2018 7th International Conference on Advanced Materials and Computer Science (ICAMCS 2018)

Numerical Simulation of Dynamic Flow in Four Screw Extruders Using 2D Finite Element Method with Particle Trajectories

Junxue You[a, *], **Xiangzhe Zhu**[b]

School of Mechanical Engineering, Liaoning Shihua University, Fushun, Liaoning, China

[a] arisnow@163.com, [b] xzzhu@126.com

*corresponding author

Keywords: Rhombic-layout four screw extruder, Numerical simulation, Mixing efficiency.

Abstract: A novel rhombic-layout four screw extruder was designed based on the conventional twin-screw extruder. A numerical simulation of two-dimensional flow field in this four screw extruder, as well as in the twin screw extruder, was carried out using the finite element method (FEM) and the mesh superposition technique (MST) provided by the commercial CFD code, Polyflow. The purely viscous fluid was assumed to obey the Bird-Carreau constitutive model. On the basis of the velocity field, we used statistical post-processing software, Polystat, to calculate the typical mixing evaluation parameters, such as the time-averaged efficiency, instantaneous efficiency, logarithmic stretch and rate of dissipation in the four screw extruder, and compared the aforementioned parameters with the twin-screw extruder. Moreover, the advantages of four-screw extruder can be comprehensively analyzed in comparison with the twin screw extruder. Moreover, trajectories of the particle groups were captured easily, and the difference of dynamic characteristics between the four and twin screw extruder were employed from dynamic viewpoint. The results show that mixing is highly dependent on the initial position of the particles and that the four screw extruder had better distributive mixing ability than the conventional twin screw extruder.

1. Introduction

The four-screw extruder is a new type of equipment gradually developed in recent years. It can meet the better demand of high efficiency and energy saving and can be used in the follow-up processing of petrochemical products. Considering the limitation of conventional single and twin screw extruders, their ordinary structure reflects a relatively poor mixing efficiency. So different kinds of combinations or different arrangement forms of the same parts are often used in production to meet the different demands of production and processing [1].

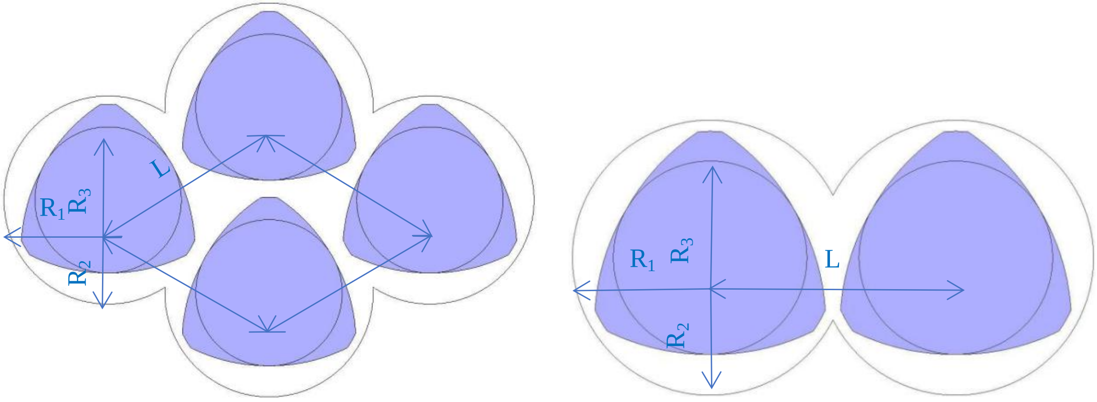
The mixing mechanism of the combined screw extruder is more complex than that of the conventional single or twin screw extruder. Multi-screw extrusion technology, with its unique advantages, can make up for the shortcomings of single or twin screw extrusion, and is getting more and more attention in recent years. In the field of extrusion, the current research has been focused on tri-screw extruder with one font and triangle arrangement [2]. So, we designed a four screw extruder with codirectional conventional thread elements based on the structures of existing extruders as the research object. The two-dimensional flow in the complicated conveying screw element channels of a corotating four-screw extruder was solved using FEM and MST mentioned before to establish the physical model and to calculate the distributive mixing ability using particle tracing technique,in order to study the special flow law of material particles in the center section of four-screw extruder [3]. Evaluated the mixing performance of the two screw extruders and discuss the particle trajectories formed by a randomly released particle, the trajectory of single particle is easy to show its mixing mechanism [4-5].

