Research Article

Numerical Simulation of Mixing Characteristics in the Eccentric Rotor Extruder with Different Process Conditions and Structural Parameters

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Numerical simulation was performed with the computational fluid dynamics analysis software POLYFLOW to investigate the influence of different process conditions and structural parameters on mixing characteristics of the eccentric rotor extruder. The intensity of shear and elongational flow strengthened when the rotational speed increased, but the time for material to stay in the extruder will be reduced. At the same time, the increase of radius and eccentricity could effectively promote the mixing performance. On the contrary, the mixing capacity reduced with the increase of the pitch. The results can be useful to optimize the structure design and guide production.

1. Introduction

During extrusion processing, the mixing characteristics of the extruder are directly related to the quality of the products. In order to improve the mixing effect of polymer materials and the product performance, the eccentric rotor extruder (ERE) was invented by Qu et al. [1]. Its plasticating and conveying theory are based on elongational rheology which are totally different from the traditional screw extruder [2]. As shown in Figure 1, the ERE consists of a stator and an eccentric rotor disposed in the inner cavity of the stator. The eccentric rotor comprises multiple alternately disposed spiral segments and straight segments, and the stator cavity comprises multiple alternately disposed spiral segments and straight segments corresponding with that of the rotor. During the polymer processing, the eccentric rotor will be forced to rotate around its own axis and revolves in the long round cavity of the stator at the same speed but in the opposite direction due to the structural limitations of the inner cavity of the stator. The materials

between the stator and rotor receive the pulsed volume deformation when periodically compressed and released, thus completing the plasticating and conveying process dominated by the continuous elongation flow.

The present experimental research about the ERE proved that this innovative equipment has the advantages of low energy consumption, positive displacement transportation, strong dispersing mixing ability and wide adaptability. Wu et al. [3, 4] used the ERE to fabricate the poly(L-lactide) (PLLA)/organo-modified montmorillonite (OMMT) nanocomposites in different OMMT concentrations. The results showed that the OMMT nanoparticles were uniformly dispersed in the PLLA matrix and mainly existed in intercalation mode. The intercalation and exfoliation process of OMMT in the ERE may be a double-side exfoliation, which is more effective than the layer-by-layer peeling mechanism based on the shear flow. The OMMT nanoparticles had good dispersion and intercalation effect under the action of tensile deformation, which provided a good processing method to improve

FIGURE 1: The schematic diagram of the ERE.

the properties of PLLA and expand its application. Cao et al. [5] processed ultrahigh molecular weight polyethylene (UHMWPE) by the ERE without any processing aids and then compared with a conventional rotational batch mixer based on a shear flow. The morphological and rheological characterization verify that the technique based on the elongational flow could effectively reduce melting defects and yield more homogeneous morphology within the extruding samples relative to the conventional batch mixing. The crystallinity for the sample prepared under an elongational flow is lower than that processed under a shear flow. Lin [6] firstly introduced the ERE to prepare PP/POE blends and studied the effect of POE proportions, rotational speed and DCP contents on the structure and properties of PP/POE blends. The results showed that volume fluctuation elongational flow generated by ERE had strong dispersive mixing ability, made that POE could be dispersed evenly in PP matrix. The mechanical tests revealed that PP/POE blends had optimal values of general mechanical properties when POE content was 30% and the rotational speed was 45 r/min. The addition of DCP can both bring POE cross-linking and PP degradation. With the increase of DCP contents, the crystal size of PP increased gradually and crystallization was more and more complete. The numerical simulation method is an important method for studying extrusion processing. Chen et al. [7] used POLYFLOW to analyze the velocity profile and the flow stretching in three rotor cross sections with different geometries to reveal the relationship between the geometry and mixing ability of rotor cross section. The rotor geometry was quantified with pressurization coefficient S and the distribution was evaluated numerically with the particle tracking technology. The results showed that the rotor cross-section with larger S would have stronger mixing ability. Decreasing wedge angle α or width of wing tip e , as well as increasing maximum clearance H_0 , would induce the

