

Uniformity Correction for a Fluid Coating Head

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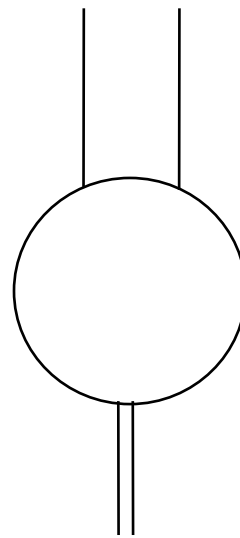
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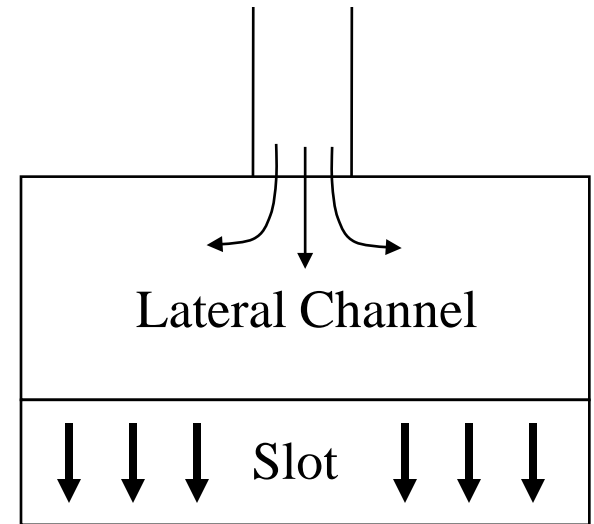
> Basic Coating Head Design

- **A basic fluid coating head has three components:**

- Fluid inlet pipe
- Low impedance lateral channel
- High impedance exit slot



Side

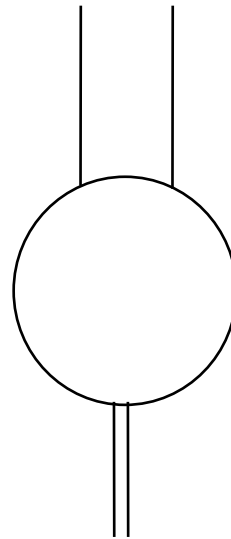


Top

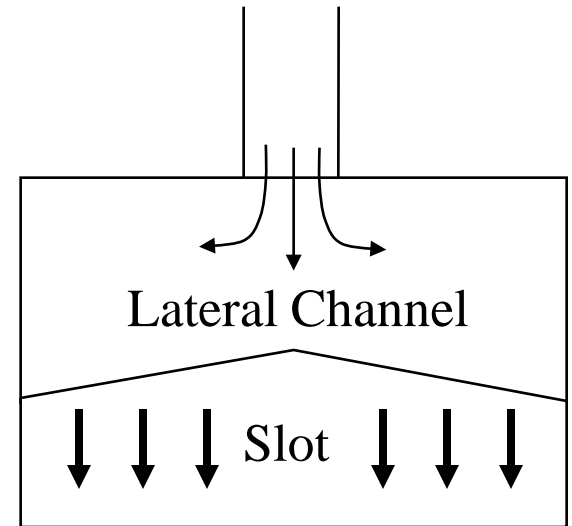
- **Lateral channel distributes liquid evenly across exit slot**

> Basic Uniformity Corrections

- **Flow impedance in the lateral channel causes a pressure gradient that results in non-uniform coating**
- **The channel shape and/or the slot length can be tailored to correct for this**



