IMPROVE MIXING BY GENERATING ELONGATIONAL FLOW

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Introduction

Most dispersive mixers used in single screw extruders use geometries that generate shear flow to disperse agglomerates or droplets. However, shear flow is rather inefficient in dispersing agglomerates or droplets. Elongational flow is much more efficient than shear flow in achieving effective dispersion. As a result, if we want to achieve good dispersive mixing in a single screw extruder we need to use mixer that create elongational flow. A new class of mixing devices was developed with the specific objective to achieve strong elongational flow. These CRD mixers combine dispersive and distributive mixing capability.

Background

In polymer mixing we usually distinguish between distributive and dispersive mixing. Distributive mixing aims to improve the spatial distribution of the components without cohesive resistance playing a role; it is also called simple or extensive mixing. In dispersive mixing cohesive resistances have to be overcome to achieve finer levels of dispersion; dispersive mixing is also called intensive mixing. The cohesive component can consist of agglomerates where a certain minimum stress level is necessary to rupture the agglomerate. It can also be droplets where minimum stresses are required to overcome the interfacial stresses and deform the droplet to cause break-up.

Dispersive mixing is usually more difficult to achieve than distributive mixing. Single screw extruders are generally considered to be poor dispersive mixers while twin screw compounding extruders have much better dispersive mixing capability. However, when we analyze the mixing process in co-rotating twin screw extruders (1), it is clear that the main mixing action does not occur in the intermeshing region but in the region between the pushing flight flank and the barrel. This is particularly true when the flight helix angle is large as it is in kneading disks.

Dispersive Mixing in Twin Screw Extruders

The reason that twin screw extruders make good dispersive mixers is that the space between the pushing flight flank and the barrel is wedge shaped and thus creates elongational flow as the material is force through the flight clearance. Shear flow is not very efficient in achieving dispersive mixing because particles in the fluid are not only sheared they are also rotated, see figure 1. In elongational flow particles undergo a stretching type of deformation without any rotation; rheologists call this “irrotational flow,” see figure 1.

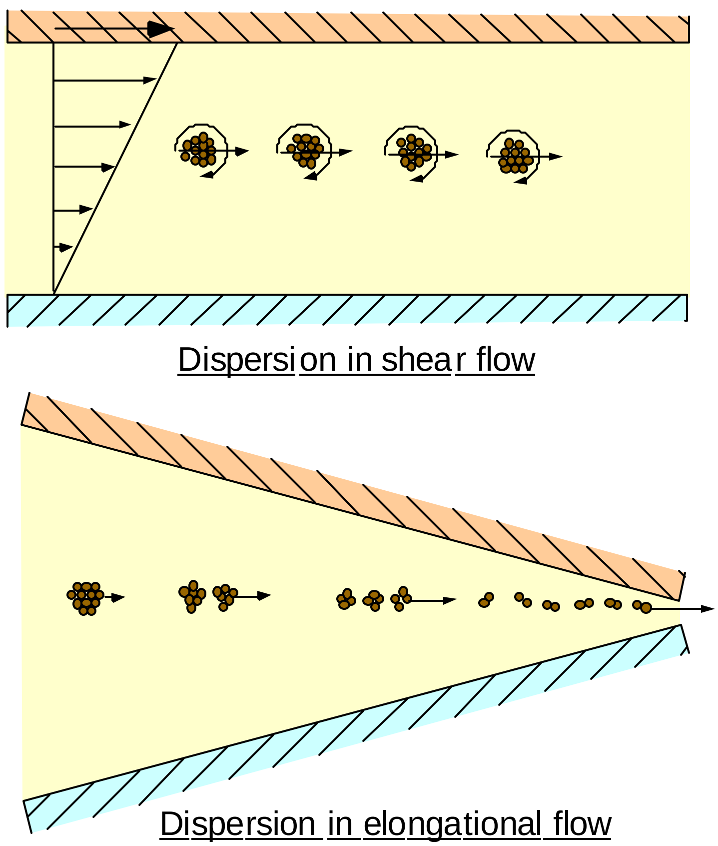

Figure 1, dispersion in shear and elongational flow

Since there is no rotation in pure elongational flow the deformation of the fluid is effectively transferred to the clusters in the fluid. This results in tensile forces acting to pull apart the clusters into smaller clusters.

