Slot coating of particle suspension

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1. Introduction

Coating process is widely used in the manufacturing of different kinds of products, including adhesive tapes, magnetic tapes, disks, optical films and displays. Slot coating process is used in the manufacturing of products that require high precision, as slot coating belongs to a class of coating method known as premetered coating, in which all the fluid fed to the coating head is applied to the web.

For many applications, coating liquids are polymer solutions or colloidal suspensions, or both. The common and simplified approach is to study the flow as Newtonian and evaluate its viscosity based on the average particle concentration. However, experimental data, such as Leighton and Acrivos (1987), show that particle distribution is non-uniform in shear flows. The microstructured of the product is extremely important for its functionality. Therefore, it is crucial to understand and predict the particle distribution in the coated film.

There are works in the literature that studied particle distribution in shear flows considering different particle migration mechanisms. For instance, both Min and Kim (2010) and Silva and Carvalho (2013) described the total flux of particles by the migration mechanisms proposed by Phillips et al. (1992). Even though those studies presented important contributions to study coating of particle suspensions, such as the two-way coupling analysis effect and the effect of film thickness in the final particle distribution, they were limited to some aspects of the process. Neither works studied the influence of sedimentation of particles in the coated film, nor the influence of particle concentration in the liquid surface tension.

The goal of the present work is to study the different migration mechanisms that may affect the final particle distribution in the coated film; such as diffusive mechanisms and sedimentation. Besides that, another objective is to study the influence of surface tension gradient in the final particle distribution. In order to do so, surface tension will be evaluated as a function of particle distribution along the interface and particle migration from the bulk to the interface is considered instantaneous.

2. Mathematical Formulation

Slot coating flow, as presented in figure 1, is extremely complex because of the presence of the free surfaces. Therefore, besides the mass and momentum conservation equations, the flow domain is also unknown and needs to be determined. The mathematical formulation of the problem is described in more details in Araujo and Carvalho (2014). Here, we only present equations that describe the particle transport and the evaluation of surface tension as a function of surface particle concentration.

In order to determine the concentration field, the particle transport equation is used (eq. 1). In this equation, the diffusive term is a function of the total flux of particles due to different migration mechanisms. This total flux of particle is described by three different migration mechanisms as described below:

$$\mathbf{v} \cdot \nabla c + \nabla \cdot \mathbf{N} = 0 \qquad (1)$$

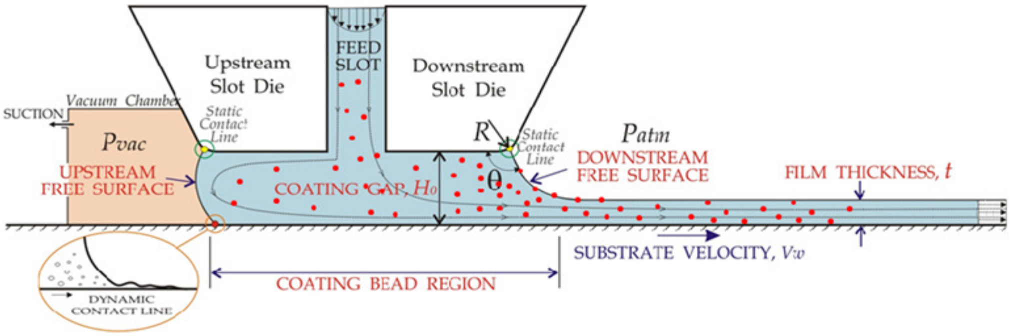


Figure 1. Scheme of the slot coating process.

1. Shear rate gradient migration mechanism: Shear rate is related to particle collision frequency. Higher shear rate areas yields higher collision frequency between particles than lower shear rate areas. Therefore, particles that suffer more collisions from one side than from the other side will migrate in the direction of the lower frequency collision area. As a consequence, particles migrate from high shear rate areas to low shear rate areas. In order to describe this mecanism, the model proposed by Phillips et al. (1992) is used, where particle migration due to shear rate gradient is given by eq. 2.

$$N_C = -K_c\, a^2\, (c^2\, \nabla\dot{\gamma} + c\, \dot{\gamma}\, \nabla c) \tag{2}$$

Where K_c is a proportionality constant of order unity, a is the particle radius, c represents particle concentration and $\dot{\gamma}$ is the shear rate.

