A NEW DISPERSIVE AND DISTRIBUTIVE STATIC MIXER FOR THE COMPOUNDING OF HIGHLY VISCOUS MATERIALS

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Abstract

In the compounding of polymers, static mixers are commonly used for distributive mixing. However, successful compounding generally requires both distributive and dispersive mixing; where the most difficult mixing involves the dispersion of materials having widely different viscosities. The best method to accomplish successful dispersive mixing is to expose the material to extensional flow. Furthermore, in terms of power consumption, extensional flows are far superior to the shear-type flows found in most mixing systems. This paper presents a new dispersive and distributive static mixer (DDSM), which exposes the fluid element to continual extensional flow for enhanced mixing.

Introduction

Oftentimes during the processing of polymers, it is desirable to add additional compounds to the melt stream to produce color, enhance properties, or produce a polymer blend. Furthermore, it is often desirable to produce this mixing in the absence of moving parts. In these cases, a static mixer is necessary to produce a homogenized uniform melt.

When comparing static mixers with conventional dynamic agitators, the former require much lower power input, require little or no maintenance, and generally produce effective mixing in a small amount of space. Fluids entering a static mixer are typically divided by baffles and mixing occurs by the continual splitting and recombination of flow streams. The continuous dividing of flows virtually ensures uniformity in composition, concentration, viscosity and temperature.

The current state of the art of static mixers for the polymer industry can produce an extremely uniform mixture for materials with nearly equal viscosities. However, when mixing incompatible compounds with large viscosity ratios, the current generation of static mixers is often unable to sufficiently disperse the secondary phase material.

The static mixer described in this paper attempts to alleviate many of the shortcomings of current static mixers by providing both distributive and dispersive mixing capabilities. In this paper, we will examine the limitations of the current generation of static mixers and provide the rational by which the new DDSM static mixer was developed.

Limitations of Current Static Mixers

Most commonly used commercial static mixers rely on laminar flows to continually split and redistribute the material uniformly. While this methodology works well for compatible systems with nearly identical viscosities, when blending systems with large viscosity ratios existing static mixers lack effectiveness. In order to break-up or disperse secondary phases in these types of systems, the current generation of mixers relies on generating large shear stresses. However, it is well known in the polymer mixing community that dispersion of agglomerates by shear is ineffective at large viscosity ratios.

The classic study by Grace (1) showed that as the viscosity ratio becomes greater than around four ($\mu_1/\mu_2>4$), simple shear flows cannot overcome the interfacial tension between the compounds and particles cannot be broken up. However, the study also showed that elongational flows are much more effective at dispersive mixing and do not exhibit any limit based on viscosity ratio. To date, commercially available static mixers still rely on shear to produce mixing and are not generally effective at dispersive mixing.

One of the most commonly used static mixers is the twisted tape mixer schematically shown in Fig. 1. As the fluid is rotated by the dividing wall, the interfaces between the fluids increase. The interfaces are then reoriented by 90º once the material enters a new section. The stretching-reorientation sequence is repeated until the number of striations is so high that a seemingly homogeneous mixture is achieved.

Numerous variations on the twisted tape exist in industry today. In general, these mixing elements are made from intersecting bars or sheets welded together to form open channels. These elements, when placed end to end along the section of a pipe, form the static mixing device. The fluids to be mixed enter the unit and are split into individual streams in the channels. These channels provide strong transversal flow and fluid exchange at the pipe wall. At each channel intersection, a portion of the material splits into an adjacent channel and distributive mixing is achieved. One such popular mixer, as shown in Fig. 2, manufactured by Koch produces a high degree of splitting in the melt stream and can produce good levels of homogeneity.

However, the aforementioned commercial static mixers still have difficulty in producing effective dispersive mixing in high viscosity ratio systems.

