CO-ROTATING FULLY INTERMESHING TWIN-SCREW COMPOUNDING: ADVANCEMENTS FOR IMPROVED PERFORMANCE AND PRODUCTIVITY

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Abstract

The co-rotating fully intermeshing twin-screw extruder is the primary production unit for compounding of polymer based materials. It also has had a long term presence in processing material in the chemical and food industry and more recently in pharmaceuticals. While this equipment celebrated its 50^{th} anniversary several years ago and might be considered a "mature" technology, it has not experienced a decline in new developments as might be expected, but rather a significant number of advancements continue to evolve. This paper will highlight several significant developments of the past 10 to 15 years. These are the implementation of high torque (power) designs, the use of increased rpm in conjunction with high torque for improved operating flexibility and productivity, and finally a technology breakthrough for feeding difficult to handle low bulk density materials.

Introduction

While several initial concepts for co-rotating twin-screw devices were patented in the early 1900's by Wuensche [1] and Easton [2, 3], the co-rotating design used as the basis for essentially all twin-screw compounding systems marketed today is based on the self-wiping element geometry know as the Erdmenger profile.

The initial design and development of this self-wiping element profile is described in German Patent 862,668 granted to W. Meskat and R. Erdmenger in 1952 with a priority date of 1944 [No US patent filed]. The objective of the design at that time was for mixing high viscosity liquids already in the fluid state, such as post-polymerization reaction products.

The above noted patent along with the numerous related patents which followed (all issued to Erdmenger or one of his colleagues at Bayer) defined the base design parameters for the eventual development and commercialization in the late 1950's by Werner and Pfleiderer of the ZSK twin-screw extruder, as well as the many copies introduced during the intervening 50 plus years. The key feature of the design is the self-wiping characteristic of one screw with respect to the other. This eliminates stagnation and eventual degradation of material as it is transported along the length of the compounding extruder.

As mentioned, the overall importance of the invention of this self-wiping screw geometry is that it is the basic patent related to the co-rotating twin-screw compounding system predominantly used today in the plastics, food and chemical industry. (For additional information related to the early development advances please see the ANTEC 2009 paper by Andersen et al. [4] and White's 1991 book on Twin Screw Extrusion [5].)

Since the development of the basic principles for co-rotating twin-screw extruder there have been a significant number of incremental improvements to the technology. These include numerous new screw element geometries as noted by Bierdel [6], the two-lobe element profile for increased internal free volume (the initial profile described in the first Erdmenger patent was based on a low free volume 3 lobe geometry), new screw shaft geometries for improved power transmission, and new process applications for the system [7]. However one of the most significant steps forward was achieved with the identification of the fundamentals of high rpm / high torque compounding technology [8]. This is the basis for US Patent 6,042,260 granted to Heidemeyer et al. on March 28, 2000.

High torque, high rpm co-rotating twin-screw compounding technology

Since the introduction of the first high torque, high available rpm ZSK MegaCompounder (Mc) in the mid 90's, new advances in power transmission technology (gearbox as well as screw shaft design and material of construction) have permitted an additional 50% increase in torque capacity from the Mc specific torque or power volume factor of 11.3 Nm/cm³ to the Mc^{18} of 18 Nm/cm³. (Power volume factor: Md/a^3 [Md = torque per shaft (Nm), a = centerline distance (cm)]) .

The impact of this advancement in power transmission capacity is a resultant significant increase in productivity (production rates), efficiency and system flexibility for compounders.

The key to the success of this technology is the increase in the power (torque) transmission capacity in combination with increased screw rpm. A system that simply runs at higher rpm will at some juncture impart enough additional energy to the material being processed to cause degradation.

