COUNTER-ROTATING TWIN-SCREW EXTRUDERS

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GENERAL CHARACTERISTICS OF COUNTER-ROTATING TWIN-SCREW EXTRUDERS

Counter-rotating twin-screw extruders are used for a variety of plastic products and processes. It is interesting to note that closely intermeshing, counter-rotating twin-screw extruders can be designed to pump materials in a non-drag flow manner in locked C-shaped chambers. Only this device (and ram extruders) can convey via positive displacement, as compared to the drag flow single-screw extruder and semi-drag flow co-rotating twin-screw extruder.

There are two distinct and separate families of counter-rotating twin-screw extruders:

- High-speed and energy input, with both intermeshing and non-intermeshing designs, melt the polymer early and are designed as mass-transfer devices, with the primary applications being mixing, devolatilization, and reactive extrusion (HSEI).
- Low-speed, late fusion, intermeshing with either parallel or conical screws are designed to avoid energy input and do not melt the materials (typically PVC) until the middle or latter part of the process section (LSLF).

High-speed, energy input (HSEI) counter-rotating twin-screw extruders can be intermeshing or non-intermeshing. The co-rotating intermeshing mode, as previously discussed, dominates the compounding market, having captured over 90% of current installations. Counter-rotating designs are primarily used for specialty applications—such as high-level devolatilization and reactive extrusion.

By contrast, low-speed, late fusion (LSLF) counter-rotating twin-screw extruders are primarily used for PVC and other shear-sensitive formulations that benefit from a design that minimizes energy input combined with pumping uniformity. These devices are often inadequate to perform energy-intensive processing. As implied by the category, the LSLF counter-rotating twin-screw extruder operates with lower rpm than its high-speed cousin.

Just like any extruder, control parameters for the counter-rotating twin-screw extruder include screw speed, feed rate, temperatures along the process section, and vacuum level. Monitor-only parameters include melt pressure, melt temperature, and motor amperage. The motor (AC or DC) inputs energy into the process via interacting twin screws imparting both shear and energy. Higher screw speeds result in more shear for a given screw design. Barrel sections are electrically heated and cooled by liquid or air, depending upon the machine configuration and heat-transfer requirements of the process.

As in co-rotation, the gearbox transmits power from the motor to the screws, reduces the motor speed to the desired screw rpm, maintains the angular timing of the screws, and takes the thrust load from the screw set. The gearbox is usually separated into two distinct parts—the reduction section and the distribution section. The reduction gearbox is a conventional helical gearbox, which reduces the motor input speed (1,800 rpm, for example) to the screw output maximum speed, which may be anywhere from 10 to 500+. In the process of reducing the speed, the torque is multiplied by the same ratio—so all the shafts, gears, and bearings have to be designed to continuously transmit the torque rating of each part of the gear system. The distribution gear section takes a single-shaft input from the reduction gear and transmits it to two (2) parallel output shafts. As a safeguard, a mechanical over torque coupling is utilized that connects the motor shaft to the gearbox input shaft and automatically uncouples/disengages the motor if the torque exceeds a preset level.

The feed system is a critical component in any counter-rotating twin-screw extrusion system. Various delivery mechanisms are used for feeders, including screw-augers, vibratory trays, and belts. Liquid feed streams typically use piston or gear pumps to set the rate to the extruder system, depending upon the viscosity of the liquid, and can utilize a heated or ambient reservoir/piping. Feeders can be either volumetric or loss-in-weight, depending upon the nature of the installation.

For low-speed counter-rotating twin-screw extruders, the feed system can be a flood fed hopper, where the hopper sits over the extruder feed throat, which relies on gravity to move the materials into the machine. In this case, the screw rpm determines the throughput rate. For PVC materials, the formulation is generally pre-mixed in a high-intensity mixer and the hopper is filled. Another option is to take the same PVC pre-mix, but to meter it to the extruder feed throat via starve feeding, making the feed rate independent of the screw rpm. Crammer feeders can be used for highly filled or low bulk density formulations.

