COMPARATIVE STUDY OF RHOMBOIDAL DISTRIBUTIVE MIXING SECTIONS USING COMPUTER MODELING

Antoine C. Rios, Paul J. Gramann, Ephraim Stanfield and Tim A. Osswald
Polymer Processing Research Group
Department of Mechanical Engineering
University of Wisconsin-Madison
Madison, Wisconsin 53706

Abstract

The rhomboidal mixing section is becoming very popular among processors to provide distributive mixing. Currently, several different designs are used but the details of the flow behavior and mixing efficiency is not well understood. This information is needed to be able to design and find the most efficient rhomboid geometry. In this paper six different geometries with various pitches (helix of rhomboids) are analyzed using a 3-dimensional boundary element method (BEM). The geometries are compared according to mixing efficiency, pressure and energy consumption. The results lead to recommendations of the most effective rhomboidal mixing section.

Introduction

Mixer design is slowly changing from being a complete experimental process to a partially numerical and experimental one. Numerical simulation has an advantage that analysis and optimization can be done before the device is built. Consequently, the design of new mixing devices becomes less expensive and at the same time faster.

The rhomboidal mixing section is becoming a standard for improving mixing during extrusion. This mixing device can have numerous configurations depending on the number and pitch of the helical cuts, Fig.1. The rhomboids performance depends completely on the type of configuration to be used. Therefore, an optimization of the design parameters is desired in order to obtain the most efficient geometry.

The research reported here provides insight into the mixing that occurs in the rhomboidal section and to ultimately optimize its design. A numerical analysis of six different rhomboid mixing sections, each having a different pitch is presented here. Figure 1 shows the geometries used and Fig.2 and Table 1 list the main specifications of each rhomboidal section. For the study a 3-dimensional flow simulation program; using the boundary element method (BEM) was used to solve the flow field of each rhomboid. For each case, after the flow field was calculated, the mixers efficiency was assessed. The efficiency was measured by analyzing the mixing performance along with the pressure and energy consumption for each of the six geometries.

Background

The design parameters (i.e. helix angle) used for the rhomboidal mixing section significantly affect the mixer's performance. Several researchers have performed experiments with rhomboidal mixing sections [1-4]. These studies used various rhomboidal designs, and for all cases, an improvement in mixing was observed. Rios et al. [5] tested three different rhomboidal mixing sections in which the design had a great influence on the experimental results. Other studies [6-8] used a numerical approach for analyzing the flow inside a rhomboidal mixer, but without performing any optimization.

The mixing action that takes place can be broken down into two major categories—distributive mixing and dispersive mixing. The first exists when the homogenization of a secondary phase within the matrix is desired, and the latter, when the breaking of the secondary phase into smaller particles is desired. The mixing phenomena highly depends on the material behavior during the process. For distributive mixing, high strains are required in order to increase the interfacial area between the two or more phases and reduce the striation thickness of the secondary phase. For dispersive mixing the presence of high stresses, which is dependent on the rate of strain, is more important.

The complexity of the flow inside the rhomboidal mixing sections makes the mixing analysis extremely difficult. Several techniques exist for quantifying mixing in polymer processing equipment [9-12]. One common technique, used both numerically and experimentally to analyze mixing is the residence time distribution (RTD) [13]. This parameter also provides information on the conveying performance of the mixer and is commonly used to determine if a material will be in the mixer too long for degradation to occur.

Analysis

Numerical Simulation

To analyze the flow field inside the mixing section several numerical techniques have been used. Domain type methods (i.e. finite differences and finite elements) have been used successfully in analyzing flow inside mixers, but they require excessive computational power and labor intensity to generate the required domain discretizations. The method used for this research is the boundary element method (BEM). This technique requires only surface discretization; thus, the required mesh is reduced from three dimensions to two dimensions. Consequently, the computer and human power is reduced substantially. The geometries used in this study generally consisted of between 1000 and 1400 quadratic shell elements and between 3000 and 4200 nodes. For the mixing analysis, 200 particles were randomly located at the beginning of the mixing section and tracked until they exited the mixer. All calculations were completed on a desktop computer; a Silicon Graphics Indigo 2 R1000. The time required to solve for the unknowns was approximately 4 hours. Time for particle tracking highly depends on the time step and was approximately 20 hours.

