Proceedings of the 29th Polish-Slovak Scientific Conference on Machine Modelling and Simulations 2024, Poland

Validation of a CAE Tool Based on Chris Rauwendaal's Model for the Design of Spiral Mandrel Dies that Ensures Uniformity of Extruded Film Thickness

P. Cyprys[a,b,*] and M. Macko[a]

[a] *Kazimierz Wielki University, Faculty of Mechatronics, Kopernika 1, 85-074 Bydgoszcz, Poland*
[b] *Łukasiewicz Research Network — Institute for Engineering Polymer Materials and Dyes, Marii Skłodowskiej-Curie 55, 87-100 Toruń, Poland*

Doi: 10.12693/APhysPolA.145.806 *e-mail: pawel.cyprys@impib.lukasiewicz.gov.pl

The high degree of thickness uniformity of the extruded polymer tube is one of its most important geometric features. A factor that has a direct impact on this is the die, especially the mandrel. Correctly designed, it ensures, among other things, a high degree of homogenization of the processed polymer and uniform distribution of the volume flow rate along the circumference, which has a key impact on the quality of the extruded film. Due to the number of variables affecting the flow of polymer through the die, a number of simulations are required to find the optimal design. This paper presents the validation of a tool based on Chris Rauwendaal's mathematical model for performing fast numerical calculations to determine the geometric parameters of the spiral mandrel to ensure the thickness of the extruded film is as uniform as possible. Simulations were carried out based on 13 geometric and processing variables, from which 3 key geometric parameters were selected. In order to select a set of parameters that ensure the optimal distribution of polymer flow at the exit, a series of simulations were carried out for several levels of values of the aforementioned key parameters. The obtained set of geometric parameters was used to manufacture a spiral mandrel, which was used in the process of validation of the computer aided engineering tool by the experimental method.

topics: spiral mandrel, extrusion, blown film

1. Introduction

Blown film extrusion is a commonly used process for the production of film products. Advantages of this process over cast film include the ability to produce films of different widths with the same tool and the lack of edge trim removal [1, 2]. The computer aided engineering (CAE) tool used in this process is a blown film die. Of all the die types, the spiral mandrel die is the most commonly used [3]. Properly designed, it provides a uniform melt distribution and eliminates the formation of weld lines typical of less complex die types [4].

The design of the spiral mandrel die is characterized by spiral channels (mostly in an even number) whose depth linearly decreases as they approach the end, while the dimension of the gap between the mandrel and the body increases. As the melt spirals upward around the mandrel, it starts to leak to the adjacent channels due to the increasing clearance [4]. The geometry of a spiral distributor development is shown in Fig. 1. The parameters describing the geometry of a spiral mandrel are: N — number of grooves, φ — groove helix angle, ψ — spiral runout angle, β — taper angle of the annular channel, W — perpendicular groove width, w — perpendicular flight width, H — groove depth, D — mandrel diameter, δ_0 — initial flight clearance, l_m — axial groove length.

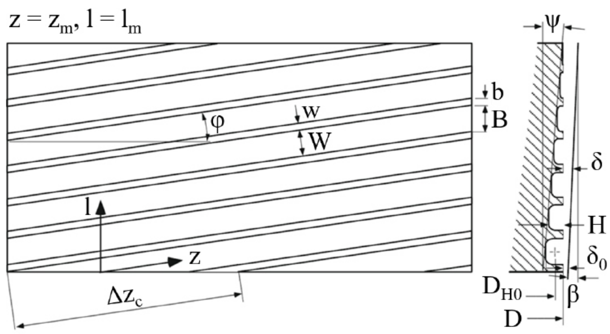

Fig. 1. Geometry of the unrolled spiral mandrel with design parameters.

2. Modeling

The modeling of polymer flow through the spiral mandrel was done using a tool based on the model proposed by Chris Rauwendaal with the following assumptions [5]:

- The curvature of the mandrel is neglected.
- Constant pressure in planes is perpendicular to the mandrel axis.
- The flow in a channel can be approximated by the pressure flow in a rectangular channel by using the shape factor.
- The leakage flow in the flight clearance can be approximated by the pressure flow in a rectangular channel.
- The leakage flow does not affect the flow in the spiral channel.
- The polymer melt is temperature independent and behaves as a power-law fluid.