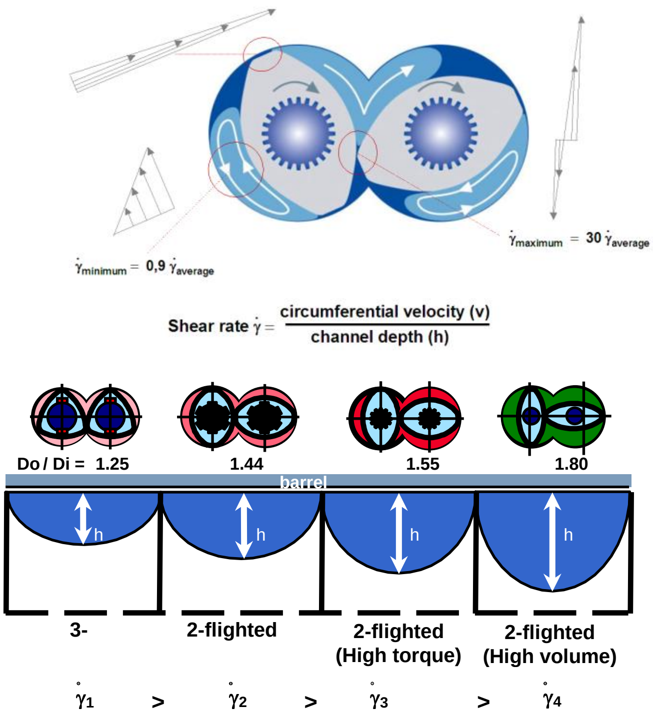

Figure 1: Shear scenario in a twin screw

Figure 2 illustrates this latter point. It shows that the average shear rate (energy input) increases linearly with screw rpm for any screw Do/Di (outer diameter to inner diameter ratio). Therefore the resultant material discharge temperature will increase proportionately.

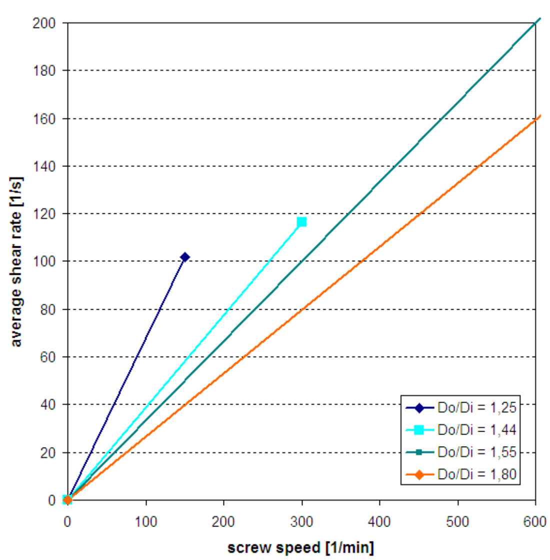

Figure 2: Impact of Do/Di & rpm on Shear Rate

Since the twin-screw compounder runs primarily in a starve feed mode, the higher power transmission capability provides the compounding unit the ability to process at a higher fill factor and therefore rate per rpm (i.e. Figure 3 comparison of lower fill degree left graphic vs. the higher fill degree right graphic). In turn, this fill factor increase has a positive impact on lowering material temperature.

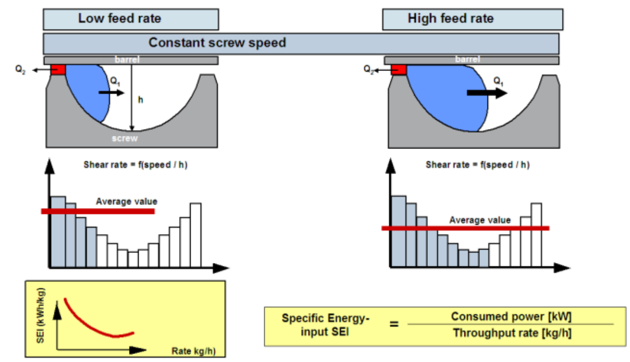

Figure 3: Impact of degree of fill on average shear rate

As shown in the screw channel for the right portion of Figure 3, the additional material is added to the screw profile in the deeper (lower shear rate) middle section of the element geometry profile. This in turn reduces the average shear rate for all the material and consequently the total energy input (i.e. resultant discharge temperature) per kg of product produced. Therefore the processor has the flexibility to run the extruder at higher rpm without exceeding material temperature limits.

