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A comparative analysis of sheeting die geometries using numerical simulations

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Abstract. The flow behavior of polymer melts within a slit die is an important consideration when designing a die geometry. The quality of the extruded polymer product can be determined through an evaluation of the flow homogeneity, wall shear rate and pressure drop across the central height of the die. However, mathematical formulations cannot fully determine the behavior of the flow due to the complex nature of fluid dynamics and the nonlinear physical properties of the polymer melts. This paper examines two slit die geometries in terms of outlet velocity uniformity, shear rate uniformity at the walls and pressure drop by using the licensed computational fluid dynamics package, Ansys POLYFLOW, based on the finite element method. The Carreau-Yasuda viscosity model was used for the rheological properties of the polypropylene. Comparative analysis of the simulation results will conclude that the modified die design performs better in all three aspects providing uniform exit velocity, uniform wall shear rates, and lower pressure drop.

Keywords: polymer; slit dies; sheeting dies; coat-hanger dies; Carreau-Yasuda viscosity model; three-dimensional FEM simulations; Ansys POLYFLOW; pressure drop; flow homogeneity

1. Introduction

Extrusion is a major manufacturing technique used to produce a wide range of products of continuous profiles such as tubes, wire insulation coating, plastic sheets, and films. Processing by extrusion has been used in the polymer industry for a considerable amount of years as it is a quick, simple and versatile operation that transforms raw materials into finished parts or products (Rauwendaal 2014, Wieme *et al.* 2018, Sauceau *et al.* 2011). Polypropylene (PP), which is well-known as semi-crystalline polymer (Lei *et al.* 2013), is one of the highly demanded material in the

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industry (Drozdov *et al.* 2012) due to its ability of retaining its mechanical properties at elevated temperatures (Yaragal and Ramanjaneyulu 2016) and high fatigue strength (Vogel *et al.* 2015).

Over the last few decades, much emphasis has been drawn on the development of extrusion dies with slit shape openings used for the production of films and sheets with large width-to-height ratios (Smith and Wang 2005). The most common dies in film and sheet production employ the coat-hanger and T-slot design concepts.

The slit die cavity consists of the three main components: the distribution manifold, the subsequent pre-land and primary land (Han and Wang 2012).

The main concern for die manufacturers is the design of a die cavity capable of providing product homogeneity with minimal processing cost. Therefore, uniform velocity profile at the die outlet and minimum pressure drop are important considerations to achieve the product of high quality with minimum power requirements (Gifford 1997, Smith *et al.* 1998). Uniform flow across the die exit can be achieved through proper design of manifold geometry (Lebaal *et al.* 2009, Morris 2016, Wang 1991). Vlachopoulos and Strutt (2009) claim that pressure drop can be controlled by changing the taper and the curvature of the manifold. In addition, Yilmaz and Kirkkopru (2015) claim that uniform shear rate is a necessary condition for coat-hanger die design regardless of the material type being produced. However, the optimization of die geometry is difficult, time-consuming, and sometimes impossible to perform because of the high number of variables and interactions. In addition, the manufacture of the excessively complex die design will be economically unfeasible. Die investigators usually develop the manifold design applying the "trial and error" approach considering both flow homogeneity and manufacturing cost (Chen *et al.* 1997).

A great quantity of studies has been generated on the design and optimization of slit dies. Mostly, the die geometry is investigated using two approaches, i.e., analytical calculation and numerical methods. The analytical approach is used to predict initial geometry of a slit die and restricted by the number of approximations, while numerical methods enable the investigation of complicated die geometries considering the complex nature of the polymer melts (Sander and Pittman 1996).

Hornsby (1992) reviewed a number of papers devoted to the analytical calculation of the slit die geometry. Most of these papers investigated the isothermal flow of power-law fluids through a die body using one-dimensional or two-dimensional analysis and proposed expensive to manufacture models with high pressure drops. Röthemeyer (1969) proposed a new die geometry which has no distribution manifold by using an analytical approach, however, this design has not found practical use due to manufacturing difficulties. Wortberg and Tempeler (1983) created a die design through mathematical modeling which has exchangeable lips to extrude different materials under different operating conditions, but this die was prone to deflections. Görmar (1968) developed a design procedure based on the Prandtl-Eyring constitutive equation, but the die design is restricted to specific material and flow conditions.

Wang (1991) examined a flow of power-law fluids in slit dies and coat-hanger dies by applying three-dimensional finite element method. He discussed the effect of die geometry on the flow distribution by calculating the pressure and velocity distribution. Wen *et al.* (1994) also performed three-dimensional finite element analysis to determine the effects of inertial force, power-law index, and the inlet geometry of slit dies on flow uniformity of the polymer melt. Yilmaz and Kirkkopru (2015) developed a procedure to create a coat-hanger die design capable of providing uniform outlet velocity with uniform wall shear rate and circumferential constant pressure of the polymer melt. They used a power-law model to describe the behavior of the solution obtained by numerical computation software. Stephen *et al.* (2006) studied the flow behavior of the polymer melt through a comparison of simulated results with experimental values. The numerical simulation results, i.e., pressure profiles and volumetric flow rates were obtained using a power-law viscosity model. Choudhary and Kulkarni (2008) developed a three-dimensional computational fluid dynamics model (CFD) to determine pressure drop, flow and temperature uniformity in two different coat-hanger dies used for polymer extrusion. They used Carreau-Yasuda viscosity law to predict the behavior of the melt flow. Smith and Wang (2005) examined five different viscosity models, i.e., the power-law, Cross, Bingham, Carreau-Yasuda, and the Ellis, on the flow distribution in a coat-hanger die using the integration of finite element flow simulations, sensitivity analysis, and optimization. They also determined the tradeoff between the pressure drop and flow rate when applying optimization procedure.