The flow in the spiral channel $\dot{V}$ is expressed as

$$\dot{V} = \frac{F_P\, W\, H^2}{2\,(s+2)}\left(\frac{H g_z}{2m}\right)^s, \tag{1}$$

where F_P is the shape factor, W is the groove width, H is the groove depth, s is the reciprocal power law index, g_z is the helical down channel pressure gradient, and m is the consistency index.

The leakage flow per unit tangential distance $\dot{V}_{\acute{l}}$ is expressed as

$$\dot{V}_{\acute{l}} = \frac{\delta^2}{2(s+2)}\left(\frac{\delta\, g_l}{2m}\right)^s, \tag{2}$$

where δ is the flight clearance, g_l is the axial pressure gradient, with

$$g_z = g_l \sin(\varphi), \tag{3}$$

where φ is the groove helix angle.

Assuming the density to be constant, the mass balance for the first section of the die can be made. This results in the following relation flow

$$\dot{V}\,(z{+}\Delta z) = \dot{V}\,(z) - \dot{V}_l\,(z)\,, \tag{4}$$

for $z{\leq}\Delta z_C$, where Δz is the size of the channel element in the z direction, Δz_C is the distance in the z direction to the next channel entry point, and

$$\dot{V}_l\,(z) = \dot{V}_{\acute{l}}\,(z)\,\Delta z\,\cos(\varphi), \tag{5}$$

For the second section, the mass balance gives the relation flow

$$\dot{V}\,(z{+}\Delta z) = \dot{V}\,(z) + \dot{V}_l\,(z{-}\Delta z_C) - \dot{V}_l\,(z)\,, \tag{6}$$

for $z > \Delta z_C$.

The calculations were made in a step-wise manner. Due to the negative leakage flow mentioned in work [6], the calculations automatically end at the final stage of the spiral channel. Therefore, it is assumed that the uniformity results obtained by calculation should be lower than those obtained experimentally.

TABLE I

Specific model input parameters.

Parameter	Symbol	Unit	Value
Number of grooves	N	–	6
Taper angle of the annular channel	β	°	2
Perpendicular groove width	W	mm	4
Mandrel diameter	D	mm	60
Initial flight clearance	δ_0	mm	0.1
Throughput-extruder	Q	kg/h	6
Specific volume	v	cm^3/g	1.22
Shape factor	F_P	–	0.45
Consistency index	m	Pa s	14000
Power law index	n	–	0.4

TABLE II

Tested values of input design geometric parameters.

Parameter	Symbol	Unit	Level of design parameter				
			1	2	3	4	5
			Values				
Groove helix angle	φ	°	10	15	20		
Spiral runout angle	ψ	°	4	8	10	12	14
Initial groove depth	H_0	mm	4	5	6		

Due to the level of complexity, it is impossible to perform calculations to ensure an optimal design that will result in the geometry of the spiral mandrel. The design process must be reversed, i.e., it is necessary to simulate the flow of the melt through the die for a given set of geometric parameters [7].

For this reason, multiple calculations were made to ensure flow uniformity with the parameters shown in Table I and with each tested set of parameters shown in Table II.

Based on the results obtained from 45 calculations, a set of parameters was selected to ensure flow uniformity equal to 0.93, i.e., $\varphi = 10°$, $\psi = 4°$ and $H_0 = 5$ mm. The flow uniformity was calculated as

$$UI = 1 - \sqrt{\frac{1}{N}\sum\nolimits_{i=1}^{N}\left(\frac{q_i}{\bar{q}} - 1\right)^2}\,, \tag{7}$$

where UI is the flow uniformity, q_i is the leakage flow at element i, $\bar{q}$ is the average value of q, N is the number of elements [8].