Side



Top

> Another form of Correction

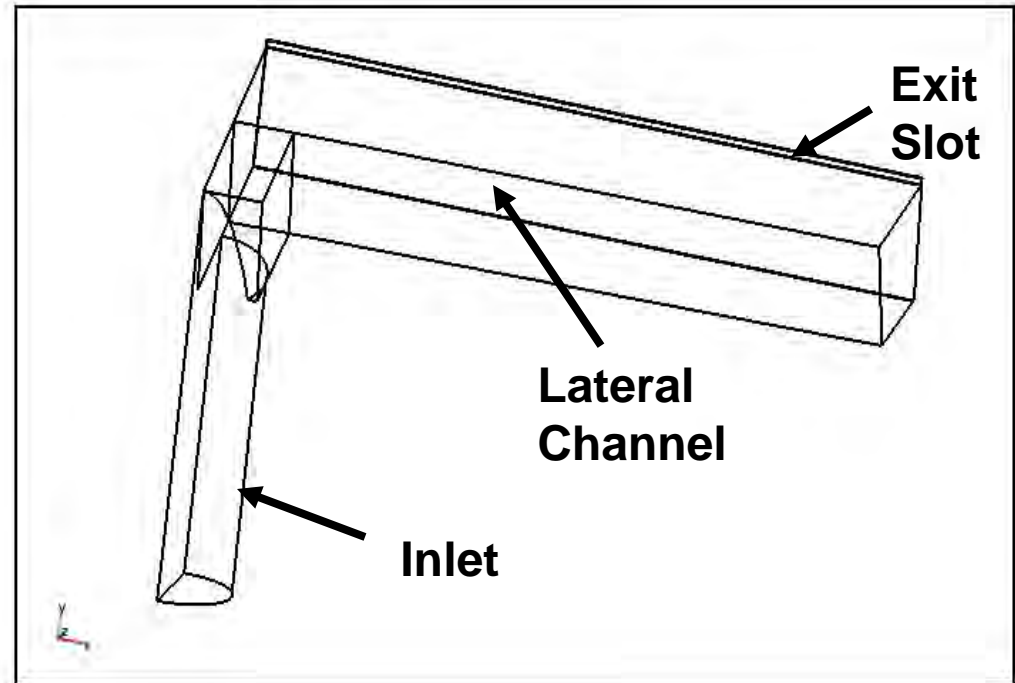
- **We were presented with a coating head that was designed for Newtonian fluids, and it was very non-uniform when used with one of our non-Newtonian fluids**
- **Rather than suffer the large expense of designing a custom die for this fluid, we decided to try a non-mechanical solution**
- **Try changing the temperature as it flows through the head is a way that corrects for the pressure change to first order.**

> Coating Head Modeled in this Study

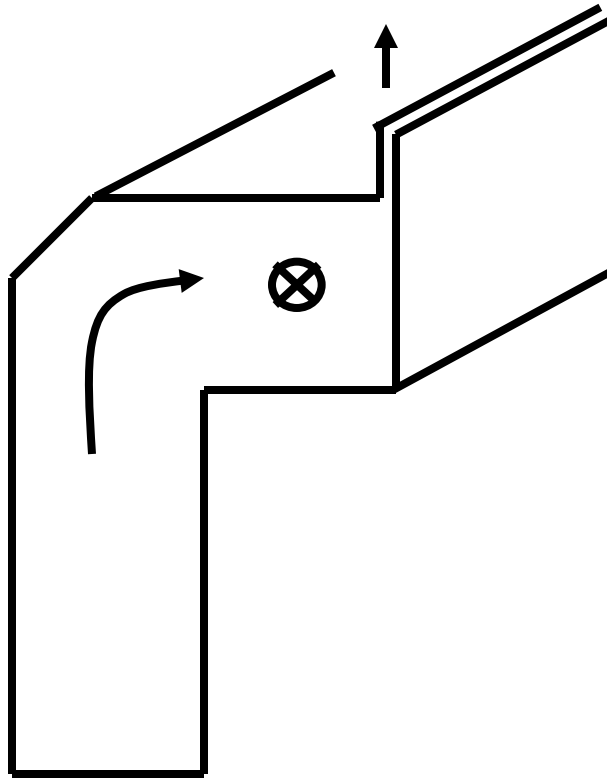
Coating head is symmetric, so we model only half.

Fluid inlet and exit slot are disposed differently of make the heads stackable.

Multiple layers of fluid are piled up and coated together.