Most of the analytical and numerical studies mentioned above describe the flow of the polymer melt by the power-law model. Although the power-law model is versatile and has numerous applications, it is no longer applicable for polymers with low shear rates (Liu *et al.* 1994). The Carreau-Yasuda model is preferred over the power-law model as it involves five parameters and can more accurately explain fluid rheology (Hayat *et al.* 2014). Abbasi *et al.* (2015) claimed that the Carreau-Yasuda model is valid for both the lower and upper ends of the shear rate ranges. Three-dimensional analysis of the fluid flow through a die requires a continuous viscosity correlation which may vary from zero shear rate up to higher shear rates that may be encountered in the die (Gifford 1997).

This research study has been concentrating on a comprehensive analysis of polymer melt flow in a coat-hanger die currently used by a local polypropylene sheet manufacturer. Three-dimensional CFD techniques were used to examine the quality of the die and make recommendations for further improvement, and a new design was proposed. The CFD model is created and studied by evaluating computational results obtained from a commercially available package, Ansys POLYFLOW (Version 19.1), based on the finite element method (FEM). The aim of the research is to provide a comprehensive analysis of the flow within the existing die design and compare it with the flow behavior inside the proposed die design. The Carreau-Yasuda model has been employed in the polymer flow analysis as it is valid for both lower and upper ends of shear rate ranges. Detailed information of flow and its behavior within a die will be provided through computer visualization. Finally, this study will conclude that the proposed design provides more uniform velocity distribution at the exit, uniform shear rate in the die walls and has a lower pressure drop compared to the existing die geometry.

2. Methodology

2.1 Geometric model

This study considered the geometries of the existing die and improved die with modified manifold to test for the flow uniformity. This study is concerned mainly about the inner geometry of these dies since the behavior of the fluid body flowing through the die channels is going to be determined. Both dies are designed for extruding sheets of 720 mm width and 3 mm thickness. Following geometries of the fluid bodies inside the dies are created.

The velocity uniformity at the die exit will be examined using Ansys POLYFLOW (version 19.1) by setting appropriate boundary conditions and parameters for Carreau-Yasuda viscosity model. The software also can provide pressure values.

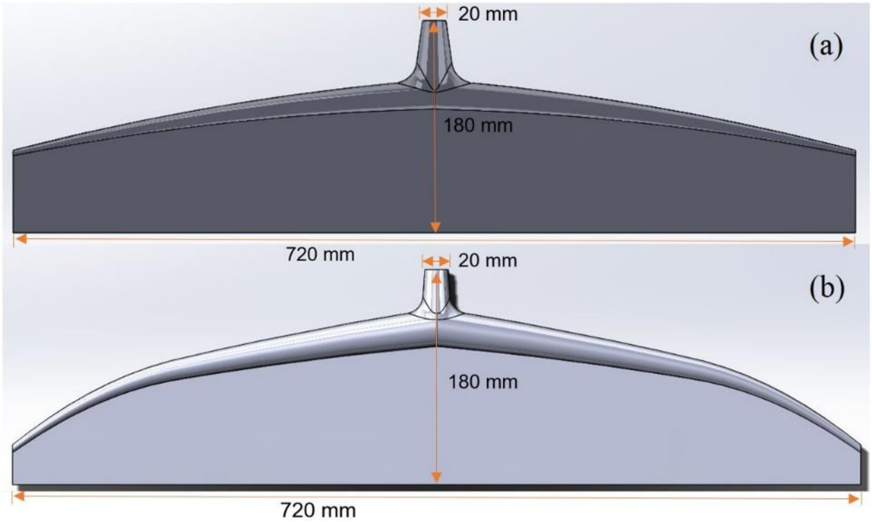

Fig. 1 (a) existing die geometry; (b) modified die geometry

2.2 Governing equations

The assumptions of the dynamic flow analysis on the polymer melt through a sheeting die are as follows:

- The polymer melt is incompressible non-Newtonian fluid;
- The polymer melt flow appears with steady state, isothermal and fully-developed flow;
- The die cavity is completely filled with polymer melt;
- No-slip condition between die wall and polymer melt.

With the assumptions mentioned above, the mathematical model applied in this study will include the following continuity and momentum conservation equations:

$$\nabla \cdot v = 0 \tag{1}$$

$$\rho v \cdot \nabla v = -\nabla P + \nabla \cdot \tau + \rho g \tag{2}$$

where ∇ is the gradient operator, v is the velocity vector, P is the hydrostatic pressure, τ is the stress tensor, ρ is the material density, and g is the acceleration due to gravity. The constitutive equation with viscosity function is as follows:

$$\tau = \eta \dot{\gamma} \tag{3}$$

where γ is the shear rate and η is the apparent viscosity.

