of solvents.

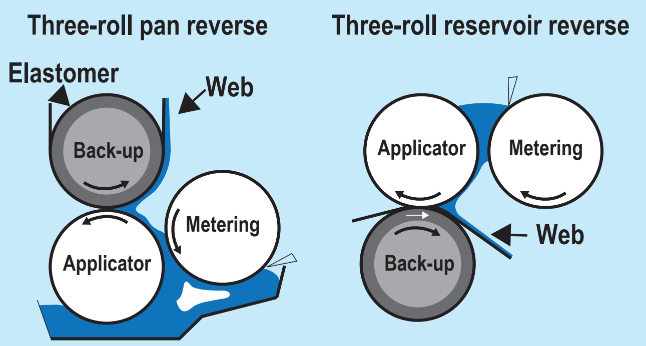

Figure 1 Pan-fed (left) and reservoir-fed deformable roll coating systems

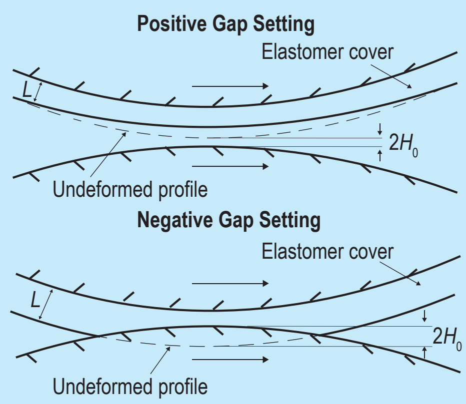

Figure 2 Positive gap (upper) and negative gap (lower) deformable roll coating systems

2. Previous Studies

2.1 Experimental

Key experimental studies of deformable roll coating systems include those of: Coyle[2], who measured film thicknesses as a function of the roll separating force; (ii) Ascanio & Ruiz[3] who measured pressure distributions in a deformable nip of a counter-rotating roll pair; (iii) Ascanio *et al*[4] who measured the pressure distribution and flow characteristics in a forward deformable roll coater with Newtonian fluids operating at high speed; and (iv) Ascanio *et al*[5] who have reported the same for complex rheology fluids; Cohu & Magnin[6] who measured the effect of the elastomer layer thickness, L, (see Fig. 3) on the coated film thicknesses. One of the main results from their work is that decreasing L below a critical value decreases the coated film thicknesses significantly. These experimental and theoretical studies have been reviewed by Chong[7] and Chong *et al*[8]. The latter also investigated the onset of the ribbing instability for both positive gap and negative gap settings.

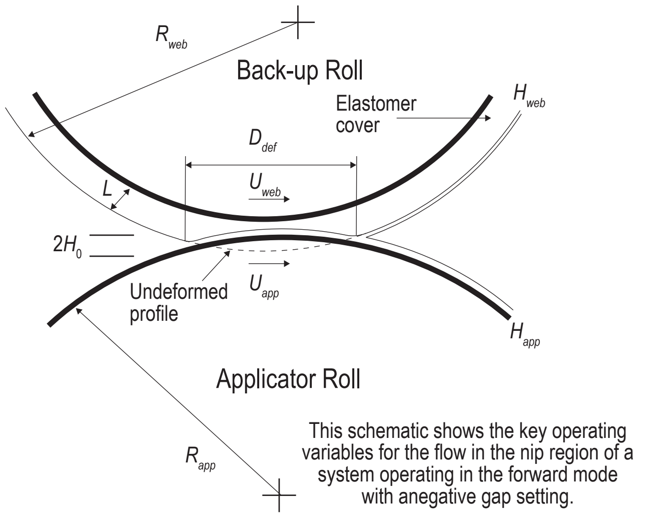

Figure3 Key variables in deformable roll coating

2.2 Theoretical

Deformable roll coating systems are difficult to model. Coyle[2] presented the first simple analysis of the flow in the gap, in which the local hydrodynamic pressure is assumed to be directly proportional to the local deformation of the elastomer. This model, which is referred to as the "Constrained Column Model" or CCM, was used to predict the variation in H_{web} (see Fig. 3 for a description of the key variables for both positive and negative gap regimes).

