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Gear Pump Design

for Pumping of Shear Thinning Materials in Slot Die Coating

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Abstract

When comparing pump styles for slot die coating operations, gear pumps are commonly used because they offer consistent metering without surging. Their primary disadvantage is that they induce a large amount of shear onto the fluid, which is problematic if the fluid or mixture is shear sensitive as it can lead to process complications. To alleviate this issue, several design characteristics can be chosen to allow for stable pumping with less shear than would be imparted with a pump chosen for a Newtonian fluid. This refiguring will primarily be accomplished by increasing the pump displacement thus allowing for a lower gear rpm, a step that will result in a decreased pump consistency. The give and take means that a process design decision will have to be made considering whether this trade-off is worthwhile. Different gear styles can help the pump consistency that results from a larger displacement, but they are more difficult to manufacture and therefore, more expensive.

Introduction

Using slot die is a common technique for coating pressure sensitive adhesives. This method requires adhesive to be directly metered onto a substrate at a consistent rate, primarily through the use of a gear pump. Because of the direct metering of this coating method, any inconsistencies or surging in the fluid pumping will be directly transferred to the coating. For this reason, the gear pump selection is extremely critical to the equipment's performance.

For Newtonian fluids without suspended particles, the selection of a gear pump is relatively straightforward. Since shearing the material is not a concern and particulate will not jam the gears, a system with low slip and a high enough rpm to remove any noticeable surging will suffice. For shear thinning fluids however this selection can become much more complicated.

The design of the slot die works off the principle that back pressure is necessary to spread the coating to the desired width. If the coating will shear thin, such as solvated pressure sensitive adhesives do, the viscosity decreases as fluid is pumped to the die, resulting in increased difficulty in building the necessary back pressure to achieve a uniform coating. Some solutions will also shear separate, permanently damaging the product. For these reasons, the gear pump selection needs to carefully performed to allow the material to shear as little as is possible while still maintaining a consistent flow.

Gear pump designs

Gear pumps are a style of positive displacement pumps. They work by using two gears that come in and out of mesh to create a small suction pressure at the pump inlet and a positive pressure at the pump outlet. Gear pumps come in two distinct designs, internal (figure 1) and external (figure 2). Both styles work off the same principle where the rotations of the gears creates a cavity on the inlet side that is filled with fluid and transported to the outlet side; then the meshing of the gears pushes the material out of the pump (Norton, 2012). Generally, gear pumps are a poor choice for shear sensitive materials because they do exert considerably more shear than other pumping option such as progressive cavity pumps. The steady flow requirements for slot die coating will generally out weigh the challenge of working with shear sensitive fluids.

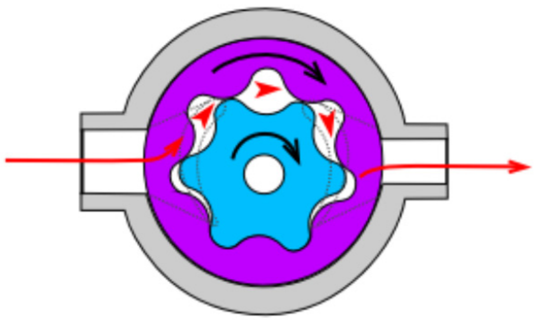

Figure 1: Internal gear pump
http://en.wikipedia.org

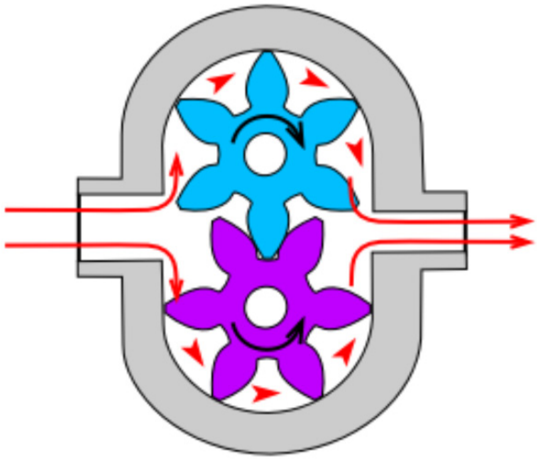

Figure 1: Internal gear pump
http://en.wikipedia.org

Internal gear pumps are best suited for high viscosity applications, where external gear pumps work better in high pressure applications. Internal gear pumps can be used at low viscosities, but will loose pumping efficiency since they have fewer gear teeth in contact with the sealing surface when compared to an external gear pump. An advantage of internal gear pumps is that they generally will shear the material less than an external gear pump will. Even so, external gear pumps allow for tighter internal clearances; thus providing a more consistent flow rate and greater pump efficiency, especially when pumping low viscosity fluids. Another flaw of the internal gear pump is that the bushing for the outside gear is within the product flow area (GearPump.com, 2010). For sensitive products, this is a potential source of contamination. Because consistency is key for slot die coating, external gear pumps are selected even though they shear material more.