The viscosity (η) model used to characterize the rheological properties of the polypropylene (PP) is Carreau-Yasuda law:

$$\eta = \eta_0 [1 + (\lambda \dot{\gamma})^{\alpha}]^{\frac{n-1}{\alpha}} \tag{4}$$

where η is the shear-rate viscosity, η_0 is the zero-shear-rate viscosity, λ is the time constant, $\dot{\gamma}$ is the shear rate, α and n are exponential constants (Polychronopoulos and Vlachopoulos 2018).

Table 1 List of parameters used in simulation (Huang *et al.* 2004)

Parameter	Value
Zero-shear rate viscosity, η_0	8920 Pa s
Time constant, λ	1.58 s
Power-law index, n	0.496
Index that controls the transition from the Newtonian plateau to the power-law region, α	2

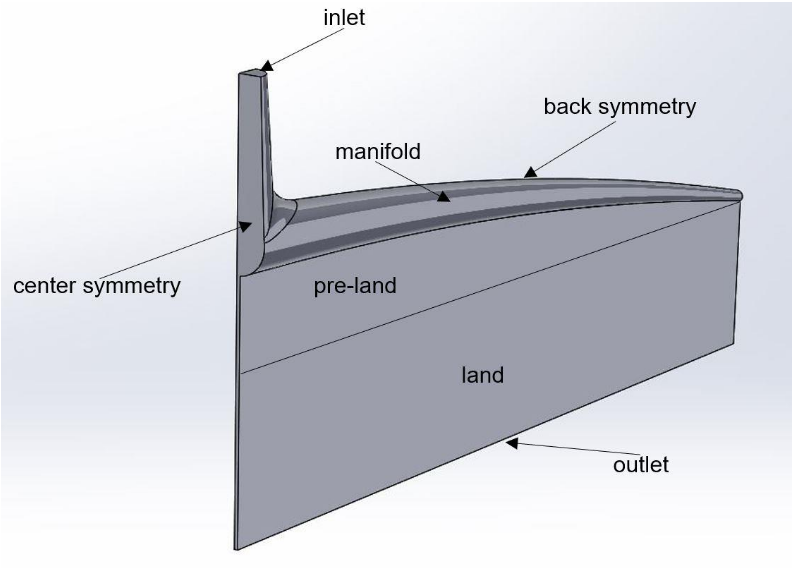

Fig. 2 The schematic diagram of the sheeting die

2.3 Material properties

When simulating material forming processes, it is important to introduce rheological properties of the material to determine the resulting material behavior (Zhou and Li 2010). The constant parameters of the viscosity model for polypropylene shown in Table 2 were obtained by the fitting of the capillary rheological data to the viscosity model:

2.4 Boundary conditions

In this Finite Element Analysis, only one-fourth of the die fluid body will be simulated due to the symmetrical feature of the sheeting dies. The boundary conditions are same for both fluid bodies (Figure 2). At the inlet, the flow is assumed to be fully-developed with the volumetric flow rate of $5 \times 10^{-5}\ \mathrm{m^3/s}$. A no-slip boundary condition, or wall adhesion, is applied on the wall. This means that normal and tangential velocities at the wall were set to zero. At the symmetrical planes, the boundary conditions of zero normal velocity and zero shear rate along the planes were applied. Finally, boundary conditions at the outlet were defined as zero normal and tangential forces.