The sequence of process operations in a counter-rotating twin-screw extruder is almost identical to the co-rotating design. Flighted screw elements push material forward past barrel ports, through mixers, and out of the extruder to the die. Zoning elements isolate operations within the extruder. Mixing elements can be distributive or dispersive in nature. Screw designs can be made shear intensive or passive, based upon the intended range of applications.

High-speed, Energy Input (HSEI) Counter-Rotation

There are various types of HSEI counter-rotating twin-screw extruders with the commonality being that the machine is primarily designed to input energy into the process. The following is a description of different models that are available.

Traditional intermeshing and parallel design

The traditional counter-rotating intermeshing twin-screw extruder designed for mass transfer operations was embraced in the 1970s for the manufacture of color masterbatch and similar products (Figure 1). Looking into the feed throat, the screws rotate outward to facilitate feeding of the material on both screws. In the screw intermesh region, the flight of one of the screws penetrates the flight depth of the second screw and the velocity of the screws' intermesh is in the same direction. This region is referred to as the calender gap. Screw rotation forces materials up and through the calender gap (Figure 2) to facilitate melting and mixing, as the processed materials experience an extensional shear effect. Essentially, the entire length of the screw can

Figure 1. Traditional counter-rotating intermeshing compounding screw design.

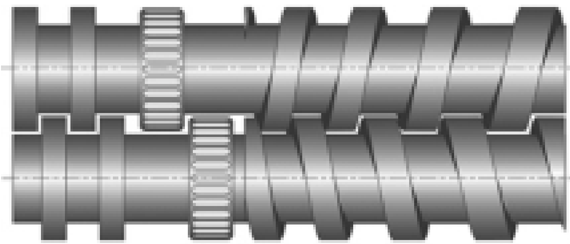

Figure 2. Top view counter-rotating, intermeshing calender gap and gear mixer.

function as a mixing device as materials continually experience the extensional mixing and shear associated with the calender gap. In addition to calender gap mixing, gear mixers can be utilized for distributive mixing, as well as blister rings for planar shear mixing, and/or to provide a seal for vacuum venting. At the discharge end of the screws, the traditional counter-rotating intermeshing can be designed to pump in a C-locked chamber (Figure 3).

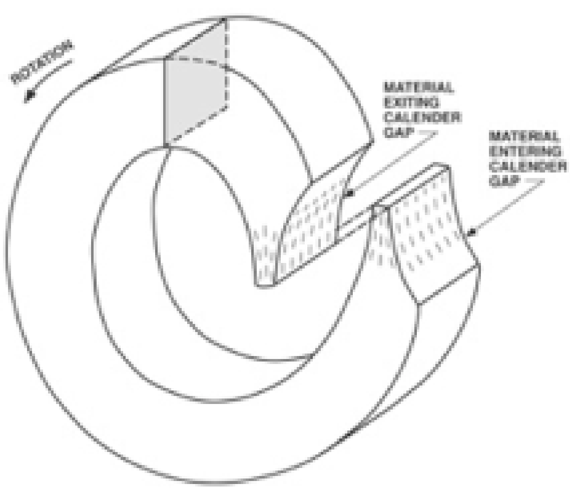

Figure 3. Example c-locked chamber.

Screw diameters for this type of twin-screw extruder range from 18 to 135 mm. A typical process length is 20 to 30 to 1 L/D. Because of screw deflection inherent with the materials traveling through the calender gap, the screw rpm is typically limited to 150 or below. Barrels and screws can be either one-piece or modular, and the relatively low screw rpm allows either air or liquid cooling to be considered.

"Counterflight" intermeshing and parallel design

A new approach to mixing in counter-rotation was introduced by Leistritz in the 1990s, referred to as "counterflight." Counterflight technology shifts the mixing from the calender gap to lobal mixing elements, as in co-rotation. In co-rotation the rotational clearances typically limit the lobe count to two, hence the term "bi-lobal." In counter-rotation, up to six lobes are possible at the same flight depth (Figure 4). This translates into more mixing events for each screw rotation.

