Mixing Characteristics of Polymer Melt in Triple Screw Extruders with Combined Screws using Finite Element Method

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Abstract. The triple screw extruder is a new equipment of polymer processing. A three-dimensional modelling of a triple screw extruder with combined screws of convey and mixing elements is adopted to investigated the flow and mixing characteristics by using Polyflow software based on finite element method. The axial velocity and pressure distributions in the special central region of the triple screw extruder are specially analyzed. Some mixing evaluated parameters, such as area stretching rate, the probability of mixing index, segregation scale and residence time distribution in different boundary conditions are calculated based on particle tracing method. Moreover, the effects of screw clearance and inlet flow rate of combined screws on the mixing characteristics of polymer melt are discussed. The results show that the increase of the screw clearance can increase the residence time and improve the mixing efficiency of extruder. With the decrease of inlet flow, the distributive mixing efficiency in the triple screw extruder increase gradually.

1. Introduction
In recent years, a new type of triple-screw extruder is developed gradually in polymer industry, which can better meet the needs of high-efficiency and energy-saving products. There are many reports [1,2] on numerical simulations of flow and mixing characteristics of triple-screw extruders with simple screw elements. The special central region and three intermeshing regions of the triple-screw extruder make its geometry more complex, which is determined by the combination forms of the combined screw. Screw element is the core component of triple-screw extruders, which determines the mixing quality. In the process of mixing, the area of the geometric center region presents a dynamic periodic change of ‘large-small-large’ in the process of screw rotation, and the clearance between three
screws has a great effect on the area of the central region, especially when the area of the central region is the smallest. At the same time, polymer melt in the clearances of multiple intermeshing regions and between the barrel and screws has also great shear rate for increasing the material mixing, so the clearance size is one of the important factors affecting the mixing properties of the triple-screw extruder \cite{3-5}.

Boundary conditions also has a great effect on the melting and mixing of polymer melt in the triple-screw extruder with combination screws \cite{6,7}. In this paper, the influence of the inlet flow rate on the material mixing is studied quantitatively. The velocity distribution and shear rate distribution of the axial section, as well as the axial average area stretching rate distribution, axial pressure distribution, area stretching rate probability, separation scale and other mixing evaluation parameters are compared and analyzed. This study focuses on the influence of different clearance and inlet flow rate of the triple-screw extruder on the mixing efficiency, which provides theoretical reference for the optimal design of the new triple-screw extruder.

2. Finite element model and simulation conditions

The geometric model of the combined screw of the triple-screw extruder in this paper is shown in Figure 1. The establishment of the finite element model uses the GAMBIT software package. In order to more accurately observe the extruder clearance between the screw and the barrel, a two-layer boundary layer is used to divide the grid of the central region. The total number of grids and nodes of the finite element model in the triple-screw extruder are 56160 and 69322, respectively. The finite element model and rotation direction of three combined screws are shown in Figure 1b. The total number of grids and nodes of three combined screws are 32125 and 9637, respectively. Mesh superposition technique is used to combine the flow region and screws \cite{8-10}.

In order to study the influence of screw clearances on the flow field of the combined screw, three models with screw clearance of 0.3mm, 0.5mm and 0.8mm are selected, respectively. For the comparative analysis of different inlet flow, the inlet flow of the combined screw with a clearance of 0.5mm is set as $2.5 \times 10^{-6}$ m$^3$/s, $6 \times 10^{-6}$ m$^3$/s and $10 \times 10^{-6}$ m$^3$/s, respectively. Boundary conditions are following as: set the normal speed and tangential speed of the inner surface of the barrel as zero, that is, $V_n=0$, $V_s=0$; screw speed as 50 r/min; set the normal force and tangential force at the flow outlet as zero, that is, $F_n=0$, $F_t=0$. The parameters of polyethylene material is not sensitive to temperature.

![Figure 1. Finite element model of triple-screw extruder.](attachment:image_url)
3. Results and discussions

3.1. Velocity distribution

Figure 2 shows the velocity distribution of the central axis section of the combined screw at $t=0.2s$ under different clearances. Observing the distribution of the cloud image, a blue back flow area is generated at the position of reverse kneading block. The screw element has a certain forward conveying capacity. Under different screw clearances, the change of each group's cloud image is not obvious. Observing the left scale of each group's numerical distribution, we can see that with the clearances increasing gradually, the velocity distribution in Z direction decreases slightly in turn. The above phenomenon shows that with the increase of screw clearance, the axial velocity keeps the original distribution trend, but it can reduce the axial velocity to a certain extent, which is beneficial for material mixing.

![Figure 2. Axial velocity distribution of different screw clearances](image)

3.2. Pressure distribution

Figure 3 shows the pressure distributions of the central axis section of the combined screw at $t=0.2s$ under different clearances. Observing the cloud map distribution, the pressure distribution trends of the triple screw extruders in different screw clearance are basically same. The polymer particles experience the process of pressure decreasing from the inlet to the outlet. In the position of kneading block, the trend of pressure reduction is more obvious. This is because the kneading block element belongs to the mixed element and has the function of reducing pressure, while the screw element belongs to the conveying element and has the function of building pressure. At the same time, it can be concluded that with the decrease of screw clearance in triple screw extruder, the change of pressure difference decreases in turn, but the pressure distribution keeps the decreasing trend. Generally, the larger the decreasing pressure difference is, the more favorable it is for the polymer particles to be fully mixed, while the maximum pressure difference is for the combined screw with a clearance of 0.3mm.