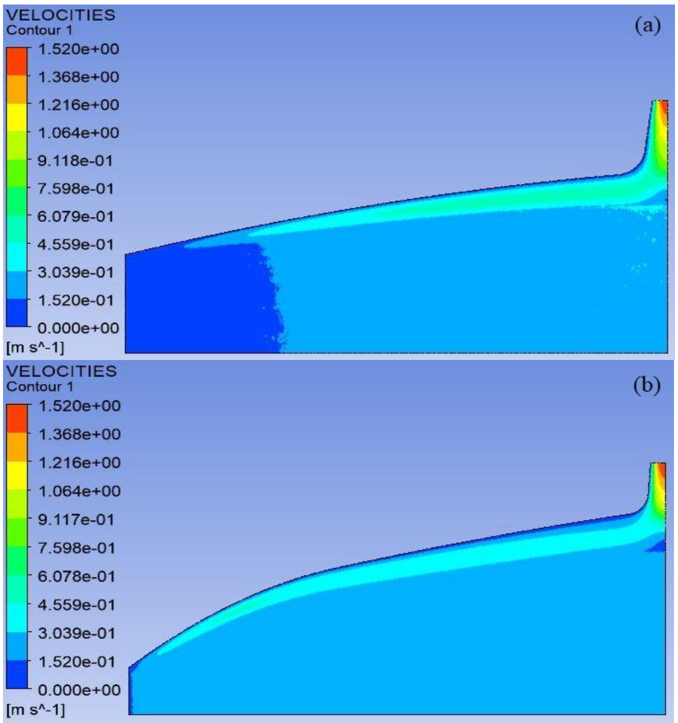

Fig. 3 Velocity contour plots: (a) existing die design; (b) modified die design

3. Results and discussion

The simulation results of the aforementioned die designs are provided in terms of contour plots, tables and graphs in Figures 3-9 and Tables A1 and B1. The velocity contour plots in Figure 3 represent the velocity distribution across the mid-plane of the die bodies. According to Figure 3a and 3b, the maximum velocity can be observed at the entrance where the fluid with fully-developed flow comes in. Figure 3a depicts the significant changes in the manifold, pre-land and land velocity magnitudes from the middle to the edge of the existing die body. The velocity distribution in the manifold drops from the range of 0.6079-0.4559 m/s at the middle section to the range of 0.1520-0.0000 m/s at the edge. At the pre-land and land of the existing die, the velocity distribution drops from the range of 0.3039-0.1520 m/s at the middle section to the range of 0.1520-0.000 m/s at the edge. According to the velocity contour plot of the modified die design shown in Figure 3b, the velocity distribution in the manifold is comparatively uniform and falls in the range of 0.4559-0.3039 m/s. The velocity magnitudes at the pre-land and land of the die are also even and fall in the range of 0.3039-0.1520 m/s. However, there is a small region at the middle where the manifold and pre-land meet with very low velocity in the range of 0.1520-0.0000 m/s. This region is called stagnation zone. The stagnation zone can also be observed from the existing die velocity contour plot. Stagnation areas may cause thermal degradation as the melt will be exposed to high temperatures for a long time. Therefore, manufacturers try to eliminate it when designing extrusion dies (Kostic and Reifschneider 2006).

In order to inspect the stagnation zone, the isometric views of both designs with their contour plots have been provided in Figures 4a and 4b. It can be noticed that the size of the stagnation

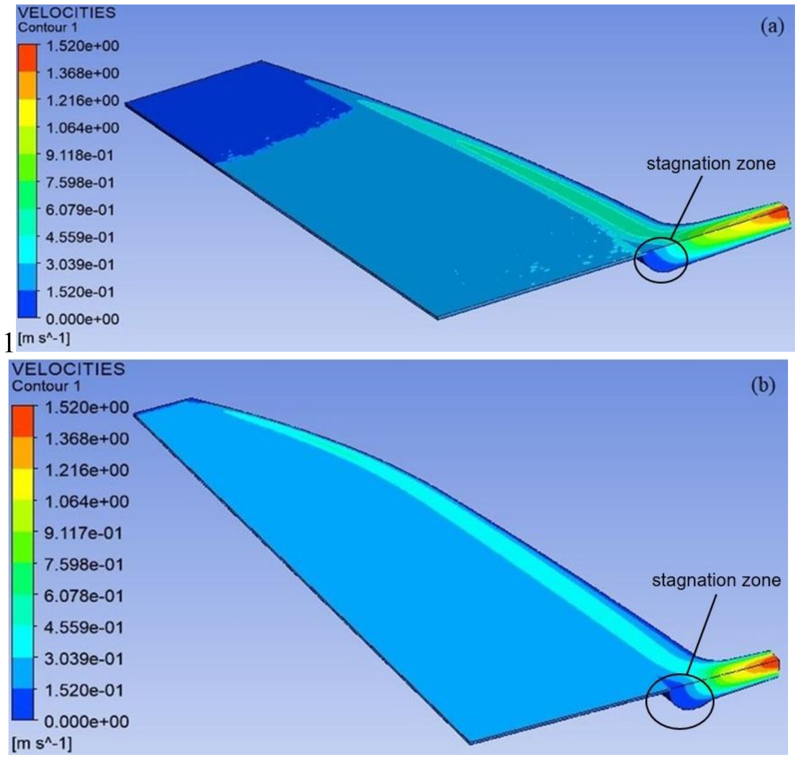

Fig. 4 Stagnation zones: (a) existing die design; (b) modified die design

zones are nearly same for both dies, however, the existing die has two-layered stagnation area with different velocity fields. Inner region of stagnation zone is dark blue with velocity distribution ranging between 0.1520-0.0000 m/s, while outer region is of the lighter color with velocity ranging between 0.3039-0.1520 m/s. To observe how the size of the stagnation zone changes across the width, the contour plots of the velocity field on section planes for both designs have been provided (Figures 5a and 5b). In both cases, the stagnation areas become negligible as it goes far from the central plane. The reason for the flow being stagnated near to the center of the manifold is that the radius of the manifold is maximum there, hence longer time is required for the melt to reach the pre-land zone from the manifold cavity compared with the regions far from the center where the radius of the manifold is lower. In addition, the velocity of the fluid coming from the entrance is higher at the center of the manifold, accordingly, there is a high pressure drop at the local zone. In order to streamline the flow at this region, the geometry of the flow channel should be modified.