As an example, Figure 4 shows a comparison of 2 generations of twin-screw compounding units based on a ZSK 45 geometry (D_o/D_i = 1.55) processing 30% glass filled nylon 6, the ZSK McPLUS (Md/a³ = 13.6) and the ZSK Mc^{18} (Md/a³ = 18).

In the top portion of Figure 4, the throughput rate is shown as a function of the screw speed for the 2 generations. The data come from a trial where the PA-compound is processed on a ZSK 45 under McPLUS conditions (torque = 715 Nm/shaft, Md/a³ = 13.6) and Mc^{18} conditions (torque = 930 Nm/shaft, Md/a³ = 18). The samples were taken in each case at 85 % torque. As would be expected, the unit with the greater power volume factor (ZSK Mc^{18}) has the greatest throughput rate, in this particular example the rate increase is about 50% while the Md/a³ increase is just 30 %.

Higher torque, however, does not necessarily imply higher throughput rates. Focusing on production, on the McPLUS a given throughput rate of 650 kg/h must be produced at a screw speed of 1089 rpm. If the Mc^{18} with the higher power volume factor is chosen, the same throughput rate can be achieved at 672 rpm. As a consequence also the average shear rate and hence the specific energy input SEI will drop, as shown in the lower portion of the figure.

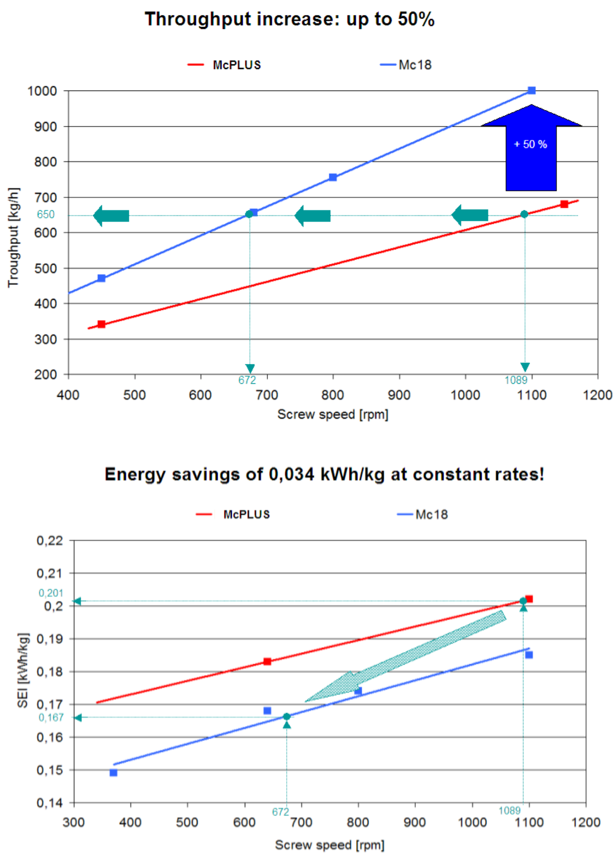

Figure 4: Comparison of rate and SEI for 30% glass filled PA6 vs. rpm for two generations of extruders based on the ZSK 45 geometry and 85 % torque level.

By combining these two results (higher rate at lower SEI), this data shows that there is a double economic advantage for using the highest power volume factor equipment available.

First, because of the lower SEI (Specific Energy Input), the higher Md/a^3 unit can produce an increased throughput rate which is disproportionately greater than the percent increase in the power volume factor for one machine generation to the other.

