Uniformity Correction for Fluid Coating Head

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Abstract: Slot coating is a widely used commercial process for applying one or more thin layers to a substrate such as paper, fabric, film or other material. In many cases, a highly uniform thickness is required, and the coating head is carefully corrected to ensure a uniform flow from its output slot. However, a coating head that has been corrected for use with a Newtonian fluid may not produce a uniform coating when used with non-Newtonian fluids, and the correction for non-Newtonian fluids is itself fluid dependent. This work illustrates a first-order correction that can be used to help recover uniformity with an adjustment of inlet fluid temperature.

Keywords: Coating head, uniformity, Navier-Stokes, non-Newtonian, thermal, correction.

1. Introduction

In the slot coating process, an applicator is used to deposit one or more uniform fluid layers onto a moving substrate. The layers may be the active components of a product (e.g. dyes on a printer ribbon, or glue on an adhesive tape) or they may simply alter the natural physical properties of the substrate. For example, coatings are used to improve chemical resistance, coefficient of friction, color, ink absorption, electrical conductivity or appearance, or to provide barriers against water, oxygen, scratching, staining or other environmental insults.[1] The machine that applies the coatings is generally required to provide a coated layer of uniform thickness across a very wide substrate (also known as a "web"), and then to dry or fix the coating in some manner. It is within the scope of current practice to apply films over webs more than a meter in width at rates of several hundred meters/minute.

The coating fluid is typically supplied through a central pipe to a coating head that is responsible for distributing it evenly from a wide exit slot. Uniformity of distribution is usually achieved by providing an internal cavity of relatively large cross-section that allows the fluid to flow sideways in the coating head with very little flow impedance, distributing it evenly across a very thin output slot of much higher flow impedance. Fig. 1 shows a schematic top and side view of such a distribution system.

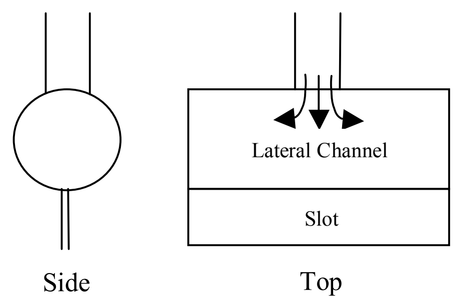

Figure 1. Schematic diagram of the coating head function.

Despite the relatively large cross section of the lateral distribution channel, fluid flow through the lateral channel and exit slot results in pressure gradients that produce some degree of pressure variation across the width of the head. This leads to a variation in the delivered fluid flow rate, and therefore to uneven thickness of the deposited film. Typically, the pressure is highest in the center of the head and lowest at the ends.[2]

1.1 Uniformity Corrections

A great deal of engineering has been applied to the correction of these non-uniformities. Most commonly, one may tailor the length of the exit slot to compensate for the pressure variation along the head, as represented in a highly exaggerated form in Fig. 2. A shorter exit slot requires less pressure to deliver the same flow rate of coating fluid. In Fig. 2, the exit slot length is graded such that it is shorter near the ends of the coating head, where the pressure is lowest, and longer in the center where the pressure is highest. With a carefully designed slot profile the fluid delivery can be tuned to provide a coating thickness that is accurately uniform with a precision of better than 1%.

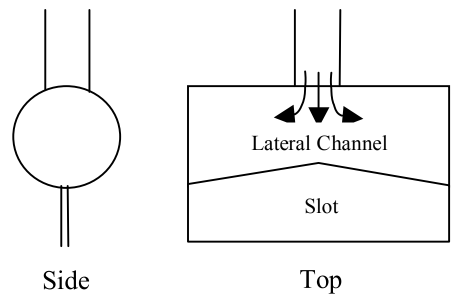

Figure 2. Coating head with a (highly exaggerated) tapered slot length for uniformity correction.

Interestingly, if the coating fluid is a Newtonian fluid (i.e. if its viscosity is independent of shear), the required correction profile is independent of viscosity and flow rate. This is not the case for general non-Newtonian fluids, for which the cross-web profile must be designed with a specific fluid and flow rate in mind, but it does apply to non-Newtonian fluids of the so-called "power law" variety, for which the viscosity is related to the shear by

$$\eta = K\left(\frac{\partial u}{\partial x}\right)^{n-1}$$

For these fluids, the optimum profile depends only on the power law index n (which may, however, be a function of temperature).