increase of S , and further resulting in the improvement of the mixing ability. Rotor geometry quantification with S would intuitively reveal the relationship between rotor geometry and the mixing ability. Xu [8] proposed a new mapping method for the numerical simulation of melt flow in the complicated forward conveying element of a corotating twin screw extruder. After inputting the exported data of the flow field from POLYFLOW, used the self-developed code to characterize the mixing behavior under different rotation speeds of the screw elements. Advection evolution of passive particle groups was simulated by a fourth-order Runge–Kutta tracking method and examined the effect of screw rotation speed on distributive mixing. The results showed that the mixing was highly dependent on the initial position whether the particle groups were first placed close to or far away from the intermeshing zone. Cheng et al. [9] carried out particle tracking technique to simulate mixing process of a highly viscous Newtonian fluid in a horizontal self-cleaning twin-shaft kneader. The result of finite element method proved that the horizontal twin-shaft kneader is efficient for mixing highly viscous fluids due to the intermeshing of kneading bars. There exists a strong intermeshing interaction between the kneading bars mounted on the rotating shafts in the overlapping zone, which can disrupt the cluster and promote the material exchange in the angular position.

Prior research on the ERE has mainly focused on the theoretical description of processing, preparation and researching the composite materials formed by the ERE. However, we knew of no research on the mixing numerical simulation for the ERE and visualization of mixing process have been performed. It is desirable to use numerical simulation to study the relationship between unique structure and mixing performance. In this study, the finite element Computational Fluid Dynamics (CFD) analysis software POLYFLOW (ANSYS, Inc.,

USA) was used to perform the numerical simulation of polymeric melts flow characteristics for melt conveying section in the ERE. The numerical simulation of mixing characteristics for the ERE was performed based on the polymeric melt flow characteristics through particle tracking applied. Dispersive mixing and distributive mixing characteristics were evaluated by using the statistical post-processor program of POLYSTAT (ANSYS, Inc., USA). By modifying rotational speed, radius, pitch and eccentricity in the numerical simulation model, the effects of process conditions and structural parameters on the mixing characteristics of the ERE were studied. We suggest that the results of the study can be used for optimizing the structure design and guiding production.

2. Numerical Simulation

2.1. Models and Governing Equation. Considering the symmetry and periodicity of the model, only the 2 pitches length of the rotor geometric model was built to decrease the computational costs of the simulations. The simplified geometry model is illustrated in Figure 2.

The initial position of a rotor with radius R is located at the top of the stator inner cavity which is the fluid field. The distance between the center of the rotor and the center of the stator is 2 times the eccentricity e . The pitch of the stator inner cavity is 2 times the rotor pitch p . The clearance between the rotor and the stator h is 0.3 mm. The influence of structural parameters on mixing properties is explored by changing radius R , eccentricity e and pitch p .

As described above, the eccentric rotor rotates clockwise around its axis in the right-hand coordinate system, and counterclockwise around the center of the stator. The rotational speed ω and revolution speed have the opposite direction but the same size. The relationship between velocity v at the center point of rotor and time t can be described as follows:

$$v = \pm 2e \cdot (\cos \omega t - 1). \quad (1)$$

This complex motion can be specified using a user-defined function (UDF). Meanwhile, the model was meshed into hexahedral elements with the pre-processor GAMBIT from ANSYS, Inc., as shown in Figure 3.

The model, whose mesh was processed with the mesh superposition technique both to simplify the mesh generation and to avoid any remeshing technique or sliding meshes. It is necessary to refine the whole mesh as much as possible to improve the quality of the mesh, because the spiral structure of the stator cavity and the rotor models are easy to cause the high distortion of the three-dimensional mesh. In addition, the gap thickness in the local boundary area during the rotor movement is only 0.3 mm. In order to ensure the accuracy of simulation, the boundary layer size should increase along the radial direction of the stator cavity wall and the rotor outer surface. Finally, the stator cavity mesh of 512000 elements and 526305 vertices, and the rotor mesh of 327680 elements and 338065 vertices. The “EquiAngle Skew” in Gambit is 0–0.45 and 0–0.4, respectively, which shows that the mesh quality is well. “EquiAngle Skew” is an index for evaluating mesh quality.

