The flow of coating color in forward-rotating roll coaters

Fernando M. Brea
Section manager, Latex Technical Service, Dow Quimica Argentina S.A., Avda. Leandro N. Alem 896, 1001 Buenos Aires, Argentina

Garth D. Williamson
Development leader, Dow Chemical U.S.A., Latex Coatings and Binders Dept., 2040 Willard H. Dow Center, Midland, MI 48674

ABSTRACT *A procedure is described for calculating the shear rate distribution and minimum gap between a pair of rolls in a forward-rotating roll coater such as the Massey coater or the gate roll coater. This information is needed in assessing whether or not various runnability problems are likely to occur on a forward-rotating roll coater. In such an assessment, the rheology of the color must be characterized at high and low shear rates.*

A mass balance for a multiple-roll system is coupled with an analysis of flow in forward-rotating rolls based on the lubrication approximation. Equations are developed and used to calculate the flow rates through the different nips and the shear rate distribution between a given pair of rolls. An example is presented for a system consisting of five metering and transfer rolls and an applicator roll. Calculated values are presented for the minimum gap between rolls and the shear rate distributions involved.

KEYWORDS
Coated papers
Coaters
Coating color
Equations
Flow measurement
Rheology
Roll coaters
Rolls
Runnability
Shear rate

In roll coating operations that are carried out on-machine, production rates can be limited, and paper quality adversely affected, by how well the coater will run with a particular coating and basesheet. Roll coater runnability problems are usually related to improper color rheology and coater operating conditions. It is important to be able to predict the potential for runnability to occur.

In the laboratory, one can develop a basis for predicting the tendency for rheologically induced runnability problems to occur on a roll coater by characterizing the flow properties of the coating. However, these measurements must be made over the same rates of deformation the color will experience on the coater. In order to do that, one needs to know the shear rate distribution between any pair of rolls in a multiple roll system.

Therefore, we present a method for calculating the shear rate distributions between any pair of rolls of in a multiple roll system. Using this technique, one can predict the potential for a coating to develop various runnability problems in a forward-rotating roll coater such as the Massey or gate roll.

A brief history of roll coaters

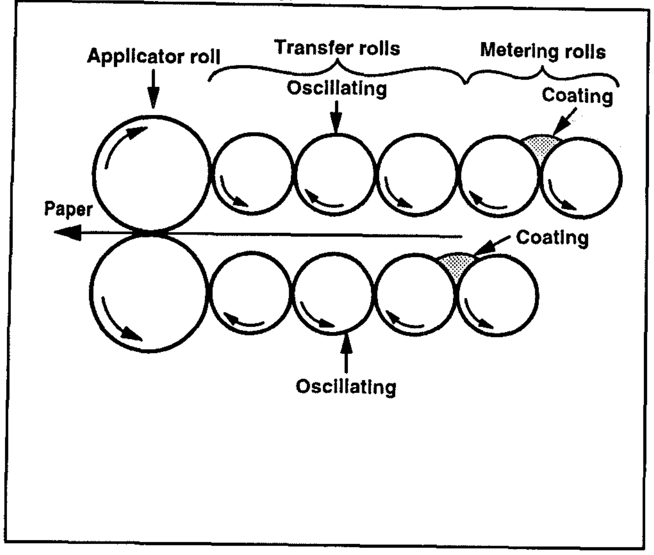
On-machine coating of magazine paper became possible in North America in 1933 with the development of the Consolidated (Massey) coater by Peter J. Massey (*1-3*). At that time, this new transfer roll coater helped revolutionize the coated paper industry.

The advantages of the Massey roll coater over other coating machinery of that time were considerable. The Massey coater provided a convenient means to apply a relatively pattern-free coating. At solids contents of 40-65%, the coating could be applied in weights of 6-22 g/m^2 to each side of a paper web traveling at top machine speeds of the time (*4*).

