SENSITIVITY OF FLOW DISTRIBUTION AND FLOW PATTERNS IN PROFILE EXTRUSION DIES

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Abstract

Fluctuations of the operating conditions or slight variations of the polymer rheology may occur during long-term productions, affecting the performance of the die in an extent dependent on its flow distribution sensitivity. In this work, four extrusion dies are optimised (balanced) using different design methodologies. These are compared in terms of their performance and stability to some operating conditions and polymer rheological properties. A finite-volume based computational code is used to perform the required simulations of the non-isothermal three-dimensional flows, under conditions defined by a statistical Taguchi technique. Correlation between the flow patterns developed and flow distribution sensitivity is also investigated.

Introduction

To achieve a specified geometry for an extruded profile with minimal degree of internal stresses, flow balancing of the die is required. Two main strategies are commonly adopted to balance the flow in an extrusion die: i) Strategy 1 (ST1) searches for the best set of flow channel lengths of the extrusion die final parallel zone to obtain in each channel a local average velocity equal to the average velocity of the profile [1-5]; ii) Strategy 2 (ST2) searches for the best set of flow channel thicknesses of the extrusion die final parallel zone to obtain local flow rates that allow the attainment of the required thickness in the profile after draw-down (pulling promoted by the haul-off unit) [1,2].

The first strategy always results in a final solution where cross flow must be accurately described. Therefore, it demands 3D flow simulations and is expected to generate a final solution particularly sensitive to fluctuations of the operating conditions and polymer rheological properties. However, imposition of constant zonal average velocity everywhere will contribute to minimise the degree of internal stresses of the extruded profile, thus increasing its dimensional stability. The disadvantages of this strategy are expected to be minimized by the inclusion of flow separators [3], but its use must be well thought in order to minimise the risk of mechanical failure of the extrudate at the weld lines formed.

On the other hand, for the second strategy the cross flow is minimized and a one- or two-dimensional flow simulation may probably be accurate enough to describe the corresponding flow field [2]. The final optimised geometry of the flow channel will be less dependent of the operating conditions/polymer rheological properties, but the extrudate will experience different draw ratios after emerging from the die, thus contributing to the development of stress gradients and consequent reduction in dimensional stability.

Despite their differences, both strategies implicitly consider that all the dimensions of the extruded profile must be satisfied within pre-defined tolerances. However, when the thickness of a specific wall is associated to a less restrictive condition, a third strategy, Strategy 3 (ST3), may be adopted: that of finding the most appropriate flow channel thickness to obtain a local average velocity equal to the average velocity of the profile. This strategy is expected to combine the advantages of ST1 and ST2 but will have a drawback on the profile dimensions since its thickness cannot be imposed.

To perform the automatic optimisation of the die flow channel, a set of operating conditions and melt rheology is considered. However, fluctuations of the operating conditions and variations of the melt rheology are expected to occur during long-term runs, or by voluntary change of the polymer grade used, and this may reduce the performance of the extrusion die. The sensitivity of flow distribution to processing parameters will be studied using extrusion dies whose flow channels were optimised using different design strategies, namely ST1 or ST2 applied to each and all of the channels and a 'mixed design', i.e., simultaneous use of ST1, ST2 and ST3 to different parts of the die. To complete this study, a fourth die will be optimised using ST1 in a die having flow separators.

Therefore, the objective of this study is to analyse the relative importance of several factors on the performance of extrusion dies and to compare its stability and versatility as a function of the design strategy adopted in its design.