Using Twin Screw Mixing Mechanism in Single Screw Extruders

In the past it was considered to be difficult to generate elongational flow in single screw extruders. However, this is not the case at all. There are at least two simple ways in which elongational flow can be achieved in single screw extruders.

One is by using a slanted pushing flight flank so that the material is stretched as it is forced through the flight clearance. The other way is by using tapered slots in the flights. The tapered slot accelerates the fluid as it flows through the slots and thus creates elongational deformation. The dashed arrows in figure 2 indicate the screw velocity, the solid arrows indicate the melt velocity relative to the screw.

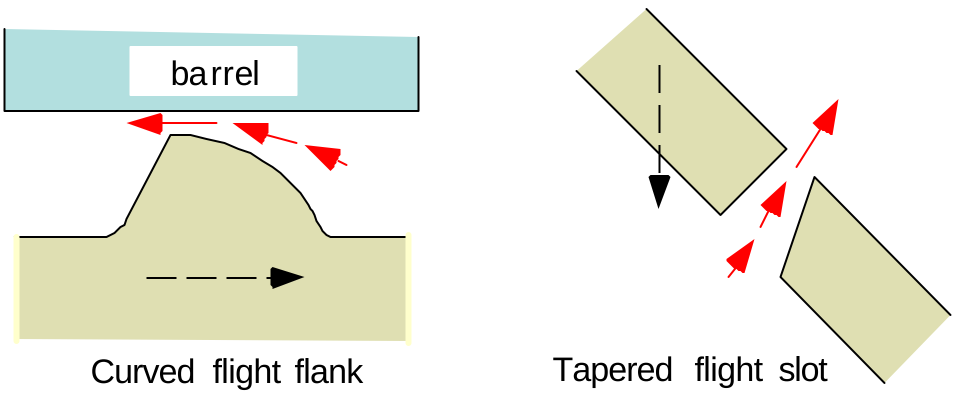

Figure 2, Two methods of creating elongational flow in the CRD mixer

The new dispersive (CRD) mixers developed by Chris Rauwendaal (2-4) use both methods to create elongational flow. The tapered slots in the flights serve to increase distributive mixing as well as dispersive mixing. If the material is not randomized in its passage through the mixer, only the outer shells of the fluid will be dispersed leaving the inner shells undispersed (5). Therefore, it is critical to incorporate both distributive and dispersive mixing ability within the mixer.

The initial design of the CRD mixer (2) was developed using the concept of the passage distribution function (6), while the final geometry was developed using a detailed three-dimensional flow analysis. The 3D flow analysis was performed using BEM*flow* (7), a boundary element flow analysis package originally developed at the University of Wisconsin, Madison by Professor Osswald and co-workers. The boundary element analysis allows a complete description of flow, so that the stresses, the number of passes over the mixing flights, the number of passes through the tapered slots, residence time, etc. can be quantified for a large number of particles. The CRD mixer may well be the first complex mixing device developed solely based on engineering calculations and computer modeling.

With BEA many particles can be tracked as they flow through the mixer. For each particle the flow number can be determined along its streamline. The flow number is a measure of the strength of the elongational flow relative to the shear flow; its value is between zero and one. A flow number of one indicates pure elongational flow, a flow number of zero indicates pure rotation. A flow number of 0.5 indicates simple shear flow. Figure 3 shows the flow number of a particle traveling through a CRD mixer.