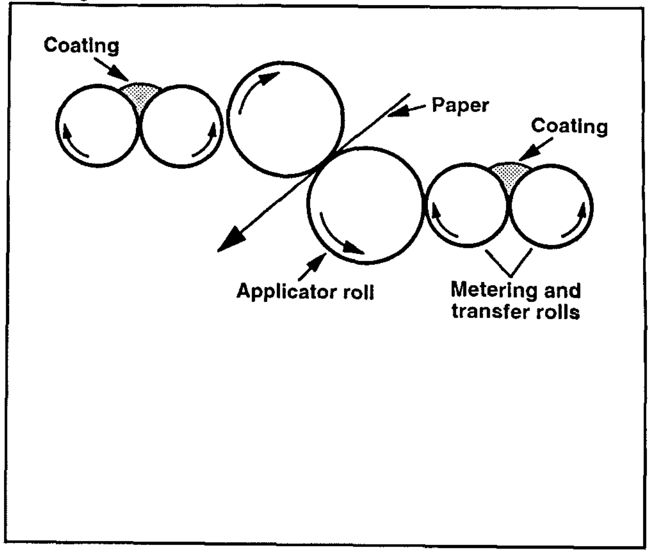
The Massey coater, shown in **Fig. 1**, served as a prototype for other transfer roll coaters, such as the West Virginia (*5*), Combined Locks (*6, 7*), St. Regis/Faeber (*8, 9*), and others that were developed and installed on paper machines from the late 1930s to the mid-1950s. Illustrations of most of those coaters and comparisons of their operating parameters can be found in other publications (*4, 10-12*).

Following the successful installation in 1956 of the first blade coater for the production of coated printing papers, the use of forward-rotating roll coaters such as the Massey began

1. The Consolidated (Massey) roll coater



2. The gate roll coater



to decline as a primary method of coating paper on-machine. In North America, the main function of these machines became that of on-machine precoaters.

In the early 1960s, newer roll coaters such as the gate roll (*13*) and its forerunners also began to be used for precoating. The gate roll coater, shown in **Fig. 2**, proved to be simpler in design, more versatile, and easier to operate than the older transfer roll coaters. In North America, this development lead to a further decline in the use of coaters such as the Massey.

Today, transfer roll coaters are still used to some extent in North America as on-machine precoaters in the production of double-coated, enamel printing papers or as the primary method of coating some specialty papers. In other parts of the world, however, these coaters continue to be used on the paper machine as the primary method of producing high-quality coated printing papers.

Background

Some common runnability problems in roll coaters such as the Massey or gate roll are:

- Fluttering of the paper web as it leaves the nip of the applicator rolls (*11*)
- Formation of a film-splitting pattern known as "orange peel" (*4*)
- Ribbed flow of coating in the coater (*14*)
- Upward splashing and downward spitting of coating from the nip of two rotating rolls (*13*).

All these phenomena are governed by the flow characteristics of the coating; however, web fluttering and orange peel are also influenced by properties of the base paper (*4*).

In all these runnability problems, color viscosity plays a significant role. For example, the tendency for ribbed flow to occur has been related to the viscous and surface tension forces of the coating in a dimensionless group called the "capillary number" (*14*). The capillary number is the coating viscosity times the average speed of two rolls forming a nip divided by the surface tension of the coating. Higher capillary numbers indicate a greater tendency for ribbing to occur. However, since coating colors are highly shear-sensitive materials, it is necessary to know the distribution of shear rates the color actually experiences while it is passing between a pair of rolls in a forward-rotating roll coater in order to determine color viscosity. Once a realistic color viscosity has been determined, the capillary number can be calculated and used.

A simple and rapid method for estimating shear rates in blade and air knife coaters was reported by Tran and Schempp (*15*). They also suggested that this method could be used for roll coaters. The main limitations of their approach in regard to roll coaters are two assumptions:

1. The shear rate between a pair of rolls is linear.
2. One half the minimum gap between any pair of rolls in the metering train is equal to the wet film thickness of coating applied to the paper.

Finally, this method does not take into account the influence of the rheological behavior of coating colors.

