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Flow Balancing in Extrusion Dies for Thermoplastic Profiles

Part II: Influence of the Design Strategy

To achieve a specified geometry for an extruded profile with minimal level of stress gradient induced by pulling, flow balancing of the die is required. To fulfil this requisite, a set of operating conditions and polymer rheological properties is considered during the design step. However, fluctuations of the operating conditions and/or slight variations of the polymer rheological properties are expected to occur during long-term production. Their effect on the performance of an extrusion die will depend, among other things, on the sensitivity of the flow distribution within the die. In this work, an extrusion die is optimised (balanced) using four different design methodologies and the final shapes of the die are compared in terms of their absolute quality (when used in the optimal conditions) and stability to the factors considered. For this purpose, 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 statistic Taguchi technique. The influence of some operating conditions on the flow distribution is assessed and the effect of the polymer melt rheology is also investigated. It was concluded that the use of different design methodologies lead to different results in terms of flow balancing and sensitivity to the factors considered and that the most balanced and stable extrusion die was that generated by the strategy based on the parallel zone thickness control.

1 Introduction

There are two main strategies commonly adopted to balance the flow in an extrusion die:

i) *Strategy 1* (ST1) searches 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 to 5];
ii) *Strategy 2* (ST2) searches 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 is present. 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 level of stress gradient of the extruded profile, induced by pulling, 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 minimised 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 on 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 the reduction in dimensional stability.

Despite their differences, both strategies implicitly consider that all the dimensions of the extruded profile have the same importance and 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, as in ST2, to obtain a local average velocity equal to the average velocity of the profile, as in ST1. 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

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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.

2 Outline of the Software Package

The methodology developed for the automatic optimisation of flow balancing in profile extrusion dies begins with the division of the cross section of the die parallel zone into elemental sections (ES) [3]. The next step consists on the selection of the design strategy to be applied to each elemental section. Then, the best geometry of the die will be automatically searched using an in-house software package [6]. Briefly, the software used to perform the required numerical simulations of the non-isothermal flows 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:

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

In Eq. 1, V_i is the average melt velocity in elemental section i, V_{obj_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. More details on the software package can be found in the first part of this work [6].

3 Optimisation

The polymer used in the simulations is the polypropylene homopolymer extrusion grade modelled using a Bird Carreau constitutive equation coupled with an Arrhenius law, as described in *Nóbrega* et al. [6].

Fig. 1 depicts the initial cross section of the die before optimisation, common to all case studies here presented, with dimensions identical to that of the profile being produced. This die was then optimised using the four design methodologies defined below, together with the optimisation algorithm based on the *experimental procedure* described elsewhere [6] under the following operating conditions: temperature of the external die wall (T_w) equal to the melt inlet temperature of 230 °C and flow rate corresponding to an average melt bulk velocity (V) of 0.1 m/s at the die exit.

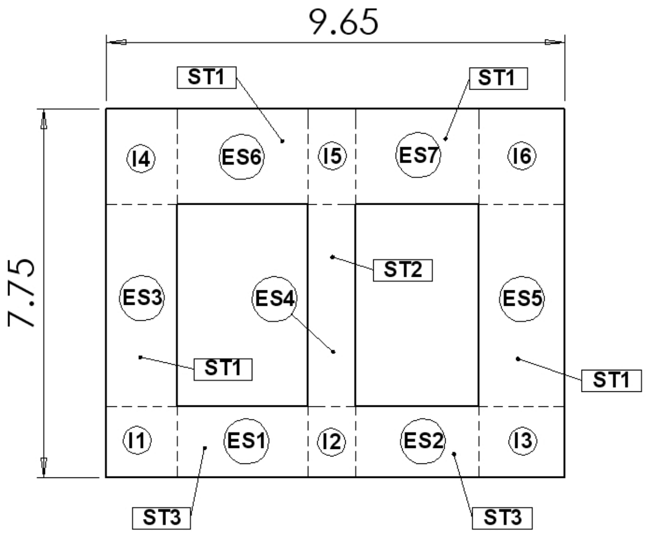

Fig. 1. Cross section of the profile to be produced (dimensions in mm), elemental (ES) and intersection (I) sections considered for optimisation purposes (in Design Methodologies 1, 2 and 3) and strategies (ST) adopted in Design Methodology 3

All the simulations were carried out with the following thermal boundary conditions: adiabatic 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 Fig. 1. The intersection zones (I), resulting from the intersection of two or three ES, have dimensions that are not controllable as those of the neighbouring elemental sections implicitly defining them. Nevertheless, their contribution is important and must be included in the computation of the value of the objective function for performance assessment purposes.