The gears for gear pumps also come in several styles, spur, helical, and herringbone (figure 3).

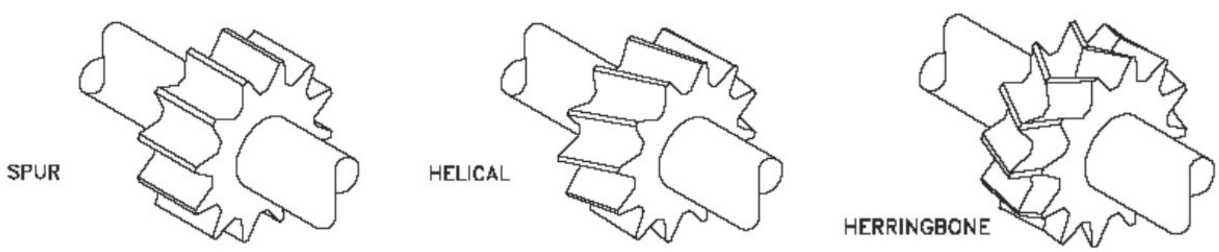

Figure 3: Types of Gears
http://www.engineersedge.com/pumps/helix_spur_gear_pump.htm

Spur gears are the standard style where the teeth run parallel to the gear's axis. These are the easiest to manufacture, and therefore the least expensive. Their disadvantage is that the entire length gear tooth will engage the driven gear at the same time, potentially resulting in surging. In helical gears the point of engagement will vary along the tooth as the gear rotates. This results in the discharge pressure being held more constant than it would be for a similar displacement spur gear. The herringbone gear pump is a further modification on the helical gear, with it basically being two helical gears placed side by side. This geometry makes the center of the gears the first discharge location, followed by the contact points moving towards the outside of the gears (Engineers Edge, 2012). This pattern provides an even, steadier flow than the helical gears. Witte Pumps and Technology GbmH provided the approximation (Figure 4) for how the pulsation of the different gear types compare:

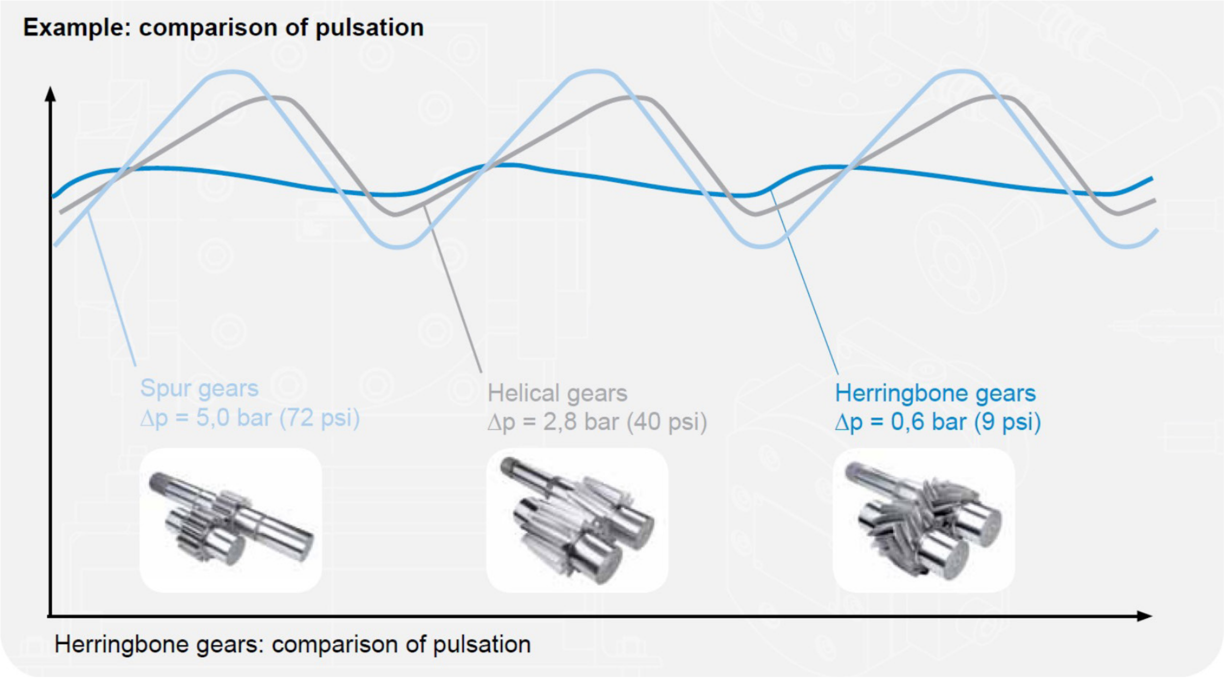

Figure 4: Pump Pulsation for Different Gear Types

(Witte Pumps and Technology GmbH)

Herringbone gears also allow the power transition from the driving to driven gear to be smoother than the helical gear because the horizontal forces are canceling each other out, so the gears are not trying to axially push away from each other (Engineers Edge, 2012). Herringbone gears are however more expensive to produce, so the cost to benefit trade off will likely remove any favorability that they would have (Norton, 2012). This decision would require an economic analysis for how long the product will be produced and what its profit would be.

Shear thinning materials

Non-Newtonian liquids describe any fluid where the viscosity varies depending on the shear rate exerted on it, as shown in figure 5. This process is also often defined as the shear stress not varying linearly with the shear rate, which is shown in figure 6. Shear thinning, or pseudo plastic, fluids will decrease in viscosity as shear is applied; the opposite for shear thickening or dilatant fluids. The majority of non-Newtonian liquids are shear thinning, which will be the focus of this analysis.

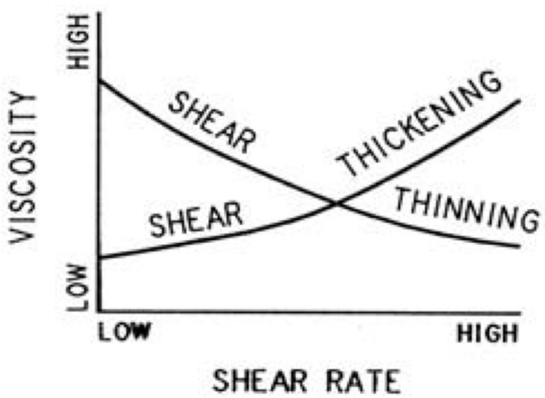

Figure 5: Viscosity vs Shear Rate
pumpschool.com, 2007

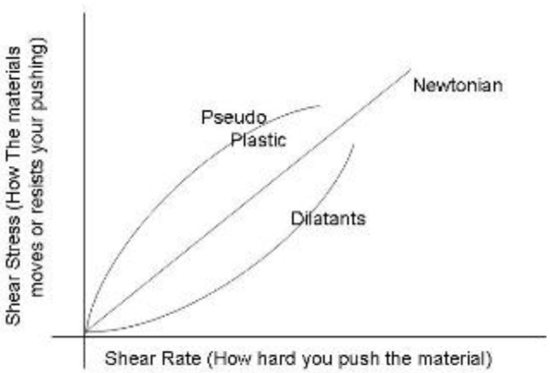

Figure 6: Shear Stress vs Shear Rate
pumpschool.com, 2007

For Newtonian fluids, shear stress is defined by

$$\tau_{yx} = \mu \frac{du}{dy}$$

Where ***μ*** is the fluids viscosity and ***du/dy*** is the shear rate. For setups with two plates moving relative to each other, the shear rate can conceptually be understood as the relative velocity of the plates divided by their separation.

For non-Newtonian fluids, the shear stress equation becomes

$$\tau_{yx} = k \left(\frac{du}{dy}\right)^{n}$$

Where ***n*** is the flow behavior index and ***k*** is the consistency index. This equation can be simplified to

$$\tau_{yx} = \eta \frac{du}{dy}$$

with

$$\eta = k \left(\frac{du}{dy}\right)^{n-1}$$

h is referenced as the apparent viscosity. Since both *k* and *n* are material dependent, the equation conceptually means that the greater the deformation rate (shear rate, *du/dy*) the lower the apparent viscosity (Fox 1998).

