The University of Bradford Institutional Repository

Author(s): Benkreira, H. , Patel, R., Edwards, M.F. and Wilkinson, W.L.

Title: Classification and analyses of coating flows

Publication year: 1994

Journal title: Journal of Non-Newtonian Fluid Mechanics

ISSN: 0377-0257

Publisher: Elsevier Ltd.

Publisher's site: http://www.sciencedirect.com

Link to original published version: http://dx.doi.org/10.1016/0377-0257(94)80035-9

CLASSIFICATION AND ANALYSES OF COATING FLOWS

H. Benkreira* and R. Patel

Dept. of Chemical Engineering, University of Bradford, BD7. 1DP UK.

M.F. Edwards (FEng)

Unilever Research Port Sunlight Laboratory, UK. (Formerly Professor of Chemical Engineering at the University of Bradford, UK.)

W.L.Wilkinson (CBE, FEng, FRS)

British Nuclear Fuels, UK. (Formerly Professor of Chemical Engineering at the University of Bradford, UK.)

Abstract

A classification of coating flows is presented to facilitate a fundamental approach to their study. Four categories are observed: free, metered, transfer and gravure coating flows. They are all limited by free surface(s) which make their analysis difficult. Various analytical approaches have been used and these are briefly reviewed in this paper.

Keywords: coating flows; free coating; metered coating; transfer coating; gravure coating.

---

1. Introduction.

Coating flows are fluid flows which result in thin films of liquid forming onto surfaces. Such flows occur naturally or are engineered for the manufacture of a variety of products such as wall paper and adhesive tapes, photographic and X-ray films, magnetic tapes for audio, video and computer use, electronic circuit boards, printing plates for papers, books and magazines, coated papers for printing etc.... With these products, the coated layer on the substrate is the functional

*Corresponding author.

part, it is made of a liquid- solid or polymeric formulation of specific physical and rheological properties and it must be of a certain thickness and uniformity to fulfil the application for which it is designed. Also, the speed at which the coated film is required differs depending on applications and controls the economics of the operation. No one coating flow can operate to yield the wide range of film thickness - speeds required in practice without exhibiting non uniformity (instabilities) on the free surface, entraining air within the film or breaking altogether. Indeed, most coating flows have a narrow stable window of operation, not easily predictable, hence the reliance on experience when designing or operating coaters. Inevitably, difficulties arise with new applications which require more strict specifications on quality. Clearly a classification of the coating methods available and their flow analyses is useful in this context. This is the subject of this paper which draws on work carried out by the authors and other researchers in this important area of fluid mechanics where a-priori the fluids must be regarded as non-Newtonian.

2. Classification

Limiting the classification to coating flows leading to the continuous formation and deposition of a film onto a surface, we observe that this can be carried out in one or a combination of the following broad ways:

(i) withdrawal of liquid from a pool by a moving substrate, i.e. free coating flow,

(ii) metering an excess amount of liquid in a flow geometry to form a film onto a moving substrate, i.e. metered coating flow,

(iii) delivering the exact amount of liquid in a flow geometry to form a film and then transferring it onto a moving substrate, i.e. transfer coating flow,

(iv) allowing a moving substrate to wipe a proportion of a coating trapped in the cells of a printed or gravure roller, i.e. print or gravure coating flow.

These coating flows have been developed with the purpose of:- precision and independence of film thickness from the physical properties of the liquid and the speed of the substrate and - reduction of film thickness to lowest possible values whilst keeping the above requirements on precision and independence from operating conditions. Types (i) to (iv) coating flows progressively respond to these needs and are now examined further.

3. Free Coating Flows

This is a simple flow scheme which results from the withdrawal of liquid from a pool by a moving plane or a rotating cylinder, as illustrated in Fig. 1. In both cases, all the operating variables play a part in controlling the thickness of the film formed, its stability and air entrainment. Since the rotating roller flow is essentially an inclined plane in curvilinear coordinates, the angular withdrawal case is representative of a general free coating flow. No complete solution of such a flow problem is available; approximations of the film thickness, h_o, developed far upstream are obtained depending on the flow conditions which can be represented by the capillary ($Ca = \mu u_w/\sigma$) and Reynolds ($Re = \rho\, u_w\, h_o/\mu$) numbers.