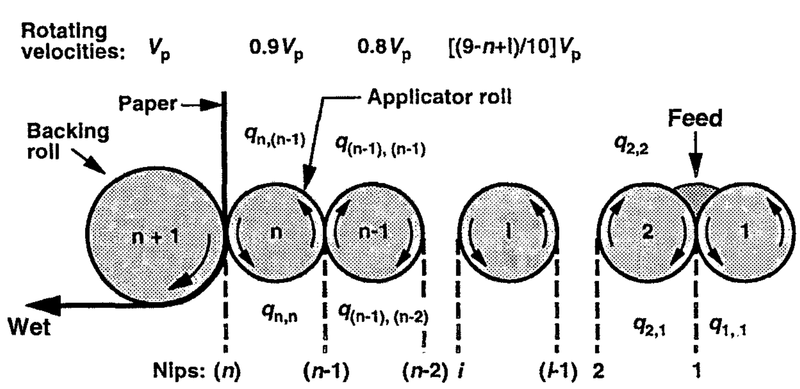
The flow of fluids in forward roll coaters has been extensively studied using the lubrication approximation as a model (*14, 16*). We have used the lubrication approximation as a starting point to show how one can calculate the shear rate distributions between any pair of rolls in a forward-rotating roll coater. Besides knowing the roll diameter and rotating velocities, one must also know the separating distance or gap between rolls to carry out these calculations.

No data have been reported so far relating roll velocities to the minimum gap between rolls and the coating weight applied to the paper in a forward-rotating roll coater such as a Massey or gate roll. Therefore, using experimental data available for a pair of rolls (*17*) in combination with a mass balance, we present a method for obtaining the minimum gap between any pair of rolls in a roll coater. This method is applicable to transfer roll coaters with any number of rolls.

Mass balance in a multiple-roll system

Figure 3 shows a multiple-roll system consisting of n rolls. The color is fed at the entrance nip between Roll 1 and

3. Parameters for the multiple-roll system having n rolls



I. Minimum gap between rolls

Paper velocity, cm/s	566
Solids conc., % by wt.	0.60
Color wt./unit vol., g/cm³	1.5
Dry coat wt., g/m²	12
Number of rolls	5
Minimum gap, h_i, μm for i =	
4	37
3	57
2	79

Roll 2 and is transferred forward toward Roll n, which finally coats the paper web.

In the figure, *Feed* represents the flow rate of the color feed per unit of roll width, and *Wet* represents the flow rate of the wet coating on paper per unit of roll width. The color flow rate per unit width is expressed as $q_{i,j}$, where i is the roll number and j is the nip the color comes from.

When an overall mass balance is performed under steady state conditions, then

$$Feed = Wet \tag{1}$$

Now, if one considers only the applicator roll, n, and the backing roll, $n+1$, then

$$Wet = q_{n,(n-1)} - q_{n,n} \tag{2}$$

$$q_{(i+1),(i+1)} + q_{i,(i-1)} = q_{(i+1),i} + q_{i,i} \tag{3}$$

for $i = 1 \ldots (n-1)$

From Eqs. 1-3, we obtain Eq. 4:

$$\begin{aligned} Feed = Wet &= q_{(i+1),i} - q_{(i+1),(i+1)} \\ &= q_{i,(i-1)} - q_{i,i} \end{aligned} \tag{4}$$

for $i = 1 \ldots (n-1)$

The gap between a pair of rotating rolls

Experimental studies carried out with Newtonian and non-Newtonian liquids established simple equations to calculate the total flux per unit width through a nip and the ratio of the split fluxes as a function of the rolls' linear velocities and the gap between rolls (*16-19*). For non-Newtonian liquids and a pair of rolls as shown in Fig. 4, these equations become:

$$q_{i,i} + q_{(i+1),i} = 1.43\, h_i\, (U_i + U_{i+1})/2 \tag{5}$$

$$q_{i,i}/q_{(i+1),i} = (U_i/U_{i+1})^{1.54} \tag{6}$$

where

h_i = minimum separating distance between Roll i and Roll $i+1$

U_j = rotating velocity of Roll j.

For a multiple-roll system, roll velocities increase as the color moves from the feed to the applicator rolls. If the velocity of Roll j is considered to be in keeping with the roll velocity profile as depicted in Fig. 3, the velocity of Roll j becomes:

$$U_j = V_p\,(9 - n + j)/10 \tag{7}$$

where V_p is the paper velocity, which we assume to be equal to the linear velocity of the backing roll.