A common example of a material that behaves this way is paint. When it is spread, its viscosity drops to allow for even coverage, but when the shear stops, the paints viscosity increases to keep it from dripping. In applications such as this, shear is desirable because it allows for transfer of the fluid with less force. For many applications though, the imparted shear is damaging to the material. For example, in polymer based materials the shear can break up polymer chains, permanently altering the materials characteristics. Others will separate into their base components under shear; these are called shear separating materials (Fox, 1998). Understanding the behavior of the material being processed is crucial to successfully developing process equipment.

Shear through the gear pump

Gear pumps are considered a poor choice for shear sensitive material because of the large amount of shear they produce (Pumps School, 2012). This is due to the high contact surface to volume ratio that gear pumps have. The primary material contact points though gear pumps are both the gear teeth and the pump cavity walls that the teeth face. Shear rate going through the pump will then be governed by the depth of the gear tooth cavity, including the gear to wall tolerance (*dy*) and the rpm that the pump is turned at (*du*).

Typical gear wall clearances range from approximately 5 to 10 mil. A tighter tolerance will influence the amount of shear that the pump exerts in several ways. First, the pump will decrease the pumping efficiency as the tolerance increases. This action requires the pump rpm to be increased, resulting in a higher *du* and greater shear. Second, the tighter tolerance will decrease the distance from the base of the gear to the wall of the pump cavity (*dy*). The lower *dy* will increase the shear exerted. Many blends also contain undissolved particulate, which can bind gear pumps with too high of tolerances. The balance of these two effects will be determined by the material properties of what is being pumped. If it is a high viscosity fluid, the pumping efficiency will stay high even with higher tolerances, meaning that a pump with looser gears would likely be more desirable. However, for a material with low viscosity, the opposite would be true as pumping efficiencies would drop much more drastically, requiring a higher pump rpm to achieve the same output flow rate.

Gear pump rpm will be driven by the pump displacement per revolution and the previously outlined pumping efficiency. For gears of the same 2D design, the rpm can be altered by changing the length of the gears. The pumping efficiency drops as the gears are lengthened since the contact surfaces are increased; though this change is influenced more by the pump's tolerances.

Predicting optimum equipment setup

Equipment selection will be driven firstly by the requirements of the end product and the amount of investment available. There are many possible vendor choices, but for this example the selected style is the NPC by Northern Pump. This style was chosen because it comes in six different configurations that allow the different design characteristics to be tested separately. An outline of the different styles is below:

	NPC-0.5	NPC-1	NPC-3	NPC-5	NPC-10	NPC-15
Gear O.D. (inch)	0.752	0.752	0.752	1.286	1.286	1.286
Gear O.D. Clearance (inch)	0.00665	0.00665	0.00665	0.00985	0.00985	0.00985
Side Clearance (inch)	0.00375	0.00375	0.00375	0.00575	0.00575	0.00575
Bearing Clearance (inch)	0.002	0.002	0.002	0.002	0.002	0.002
Displacement (gallon/rev)	0.000131	0.000262	0.000785	0.001300	0.002607	0.003915
Gear Length (inch)	0.256	0.512	1.536	0.870	1.745	2.620

Shear rate for each setup will be calculated using:

Gear length actually does not become part of the calculation because it would have both the gear circumference and clearance multiplied by it, so the terms cancel out. The rpm is driven by the coating width, thickness, and line speed, as well as the pump slip. The pump slip is a function of the differential pressure across the pump, the viscosity of the fluid, and the clearances around the pump. The slip can be estimated using the equation below provided by Northern Pumps:

$$Shear\,Rate \approx \frac{\pi * Gear\ Diameter * RPM}{Gear\ Clearance}$$

The pressure differential being part of the slip calculation shows the possibility of setting up the system so as to have no pump slip; this is accomplished by matching the inlet and outlet pressures , resulting in only using the gear pump as a metering device. While this is possible, pressurizing the inlet fluid can be difficult and is often outside of the safety limitations of the intermediate holding tank. This process also requires careful regulation. For these reasons slip will usually need to be accounted for and documented.

