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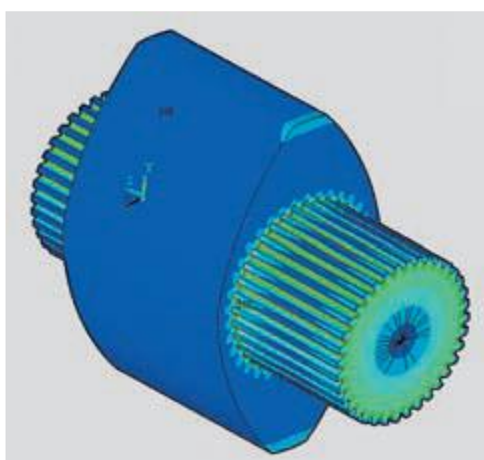
**Understanding boundary conditions in a TSE- what limits operating at higher rates?**

Co-rotating, intermeshing twin screw extruders mix plastics with additives and fillers to impart desired properties into the final product. Dispersive/distributive mixing and venting are strategically performed in the TSE process section. As with most manufacturing operations, the twin screw system it is often the goal to operate at the maximum attainable rate while making a quality product.

By definition, a “boundary condition” the operating parameter that prevents higher throughput rates from being produced. A simple example is screw speed/rpms, so if screw rpms are increased from 400 to 800, attainable kgs/hr might also be doubled, as long as another boundary condition was not encountered. Examples of typical boundary conditions are as follows:

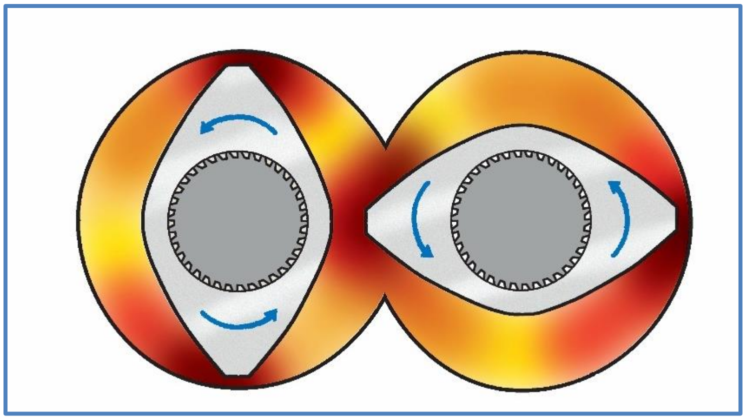
**Torque**: A torque limited process is when there’s not enough power (kW or HP) from the motor to turn the screws and pump the materials through the TSE process section and front end/die system. The screw shaft is what limits torque transmission in a TSE. The screw shaft rating is denoted in Newton-Meters or equivalent (both shafts) and design factor include: cross-section shaft dimension, shaft metallurgy, spline geometry and shaft hardening process. State-of-the art asymmetrical splined shafts transmit power from the motor isolates a tangential force vector into the screws.



TSE element of asymmetrical splined shaft

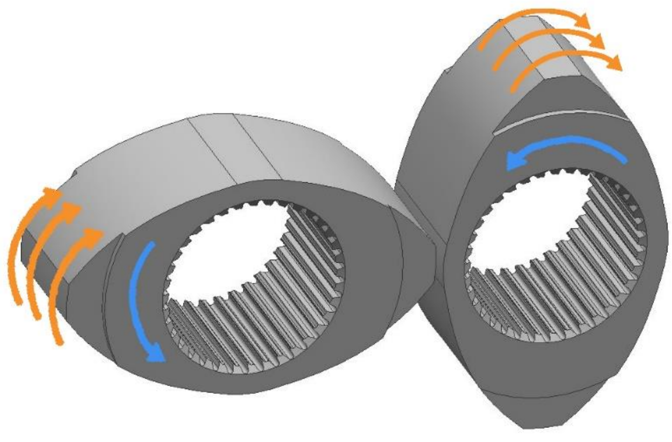
Processing of a fractional melt HDPE or PP formulation might be torque limited, so a TSE with a higher NM torque rating (all else being equal) run at a higher rate than TSE with a lower torque rating. TSE factors to increase the rate for a torque limited process might involve removing kneading elements and increasing the zone temperature setpoints in the melting zone.