Mixing

Most current static mixers rely on shear stresses to achieve breakup of agglomerates. However, since elongational flow generates higher stresses, it is more efficient in breaking up agglomerates. Therefore, it would be preferred to have strong elongational flow in the dispersive static mixer. Also, to achieve a fine level of dispersion it is generally necessary for the agglomerates or droplets to be broken down several times. This means that multiple passes through a high stress region are critical for proper dispersive mixing. A single pass through a high stress region (HSR) is not sufficient in most cases. If an agglomerate is of the order of 1000 μm and needs to be reduced to the 1 μm level, then it will take about 10 rupture events if we assume that each event reduces the size by 50 percent (2). In addition, break-up can only occur if sufficient time is given for this to transpire (3).

Since elongational flows can generate significantly higher stresses to disperse agglomerates, the resulting energy requirement to produce mixing is accordingly much lower than with shear flows. Based on the classic study by Erwin (4) in the 1970's, Figure 3 shows the ratio of energy input requirements for shear and elongational flows to produce a specific dispersed phase size. The graph shows that as the interfacial area of the agglomerates, A, is increased from the initial surface area, A_o, shear flow is an extraordinarily inefficient way to mix. As the figure illustrates, shear flows are always less efficient, i.e. require more energy, to produce dispersion than elongational flows. Also readily evident from the figure is the fact that the energy required for elongational flow can be many orders of magnitude *less* than for shear flow.

Given the advantages of elongational flow, some quantitative measures must be defined to numerically evaluate a new mixing device. One such measure, the flow number, has been extensively used by many authors (5-8) to ascertain the type of flow in a given geometry. The flow number, λ, is defined by Eq. 1 in terms of the magnitude of the strain rate tensor, $\dot{g}$, and the vorticity tensor, ω. The flow number is a measure of the type of flow in the system and varies between a value of 0 and 1. For a flow number of 0, the system is undergoing purely rotational flow and no effective mixing can occur. A flow number of 0.5 denotes simple shear flow, while a value of 1.0 denotes pure elongational flow. In commercial applications, whenever the flow number is greater than or equal to 0.7, the system is thought to be generating effective elongational flow for dispersion.

$$l = \frac{\dot{g}}{\dot{g}+w} \tag{1}$$

Equally important as the flow number, is the magnitude of the separation forces that the mixer can impart to the fluid. In simple shear flow, the force that is applied is given by Eq. 2 (8), and for pure elongational flow by Eq. 3. Here, η_s is the shear viscosity of the carrier fluid, η_e the elongational viscosity, and r the radii of particles to be broken up. Considering the Trouton relationship, where the elongational viscosity is usually three times the shear viscosity, the equations indicate that elongational flows can generate substantially higher separation forces than shear flows.

$$F_{shear} = 3ph_s \dot{g}r^2 \tag{2}$$

$$F_{elong} = 6ph_e \dot{g}r^2 \tag{3}$$

A New Dispersive/Distributive Static Mixer

With the aforementioned requirements and caveats, a new static mixer geometry has been developed that dramatically improves dispersive mixing. Furthermore, this new mixer, patent pending, maintains substantial distributive mixing capabilities as well. By taking advantage of the strengths of elongational flows, the new static mixer has shown excellent promise in generating effective dispersive mixing.

The present invention provides a static mixer head that generates not only distributive mixing but also dispersive mixing. Distributive mixing is accomplished by providing a series of baffles along the length of the mixing tube, each baffle being angled relative to the previous baffle. Dispersive mixing is accomplished by utilizing baffles that define a converging pathway for the mixing materials. The converging pathway promotes elongation and corresponding dispersion of the mixing material, Fig. 4. The arrangement of the baffles is such that the fluid element experiences a continual elongational flow, ensuring enough time for break-up. Further, all material passing through the mixer is assured to encounter the HSR a multiple number of times.