The main concern of this study is the flow field at the die outlet, since the uniform distribution of the velocity at the outlet is an important consideration for a high quality product. In order to determine the flow uniformity, 19 equally spaced probes were chosen along the x-axis of the die outlet. Accordingly, 19 velocity values were extracted for both designs and filled in Table A1 (Appendix A). To compare the velocity fields of the dies, the velocity distribution at the die exit (in m/s) versus the width of the die (in mm) graph was plotted in Figure 6. Figure 6 shows that the outlet velocity of the existing die is maximum (0.276735m/s) at the middle section (x=0 mm) and reaches minimum value (0.0744391 m/s) at the edge (x=340 mm), while outlet velocity

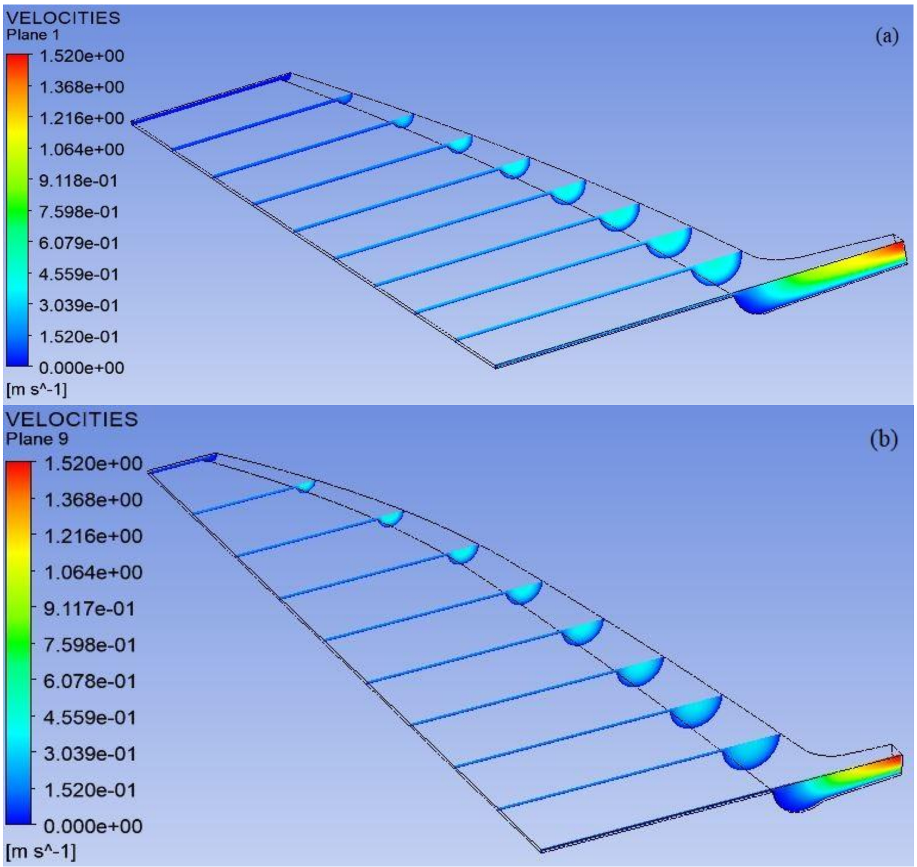

Fig. 5 Contour plots of velocity on section planes: (a) existing die design; (b) modified die design

distribution of the modified die falls between 0.185826 and 0.20708 m/s which can be considered as relatively uniform velocity distribution. It should be noticed that the velocity at x=360 mm is 0 m/s due to no slip condition at the wall, and therefore, it will be ignored when examining the flow uniformity. To properly observe the deviation of the modified die velocity magnitudes from the outlet mean value, the graph shown in Figure 7 was plotted. Thus, the percentage flow deviation about its mean value is calculated to be 2.973 % (note that velocity at x=360 mm was not taken into calculation), while for existing die design the percentage flow deviation is 31.739 %. This also means that the volumetric flow rate at the exit has the same deviation from its mean value, since the height of the die opening is constant across the width.

Figure 8 represents the pressure fields in two die designs. The die body deflection can be predicted through examining pressure contour plots. Comparing contour plots in Figure 8a and 8b, it can be noticed that the pressure contour lines of existing die are not quite parallel to the die exit width. This indicates that the flow field at the die edge is uneven. In order to make pressure contour lines of the existing die parallel, the radius of manifold near to edge should be increased or the curvature of the manifold channel should be modified. In turn, the pressure contour lines of modified die are parallel to the die exit width, which should be the case for the die capable of providing uniform flow. However, comparing the pressure magnitudes at the outlet, it was determined that both designs have significant variations in pressure. The pressure magnitudes can