![Figure 3. Pressure distribution of different clearance sections](image)
3.3 Effect of screw clearance on the mixing characteristic

Figure 4a shows the probability distribution of mixing index of four kinds of combined screws under different clearances. When the mixing index is between 0 and 0.5, the flow pattern is shear, when the mixing index is greater than 0.5, the flow pattern is stretch, and the contribution of stretch flow to the mixing is higher than that of shear flow. It can be seen from the Figure 4a that as the screw clearance increases in turn, the curve shows a slight shift to the right in black, red and blue, which shows that the shear and tensile flow increases slightly with the gap, and the dispersion and mixing effect becomes better and better with the screw clearance increasing.

Figure 4. Effect of screw clearance on the mixing index and residence time distribution

Particle tracer technology is adopted [11] to study the flow law of particles on the trajectory. After the calculation, post-processing Settings are made in polystat and corresponding processing results were obtained. Figure 4b shows the residence time distribution (RTD) curve of the combined screw. For convenience of observation, the curve is locally amplified in the figure. As can be seen from the figure, each group of curves is close to each other, which is a quantitative analysis. $\Delta T$ is usually used to represent $T_{75}-T_0$, and $T_0$ represents the outflow time of the first particle. $T_{75}$ represents the time for 75% of particles to flow out of the flow field. The smaller $T_{75}$ is, the more favorable it is for mixing. The smaller the $\Delta T$ value, the better the mixing effect will be. Therefore, appropriately increasing the gap can increase the residence time distribution and improve the polymer mixing quality.

3.4 Effect of inlet flow on the mixing characteristics

Figure 5a is the distribution of the logarithmic of area stretching rate in the combined screw of the triple screw extruder. It can be seen Figure 5a that the axial direction shows an exponential increase trend, which is one of the necessary conditions for effective laminar mixing, indicating that the combined screw of the triple-screw extruder has a good dispersive mixing capacity. With the decrease of the inlet flow in turn, the magnitude of logarithmic of area stretching rate increases obviously, and the magnitude of logarithmic of area stretching rate with $2.5\times10^{-6}$ m$^3$/s inlet flow is much higher than that of $6\times10^{-6}$ m$^3$/s and $10\times10^{-6}$ m$^3$/s inlet flow. The magnitude of red curve is 41.4% higher than that of blue curve, and the magnitude of black curve is 118.0% higher than that of red curve. The large difference shows that the stretching effect increases with the decrease of the inlet flow rate, and the stretching effect increases with the decrease of the inlet flow rate. However, the area stretching rate is
one of the important parameters to measure the efficient mixing of particles. Many literatures have reported that the tensile effect is more beneficial to the dispersive mixing of extruders than the shear effect.

![Logarithmic of area stretching rate and segregation scale](image)

**Figure 5.** Effect of inlet flow on logarithmic of area stretching rate and segregation scale

Figure 5b shows the comparison curve of the segregation scale of the combined screw under different inlet flows. For the convenience of observation, a partially enlarged view is placed in the figure. Observing the curve, the separation scale of each group has a sharp decline at the beginning, indicating that the distribution and mixing ability is strong at this stage, and then the separation scale curve is relatively stable, and each fluctuates within a small range. With the increase of the inlet flow, the mesoscale curves of each group also increased in turn. The separation scale is a parameter to evaluate the overall distribution and mixing ability of extruder, and it cannot get the specific position of weak mixing ability from the distribution curve. When the separation scale is reduced, the concentration difference of particle distribution is reduced, and the distribution and mixing ability is better. Therefore, as the inlet flow decreases in sequence, the segregation scale decreases, and the distribution and mixing ability increases in sequence.

4. Conclusions

By comparing and analyzing the visual results of axial velocity, pressure and shear rate of the combined screw under different clearances, and further studied the influence of different clearances on the fluid flow field characteristics of the combined screw through more intuitive curve statistical analysis. The results show that the small clearances make the shear action of polymer particles more intense in the meshing region. However, increasing the clearances can reduce the axial velocity and the frequency of high shear action. Moreover, increasing the clearances can enhance the tensile flow, which is conducive to the full mixing of particles. Small clearances can reduce the separation scale, but the RTD curves show that the $\Delta T$ value of the combined screw with large clearance is smaller. Therefore, properly the increase of the screw clearance can increase the residence time and improve the mixing quality of the product.

Moreover, the influences of different inlet flows on the fluid flow and mixing characteristics of the combined screw are investigated based on the statistical analysis. The results show that increasing the inlet flows can slightly enhance the shear rate. However, the combination of relatively small inlet flow
can effectively reduce the axial velocity, that is, shorten the time of high shear action. With the decrease of the inlet flow, the tensile action becomes more frequent, and the mixing of particles in the smaller inlet flow is subjected to a stronger tensile action. The increase of inlet flow can increase the negative pressure difference. However, with the decrease of inlet flow, the separation scale decrease and the distribution mixing capacity gradually increase. At the same time, the smaller the inlet flow, the more reasonable the RTD curves distribution and the better the mixing effect. Therefore, it seems that the mixing effect of smaller inlet flow is more ideal.

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