Application of Computational Fluid Dynamics to Design of Polymer Extrusion Dies

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Abstract. Extrusion is one of the most widely used processes for polymer processing, e.g., producing film, pipe, sheet, cable and pellet. The shape of extrusion die has an important part for the manufacturing products. The purpose of this study has been to confirm the influence of nozzle shape on polymer flow. We calculated the die flow simulations in the various parameters. The calculation results are expected to improve the efficiency of pelletization. A commercial computer fluid dynamics program Ansys Fluent was used to calculate the die passage. The parameters for the calculations were taper angle, outlet diameter, properties of polymer and two models. The governing equations were the incompressible momentum equation and the continuity equation. As results, the increase in flow rate was confirmed by increasing taper angle and outlet diameter in the specific dimensional range. The average outlet velocity of single and multi-nozzle models almost corresponded in each same parameter.

1. Introduction

Extrusion is one of the most widely used processes for polymer processing, e.g., producing film, pipe, sheet, cable and pellet. In each type of extrusion, the polymer is forced through a die to create the desired shape. The shape of extrusion die is an important part for the manufacturing products. It determines the cross-sectional shape of products and makes the flow distribution more uniform. The die design of extrusion is needed knowledge about material characteristics, flow, heat transfer phenomena, and extensive experience with extrusion processing [1]. The predicting these effect is very complex task. Design of the complex extrusion die is still an art rather than a science.

Plastic pellet production process known as pelletization is combining the polymer strand fabrication by extrusion and cutting techniques. In pelletization, the properties of polymer pellet change slightly depending on the processing time. The reduction of processing time will stabilize the quality of the pellet and increase the production rate. One of the method to reduce the processing time is to increase of extrusion pressure. The adjustment of extrusion pressure is difficult task due to constraint of equipment.
Therefore, we proposed on optimization of die. The die that is easy to pass through can shorten processing time and reduce quality irregularity of the pellet. The die for the pelletization has several types. This many type is based on taper nozzle. In this study, we focused on the die in which taper nozzles were arranged in double rows of staggered types.

Numerical simulation is expected one of the method for trial and error on die design. Extrusion die design for a new product and product improvement is developed on the basis by experiments and in-plant trials. In many cases costly experiments can be replaced by numerical simulation. The numerical simulation has the potential to uncover important interior details of the extrusion process, such as velocity, shear stress, pressure, and temperature fields in the region of interest, which is not possible to do experimentally [1,2].

Various studies are conducted on numerical simulation of extrusion die design. However, most studies of numerical simulation for extrusion die design have focused on profile extrusion [1-9]. Very few studies have been reported on die design for pelletization. Therefore, little is known about typical optimized shape parameters in the die design for pelletization.

The purpose of this study is to confirm the influence of nozzle shape on polymer flow. In this paper, the parameters of calculations were the outlet diameter $D_{out}$, the taper angle $\theta$, the properties of polymer, two kinds of models. The models were prepared simple two-dimensional models and three-dimensional models with reference to the actual die. The evaluation of this study focused on the velocity distribution of the outlet.

2. Numerical method

Ansyo Fluent is a finite element computational program for heat and fluid problems. The Ansyo Fluent 17.2 was used in this study.

The single nozzle model for the simulation is shown in Figure 1. The single nozzle models were made by DesignModeler. The polymer flows through the large inlet to the small outlet via tapered wall part. The drawing of the multi-nozzle models is shown in Figure 2. The multi-nozzle models were made by SolidWorks. The dimensions of the single nozzle model were determined with reference to Figure 2. The influence on the flow field by varying the parameters were calculated.

![Figure 1. Single nozzle model.](image1)

![Figure 2. Drawing of multi-nozzle model.](image2)

The governing equations of the calculation were the incompressible momentum equation (1) and the continuity equation (2). Gravitational forces are neglected. The simulation was discretized by finite volume method and solved by SIMPLE method.
\[
\frac{\partial v}{\partial t} = -\nabla \cdot p + \nabla \cdot \tau_{ij} \quad (1)
\]
\[
\nabla \cdot v = 0 \quad (2)
\]

In boundary conditions, the inlet was set pressure-inlet and imposed gage pressure 115000 Pa. The outlet was set pressure-outlet and imposed gage pressure 0 Pa. The wall was set no slip condition. The simulations were performed time-transient, time step size 0.01 s and number of time step 300. The simulation was confirmed that the flow becomes almost steady-state within the calculation time.

The simulations were performing by varying outlet diameter, taper angle, property of polymer and simulation model. The outlet diameter \(D_{\text{out}}\) was 7.5, 9.5 and 11.5 mm. The taper angle \(\theta\) were 60° and 90°. The materials of extrusion were two kinds of polymers. The polymers were used a power-low viscosity model.

\[
\eta = k \gamma^{n-1} \quad (3)
\]

The properties of polymer are showed in Figure 3. In order to prevent divergence in calculation, the viscosity was set upper and lower limit. The viscosity of the polymer A is lower than the polymer B. The viscosity upper and lower limits of the polymer A were set 800 and 70 Pa·s. The viscosity upper and lower limits of the polymer B were set 1400 and 100 Pa·s.