FIGURE 2: Geometry model of rotor and flow domain in melt conveying section.

FIGURE 3: Mesh models of melt conveying in the ERE rotor (a) and stator cavity (b).

The closer it approaches 0, the better the mesh quality. At the initial time, the POLYFUSE module is used to combine the rotor mesh and stator cavity mesh, and the rotor mesh is moved to the top of the stator cavity as the initial position, with a gap between the two. The flow domain consists of stator and ERE rotor is filled by polymer melt in the simulation.

To perform numerical simulation of the melt flow characteristics in the ERE, some assumptions were made as follows:

- (1) The flow is laminar.
- (2) The flow is isothermal.
- (3) The fluid is incompressible and purely viscous, nonnewtonian.
- (4) No-slip near the wall.
- (5) Neglecting the inertia and gravitational forces.

Based on the assumptions for the numerical simulation, the governing equations could be described as follows:

Based on the assumptions above the control equations are as follows:

$$\text{Continuity equation : } \nabla \cdot \mathbf{u} = 0, \quad (2)$$

$$\text{Momentum equation : } \nabla \cdot \boldsymbol{\tau} - \nabla p = 0, \quad (3)$$

$$\text{Constitutive equation : } \boldsymbol{\tau} = 2\eta\mathbf{D}, \quad (4)$$

$$\mathbf{D} = \left(\frac{\nabla \mathbf{u} + (\nabla \mathbf{u})^T}{2} \right), \quad (5)$$

where $\mathbf{u}$ is the velocity vector; $\boldsymbol{\tau}$ is the stress tensor; p is the melt pressure; η is the melt viscosity; $\mathbf{D}$ is the deformation rate tensor; T is transpose. And the boundary conditions of the flow domain simulation were as follows:

Inflow and outflow: $F_n = 0$, $F_t = 0$;

Inner wall of stator: $V_n = 0$, $V_t = 0$;

Rotor: defined as moving part, the law of motion is defined by UDF.

Where F_n is normal force, F_t is tangential force, V_n is normal velocity, V_t is tangential velocity. In mixing simulation task, 1000 material points were located initially at the inflow, the inner wall of stator was nonpenetrable.

2.2. Material and Methods. In this paper, we select PP (N-Z30S, Sinopec Guangzhou branch) as simulation material. As an initial approximation, the PP melt was simplified as an isothermal and generalized newtonian fluid with a Bird-Carreau law relationship describing its shear-thinning behavior.

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)(1 + \lambda_t^2 \dot{\gamma}^2)^{(n-1)/2}, \quad (6)$$

where η is the shear viscosity, η_∞ is infinite-shear-rate viscosity, η_0 is zero-shear-rate viscosity, λ_t is natural time, $\dot{\gamma}$ is shear rate and n is the power-law index. The parameters in the Bird-Carreau law were determined in a rotary rheometer as follows: $\eta_0 = 1162 \text{ Pa} \cdot \text{s}$, $\eta_\infty = 0.23 \times 10^{-3}$, $\lambda_t = 0.67 \text{ s}$ and $n = 0.64$. The shear viscosity curve and the fitting curve of the Bird-Carreau model as shown in Figure 4.

In this paper, using the transient, isothermal model and iteration solution, mini-element interpolation was used for the velocity, linear interpolation for the pressure, Pichard interpolation for the viscosity. Discretize the Equations (2)–(6) and solve the discretized equations using the implicit Euler method.