Along with the shear rate calculation, the pump consistency needs to be estimated to make the best possible approximation of how the pump will perform. To achieve a steady pump speed, an encoder is often installed on the motor controlling the pump. This device will provide constant feedback on the pumps actual speed to the variable frequency drive controlling the pump. Though even with an encoder, the pump rpm can be expected to vary by ± 0.2 rpm. At high speeds this amount is negligible, but at lesser speeds where the shear rate is lower this variation can result in product which does not meet the required specifications. Using helical or herringbone gears, instead of spur gears, can decrease surging. The cost to benefit would have to be evaluated for each product, but for this demonstration a pump variation of 0.5% will be the maximum acceptable.

Demonstration of Principle

Example 1 will be for a relatively low viscosity for pressure sensitive adhesive pumped at a slow speed, narrow coated width, and average thickness. This setup would be typical of a pilot line or a large product development line.

Coating Parameters

Dry Coat Weight	70 gsm
Solids content	58%
Fluid's Specific Gravity	0.9
Initial Viscosity	2,500 cps
Coated Width	210 mm
Line Speed	0.9 mpm
Discharge Pressure	20 psi
Inlet Pressure	4 psi

	NPC-0.5	NPC-1	NPC-3	NPC-5	NPC-10	NPC-15
RPM	56.1	28.5	9.9	6.9	3.6	2.5
Slip (gal/min)	0.000643	0.000762	0.001043	0.002315	0.002762	0.003210
Volumetric Efficiency	91.2%	89.8%	86.5%	74.3%	70.8%	67.6%
Pump Variation	0.36%	0.70%	2.03%	2.89%	5.51%	7.90%
Shear Rates	665	338	117	95	50	35

Based on the presumed pump variation requirement, not more than 0.5%, only the NPC-0.5 would be acceptable. If the exhibited shear proves to be damaging to the material than some of the coating parameters, such as the width or line speed or the acceptance criteria, would have to be revisited.

The next example will be for the same product, but at a full commercial scale.

Coating Parameters

Dry Coat Weight	70 gsm
Solids content	58%
Fluid's Specific Gravity	0.9
Initial Viscosity	2,500 cps
Coated Width	570 mm
Line Speed	2 mpm
Discharge Pressure	20 psi
Inlet Pressure	4 psi

	NPC-0.5	NPC-1	NPC-3	NPC-5	NPC-10	NPC-15
RPM	313.9	157.4	52.9	32.9	16.6	11.1
Slip (gal/min)	0.000677	0.000801	0.001097	0.002334	0.002784	0.003236
Volumetric Efficiency	98.4%	98.1%	97.4%	94.5%	93.6%	92.6%
Pump Variation	0.06%	0.13%	0.38%	0.61%	1.21%	1.79%
Shear Rates	3,721	1,866	627	451	227	153

For the larger scale the NPC-0.5 can be assumed to produce material at a consistent rate, but the shear rate is six times what it was on the smaller line. Here the NPC-3 would be the likely choice. It is note worthy that the shear rates generated at the small and large scale with these pump choices are very similar. This would likely increase the probability of success with scaling up the process since the commercial die could be designed to the same requirements as the development one.

Example 3 will be for a higher viscosity pumped at a faster speed and on a line that can accommodate a wider coated width. The wider coated width also results in a higher discharge pressure necessary to spread the material.

Coating Parameters

Dry Coat Weight	70 gsm
Solids content	58%
Fluid's Specific Gravity	0.9
Initial Viscosity	2,500 cps
Coated Width	570 mm
Line Speed	2 mpm
Discharge Pressure	20 psi
Inlet Pressure	4 psi

	NPC-0.5	NPC-1	NPC-3	NPC-5	NPC-10	NPC-15
RPM	313.9	157.4	52.9	32.9	16.6	11.1
Slip (gal/min)	0.000677	0.000801	0.001097	0.002334	0.002784	0.003236
Volumetric Efficiency	98.4%	98.1%	97.4%	94.5%	93.6%	92.6%
Pump Variation	0.06%	0.13%	0.38%	0.61%	1.21%	1.79%
Shear Rates	3,721	1,866	627	451	227	153

In this case, the smaller pumps would not have been able to produce the required speed because they have a maximum rpm of 360. The NPC-10 would likely be the optimal choice as it induces the smallest amount of shear while still meeting the pump variation requirement.

The final example will be for a very low viscosity adhesive that is being coated at a fast rate.