<u>Low Ca and negligible Re</u>

When surface tension effects are important and inertia is negligible, a one dimensional description of the flow is feasible [1-3] and produces estimates of the film thickness as:

$$T_o = h_o / h^* = 0.944\, Ca^{1/6} (1 - \cos\alpha)^{-1/2} \qquad (1)$$

which are in agreement with experimental data [1,3]. In the above equation, $h^* = (\mu u_w / \rho g)^{1/2}$ is a characteristic film thickness obtained by balancing viscous and gravity forces.

(b) Intermediate Ca and Re

When inertia forces are introduced, the model equations become non linear two dimensional and simplifications become necessary to produce solutions to the problem. The simplest approach is to consider first order inertia terms only as was done by Soroka and Tallmadge [4] and later by Tharmalingham and Wilkinson [5] to obtain corrections to the above equation. The predictions so obtained however are still limited and apply to Ca <1. A more comprehensive inclusion of inertia effects was carried out by Esmail and coworkers [6,7] who used the thin film approximation in the continuity and Navier-Stokes equations:

$$u_x + v_y = O. \tag{2}$$

$$\rho(\mathrm{uu}_x + v u_y) = -p_x + \mu u_{yy} - \rho g \sin\alpha \tag{3}$$

$$O = -p_y + \mu v_{yy} - \rho g \cos\alpha \tag{4}$$

subject to the following boundary conditions at the moving wall and the free surface:

$$u(x, o) = v(x, o) = O \tag{5}$$

$$u_y(x,h) = O \;\; ; (p - 2\mu v_y + \sigma h_{xx})(x,h) = O \tag{6}$$

Using the direct method of Galerkin, Esmail and Hummel [6] transformed these equations into a single differential equation which they integrated from the constant film region where h = h_o to the static meniscus (x_s, h_s) where the balances of forces was assumed to be:

$$\left(\frac{\sigma}{2\rho g} h^2{}_{xx} + h_x \sin\alpha\right)(x_s, h_s) = 1 - \cos\alpha \tag{7}$$

Typical results of the numerical integration for vertical withdrawal are presented in [6] where the dependence of T_o on Re and Ca is replaced by an equivalent T_o (γ, Ca) with $\gamma = \sigma\ (\rho/\ \mu^4\ g)^{1/3}$ a fluid property number which essentially describes the effect of Re since $\gamma \equiv$ (Re/Ca)$^{2/3}$. Thus at fixed γ, large Ca leads to high Re whereas at fixed Ca, large γ correponds to high Re. A branching of the curves T_o (γ, Ca) is observed as Ca and γ are increased showing the limiting effect of inertia on the thickness of the films formed. The more viscous flow (Re $\simeq$ 0) exhibits a large constant T_o($\simeq$ 0.8), the rapid flow (Re > 10) exhibits a smaller constant T_o ($\simeq$ 0.5). A good agreement with experimental data is observed for a wide range of Ca (up to 50) and Re (up to 10). This theory gives a significant improvement to predictions obtained with eqn. (1). Another important observation is that the effect of the angle, α on film thickness is not simply correcting for the effect of gravity on bulk flow. As this angle varies, the shape of the coating meniscus varies greatly and this must have an effect on the film thickness [6,7]. This theory however does not provide a limit to coating flow which is observed at high Reynolds numbers.

(c) Large Re free coating

Cerro and Scriven [8] have examined this limiting flow behaviour using a rapid flow analysis based on an integral momentum balance written across the film thickness from 0 to h as:

$$\rho \frac{d}{dx}\int_o^h u^2 dy = \mu u_y(h) \quad \mu u_y(o) - \rho g h \tag{8}$$

with parabolic velocity distributions upstream in the static meniscus region and downstream where the film thickness levels to a constant value. Solving the resulting equations as an initial value problem, they obtain a limit for vertical withdrawal as:

$$T_o = 0.5439 \tag{9}$$

Campanella and Cerro [9] extended this analysis to angular (roll) withdrawal and established bounds for T_o as:

$$\frac{0.4714}{(\sin\alpha)^{1/2}} < \mathrm{T_o} < \frac{0.5439}{(\sin\alpha)^{1/2}} \qquad 35^{\mathrm{o}} < \alpha < 90^{o} \tag{10}$$

$$T_o < \frac{0.5439}{(\sin\alpha)^{1/2}} \qquad \alpha > 90^{\mathrm{o}} \tag{11}$$

These criteria fit in with the experimental data of Tharmalingham and Wilkinson [5] and Gutfinger and Tallmadge [10]. All the theories developed above can be extended to purely non-Newtonian viscous behaviour [11-15]. Although much progress has been made in the analysis of free coating, there still is a need for a unified theory capable of predicting film thickness for the entire range of stable operating conditions. Computer based solutions using finite element methods are now feasible.