Optimisation

The methodology developed for the automatic optimisation of flow balancing in profile extrusion dies is

described in Nóbrega et al. [6]. Briefly, the software consists of a 3D computational code, based on the finite volume method [7], and an optimisation algorithm associated with the minimisation of an objective function [6], which drives the automatic search of the final solution. This objective function has two terms, one accounting for the flow distribution and the other accounting for the relative length of each channel in the parallel zone, both of which are required to optimise a given die geometry [6]. However, a simplification may be introduced when the purpose is to carry out a sensitivity analysis, as it is the case here. Since the die geometry will then be kept unchanged, it suffices to retain the flow distribution term in the objective function, which becomes:

$$F_{obj} = \sum_i \left[\left(1 - \frac{V_i}{V_{obj_i}} \right)^2 \frac{A_i}{A} \right] \qquad (1)$$

In Eq. (1), V_i is the average melt velocity in elemental section i, is the average velocity required in that section to guarantee a pre-defined thickness, A_i is the cross-section area of section i and A is the total cross-section of the flow channel. This objective function tends to zero for a perfectly balanced die.

The polymer used in the simulations is the polypropylene homopolymer extrusion grade described in Nóbrega et al. [6].

Figure 1 depicts the initial cross section of the die before optimisation, common to all case studies here presented. This die was then optimised using the four design methodologies defined below, together with the optimisation algorithm described elsewhere [6] under the following fixed conditions: i) temperature of the external die wall (T_w) equal to the melt inlet temperature of 230ºC; ii) flow rate corresponding to an average melt bulk velocity (V) of 0.1 m/s at the die exit; iii) zero-shear-rate viscosity of the melt (η_0) of 55800 Pa.s; iv) melt power-law index (n) of 0.30.

All the simulations were carried out with the following thermal boundary conditions: insulated internal walls (including the separators) and isothermal external walls (in direct contact with the heating elements). The division of the geometry into elemental sections is shown in Figure 1.

In terms of design methodologies, the following were considered:

i) Design Methodology 1 (DM1) – exclusive use of design Strategy 1 (ST1) applied to all ES;

ii) Design Methodology 2 (DM2) – exclusive use of design Strategy 2 (ST2) applied to all ES;

iii) Design Methodology 3 (DM3) – three design strategies (ST1, ST2 and ST3) were used as shown in Figure 1;

iv) Design Methodology 4 (DM4) – exclusive use of design Strategy 1 (ST1), applied to all ES, using flow separators (axial walls).

Sensitivity study

The factors assessed in the case studies presented in the following section can be divided in two different groups: i) controllable process parameters, such as the global average melt velocity (or throughput), V, and the temperature of the external die walls, T_w; ii) melt rheological properties, such as the zero-shear-rate viscosity, η_o, and the power-law index, n, which are not directly controllable during extrusion.

The conditions for the numerical experiments to be presented were set using a statistical Taguchi technique [8, 9], with three levels for each factor, in a range of ±20%. The comparison of the flow distribution is done via the objective function (F_{obj}) defined by Equation 1. However, the discussion will be extended to other potentially important results, namely: the total pressure drop (ΔP), the maximum shear rate ($\dot{\gamma}_{max}$), the average melt temperature at the die exit ($\overline{T}$), and the standard deviation of the melt temperature at the die exit (σ_T).

Results and discussion

Performance of the optimised dies

The general geometry of the dies and their main dimensions are shown in Figure 2 and Table 1, respectively. It should be noted that after optimisation some of the ES optimised via Design Methodologies 1 and 4 have very low length-to-thickness ratios, which reveals some limitations of the methodologies based on the length optimisation: see, for example, ES 1 to 4 in die obtained with DM1 (die DM1) and ES 3 to 5 in die obtained with DM4 (die DM4).

Table 2 summarizes the main results. In terms of the flow distribution, which is the most important result here considered, it can be concluded that the die leading to the most equilibrated flow is that corresponding to DM2 which has the lowest value of the objective function (circa 0.019). For the other dies the objective function has higher but similar values: 0.047, 0.050 and 0.042 for Design Methodologies 1, 3 and 4, respectively. The best performance of die obtained with DM2 was expected since the main objective of strategy 2 is to diminish the local differences in flow restriction. Surprisingly, the same strategy was not so efficient when applied only to some ES, as in Design Methodology 3, since it did not improve the results obtained with Design Methodology 1. However, it should be mentioned that die DM3 has values of ES lengths higher than those of die DM1, showing only one low L/t value of 6, for ES3, while the remaining values are higher than 12.

