Improved Model for the Secondary Cavity of a Coating Die

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ABSTRACT

Coating dies form a uniform layer from liquid supplied through tubing. The liquid is distributed by a cavity of low resistance to flow and adjoining narrow slot of high resistance which span the coating width. A second cavity/slot combination is common for meeting high uniformity requirements and for accommodating liquids differing in flow rate and rheology.

Flow models for the secondary cavity usually consider only axial flow even though flow is primarily transverse. There is an alternative model which treats the axial flow as a perturbation of the primary cross flow. This perturbation model applies for the low axial flow rates that arise in a well-designed die. The parameters for the perturbation model were computed for a typical cavity shape with a commercial CFD application, and the results were correlated for use in die design. Reasonably accurate parameters can also be generated by an approximate method. The application of the perturbation model is demonstrated through an analysis of the effectiveness of the secondary cavity at improving flow distribution.

With asymptotic regimes known for both high and low axial flow rates, a method for blending the regimes is proposed to accommodate all axial flow rates in the secondary cavity.

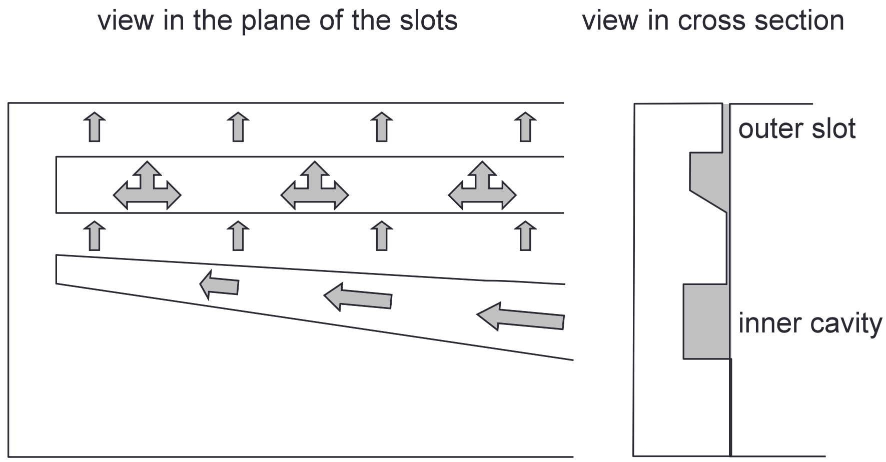
INTRODUCTION

Precision coating dies are expensive to fabricate and can serve indefinitely. As such an important design consideration is their versatility. In particular, dies that can perform well over a range of flow rates and rheological behavior are valued. Two-cavity coating dies are preferred over single-cavity designs for versatility and for meeting tight distribution requirements. As shown in the figure, a primary cavity and slot combination accomplishes a first distribution of the coating liquid, and a secondary cavity and slot combination improves the distribution.

Unlike flow in the primary cavity, flow in the secondary cavity is primarily transverse to its axis. Axial flow takes place when the flow distribution in the inner slot is not perfect and improves distribution.

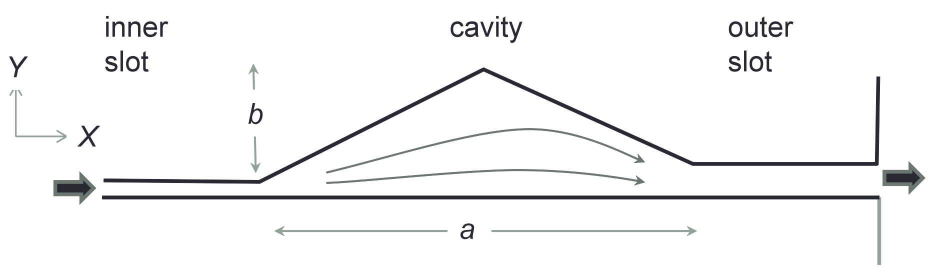
The cross flow in the secondary cavity determines the viscosity of shear-thinning liquids. This viscosity reduction is conducive to axial flow. On the other hand, the inertia of the cross flow impedes axial flow. Most often, flow in the outer cavity has been modeled as axial flow in a conduit, just as flow in the primary cavity is modeled. This approach, however, ignores the important effects of the cross flow.