From Eqs. 5-7, we obtain Eqs. 8 and 9.

$$\frac{q_{i,i}}{V_p} = \frac{q_{(i+1),i}}{V_p}\left[\frac{9-n+i}{10-n+i}\right]^{1.54} \text{ for } i=1\ldots(n-1) \tag{8}$$

$$h_i = \frac{q_{i,i} + q_{(i+1),i}}{V_p}\ \frac{20}{1.43}\ \frac{1}{[17 + 2\,(1+i-n)]} \quad \text{for } i = 1\ldots(n-1) \tag{9}$$

Starting at nip n, it is possible to calculate the gaps between rolls for all the nips by using Eqs. 4, 8, and 9. **Table I** shows the results for a five-roll system and a backing roll. For a given dry coat weight G, solids concentration S, and color weight per unit volume d, the following relationship holds,

$$Wet/V_p = G/dS \tag{10}$$

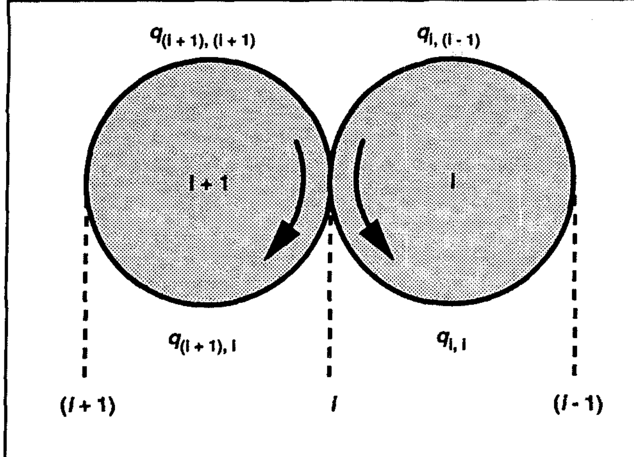
Shear rate distributions for a pair of rotating rolls

In accordance with the analysis presented by McKelvey for rolling plastic materials (*20*), shear rate distributions and velocity profiles can be calculated readily once the gap between rolls is obtained from the mass balance presented in the last section.

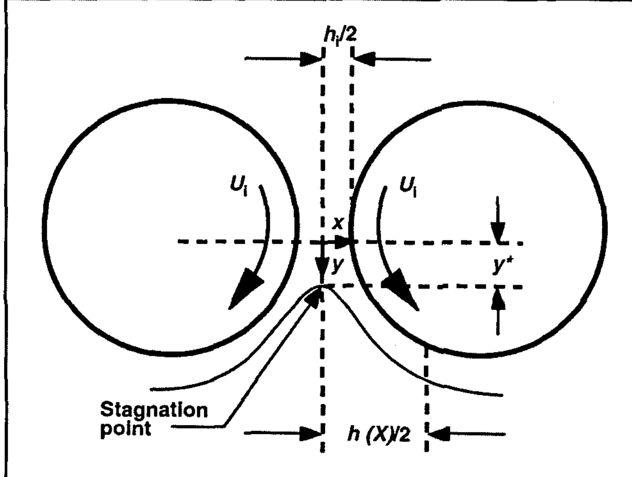
In the case of the rolling of plastics, the calendered material leaves the nip without wetting the rolls. Consequently, these results are not applicable to our problem in the vicinity of the stagnation point, where the film splits. The analysis of the coating problem entails the condition that there is enough color in the system to flood the entrance nips.

Let us consider a pair of equal-diameter rolls rotating at the same speed. As shown in **Fig. 5**, $h(X)$ represents the separating distance between rolls which is a function of y. The minimum gap between rolls is $h(X)_{y=0} = h_i$. For non-Newtonian fluids that obey the power law model to describe the response to an applied stress, two constants K and a as defined by Eq. A8 are used to characterize rheological behavior. Then shear rate distribution between rolls becomes:

4. Flow rates on a pair of rolls



5. The gap between rolls and the film splitting distance



II. Shear rate distribution at the roll surface

a	*Shear rate,* s^{-1}	ϵ	*y/y**
1.00	-254,780	0.00	0.00
1.00	-138,092	0.36	0.20
1.00	24,446	0.73	0.40
1.00	93,576	1.09	0.60
1.00	102,834	1.45	0.80
1.00	91,983	1.81	1.00
0.80	-276.012	0.00	0.00
0.80	-138,903	0.38	0.20
0.80	39,234	0.76	0.40
0.80	105,833	1.15	0.60
0.80	109,835	1.53	0.80
0.80	95,520	1.91	1.00
0.60	-311,398	0.00	0.00
0.60	-137,782	0.41	0.20
0.60	63,852	0.82	0.40
0.60	124,287	1.24	0.60
0.60	119,769	1.65	0.80
0.60	100,345	2.06	1.00
0.40	-382,170	0.00	0.00
0.40	-127,545	0.47	0.20
0.40	111,636	0.93	0.40
0.40	155,056	1.40	0.60
0.40	134,951	1.87	0.80
0.40	107,313	2.33	1.00
0.20	-594,487	0.00	0.00
0.20	-52, 126	0.60	0.20
0.20	234,357	1.20	0.40
0.20	215,791	1.80	0.60
0.20	160,979	2.40	0.80
0.20	118,264	3.00	1.00

III. Shear rate distribution at the nip between rolls

$x/(h_i/2)$	*Shear rate,* s^{-1}
1.00	339,707
0.95	306,585
0.90	275,163
0.85	245,438
0.80	217,412
0.75	191,085
0.70	166,456
0.65	143,526
0.60	122,294
0.55	102,761
0.50	84,926
0.45	68,790
0.40	54,353
0.35	41,614
0.30	30,573
0.25	21,231
0.20	13,588
0.15	7,643
0.10	3,397
0.05	849
0.00	0

At $y = 0$ and $a = 0.5$.

$$\dot{\gamma} = \frac{(2n + 1)}{a} \frac{2}{h_i} \phi^{1/n'} \frac{U_i(\epsilon_i^2 - \lambda^2)}{(1 + \epsilon_i^2)^2} \quad \text{for } \epsilon_i^2 > \lambda^2 \tag{11}$$

$$\dot{\gamma} = -\frac{(2n' + 1)}{a} \frac{2}{h_i} \phi^{1/n'} \frac{U_i(\lambda^2 - \epsilon_i^2)}{(1 + \epsilon_i^2)^2} \quad \text{for } \lambda^2 > \epsilon_i^2 \tag{12}$$

with

$$(1 + \epsilon_i^2) = h/h_i \tag{13}$$

$$\epsilon_i = y/ (R\, h_i)^{1/2} \tag{14}$$

$$\phi = x/ (h/2) \tag{15}$$

$$\lambda^2 = \frac{(q_{(i+1),i} + q_{i,i})}{U_i h_i} - 1 \tag{16}$$

The steps to arrive at Eqs. 11 and 12 are shown in the appendix. These equations reduce to Eq. 17, as given by McKelvey (*20*) for a Newtonian fluid, when $a = 1$.

$$\dot{\gamma} = \frac{6U_i}{h_i} \phi \frac{(\epsilon_i^2 - \lambda^2)}{(1 + \epsilon_i^2)^2} \tag{17}$$

Coyle (*14, 21, 22*) considers in his analysis two dimensional flow, and rolls with different diameter and rotating velocities.

Velocity profiles and the stagnation point

The expression for the velocity profile for a non-Newtonian fluid can be obtained by integrating the shear rate distribution. The result is Eq. 18.

$$\frac{V_y}{U_i} = \{(a + 1) + (2a + 1)\lambda_i^2 [1 - \phi^{(a+1)/a}] - \epsilon_i^2[a - (2a + 1)\, \phi^{(a+1)/a}]\} / [(a + 1)(1 + \epsilon_i^2)] \tag{18}$$

At the point where the film splits, as shown in Fig. 5, the relationship of Eq. 19 holds.

$$\left(\frac{V_y}{U_i}\right)_{\phi=0} = 0 \tag{19}$$

Then from Eqs. 18 and 19, we have Eq. 20.

$$\epsilon^* = \frac{y^*}{\sqrt{Rh_i}} = \pm \left(\frac{(a + 1) + (2a + 1)\lambda^2}{a}\right)^{1/2} \tag{20}$$

Both Eqs. 18 and 20 reduce to the expressions valid for Newtonian fluids when $a = 1$ (*20*).

Results

Shear rates along the roll surface are shown in **Table II** starting at the nip, where $y = 0$, up to $y = y^*$ where the film splits. (See Fig. 5.) **Table III** shows how shear rate varies within the nip ($y = 0$) from the centerline, where $x = 0$, up to the roll surface, where $x = h_i/2$.