**Volume**: A volume limited process is when the free volume in the TSE keeps more material from being metered into the process section. The Outside Screw Diameter divided by the Inside Screw Diameter, referred to as the OD/ID ratio is an indicator of the available free volume in a TSE at a given screw diameter. Since twin screw manufactures do not have standardized screw sizes, the cc's/diameter is the best indicator. As an example, when comparing a 70 mm TSE with 1.55 OD/ID ratio with 240 cc/dia to a ZSE-75 MAXX with 1.66 OD/ID ratio with 300 cc/dia., a 30% throughput rate increase can be expected, all else being equal. Other factors that can increase the attainable rate of a volume limited process are targeted at maintaining feed densities and can include: material handling equipment, minimize the drop distance of the LIW feeder to the TSE (or side stuffer), oversized side stuffer screws with baffled drop chute, vacuum assist processing, barrel temperature profiles, screw and vent design in the TSE process section.

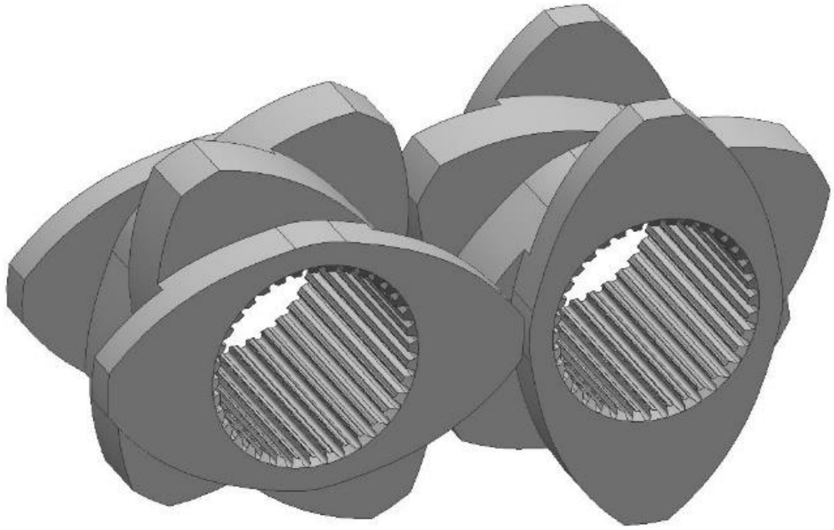


Free volume in ZSE-MAXX process section (in orange)

**Mass Transfer-Dispersive Mixing:** Dispersive mixing requirements for color masterbatch for thin film or fiber processes may set the boundary condition and be the limiting factor to achieve higher rates. Dispersive mixing relies on the strong forces being applied by rotating screws to the polymer matrix. Wider the kneading elements accentuate extensional mixing and planar shear effects that results in dispersive mixing. Narrow kneading elements, by comparison, facilitates high division rate mixing with minimal extensional effects, causing a distributive mixing effect. Kneading elements can be arranged with a forward pitch (less aggressive), neutral, or reverse pitch.



Mixing mechanism in wide kneading/mixing elements for dispersive mixing

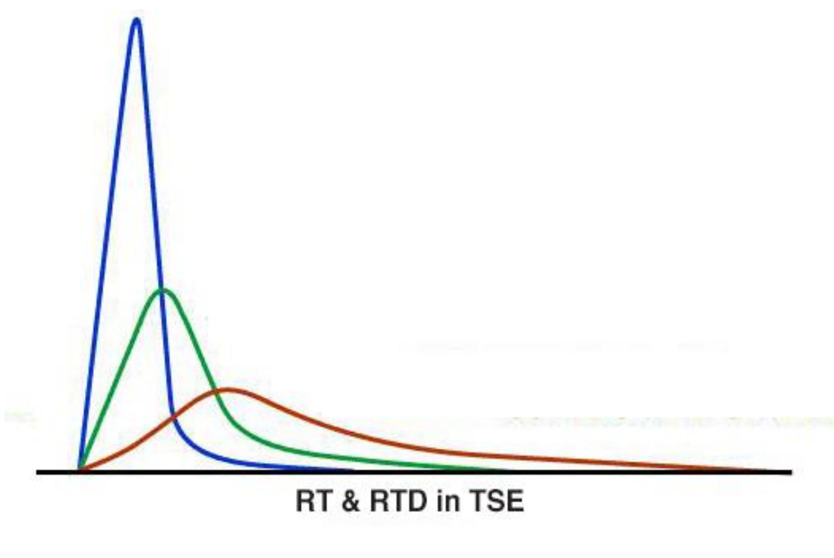


Example kneading blocks: narrower disks = distributive, wider disks = dispersive

The following statements help to understand the mixing effects inherent with any TSE:

- Channel region: The mixing rate in the TSE channel is similar to a single screw extruder (and much lower as compared to the other TSE regions)
- Overflight gap: Between the screw tip and the barrel wall is where the material undergoes significant planar shear effects
- Extensional mixing: Extensional mixing occurs as the material "accelerates, stretches and breaks" in the transition from the channel to the overflight gap
- Apex (upper/lower): Upper and lower apex regions are where the material "feels" the 2nd screw that results in directional flow changes, compression/expansion and axial mixing effects
- Intermesh: A small, finite amount of material passes between the screws and experiences intensive shear forces (and maybe degradation)

Feed rate versus screws rpm determines the Residence Time Distribution, and with the screw design and temperature profile, regulates the mass transfer/mixing properties of the process.



