A NEW NON-CONVENTIONAL CONCEPT FOR DESIGN OF SHEET EXTRUSION DIES

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Abstract

A new non-conventional die design for extrusion of plastic sheet is introduced. Instead of using a conventional sheet die design, such as the coat-hanger, or fishtail design, a completely non-conventional innovative die geometry was developed to achieve a highly uniform velocity distribution at the die exit (die balancing). While balancing the flow at the die exit, with the new die concept, the pressure drop in the die was reduced to about 29% of the original value, and the sharkskin instability was also eliminated from the extrusion process.

Introduction

Design of a die for extrusion of thin sheets or films is a challenging problem because it requires development of a flow channel geometry which can uniformly distribute the flow starting from a circular channel at the entrance into a slit with a large width to thickness ratio at the exit. Even though different types of dies, namely, T-dies, fishtail dies, and coat-hanger dies [1] have been used to obtain an appropriate flow channel for sheet (or film) extrusion, the basic underlying concept in all these dies used in the past is the same. The flow channel in these dies starts with a relatively thick melt distribution channel, called manifold, which is followed by thinner region near the exit, called land. The thinner land near the die exit provides flow resistance such that the flow is distributed in the manifold before it enters into the land region. The difference in the three die types listed above is the geometry of the manifold employed for polymer melt distribution.

The main goal in design of a sheet die is to obtain a uniform velocity distribution at the die exit; which is critical for uniformity of the thickness of the extruded sheet [1, 2]. In all the sheet extrusion dies which are currently used in the industry, uniformity of the velocity distribution at the die exit is obtained by using a relatively long die land. A longer length of the die land provides a higher flow resistance, and therefore, improves the distribution of the flow in the manifold before it enters into the land region of the die. However, a longer land length rapidly increases the pressure drop in the die, resulting in a lower production rate for the limited pressure available at the die entrance for a given screw extruder. A larger pressure drop in the die is also conducive to flow instabilities such as sharkskin formation, which refers to formation of uneven patterns on the surface of the extruded sheet.

Various types of sheet dies such as T-dies, fishtail dies and coat-hanger dies have been successfully used to extrude sheet for more than forty years. Taking the rheology of the polymer into account, simple design equations have been developed for these dies during this period. These design equations, such as those available in reference [1], along with the past experience with these die geometries, has guided the die designers in development of the proper flow channel geometry for the required sheet dimensions. Another advantage of these commonly used conventional sheet die geometries is the simplicity of the flow channel geometry which can be easily machined.

When the sheet extrusion die concepts such as T-dies, fishtail dies and coat-hanger dies were first developed more than forty years back, sophisticated flow simulation software were not available, neither were the numerically controlled (NC) machines for manufacturing of the dies. Therefore, at that time it was important to have die geometries which can be analyzed using simple analytical equations and can be easily machined. With the sophistication of the flow simulation software now available, which can accurately and quickly predict the velocity, pressure, and temperature distributions in the die, and with the NC machines of today which can easily machine complicated die geometries, there is no reason at this point to limit the die design for sheet extrusion to the conventional die geometries. With the general goal of obtaining a uniform velocity distribution at the die exit and minimum possible pressure drop in the die, designers now have the freedom of exploring non-conventional geometries which can achieve these goals.

The New Die Concept for Sheet Extrusion

In this work a new die concept was developed for extrusion of a 1.52 cm (0.6 inch) thick, 60.96 cm (2 ft) wide sheet from a highly filled high-density polyethylene (HDPE). The company for which this die was designed already had a die with coat-hanger type of manifold for extrusion of the HDPE sheet. The geometry of this original die is shown in Fig 1. The HDPE sheet could be extruded using this original die, but large fluctuations were encountered in the extrusion process and the extruded sheet surface had highly uneven patterns typical of sharkskin instability in extrusion. The uneven pattern from the sheet surface could not be eliminated, even though a wide range of processing conditions was examined.

