Basic Screw Geometry

“Things Your Screw Designer Never Told You About Screws!!”

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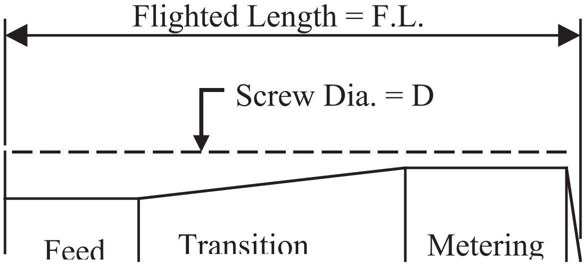
Introduction

In the plastics industry today and as has been since the start of plastic extrusion, the end user has depended on the Original Equipment Manufacturer (OEM) and/or screw manufacturer to supply them with the proper screw design for their material and process. Most processors have learned over the years a few critical points pertaining to screw design, but never totally understanding the reason why their suppliers have recommended certain aspects to the screws that they have purchased. Hopefully, this paper will explain some of the basic knowledge needed in order for an end-user to make the proper decisions when using or purchasing a new single screw for a smooth bore application.

Nomenclature

Before we get started we need to define some of the basic components of the single flighted screw. These terms are shown in figure 1:



$$L/D = \frac{\text{Flighted Length (F.L.)}}{\text{Screw Diameter (D)}}$$

Figure 1

L/D Ratio

Some OEMs define their particular L/D ratio (or Length per Diameter ratio) differently from one to another. Some manufacturers define it as being the “enclosed” portion of the screw, or they measure the flighted length from the front side of the feed port to the end of the screw. Some measure the flighted length from the center of the feed port opening, while others measure the actual “effective” length or the entire flighted length when determining the L/D ratio. How they define the L/D ratio can be one issue, but the actual amount that the screw manufacturer has to machine is determined as shown in Figure 1. An example how to determine the L/D of a 2.5” screw would be as follows:

Screw Dia. = 2.5”
Flighted length = 63” Therefore,

L/D = 63” / 2.5” = 25.2 L/D

An OEM would classify this machine as a 24:1 L/D extruder, but the screw manufacturer will typically cost it as a 25.2 L/D because that is the actual amount of machine work which the screw manufacturer must do to complete the product.

Typical extruder L/Ds are 24:1 and 30 or 32:1, but there are special applications where extruders are built as short as 10:1 L/D and as long as 50:1 L/D. The proper L/D is determined by the process and application that is being satisfied.

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When the paper was prepared, Mr. Womer was affiliated with New Castle Industries Inc., acquired by Xaloy in 2003.

Feed Section - Depths

Referring to Figure 1, the feed section of the screw is the first element of the screw where the polymer is introduced to the screw. Typically, on smooth bore extruders, this is the deepest portion of the screw. On smaller screws, 2.5” diameters and smaller, special attention needs to be given to this section of the screw in order to reduce the risk of twisting the screw in half due to over torquing of the screw. Sometimes it is advisable to have small screws manufactured out of 17-4 Ph stainless steel or other high yield material in order to reduce the risk of this type of failure.

As a rule of thumb, the feed section of a screw should not be deeper than:

$$Fd_{\max} = .2(ScrewDiameter) \qquad \text{Eq. 1}$$

This is for screws that are 4.5” diameter and smaller. For example, a 2.5” screw would be:

$$Fd_{max} = .2*(2.5'') = .500'' \qquad \text{Eq. 2}$$

If the screw design should require the screw to have a feed depth of more that this Fd_{max} value, then proper torque calculations should be done. Then, if the yield strength of the screw is going to exceed more than a 2:1 safety factor of the original steel for which the screw is being manufactured, then a higher yield strength steel needs to be chosen.

Feed Section – Lengths

The main function of the feed section of a screw is to perform the function of solids conveying. The basic theory of solids conveying is “the plastic must stick to the barrel and slip on the screw in order for the polymer to be moved forward”. For this function to happen the coefficient of friction (COF) of the polymer must be greater at the barrel wall than it is at the root of the screw. Therefore, some polymers inherently have better COFs then others. So in the case of these resins long feed section lengths are not needed. Typically, for most resins a feed section length of four to five diameters past the feed throat opening will allow enough pressure to be developed to convey the material forward.

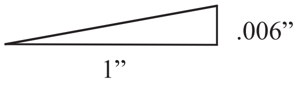
In the case of poor feeding resins or materials with low COF, a feed section length of eight to ten diameters may be used. Typically, one of the reasons for longer feed sections is to allow for more heat to be introduced to the solid form of the resin, causing it to stick to the barrel, which then will help develop the pressures needed for good solids conveying. It should also be mentioned at this point that in the case of poor feeding materials, it is also beneficial to use internal screw cooling in order to keep the root of the screw cool and to improve the COF between the resin and the steel at the screw root.

It should be mentioned here, that in order to find a means to improve solids conveying on material which have poor COF, groove feed technology was developed in Europe during the early 1960s. This technology has yet to be totally accepted in the United States, but it is slowly becoming an important processing technique.