Ruschak and Weinstein (*Polymer Engng and Sci.*, **37**, 1970-6, 1997) proposed a different approach that begins with the cross flow. The implementation of this cross-flow model and comparisons with the axial-flow model follow.



IMPLEMENTATION OF THE CROSS-FLOW MODEL

A power-law liquid is considered with viscosity given by $\mu = m/\left[\dot{\gamma}^2\right]^{(1-n)/2}$ where m is the consistency, n is the power-law index, and $\dot{\gamma}$ is the shear rate. First, the two-dimensional flow across the cavity, shown in the figure, is computed. This may be done approximately, but here the commercial CFD program ANSYS Fluent is used. The cavity may be any shape but in this study is a 30°-120°-30° triangle. The computation determines the velocity components and the viscosity in the cavity, denoted with overbars, $\bar{U}(X,Y)$, $\bar{V}(X,Y)$, $\bar{\mu}(X,Y)$.



Next, the dominant terms in the axial component of the momentum equation are considered. Axial flow is treated as a perturbation of the two-dimensional cross flow. Note that the equation incorporates the results of the two-dimensional cross flow calculation.

$$\rho\left[\bar{U}\frac{\partial W}{\partial X}+\bar{V}\frac{\partial W}{\partial Y}\right]=-\frac{dP}{dZ}+\frac{\partial}{\partial X}\left[\bar{\mu}\frac{\partial W}{\partial X}\right]+\frac{\partial}{\partial Y}\left[\bar{\mu}\frac{\partial W}{\partial Y}\right]$$

Here, Z is the axial direction, W is the axial component of velocity, and P is pressure. The substitution

$$W = -\frac{dP}{dZ}T \qquad \text{leads to} \qquad \rho\left[\overline{U}\frac{\partial T}{\partial X} + \overline{V}\frac{\partial T}{\partial Y}\right] = 1 + \frac{\partial}{\partial X}\left[\overline{\mu}\frac{\partial T}{\partial X}\right] + \frac{\partial}{\partial Y}\left[\overline{\mu}\frac{\partial T}{\partial Y}\right]$$

$$T = 0 \quad \text{on boundary}$$

This equation has the form of a convective heat transfer problem and was also solved using ANSYS Fluent. The axial velocity is then integrated to give the axial flow rate Q and the flow equation

$$Q = \int\!\!\int W\,dX\,dY = -\frac{dP}{dZ}\int\!\!\int T\,dX\,dY \qquad \rightarrow \qquad -\frac{dP}{dZ} = \frac{\mu_c Q}{cA^2}$$

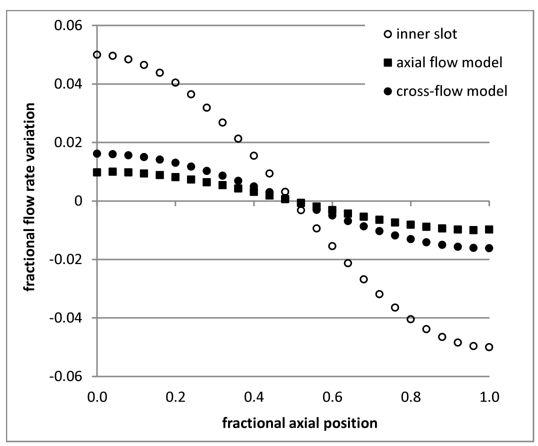
Here A is cavity area, $\mu_c = m\Big/\left[\overline{q}/b^2\right]^{1-n}$ is a characteristic viscosity, b is cavity depth, $\overline{q}$ is the average flow rate per unit width, and c is the shape factor. The shape factor depends upon power-law index n and Reynolds number $\mathrm{Re} = \rho\overline{q}/\mu_c$. The shape factor results can be correlated for ready access in design problems.

RESULTS

With the shape factor computed and correlated, calculations were performed for a sinusoidal variation of flow in the primary slot. A useful measure of outer cavity effectiveness is the damping factor, obtained by dividing the pk-pk amplitude of flow variation in the primary slot by that in the secondary slot. A high damping factor is favorable for flow uniformity. Both the cross-flow model and the axial-flow model were computed.