In order to eliminate the sharkskin formation from the HDPE sheet, the monoextrusion die module of the polyXtrue software [3] was used to optimize the die channel geometry. The goal was to obtain a highly uniform velocity distribution at the die exit, while simultaneously reducing the pressure drop in the die. Instead of using a conventional sheet die design, such as coat-hanger design, or fishtail design, a completely non-conventional die geometry, shown in Fig. 2, was developed to achieve a uniform velocity distribution at the die exit. In the non-conventional die geometry for sheet extrusion, immediately after the circular entrance channel, a coat-hanger type of manifold with a constant manifold depth across the complete die width was employed. In order to maintain a small pressure drop across the die, when a relatively small die land was employed with this coat-hanger type manifold, the velocity was higher near the center and smaller near the two sides of the die. Of course, the uniformity of the exit velocity could have been improved by increasing the length of die land, but the longer die land would have rapidly increased the pressure drop in the die. Therefore, instead of increasing the length of die land, an additional feeder plate, which is commonly used in profile dies, was inserted between the coat-hanger type manifold and the die land. In order to slow down the flow near the center of the die, the feeder plate depth was kept the same as the die land depth, which is the same as the thickness of the extruded sheet. However, to accelerate the flow near the two sides, the feeder plate depth on the two sides was kept the same as the coat-hanger manifold depth. The larger feeder plate depth on the sides was linearly decreased to the smaller depth near the center by wedge-shaped transition regions on both sides of the feeder plate. The feeder plate was connected to the die land by a short converging section. Two of the main design parameters which are crucial for obtaining a uniform velocity distribution at the die exit are the location and width of the wedge-shaped transition regions in the feeder plate. The appropriate location and width of the wedge-shaped regions in the feeder plate were iteratively improved by examining the velocity distribution in the die predicted by the software. The die channel geometry was iteratively improved by simulating the flow using the software in each design iteration. Eight design iterations were required to reach the final die geometry shown in Fig. 2. With the help of flow simulation using the software, these eight design iterations were completed in a relatively short development time of 5 days.

Rheology of the Highly Filled HDPE

Viscosity of the highly filled HDPE used to extrude the plastic sheet is shown in Fig 3. The experimental data shown by the different symbols in the figure was used to fit the Cross-WLF model [4]. The viscosity predicted by the Cross-WLF model (Eqn. 1) is also shown in Fig 3.

$$\eta = \frac{\eta_0}{1+\left(\eta_0 \dot{\gamma}/\tau^*\right)^{1-n}}, \quad \eta_0 = D_1 \exp\left[-\frac{A_1 (T-T_a)}{A_2 + (T-T_a)}\right] \quad (1)$$

The values of Cross-WLF model parameters thus obtained are $n = 0.1$, $\tau^* = 3.17 \times 10^5$ Pa, $D_1 = 2.134 \times 10^{12}$ Pa.s, $T_a =$ 183 K, $A_1 = 25.61$, $A_2 = 170.73$ K. The melt density, heat capacity, and thermal conductivity were assumed to be constant at 3.03 g/cm^3, 1000 J/kg.K, and 1.332 W/m.K, respectively. The cross-WLF viscosity model, along with the thermal conductivity, heat capacity, and density of HDPE was used to simulate the flow in the sheet dies.

Results and Discussion

As mentioned before, the new non-conventional die geometry for sheet die was developed by iteratively improving the geometry using the software. Eight design iterations were required to reach the final die geometry shown in Fig. 2. The predicted velocity, pressure and temperature distributions in the original die (Fig. 1) and in the final die geometry reached after eight design iterations (Fig. 2) are compared in this section.

Velocity Distribution

For the original and the new die designs, the velocity distributions at the inlet, exit and three intermediate cross-sections predicted by the software are shown in Figs. 4 (a) and 4 (b) respectively. The original die had a thinner plate between the manifold and the die land. In this thinner plate between the manifold and die land in the original die the velocity in Fig. 4 (a) is quite large. Since the thickness of the opening in the feeder plate between the manifold and the die land in the new die is the same or larger than the thickness of the die land, in the new die geometry the velocity decreases rapidly as soon as the polymer enters the manifold and remains low through out the die. In the original die geometry, in Fig. 4 (b), the velocity distribution at the die exit is significantly larger at the two locations near the middle and is low near the two sides. In the velocity distribution for the new die geometry shown in Fig. 4 (b), the velocity at the die exit is highly uniform across the complete width of the die.

Pressure Distribution

The pressure distributions at various cross-sections of the original die and the newly developed die geometry as predicted by the software are shown in Fig. 5 (a) and (b) respectively. As expected, for both the dies the predicted pressure is zero at the exit and increases towards the entrance. It should be noted that because of the relatively short die land, and because of the much thicker feeder plate between the manifold and the die land, the total pressure drop in the new die is much smaller than the pressure drop in the original die. The total pressure drop in the new die geometry is only about 8 MPa whereas in the original die the predicted pressure drop is about 28 MPa. That is, for the same flow rate, the pressure drop in the improved die geometry is only about 29% of the pressure drop in the original die. Accordingly, for the pressure available from the extruder, the throughput rate was increased to more than three times the original throughput rate.

