DISTRIBUTIVE MIXING IN VARIABLE INTERMESHING CLEARANCE MIXERS: SIMULATION AND EXPERIMENTS

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ABSTRACT

Distributive mixing performance in Variable Intermeshing Clearance (VIC) mixers was studied numerically and verified experimentally. A fluid dynamics analysis package (FIDAP), based on the finite element method, was employed to simulate the flow patterns in the original lab size mixer (VIC1) and a new design with an enlarged mixing chamber (VIC2). Distributive mixing was studied numerically by means of tracking the evolution of particles originally gathered as clusters. The results of numerical simulations were checked against experimental data to verify the validity of the model. Both the numerical simulations and the experimental data indicate that the VIC2 design, with an enlarged mixing chamber, shows consistently better distributive mixing results in comparison with the traditional VIC1. In both mixers, increasing the inter-rotor clearance improves distributive mixing. However, enlarging the gap size too much in the bridge region, in the VIC2 mixer, becomes detrimental for mixing. The initial position of the clusters is also important in distributive mixing. Clusters located in the middle of the bridge region are better distributed than the ones located on the sides, particularly at small inter-rotor clearances.

INTRODUCTION

Mixing is a key step in almost every polymer processing operation and therefore its fundamental understanding is of paramount importance. Yet modeling the mixing process in real mixing equipment is not an easy task. Due to the very complex geometry and the time dependent flow boundaries encountered in most processing equipment, numerical simulations are the only alternative for solving the flow problem. The computational schemes employed are based on finite difference, finite element and boundary element methods. Besides the intrinsic round-off error encountered in all numerical methods, there are in most cases an additional number of simplifying assumptions required to obtain a solution for the flow problem. Therefore, comparison of the numerical results with experimental data becomes essential for validation of the model.

The comparison between computational and actual experiments is not trivial. Ottino and coworkers conducted very elegant combined experimental-computational studies of chaotic mixing in slow flows. Kalyon and coworkers developed experimental techniques to investigate the growth of interfacial area in single screw and intermeshing co-rotating twin screw extruders. These authors also presented some comparisons between experimental results and numerical computations for the interface shape. Avalosse and Crochet compared numerical results with experimental observations for the dispersion of a colored material spot in co- or counter-rotating cam devices (2D flow analysis). These authors also compared concentration maps for pigmented tracers obtained in a 3D flow simulation of a Kenics mixer with experimental observations in a similar device. Wang and Manas-Zloczower compared the results of numerical simulations in terms of tracer trajectories with experimental data from flow visualizations in a simplified cavity transfer mixer. Osswald and co-workers presented an analysis of distributive mixing in the

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rhomboidal mixing section of a single screw extruder using both computer simulations and flow visualization techniques.

In this work we review some of the numerical results obtained for the analysis of distributive mixing efficiency in a Variable Intermeshing Clearance (VIC) mixer\textsuperscript{12,13} and present experimental data validating our theoretical predictions.

MODELING

The Variable Intermeshing Clearance (VIC) mixer is an intermeshing internal mixer which possesses the unique feature of being able to vary the clearance between the rotors by adjusting the rotating shafts during the mixing process. The VIC mixer is manufactured by Pomini SpA, Italy.

In our previous work\textsuperscript{12,13} we characterized the flow geometry and analyzed the mixing performance of the first generation of VIC mixers (VIC1) and of a new design (VIC2) with an enlarged chamber. Flow patterns were obtained using FIDAP—a fluid dynamics analysis package based on the finite element method. The problem of time dependent flow boundaries was solved by selecting a number of sequential geometries to represent a complete mixing cycle.

Distributive mixing was studied numerically by means of tracking the evolution of particles originally gathered as clusters. We used a particle tracking algorithm in which the location of the massless, non-interacting particles is calculated by integrating the velocity vectors with respect to time:

\[ X(t_1) = X(t_0) + \int_{t_0}^{t_1} V(t) dt \]  

In Equation (1) above, \( X(t_1) \) is the location of a particle at any time \( t_1 \), \( X(t_0) \) is the location of the same particle at time \( t_0 \), and \( V(t) \) is the time dependent velocity vector for the particle.

Fig. 1.—Time evolution of the parameter \( \epsilon \) for the VIC1 and the VIC2 at different inter-rotor clearances. Material: SBR compound. Rotational speed: 60 rpm,\textsuperscript{12,13}
In order to quantify the degree of distributive mixing, we used the concept of pairwise correlation functions and defined a parameter $\epsilon$ to gauge mixing realization. Parameter $\epsilon$ defined in Equation (2) probes the departure of an actual particle distribution, at any mixing time, from an ideal particle distribution:

$$\epsilon = \frac{\int_{r=0}^{r=\text{max}} \left[ c(r) - c(r)_{\text{ideal}} \right]^2 4\pi r^2 dr}{\int_{r=0}^{r=\text{max}} c(r)_{\text{ideal}}^2 4\pi r^2 dr}$$

(2)