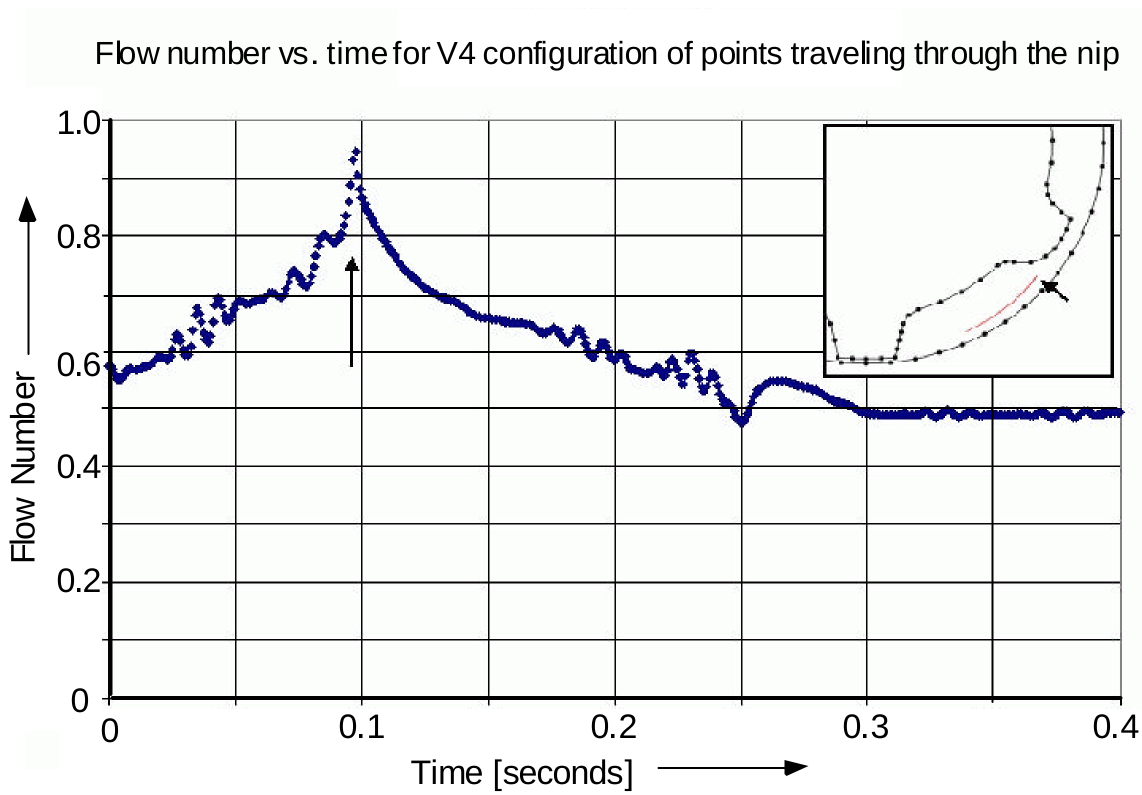

Figure 3, Flow number vs. time in CRD mixer

It is interesting to note that the highest flow number is about 0.95; this is almost pure elongational flow. Similar analyses on twin screw extruders indicate that the highest flow number is about 0.80. The reason that a good single screw mixer can achieve stronger elongational flow than a twin screw extruder is that there are rather severe design constraints for the screw geometry in intermeshing twin screw extruders (1). In single screw extruders we more design freedom and we can actually create more effective elongational flow as a result.

Experience from the Field

As of September 2000 over one hundred extruders are running with CRD mixers. The current applications are color concentrates, foamed plastic, post-consumer-reclaim with calcium carbonate, medical applications, heat shrinkable tubing, wire coating, carbon black dispersion in polyolefins, and blown film extrusion of low melt index metallocenes. All current applications are on single screw extruders in sizes ranging from 19 to 200 mm (0.75 to 8.0 inch). CRD mixing screws are also used in injection molding and even in twin screw extruders.

In the manufacture of color concentrates it was possible to produce even the most difficult material, phthalate blue, with good quality using a single screw extruder. The foamed plastic application polystyrene was foamed with a physical blowing agent carbon dioxide, a demanding application requiring very good dispersive and distributive mixing. The foamed product was found to have uniform cell size and excellent surface quality, while the extrusion process was very stable with respect to melt pressure and temperature.