Coating Parameters

Dry Coat Weight	70 gsm
Solids content	58%
Fluid's Specific Gravity	0.9
Initial Viscosity	2,500 cps
Coated Width	570 mm
Line Speed	2 mpm
Discharge Pressure	20 psi
Inlet Pressure	4 psi

	NPC-0.5	NPC-1	NPC-3	NPC-5	NPC-10	NPC-15
RPM	313.9	157.4	52.9	32.9	16.6	11.1
Slip (gal/min)	0.000677	0.000801	0.001097	0.002334	0.002784	0.003236
Volumetric Efficiency	98.4%	98.1%	97.4%	94.5%	93.6%	92.6%
Pump Variation	0.06%	0.13%	0.38%	0.61%	1.21%	1.79%
Shear Rates	3,721	1,866	627	451	227	153

The shear rates stay relatively consistent with the product in example 3 which is processed at similar conditions, but the pump efficiency drops considerably.

These exercises confirm that gears with a larger displacement running at a slower rpm are the best way to reduce the shear that is exerted on the material; however, the product's stability decreases with this change. It also shows that the volumetric efficiency of the pump is virtually unchanged for the product at 14,000 cps, but drops a noticeable amount for the 2,500 cps product and get so low for the 250 cps product that it would likely ruin the pumping stability. The affect of slip on the shear rate is most apparent in example 4 between the NPC-3 and NPC-5. For the other examples, the difference in shear between these two pumps was much more significant than it is for this example.

Conclusion

There are three primary design criteria available when selecting a gear pump, displacement (either through larger gear diameter or length), clearance, and gear style. While clearance does affect the shear rate through the slip calculation, it will primarily be selected based on the solid content in the pumped fluid. Gear style does not have a large affect on the shear rate, but it does have a major impact on the stability of the pump. Herringbone gears provide a significantly more stable flow than spur or helical gears, potentially allowing for a larger acceptable pump variation. If a larger pump variation is allowable then gears with a larger displacement could be used. This would accommodate a lower pump rpm, which would provide a lower shear rate.

Gear length and diameter also influence how high the shear rate through the pump is. Since the length of the gear does not manipulate the shear rate, a long gear with a small diameter would have a lower shear rate than a gear with an equal length and diameter—even if the gears have the same displacement rate. To illustrate this point the NPC-3 length was extended until its displacement was equal to the NPC-5. Here are the dimensions:

	NPC-3 Ext	NPC-5
Gear O.D. (inch)	0.752	1.286
Gear O.D. Clearance (inch)	0.00665	0.00985
Side Clearance (inch)	0.00375	0.00575
Bearing Clearance (inch)	0.002	0.002
Displacement (gallon/rev)	0.001300	0.001300
Gear Length (inch)	2.56	0.870

Traditionally a gear with a diameter of 0.752″ and a length of 2.56″ would be impractical in a pump, but it can be used to illustrate the point about longer gears. Using the same process conditions the following shear rates were calculated.

The ratio between the two shear rates will vary, but the NPC-3 Ext would produce about 85% of the shear that the NPC-5 would. Certainly a possible improvement, but likely not practical in the actual operation of the pump since the inlet would have to accommodate providing fluid to the outside portions of the 2.56″ width gears, but would only have a height of approximately 0.5″.

	NPC-3 Ext	NPC-5
RPM	94.0	95.2
Slip (gal/min)	0.00258724	0.004196623
Volumetric Efficiency	97.9%	96.6%
Pump Variation	0.21%	0.21%
Shear Rates	1,114	1,306

The conclusion for how to pick the optimal gear pump for a process ends up being dependent of the process parameters and the acceptance criteria for the final product. The largest factor is the speed of the pump. If shear is the primary concern, run with the largest pump displacement possible that still meeting the consistency needs of the end product. For low viscosity fluids, attempt to match the inlet and outlet pressures within reason to minimize the influence that slip can have.

As the gears in the pump increase in size, the slip and pump inconsistency will increase, so this will have to be balanced with the decrease in shear. An understanding of how the material being processed reacts to shear will be crucial in determining how these will be balanced. Some materials simply decrease in viscosity, which can usually be dealt with downstream. Others will separate into their base components. If this is happening, shear will have to be carefully monitored, possibly to the point where a different coating technique such as knife over roll would be better suited for the material.

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