Coating Die Design for Suspensions

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I. Introduction

Solid particles are frequently added to coating solutions to improve the quality or to enhance the functions of coated products. Diffusers for LCD panels and CIGS solar cells made by wet coating process are just a few examples. Two issues arise for delivering solutions with particles added, i.e., the solutions may have yield stress [1-4] or sedimentations may appear in the manifolds for conventional coat-hanger or T-dies. It is desirable to have a coating die that in addition to delivering a uniform liquid film, particle sedimentation can be avoided. A novel idea is proposed here to the design of a coating die as shown in Fig.1, the die has four pieces of elements, besides the top and bottom plates, there are two specially designed shims A and B. A rectangular manifold of varying width can be found by assembling the four pieces together. A and B can be easily replaced for different coating solutions. This design is quite flexible, high shear rates in the manifold can be maintained. Theoretical design is necessary to determine the contours of the A, B shims so that a uniform liquid film can be produced.

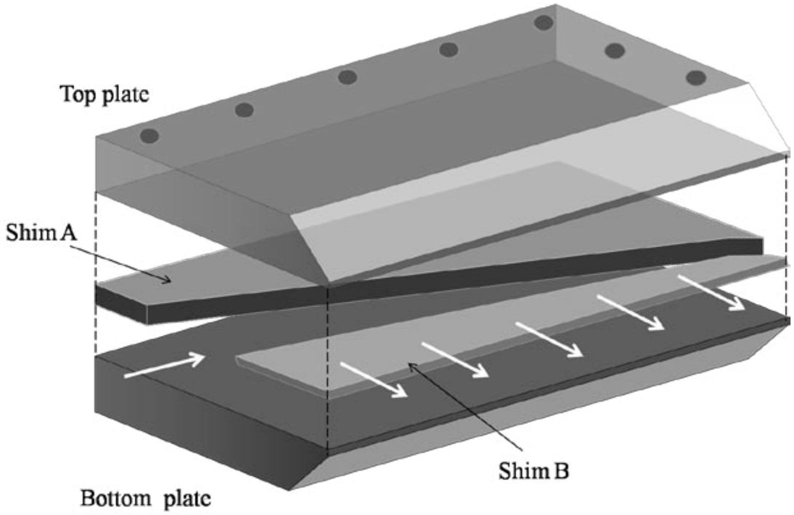

Fig.1 The idea of the new design

II. Theoretical

We have considered three approaches to simulate fluid flow inside the coating die, i.e., 1D lubrication approximation, 2D Hele-Shaw flow model and complete 3D finite element simulations. These three approaches are explained briefly as follows. The coating solutions are suspensions and are assumed to obey a modified Bingham Model in the 1D lubrication approximation as follows [5]：

$$\underline{\underline{\tau}} = -\mu_1 \dot{\underline{\underline{\gamma}}} \qquad \text{when } \frac{1}{2}\left(\underline{\underline{\tau}} : \underline{\underline{\tau}}\right) \le \tau_0^2$$

$$\underline{\underline{\tau}} = -\left[\mu_0 + \frac{\tau_0\left(1-\frac{\mu_0}{\mu_1}\right)}{\sqrt{\sqrt{\left|\pi_D\right|}}}\right]\dot{\underline{\underline{\gamma}}} \qquad \text{when } \frac{1}{2}\left(\underline{\underline{\tau}} : \underline{\underline{\tau}}\right) > \tau_0^2 \qquad \mu_1=1000\mu_0 \tag{1}$$

in the 2D and 3D simulations, viscosity function is slightly different[6]:

$$\eta = \eta_0 + \frac{\tau_0\left[1-\exp\left(-\kappa\sqrt{\left|\pi_D\right|}\right)\right]}{\sqrt{\left|\pi_D\right|}} \tag{2}$$

(A) 1D lubrication approximation

It is based on the pressure drop/flow rate equations for Bingham fluids in the rectangular manifold and the slot as follows. For fluid flow in the manifold, we obtain

$$Q = \frac{ab^3}{12\mu_0}\left(-\frac{dp}{dy}\right)\left(\frac{dy}{dx}\right)\left[1-\frac{3}{2}\left(1-\frac{\mu_0}{\mu_1}\right)\left(\frac{2\tau_0\left(1+\frac{b}{a}\right)}{b\left(-\frac{dp}{dy}\right)\left(\frac{dy}{dx}\right)}\right)+\frac{1}{2}\left(1-\frac{\mu_0}{\mu_1}\right)\left(\frac{2\tau_0\left(1+\frac{b}{a}\right)}{b\left(-\frac{dp}{dy}\right)\left(\frac{dy}{dx}\right)}\right)^3\right] f_1\left(\frac{a}{b}\right) f_2\left(\frac{\tau_0}{\tau_w}\right) \tag{3}$$