Coyle's work[2] has been extended by coupling the CCM with better models of the liquid flow in order to analyze the positive gap regime.[1] Most elastomers are effectively incompressible, a feature for which analyses involving a CCM are strictly invalid. Work by Young[9] and Gostling *et al*[10], developed an alternative approach which takes account of both the elastomer's incompressibility and the effects of layer thickness during deformable roll coating. It shows that:

- Hookean spring models are unable to model effectively the deformation of an incompressible compliant layer.
- Scaling arguments suggest that layer thickness and elasticity may have similar effects on the field variables.
- For negative gaps and capillary numbers, Ca, of O(1) ($Ca=\mu(U_{web}+U_{app})/\sigma$ where μ=viscosity and σ=surface tension) the effect of varying either viscosity or speed and hence Ca is to significantly alter the coating thickness.

The viscoelastic properties of roll covers on deformable roll coating has been explored experimentally by Chong[7].

3. Film Thickness Predictions in Deformable Roll Coating Systems

The main aim of analyzing deformable roll coating systems is to predict the coating thickness, H_{web}, placed on the web as a result of the competition between hydrodynamic pressures, elastic restoring forces, and applied load. The relative importance of each of these effects can be estimated in terms of a number of dimensionless ratios. If E is Young's modulus for the elastomer layer, R_{eff} is the effective roll radius (defined by $2/R_{eff} = 1/R_{web} + 1/R_{app}$), H_0 is the half-gap width, μ is the liquid viscosity, and U_{ave} is the average roll speed (given by $U_{ave} = ½(U_{web} + U_{app})$), then these are:

- The **LOAD NUMBER**, F. For a specified load, W, per unit roll length, the thickness, H_{web}, is controlled by varying the load number, the ratio of applied load to elastic restoring force:

$$F = \frac{W}{ER_{eff}} \tag{1}$$

- The **GAP NUMBER**, G. For a pre-set gap, $2H_0$, the thickness, H_{web}, is controlled by varying the gap number, the ratio of semi-gap width to effective roll radius:

$$G = \frac{H_0}{R_{eff}} \tag{2}$$

- The **ELASTICITY NUMBER**, Es. The relative importance of hydrodynamic pressures to elastic restoring forces is measured by the elasticity number, Es:

$$E_s = \frac{\mu U_{ave}}{ER_{eff}} \tag{3}$$

Another important parameter in deformable roll coating is the ratio L/R_{eff}. This is because if the surface deformations are of the same order of magnitude as L, the contact width will be reduced, the load more concentrated, and the coating thinner. For highly-loaded situations with an incompressible elastomer the distance over which the elastomer surface deforms, D_{def} say, can be approximated by Hertz's classical theory

$$D_{def} \approx 2\left(\frac{3W\,R_{eff}}{\pi E}\right)^{1/2} \tag{4}$$

Note that for a system with R_{eff}=10cm, a soft elastomer with E=1x10^6 Pa, and an applied load of 1000N m^{-1}, the above expression predicts $D_{def} \approx$ 20mm, which is larger than a typical elastomer thickness of 12mm! Clearly it is important to be aware just how the elastomer thickness L compares with D_{def}.[1]

The range of parameters occurring in deformable roll coating systems with rubber covered rolls have been estimated by Coyle[2]: 0.1Pas ≤ viscosity (μ) ≤ 5Pas; 0.1m/s ≤ average roll speed (U_{ave}) ≤ 1m/s; 1x10^6 Pa ≤ E ≤ 1.5x10^7 Pa; 0.006m ≤ elastomer layer thickness (L) ≤ 0.02m; 0.05m ≤ effective roll radius (R_{eff}) ≤ 0.15m; 1x10^3 N/m ≤ applied load (W) ≤ 1.5x104 N/m. Typical ranges of the above parameters are for F in the range 0.001 to 0.3, Es in the range 10^{-4} to 10^{-8}, and G is in the range –0.01 to 0.01 (- indicating a negative gap setting).