Mesh density strongly affects on calculation accuracy. It is necessary to confirm the effect of the mesh size on calculation accuracy. The numerical simulations were performed for \(\theta = 60°\), \(D_{\text{out}} = 7.5\) mm, polymer A, single nozzle model by varying the element size of mesh. The element sizes of the mesh were \(D/5, 10, 15, 20\) and 100. Since these results, the velocity difference of each element sizes was little. The element size \(D_{\text{out}}/10\) was used for the calculations of this paper. The element size of the mesh is one tenth of the outlet diameter \(D_{\text{out}}\) in each simulation.

3. Results and Discussion

3.1. Single nozzle models

Figure 4 shows the velocity contour for the taper angle \(\theta = 60°\), the outlet diameter \(D_{\text{out}} = 9.5\) mm, the polymer A and single nozzle model. The velocity of the upper domain is smaller than lower domain. The velocity of center domain is larger than nearly wall. The maximum velocity appears at the center of outlet.

In above, the polymer accelerates in the taper domain and obtains the maximum velocity at the center of outlet. Therefore, the taper domain affects on the outlet velocity. In order to find the effect of flow field on the taper angle, the relationship between the average outlet velocity and the taper angle are shown in Figure 5. Figure 5 shows the average outlet velocity for \(\theta = 60°, 90°\), \(D_{\text{out}} = 9.5\) mm, polymer A, and single nozzle model. The average outlet velocity was calculated to compare with another parameter condition. The average outlet velocity at \(\theta = 90°\) is 1.09 times as large as \(\theta = 60°\).

The outlet diameter is one that affects on the outlet velocity. For the confirmation for the effect of the outlet diameter, the relationship between the average outlet velocity and the outlet diameter are shown in Figure 6. Figure 6 shows the average outlet velocity for \(\theta = 60°, 90°\), \(D_{\text{out}} = 7.5-11.5\) mm,
polymer A, and single nozzle model. The average outlet velocity is increasing with increasing the outlet diameter. The average velocity at $\theta = 90^\circ$ is larger than $\theta = 60^\circ$ for each outlet diameter.

In practical production, a common pelletizing die is used for different kind of polymer. It is important to confirm the effects of properties of polymer. The two kinds of polymers were compared. Figure 7 shows the average outlet velocity for $\theta = 60^\circ$, $90^\circ$, $D_{out} = 7.5$-$11.5$ mm, polymer A, B and single nozzle model. The average velocity of the polymer A is larger than the polymer B at same condition. For the slope of plot owing to the outlet diameter, the polymer A is also larger than the polymer B. Therefore, the effect of the outlet diameter is greater as low viscosity. The effect of the taper angle is relatively smaller than another parameter.

![Figure 4](image1.png)

**Figure 4.** Velocity contour for $\theta = 60^\circ$, $D_{out} = 9.5$ mm, polymer A and single nozzle model.

![Figure 5](image2.png)

**Figure 5.** Average outlet velocity for $\theta = 60^\circ$, $90^\circ$, $D_{out} = 9.5$ mm, polymer A and single nozzle model.

![Figure 6](image3.png)

**Figure 6.** Average outlet velocity for $\theta = 60^\circ$, $90^\circ$, $D_{out} = 7.5$-$11.5$ mm, polymer A, and single nozzle model.

![Figure 7](image4.png)

**Figure 7.** Average outlet velocity for $\theta = 60^\circ$, $90^\circ$, $D_{out} = 7.5$-$11.5$ mm, polymer A, B and single nozzle model.
3.2. Multi-nozzle models

The die for pelletization is usually arranged with the tapered nozzles. The upper taper shapes of the tapered nozzles are slightly lack due to overlapping nozzles as shown in Figure 8. The effect of overlapping nozzles on the polymer flow is still unclearly since the complex flow might be occurring. Figure 8 shows the velocity contour for $\theta = 60^\circ$, $D_{out} = 9.5$ mm, the polymer A and multi-nozzle model. The contour seems to be almost same with single nozzle model shown in Figure 4. The maximum velocity of each holes appears at center of the hole.

The comparison of the average outlet velocity with single nozzle models and multi-nozzle models is shown in Figure 9. Figure 9 shows the average outlet velocity for $\theta = 90^\circ$, $D_{out} = 7.5$-11.5 mm, polymer A, single and multi-nozzle model. The results of single and multi-nozzle model almost corresponded. Since the results, the effect of overlapping nozzles is little small. From the point of calculation time, the simulation of single nozzle model is valid for die design than the multi-nozzle model. However, if the model is set lager the outlet diameter and the taper angle, the upper taper shape become short and the effect of overlapping nozzles may appear.

![Figure 8. Velocity contour for $\theta = 60^\circ$, $D_{out} = 9.5$ mm, polymer A and multi-nozzle model.](image)

![Figure 9. Average outlet velocity for $\theta = 90^\circ$, $D_{out} = 7.5$-11.5 mm, polymer A, single and multi-nozzle model.](image)

4. Conclusion

In this paper, the purpose is to confirm the influence of nozzle shape on polymer flow. We calculated the die flow simulations in the various parameters. The parameters of calculations were the outlet diameter $D_{out}$, the taper angle $\theta$, the properties of polymer, single and multi-nozzle models. The largest outlet velocity was for $D_{out} = 11.5$ mm, $\theta = 90^\circ$ and polymer A. The smallest outlet velocity was for $D_{out} = 7.5$ mm, $\theta = 60^\circ$ and polymer B. The average outlet velocity of single and multi-nozzle models almost corresponded in each same parameter. The calculation time of the single nozzle model is shorter than the multi-nozzle model. Therefore, the simulation of single nozzle model is valid for pelletizing die design in the specific dimensional range.
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