2. Theoretical model

2.1. Physical model

The physical model of a rhombic-layout four screw extruder is displayed as Figure 1a. The sizes of the four screw extruder are as follows: the barrel diameter is R_1=18.5mm, the inner diameter is R_2=13mm, the outer diameter is R_3=17mm, the centerline distance is L=33mm. With the periodic rotation of the screw, the central areas of the two triangles show corresponding periodic changes.

To compare the experimental data, the twin-screw extruder with the same data as rhombic-layout four screw extruder is also designed, its physical model is shown as Figure 1b.



(a) Four screw extruder (b) Twin screw extruder

Figure 1 Physical models of the rhombic-layout four screw and twin screw extruder.

2.2. Mathematical model

Finite element method (FEM) simulations were carried out by the commercially available CFD software, Polyflow, by Fluent Inc., using a mixed Galerkin formulation. The isothermal continuity and momentum equations are respectively expressed as

$$\nabla \cdot v + \frac{\beta}{\eta} \Delta P = 0 \tag{1}$$

$$H(\mathrm{v} - \bar{\mathrm{v}}) + (1 - H)(-\nabla P + T + \rho g - \rho a) = 0 \tag{2}$$

The stress tensor is described as:

$$T = 2\eta(\dot{\gamma}) D \tag{3}$$

The simulations modeled the stress response with the Bird-Carreau equation:

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)[1 + (\lambda\dot{\gamma})^2]^{(n-1)/2} \tag{4}$$

The parameter values for the zero shear viscosity ($\eta_0 = 5520 Pa \cdot s$), for the infinite shear viscosity ($\eta_\infty = 0$), $\dot{\gamma}$ is the rate of shear, $\lambda = \sqrt{2\Pi_D} = 0.049\mathrm{s}$, $n = 0.5$.

The mixing index λ_{mz}, listed as follows, is widely used to evaluate the dispersive mixing.

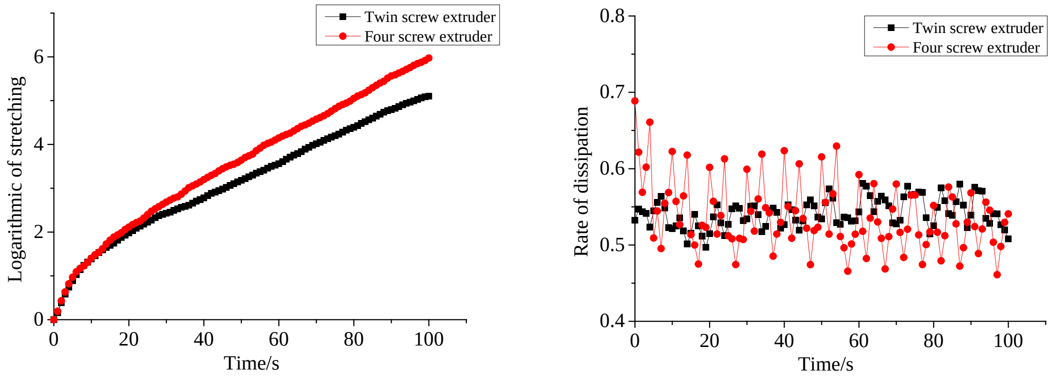
$$\lambda_{\mathrm{mz}} = \frac{|\mathbf{D}|}{|\mathbf{D}| + |\mathbf{W}|} \tag{5}$$

Where λ_{mz} ranges from 0 to 1. when λ_{mz} equals 0, consider it as pure rotating flow. When λ_{mz} equals 0.5, consider it as simple shear flow. When λ_{mz} equals 1, consider it as pure tensile flow.