2. Viscosity gradient migration mechanism: A non-uniform particle distribution yields areas with high and low viscosity. Viscosity means resistance to motion; hence in areas with high viscosity it is harder for particles to flow than areas with low viscosity. Finally, particles will just migrate in the direction of the low viscosity areas where they can flow more freely. The constitutive equation used to describe this mechanism is also the one proposed by Phillips at al. (1992) and is presented in eq. 3.

$$N_\mu = -K_\mu\, \dot{\gamma}\, c^2 \left(\frac{a^2}{\mu(c)}\right) \frac{d\mu(c)}{dc} \nabla c \tag{3}$$

Where K_μ is a proportionality constant of order unity, μ is the viscosity which is a function of particle concentration. Krieger (1972)'s model is used to describe viscosity as a function of particle concentration.

3. Sedimentation: If particles are heavier than the liquid, then they will migrate towards the bottom of the film and sediment. In order to take this mechanism into account, the Stokes velocity is considered together with a correction factor that considers particle concentration, proposed by Miskin at al. (1996). The flux for the migration mechanism due to sedimentation (eq. 4) is:

$$N_S = \frac{2}{9} \frac{\Delta\rho\, g\, a^2}{\mu_l}\, c\, \frac{1-c}{\mu_s} \tag{4}$$

Where $\Delta\rho$ is the density difference between particles and liquid, g is the gravity, μ_l is the liquid viscosity and μ_s is the suspension viscosity.

Finally, the total flux of particles due to different migration mecanisms is described as:

$$\mathbf{N} = N_C + N_\mu + N_S \tag{5}$$

In order to study Marangoni effect, surface tension is described as a function of surface concentration. A linear constitutive equation is used to describe surface tension as a function of interface concentration and is presented in equation 6. This linear behavior is also reported by experimental data, such as Okubo (1995).

$$\sigma = \bar{\sigma} - \beta \cdot (c - \bar{c}) \quad (6)$$

Where $\bar{\sigma}$ is a reference value of surface tension which is related to concentration $\bar{c}$, and β is the constant that measures particles strength. As a conclusion, higher particle concentration areas yields lower surface tension than lower particle concentration areas. Consequently, particles migrate from high to low particle concentration areas due to marangoni flow.

3. Results

Slot coating process of particle suspension is studied and the particle profile on the coated film for different values of $\Delta\rho$ are presented in figure 2. The x-axis presents particle concentration over average particle concentration, which is 0.4 for the present case. The values of the parameters used for this case are presented in table 1. For this case, particles are considered surface-passive and, consequently, surface tension is constant. The final film thickness is one fourth of the gap.

Table 1. Characteristics of the flow, liquid and particles in the simulations.

Parameter	Value	Parameter	Value
$\boldsymbol{a}$	$0.004\ mm$	K_c	0.8
$\boldsymbol{g}$	$9.8\ m/s^2$	K_μ	1.6
$\boldsymbol{V}$	$100\ mm/s$	$\bar{c}$	0.4
$\boldsymbol{\mu_l}$	$0.03\ mm^2/s$	$\bar{\sigma}$	$60\ mN/m$