Many ways of characterizing mixing have been proposed over the years, with no one method being able to quantify all aspects of mixing for every process. Given a motion $\mathbf{x} = \chi(\mathbf{X}, t)$ where initially $\mathbf{X} = \chi(\mathbf{X}, 0)$ for an infinitesimal material line segment $d\mathbf{x} = \mathbf{F} \cdot d\mathbf{X}$ located at position $\mathbf{x}$ at time t where the deformation tensor is $\mathbf{F} = \nabla \chi$, the length of stretch of a material line is defined as $\lambda = |d\mathbf{x}|/|d\mathbf{X}|$. Then the local efficiency of mixing e_λ is then defined as [10, 11]:

$$e_\lambda = \frac{\dot{\lambda}/\lambda}{(\mathbf{D} : \mathbf{D})^{1/2}} = \frac{D \ln \lambda / Dt}{(\mathbf{D} : \mathbf{D})^{1/2}}, \quad (7)$$

where the rate of strain tensor $\mathbf{D}$ is the symmetric part of the velocity gradient tensor. This efficiency quantitatively characterizes the stretching rate during mixing and can be thought of as the fraction of the energy dissipated locally that is used

FIGURE 4: The fitting curve of PP melt under the Bird-Carreau model.

to stretch fluid elements. The time averaged efficiency is defined as [12]:

$$\langle e_\lambda \rangle = \frac{1}{t} \int_0^t e_\lambda dt. \quad (8)$$

For 3D flows, let define an infinitesimal surface “ dA ” with a normal direction $\hat{N}$. With time, this surface deforms; at time t , this surface is noted “ da ”, with a new normal direction $\hat{n}$. The area stretch S is the ratio of the deformed surface “ da ” at time t , over the initial surface “ dA ”, $S = S(\mathbf{X}, \hat{N}, t) = da/dA$, then we have [13, 14]:

$$e_s(\mathbf{X}, \hat{N}, t) = \frac{\dot{S}/S}{D}, \quad (9)$$

$$\langle e_s \rangle(\mathbf{X}, \hat{N}, t) = \frac{1}{t} \int_0^t e_s(\mathbf{X}, \hat{N}, t) dt. \quad (10)$$

Extensional flow is much more efficient to break up droplets than shear flow. In order to estimate the fraction of the matter going through extension, the mixing index M was defined as follows [15, 16]:

$$M = \frac{\dot{\gamma}}{\dot{\gamma} + \omega}, \quad (11)$$

where $\dot{\gamma}$ the equivalent shear rate, ω is the magnitude of the vorticity vector. The mixing index can range from 0 to 1. At 0, the flow is locally a plug flow; at 0.5, the flow is locally a pure shear flow; while at 1, the flow is locally a pure extensional flow [17, 18].

The flow field inside the mixing section of the ERE was simulated by POLYFLOW. After the flow field was computed,

FIGURE 5: Dispersion of particles in one rotation cycle.

a mixing task was executed by using the mixing module program to calculate the trajectories of 1000 material points which were located initially at the entrance of melt conveying in the ERE. Then, the mixing characteristic parameters inside the flow domain were analyzed using POLYSTAT statistical module to evaluate the local value of the mixing characteristic parameters respectively.

3. Results and Discussion

3.1. Visualization of Mixing Process. The EXTRACT function of POLYSTAT can be used to observe the trajectory of the tracking particles at every moment and the results can be used to evaluate the dispersion of particles in the flow field. The images of the tracking particles in one rotation cycle shown in Figure 5. The parameters for this simulation are as follows: radius $R = 17$ mm, pitch $p = 16$ mm, eccentricity $e = 3$ mm, rotational speed $n = 25$ r/min. The 1000 tracking particles with different colors were fed instantaneously in the inflow of the melt at 0 s. Five different colors of particles represent different materials. The particles gradually began to disperse with the rotation of the rotor. After a rotation period, the particles with different colors have a good dispersion effect. This indicates that the ERE had a great dispersive capability.

The distribution functions of distance between neighbouring points at different times could be calculated in the Figure 6.

At start, all points were close together: this corresponds to the black peak curve in the left chart. Next, as points distributed, the distance between particles increased with the rotation of the rotor. Their inter-distance increased leading to a widening and a flattening of the distribution functions. This shows that as distribution improves, the distribution of particles is random in the extruder.