A general guide for rate increase is:

$$\text{New Rate} = \text{Old Rate} * \frac{Md/a^3{}_{\text{High Power}}}{Md/a^3{}_{\text{Low Power}}} * \frac{SEI_{\text{Low Power}}}{SEI_{\text{High Power}}}$$

Second, there is an absolute energy saving per kg of product produced. In our specific case at 650 kg/h the SEI dropped from 0.201 kWh/kg to 0.167 kWh/kg which equals 17 % energy cost savings.

An additional point needs to be stressed about high torque high rpm compounding extruders. These machines do not have to be run, or even designed to run, at maximum rpm. As shown in Figure 4, there are rate increases and energy savings advantage at any rpm.

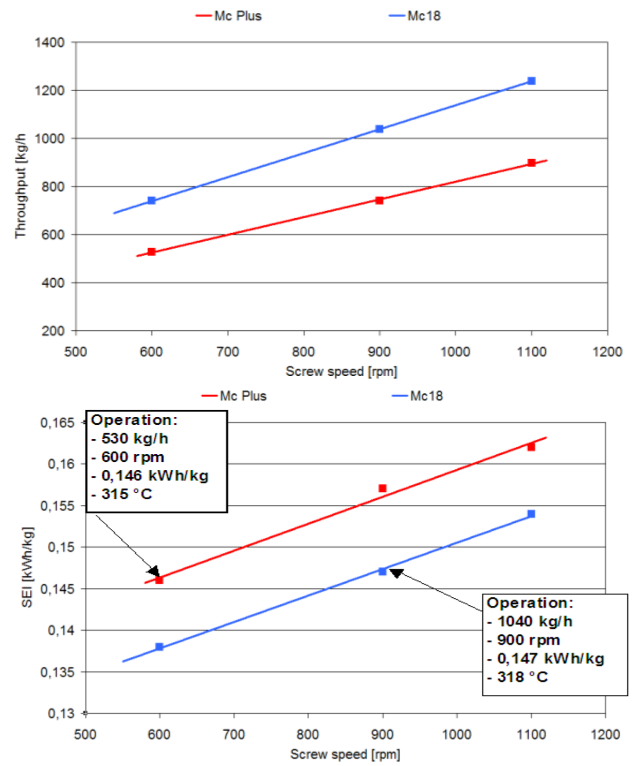

Figure 5: Comparison of rate and SEI for 30% glass filled PBT vs. rpm for two generations of extruders based on the ZSK 45 geometry and 85 % torque level.

However, there is another power/rpm synergy that permits a second disproportionate increase in rate and therefore production economics. Figure 5 illustrates the really significant impact of combining high torque with high rpm.

If the original temperature of 315 °C is satisfactory for the production of 530 kg/h on a ZSK 45 McPLUS, then the rpm can be increased to 900 with an associated rate of 1040 kg/h and a material discharge temperature of 318 °C, practically the same as the lower torque operating system. This is a rate increase of more than 95 % from the original 530 kg/h.

The productivity and economic impact of increasing throughput by practically 100% is significant. However, there is another potential option for the company looking at installing a new line. If you do not need to produce 1040 kg/hr, but only the original lower rate of 530 kg/hr, then you may be able to purchase a smaller diameter extruder. As example, the new ZSK 45 Mc^{18}, has more than 10% greater kW vs. rpm than the ZSK 50 Mc and has only slightly lower kW than the ZSK 50McPLUS, see also Figure 6.

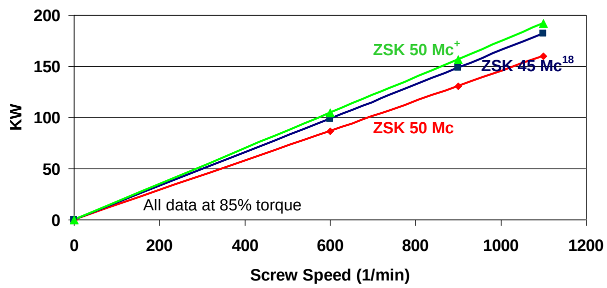

Figure 6: Comparison of available power for ZSK 45 Mc^{18} vs. previous generations of the larger diameter ZSK 50 compounding extruder.