Considering the remaining results shown in Table 2, it can be concluded that die DM1 has the best performance since it has the minimum total pressure drop, melt average temperature and melt temperature standard deviation.

These results are a consequence of its lower ES lengths, the controllable variable used in its optimisation. Therefore, a similar performance could be expected for die DM4, in which the ES lengths were also the controllable geometrical parameter. However, the thickness (0.5 mm) of the separators included in this die decreased its cross section flow area thus leading to undesirable increases in pressure drop, shear rate and temperature.

Sensitivity analysis

The set of nine experiments carried out for each design methodology, following the Taguchi technique, enabled to conclude that all the factors considered were independent. The factors with statistical significance for each design methodology and result considered are shown in Table 3. From these data, it is possible to conclude that, with the exception of the objective function, the factors affecting each result are the same for all dies included in the investigation and that the standard deviation of the melt temperature at the die exit is not affected by any factor.

Concerning the flow distribution, the data in Figure 3 show that the processing conditions assumed to perform its optimisation with Design Methodology 1 are not those that result in its maximum performance, since a decrease in the wall temperature, T_w, reduces the value of the objective function. This is a consequence of a more favourable flow distribution, and does not invalidate the optimisation methodology used, which is merely based on geometrical parameters. However, as T_w is a controllable factor, it may be included in future improvements of ST1. Results shown in Figure 3 also indicate that the factors V and η_0 have a negligible influence on flow distribution, for all the design methodologies considered.

Generally, pressure drop decreases with increasing temperature, decreasing value of the power-law index and decreasing limit viscosity (see Figure 3), since all these variations promote a decrease in the shear viscosity. An increase in flow rate will also increase the pressure drop, but to a lower extent due to the shear-thinning behaviour of the melt.

As shown in Figure 3, the maximum shear rate clearly increases with the flow rate, as expected. The decrease of the maximum shear rate with a lower shear-thinning intensity (increase in power-law index) is also an expected result, since the velocity profile changes progressively from a plug-flow type, for low values of n, to a parabolic shape, when the fluid is Newtonian. However, the decrease is not as high as expected due to the redistribution of the flow, which affects the shear rate field. The wall temperature and zero-shear-rate viscosity should not directly affect the shear rate field. Therefore, the variations in the maximum shear rate due to the variation of T_w can be attributed to flow redistribution. On the other hand, the variation of η_0 has negligible effect upon the flow distribution, as can be seen in Figure 3, and, hence, in this case the shear rate field is maintained.

The effect of n, V and η_0 on the melt average temperature is the expected (see Figure 3) since an increase in any of these factors will contribute to increase the viscous dissipation.

The maximum variations of F_{obj}, ΔP, $\dot{\gamma}_{max}$, and $\overline{T}$ due to the factors considered in the study are listed in Table 4. These values were computed by dividing the difference between the maximum and minimum values by the corresponding reference value. Taking into consideration this information and that contained in Table 3, it can be concluded that in terms of flow distribution die DM2 is only sensitive to the variation in T_w. This die is also the less sensitive to variations of the factors considered, with a maximum variation of 10%.

The advantage of using ‘mixed strategies’ in Design Methodology 3 is now apparent. In spite of having an objective function value similar to that of die DM1, when used under the reference conditions (circa 0.050, as shown in Table 2), die DM3 is much less sensitive to variations of the various factors considered here, showing a maximum variation of 12% against the 28% variation of die DM1 (see Table 4). In this respect, the worst dies are those corresponding to Design Methodologies 1 and 4 (where the ES lengths were the controllable geometric parameters), which underwent maximum variations of 28% and 64%, respectively. Nevertheless, die DM1 is more stable than die DM4, in spite of being affected by a higher number of factors.