3. Results and discussion

3.1. Logarithmic stretch and rate of shear

Logarithmic stretching is an important tool for comparing mixing efficiency. It can be seen from Figure 2a that the tensile rate of the screw extruder increases exponentially with the increase of time, which is a characteristic of chaotic mixing. The value of four-screw extruder is always greater than that of twin-screw extruder. In terms of the rate of shear, with the images shown as Figure 2b, both kinds of arrangements show periodic fluctuation. Also the fluctuation of the four-screw extruder is more intense than that of the twin-screw, reflecting a better mixing efficiency.

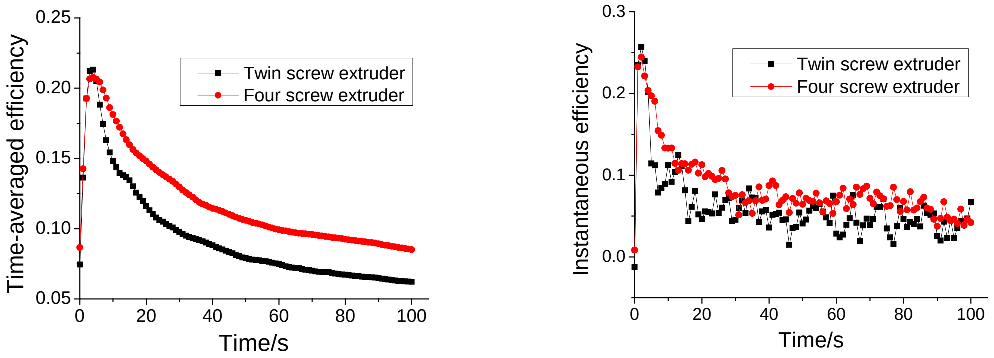


(a) Logarithmic stretching (b) Rate of dissipation

Figure 2 Comparison of logarithmic stretching and rate of dissipation between two models.

3.2. Time-averaged efficiency and instantaneous efficiency

As the mixing time increases,the value of time-averaged efficiency is greater than 0 and tends to be smooth, which is a necessary condition for effective mixing of screw extruder. According to the curve of time-averaged efficiency shown as Figure 3a, the maximum time-averaged efficiency of twin-screw extruder is slightly larger than that of four-screw extruder, and then followed by a rapid decline, the curve is always below the four-screw curve. Figure 3b compares the average instantaneous mixing efficiency between the two extrusion sections, finding that the average instantaneous mixing efficiency in all models present a steep rise at the beginning of the curve, and then it gets smaller and smaller over time. Considering its special structure, the particles are usually in a complex state of stretching with a positive instantaneous efficiency or compressing with a negative instantaneous efficiency, causing an aperiodic fluctuation of instantaneous mixing efficiency as shown in the figure. From the curve we can see that the instantaneous mixing efficiency of rhombic-layout arrangement is higher than that of twin-screw after the fluctuation tends to stabilize. These two curves are shown as Figure 3.

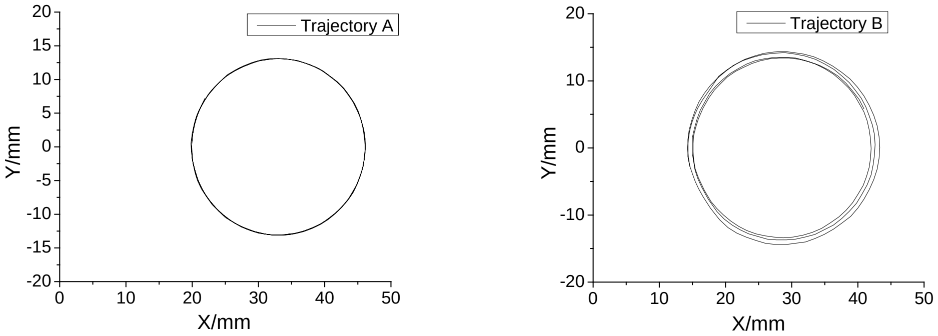


(a) Time-averaged efficiency (b) Instantaneous efficiency

Figure 3 Comparison of time-averaged efficiency and instantaneous efficiency between two kinds of models.