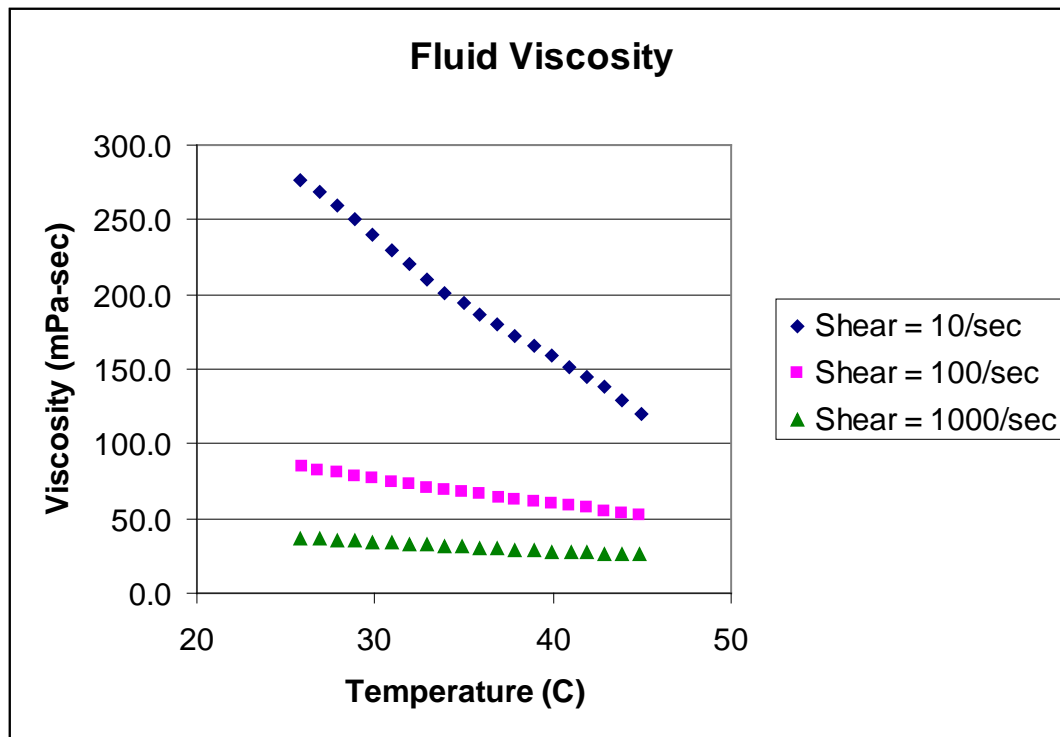


> Rough sketch of cross section



> Fluid Properties

- The fluid in this model is highly shear-thinning, having a viscosity that is a complicated function of temperature, shear, and composition.



> Shear

- **This behavior was modeled as a power-law fluid with coefficients that vary with temperature**

$$\eta = K \square shear^{n-1}$$

$$\log(\eta) = \log(K) + (n-1) \square shear$$

- **The values of log(K) and n were found to be nearly linear functions of temperature (around T=298 K) and were fit well by quadratics:**

$$\log(K) = 19.0 - 0.09T + 9 \times 10^{-5} T^2$$

$$n = -0.14 + 0.0035T - 3.5 \times 10^{-6} T^2$$

> Shear

- **Since the geometry takes twists and turns, we used a full three-dimensional, invariant expression for the shear:**