4. Metered Coating Flows

Here a boundary is put in place to reduce the extent of flow as shown in Fig. 2a,b,c. Clearly for a given substrate speed and fluid we can reduce the thickness of the emerging film by reducing the gap between the boundary and the moving substrate but also by allowing the boundary to move in opposite direction to the substrate. We have now arrived at reverse roll coating (Fig.2b) where the moving boundary in the shape of a roller is convenient. We may also drive the moving boundary in the same direction as the substrate thus splitting the emerging flow into two films as in forward roll coating depicted in Fig.2c. No other means are available to reduce the film thickness further except that a vacuum may be applied upstream of the boundary or across it if it were porous to reduce the pressure flow contribution. All these geometries show a feed region upstream of the flow and a film(s) formation region downstream. Upstream where the regions are narrow, a lubrication flow may be assumed and

$$p_x = \frac{12\mu}{h^2(x)}\left(\frac{u_1+u_2}{2} - \frac{q}{h(x)}\right) \tag{12}$$

expresses the variation of the pressure gradient, in the direction, x, of flow with gap, h, between the boundaries and volumetric flow rate, q, across; u_1 and u_2 are the velocities of the stationary or moving walls. In blade type metered flow u_2 would be zero; in reverse roll coating u_2 would assume a negative value. A general expression for q is:

$$q = u_1 h_1 + u_2 h_2 \tag{13}$$

Pressure conditions at the points limiting the feed region are necessary to solve the above equations. The problem is that these positions x_i and x_e and the pressures at them, are not known and further approximations have to be made to obtain an analytical solution. Two scenarios arise:

(i) When the coating flow lends itself to plausible conditions, such as in blade coating (Fig. 2a) where the flow length is known, we may assume the whole region underneath the blade to be governed by the above equation and that pressures at the extremities are zero. Such a model, used by Middleman [16], gives a dimensionless film thickness which is function of the geometry of the system only and is compatible with experiment data. A solution which accounts for the effect of speed, viscosity and surface tension can be sought by allowing the pressure downstream to be set by the coating meniscus formed, i.e.

$$p\ (x_e) = -\sigma/r_c \tag{14}$$

with the radius of curvature, r_c, related to the dimensions at exit of the flow. For blade coating, it would approximate to:

$$r_c = h\ (x_e) - h_1 \tag{15}$$

and a solution to eqn. (12) can be expressed as:

$$\frac{\sigma}{h(x_e)-h_1}=12\mu\left(\int_{x_i}^{x_e}\frac{u_1}{2h^2(x)}dx-\int_{x_i}^{x_e}\frac{u_1 h_1}{h^3(x)}dx\right) \tag{16}$$

h_1 the film thickness formed, being the only unknown.

(ii) When the flow geometry does not help to approximate x_i and x_e, p (x_i) and p (x_e) as in two-roll coating operations where the separation meniscus does not detach from the solid boundary, solutions are sought by assuming first that the feed region extends far upstream ($x_i \rightarrow -\infty$) and that p (x_i) is known. Also, the pressure downstream p (x_e) can be assumed to be nil or $= -\sigma/r_c$ (with an appropriate r_c) as was done for blade coating above. In forward roll coating for example, Fig. 2c, the radius of curvature can be approximated by:

$$r_c = \tfrac{1}{2}\,(h\,(x_e) - h_1 - h_2) \tag{17}$$

and a solution to eqn. (12) is:

$$\frac{2\sigma}{h(x_e)-h_1-h_2}=12\mu\left(\int_{x_i}^{x_e}\frac{u_1+u_2\,dx}{2h^2(x)}-\int_{x_i}^{x_e}\frac{u_1 h_1+u_2 h_2}{h^3(x)}\right) \tag{18}$$