The boundary element method has been utilized by several researchers with great success [5,8,11,14]. With BEM, the dispersive and distributive mixing effect, streamlines, pressures, residence time distributions and torque can be calculated. The BEM simulation used in this research was based on a Newtonian and isothermal model. These assumptions are only valid when qualitatively optimizing the mixer; where the general tendencies of mixing are important rather than the fine details of the flow.

Distributive Mixing Analysis

Distributive mixing is dependent on the amount of strain imposed to the material. The total strain that the material has undergone at time, t', can generally be described by

$$\gamma(t') = \int_0^{t'} \dot{\gamma}(t)\,dt \qquad (1)$$

where, $\dot{\gamma}(t)$ is the magnitude of the strain rate. Generally, it is desired to impose as large a strain as possible to generate the most effective mixing. However, this does not take into account initial conditions and material reorientations [9], which enhance distributive mixing.

The shape of the cumulative residence time distribution (CRTD) can also be a useful measure of mixing, but only for mixing in the axial direction [15]. The more detrimental case for mixing is plug flow where the CRTD is a vertical line.

Dispersive Mixing Analysis

Dispersion can be assessed by considering the type of flow and the stress, which is proportional to the strain rate, that the material undergoes. When elongational flow is present, the maximum forces trying to disperse an agglomerate is twice as large than for shear flow [16]. Therefore, elongational flow is preferred over shear flow for dispersive mixing. To evaluate the type of flow several researchers have used the flow number [5,8,11,12,14], which is defined as

$$\lambda = \frac{\dot{\gamma}}{\dot{\gamma} + \omega} \qquad (2)$$

where $\dot{\gamma}$ and ω are the magnitude of the strain rate and vorticity tensors, respectively. The flow number is a non-dimensional quantity that ranges from 0 for pure rotational flow to 1 for pure elongational flow with 0.5 denoting shear flow. In practical applications a purely elongational flow ($\lambda = 1$) is not possible. However, when optimizing for dispersive mixing the goal is to approximate a flow number of 1.

Pressure and Torque Analysis

The pressure and torque are important measures since they define the size of various components on the extruder. A mixing section consuming higher pressure requires a screw that can build more pressure in order to keep the flow rate unchanged. In this paper the flow rates were calculated by integrating the velocity of the material across the output side of each mixer. The flow rate for all the rhomboidal sections was kept constant and the pressure drop was calculated.

The torque required to turn the screw at the specified velocity is important for calculating the efficiency of the mixer. Torque is also a factor that defines the size of the motor and screw of the extruder. In general, the lower the torque and pressure consumption, the more efficient and economical the extruder will be.

Results and discussion

Table 2 shows the results obtained from the simulation. To aid in the analysis of these data the results were normalized and shown in Table 3. The time with higher dispersion capability (THDC) is introduced in Table 2. The THDC is defined as the percentage of the time that the material undergoes a flow number higher than 0.5 and a strain rate higher than the mean strain rate. This parameter is similar to the one used in reference [12], except that time is used instead of the volume. For dispersion, a high THDC is desired because the longer the material experiences a high stress and high flow number, the greater the possibility for dispersion. It is important to note that THDC alone is not a good measure for the ability to disperse. The presence of a high mean strain rate is also important. With these quantities the dispersive capacity of the different mixers can be compared.

The selection of the best mixer will depend on the desired mixing mechanism, and by balancing the mixing capability with the pressure consumption and torque requirements. The rhomboidal 2D-2D section was predicted to have the highest mixing capability, but at the same time it has the highest pressure consumption and torque demand. Figure 3 shows the CRTD for the six mixing sections. The rhomboid 2D-2D has the residence time showing the best mixing in the axial direction. The rhomboid 2D-2D has also the highest mean residence time ($\bar{t}$) by a factor of 3. In this section, as the material splits around the rhomboid, it can be transported back axially. Whereas when splitting occurs in the other five geometries all material pumps forward; giving lower $\bar{t}$. For materials that are sensitive to degradation the 2D-2D section is not recommended.

The six geometries have a similar flow number of approximately 0.5. In general, these mixers observe a shearing-type flow which is easiest to generate and is typical for most mixing sections. High flow number are only encountered in only few sections and for a small amount of time.