3.3. Distributive mixing

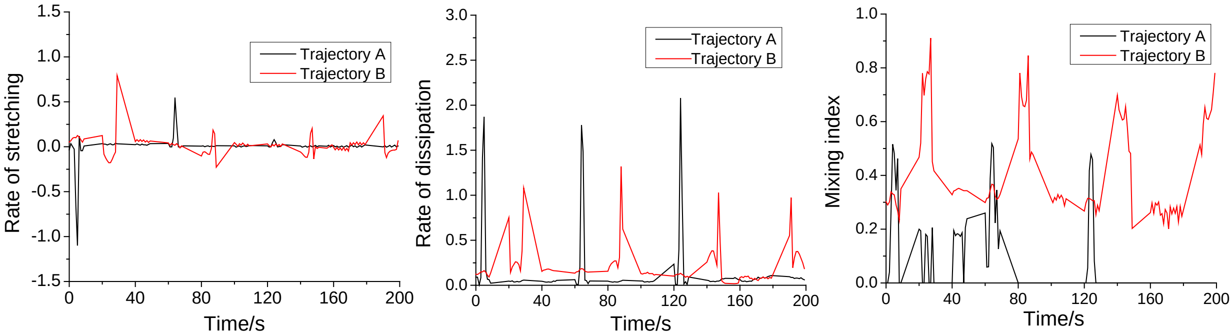
The particle trajectories were varied as the extruder mixing the melt. The tracking time was set as 200s. At the rotational speed of 1 rpm, two tracer particles moving in twin screw extruder and four screw extruder were randomly chosen, and their trajectories are as follows. One displays the particle moving around the root of the twin screw, defined as trajectory A, which is shown in Figure 4a. Defined the particles moving around the right screw in the four screw as trajectory B,shown as Figure 4b.



(a) Twin screw extruder (b) Four screw extruder

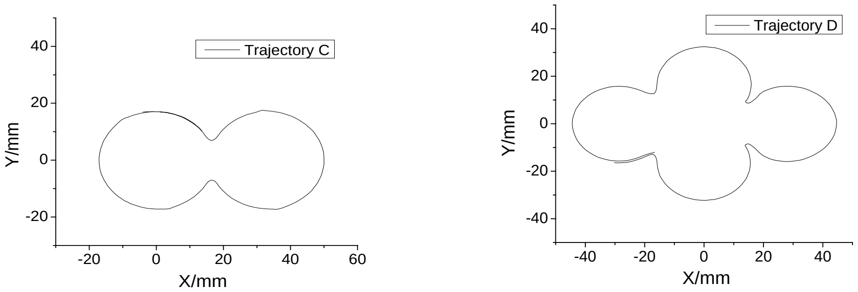
Figure 4 Two trajectories moving in the root of twin and four screw extruders.

While calculating the trajectories of these particles, we also recorded the rate of stretching, shear rate, mixing index of the particles at each time, to analyze the material particles statistically. It is clear to see from Figure 5 that the fluctuation of the rate of stretching is more intense than that of twin-screw. The reason why the tensile rate fluctuates violently is that the particles are extruded by more than one screw as they passed through the center, the mixture works better at this point. The mixing index of the four-screw extruder is far more than the twin-screw extruder, especially when the rate of stretching fluctuates strongly. The maximum mixing index of twin-screw root is 0.5, and the four-screw can be as much as 0.9. The mixing effect of four-screw at the root of screw proves better than that of twin screw extruder.



(a) Rate of stretching (b) Rate of dissipation (c) Mixing index

Figure 5 Comparison of the rate of stretching, dissipation and mixing index between two trajectories of the twin and four screw extruders.