In the PCR application film scrap is extruded with relatively high levels of calcium carbonate, up to thirty percent. The dispersion quality achieved in this application is excellent. It should be noted that this is an application that would normally use in twin screw extruder; single screw extruders are generally considered not to be capable of handling these types of compounding jobs. In the blown film application major problems were poor film quality and the inability to feed more than three percent fluff with the virgin plastic without generating gels in the film. The CRD mixing screw was able to improve film quality and handle up to twelve percent fluff without generating gels.

In all applications the CRD mixing screws have been able to achieve better mixing at equal or higher levels of output at lower levels of power consumption and lower melt temperatures. In most cases, the CRD mixing screws replaced barrier screws with mixing elements added after the barrier section. Since barrier screws are based on shear mixing, while CRD mixing screws are based in elongational mixing, the good results prove that elongational mixing is more efficient than shear mixing.

The good results with respect to gels indicate that elongational mixing devices can effectively disperse gels as opposed to shear mixing devices. Luciani and Utracki found similar results in experiment using their extensional flow mixer (8). The experience from the field was obtained with a fifth generation mixing device, the CRD5, see figure 4. This mixer has four parallel flights with tapered slots in the flights. Each wiping flight segment is followed by three mixing flight segments. Tapered slots separate the flight segments. The wiping segments are offset such that the mixer wipes the entire barrel surface. Complete wiping of the barrel surface is important to achieve efficient heat transfer between the plastic melt and the extruder barrel.

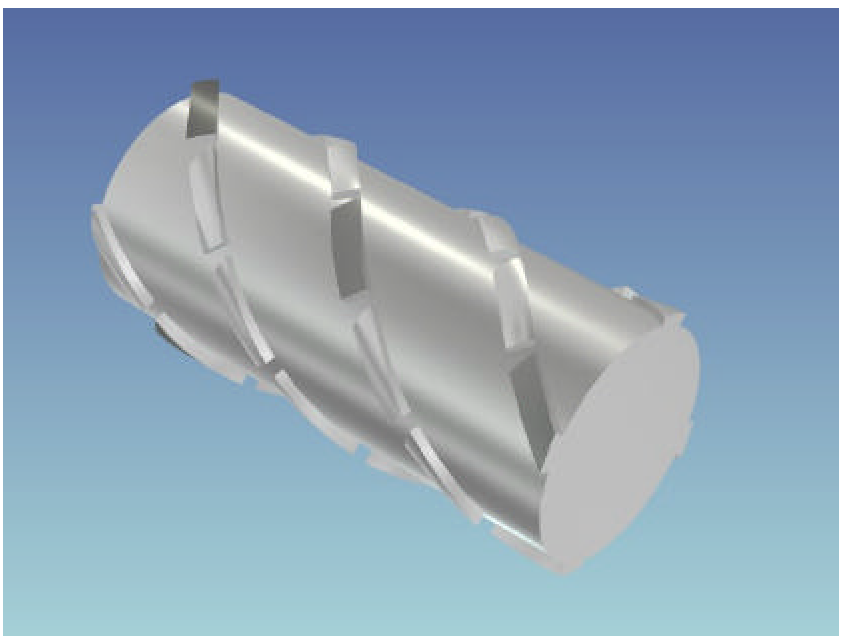

Figure 4, Three dimensional rendering of a CRD5 mixer

Application to Injection Molding

Mixing is not only important in extrusion, it is equally important in injection molding. CRD mixing elements can be added to an injection screw. Most injection screws have a non-return valve (NRV) at the end of the screw to prevent the molten plastic flowing back into the screw during injection. It is possible to incorporate mixing capability into the NRV to combine two functions within one device.

Figure 5 shows an example of a CRD mixing element incorporated in a slide ring NRV for injection molding (11).