In addition to nonuniformities from pressure gradients, the slot may be physically distorted by the internal fluid pressure. For this reason coating heads are manufactured of thick steel or of ceramics with very high Young's modulus. A commercial coating die may be more than a meter wide and several cm thick, with precisely machined and finished channel and slot. To capitalize on the expense of such a valuable resource, it is worthwhile to investigate conditions in which a single coating head can be made to suffice for a variety of fluids, both Newtonian and non-Newtonian, and in particular to find operating conditions under which observed uniformity variations may be corrected without a new head design.

2. Model Description

In this work, we looked at the degree to which we could use a temperature adjustment of the coating fluid to correct for non-uniform coating thickness. The fluids in question have viscosities and power low coefficients that are functions of temperature, higher temperature generally leading to lower viscosity. If the inlet fluid has a temperature different than the walls of the coating head, then the fluid temperature (and therefore its viscosity) changes as it is distributed through the head. The resulting viscosity changes can be used to help compensate for pressure variations.

For example, if the fluid delivery is lower at the sides than at the center of the exit slot, as a result of higher central pressure, then we can deliver cooler, higher viscosity, coating fluid to the center of the head. The temperature of the fluid will slowly equilibrate with the head as it is distributed to the ends of the output slot, thus yielding a decreasing viscosity from center to edge of the head. To the extent that this decrease can mimic the decrease in fluid pressure, it can be used as a first order uniformity correction.

The coating head that we have modeled is a variation on the schematic design shown in Fig. 1, and it differs in three principal ways: 1) the cross-section is more rectangular than circular; 2) the lateral channel is shaped somewhat like an airplane wing, with a cross-sectional area that decreases from the center of the head to the sides. 3) The output slot is nearly perpendicular to the lateral channel, rather than extending it in the direction of the inlet pipe.

A perspective view of one-half of the full structure is shown later in Fig. 3. From a modeling standpoint, one of the most challenging aspects of this problem is the extreme difference in length scales along three dimensions. While the full head is 0.2 meters in width, the lateral channel is only several centimeters in height and width, and the exit slot has only 0.3 mm clearance.

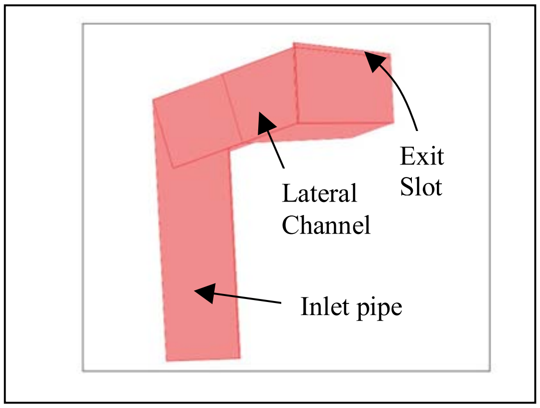

Figure 3. Perspective view of the modeled coating head. This drawing represents one-half of the entire head, which is symmetric about its central plane. The inlet pipe is circular, and the exit slot emits fluid in the vertical direction.

Because of the disparity in scale, care must be taken in meshing. Since the exit slot requires elements a fraction of a millimeter in dimension, we need thousands of these elements to encompass the full length and height of the slot. (The actual coating head on which this preliminary model is based is almost 8 times longer, and is even more of a problem.) The "free mesh parameters" feature of COMSOL Multiphysics was used to generate a satisfactory mesh for the output slot, and to merge this mesh gradually into a coarser mesh for the channel.

Due to the memory requirements of this problem, we use the GMRES iterative solver. The boundary conditions for the fluid problem are no-slip walls, with the following exceptions: 1) The inlet is given a velocity boundary condition, using a quadratic velocity profile in the circular inlet pipe; 2) The outlet is set to zero pressure; 3) Due to the symmetry of the coating head, only one-half of the full structure is modeled and the slice down the middle of the head is given a symmetry boundary condition for Navier-Stokes.

For the thermal problem, the walls are set at the operating temperature of the coating head, which is generally above room temperature. The fluid is delivered to the head at a lower temperature, and this inlet temperature is parameterized and varied from run-to-run to find the temperature for optimum uniformity. At the exit slot, the boundary condition is that for convective transport of heat, based on velocities provided by the Navier-Stokes solution. At the central slice through the coating head, an insulating boundary condition is used, since the symmetry assures us that no heat will cross this plane.

Throughout the calculation the fluid shear must be calculated in order to evaluate the viscosity of the highly shear-thinning coating fluid. For this purpose, we used a full rotationally invariant expression for the shear.[3]

$$\text{shear}^2 = \left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)^2 + 2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{\partial w}{\partial z}\right)^2$$

As a full multiphysics problem, in which the fluid flows and temperatures are solved simultaneously, convergence has not been observed from any easily specified initial condition. For this reason, solutions are begun by segregating the Navier-Stokes solution from the thermal solution, and alternating between them a few times to arrive at a good starting point for a simultaneous solution. Once a converged solution has been obtained for some inlet temperature, it can be successfully used as an initialization for other temperatures.