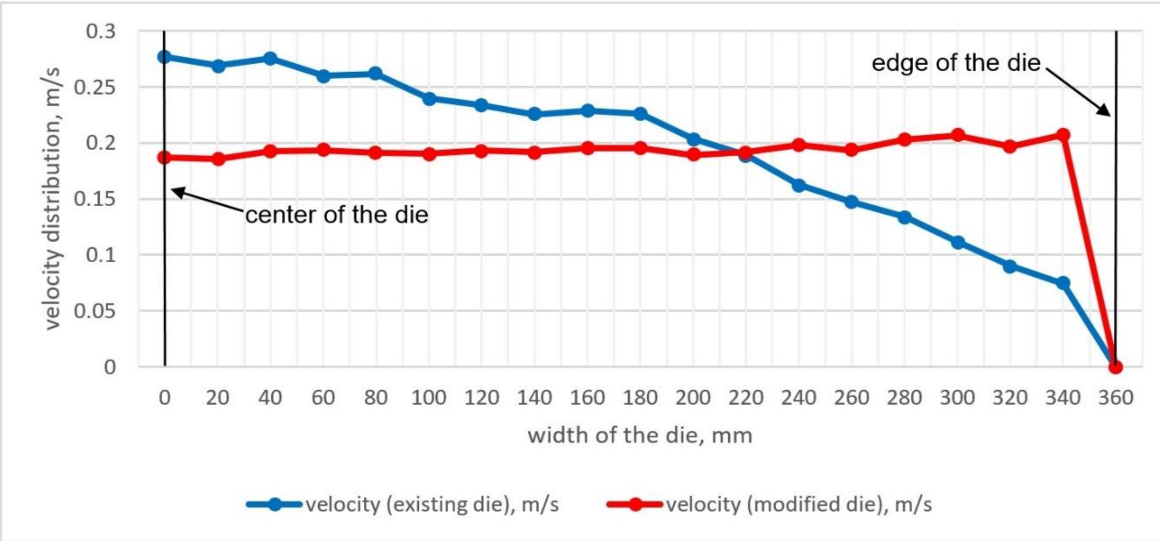

Fig. 6 Outlet velocity distribution plot

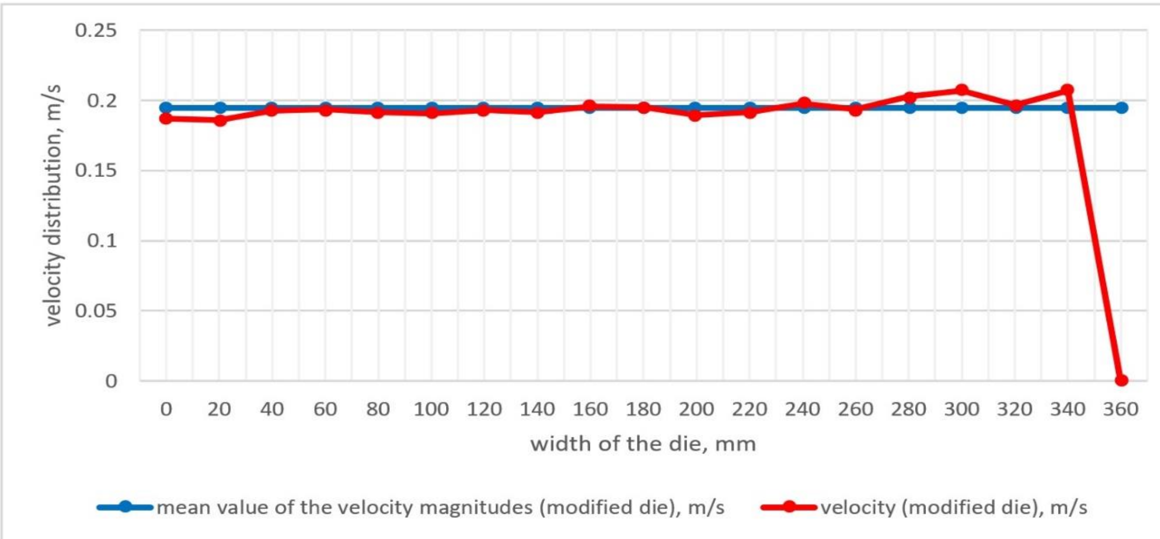

Fig. 7 Deviation of the modified die velocity from output mean value

be found in Table B1 (Appendix B), and corresponding graph of the outlet pressure (in MPa) versus die width (in mm) is shown in Figure 9. The deviation of the output pressure about its mean value for existing design and modified design are 55.505 % and 19.059 %, respectively. In addition, the maximum pressure drop along the centre line for existing die design and modified design are 13.8 MPa and 12.3 MPa, respectively. Thus, the modified die is advantageous in terms of power requirements as it operates with lower pressure drop.

Figure 10 depicts the shear rate contour plots at the die walls of both die designs. It can be noticed that the maximum shear rate values are appeared to be at the regions near the entrance due to the maximum flow rate in the entrance channel. By comparing shear rate contour plots of