In Equation (2), $c(r)$ and $c(r)_{\text{ideal}}$ are the coefficients of the probability density function for the actual and the ideal particle distribution, respectively. The concept of using pairwise correlation functions to quantify distributive mixing was discussed in more detail in our previous work.\textsuperscript{12,14,15}

The results of our analysis, in terms of the dynamics of the parameter $\epsilon$ for the VIC1 and VIC2 designs at different inter-rotor clearances, are shown in Figure 1. These results were obtained by looking at the evolution of particle distributions for 30,000 particles initially clustered in 50 agglomerates placed in the bridge region of the mixer. In general, increasing the inter-rotor clearance improves distributive mixing for both mixer designs, with a clearly better performance for the VIC2 mixer. However, enlarging the gap size too much in the bridge region (for the VIC2) is detrimental for distributive mixing. Indeed in the VIC2 design, an inter-rotor gap clearance of 14.5 mm shows similar mixing results with the 1 mm gap.

**EXPERIMENTAL**

Experiments designed to study distributive mixing were carried out in the VIC1 and VIC2 mixers. A silicone rubber (M-3393) from Dow Corning, consisting of 100 parts (per weight) polydimethyl, methylvinylsiloxane (PDMS) and 1.2 parts 2,4-dichlorobenzoyl peroxide, was used in the trials. The silicone rubber compound was cut into small pieces and fed slowly from the hopper into the mixing chamber. In all of the experiments, filling factors close to unity were used. About 10% by weight excess material (beyond the mixer capacity) was fed into the hopper in order to prevent air entrapment during the mixing process. All experiments were carried out at room temperature and a ram pressure of 0.655 MPa (95 psi).

Colored tracers obtained by incorporating a paste of colored pigment into the silicone rubber were used in the experiments. Before placing the colored tracers into the mixer, the silicone rubber

![Fig. 2.—Schematic representation of the initial position of the colored spherical blobs of diameter 2 cm.](image-url)
in the mixing chamber was homogenized by running the mixer at 60 rpm for about 2–3 minutes. The rotor position at the beginning of each trial was labeled. The colored tracers were placed into predetermined positions in the mixer. Experiments were carried out and the mixer was stopped. The material in the mixing chamber was cured in place by raising the temperature to 110–116 °C at a rate of 2 °C per minute. Rubber vulcanization was completed in about 1 hour and the material was removed from the mixer. The vulcanized rubber is semitransparent and, for most of the part, the specimen thickness is less than 1.5 cm. These characteristics allow for an overall qualitative judgement on distributive mixing performance throughout the sample, without having to cut the specimen.
RESULTS AND DISCUSSION

Distributive mixing in the VIC1 and VIC2 mixers at various inter-rotor clearances was studied in experiments performed using 3 colored tracers placed in the bridge region of the mixer. Figure 2 shows schematically the initial position of the tracers used in the experiments. In all of the experiments we used a rotational speed of 5 rpm.

Tracer distributions, after 4 revolutions in the VIC1 mixer at inter-rotor clearances of 1.8 and 6 mm, are shown in Figure 3. The results clearly indicate that distributive mixing is better when using the larger size gap between the rotors. Similar conclusions were reached in numerical simulations as presented in Figure 1.

Experimental results obtained in the VIC2 at different inter-rotor clearances are shown in Figure 4. Distributive mixing is enhanced when increasing the gap between the rotors from 1.8
mm to 6 mm and 10 mm. However, at 13.8 mm inter-rotor clearance, mixing is poor and the results obtained are only slightly better than the ones obtained when using a 1.8 mm gap size. Theoretical results presented in Figure 1 corroborate these findings.

When comparing the results in Figures 3 and 4, the VIC2 shows superior distributive mixing performance in comparison with the VIC1 mixer, at similar inter-rotor clearances. This result is a consequence of the new design with an enlarged chamber allowing for enhanced motion in the bridge region. This outcome was also evident from the numerical simulation analysis presented in Figure 1.

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**Fig. 4.** Colored tracer distributions in the VIC2 mixer after 4 revolutions: (a) I.C. = 1.8 mm, view from the negative $y$ direction; (b) I.C. = 1.8 mm, view from the positive $x$ direction; (c) I.C. = 6.0 mm, view from the negative $y$ direction; (d) I.C. = 6.0 mm, view from the positive $x$ direction; (e) I.C. = 10.0 mm, view from the negative $y$ direction; (f) I.C. = 10.0 mm, view from the positive $x$ direction; (g) I.C. = 13.8 mm, view from the negative $y$ direction; (h) I.C. = 13.8 mm, view from the positive $x$ direction.
All of the data presented in Figures 3 and 4 seem to indicate that the red color (blob placed in the middle of the bridge region) is better distributed than the blue or the green tracers. We simulated the dynamics of particle distribution in the VIC2 mixer by placing the original clusters in different positions of the bridge region. We placed 54 clusters made of 10,000 particles in the right, middle and left side of the bridge region, respectively (Figure 5). Following the trajectories of the 10,000 particles, we show the particle distributions at different mixing times. Although the simulations were performed for a different material (SBR compound) and under different operating conditions (inter-rotor clearance of 6.5 mm and a rotational speed of 60 rpm), the results in Figure 5 agree qualitatively with the experimental observations in Figures 3 and 4. Clusters placed initially in the middle of the bridge region are better distributed than clusters placed on the sides. This outcome is a consequence of the general rotor design with a larger gap...
between the rotors in the middle of the bridge region as compared to the ones on the sides. This is particularly important at small values of the inter-rotor clearance, but affects the mixing results even at larger gap sizes. In essence, the size of the gap between the rotors governs the ratio of the circumferential to the axial flow, with the former affecting primarily distributive mixing.