3. Results

Figures 4-6 illustrate the pressure, temperature and fluid flows typical of converged results. Fig. 4 shows the pressures along the head when the fluid inlet temperature is the same as the temperature of the coating die. If the fluid were a Newtonian fluid then the die would be corrected to compensate for this pressure, and no non-uniformity of fluid delivery would occur. However, with the non-Newtonian fluids, this compensation is not effective.

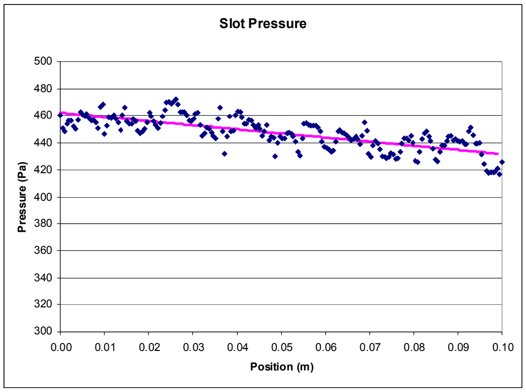

Figure 4. Pressure at the entrance of the exit slot as a function of lateral position on the coating head. The inlet temperature of the coating fluid is the same as that of the coating die.

Fig. 5 shows the flow pattern of fluid within the head, traversing the inlet pipe, spreading laterally down the lateral channel, and then emerging throughout the entire exit slot.

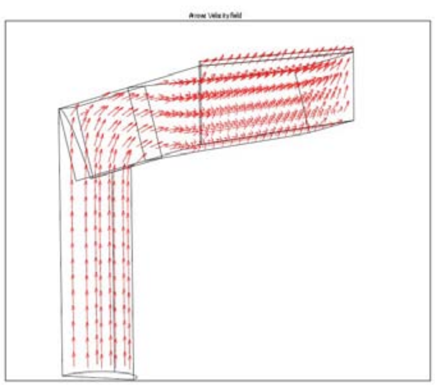

Figure 5. Flow of liquid through the coating head. The fluid rises through the feed pipe and spreads down the lateral channel, feeding the exit slot along the way.

The resulting fluid temperatures, plotted in slices down the long dimension of the head, are shown in Fig. 6. In traveling the length of the head, the fluid is clearly warmed by the walls of the head, and its viscosity is thereby lowered, increasing the fluid delivered to more remote parts of the exit slot.

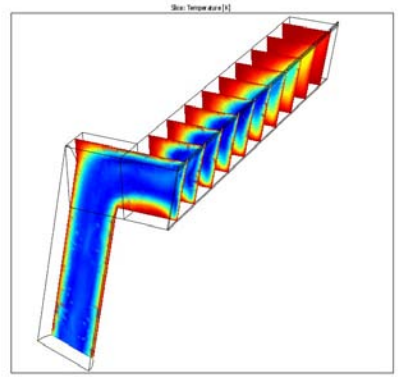

Figure 6. Temperature profile of the coating fluid when the inlet fluid temperature is 10C below the temperature of the coating head. As the fluid flows down the lateral arm, it is progressively warmed and its viscosity decreases.

In general, the fluid flow rates along the exit slot are accompanied by noise whose peak amplitude is comparable to the size of the corrections being made. However, the trends in these solution are quite reproducible and can be brought out either by low-pass filtering of the noise or, preferably, by fitting the exit velocity to a linear function as shown in Figure 7.

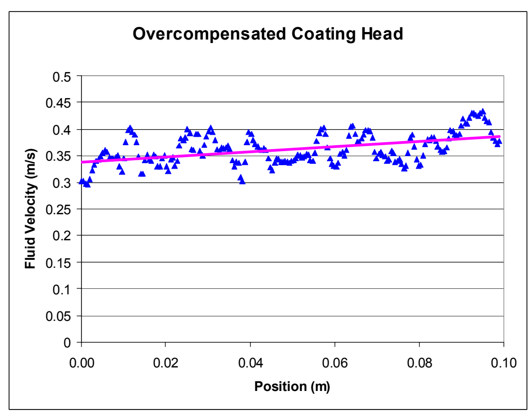

Figure 7. Fluid delivery variation along the coating head when the inlet fluid temperature is too low and is overcompensating for the pressure variations. The data are fit with a linear function whose slope is used as the measure of nonuniformity.