Transition Section

The transition or compression section of a conventional screw is where most of the melting of the polymer takes place. This is the portion of the screw that “transcends” from the feed depth to the metering depth and where work is done on the resin causing melting to occur. In this section of the screw, the root of the screw gradually becomes shallower forcing the material towards the barrel wall where the melting takes place.

Example 1:



$$F = .006'' / 1'' = .006 \text{ in./in}$$

The most important factor that must be acknowledged in the designing of the transition section is that the slope of the transition should match the melting rate of the material as closely as possible. In order to maximize the throughput rate of the extruder and reduce the amount of wear that will occur to the screw and barrel components, this computation is very critical.

Later in this paper compression ratio will be discussed and will be tied into this section.

Typically, for a 24:1 L/D screw the transition section will be between five and ten diameters long, depending on the type of polymer being processed.

Metering Section

The metering or pumping section of the screw is where the melting of the polymer is completed and pumping to overcome the headpressure takes place. Simple calculations such as:

$$Rate = 2.3 * D^2 * h_m * SG * N \qquad \text{Eq. 3}$$

Rate = throughput (lb/hr)
D = Screw Diameter (inches)
h_m = Metering Depth (inches)
SG = Specific Gravity of Polymer (gm/cc)
N = Screw Speed (RPM)

…can be used to estimate a screw’s throughput rate or by back-calculating a metering depth could be determined for an approximate amount of throughput desired. This is true primarily for low headpressure applications only.

Compression Ratio

Compression Ratio is probably the most misused, misunderstood, but widely used term of the screw terminology. Most people understand the definition of compression ratio as shown in Figure 2:

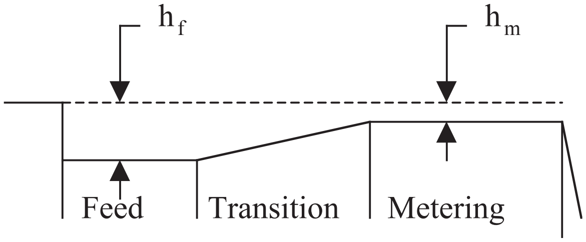


Figure 2

Therefore:

$$\text{Compression Ratio} = \frac{h_f}{h_m} \qquad \text{Eq. 4}$$

An example of this would be if a 2.5” screw had a feed depth (h_f) of .300” and a metering depth (h_m) of .100” then the compression ratio would be defined as being:

Example 2:

$$CR = .300'' / .100'' = 3{:}1 \qquad \text{Eq. 5}$$

But, there also could be a 2.5” screw with a feed depth (h_f) of .450” and a metering depth of (h_m) = .150” and it would have a compression ratio of:

Example 3:

$$CR = .450'' / .150'' = 3{:}1 \qquad \text{Eq. 6}$$

Both screws have a compression ratio of 3:1 but they are totally different. The first one will have a much higher shear rate, plus it will also only have approximately 2/3 the throughput rate. The second screw will have a much lower shear rate and be able to process more shear sensitive materials and it will have a higher throughput rate.

Plus, the slope of the transition hasn't even been considered in this case. Two screws could have different compression ratios; but if the length of the transition section was different, they could still have the same melting rates.

When describing the geometry of a screw, make sure that all of the details are examined.

Accurate pumping capacities can be calculated by using more complex formulae, but a more thorough understanding of polymer flow must be a major factor to the screw designer.

Compression Ratio for Barrier Screws

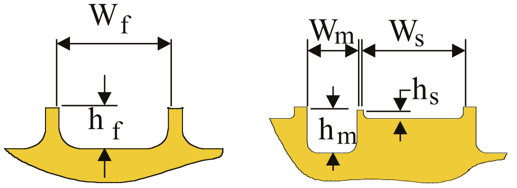
As just mentioned, most individuals understand "compression ratio" as being the feed depth divided by the metering depth. This is what is normally referred to as "Depth Compression Ratio", but there is a more accurate method to calculate true compression ratio and that is referenced to as "Volumetric Compression Ratio", this is shown in the following formula:

$$VCR = \frac{\left[h_f (L_f - n_f e_f)\right] * (D - h_f)}{\left[h_m (L_m - n_m e_m)\right] * (D - h_m)} \qquad \text{Eq. 7}$$

VCR = Volumetric Compression Ratio
h_f = Feed Depth
h_m = Metering Depth
L_f = Lead in the Feed Section
L_m = Lead in the Metering Section
n_f = Number of flights in the Feed section
n_m = Number of flights in the Mtg. Section
e_f = Width of the main flight in the Feed
e_m = Width of the main flight in the Mtg.
D = Outside Diameter of the screw

This formula is more complex, but it gives more accurate value for the true compression ratio. This formula determines the amount of cross sectional area there is in the feed section and compares it with the volume of the screw's cross-section in the metering section of the screw.