Flow patterns

The previous results can be further understood if the flow paths are analysed. Figure 4 shows the streamlines developed in the flow channel region corresponding to the profile inner wall (ES4), the most restrictive one, both for DM1 and DM2, whose optimisations were performed on the length (ST1) and on the thickness (ST2), respectively. As can be observed in both cases, thickness reduction promotes lateral flux from the lower to the higher thickness regions. Therefore, when ST1 is adopted, the parallel zone of the die must end before fully developed flow occurs, to avoid losing the flow balance. On the contrary, if ST2 is adopted, the flow at the parallel zone should be completely developed. This fact justifies the higher stability presented by the die optimised using ST2.

Conclusions

In this work several die design methodologies are compared in terms of the performance of the generated dies when operated under reference optimisation conditions. Then, the sensitivity of these dies to several factors was investigated in detail. The most important result of the comparison was the flow distribution, but other potentially relevant results where also included in the analysis.

The main conclusions are the following:

i) In terms of flow balancing, the most efficient strategy is Strategy 2 (ST2), used in Design Methodology 2, in which the controllable geometric parameter is the thickness of the elemental sections considered for optimisation purposes. The die generated with ST2 was simultaneously the most balanced die under reference conditions and the least sensitive to variations of the operating parameters around the reference values;

ii) The effect of flow separators was assessed by comparing dies generated by Design Methodologies 1 and 4 (i.e., ST1 and ST4), in which the controllable geometric parameter is the length of the elemental sections. The use of separators slightly improves the flow distribution when the reference optimisation conditions are considered, but increases the sensitivity of the die to the variation of process operating conditions. The use of separators usually leads to worst results than its absence;

iii) Strategy 1 may be improved through the inclusion of the wall temperature as an additional controllable parameter of the optimisation algorithm;

iv) As expected, the simultaneous use of several strategies combines their advantages. Consequently, die DM3 shows ES lengths higher then those of die DM1 and, at the same time, it is less sensitive to variations of the factors investigated;

v) For all the cases, the flow rate and the zero-shear-rate viscosity did not affect the flow distribution;

vi) The flow patterns developed explain the differences in sensitivity verified of the dies considered in this work.

References

[1] Sienz, J., Bulman, S.D., Pitman, J. F. T.: Paper presented at the 4th ESAFORM Conference, Liege, Belgium, April (2001)

[2] Svabik, J., Placek, L., Saha, P.: Int. Polym. Process. 14, p. 247 (1999)

[3] Carneiro, O. S., Nóbrega, J. M., Pinho, F. T., Oliveira, P. J.: J. Mat. Process. Tech. 114, p. 75 (2001)

[4] Nóbrega, J. M., Carneiro, O. S., Pinho, F. T., Oliveira, P. J.: Paper presented at the SPE Annual Technical Conference, Dallas, U.S.A., May (2001)

[5] Nóbrega, J. M., Carneiro, O. S., Pinho, F. T., Oliveira, P. J., Paper presented at the 17th Annual Meeting of the Polymer Processing Society, Montreal, Canada, June (2001)

[6] Nóbrega, J. M., Carneiro, O. S., Oliveira, P. J., Pinho, F. T., Paper presented at the 18th Annual Meeting of the Polymer Processing Society, Guimarães, Portugal, June (2002)

[7] Oliveira, P. J., Pinho, F. T., Pinto, G. A.: J. Non-Newt. Fluid Mech. 79, p. 1 (1998)

[8] Ross, J. P.: Taguchi Techniques for Quality Engineering. McGraw Hill, New York (1998)

[9] Schmidt, S. R., Launsby, R. G.: Understanding Industrial Designed Experiments, 4th Ed. Air Academy Press, Colorado (1994)

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Table 1 – Main dimensions (in mm) of the optimised dies (the optimised variables are underlined).