where h_1, h_2 and x_e are all unknown. More equations are needed to locate x_e and these are given by assuming that at x_e, the velocity is zero and the flow splits such as du/dy (x_e) = 0 (Prandtl-Hopkins separation conditions [17]). Many analyses of metered coating flows have been carried out along these lines. For forward roll coating, a dimensionless total flow rate, $\lambda = (u_1h_1 + u_2 h_2)/^{1/2}\ h_o\ (u_1+u_2)$, of about 1.30 and a flux distribution, $h_1/\ h_2 = (u_1/u_2)^{0.5}$ are predicted and describe the trend of the experimental data (Benkreira, Wilkinson and Edwards [18]). For reverse roll coating, the above analytical treatment yields a dimensionless flow rate, $\lambda = u_2\ h_2/h_o\ (u_2 - u_1)$ of about 0.65 consistent with experimental data at low speed ratio u_1/u_2 (Benkreira, Wilkinson and Edwards [19]).

Inspite of the fair agreement with experimental data the whole approach described above is flawed; it ignores the regions either side of the feed region, particularly downstream where the film is actually forming and where the lubrication approximation is not valid as explained by Taylor [20] and Pearson [21]. In principle, the film formation region which extends from x_e to x_s (the real separation point) should be analysed assuming a full 2D free surface flow analysis and matched at x_e with the lubrication portion of the flow. Pitts and Greiller [22] initiated this approach and produced an approximate solution of the biharmonic equation, for the symmetrical forward roll coating using the full traction boundary conditions on the free surface which they approximated to a parabola. Pitts and Greiller's predictions for the position of the separation point where in satisfactory agreement with their experimental data. This procedure was also used by Williamson [23] who solved the biharmonic equation numerically when the separation interface is expressed by a polynominal in the symmetrical forward roll coating. Further developments have been made with the advent of fast computers and efficient numerical algorithms as indicated by the work of Coyle, Macosko and Scriven [24]. Closer agreement with experimental data has been achieved by this approach which reproduces for example the film split ratio $h_1/h_2 = (u_1/u_2)^{0.65}$ measured by Benkreira et al.[19]. More importantly, such an approach is essential for stability analyses which rely on accurately predicted free surface position and profile [25].

5. Transfer Coating Flows

In this system, a uniform film flow per unit width, q, is transferred onto a moving substrate. At any substrate velocity, u_w, the film thickness on the substrate, h_w (= q/u_w), can be controlled to any desired value by varying q. This operating scheme is attractive since it removes the dependency of film thickness on operating variables, the substrate speed in particular. However, it relies on a uniform and controlled film flow, q, being provided. Coating flows which fall in this category originate from slots or extrusion dies, curtains or slides and single and multiple rolls coaters. In all cases, the range of q and u_w which can be achieved must be limited by the onset of free surface instabilities and/or air entrainment on the final film. The design of the interfacing unit between the film flow supplied and the final film formed controls the operating range. It is this interfacing unit which we refer to as a transfer coating flow unit, examples of which we now examine.

(a) roller based transfer coating

Here the uniform film flow orginates from a roll coating operation and is controlled by a free coating flow (single roll) or a metering coating flow (pair of rollers as in forward or reverse roll coating). The transfer flow is carried out in a "kiss" contact mode to ensure almost complete transfer (Fig. 3a). The tension applied on the substrate and the wrap angle are additional parameter and they, together with the operating variables controlling, q, must fix the range of the stable film thicknesses which can be formed. No work in this area has been reported and it is presumed in practice that if the film flow q is stable, the final film also will be stable and free from air.

(b) slide coating

Here a uniform film flows over an inclined surface prior to meeting a moving substrate (Fig. 3b). Because the film flow is entrained, two coating meniscus are formed, one of them connecting two contact (solid-liquid-air) lines. The resulting coating bead controls stability and air entrainment and is clearly very difficult to predict in terms of the flow within it. Vacuum pressure can be used as an external controlling variable to pin the lower meniscus and retard the onset of air entrainment. Also known as bead coating, this transfer coating flow forms a continuous film only when the speed of the moving substrate lies within a certain range [$u_{w,min}$, $u_{w,max}$]. The experimental work of Tallmadge, Weinberger and Faust [26] defines the upper speed limit $u_{w,max}$ as that at which the amount of fluid bridging the gap between the slide and the substrate is not sufficient to maintain a bead and a uniform film. In practice, this manifests itself with a thin bead and a film which splits into two streams at $u_{w,max}$. More streams appear when the $u_w > u_{w,max}$ and air is sucked in. At the lower limit, the film narrows, the liquid is unable to bridge the gap and at the limit, $u_{w,min}$ it drips off the slide without touching the web. Clearly, the volumetric flow rate of liquid feeding the transfer flow must control these limits; the gap, the angle between the slide and the web, the vacuum applied and the physical properties of the fluid may also have an effect. The experiments of Tallmadge et al [26] show that the flow rate has a primary influence and gap the least effect. Their data can be expressed as:

$$u_{w,max} \ \alpha \ \ q^{0.8} \ \mu^{0.3} \ h_o^{0.15} \tag{19}$$

Guttoff and Kendrick [27] observed that compared with atmospheric operation, a small vacuum increased the limit of coatability and allowed the production of thinner films. Higher vacuums it must be noted gave little further decrease in film thickness. Also observed by Guttoff and Kendrick is that the maximum velocities with no bead vacuum are identical to the plunging tape air entrainment velocities [28,29] and that polymeric solutions showed wider limits of coatability because of their larger elongational viscosities.

(c) <u>slot coating</u>

Here the film flow q is delivered by a slot (Fig. 3c.) and then transferred onto a moving substrate. The coating bead which forms has two meniscii both attached to the slot edges unlike slide coating where the upper meniscus is "free". Lee and Liu [30] developed the similarity with slide coating and showed that below a critical capillary number Ca_c, both flows behave similarly. Above Ca_c, they observed that the same thickness can be coated at much higher speed so that $u_{w,max}$ is much higher than for slide coating. Their data indicate that above Ca_c, slot coating produces film with minimum thickness about 60 to 70% of the gap size independently of web speed and liquid properties.

(d) <u>die coating</u>

In order to widen the limit of coatability, a die instead of a slot can be used. In such a design (Fig. 3d.), the liquid is given greater contact with the web and both the geometry of the die and a vacuum upstream can be manipulated to control flow in the bead and increase $u_{w,max}$.

6. Gravure or Print Coating Flows

The operation uses a roller with a pattern which is either chemically or mechanically engraved on it. Typical patterns are the quadrangular, trihelical and pyramidal with cell volume per unit area of about 10-50x10^{-6} m^3/m^2 and a wetted area coverage of 0.80-0.90 m^2/m^2 of roller surface. These cells are flooded with liquid and wiped by a blade pressed against the rotating roller. The ensuing liquid is then transferred directly onto the substrate (direct gravure) as illustrated in Fig. 4 or onto a transfer roll which applies the coating to the substrate (indirect or offset gravure coating). The applied blade load and the hydrodynamic pressure generated by the liquid underneath the blade control the thickness of the film formed over the filled gravure cells. Clearly, gravure coating flow describes the situation where these loads are such that the blade wipes clean the periphery of the roller leaving only the gravure cells filled with liquid. Benkreira and Patel [31] described the loading conditions required for gravure coating; their data show that higher volume factor are helpful but that true gravure coating is not easily achieved. The transfer of the liquid from the cells to the moving substrate was also studied experimentally by Benkreira and Patel [32] and their findings suggests that about 1/3 of the cell volume is transferred as a film at large speeds regardless of speed ratios (between the moving web and gravure roller). At low speeds, there appears to be a maximum in the film thickness curves for the trihelical and pyramidal cell configurations suggesting that larger films are formed i.e. these cells empty better at low speeds. The reverse is observed with the quadrangular geometry where a minimum occurs at low speeds. At present no theory is available to explain these findings and further work is required. Note that in our classification, gravure coating could also fall in the transfer coating flow category since a film is formed as a result of liquid transferring from the cells to the substrate.

7. Conclusion

This brief review suggests that coating flows can be classified for the purpose of analysis. Common features appear throughout but the challenging task is to develop a fundamental model for film formation which can be adapted to all coating flows. Other features not yet completely resolved concern flow instabilities and air entrainment as well as the effect of non-Newtonian behaviour. With all these aspects, coating flows have now become an important area of research in fluid mechanics [33-35].

Acknowledgements

The financial assistance of the Science and Enginering Research Council (UK) is gratefully acknowledged. Dr. H. Benkreira wishes to thank Dr. W.C. MacSporran a colleague in the Department of Chemical Engineering at the University of Bradford for the numerous constructive discussions on coating flows.