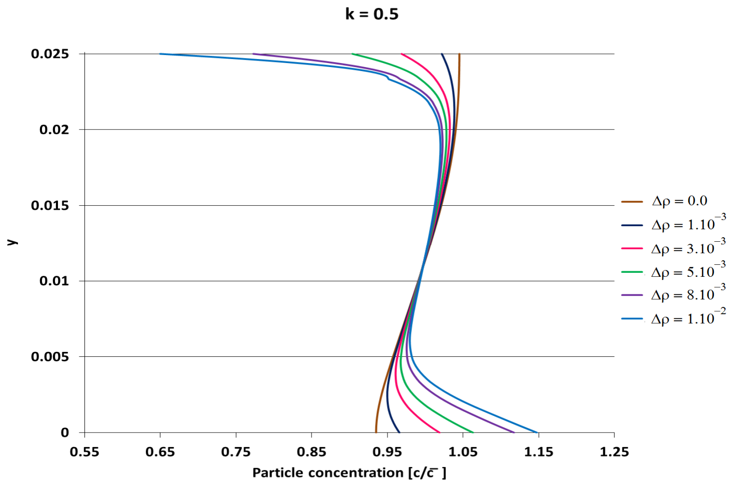
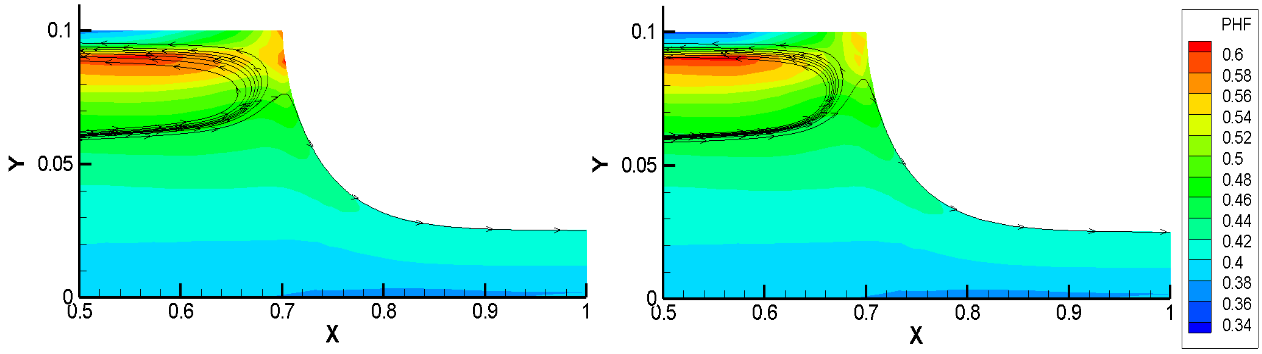


Figure 2. Final particle distribution in the coated layer; unit for the density difference is g/mm^3. Parameter $k = K_c/K_\mu$.

As the density difference between particles and liquid increases, particle concentration at the top of the film decreases and at the bottom increases. Sedimentation is not strong enough to change the whole particle profile as the settling velocity (maximum value of $U = 1.16 \cdot 10^{-2}\ mm/s$) is much slower than convective velocity, or web speed ($V = 100\ mm/s$).

The results considering surface tension as a function of surface concentration are shown in figures 3 and 4. From figure 3a to 3b, β increases and, as a consequence, the recirculation pattern changes and the stagnation point is shifted in the direction of the contact line. Surface tension smooths particle concentration along the interface. Even though surface tension does change downstream flow it does not change final particle distribution, as is shown in figure 4.



a) β = 0.0 b) β = 17.0

Figure 3. Effect of the surface tension in the downstream flow.

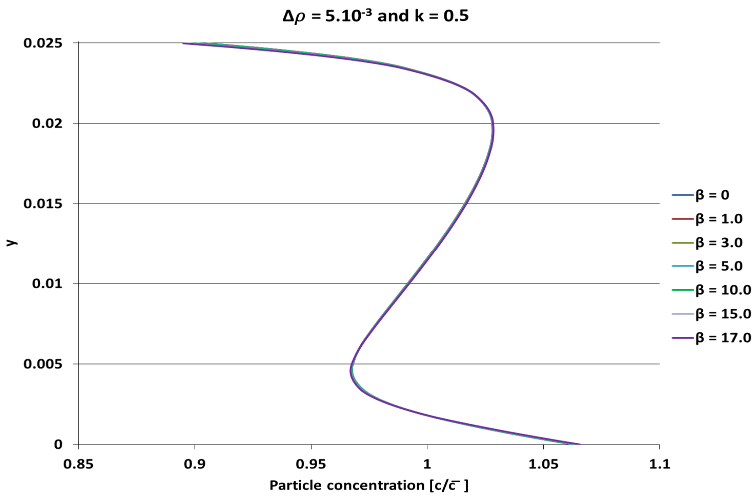


Figure 4. Effect of the surface tension in the final particle distribution.

4. Final Comments

A model to describe the coating process with particle suspension is presented, in which different migration mechanisms are considered, including particle sedimentation. Results show that even though convective transport is much stronger, sedimentation is still capable of changing top and bottom of the coated film. The effect of considering surface tension as a function of the particle concentration along the interface is evaluated. For that, we have that surface tension is capable of changing the downstream recirculation and the stagnation point in this region. However, surface tension does not change final particle distribution profile at the conditions considered.

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