The dispersive mixing capability of the six geometries is quite similar. Since, the 2D-3D section was calculated to have the lowest pressure drop we may conclude that this is a better dispersive mixer. The mixer able to convey the most strain was found to be the rhomboid 2D-2D. This rhomboid gives more than twice the strain than the other sections making it the best distributive mixer analyzed.

Conclusion

The tools used for this research demonstrated the usefulness of the BEM simulation for optimizing the rhomboidal mixing section. In this study the rhomboid 2D-2D was predicted to have the highest mixing capability, for both dispersive and distributive mixing. However, after the pressure consumption and torque were considered, the 2D-2D section will be the best distributive mixer, in agreement with experimental work by Rios et al [5]. The 2D-3D mixer was calculated to have the lowest pressure consumption, and overall, is the best dispersive section from the six rhomboids tested. In this paper an optimization was successfully done on the rhomboidal mixing section by analyzing six different mixing geometries. Great insight was given on the flow phenomena that occurs in this mixing systems. By no means do the authors feel that this mixing section has been completely optimized. Further analysis on the helix angle and number of cuts, among others, will be performed in the future.

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Rhomboid	Pitch	Number of Cuts	Width, W (mm)
1D2D	1D	4	6.55
	2D	6	10.91
1D3D	1D	4	6.55
	3D	6	16.36

1D4D	1D	4	6.55
	4D	6	21.82
2D2D	2D	6	8
	2D	6	8
2D3D	2D	6	8
	3D	6	16.36
2D4D	2D	6	13.1
	4D	6	21.82

Table 1. Dimensions of rhomboidal mixing sections (h=5 mm, r=3 mm).

Rhomboid	ΔP	Torque (Nm)	Flow no.	Strain rate	$\dot{t}$	Mean Strain	% THDC
1D2D	98	5.8	0.46	14.5	7.02	103.8	4.7
1D3D	143	6.1	0.46	13.6	5.88	80.7	5.9
1D4D	87	6.7	0.47	13.7	7.01	96.9	6.4
2D2D	189	8.3	0.49	11.1	20.71	218.2	10.7
2D3D	56	6.2	0.47	14.1	5.30	75.1	5.4
2D4D	134	6.6	0.47	14.2	5.03	72.0	4.3

Table 2. Numerical results

Rhomboid	ΔP	Torque (Nm)	Flow no.	Strain rate	Mean Strain	% THDC
1D2D	0.52	0.70	0.94	1.00	0.48	0.44
1D3D	0.76	0.73	0.94	0.94	0.37	0.55
1D4D	0.46	0.81	0.96	0.94	0.44	0.60
2D2D	1.00	1.00	1.00	0.76	1.00	1.00
2D3D	0.30	0.74	0.96	0.97	0.34	0.50
2D4D	0.71	0.79	0.96	0.98	0.33	0.40

Table 3. Normalized results

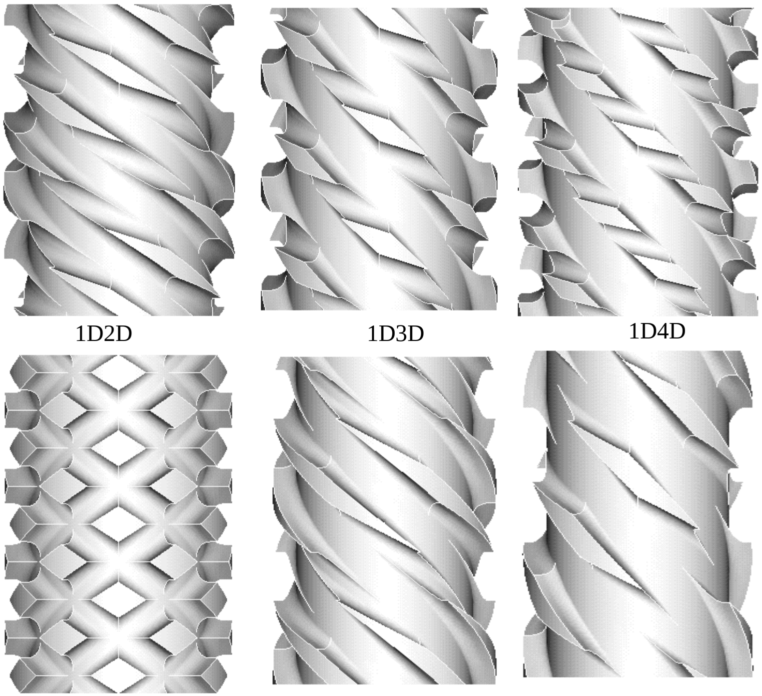

Figure 1. Rhomboid geometries analyzed.