For fluid flow in the slot section, we have

$$q = \frac{W^3 p}{12\mu_0 h}\left[1-\frac{3}{2}\left(1-\frac{\mu_0}{\mu_1}\right)\left(\frac{2\tau_0 h}{Wp}\right)+\frac{1}{2}\left(1-\frac{\mu_0}{\mu_1}\right)\left(\frac{2\tau_0 h}{Wp}\right)^3\right] \tag{4}$$

Since the loss of fluid in the manifold is equal to the amount that enters the slot section, material balance requires:

$$q = -\frac{dQ}{dy} \tag{5}$$

In addition to simulating the flow distributions, an optimal design for perfect lateral flow uniformity is possible by fixing the flow rate distribution per unit length.

(B) 2D Hele-Shaw Flow

Since we have a shallow manifold with rectangular cross-sectional area, the steady flow in both the slot section and the manifold can be properly represented by the 2-D Hele-Shaw flow. The mathematical formulation for 2D Hele-Shaw flow of a fluid that obeys a modified Bingham model is as follow:

$$\frac{\partial}{\partial x}\left(\delta\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\delta\frac{\partial p}{\partial y}\right)=0 \qquad \delta = \int_0^B \frac{z^2}{\eta}dz \tag{6}$$

(C) 3D Finite Element Simulations

We consider an incompressible liquid flowing inside a die, the governing equations of the flow system are as follows:

$$\underline{\hat{\nabla}} \cdot \underline{\hat{v}} = 0 \tag{7}$$

$$\mathrm{Re}\left(\underline{\hat{v}} \cdot \underline{\hat{\nabla}}\underline{\hat{v}}\right) = -\underline{\hat{\nabla}}\hat{p} - \underline{\hat{\nabla}} \cdot \underline{\underline{\hat{\tau}}} \tag{8}$$

III. Experimental

Two test fluids which include PMMA and aluminum particles mixed with glycerol solutions were used. The experimental set-up is displayed in Fig. 2 for uniformity tests. Sedimentation at the ends of the die can also be observed.

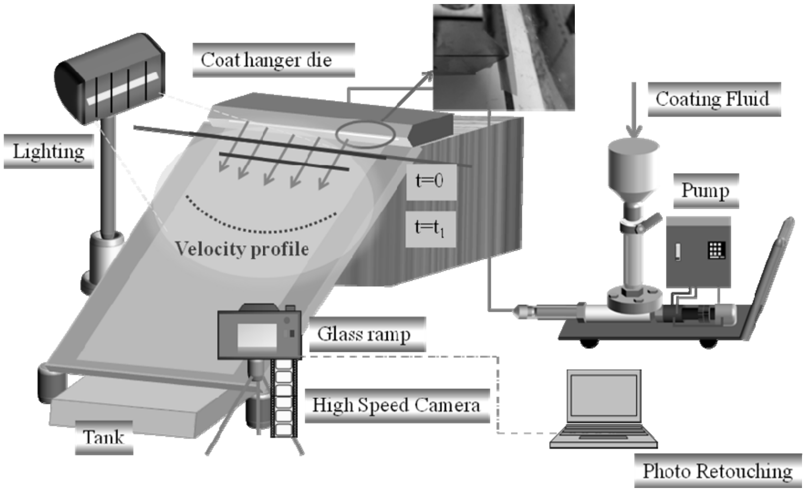

Fig.2 Experimental set-up

IV. Results and Discussion

The die geometry based on the 1D lubrication approximation for different Bingham numbers are displayed in Fig.3, For a given coating fluid, geometric parameters and operational variables, the lubrication model can lead to an optimal design, which can deliver a thin liquid layer with 100% uniformity. The predicted flow distributions of B2 die are shown in Fig.4, apparently much higher flow rates are found at the ends of the die. Because of the machining limit and the edge effect, the manifold of the die can be enlarged and the flow distributions have been improved by varying the shapes of the shim with 3D numerical verifications.