The percentile shows the results of the application of mathematical statistics to the mixing characteristic parameters. In statistics, a percentile is the value of a variable below which a certain percent of observations fall. For example, If the maximum shear rate corresponding to the 10th percentile is 100/s, it means that the maximum shear rate experienced by 10% of the particles is less than or equal to 100/s, and the maximum shear rate experienced by 90% of the particles is greater than 100/s. In this paper, the influence of different rotor rotational speed and structural parameters on mixing performance was

FIGURE 6: Distribution functions of distance between neighbouring points at different times.

studied based on the maximum shear rate, stretching rate, time averaged efficiency, mixing index and the residence time distribution. The results shown as 10%, 50%, 90% percentile curves to give a clearer distribution of the mixing characteristic parameters. Three percentiles represent the largest, middle and smaller values, respectively.

3.2. The Influence of Rotor Rotational Speed on Mixing Properties. The percentile of the mixing characteristic parameters with different rotational speeds was selected after a rotation cycle. The speed was set to 15, 25, 35, 45, and 55 r/min, respectively. And the basic dimensions of the model are as follows: radius $R = 17$ mm, pitch $p = 13$ mm, eccentricity between the stator and rotor $e = 3$ mm. The mixing characteristic parameters with different values for rotational speed are shown in Figure 7.

Figure 7 shows the maximum shear rate and maximum stretching rate in various percentiles of the particles experienced under the different rotational speeds. With the increase of the rotational speed, the maximum shear rate and stretching rate gradually increased for each of the three percentiles. When the percentile is 50%, the maximum shear rate and stretching rate increased the most from 35 r/min to 45 r/min. This shows that half of the particles experienced the fastest increase in the maximum stretching rate and shear rate. When the percentile is 90%, the increase of the maximum shear rate and stretching rate experienced from 35 r/min to 45 r/min and from 45 r/min to 55 r/min were the fastest. The speed of improving the mixing performance through comparative analysis three percentiles is the most obvious when the rotational speed is 45 r/min.

The maximum time averaged efficiency and mixing index experienced by the particles in the three percentiles under the different rotational speeds are shown in Figure 8. All the maximum time averaged efficiency curves in the graph were larger

FIGURE 7: Influence of rotor rotational speed on the maximum shear rate (a) and stretching rate (b).

FIGURE 8: Influence of rotor rotational speed on the maximum time averaged efficiency (a) and mixing index (b).

than 0, indicating that almost all particles experienced the stretching flow. In the 90th percentile, the maximum time averaged efficiency were larger than 0.37 at the end of one cycle, which means in these particles about 37% of the mechanical energy was used to generate stretching. When the speed is 45 r/min, the mechanical energy used to stretch the melt is most. The maximum mixing indexes for rotational speed were close in the 10th percentile and the 50th percentile. The maximum mixing indexes under different speeds were greater than 0.67 in the 90th percentile, which means that more particles experienced extensional flow. In the 90th percentile, the maximum mixing index showed a zigzag change with the speed increased, and reached the maximum at the speed of 45 r/min.

When the rotational speed increased, the intensity of flow field strengthened, but the time for the material to stay in the extruder will be reduced. Therefore, the residence time distribution should be taken into account in evaluating the mixing performance.

There were more than one wave peak in each residence time distribution curve, indicating that the particles left the exit in a batch. And the time of the first wave peak on each curve was about in the 3/4 rotation period. In addition, the overall width of residence time distribution narrowed with the rotational speed increased. The residence time distribution of 15 r/min and 25 r/min was obviously better than other rotational speeds, and the residence time distribution width of 45 r/min was greater than 35 r/min or 55 r/min by observing

FIGURE 9: Influence of rotor rotational speed on residence time distribution.

the width of the peak residence time distribution curve in the Figure 9.