To use Eqs. 11 and 12, U_i/h_i was taken as the average of the values that correspond to Nips 3 and 4. If the shear rate is calculated according to the method proposed by Tran and Schemp (*15*), for the same conditions shown in Table I, the value obtained is 150,000 s^{-1}.

This value is comparable with the value from the analysis presented here for a Newtonian fluid if an average is taken between the maximum and minimum shear rates within the nip.

Velocity profiles are not shown here because their shapes have been already discussed (*20*).

Discussion

Equations to calculate shear rate distributions have been derived by coupling results from the lubrication theory with a mass balance for a multiple-roll system. The example presented in Table III indicates shear rates varying from 0 to 3.39×10^5 s^{-1}. Consequently, when characterizing a coating color, we must be aware that rates of shear over a wide range shear are developed in the nips.

According to Eq. 20, the more pseudoplastic the fluid, the greater will be the distance y^* where the film splits. This was observed by Coyle in his two-dimensional flow analysis (*21*).

Conclusions

An approximate method for calculating the velocity and shear rate distributions between the rolls of a multiple-roll system has been developed. The method is applicable to Newtonian fluids and to time-independent, purely viscous, non-Newtonian fluids.

For typical operating conditions in a forward-rotating roll coater, shear rates in the nip between rolls may vary from 0 to 3×10^5 s^{-1} for moderately pseudoplastic colors characterized by $a = 0.5$.

Color rheological characterization at low and high shear rates is required to fully assess the runnability of a coating in a forward roll coater.□

Literature cited

1. Massey, P. J., U.S. pat. 1,921,368 (Aug. 8, 1933).
2. Massey, P. J., U.S. pat. 1,921,369 (Aug. 8, 1933).
3. Massey, P. J., U.S. pat. 2,105,488 (Jan. 18, 1938).
4. Kaulakis, F., Tappi 57(5): 80(1974).
5. Haywood, G. and Dayton, C. S., U.S. pat. 2,560,572 (July 17, 1951).
6. Muggleton, G. D. and Piepenberg, A. F., U.S. Pat. 2,398,843 (April 23, 1946).
7. Muggleton, G. D. and Piepenberg, A. F., U.S. Pat. 2,398,844 (April 23, 1946).
8. Faeber, H. W., U.S. pat. 2,456,495 (June 5, 1951).
9. Faeber, H. W., U.S. pat. 2,555,536 (Dec. 14, 1948).
10. An operator's guide to aqueous coating for paper and board (T.W.R. Dean, Ed.), The British Paper and Board Industry Federation, London, 1979, pp. 7.43-7.52.
11. Booth, G. L., Coating Equipment and Processes, 1st edn., Lockwood Publishing Co., New York, 1970, p. 163.
12. Dickerson, G. D., Frost, F. H., Griesheimer, R. N., Hall, H. R., *et al.*, Tappi J. 40(8): 152A(1957).
13. Alheid, R. J., TAPPI 1978 Papermakers Conference Proceedings, TAPPI PRESS, Atlanta, 1978, p. 83.
14. Coyle, D. J., Macosko, C. W., and Scriven, L. E., TAPPI 1985 Coating Conference Proceedings, TAPPI PRESS, Atlanta, 1985, p. 161.
15. Tran, H. T. and Schemp, W., Tappi J. 62(12): 107(1985).
16. Benkreira, H., Edwards, M. F., and Wilkinson, W. L., J. Non-Newtonian Fluid Mech., 14: 377(1984).
17. Benkreira, H., Edwards, M. F., and Wilkinson, W. L., Chem. Eng. Sci. 36: 429(1981).
18. Benkreira, H., Edwards, M. F., and Wilkinson, W. L., Chem. Eng. J. 25: 211(1982).
19. Benkreira, H., Edwards, M. F., and Wilkinson, W. L., Chem. Eng. Sci. 36: 423(1981).
20. McKelvey, J. M., Polymer Processing, Wiley, New York, 1962.
21. Coyle, D. J., Macosko, C. W., and Scriven, L. E., AIChE J. 33(5): 741(1987).
22. Coyle, D. J., Macosko, C. W., and Scriven, L. E., J. Fluid Mech. 171: 183(1986).

Received Nov. 15, 1991.

Accepted Dec. 10, 1991.

Presented at the TAPPI 1992 Coating Conference.