The experimental results of sedimentation and uniformity analysis are shown in Fig.5,it is clearly found that the flow rate distributions of the new design are close to uniform, the sedimentation of PMMA particles is avoided due to the flow field with relatively high shear rates. On the other hand, even though the T-die with a large manifold can deliver uniform liquid film, sedimentation of particles appeared in the end of the manifold.

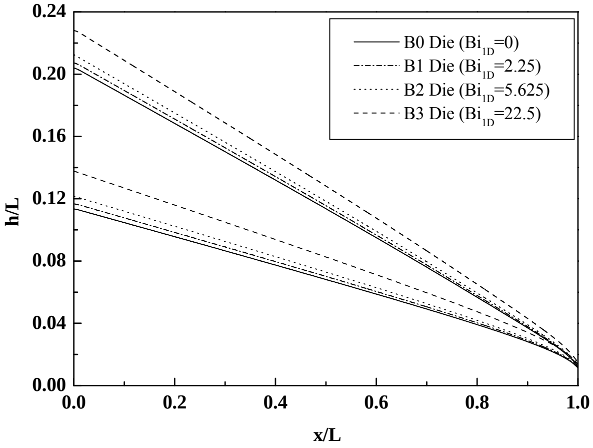

Fig.3 The geometry of the dies for different Bi number.

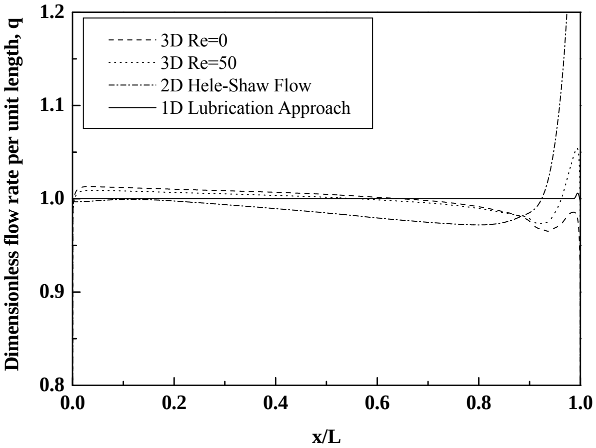

Fig.4 The flow rate distributions of B2 Die. (Bi=5.625)

V. Conclusions

We compared the sedimentation and uniformity of the new design with a commercial T-die and fishtail die experimentally, the results indicated the performance of the new design is excellent; whereas sedimentation and uniformity problems appeared in both the T-die and the fishtail die. The design can be applied to the wet coating process of CIGS solar cells and TCO films.

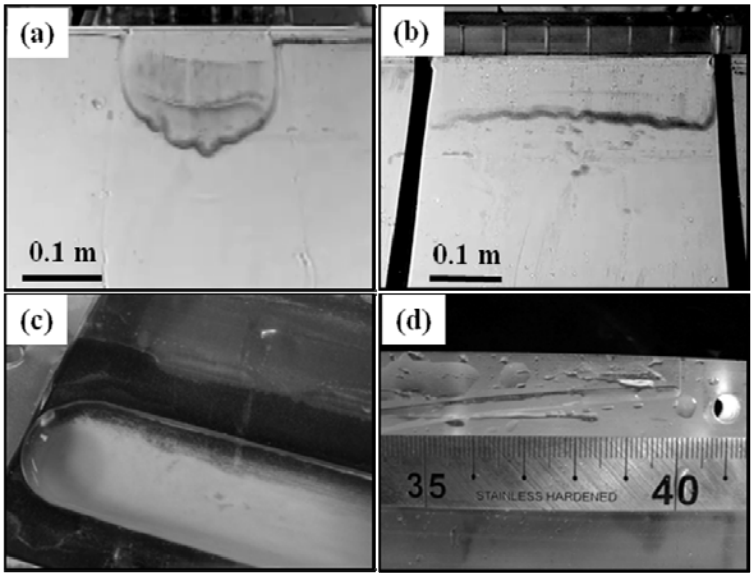

Fig.5 uniformity and sedimentation analyis:
(a)flow rate distributions of fishtail die, (b)flow rate distributions of a new design-B0 die, (c)serious sedimentation of PMMA particles in the T-Die, (d)no sedimentation of PMMA particles in the new design.

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VI. References

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