In general, the shear rate and the stretching rate increased with the increase of the rotational speed, and the fastest increase from 35 r/min to 45 r/min. The mixing index and the time average mixing efficiency were not obviously affected by the rotational speed, and the mixing index and the time averaged mixing efficiency reached maximum near the 45 r/min. The residence time of the material in the ERE was shortened as the speed increased. The residence time of 45 r/min is longer when compared to 35 r/min and 55 r/min. In summary, the ERE has the best mixing performance when the rotational speed is 45 r/min. The result of numerical simulation is in agreement with the experimental results of Lin [6]. He used eccentric rotor extruder to process PP/POE (70/30) blends. The mixing of POE elastomer particles in PP matrix was characterized by SEM and mechanical properties test. Through the experiment, it found that the mixing effect was the best when the rotating speed was 45 r/min, which was consistent with the numerical simulation results in this paper. It validated the reliability of the numerical simulation method to study the mixing performance of eccentric rotor extruder.

3.3. The Influence of Rotor Radius on Mixing Properties. The structural factors of the equipment have an important influence on the practical application of the plastic processing equipment. In order to observe the influence of the rotor radius on the mixing performance of the ERE, select different values for radius such as 13, 15, 17, 19, and 21 mm. The rotational speed was 45 r/min and other structural factors were the same as those of the previous basic models. The influence of rotor radius on the maximum shear rate and stretching rate is shown in Figure 10.

There was an evident increase for the maximum shear rate and stretching rate increased in the 90th percentile, and slight change in the 10th and 50th percentiles. The proportion of

(a)

(b)

FIGURE 10: Influence of rotor radius on the maximum shear rate (a) and stretching rate (b).

particles at high shear rate and stretching rate increased with the increase of the radius, especially the stretching rate increased more obvious. This is because the increase of the radius will increase the radial length of the rotor while the rotational speed and other structural parameters remain unchanged. The volume and weight of the rotor will become larger, and the force of the rotor on the melt will be greater at the same speed, so the maximum shear rate and stretching rate experienced by the particles will increase. High shear rate and stretching rate are good for the breaking up of the material particles into small ones.

The effect of radius on the maximum time averaged efficiency and mixing index, as shown in Figure 11. In the 10th percentile and the 50th percentile, the maximum time averaged mixing efficiency and mixing index did not change significantly with the increase of rotor radius. But the maximum time-averaged mixing efficiency and mixing index in the 90th percentile showed an upward trend as a

FIGURE 11: Influence of rotor radius on the maximum time averaged efficiency (a) and mixing index (b).

whole. Meanwhile, the maximum time averaged mixing efficiency and mixing indexes of various percentiles were almost all above 0 and 0.5 respectively, illustrating that there was a strong stretching flow field in ERE with different radius. Because although the size of the geometric model changed, a strong stretching flow field could still be generated based on topological structure and motion law remain unchanged.

It can be seen from the Figure 12 that the cures of residence time distribution under different radius almost coincided. Thus, we can make the conclusion that the change of the radius had little impact on residence time distribution. In summary, the maximum shear rate, stretching rate, time averaged efficiency and mixing index increased in the 90th percentile, but changed slightly in the 10th and 50th percentiles when the radius increases. The change of the radius can significantly affect the upper limit of the mixing characteristic

FIGURE 12: Influence of rotor radius on residence time distribution.

parameters which indicates that the increase of radius can promote the mixing performance of the ERE. At the same time, there was a particularly small impact on residence time distribution with the change of radius.

3.4. The Influence of Rotor Pitch on Mixing Properties. For the sake of studying the influence of pitch on the mixed performance of ERE, the pitch was selected as 12, 14, 16, 18, and 20 mm, respectively. Just as the control variable method which previous mentioned, other conditions remained unchanged. For example, there were rotational speed 45r/min, radius $R = 17$ mm, pitch $p = 13$ mm, eccentricity $e = 3$ mm. Influence of rotor pitch on the maximum shear rate and stretching rate as shown in Figure 13.

With the change of pitch, the maximum shear rate and stretching rate changed a little in the 10th and 50th percentile. It can be seen that the maximum shear rate and stretching rate in the 90th percentile declined and the rate of decline was various which indicated that the increase of pitch reduced the mixing performance of the ERE. This is due to the fact that the curvature of the helical surface in the rotor and stator cavity decreases and the force on the melt decreases with the increase of the pitch of the rotor while the eccentricity and the radius of the rotor remain unchanged.