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

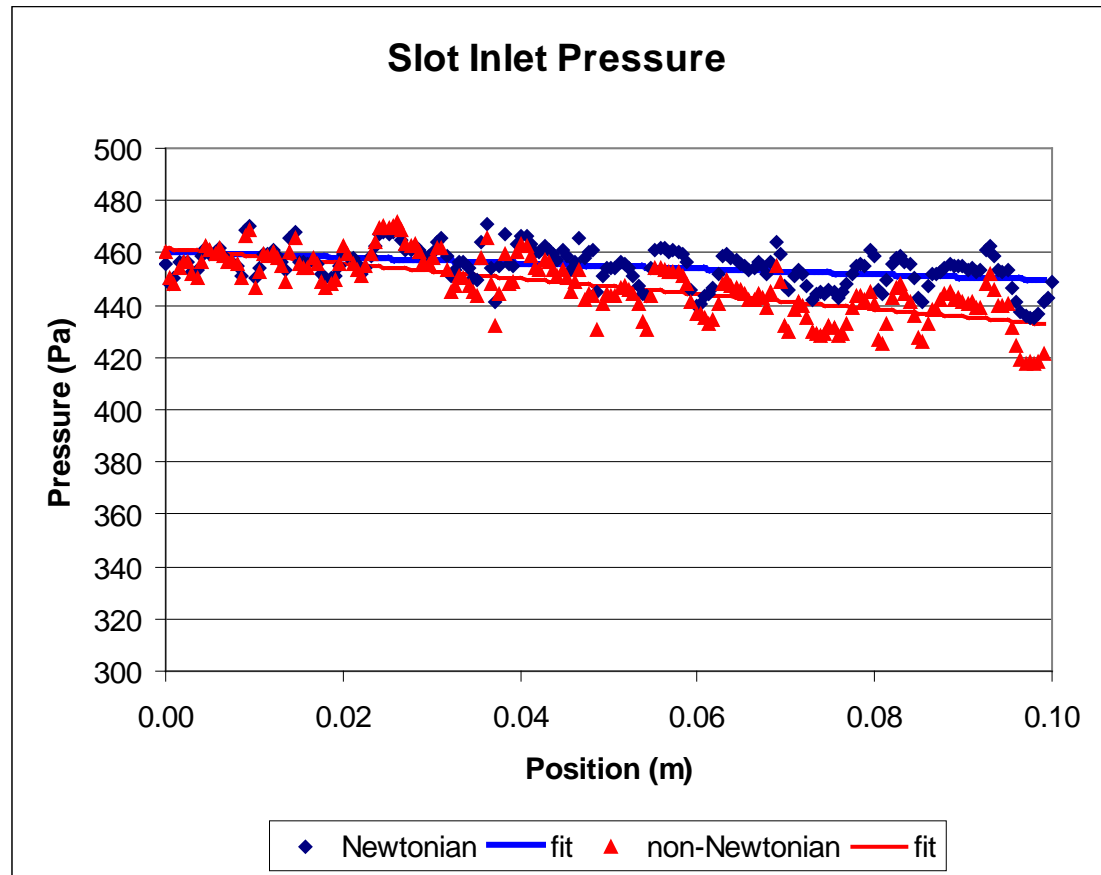
> Meshing

- **One difficult aspect of this model is meshing.**
 - The actual coating head has a lateral channel that is about 1.5 m long and several cm. in width.
 - The exit slot is 1.5 m long and has a gap of 0.3 mm
 - This leads to untold numbers of mesh points
- **For this model, we have shortened the coating head to 0.1 m, and shortened the exit slot to increase the flow rate to a value that gives a non-uniformity similar to the full coating head.**

> Pressure variation

Pressure variation at exit slot is 2.3% for a Newtonian fluid with $\eta=16.2$ mPa-s. (in blue)

With the non-Newtonian fluid used in this study, the variation is over 6%. (in red)



> Pressure variation along head

**According to Gutoff (proc. of 1992 AIChE Spring Mtg.),
for a cylindrical channel:**

$$\frac{p(F)}{p(0)} = \frac{\exp\left(\sqrt{c(1-F)}\right) + \exp\left(-\sqrt{c(1-F)}\right)}{\exp\left(\sqrt{c}\right) + \exp\left(-\sqrt{c}\right)} \approx 1 - F \left(\frac{c}{c+2} \right)$$