See Appendix next page

Appendix

Referring to **Fig. 6**, we have Eqs. A1–A5:

$$\epsilon = y/(R\,h)^{1/2} \quad \text{(A1)}$$

$$h(y) = h + y^2/R \quad \text{(A2)}$$

$$h(y)/h = 1 + \epsilon^2 \quad \text{(A3)}$$

$$\lambda^2 = Q/(Uh) - 1 \quad \text{(A4)}$$

$$\phi = x/(h/2) \quad \text{(A5)}$$

It is assumed that the circular surface can be approximated by a parabula, Eq. A2. Then the y momentum equation is integrated for an incompressible fluid neglecting the acceleration terms and the variation of velocity with y.

The subscript i has been eliminated here for simplification purposes, but it is used when Eqs. 11 and 12 are derived.

For a fluid with a viscosity that is dependent on shear rate, we obtain Eq. A6.

$$\eta\,\frac{dV_y}{dx} = \frac{\partial P}{\partial y}\phi\,\frac{h}{2}\,(1+\epsilon^2) \quad \text{(A6)}$$

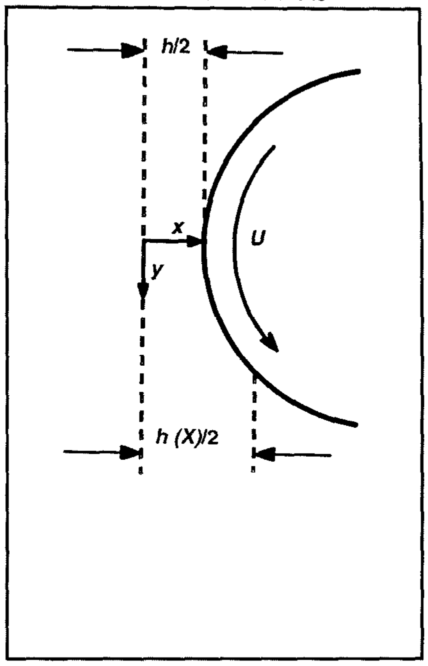
Symmetry of flow about the y axis imposes the boundary condition $\gamma\,(0) = 0$.

With the same assumptions, the y-momentum equation can be integrated twice, but now τ is introduced to eliminate x. Using the non-slip boundary condition at the roll surface, an integral expression is obtained for the velocity as a function of the pressure gradient, the viscosity, and the shear stress. After some manipulations, we obtain Eq. A7 (*20*):

$$\epsilon^2 - \lambda^2 = \frac{2}{Uh\left(\frac{\partial P}{\partial y}\right)^2}\int_0^{\tau_w} \tau^2 d\tau \quad \text{(A7)}$$

Once Eq. A8, for the low-power model expression of the shear-rate-dependent viscosity, is introduced into Eqs. A6 and A7 after some algebra, Eqs. 11 and 12 can be obtained.

$$\eta = K^{1/a}\,\tau^{(a-1)/a} \quad \text{(A8)}$$



6. Fluid flow section between rolls

Nomenclature

- d = color weight per unit volume
- *Feed* = color feed flow rate per unit of roll width
- G = dry coat weight on paper per unit surface
- h_i = minimum separating distance between rolls at Nip i
- $h(X)$ = separating distance between rolls
- i = nip number
- j = nip the color comes from
- K = constant for a power law fluid defined by Eq. A8
- n = roll number
- a = constant for a power law fluid defined by Eq. A8
- P = fluid pressure
- q = color flow rate per unit of roll width pertaining to a single roll
- Q = total flow rate through a nip
- R = roll radius
- U = linear roll rotating velocity
- V_p = paper velocity
- V_y = color velocity in y direction
- *Wet* = flow rate of wet coating on paper per unit of roll width
- x,y = coordinates defined in Fig. 5
- X = separating distance between rolls
- S = solids concentration by weight
- y^* = film splitting distance
- γ = rate of shear
- γ_w = rate of shear at roll surface
- ϕ = dimensionless coordinate defined by Eq. A5
- λ = dimensionless flow rate defined by Eq. A4
- η = shear-rate-dependent viscosity
- ϵ = dimensionless coordinate defined by Eq. A1
- ϵ^* = dimensionless coordinate defined by Eq. 20
- τ = shear stress
- σ = surface tension