The maximum time averaged efficiency and mixing index experienced by the particles under different pitches shown in Figure 14. The maximum time averaged efficiency decreased fluctuated but did not change significantly. The maximum mixing index under the different pitches decreased in 90th and 50th percentiles, which means that the proportion of extensional flow in melt decreased gradually. This may be associated with the spiral lines of the stator and the rotor soothed from steep with the increase of pitch. When the pitch increased infinitely, the geometric shape of the rotor and stator cavity is closer to the cylinder. At this time, the pressure fluctuation of the melt decreased, which made the volume tension deformation and extensional flow decrease.

(a)

(b)

FIGURE 13: Influence of rotor pitch on the maximum shear rate (a) and stretching rate (b).

There was little change about the curves of residence time distribution under different pitches in Figure 15. As a result, no matter how the pitch changed, the residence time distribution was almost the same. In summary, the maximum shear rate, stretching rate, and mixing index showed a stepped downward trend in the 90th percentile, which indicates that the increase of pitch can reduce the mixing performance of the ERE.

3.5. The Influence of Eccentricity on Mixing Properties. The eccentricity e between the rotor and stator is one of the key structural parameters for the ERE. The size of the eccentricity directly affects plastic melt volume changing during the machining process. The eccentricity was selected as 1.0, 1.5, 2.0, 2.5, and 3.0 mm. Influence of eccentricity on the maximum shear rate and stretching rate as shown in Figure 16.

There was an evident increase for the maximum shear rate increased in the 50th and 90th percentiles. It is not obvious for the maximum shear rate changed in the 10th percentile.

(a)

(b)

FIGURE 14: Influence of rotor pitch on the maximum time averaged efficiency (a) and mixing index (b).

The maximum stretching rate increased obviously in the 90th percentile. The proportion of particles at high shear rate and stretching rate increased with the increase of the eccentricity. When the eccentricity increases, the height of chambers between the rotor and stator cavity increases along the radial direction, and the geometric shape of the rotor and stator cavity becomes more sharp and convex. Therefore, the force produced by ERE on the melt increases and improves blending effect with the increase of eccentricity.

The maximum time averaged efficiency and mixing index under different eccentricities are shown in Figure 17. It can be found clearly from the figure that the maximum time averaged efficiency and mixing index increased in various percentiles. When the eccentricity increased, the radial travel and centrifugal inertia force of the rotor increased, so the maximum time averaged mixing efficiency increased due to the mechanical dissipation acting on the tensile flow field raised. The increase of eccentricity would increase the axial eccentricity of the cross

FIGURE 15: Influence of rotor pitch on residence time distribution.

FIGURE 16: Influence of eccentricity on the maximum shear rate (a) and stretching rate (b).

FIGURE 17: Influence of eccentricity on the maximum time averaged efficiency (a) and mixing index (b).

FIGURE 18: Influence of eccentricity on residence time distribution.

section of the rotor and stator cavity, and the rate of volume change of the enclosed chamber increased could strength the pulsed volume deformation of melt, so the stretching flow increased. Above explanation suggests that increasing the eccentricity is beneficial to improve the mixing performance.

It can be seen from the Figure 18 that the eccentricity had little effect on the residence time distribution. The distribution of the residence time is almost irrelevant to the structural factors, but greatly influenced by the rotational speed.

4. Conclusions

The influence of different rotor rotational speed and structural parameters on mixing performance was studied based on some mixing characteristic parameters such as the maximum shear rate, stretching rate, mixing index, time averaged efficiency and the residence time distribution. The intensity of shear and elongational flow strengthened when the rotational speed increased, but the time for material to stay in the ERE will be reduced. The ERE has the best mixing performance when the rotational speed is 45 r/min overall consideration, because it has the highest flow intensity and the optimal residence time distribution. In the aspect of structural parameters, the increase of radius and eccentricity can promote the mixing performance of the ERE. On the contrary, the mixing capacity reduced with the increase of the pitch. At the same time, there was a particularly small impact on residence time distribution with the change of structural parameters.

Data Availability

All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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