Chemical Engineering Science 165 (2017) 204–215

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Reverse roll coating with a deformable roll operating at negative gaps

H. Benkreira [a,*], Y. Shibata [a,b], K. Ito [b]

[a] School of Engineering, R&KT Centre in Advanced Materials Engineering, University of Bradford, BD7 1DP, United Kingdom
[b] Films R&D Centre, Toyobo Co. Ltd., Otsu, Japan

HIGHLIGHTS

- The paper revisits the well-established reverse roll coating but using a deformable metering roller.
- This "new" development provides a simple technique to produce very thin films, down to 1 μm at speeds up to 150 m/min.
- The data are underpinned by simple lubrication modelling.

GRAPHICAL ABSTRACT

Rubber Shore A Hardness	Viscosity (mPa.s)	Line Speed (Applicator) (m/min)	film thickness achievable (μm)
70	30	30	0.2-1.7
		90	0.3-2.8
		150	0.3-4.3

ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form 24 January 2017
Accepted 16 February 2017
Available online 6 March 2017

Keywords:
Reverse roll coating
Deformable
Negative gap
Thin films
Cascade
Ribbing

ABSTRACT

Reverse roll coating is probably the most widely used coating operation, yet its full potential has not been exploited as it is shown in this paper which considers operation with a negative gap. We demonstrate through a wide range of experimental data that such operation can yield very thin and stable films with no ribbing or cascade instabilities when low viscosity fluids are used. Typically, stable film thickness less than 5 μm can be obtained at speeds up to 150 m/min when a rubber roller is used at −100 μm gap with fluids of viscosity in the range 10–200 mPa s. These film thicknesses can be made to decrease further down to 1 or 2 μm with a judicious choice of speed ratios (applicator to metering roller) and rubber hardness. Such new findings make this simple coating method an attractive roll to roll technique for application in the newer coating technologies, such as in the production of solar cells and plastic electronics. The data obtained in this study have been underpinned by a model based on the classical lubrication theory, well developed for such flow situations. Essentially it is shown that the film thickness non dimensionalised with respect to the set negative gap is controlled through a single parameter, the elasticity number *Ne* which combines all the operating parameters. Of course, this flow problem has complexities, particularly at high speed ratios and at zero gap so the data obtained here can serve as a basis for more comprehensive modelling of this classical fluid mechanic problem.

1. Introduction

Coating or the deposition of a thin film onto a surface for decorative, protective or functional applications is an important industrial operation used to transform paper, textile, plastic and metal substrates into highly added value products. Examples are very many and include printing paper, letterpress printing plates, photographic films, medical x-rays, audio and video magnetic tapes, electronic printed circuits, controlled release medical drug substrates, flexible solar panels, membranes and a host of other products. In all these applications, the product performance and cost rely critically on how thin, uniform and fast the film can be coated. Modern roll to roll production in high-tech applications (plastic electronics and photovoltaics for example) require that the coated liquid film be no more than a few microns (subsequently drying into nanometers layers) and produced at speed higher than 0.5 m/s without any defects such as ribbing which may form on the surface of the film as a result of flow instabilities or tiny air bubbles which may be entrained during flow as a result of dynamic wetting failure.

* Corresponding author.
E-mail address: H.Benkreira@bradford.ac.uk (H. Benkreira).

http://dx.doi.org/10.1016/j.ces.2017.02.034

Notation

Ca	capillary number $[=\mu v_A/\sigma]$
c_l	rollers contact length $[=2\sqrt{2rh_N}]$
E	rubber elastic modulus
E'	rubber storage modulus
E''	rubber loss modulus
E^*	rubber complex modulus
Es	zero gap elasticity number $\left[=\mu v_A\left[\frac{1-S}{2}\right]/\left[\frac{E}{l}(r^2)\right]\right]$
f_d	rubber roller deformation frequency $[=v_M/c_l]$
h	coating gap
h_A	coating film thickness formed on applicator roller
$-2h_0$	negative applied gap
H_{h_0}	dimensionless gap with respect to the half the negative gap $[=h/h_0]$
H_r	dimensionless gap with respect to the equivalent roller radius $[=h/r]$
H_{A,h_0}	dimensionless film thickness with respect to half the negative gap $[=h_A/h_0]$
$H_{A,r}$	dimensionless film thickness with respect to the equivalent roller radius $[=h_A/r]$
l	thickness of rubber sleeve on metering roller
Ne	gap scaled elasticity number $\left[=\mu v_A\left[\frac{1-S}{2}\right]/\left[\frac{E}{l}\left(\frac{h_0^3}{\sqrt{rh_0}}\right)\right]\right]$
q	coating flow rate
p	pressure
P_{h_0}	dimensionless pressure with respect to half the negative gap $[=p/\frac{E}{l}h_0]$
P_r	dimensionless pressure with respect to the equivalent roller radius $[=p/\frac{E}{l}r]$
r	equivalent radius of the two rollers $\left[=1/\left\{\frac{1}{2}\left(\frac{1}{r_A}+\frac{1}{r_M}\right)\right\}\right]$,
r_A	applicator roller radius
r_M	metering roller radius
S	speed ratio $[=v_A/v_M]$
S^*	critical speed ratio for onset of cascade instabilities
v_A	applicator roller speed
v_M	metering roller speed
x	primary flow direction
x_e	flow exit position
x_i	flow inlet position
X	dimensionless primary flow direction
y	transverse flow direction
Y	dimensionless transverse flow direction
λ^-	dimensionless flow rate in negative gap operation $\left[=\frac{\frac{1}{2}q}{v_A\left[\frac{1-S}{2}\right]h_0}=\frac{1}{2}H_{A,h_0}/\left[\frac{1-S}{2}\right]\right]$
λ^+	dimensionless flow rate in negative gap operation $\left[=\frac{\frac{1}{2}q}{v_A\left[\frac{1-S}{2}\right]h_0}=\frac{1}{2}H_{A,h_0}/\left[\frac{1-S}{2}\right]\right]$
λ^0	dimensionless flow rate in zero gap operation $\left[\lambda^0=\frac{\frac{1}{2}q}{v_A\left[\frac{1-S}{2}\right]r}=\frac{1}{2}H_{A,r}/\left[\frac{1-S}{2}\right]\right]$
δ	rubber elastic deformation
μ	viscosity of coating liquid
σ	surface tension of coating liquid