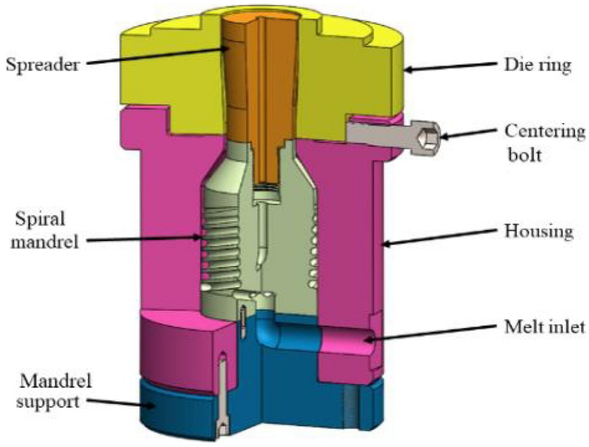

Fig. 2. Unrolled spiral mandrel geometry with design parameters.

3. Experimental results

The experimental verification of the tool was carried out using a side-fed single layer die, in which a spiral mandrel was implemented with the aforementioned geometry, providing, according to the model, a flow uniformity equal to 0.93. The cross-section through the die model is shown in Fig. 2.

The material used for verification was low-density polyethylene (LDPE) with the properties implemented in the model. The die ring was centered relative to the spreader with an accuracy of 0.02 mm. Four film samples were extruded, the widths of which are shown in Table III. Due to the end diameter of the die ring being 38 mm, the film was blown with a blow up ratio of 2.9 to 3.5. (see Table III) in order to allow for a more accurate examination of the thickness spread around the circumference. Measurement of the thickness of the extruded samples was carried out in accordance with the PN-ISO 4593:1999 standard with an increase in the number of measuring points from 20 to 60. The thickness measurements of each sample were taken in five series at distances in the winding direction of 10 cm. A summary of the course of percentage deviations from the average thickness values of the measured samples along with the theoretical waveform of leakage flow is shown in Fig. 3. The thickness uniformity of the extruded samples was calculated according to the following formula

$$UI_t = 1 - \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{t_i}{\bar{t}} - 1\right)^2}, \tag{8}$$

where UI_t is the thickness uniformity, t_i is the thickness at element i, $\bar{t}$ is the average value of t, N is the number of elements.

TABLE III

Width and blow up ratios of extruded film samples.

	Sample 1	Sample 2	Sample 3	Sample 4
Width [mm]	345	360	415	405
Blow up ratio [-]	2.9	3.0	3.5	3.4