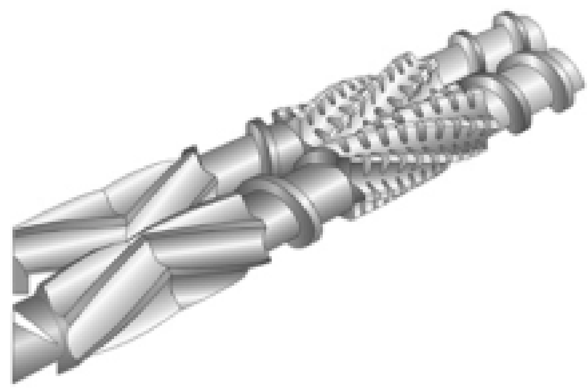

Figure 4. Example hexa-lobal counter-rotating mixers.

For instance a bi-lobal twin-screw extruder operating at 100 rpm would have 200 mixing "events" as compared to 600 for a hexa-lobal counter-rotating mixer. To allow for higher screw speeds, open flighted elements are utilized to drive material over the counterflight mixers. The redistribution of mixing to the counterflight elements combined with the minimization of a calender-gap effect allows significantly higher screw rpm without screw deflection, as compared to the traditional counter-rotating designs described above. Interestingly, counter-rotating screw designs that integrate both traditional and counterflight have been successfully employed for many specialty applications. Figure 5 shows three different areas of the screw and describes the effect achieved at each of the areas.

For the counterflight designs, screw diameters range from 18 to 135 mm. A typical process length is 32 to 52 to 1 LD and screw rpm of up to

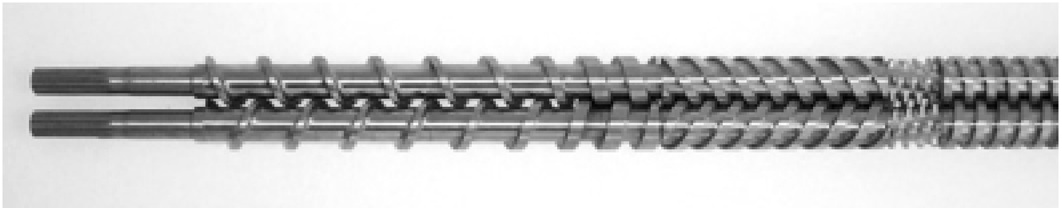

Figure 5a. Feeding and melting.

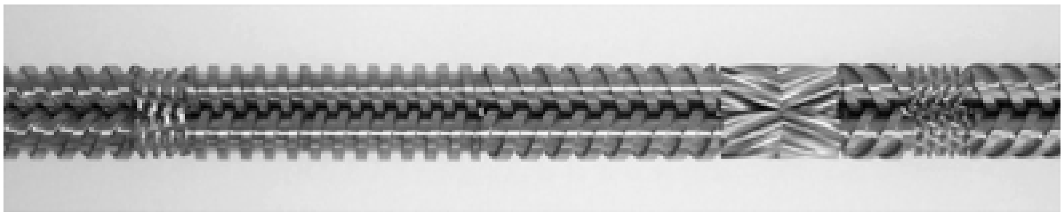

Figure 5b. Calender gap and hexa-lobal mixing.

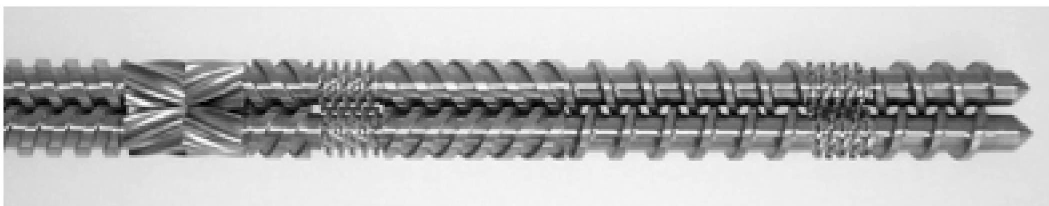

Figure 5c. Hexa-lobal mixing, degassing, thermal homogenization and discharge.

liquid cooling. Screws are also segmented and assembled on high-torque, splined shafts.