where c is a parameter computed from

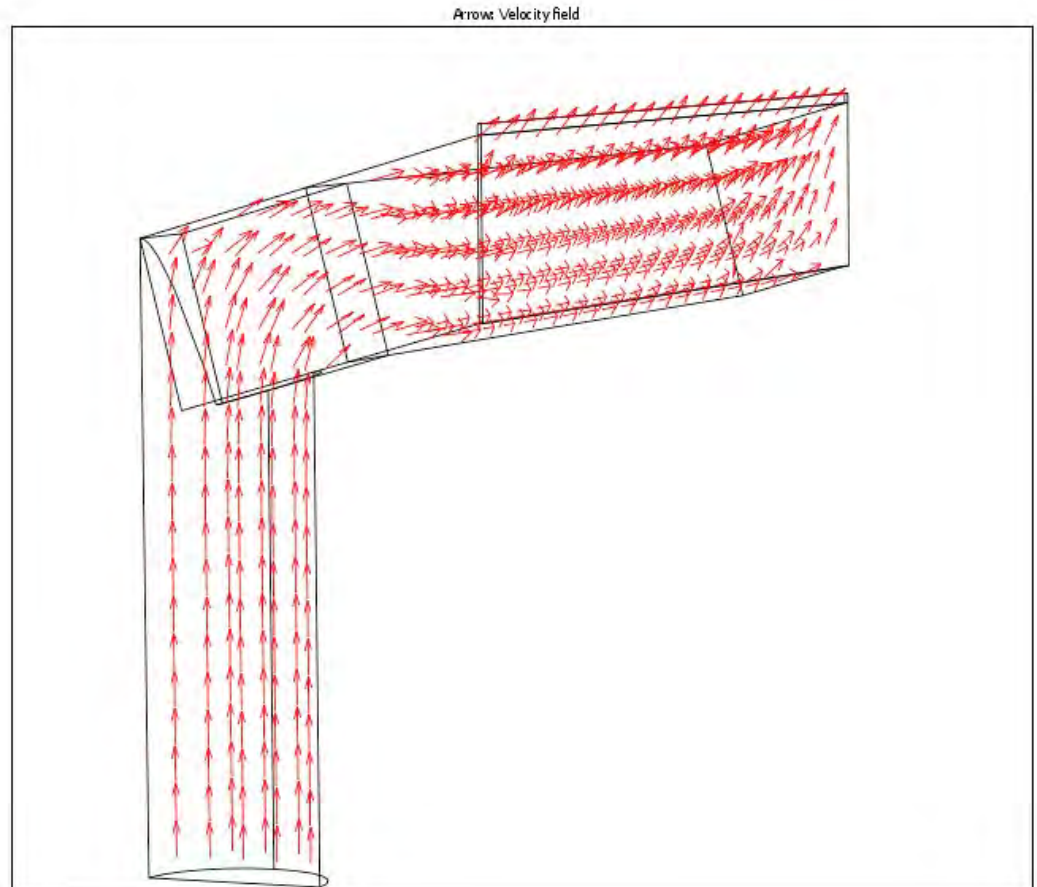
**a) the physical dimensions of the coating head
(including the length and area of the channel, and the
dimensions of the exit slot), and**

b) the power law exponent of the fluid.

F is the fractional distance from the center.