However, as shown in Figure 7, it can actually produce an equivalent or even greater output than the larger diameter unit.

As shown in Figure 4, the ZSK 45 Mc^{18} can produce approximately 600 kg/hr of 30% glass filled nylon 6 at 600 rpm, and 970 kg/hr at 1100 rpm. Making the assumption that the SEI obtained when running the ZSK 45 at Mc Plus conditions (0.18 kWh/kg at 600 rpm and 0.202 kWh/kg at 1100 rpm) translates to the larger ZSK 50 Mc Plus, then the ZSK 50 Mc Plus would produce approximately 580 kg/hr. at 600 rpm, roughly the equivalent of the ZSK 45 Mc^{18}. At 1100 rpm, the ZSK 50 Mc Plus would produce approximately 950 kg/hr., again, the same or slightly less than the ZSK 45 Mc^{18} (Figure 7).

Feed Enhancement Technology (FET)

High torque extrusion technology is only an economically viable manufacturing process when the process takes advantage of all the available power. However, many compounds produced today contain high levels of low bulk density material, such as sub-micron, non compacted talc. These materials are difficult to feed into the extruder because of the significant volume of air which must be removed. Additionally as bulk density decreases, the materials tend to fluidize more easily. Fluidization lowers the "effective" bulk density even further and exacerbates feeding issues. Typical unit operations within the compounding process where material is more susceptible to fluidization are: transfer from storage vessel to feeder, from feeder to twin-screw extruder and within the feed zone conveying section of the twin-screw extruder. While there are methods to minimize the potential for fluidization such as dense phase conveying from storage to feeder, minimization of the feeder height above the extruder feed opening, incorporating a vent into the feed hopper, extending the length of the conveying zone in the extruder feed section, the process eventually reaches a feed volume limitation, which more often than not is well below an economically viable production rate.

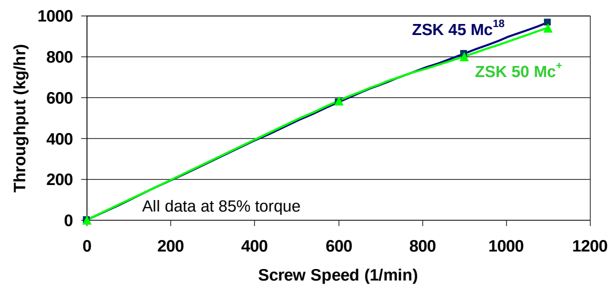

Figure 7: Rate as function of rpm for ZSK 45 Mc^{18} vs. the larger, more powerful ZSK 50 McPLUS (30% glass filled PA6).

The FET technology has been presented [9], [10] in detail. However, as background, a brief description of the principle is presented below.

The objective of FET is to increase the feed intake / feed zone throughput capacity for difficult to feed materials. This is accomplished by improving the conveying efficiency through an increase in the coefficient of friction between the feed and barrel wall i.e. minimize/eliminate wall slip.

The conveying efficiency / coefficient of friction increase is achieved by "adhering" a layer of feedstock material to a portion of the barrel wall through the application of vacuum to a specially designed section of the barrel wall in the feed zone which is porous and permeable to the gas, but not to the feed product. Therefore the pore size of the porous section of the barrel wall relative to the particle size of the powder is very crucial. Additionally the optimum vacuum level applied to the device depends on particle size and shape of the feedstock. If particles were to penetrate the pores, the efficacy of the process would be reduced. However, if powder were to penetrate the pores it could be back flushed out by applying a pressure through the vacuum line(s). While powder infiltrating the porous barrel wall could be problematic, even more critical would be the presence of polymer melt or other fluid. Both of these materials would smear over the porous surface or even penetrate the pores and clog the porous structure.