References

1. B.V., Denyagin, and S.M., Levi, Film Coating Theory. Focall Press, New York, 1964.
2. J.A., Tallmadge, A.I.Ch,E.J., 17 (1971) 243.
3. R.P., Spiers, C.V., Subbaraman, and W.L., Wilkinson, Chem.Eng.Sci., 29 (1974) 389.
4. A.J., Soroka, and J.A., Tallmadge, A.I.Ch.E.J., 17 (1971) 505.
5. S., Tharmalingam, and W.L., Wilkinson, Chem.Eng.Sci., 33 (1978) 1481.
6. M.N., Esmail, and R.L., Hummel, Chem.Eng.Sci., 34 (1979) 125.
7. K.D.P., Nigam, and M.N., Esmail, Can.J.Chem.Eng., 58 (1980) 564.
8. R.L., Cerro, and L.E., Scriven, Ind.Eng.Chem. Fundam., 19 (1980) 40.
9. O.H., Campanella, and R.L., Cerro, Chem.Eng.Sci., 39 (1984) 1443.
10. C., Gutfinger, and J.A., Tallmadge, A.I.Ch.E.J., 17 (1971) 505.
11. R.P., Spiers, C.V., Subbaraman, and W.L., Wilkinson, Chem.Eng.Sci. 30 (1975).
12. P., Groenveld, Chem.Eng.Sci., (1970) 1579.
13. C., Gutfinger, and J.A., Tallmadge, A.I.Ch.E.J., 11 (1965) 403.
14. M.N., Takic, and V.O., Popadic, Chem.Eng.Sci., 38 (1983) 285.
15. J.A., Tallmadge, Chem.Eng.Sci., 24 (1969) 471.

16. S., Middleman, Fundamentals of Polymer Processing. McGraw Hill, New York, 1977.
17. M.R., Hopkins, Brit. J.Appl.Phys., 8 (1957) 442.
18. H., Benkreira, M.F., Edwards, and W.L., Wilkinson Chem.Eng.Sci., 36 (1981) 429.
19. H., Benkreira, M.F., Edwards, and W.L., Wilkinson, Chem.Eng.Sci., 37 (1982) 277.
20. G.I., Taylor, J.Fluid.Mech., 16 (1963) 595.
21. J.R.A., Pearson, J.Fluid Mech., 7 (1960) 481.
22. E., Pitts, and J., Greiller, J.Fluid Mech., 11 (1961) 33.
23. A.S., Williamson, J.Fluid Mech., 52 (1972) 639.
24. D.J., Coyle, C.W., Macosko, and L.E., Scriven, J.Fluid Mech., 171 (1986) 183.
25. D.J., Coyle, J.Fluid Mech., 216 (1990) 437.
26. J.A., Tallmadge, C.B., Weinberger, and H.L., Faust, A.I.Ch,E.J., 25 (1979) 1065.
27. E.B., Gutoff, and C.E., Kendrick, A.I.Ch.E.J., 28 (1982) 459.
28. R., Burley, and S.B., Kennedy, Chem.Eng.Sci., 31 (1976) 901.
29. R.A., Buonopane, E.B., Gutoff, and M.M.T., Rimore, A.I.Ch.E.J., 32 (1986) 682.
30. K.Y., Lee, and T.J., Lin, Paper presented at A.I.Ch.E Spring Meeting, Orlando, March 1990.
31. H., Benkreira, and R., Patel, Chem.Eng.Sci., 46 (1991) 751.
32. H., Benkreira, and R., Patel, Chem.Eng.Sci., 48 (1993) 2329.
33. K., Ruschak, Ann.Rev.Fluid Mech., 17 (1985) 65.
34. E., Cohen, and E., Gutoff, Modern Coating Technology, VCH Publishers, New York, 1992.
35. H., Benkreira, Thin Film Coating, The Royal Society of Chemistry, Cambridge, 1993.

List of Figures

Fig. 1. Free coating flows formed by (a) a rotating cylinder and (b) an inclined plane

Fig. 2. Metered coating flows formed by (a) blade coating (b) reverse roll coating and (c) forward roll coating.

Fig. 3. Transfer coating flows formed by (a) kiss coater, (b) slide coater, (c) slot coater (d) die coater.

Fig. 4. Gravure or print coating.