> Velocity profile

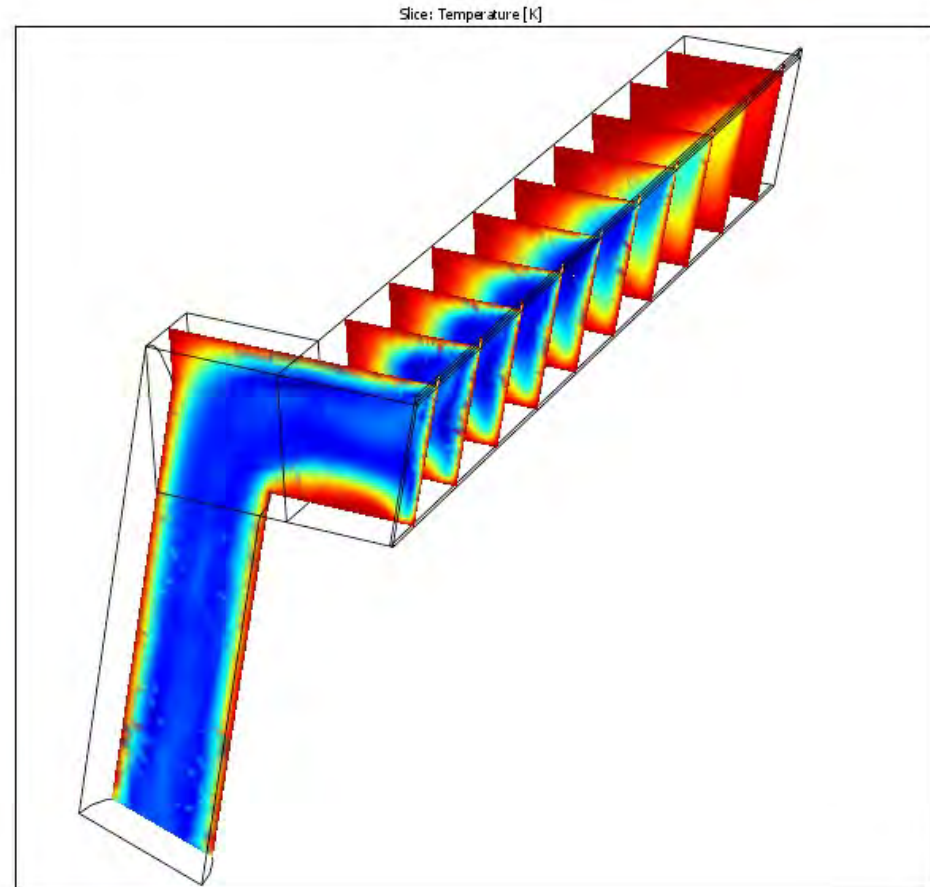
Coating fluid rises in the delivery pipe, spreads down the lateral channel, and emerges more-or-less uniformly from the exit slot.



> Temperature Profile

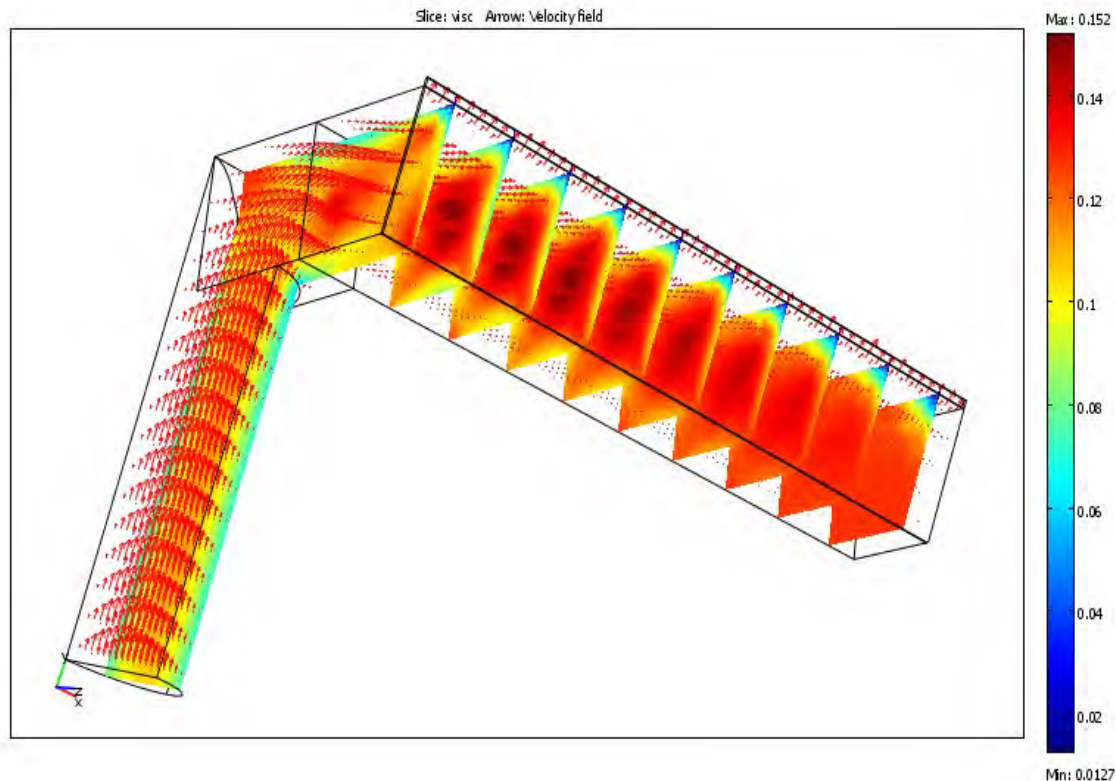
The coating head body is held at 40C. The fluid enters at a cooler temperature, here 30C.