To investigate the type of flow generated in this system the boundary element simulation program BEM*flow* (9) was used. Using this program, the geometry of the mixer can be quickly modified to help pursue the optimized geometry — one which gives high dispersive mixing with distributive mixing effects. The flow number was used as the mixing index to quantitatively measure its dispersive mixing ability. Figure 5 shows the calculated particle tracking though the mixer and Fig. 6 shows the flow number of several particles as they travel through the mixer. It is clearly evident that this mixer produces extremely high elongation flows, which are not found in most mixing devices used in industry today, especially, static mixers. Mixing sections that are typically used are shear dominate and have a flow number in the range of 0.5. The figures demonstrate how the converging baffles continually expose the fluid to an elongational flow — assuring that the material goes through the HSR multiple times and is exposed to a high forces long enough for dispersion to occur. The mixing that is produced by the staggered baffles, creates a distributive mixing effect similar to the twisted tape static mixer.

Another advantage of this mixing section is that its design was made to be relatively inexpensive to manufacture and that stagnation zones do not occur. Each baffle has a continuous tear drop shape, which creates the streamlined elongational flow. The gap between the baffles can be made according to the size of the dispersed phase needed and the pressure available.

Conclusions

The current state of the art mixing devices that are now used rely on large of shear stresses to create dispersive mixing. It is well known that the elongational flows are extremely more effective and efficient for reducing the dispersed phase. The new dispersive/distributive static mixer (DDSM) shown in this paper was designed to create high degrees of elongational flow and assure that the material will pass through several High Stress Regions (HSR) for a sufficient amount of time for break-up to occur. Further, the streamline design of this mixer reduces the possibility of stagnation to occur and makes it relatively inexpensive to manufacture. Distributive mixing is accomplished similar to that found in the twisted tape static mixer. By providing a series of baffles along the length of the mixing tube with each baffle being angled relative to the previous baffle the material is split, reoriented and combined again to produce effective mixing.

References

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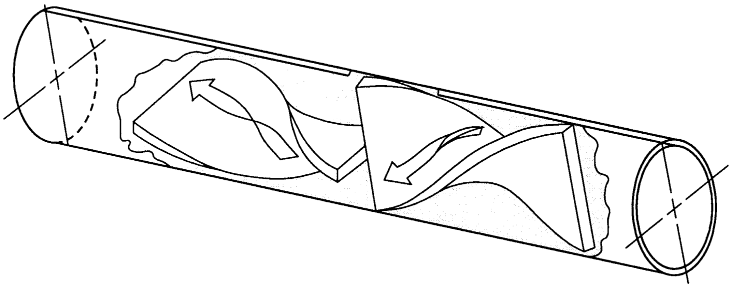

Figure 1 - Twisted tape static mixer.

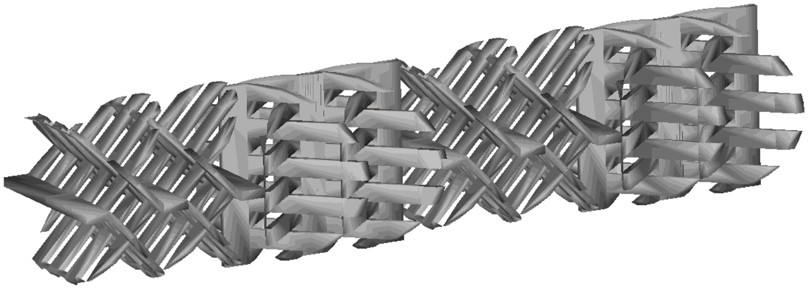

Figure 2 - Koch SMX static mixer.