Counter-rotating, non-intermeshing design (CRNI)

The CRNI twin-screw extruder has non-intermeshing screws, which allows for unique design capabilities because each screw can be designed using configurations similar to a single-screw extruder. Normally, the design of each screw is mirrored on the other screw, but this is not always the case. The screws can have forward or reverse flights, different helix angles, thick or thin flight thicknesses, multiple screw starts, and other single-screw design features. A small root diameter can be specified in the feed area to facilitate a large free volume for low bulk density feedstocks and the root diameter can be tapered up after the feed section to compress and melt the polymer. Screw elements can be matched or staggered at different points along the process length to facilitate pumping and/or mixing (Figure 6). Different types of mixing elements are available for distributive and dispersive mixing.

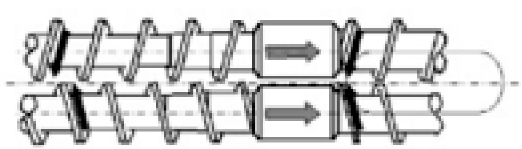

Figure 6. Example CRNI mixed and staggered screw flights.

Screw diameters for the CRNI twin-screw system range from 20 to 250 mm. A typical process length for this twin-screw configuration is 30 to 54 to 1 L/D and screw rpm of 500 or less are used. The screws are segmented and historically have been connected by triple start threaded studs. Barrels are also modular and are typically liquid cooled.

Due to absence of an intermesh and the associated geometric limitations, the non-intermeshing mode may be specified at 100 to 1 L/D or more. This can be beneficial for processes that require a long residence time (for instance, some specialty reactive extrusion applications).

LOW SPEED, LATE FUSION (LSLF) COUNTER-ROTATION

The LSLF counter-rotating twin-screw extruder shares some of the characteristics of the counter-rotating intermeshing design described above; however, this mode is characterized by a gentle melting effect and narrow residence time distribution, in combination with high-pressure pumping capabilities. Comparatively low screw rpm, late fusion screws are designed to avoid imparting too much energy to the process. These effects are of particular importance when processing a thermally sensitive material, such as PVC. As compared to the HSEI counter-rotating twin-screw extruder, LSLF mode is used for materials and/or applications where shear- or temperature-sensitive materials are being processed, high head pressures are desired, and/or the materials do not convey well by drag flow. Historically, 90%+ of this format twin-screw extruder has processed PVC materials. Currently, there is a push to expand the market applications for this mode of twin-screw extruder into alternative materials, so that in the future 70 to 80% usage for PVC may become the norm.

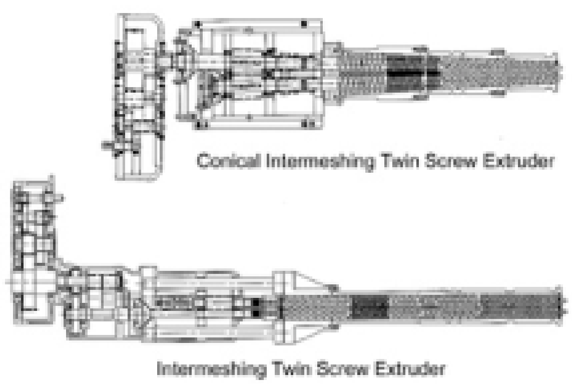

Figure 7. Schematic of conical (top) and parallel (bottom) low speed, late fusion counter-rotating twin-screw extruders.