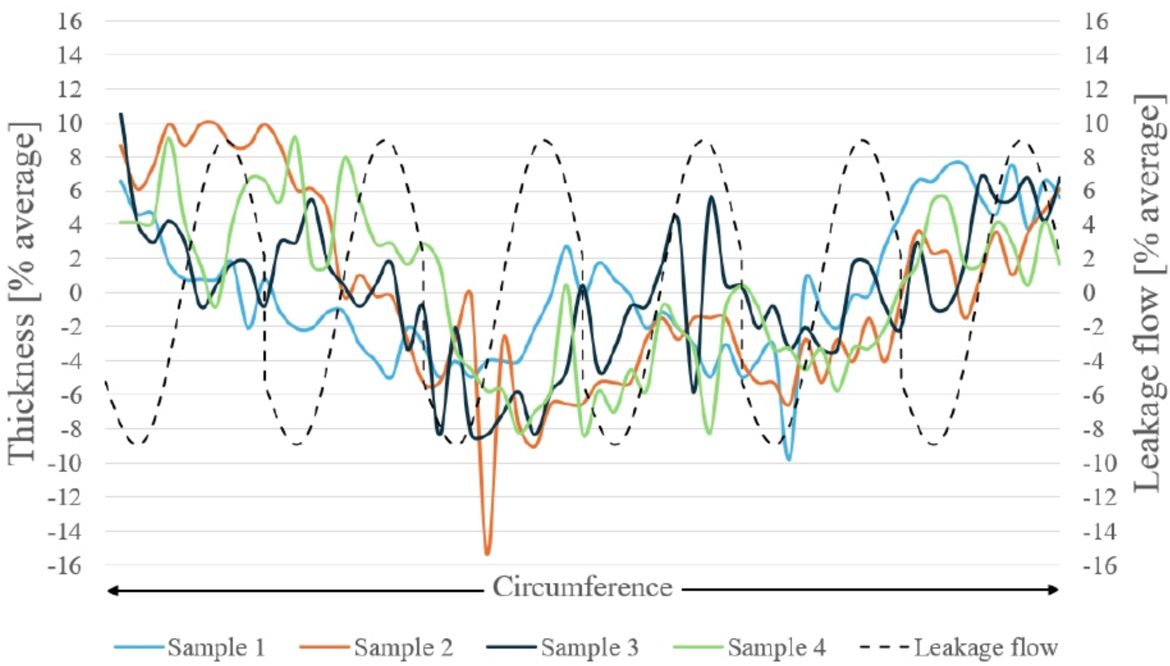

Fig. 3. Circumferential thickness and leakage flow variation as a function of position.

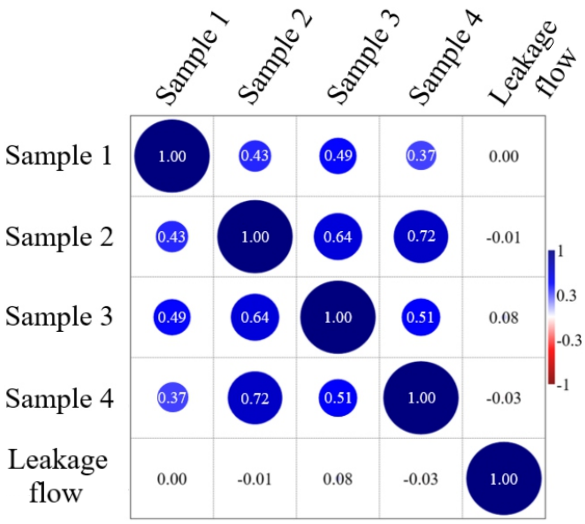

Fig. 4. Correlation coefficients of the measured values of film thickness and calculated leakage flow.

TABLE IV

Thickness uniformity values of the extruded samples.

	Sample 1	Sample 2	Sample 3	Sample 4
UI_t	0.96	0.94	0.96	0.95

The results are shown in Table IV.

The correlation coefficients of the measured values of film thickness and leakage flow obtained from the theoretical model were calculated using the statistical software PAST. The results are shown in Fig. 4.

4. Conclusions

The film thickness waveforms show non-pattern. The thickness waveforms of the extruded samples show a weak to strong positive association with each other, while there is no correlation of the samples with the theoretical leakage flow. This can be affected by uneven cooling of the film with the air ring or uneven winding of the film that strongly depends of the quality of the blown film line. Nevertheless, the samples are characterized by high values of thickness uniformity, higher than the UI value from the model. The maximum positive and negative percentage deviations of thickness are within the range calculated by the model. The tool used shows promise in designing spiral mandrel dies enabling the production of blown film with a high value of thickness uniformity.

References

[1] P.G. Lafleur, B. Vergnes, *Polymer Extrusion*, Wiley, Hoboken 2014.

[2] H.F. Giles, Jr., J.R. Wagner, Jr., E.M. Mount, *III Extrusion: The Definitive Processing Guide and Handbook*, William Andrew, Norwich, NY 2013.

[3] C. Rauwendaal, *Polymer Extrusion*, Hanser, Munich 2014.

[4] K. Cantor, *Blown Film Extrusion*, Hanser, Munich 2006.

[5] C. Rauwendaal, *Flow Distribution in Spiral Mandrel Dies*, Society of Plastics Engineers, Brookfield Center 1987.

[6] M. Malekzadeh, F. Goharpey, R. Foudazi, *Flow Analysis of Flat Spiral Dies and Comparison with Cylindrical Spiral Mandrel Dies*, Hanser, Munich 2008.

[7] C. Hopmann, W. Michaeli, *Extrusion Dies for Plastics and Rubber*, Hanser, Munich 2016.

[8] C.-C. Huang, *A Systematic Approach for the Design of a Spiral Mandrel Die*, Society of Plastics Engineers, Brookfield Center 2004.