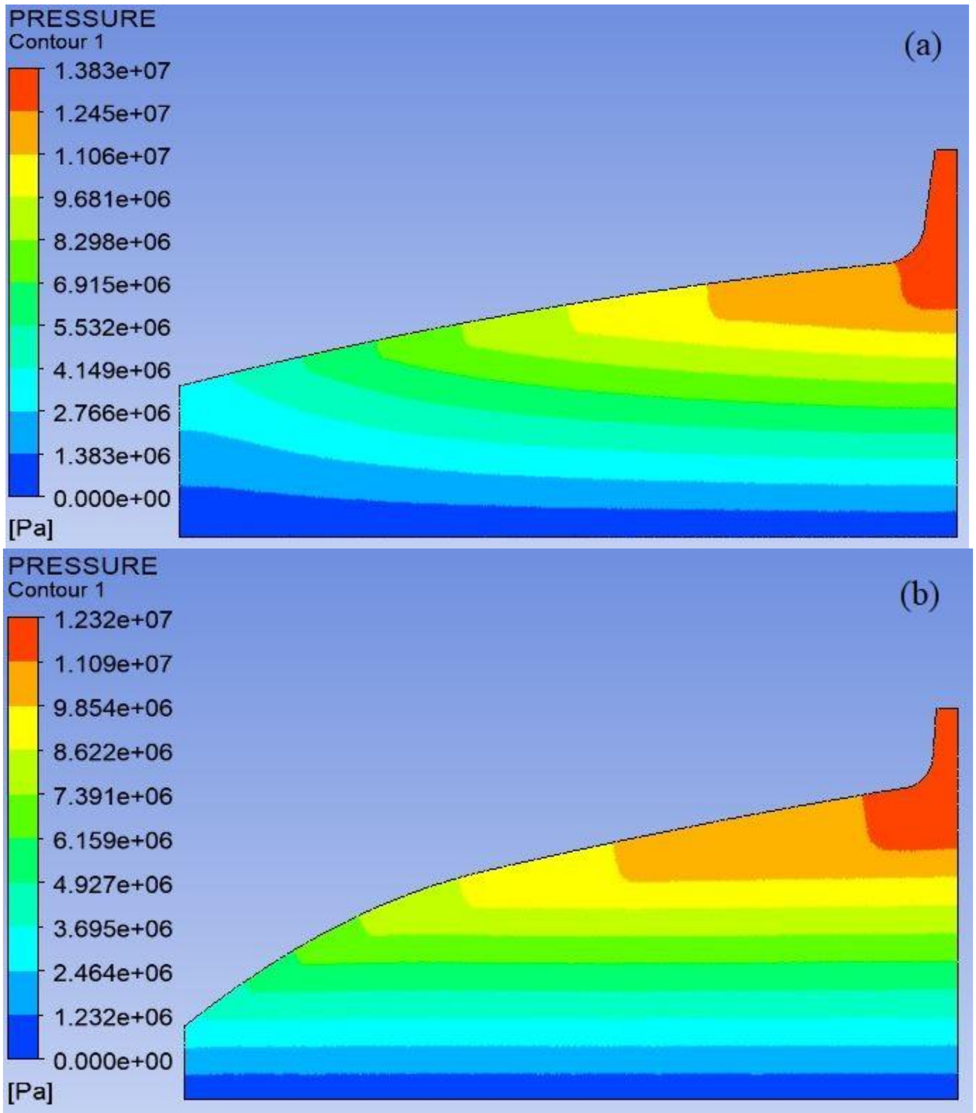

Fig. 8 Pressure contour plots: (a) existing die design; (b) modified die design

existing die (Figure 10a) and modified die (Figure 10b) designs, it is clear that the shear rate in the pre-land and land walls of modified die design is more uniform and defined by light green color. The corresponding shear rate range is 208.1-249.7 s^-1. However, the manifold shear rate magnitudes of the modified die vary over a larger range: 40.3-201.3 s^-1. The wall shear rate of the existing die geometry is non-uniformly distributed across the entire die body. In the manifold of the existing die, shear rate values fall in the range of 0.0-83.2 s^-1. The shear rate variation at the pre-land and land regions is much significant which is from 0.0 s^-1 up to 374.6 s^-1. Thus, despite that both dies represent significant shear rate variations in the manifold, the modified die is more preferable than the existing die design due to uniform shear rate distribution across the two most large die sections: pre-land and land.

