Fluid penetration into porous media during slot-die coating

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Introduction

Slot die coating is a pre-metered process that has been widely used for fabricating uniform defect free films. Recent studies have led to investigating direct coating of a porous media, which is an important field in the coating industry, with wide applications such as apparel, textiles, electronics, bioengineering and energy sector. When coating a porous media some of the coated fluid will penetrate into the pores. Although some level of the penetration is desirable to obtain specific material properties, inadequate or excessive penetration usually would be limiting. For example, if the penetration depth is too low the desired adhesion of coating to the substrate will not be obtained; whereas if it is too high, it might be detrimental to the functionality or performance of the resulting material. In spite of its apparent industrial importance, little work has been conducted to predict the penetration depth of solution into porous media based on slot die coating (or similar coating processes like roll coating and blade coating).

When modeling the penetration process, one major concern is how to determine the pressure distribution on the substrate. Letzelter and Eklund [1,2] assumed a piece-wise constant pressure distribution in their analytical model to predict the dewatering behavior in a blade coating process on paper. Ghassemzadeh et al [3,4] studied the liquid penetration into paper during a slot coating process using a 3-D pore network model of the paper and some approximately fitted pressure distributions. Yesilalan and Warner [5] derived an analytical equation to predict the maximum possible penetration depth into a woven fabric during the blade coating process. In their model, the pressure distribution on the porous substrate was approximated by the pressure distribution on a solid substrate, which was derived from lubrication theory. Their predicted penetration depths only qualitatively showed the same trend as their experimental results.

Although using approximate pressure distribution could simplify the model, this will introduce error, which may not be trivial for specific conditions. To avoid such error some researchers coupled the flow in coating bead to the flow in porous media. Chen and Scriven [6] developed an analytical model to predict the penetration of fluid into porous substrate for a flooded-nip-blade coating process. Their model used a modified lubrication theory, which calculates the pressure field and penetration depth, simultaneously. Ninness et al. [7], Devisetti and Bousfield [8] used the same method later for a metered-size press and roll coating process, respectively.

There are advantages and disadvantages of different modeling methods to predict the penetration depth. It has been shown that for enhanced accuracy coupling the flow in coating bead and the flow in the porous media is necessary. Furthermore solving Navier-Stokes equations to obtain the pressure distribution is preferred over lubrication theory because fewer simplifying assumptions are made. To our knowledge, there doesn't exit a model which solves the Navier-Stokes equations in a coating bead, and also combines the flow in coating bead and the flow in the porous media, specifically for slot die coating. In addition, very limited experimental work has been done to directly verify the penetration depth obtained by the proposed models [5].

In this paper, a new computational fluid dynamics (CFD) model of slot die coating on porous media is developed, using Comsol 4.2a. The Navier-Stokes equations for Non-Newtonian fluid are solved for flow in the coating bead which is directly coupled with the flow in porous media. Experiments of coating relatively high viscosity Non-Newtonian solution on carbon paper are conducted and the penetration depths are measured and compared with the predicted values from the CFD model.

Modeling

The geometry and boundary conditions of the slot die coating process is shown in figure 1. The whole domain is a "Laminar Two-Phase Flow" module. As shown in Figure 1, the slot die is composed of several no-slip walls, and the porous media substrate is composed of two moving walls and several control points that create small outlets between adjacent control points. Control points are only applied under the slot die because the penetration driven by pressure in the coating bead is of interest. This is reasonable for high viscous material for which the capillary force driving penetration is relatively small. 1-D Darcy's law is applied on every control point to satisfy the relationship between pressure and penetration velocity at each corresponding point, thus simulating the penetration process. The penetration velocity between adjacent control points is obtained by interpolation.

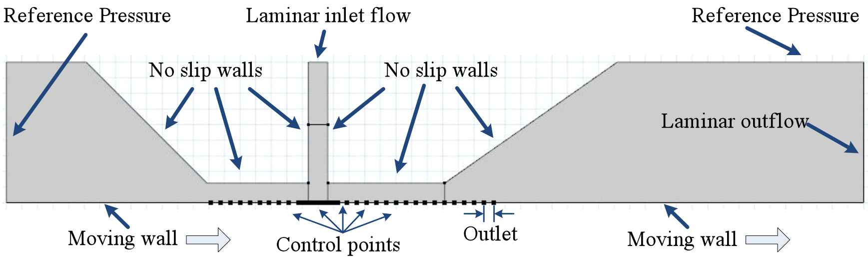

Figure 1. Geometry and boundary conditions of the Comsol Model.

Experimental Validation

Experiments of slot coating onto a porous media have been conducted under different flow rates and coating speeds. Highly viscous Non-Newtonian molasses and carbon paper Toray 060 were chosen as the coating liquid and porous media, respectively. Penetration depths are measured and compared with the values calculated by Comsol. Some preliminary results are shown in Table 1. From Table 1, it can be seen that the predicted penetration depths are relatively close to the measured values. The overall relative error is less than 30%. Considering the experiment and measurement errors, the approximation of material properties, and the simplifications used in the model, this difference is reasonable.

Table 1. Comparison between experimental penetration depths and predicted values

2-D Flow rate (mm^2/s)	**Coating speed (mm/s)**	**Measured penetration depth (micron)**	**Predicted penetration depth (micron)**	**Relative error***
1.18	5.2	49	60	22%
1.18	6.0	42	49	17%
1.42	6.8	47	60	28%

*relative error = (predicted value-measured value) / (measured value) ·100%

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