As is true with standard metering screws, it is also important to evaluate the true compression ratio of a barrier type screw. In order to determine the true compression ratio of a barrier type screw it is necessary to compare the cross-sectional area of the feed with the combined cross-sectional area at the end of the barrier section. This is shown in the Figure 3:



Cross-Section of Feed

Cross-Section @ End of Barrier

Figure 3

The Volumetric Compression Ratio of a barrier screw can be shown mathematically as follows:

$$VCR = \frac{(W_f * h_f)}{(W_m * h_m) + (W_s * h_s)} \qquad \text{Eq. 8}$$

VCR = Volumetric Compression Ratio
W_f = Channel Width in Feed Section
h_f = Channel Depth in Feed Section
W_m = Width of Melt Channel at the end of the Barrier Section.
h_f = Depth of the Melt Channel at the end of the Barrier Section.
W_s = Width of Solid Channel at the end of the Barrier Section.

h_s = Depth of the Solid Channel at the end of the Barrier Section.

This method of comparing one section to another will give a more accurate comparison.

It should be noted here that depending on who the screw designer might be, the throughput rate of the screw may be governed by the capacity of the barrier section or the pumping capability of the metering section. It totally depends on what the designer has in mind for the screw's performance.

Two Stage Screws

Two stage screws are basically two single screws placed end to end and performing two different functions. Figure 5, shows the typical nomenclature used on two stage screws:

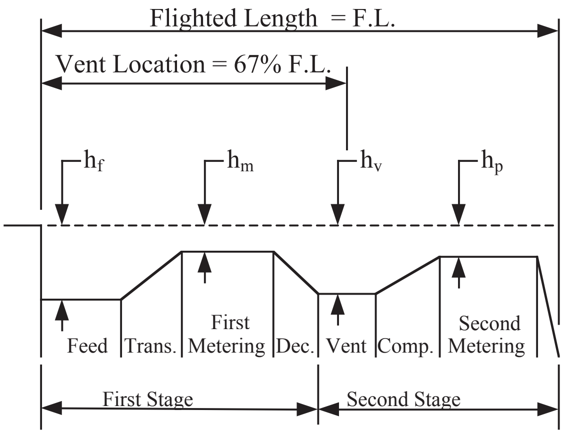


Figure 4

The primary reason extruders are vented is for devolitization of moisture or gases. Today, most two-stage extruders that are designed for devolitization are typically 30:1 or 32:1 L/D minimum. In the rubber industry, injection molding, and early in the extrusion industry, shorter L/D screws are and were used; but today's extrusion technology requires longer screws. Normally, the throughput rate of a vented extruder is two-thirds of a similar L/D non-vented extruder because on a vented extruder, a 100% melt has to be developed by the time the resin reaches the vented section of the screw. If the resin is not completely melted at the vent section of the two-stage screw, it is possible that the moisture or gases may be trapped inside an unmelted pellet and therefore are not able to escape out though the vent port of the barrel.

There are cases where a large amount of devolitization needs to be accomplished and it will require a second vent to be installed in the barrel wall. Therefore a triple-stage screw will need to be used. These types of extruders are usually 36:1 L/D or longer.

As mentioned earlier, the two-stage screw is simply two single stage screws in tandem, the first stage compression ratio is determine in the same manner as a single stage screw. It should be mentioned that in some cases barrier sections could be used in the first stage of a two-stage screw.

The primary difference in designing the first stage of the two-stage screw is that the metering section does not need to be designed to overcome any type of back-pressure. Since there is no die or downstream restriction, the first metering only has to complete the melting process and pump the resin into zero or negative pressure vent section.

In some vented applications, when highly viscous resins are being processed, it is necessary to install a vacuum pump to the vent port of the barrel to assist in the devolitization of the resin.

Finally, the primary purpose of the second stage is to allow an area for devolization to take place and then to pump the resin through the die.

In the past this has been referred to as the "pump ratio" and typically a multiplier of 1.5:1 to 1.6:1 was used.

Example 4:

$$PumpRatio = \frac{h_p}{h_m} = 1.6:1 \qquad \text{Eq. } 9$$

This method will typically work for applications where very viscous resins are being processed.

A better method of designing the second stage metering depth is to calculate the net flow of the second stage versus the net flow of the first stage using the "Drag Flow-Pressure Flow" equations for best results. The second stage metering section or pumping section must be designed so that it can over pump the first stage metering by a minimum of 25% in order to keep the vent section from flooding and cause resin to pumped out the vent port.

The second method will be very successful for keeping the vent port from flooding if good resin rheology is used in the Drag Flow-Pressure Flow equation.

Finally, to determine the depth of the vent section, normally a simple 2:1 to 2.5:1 ratio to the second metering will be sufficient to keep the resin from back flowing out of the vent port in the barrel.

Conclusion

The purpose of this paper was nothing revolutionary, but was meant to explain some of the thought processes that a screw designer uses to determine how he is going to approach a design of a screw.

As always, it is very important for the customer to furnish the screw designer with good equipment information, resin data or rheology, and process data from the existing screw.

Finally, the main purpose of this presentation was to help the audience better understand the mechanisms of each of the screw section functions. With a better understanding of each of the screws section functions, the process engineer can more easily troubleshoot a process or improve an existing screw design.

References

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