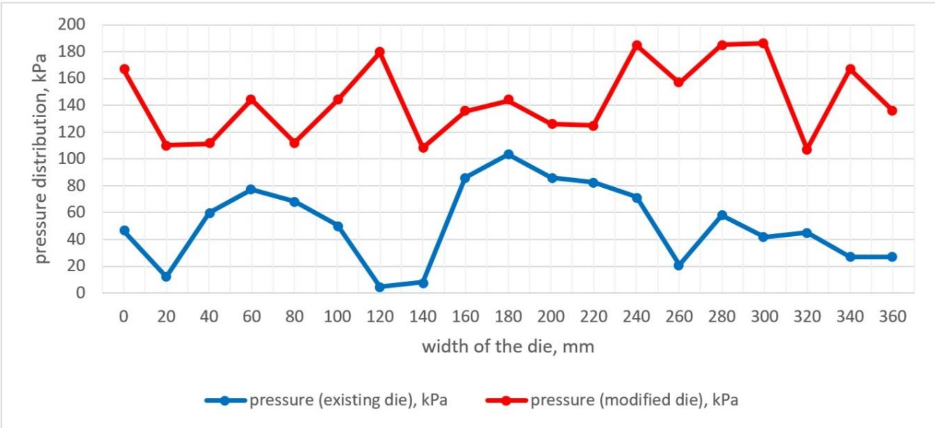

Fig. 9 Outlet pressure distribution plot

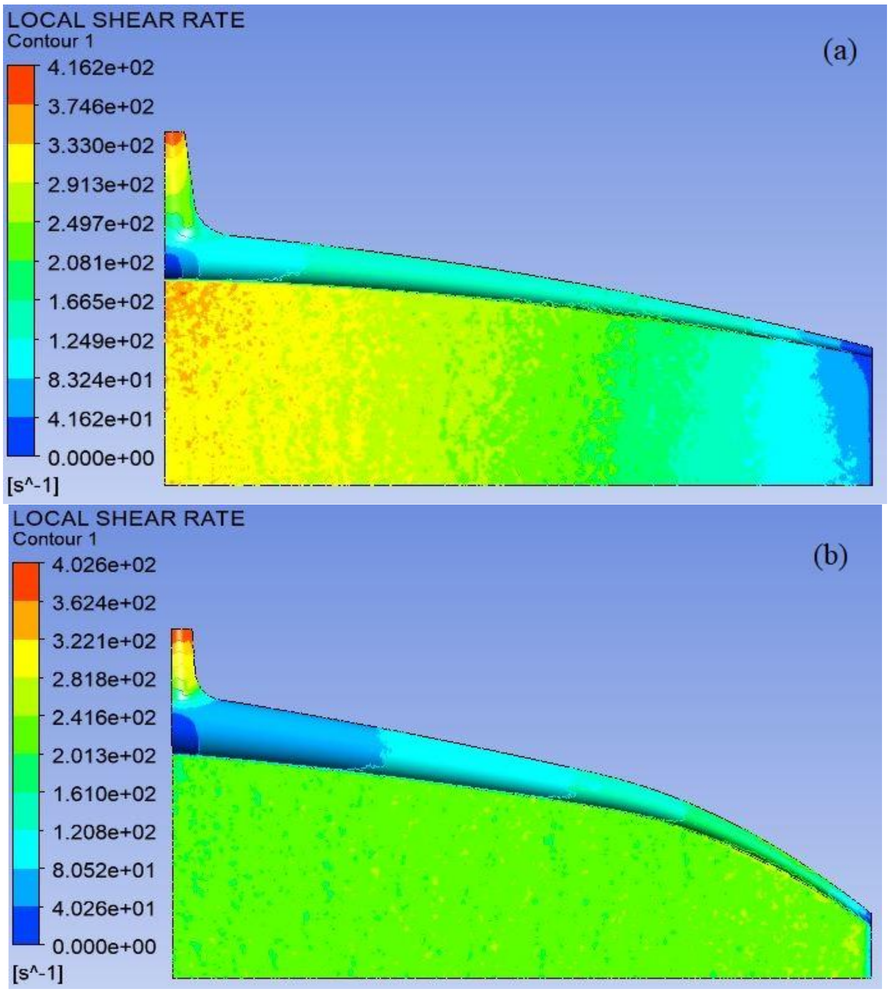

Fig. 10 Shear rate contour plots: (a) existing die design; (b) modified die design

5. Conclusions

This paper studied the flow of the polymer melt through sheeting dies. Three-dimensional CFD techniques were applied to evaluate the computational results obtained from Ansys POLYFLOW. Velocity and pressure fields were calculated for two different die designs. One of these dies is existing die currently used by a local polypropylene sheet manufacturer. Second geometry was designed such a way that it can produce the product of the same width and thickness. It was drawn from the simulation results that the geometry of improved die design performs better in both aspects, namely, flow velocity at the die outlet and pressure drop. Uniform outlet velocity and low pressure drop are very important factors defining the quality of the extruded product. The percentage outlet velocity deviation about its mean value for the existing die and improved die designs are 31.739 % and 2.973 %, respectively. From this, it can be assumed that the velocity is closely homogeneous at the modified die outlet. In turn, the outlet velocity of the existing die design is very high at the center and almost four times less at both ends. The pressure drops for the existing die and improved die designs are calculated to be 13.8 MPa and 12.3 MPa, respectively. In addition, the shear rate variation in the walls of the existing die design is significant compared to the modified die design. Hence, the modified die design will result in a better product quality due to insignificant outlet velocity variation, lower pressure drops and uniform shear rate distribution.

Author contributions

A.P. and D.W. conceived the idea of this research; D.I. developed the framework of the paper, performed numerical simulations and prepared the manuscript under the supervision of A.P., D.W., D.Z.

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Conflicts of interest

The authors declare no conflict of interest.

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WT

Appendix A

Table A1 Outlet velocity values

Width of the die, mm	Velocity (existing die), m/s	Velocity (modified die), m/s
0	0.276735	0.186818
20	0.268948	0.185826
40	0.275227	0.192373
60	0.259781	0.193537
80	0.261443	0.191419
100	0.239682	0.190405
120	0.233806	0.19311
140	0.225319	0.191668
160	0.228587	0.195582
180	0.226143	0.195095
200	0.203831	0.189362
220	0.188936	0.191779
240	0.162354	0.197924
260	0.147294	0.193557
280	0.134146	0.202769
300	0.111593	0.206638
320	0.0899728	0.196588
340	0.0744391	0.20708
360	0	0

Appendix B

Table B1 Outlet pressure values

width of the die, mm	pressure (existing die), kPa	pressure (modified die), kPa
0	46.5584	167.278
20	12.2418	110.281
40	60.0689	111.54
60	77.1132	144.468
80	68.1619	112.267
100	50.5221	144.046
120	4.77185	179.603
140	8.19546	108.231
160	86.3225	135.642
180	103.575	143.538
200	86.2397	126.222
220	82.7465	124.955
240	71.6016	184.902
260	20.781	156.875
280	57.8345	185.274
300	41.6468	186.247
320	45.1898	107.621
340	26.8093	166.819
360	26.8143	136.113