RT & RTD in TSE

Dispersive mixing applications run at comparatively lower throughput rates. As the rates are decreased or increased (at a constant screw rpm) the materials spend more or less time in mixing zones where shear effects and extension flow fields are dominant, and thus the "mixing experience" is impacted.

**Mass Transfer-Devolatilization/removal of gases:** TSEs are ideally suited for DV as the pressure gradient in the TSE process section is easily designed to accommodate zero pressures under the vents to prevent vent flooding. Devolatilization (DV) is a mass transfer limited process where unreacted monomer, solvent, water or other undesirable volatile contaminants are removed from a polymer melt during the TSE process. (up to 25% is viable) Increasing the screws rpm and/or decreasing the rate generally improves DV efficiencies. Vents can be sequenced and atmospheric, or vacuum can be applied to further enhance devolatilization effects. At high screw rpms degradation of the formulation may occur.

Heated vent stacks equipped for vacuum hook-up on ZSE-MAXX process section

Factors that affect devolatilization efficiencies include:

**Residence time under the vent or vents**- longer is better but…
- Oxygen, shear, time and temperature may contribute to degradation and side reactions
- Understand kinetics of degradation

**Surface area of the melt** - higher is better
- Smaller melt pools
- Increase screws rpms
- Decrease rate

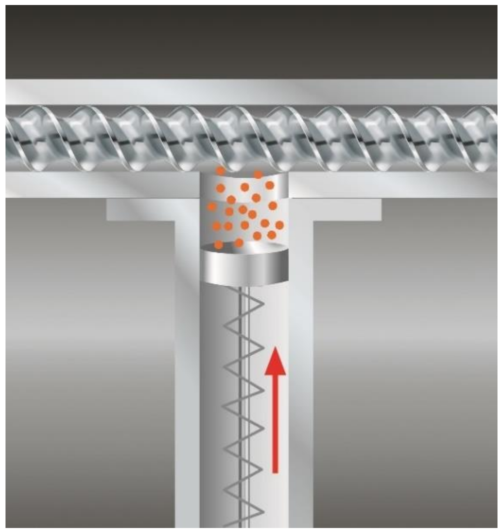
**Surface renewal**- higher is better
- Renewed surfaces come from rolling pools and partially filled screw channels
- Increase screws rpms

**Melt temperature (Tm):** A balance must be made to impart enough shear (and energy) into the process to melt the polymer and facilitate mixing/devolatilization with minimal degradation effects. Without exception, elevated Tm results in degradation of polymer formulations. A myriad of factors directly impact Tm, including but not limited to:

- Screw rpms (lower is often better, lower peak shear)
- Melting zone (extended melt zone and high temperature setpoints might help)
- Mixing elements (minimization is best mixing quality is still achieved)
- Discharge pressure (lower is better due to less overflight mixing from pumping elements)
- OD/ID ratio (higher OD/ID ratio results in lower average shear)
- Barrels design (intensive cooling bores help, 2 inlets/outlets ea. barrel is deemed state-of-the-art)

The residence time in a twin screw process section is typically in the 15 seconds to 1+ minute range. Extended residence times at elevated temperatures may be the primary cause of degradation as compared to the TSE discharge Tm. Front-end systems that include screen changers, gear pumps and dies will dictate lower a lower Tm input requirement from the TSE.

**Scarcity/cost of raw materials during the R&D phase**- In early-stage development, there is often limited amounts of expensive materials available. So the challenge is to extrude a usable sample that can be scaled-up. To accommodate limited batch processing, twin screw extruders are specified with low volume screws (1.2/1 OD/ID ratio with 1 cc dia. Free volume) and specialty feed mechanisms for micro-batch sampling. (i.e. 50 gms total) to allow sampling for scale-up purposes.



Example of a micro-plunger feeder (patent #US 7,954,991 B2) for small batch processing in a TSE

**Upstream and/or downstream limited**- A ZSE-MAXX system is just like a chain, it's only as strong as the weakest link. There are typically multiple feed streams to the twin screw extruder and a variety of auxiliary equipment. A die and downstream system are then attached to the ZSE-MAXX front-end. If any component in the manufacturing "train" does not do the job, the overall kgs/hr of the system will be limited by that piece of equipment.