With the reduced pressure drop in the new die, the shark-skin formation was eliminated when the new die was used for production of the HDPE sheet.

Temperature Distribution

For the original die and for the new die designs, temperature distributions at the inlet, exit, and three intermediate cross-sections are shown in Fig. 6. Starting with the temperature of 489 K (420 ^{o}F) at the entrance, due to shear heating the temperature near the walls of the improved die increased to 492 K. This small increase in temperature did not have any significant effect on the extrudate profile. Because of higher velocity, and hence, higher shear heating in the thinner region of the original die, the temperature in the original die increased to a higher value of 495 K.

It is noted that in the new die geometry, a thin layer of hot melt is formed near the die walls. Formation of such a layer of hot polymer melt due to a high rate of shear heating near the walls of a channel has been reported earlier in the literature [4]. In contrast, the predicted temperature at the exit of the original die is the maximum in the mid-plane between the two die walls. The predicted temperature at the exit of the new die is quite uniform across the complete width of the die with slightly larger temperature near the two sides.

Conclusions

Many of the conventional die geometries which are currently being used for extrusion of plastic sheets were first developed more than forty years ago. Since sophisticated flow simulation software packages were not available at that time, these conventional die geometries were developed by trial-and-error using intuition and experience of the designer. These conventional die geometries were intentionally kept simple by the designers for simplicity of machining because NC machining was not available at the time when these die geometries were first developed. With the sophistication of the flow simulation software and NC machines available these days, designers now have the freedom to explore new die geometries for improving the extrusion process. Such a non-conventional die geometry for sheet extrusion was developed in this work using the polyXtrue die design software.

The new non-conventional die channel geometry for sheet extrusion, which is currently being used for production of the HDPE sheet, resulted in the following benefits:

- Eliminated the shark-skin formation during the extrusion
- Increased the uniformity of the velocity at die exit, and hence, the uniformity of sheet thickness
- Reduced the pressure drop in the die by more than 70%, and increased the production rate more than three times

Even though this work was focused on development of die geometry for sheet extrusion, the three-dimensional flow simulation software used in this work can be employed to develop such non-conventional dies for other geometries including pipe, blown film, and profile extrusion.

References

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Key Words: Extrusion Die, Sheet Die, Flat Die, Die Design, Simulation, Finite Element, HDPE

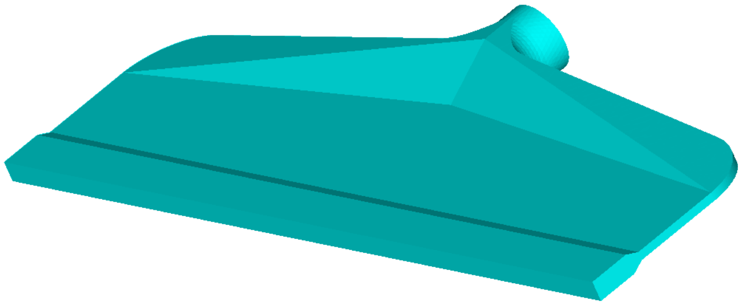


Fig. 1 Original die geometry.

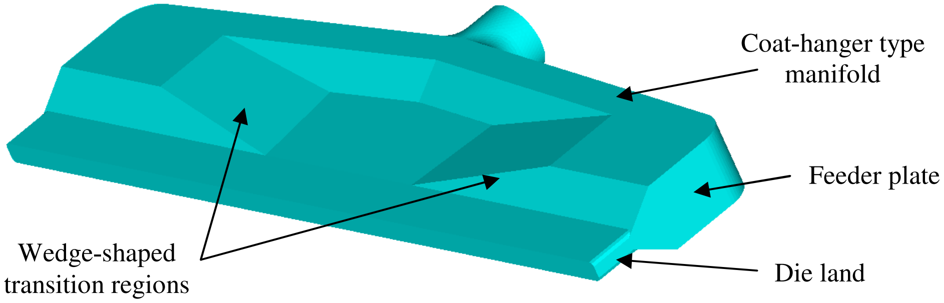


Fig. 2 Geometry of the new non-conventional die design.