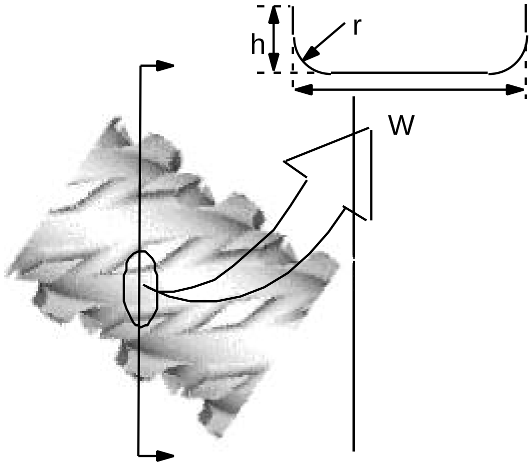

Figure 2. Schematic of the rhomboidal mixing section.

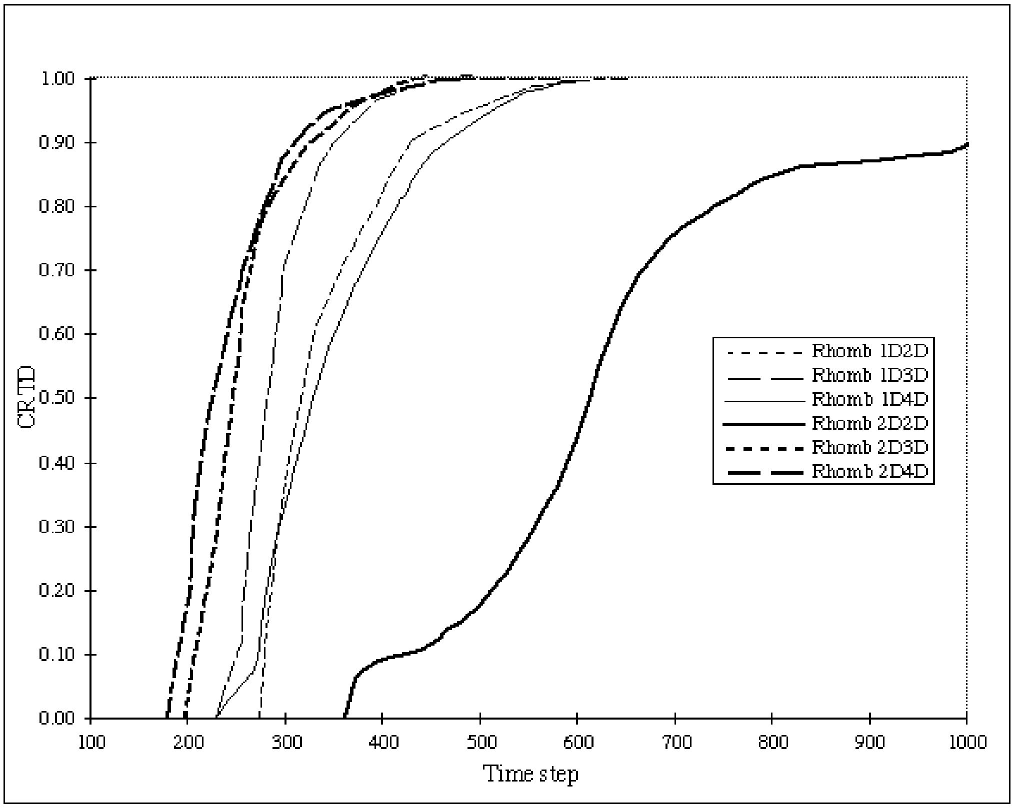

Figure 3. CRTD of the six rhomboidal mixing sections.

Key words

Rhomboidal mixing sections, mixer optimization, boundary element method, numerical simulation