The fluid warms as it travels through the coating head.



> Viscosity Profile

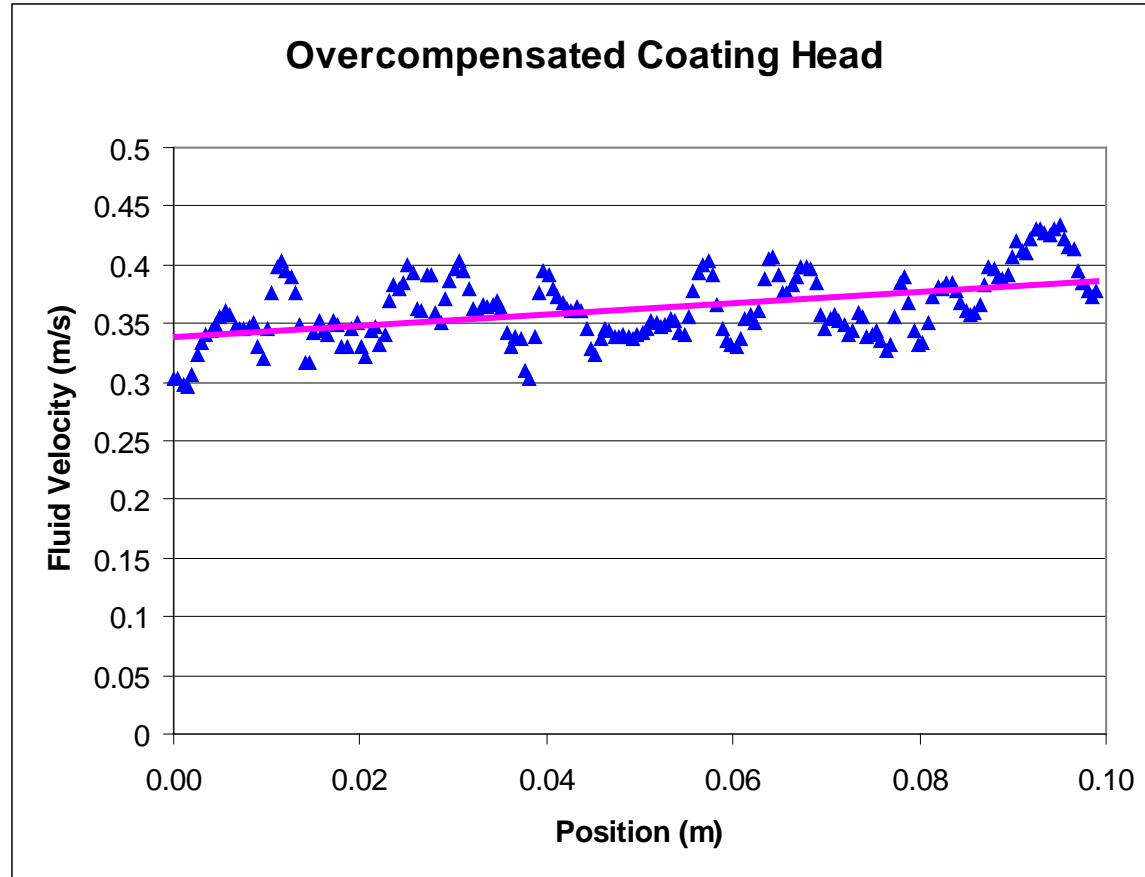
This leads to a viscosity that is highest in the center of the channel, lowest at the exit slit, and constantly decreasing as the fluid flows down the channel.