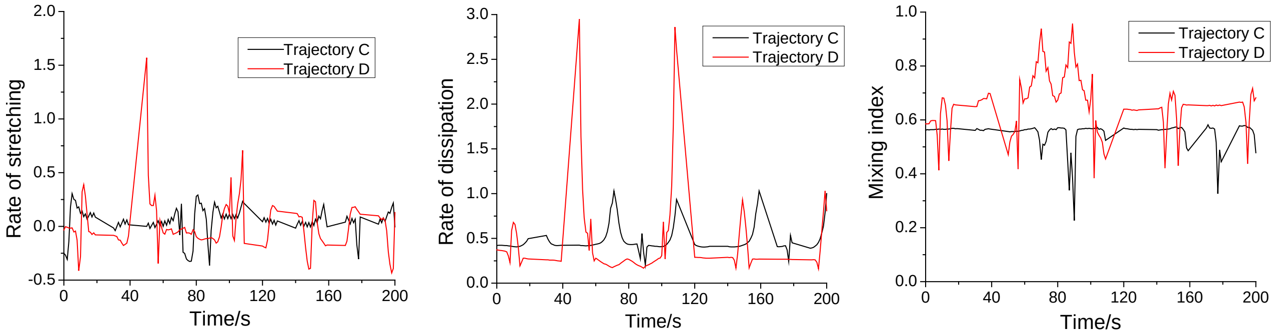


(a) Twin screw extruder (b) Four screw extruder

Figure 6 Two trajectories moving in the edge of twin and four screw extruder.

The other displays the particle moving around the outer circle of the screw. Define the left graph as trajectory C and the right graph as trajectory D, shown as Figure 6a and 6b. The particles from different initial positions shared similar trajectories, namely wandering along the screw channel from one side to the other side.

The resulting rate of stretching, rate of dissipation, and mixing index curve is shown below as Figure 7a, b and c. In twin-screw, the mixing index of the material points ranges from 0.1 to 0.6, but 0.4 to 1 in the four screw extuder. In terms of the rate of stretching curve, the fluctuation of twin-screw extruder is also not as obvious as that of four-screw extruder.



(a) Rate of stretching (b) Rate of dissipation (c) Mixing index

Figure 7 Comparison of rate of stretching, dissipation and mixing index of trajectory C and D.

4. Conclusion

The complex flow phenomena of different screw combinations in the mixing section of a four-screw extruder are studied. From the maximum shear rate, the maximum rate of stretching and other evaluation parameters, the four-screw extruder is shearing and extruding at high frequency. The tensile and mixing properties of the extruder are obviously superior to those of the twin-screw extruder. The distributive mixing ability of the central zone of the screw is very strong, just as the four-screw extruder has three more meshing zones than the twin-screw extruder, which proves that the four-screw extruder has better mixing performance. It can be seen that mixing is highly dependent on the initial position where the particles are first placed. And the particles close to the intermeshing zone experienced better mixing than those in the core regions.

Acknowledgements

This research project was fund by National Natural Science Foundation of China (Grant no. 51473073 and 50903042); Program for Liaoning Excellent Talents in University (Grant No. LR2016022) and Natural Science Foundation of Liaoning Province (Grant no. 2015020142).

References

[1] Zhu, X. Z., Xie, Y. J., Yuan, H. Q. (2008). Numerical Simulation of Extrusion Characteristics of Intermeshing Co-rotating Tri-Screw Extruder. Polymer Materials Science and Engineering. 24, 32-35.

[2] Zhu, X.Z.,Yuan, H.Q., Miao Y. (2009). Numerical Simulation of Temperature Distributions and Power Consumptions in Conveying Element of Tri-screw Extruders. Polymer Materials Science And Engineering. 25, 166-170.

[3] Xu, W.D., Qian, X.(2009). Numerical and Experimental Study on Concentration Distribution of PE-LLD/SBS Blending Process. China Plastics, 23, 70-74.

[4] Brodkey, R.S. (1981). Fundamentals of Turbulent Mixing and Kinetics. Chemical Engineering Communications, 8, 29-58.

[5] Manas-Zloczower, I. (2009). Mixing and Compounding of Polymers: Theory and Practice. Mixing (Second Edition), Hanser, 21-29.