Geometrical Variable		Initial	After optimisation DM1	DM2	DM3	DM4
ES Length	L1	22.5	6.0	22.5	22.5	20.0
	L2	22.5	6.0	22.5	22.5	20.0
	L3	22.5	6.0	22.5	9.0	1.5
	L4	15.0	4.0	15.0	15.0	2.0
	L5	27.0	19.0	27.0	24.6	2.0
	L6	30.0	30.0	30.0	30.0	30.0
	L7	30.0	30.0	30.0	30.0	30.0
ES Thickness	t1	1.50	1.50	1.63	1.87	1.50
	t2	1.50	1.50	1.63	1.87	1.50
	t3	1.50	1.50	1.64	1.50	1.50
	t4	1.00	1.00	1.25	1.25	1.00
	t5	1.80	1.80	1.73	1.80	1.80
	t6	2.00	2.00	1.75	2.00	2.00
	t7	2.00	2.00	1.75	2.00	2.00

Table 2 – Results obtained for each die Design Methodology (DM) corresponding to the conditions used in their optimisation (reference results).

DM	F_{obj}	ΔP (MPa)	$\dot{\gamma}_{max}$ (s^{-1})	$\overline{T}$ (ºC)	σ_T (ºC)
1	0.047	4.71	991.7	231.1	1.03
2	0.019	6.26	1073.1	231.5	1.64
3	0.050	5.48	857.6	231.3	1.32
4	0.042	7.30	1152.1	231.8	1.91

Table 3 – Factors with statistical significance.

Design Methodology	Results F_{obj}	ΔP	$\dot{\gamma}_{max}$	$\overline{T}$	σ_T
1	T_w, n	n, η_0	T_w, n, V	T_w, n, η_0	None
2	T_w	n, η_0	T_w, n, V	T_w, n, η_0	None
3	T_w, η_0	n, η_0	T_w, n, V	T_w, n, η_0	None
4	n	n, η_0	T_w, n, V	T_w, n, η_0	None

Table 4 – Sensitivity (percentual variation) of each result to the factors considered.

Design Methodology	F_{obj}	ΔP	$\dot{\gamma}_{max}$	$\overline{T}$
1	28	195	57	2
2	10	154	54	2
3	12	152	49	2
4	64	152	66	2

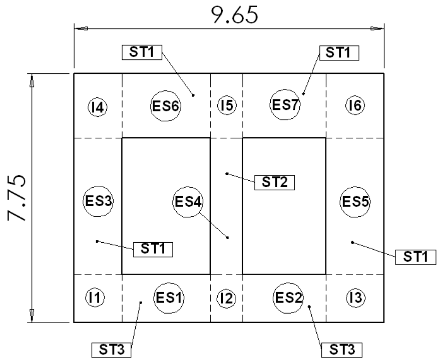


Figure 1 – Cross section of the parallel zone (PZ) of the profile die used as a case study (dimensions in mm): subdivision in elemental sections (ES), intersection (I) and identification of optimisation strategy (ST) adopted for Design Methodology 3.

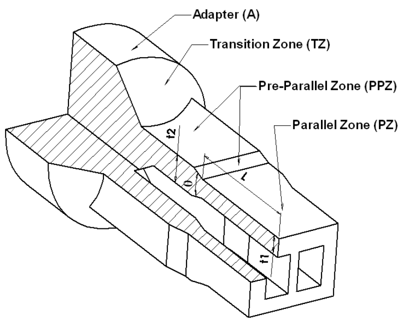
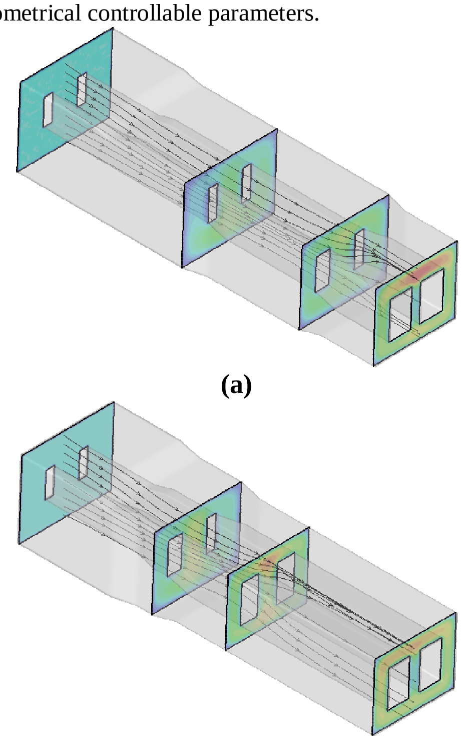