3.1 Pre-set Load, *W*

A key theoretical result is that of Hooke & O'Donoghue[11], who predicted that the minimum thickness in the gap, H_m, for highly-loaded systems with an incompressible elastomer is given by

$$H_m = 3.12\left(\mu U_{ave}\right)^{0.6} W^{-0.2}\left(4E/3\right)^{-0.4} R_{eff}^{0.6} \tag{5}$$

so that the maximum flux, Q_{def}, passing through the gap can be approximated by $Q_{def}=U_{ave}\,H_m$, leading to:

$$Q_{def} = 3.12\mu^{0.6}U_{ave}^{1.6}R_{eff}^{0.6}\left(4E/3\right)^{-0.4}W^{-0.2} \tag{6}$$

This is one important example from the literature where experimental and theoretical predictions of flux, Q_{def}, are often written in the form

$$Q_{def} = \text{constant} \times \mu^{a} \times U_{ave}^{b} \times R_{eff}^{c} \times E^{d} \times W^{e} \tag{7}$$

The exponents a, b, c, d, and e from other important studies include: Coyle *et al*[12]: 0.6, 1.6, 0.7, -0.3, -0.3 and Cohu & Magnin[13]: 0.6, 1.6, 0, 0, -0.3. Note that the actual flux passing through the nip, Q_{actual}, is the smaller of the inlet flux into the nip, Q_{inlet}, and Q_{def} where

$$Q_{inlet} = U_{app} \times \text{Pickup thickness} \tag{8}$$

If $Q_{def} > Q_{inlet}$ then the nip is said to be starved since the flux being supplied to the nip is less than that which can be supported by the deformable nip. In order to predict the thickness on the web, H_{web}, it is also necessary to know how the web and applicator roll film-split. At present no such theoretical expression exists so here we assume that the film-split is the same as in the rigid roll case.[14] Under this assumption

$$H_{web} = \frac{Q_{actual}}{U_{ave}}\frac{S(S+3)}{2(1+S)^2} \tag{9}$$

so the result of Hooke & O'Donoghue[11] predicts that H_{web} is given by

$$H_{web} = 1.56\left(\mu U_{ave}\right)^{0.6} W^{-0.2}\left(4E/3\right)^{-0.4} R_{eff}^{0.6}\frac{S(S+3)}{(1+S)^2} \tag{10}$$

where $S=U_{web}/U_{app}$ is the speed ratio.

3.2 Pre-set Gap, H_0

The above expressions predict how H_{web} varies with the applied load W. If, however, the system is operated with a pre-set gap it is necessary to know how W and H_0 (half of the pre-set gap) are related in order to predict H_{web}. Pranckh & Coyle[1] proposed a relationship between W and H_0 which led to H_{web} having the following dependence on the operating parameters:

$$H_{web} = \text{constant} \times \left(\mu U_{ave}\right)^{0.6} \times \left(-H_0\right)^{-0.2} \times E^{-0.6} \times R_{eff}^{0.2} \tag{11}$$

Note that we are only interested here in negative gap settings (H_0 is negative) since systems with positive pre-set gaps behave effectively as rigid roll systems. Work by Young[9] for incompressible elastomers with a fixed L/R_{eff} = 0.1, predicted that the relationship between W and H_0 could be approximated by

$$W = 1400ER_{eff}\left(\frac{-H_0}{R_{eff}}\right)^{1.93} \tag{12}$$

which, when substituted into the above equation relating H_{web} and W leads to the following expression for the maximum flux passing through the deformable nip

$$Q_{def} = 0.66 \times \mu^{0.6} \times U_{ave}^{1.6} \times R_{eff}^{0.786} \times E^{-0.6} \times \left(-H_0\right)^{-0.386}. \tag{13}$$

This leads to the following prediction for H_{web}:

$$H_{web} \approx 0.33(\mu U_{ave})^{0.6}(-H_0)^{-0.386} E^{-0.6} R_{eff}^{0.786} \frac{S(S+3)}{(1+S)^2} \quad (14)$$

Other examples in the literature, Chong[7], predict that the flux through deformable systems with pre-set negative gaps can be written in the following form:

$$Q_{def} = \text{constant} \times \mu^a \times U_{ave}^b \times R_{eff}^c \times E^d \times (-H_0)^e \quad (15)$$

where

Study	a	b	c	d	e
Coyle *et al*[12]	0.6	1.6	0.2	-0.6	-0.2
Kang *et al*[15]	0.5	1.5	0.0	-1.6	-0.47
Young[9]	0.6	1.6	0.786	-0.6	-0.386

As in the pre-set load cases, the flux through the system can be used to predict the film thicknesses on each roll by assuming that the film-split is the same as the rigid roll case.