The LSLF counter-rotating twin-screw extruder is primarily a positive displacement pump that conveys material with controlled melt temperatures. Various flight pitches, as well as multi-start screws are available. The calender gaps are sized for gentle mixing and minimal friction. Lower melt temperatures help minimize sizing and cooling problems of complex shapes, which is a typical end product in the PVC profile industry.

In its solid state, PVC powder has a comparatively low bulk density. The performance of the feed zone determines the uniformity of the melt over the full length of the screw. As the material passes from the feed zone into the pre-heating/pre-compression zones, a transformation from a solid to a viscous melt begins to occur. As the material enters the compression zone, flow is restricted and the finite flight volume in the compression zone generates a backpressure that compresses the material, while shear increases and the viscosity of the melt stream decreases. Devolatilization occurs late in the process, typically using multi-start screws to increase the surface area of the melt stream, and just before final pumping. In the metering zone, the primary process functions are to complete the plasticizing process and generate pressure to pump the material through a die at high pressure.

There are two types of LSLF counter-rotating, intermeshing designs—conical and parallel. These two designs (Figure 7) are defined by the diameter of the screws at the feed section versus at the tips. The parallel screw has no change in diameter as you travel down the screw, while conical screws decrease in size as you approach the tips.

In conical screws, the large-diameter feed zone has a continuous taper to the discharge end (or tips) of the screws. For example, a 55-mm model has a feed zone diameter of 114 mm and a discharge diameter of 55 mm. The conical screw design provides a natural compression over the entire length of the screws. Less dramatic pitch changes are required in the flight geometry to achieve a homogeneous melt, as compared to a parallel design. The large diameter in the feed zone provides a larger area for maximizing heat transfer and facilitates rotational shear to be applied to the incoming material. The small discharge diameter minimizes rotational shear and heat generation as the screws pump the material through the die.

A unique feature of the conical design is that the radial clearance between screws and barrel can be altered to assist in desired changes to the process. Moving the screws forward tightens the radial clearance and improves the pumping efficiency of the extruder for high head pressure applications. Moving the screws backward increases or opens up the radial clearance, increasing back flow and mechanical shear from the screws and improves mixing capability for highly filled or lubricated compounds. Conical twin-screw extruders have shorter processing sections and footprint as compared to parallel designs.

The parallel counter-rotating LSLF twin-screw extruder is differentiated from the conical extruder in that the screws are cylindrical and have a constant diameter. Radial clearance cannot be adjusted. The screws are typically longer than those of a corresponding conical design, and the screw geometry relies solely on dimensional changes to the gaps between the screw flights, the flight count, and changes in pitch to achieve the desired compression ratio to transform the feedstock from a solid to a melt. The additional length of the screws provides more versatility for sequential process tasks to be performed.

Since the diameters of the screws are constant, the same circumferential speed is provided over the entire length, and wider screw flights are typically incorporated into the design. This serves to reduce surface pressure and helps to minimize screw and barrel wear. Once wear has occurred, barrels and screws are more easily rebuilt due to the constant diameter and tolerances throughout the length of the processing zone.

LSLF counter-rotating twin-screw extruders range from 25 to 170 mm screw diameters, with motors from 10 to 300 hp. Maximum rpm varies with size, but is generally below 50 rpm and the typical process length is 20 to 28 to 1 L/D. Screws and barrels are normally one-piece, which makes the cost significantly lower compared to modular designs. Heating of the barrels is via electric band heaters, and cooling is external to barrel by either liquid or air. Screws are typically internally cored for liquid cooling, which is a preferred design feature for thermally sensitive PVC.

SUMMARY

There are many counter-rotating twin-screw extruder types from which to choose to perform various polymer-processing applications. The end product can be a pellet or extruded part. Continuing developments in counter-rotation, sometimes drawing upon co-rotating technologies, will continue to expand and improve the range of products that can be successfully manufactured, taking advantage of the unique geometric capabilities inherent with counter-rotating designs.