Figure 2 – Typical geometry of the dies and identification of their geometrical controllable parameters.



(a)

(b)

Figure 4 – Flow patterns developed in the ES4 flow channel region, for the dies obtained with: (a) Design Methodology 1; (b) Design Methodology 2.

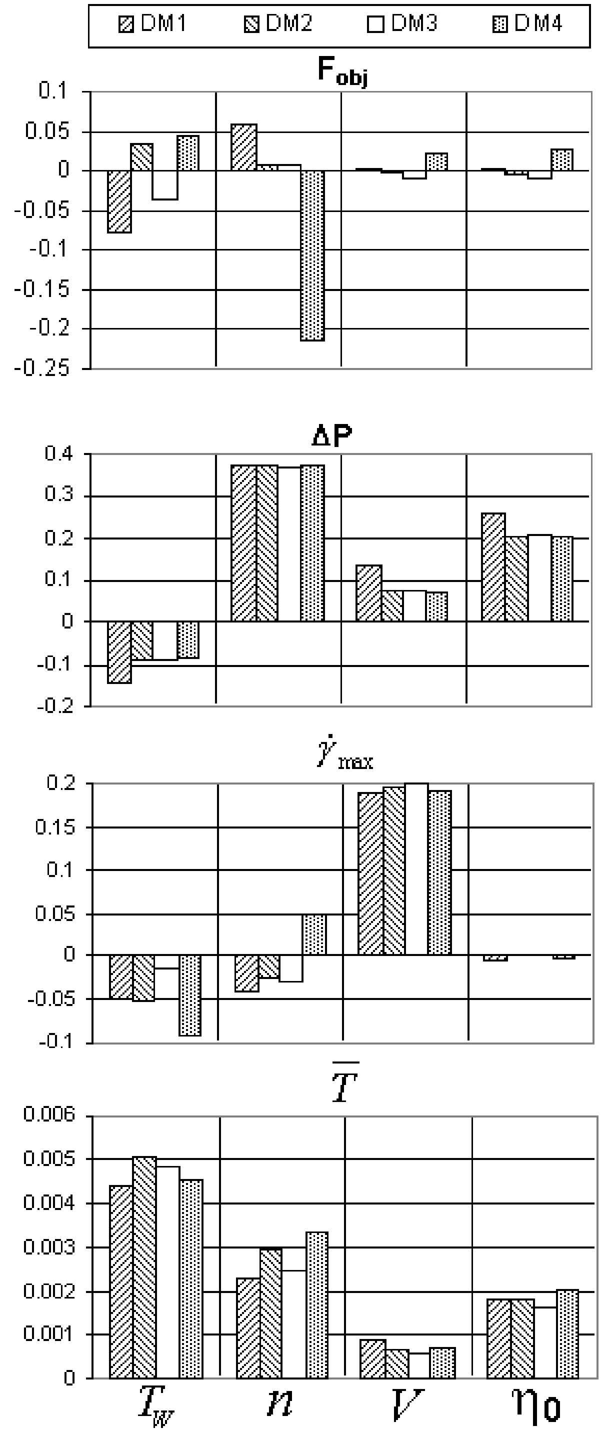


Figure 3 – Sensitivity of the results to the different factors considered: objective function; pressure drop; maximum shear rate; average melt temperature at the die exit.