3.3 Thin Deformable Layers

It is known that film thicknesses can be significantly reduced if the layer thickness, *L*, is sufficiently thin. Carvahlo & Scriven[16] proposed the following correlations for thin and thick layers:

For thin layers ($L/R_{eff} < 0.1$)

$$Q = 1.34\mu^{0.6} U_{ave}^{1.6} R_{eff}^{0.71} E^{-0.29} W^{-0.31} \left(\frac{L}{R_{eff}}\right)^{0.29} \quad (16)$$

For thick layers (L/R_{eff} 0.1)

$$Q = 0.68\mu^{0.6} U_{ave}^{1.6} R_{eff}^{0.71} E^{-0.29} W^{-0.31} \quad (17)$$

3.4 Limitations of Theoretical Models

There is no universally validated model for flow in the industrially relevant negative gap regime, so the above equations should be used with caution primarily for examining trends, rather than for obtaining specific thickness predictions. Hence, in their more general form each of the above models can be represented in the following forms.

3.4.1 For Pre-set Load:

$$Q_{def} = 3.12 \times \text{flux factor} \times \mu^a \times U_{ave}^b \times R_{eff}^c \times E^d \times W^e \quad (18)$$

which leads to

$$H_{web} = 1.56 \times \text{flux factor} \times \mu^a \times U_{ave}^{b-1} R_{eff}^c E^d W^e \frac{S(S+3)}{(1+S)^2} \quad (19)$$

3.4.2 For Pre-set Gap:

$$Q_{def} = 0.66 \times \text{flux factor} \times \mu^a \times U_{ave}^b \times R_{eff}^c \times E^d \times (-H_0)^e \quad (20)$$

which leads to

$$H_{web} = 0.33 \times \text{flux factor} \times \mu^a \times U_{ave}^{b-1} \times R_{eff}^c \times E^d \times (-H_0)^e \frac{S(S+3)}{(1+S)^2} \quad (21)$$

where the flux factor and *a*, *b*, *c*, *d*, and *e* are calibration parameters. You can modify each of these parameters to give you better agreement with your own industrial data. Finally, if you want to account for the effect of a thin elastomer layer, the above suggests that you could modify the above expressions for H_{web} by introducing an additional factor:

3.4.3 For Thin Layers (*L/Reff* < 0.1)

For pre-set load:

$$H_{web} = \text{constant} \times \mu^a U_{ave}^b R_{eff}^c E^d W^e \left(\frac{L}{R_{eff}}\right)^f \frac{S(S+3)}{(1+S)^2} \quad (22)$$

For pre-set gap:

$$H_{web} = \text{constant} \times \mu^a U_{ave}^b R_{eff}^c E^d (-H_0)^e \left(\frac{L}{R_{eff}}\right)^f \frac{S(S+3)}{(1+S)^2} \quad (23)$$

The work of Carvahlo & Scriven[16] found that the exponent *f*=0.29.

4. Stability of Deformable Roll Coating

The limits of operability for deformable roll coating are less well understood than for corresponding fixed-gap rigid roll systems; however they are known to be prone to a similar form of ribbing instability. Indeed it is commonly assumed that ribbing is an unavoidable feature of deformable systems.[1] The ribbing instability associated with deformable roll coating systems operating in the forward mode has been explored by Carvahlo & Scriven[16], who considered the case with a positive gap setting and have shown that soft elastomer coverings have a weakly stabilizing effect, enabling an increase of around 10% in speed of operation over their rigid-roll counterparts. Young[9] considered more industrially relevant negative gaps, arriving at two very important conclusions:

• For typical conditions under negative gap operation a speed increase in excess of 70% is achievable before ribbing becomes a problem.
• The flow can restabilize as the gap setting becomes more negative as a consequence of the increase in contact width between the two roll surfaces.

The experimental study of Chong *et al*[8] also found that for positive gap settings, the critical roll speed for ribbing can be increased by employing a larger gap or using a thicker covering of compliant material.

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