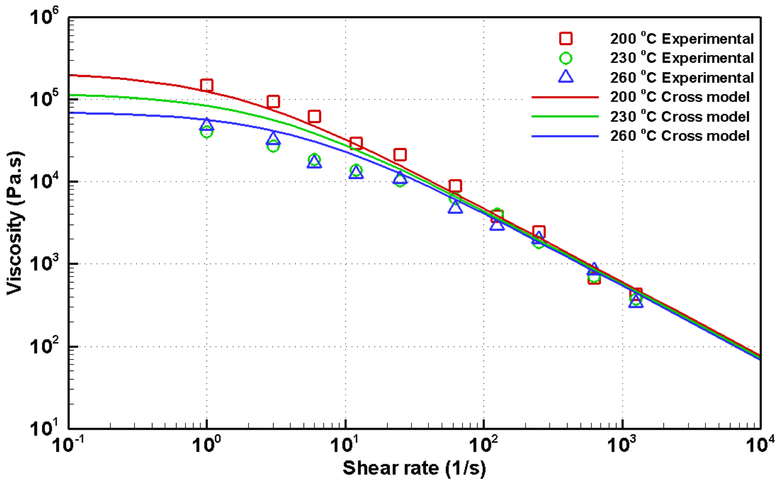
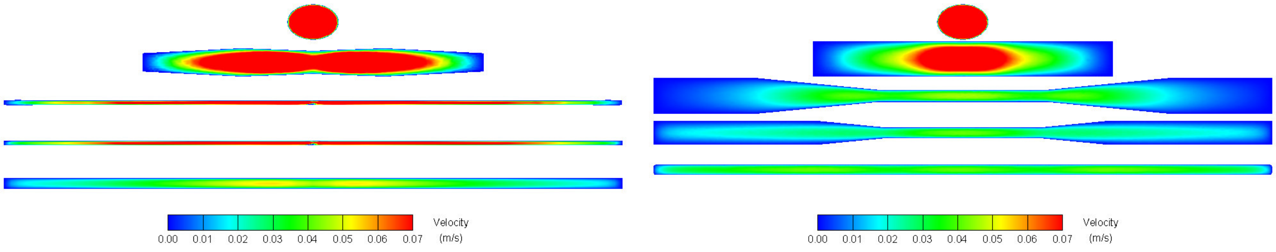
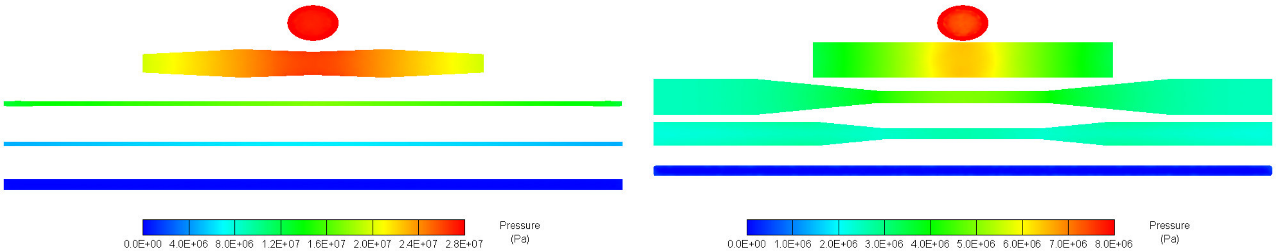


Fig. 3 Viscosity of highly filled HDPE.



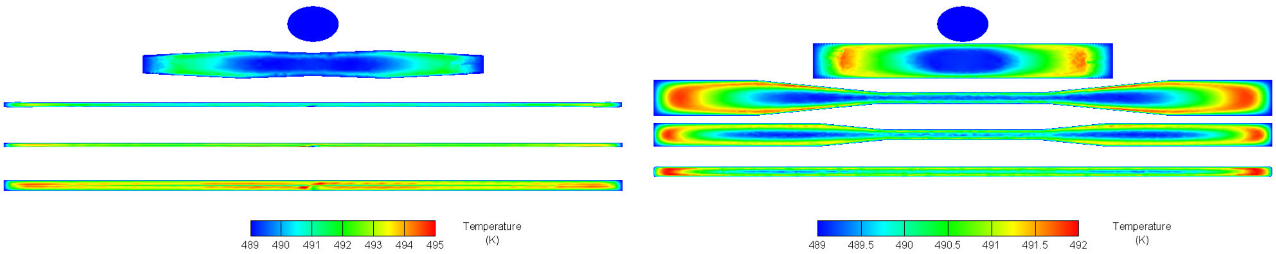
(a) (b)

Fig. 4 Velocity distributions in (a) original die, (b) new improved die.



(a) (b)

Fig. 5 Pressure distributions in (a) original die, (b) new improved die



(a) (b)

Fig. 6 Temperature distributions in (a) original die, (b) new improved die.