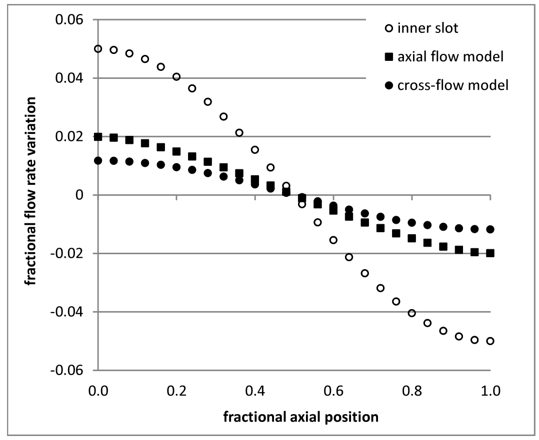
The first example is for a Newtonian liquid of low viscosity at high flow rate. In this case, the inertia of the cross flow is very important, and it impedes the functioning of the outer cavity. As the chart shows, the cross-flow model predicts a poorer distribution as the axial-flow model is unaffected by the cross flow.

value	units	parameter
0.99		power-law index
.05	Pa·sec^n	consistency
1	cm^3/sec/cm	average flow rate per unit width
50	cm	half cavity length
0.05		amplitude of variation of flow rate in inner slot
2.5	cm	outer cavity width
700	microns	outer slot height
2	cm	outer slot length

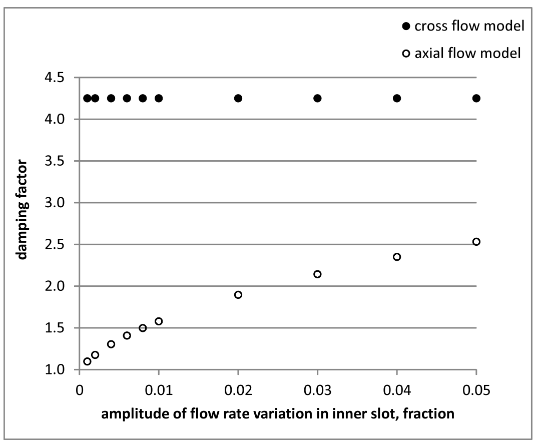


The second example is for a highly shear-thinning, viscous liquid. In this case the cross-flow model predicts a better flow distribution than the axial flow model. The axial flow model does not consider the viscosity reduction caused by the cross flow. In extreme situations of purely viscous flow, where axial flow is large, the axial-flow model may predict a lower pressure gradient. In that case, the equations can be switched at points along the cavity where the predicted pressure gradients are equal, that giving the lower pressure gradient being used. In this blended approach, the regions of highest axial flow may be described by the axial-flow model.

value	units	parameter
0.55		power-law index
1	Pa·sec^n	consistency
0.5	cm^3/sec/cm	average flow rate per unit width
50	cm	half cavity length
0.05		amplitude of variation of flow rate in inner slot
2.5	cm	outer cavity width
250	microns	outer slot height
2	cm	outer slot length



The biggest deficiency of the axial flow model occurs in cases where there is little axial flow as a result of a good flow distribution in the primary slot. As the chart shows for the conditions of the second example, the axial flow model predicts little improvement of flow distribution in this case because the shear-thinning effect of the cross flow is not considered. A small axial flow rate gives a high viscosity.



Other such calculations show that the cross-flow model is adequate under reasonable conditions of design and use. It is rare to find higher axial velocity than cross velocity. For purely viscous flow, the axial-flow model can be used locally where it predicts the smaller pressure gradient, but that situation will rarely arise.

CONCLUSIONS

The cross-flow model is preferable to the axial-flow model for flow in the secondary cavity of a two-cavity die. The shape factor for the cross-flow model depends upon power-law index and Reynolds number and can be computed with CFD and correlated for easy access. Conditions where the axial flow is strong enough to dominate shear thinning are rarely encountered. The axial-flow model is weakest when axial flow is small, as will be the case for at least some portions of the cavity.