To further verify our numerical model, we carried out simulations designed to mimic closely the experimental conditions. The rheological behavior of the silicone rubber used in the experimental trials was characterized using a Monsanto automatic capillary rheometer. A power law model with a Newtonian plateau region (Equation [3] below), whose parameters were obtained using a
best fitting procedure, was employed to describe the material flow properties:

\[
\tau = \begin{cases} 
-\eta_0\dot{\gamma} & \text{if } |\dot{\gamma}| \leq \dot{\gamma}_0 \\
-m|\dot{\gamma}|^{n-1}\dot{\gamma} & \text{if } |\dot{\gamma}| \geq \dot{\gamma}_0 
\end{cases}
\]  

(3)

with \( m = 32016.3 \text{ Pa.s}^n \), \( n = 0.208 \), \( \eta_0 = 13418.53 \text{ Pa.s} \), and \( \dot{\gamma}_0 = 3 \text{ s}^{-1} \). The complete mixing cycle in a VIC1 mixer with an inter-rotor clearance of 3.5 mm was modeled by choosing 36 sequential geometries to represent one revolution of the rotors. No-slip boundary conditions for the chamber wall and the rotor surfaces were employed. We used a filling factor of one and a rotational speed of 20 rpm to match the experimental conditions.
A spherical cluster of 2.5 mm diameter made of 10,000 particles was placed in the middle of the bridge region. In the experiment, colored silicone rubber was shaped into a sphere of similar size and positioned into a pre-shaped circular hole in the center of the bridge region. Since the ram slightly deformed the tracer, we cured the material in place prior to the start-up of the mixing operation and determined the exact position and shape of the colored silicone rubber. Figure 6 shows the initial position and shape of the cluster used in the simulations, matching the experimental observation.

Figures 7 to 9 show comparisons between experimental and simulation results after 9 seconds of mixing (3 revolutions), viewed from the positive $x$, negative $x$, and negative $y$ directions, respectively. In the simulations we marked by color/particles the entire trajectories of the mixing tracers. The agreement between numerical predictions and experimental data is quite good. Both the numerical simulation results and the experimental observations indicate that most of the tracer is distributed in a circumferential pattern in the mixer after 3 revolutions.

After 4 revolutions, the tracer is distributed slightly more in the axial direction, preponderantly in the right mixing chamber (positive $x$ direction). The results, shown in Figures 10 to 12 indicate a good qualitative agreement between the numerical predictions and the experimental data.

CONCLUSIONS

In this paper we review some of the numerical results obtained in our previous work for the analysis of distributive mixing in various variable intermeshing clearance (VIC) mixers. We also
performed experiments to investigate distributive mixing in these machines. Both the numerical predictions and the experimental data indicate that the VIC2 design, with an enlarged mixing chamber, shows better mixing performance than the traditional VIC1. In both mixers, increasing the inter-rotor clearance improves distributive mixing. However, enlarging the gap size too much in the bridge region of the VIC2 machine becomes detrimental for mixing. We also found that clusters placed in the middle of the bridge region are better distributed than clusters placed on the sides.

Fig. 6.—(a) Initial spherical cluster with radius of 1.25 cm deformed by ram pressure (b) Initial position of the deformed spherical cluster in the flow field of a VIC1 mixer.
Fig. 7.—Comparison between experimental and simulation results in a VIC1 mixer, I.C. = 3.5 mm, mixing time = 9 s (3 revolutions); view from the positive x direction; (a) experimental results, (b) simulation results.
Fig. 8.—Comparison between experimental and simulation results in a VIC1 mixer, I.C. = 3.5 mm, mixing time = 9 s (3 revolutions); view from the negative x direction; (a) experimental results, (b) simulation results.
Fig. 9.—Comparison between experimental and simulation results in a VIC1 mixer, I.C. = 3.5 mm, mixing time = 9 s (3 revolutions); view from the negative $y$ direction; (a) experimental results, (b) simulation results.
Fig. 10.—Comparison between experimental and simulation results in a VIC1 mixer, I.C. = 3.5 mm, mixing time = 12 s (4 revolutions); view from the positive x direction; (a) experimental results, (b) simulation results.
Fig. 11.—Comparison between experimental and simulation results in a VIC1 mixer, I.C. = 3.5 mm, mixing time = 12 s (4 revolutions); view from the negative x direction; (a) experimental results, (b) simulation results.
Fig. 12.—Comparison between experimental and simulation results in a VIC1 mixer, I.C. = 3.5 mm, mixing time = 12 s (4 revolutions); view from the negative y direction; (a) experimental results, (b) simulation results.
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