The choice of a linear function is based on previous work by Gutoff.[2] In this figure, the solution depicts a case in which the inlet fluid temperature has been lowered enough (20 deg. C) to overcorrect the pressure variations, leading to a flow rate which is actually higher at the extremes of the coating head than at the center. The magnitude of the linear term in the velocity fit is, in fact, an excellent measure of the degree to which the flow uniformity has been successfully corrected.

Figure 8 shows the fitted value of the linear coefficient vs. the temperature difference between the inlet fluid and the coating head. The zero-crossing of this data at a temperature difference of 8.2C indicates that this is the preferred fluid temperature reduction for uniform coating at the modeled flow rate. Using this method, we have successfully corrected (with an actual coater) flow variations of about 10% with an accuracy of better than 1%.

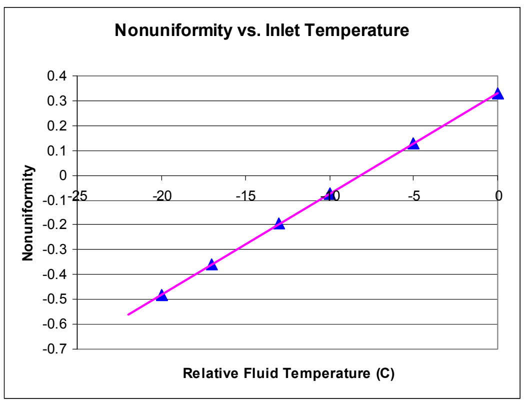

Figure 8. Nonuniformity of the coating as a function of the difference between the temperature of the coating die and the temperature of the incoming fluid. A uniform coating occurs when the fluid is cooled by 8.2C.

4. Discussion

As a check of our result, we compared with a rough calculation of the fluid pressure based on the simpler type of coating head described at the beginning of this paper. For that head the channel has constant (circular) cross-section, and Gutoff[2] has shown that the pressure distribution along the channel is:

$$\frac{P(F)}{P(0)} = \frac{\exp\left(\sqrt{c(1-F)}\right) + \exp\left(-\sqrt{c(1-F)}\right)}{\exp\left(\sqrt{c}\right) + \exp\left(-\sqrt{c}\right)}$$

where F is the distance from the center of the coating head expressed as a fraction of the half-width of the head. The quantity c is given by:

$$c = \frac{2(1+3n)^n \, 2^n H_1^{1+2n} w^{1+n}}{(1+2n)^n (1+n) \pi^n D^{1+3n} L_1}$$

for a power-law fluid with exponent n, and for a coating head of length w with a circular channel of diameter D, a slot with a gap of H_1 and length of L_1. A function g() is provided by Gutoff for converting this result into a similar result for coating heads with rectangular channels, by replacing D with an "equivalent diameter".

$$D_{equiv} = g\left(\frac{b}{a}\right) a \qquad g\left(\frac{b}{a}\right) = \frac{4}{\sqrt[4]{\pi}} \frac{\left(\frac{b}{a}\right)^{3/4}}{\sqrt[4]{f\,\mathrm{Re}}\sqrt{1+\frac{b}{a}}}$$

$$f\,\mathrm{Re} = 24\left[\begin{array}{l} 1-1.3553\left(\frac{b}{a}\right)+1.9467\left(\frac{b}{a}\right)^2 \\ -1.7012\left(\frac{b}{a}\right)^3+0.9564\left(\frac{b}{a}\right)^4-0.2537\left(\frac{b}{a}\right)^5 \end{array}\right]$$

where a is the length of the longer side of the rectangular channel and b is the length of the shorter side.

Though our coating head does not have a strictly rectangular channel, we can use these expressions to estimate that a fluid with a power law exponent of 0.6 (typical for the fluid and temperature used in the simulation), the pressure non-uniformity from center to edge of the head would be 5.8% in the absence of a temperature variation. The multiphysics calculation has produced a result of 6.6%, which is gratifyingly close. The analytical calculation is, of course, unable to address the question of pressure variation in the presence of fluid temperature variations.

5. Conclusions

With a multiphysics calculation involving the simultaneous solution of fluid dynamic and thermal diffusion equations within a fluid coating die, we have demonstrated the correction of a cross-web flow nonuniformity with a counterbalancing temperature nonuniformity. A variation of over 6% was shown to be accurately correctable, and the optimum fluid temperature was determined from an observed linear relationship between the fluid temperature and the nonuniformity.

In future work, we will investigate the dependence of the optimum fluid temperature on flow rate, determine the flow regime within which such accurate corrections may be obtained, and look for the uniformity characteristics exhibited when the correction is imperfect or the regime of applicability is exceeded.

6. References

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