Figure 5, CRD non-return valve for injection molding screws (open position)

The slide ring has multiple internal grooves that are tapered. The tapered grooves are formed by elongational pins. The pins split and reorient the fluid thus causing efficient distributive mixing. The tapered grooves accelerate the fluid and cause elongational flow with efficient dispersive mixing. The nosepiece of the valve has external pins that create a mixing action similar to that of the internal pins of the slide ring. The CRDNRV provides a convenient and cost efficient method to improve the mixing capability of injection molding screws. Good mixing action can be obtained simply by exchanging the conventional NRV with a CRDNRV.

Application to Static Mixers and Breaker Plates

The mixing mechanism of the CRD mixer has also been applied to static mixers and breaker plates. The Madison Group in cooperation with Rauwendaal Extrusion Engineering has developed the DDSM static mixer capable of distributive and dispersive mixing and the MBP, the mixing breaker plate (12). Figure 6 shows two versions of the MBP. The first one on the left has tapered circular channels to create elongational flow, the second on the right has straight tapered channels. Different plates can be stacked together to increase the mixing action.

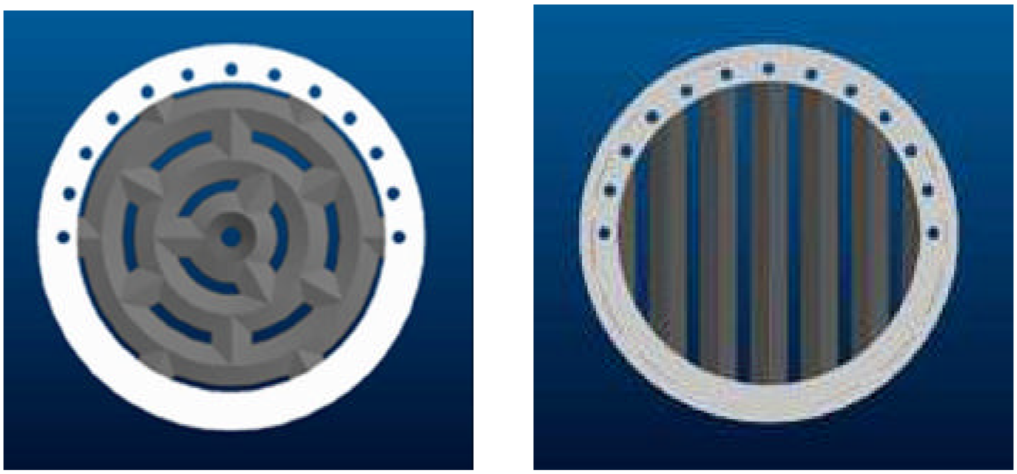

Figure 6, Two examples of the mixing breaker plate

The mixing breaker plate provides a very convenient method to increase the mixing action in an extruder. Another advantage of the MBP over conventional breaker plates is that it is much more streamlined. As a result, it has less chance of stagnation and it is easier to clean.

Conclusions

The CRD mixer allows the single screw extruder for the first time to be used in applications that heretofore were only possible on twin screw extruders. The high mixing efficiency of the CRD mixer is due to the generation of strong elongational flow and the fact that all fluid elements make multiple passes through the high stress regions. Elongational flow not only achieves more effective dispersion, it also creates less viscous dissipation than shear flow. As a result, the power consumption and temperature rise in the CRD are less than in mixing devices that rely on shear flow.

The CRD mixer is easy to manufacture, can be mounted on existing extruder screws, and fits in a normal extruder barrel, thus providing a cost effective improvement in mixing capacity. Other mixers, such as the Cavity Transfer Mixer (9) or the Crown Cup Mixer (10), require special barrel sections that increase the cost of the equipment and cost of operation. The use of the CRD mixer is being extended to injection molding and twin screw mixers and extruders. With the positive results obtained from the field it can be expected that the CRD mixer will find widespread applications in extrusion, compounding, and molding.

The CRDNRV provides a quick and convenient method to improve the mixing action in injection molding machines. The CRDNRV simply replaces an existing non-return valve. The mixing breaker plate provides a fast and easy method to enhance mixing in extruders. The mixing breaker plate also has a more streamlined design than conventional breaker plates and is easier to clean.

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