The working principle of the FET is illustrated in Figure 8. By applying the vacuum through the porous material, air surrounding the polymer or filler is evacuated as it passes the FET barrel section insert. As the air is sucked toward the insert, it entrains and carries the particles toward the insert surface. The air goes through but the material remains behind to coat the surface. This coating, or filter cake, of densified polymer powder has the effect of increasing the coefficient of friction between the wall surface and the bulk of the material. The layer of material adhering to the barrel wall due to the vacuum is continuously renewed by the rotating screws. Additionally, the bulk density of the powder is increased as it passes the insert. These two effects combine to improve the conveying efficiency.

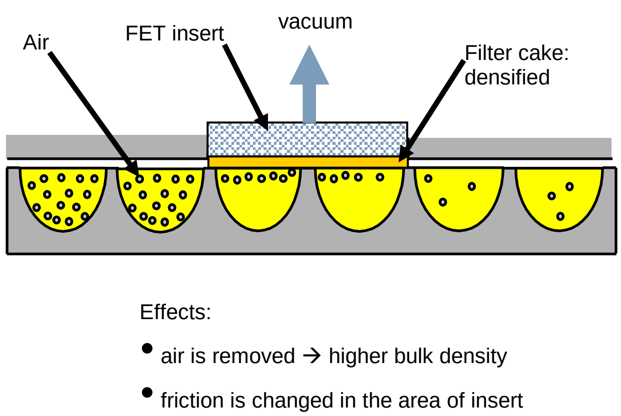

Figure 8: FET operating principle

It has been demonstrated that the overall production rate could be increased by incorporating FET [9]. However, there are other impacts of the technology. Similar to the advantages detailed previously in this paper of using a higher torque capacity compounding unit, increasing the rate of the highly filled polymer compounding line while all else remains the same, results in a lower overall energy consumption per unit of product produced. Lower unit energy translates into lower product temperature, which in turn would mean less potential for material degradation or stabilizer package consumption.

Figure 9, illustrates this point. This data is for 40% talc (Luzenac 1445) filled PP run on the new generation Coperion Mc[18] ZSK 45 mm twin-screw compounding extruder. Without the FET technology, the compounder can not take advantage of the higher torque capacity of the extruder. However, by implementing the FET, the system runs at full torque (~85%), the throughput has been increased more than 50% and the discharge temperature lowered significantly.

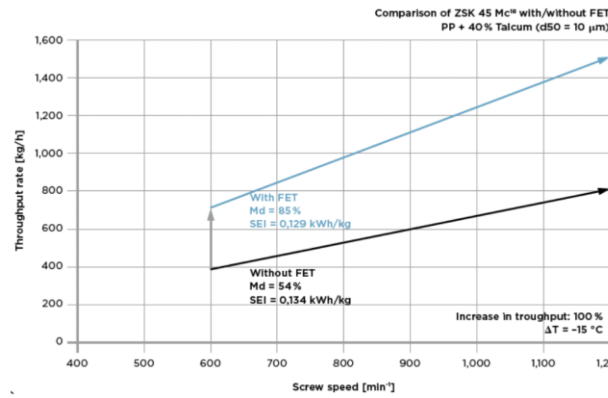

Figure 9: Impact of improved feed intake on rate and material temperature

Summary

Significantly higher throughput rates are achieved when polymers can be processed at high rpm. However, for most systems simply increasing the rpm of an existing extruder will not accomplish the desired results. While rates will be increased, product properties may fall below acceptable levels. On the other hand, by combining high rpm with increased torque capability, polymer processing economics can be significantly improved without deterioration of product properties.

Also, while compounders will continue to have issues with handling low bulk density feed materials; with FET they now have an additional tool to help them utilize the full flexibility of the twin-screw compounding extruder.

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