Of all the coating methods available, roll coating is by far the most used industrially: it is economical and simple to organize (two rotating rollers separated by a coating gap fed with the coating liquid) and can be operated over large widths (metres). Clearly, as roll coating flows are metered by a gap, the lower limit on film thickness is dictated by how small a gap the coater can be operated at. In practice, with rigid steel or ceramic rollers, gaps less than 25 μm are not used in order to prevent the possibility of the rotating rollers clashing. Also as the gaps get smaller, the accuracy of the set gap diminishes because of the roller eccentricity which can be up to 25 μm. The end result is that coated films with rigid rollers at very low gap settings exhibit significant variations in thickness both in the machine and transverse directions. To circumvent these problems and produce thinner films, a deformable rubber sleeved roller pressing against a rigid roller system forming a "negative gap" is used to create a very small coated film resulting from the elasto-hydrodynamic deformation of the rotating rollers. Such a flow situation demands that the rollers rotate preferably in the same direction at the nip to prevent possible shearing of the deforming roller. Ribbing instabilities are however inevitable in such *forward* roll coating flow (Pearson, 1960; Pitts and Greiller, 1961; Benkreira et al., 1982) unless the operation is conducted at very low speeds. The quest for a roll coating method that is stable and can be conducted at high speeds to produce very thin films leads us in the present work to consider negative gap deformable *reverse* roll coating (see Fig. 1).

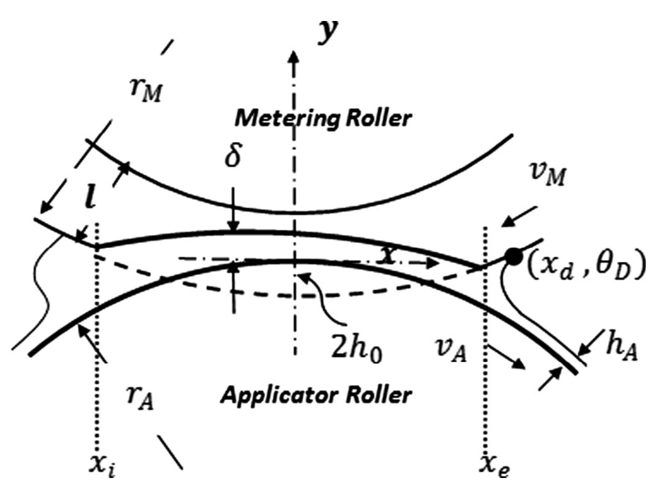

Fig. 1. Deformable reverse roll coating flow; geometry and pertinent parameters.

In this configuration, as the rollers rotate in opposite direction at the nip, the flow that exits out of the nip and forms the film will be considerably smaller than in forward roll coating particularly when the metering roller to applicator roller speed ratio approaches 1. A difficulty with operating negative gap deformable roll coating in the reverse mode is the possibility of shearing the deforming roller. However, with good design and control, such a problem can be overcome particularly if the method can be proven to deliver the very thin film thickness required by the new applications. The aim of this paper is precisely this-to assess how thin and uniform the films can be formed by this method and up to what speed. An exhaustive literature search has shown only one published work on negative gap reverse deformable roll coating, that of Sasaki et al. (2015) who observed that stability to ribbing was expanded when coating fluid viscosity is decreased. They did not however consider the other important form of instabilities in reverse roll coating, cascade (further details later), nor did they arrive at an operating guide to enable an assessment of how thin uniform films can be achieved through this method