> Overcompensation

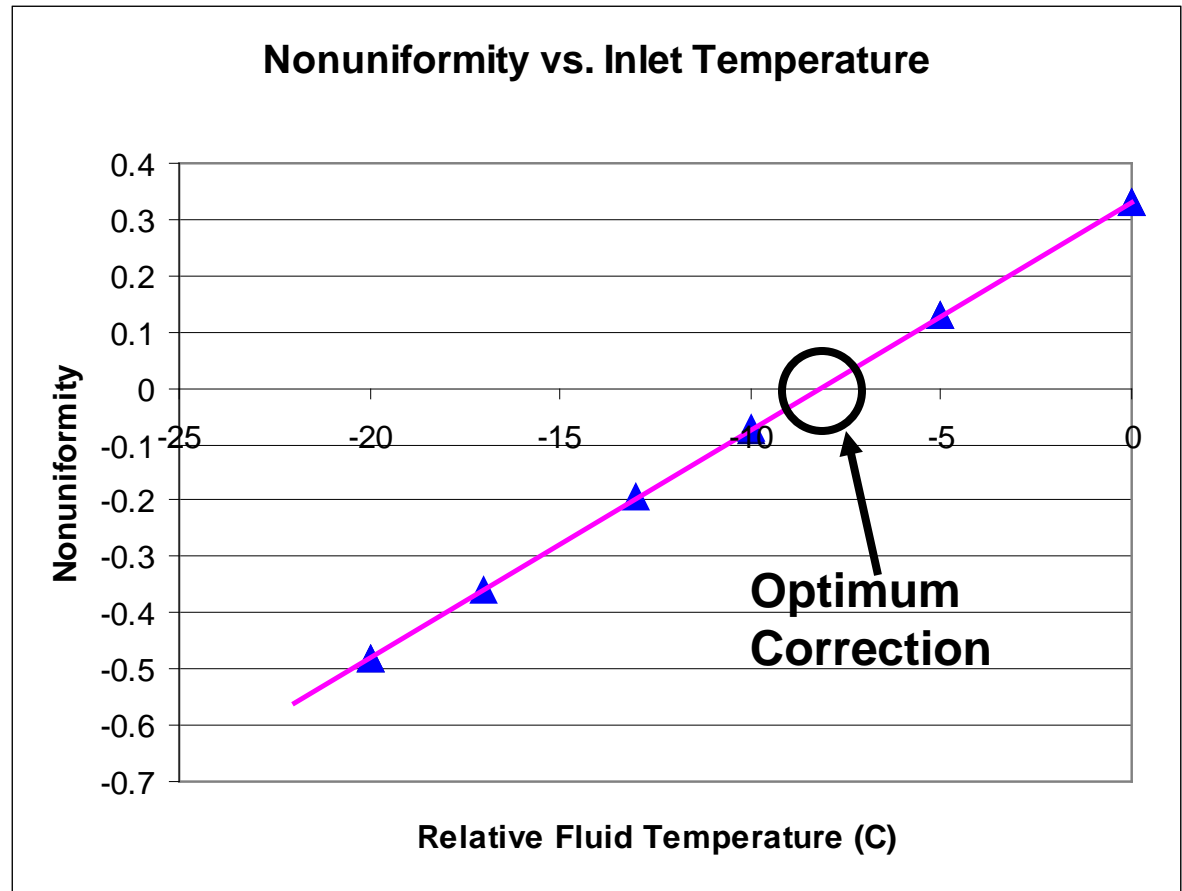
Cooling of the fluid reduces fluid delivery in the center of the coating head relative to the ends.

In this case, with a delta-T of -20C, the flow non-uniformity at the slot has become overcompensated by 12%.



> Optimizing Fluid Temperature

Running the model at multiple fluid temperatures, we found that the compensation is linear in delta-T, and best uniformity is obtained at $\Delta T = -8.2^\circ\text{C}$.



> Summary

With a model system, we have demonstrated that flow non-uniformities of a non-Newtonian fluid in a coating head can be corrected by changing the inlet temperature of the fluid.

The correction depends on the “power law” of the fluid and on the differential temperature between the coating head and the fluid.

With the help of COMSOL support, we are now investigating methods for improving the mesh for the full coating head.