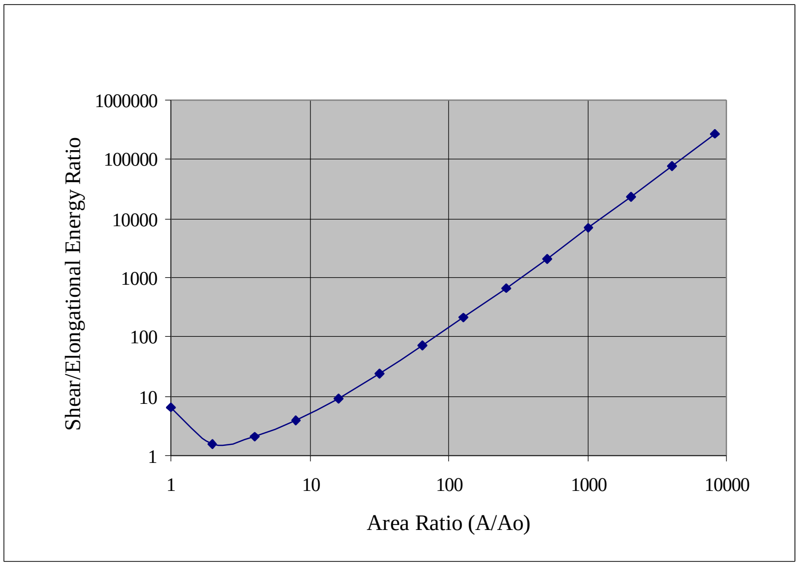

Figure 3 - Energy ratio (shear/elongational) required to produce dispersed phase of a specific size.

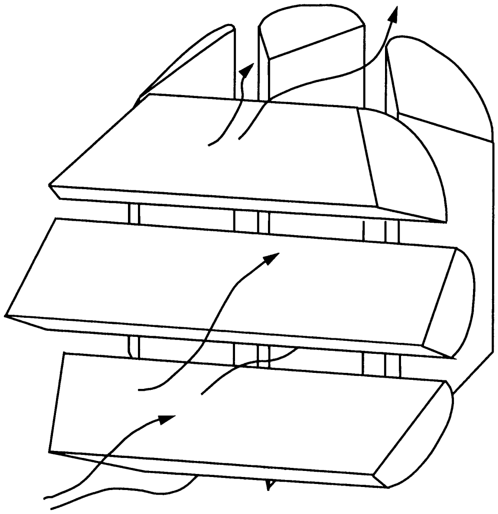

Figure 4 - Dispersive distributive static mixer (DDSM).

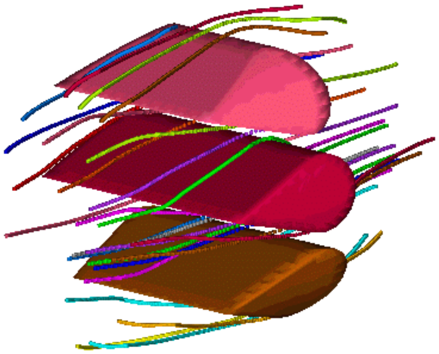

Figure 5 - Calculated particle tracking through on section of the DDSM.

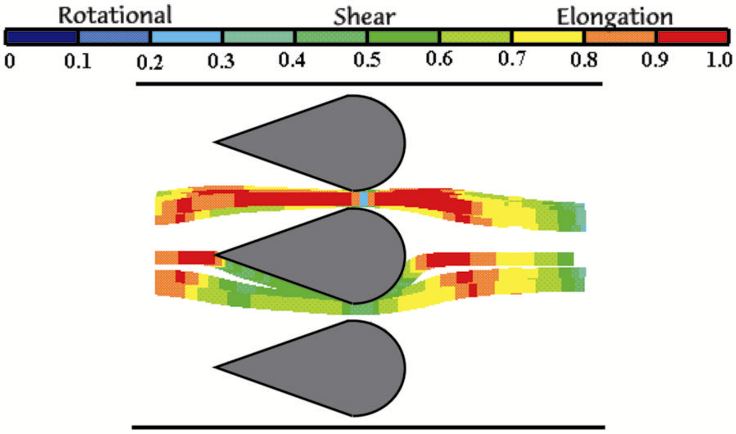

Figure 6 - Calculated flow number for particles tracked through one section of DDSM.

Keywords

Static Mixer, Extrusion, Dispersion, Mixing