In terms of design methodologies, the following was 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: strategy ST3 was selected for ES1 and ES2 because it was assumed that the lower wall of the extruded profile would not have a pre-defined thickness. Strategy ST1 was used for ES3, ES5, ES6 and ES7 since it was assumed that these sections must have pre-defined thicknesses and high dimensional stability in use. Finally, for the inner wall of the profile (ES4) a pre-defined thickness was set to minimize the occurrence of differential cooling, but it could support internal stresses without promoting the distortion of the profile. Thus, in this case strategy ST2 was used, as it facilitates the flow balancing of the neighbouring walls. This information is also summarized in Fig. 1;

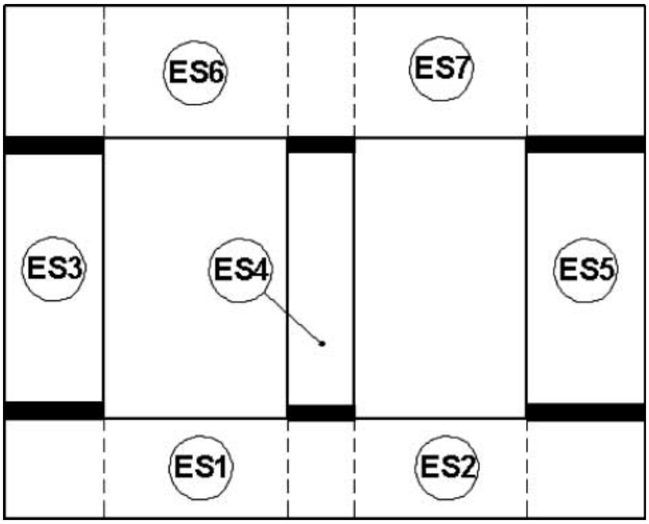

Fig. 2. Location of the separators used in Design Methodology 4

iv) Design Methodology 4 (DM4) – exclusive use of design *Strategy 1* (ST1), applied to all ES. The location of the separators (axial walls) is shown in Fig. 2.

4 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_0, and the power-law index, n, which are not directly controllable during extrusion.

The information gathered here will help to analyse the relative importance of each parameter in the first group, aimed at selecting the most significant to be included in future improvements of the optimisation methodology. The overall results, including those obtained from variations in melt rheological properties, will enable an assessment of the adequacy of the different design strategies here adopted. The comparison of the performance of the generated dies will be carried out under the conditions used in the optimisation process and through the corresponding sensitivity to variations imposed to the various factors.

Experiment (Simulation)	Factors			
	T_W °C	n	V m/s	η_0 Pa · s
1	210	0.24	0.08	44 640
2	210	0.30	0.10	55 800
3	210	0.36	0.12	66 960
4	230	0.24	0.10	66 960
5	230	0.30	0.12	44 640
6	230	0.36	0.08	55 800
7	250	0.24	0.12	55 800
8	250	0.30	0.08	66 960
9	250	0.36	0.10	44 640

Table 1. Taguchi plan of experiments (simulations)

The conditions for the numerical experiments to be presented were set using a statistics Taguchi technique [8, 9], considering three levels for each factor, as shown in Table 1. The comparison of the flow distributions is done via the objective function (F_{obj}) defined by Eq. 1. However, the discussion of results will include other potentially important results, namely: the total pressure drop, ΔP, which is relevant to determine the extruder power consumption; the maximum shear rate, $\dot{\gamma}_{max}$, to be maintained below a critical value to avoid the appearance of sharkskin; the average melt temperature at the die exit, $\bar{T}$, which is relevant to define the cooling time or length required for the extruded profile; and the standard deviation of the melt temperature at the die exit, σ_T, which is related to the development of thermal induced internal stresses in the profile. These two last results were computed using the following equations:

$$\bar{T} = \sum T_i \frac{Q_i}{Q} \tag{2}$$

and

$$\sigma_T = \sum \sqrt{(T_i - \bar{T})^2 \frac{Q_i}{Q}}, \tag{3}$$

where T_i and Q_i are the temperature and flow rate at cell i, respectively, and Q is the total flow rate through the die.

For each die, the nine simulations performed are summarised in Table 1, which lists the values assumed of the factors used. The remaining flow conditions are the same used to carry out the optimisations and were described in section 3.

5 Results and Discussion

5.1 Performance of the Optimised Dies

The general geometry of the dies and their main dimensions are shown in Fig. 3 and Table 2, respectively. It should be noted that after optimisation some of the ES optimised via Design

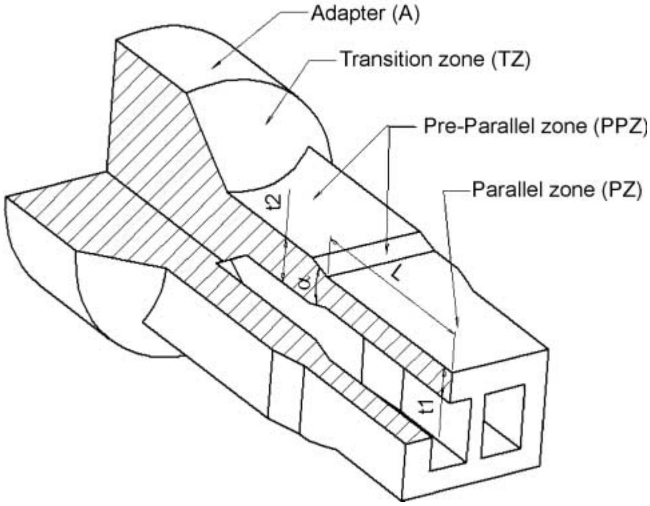

Fig. 3. Typical geometry of the dies and identification of their geometrical controllable parameters

Geometrical variable		Initial (reference)	After optimisation			
			Design Methodology 1	Design Methodology 2	Design Methodology 3	Design Methodology 4
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. Main dimensions (in mm) of the optimised dies

Design Methodology	F_{obj}	ΔP Pa	$\dot{\gamma}_{max}$ s^{-1}	$\bar{T}$ °C	σ_T °C
1	0.047305	4 710 428	991.7	231.1	1.0
2	0.019092	6 261 744	1073.1	231.5	1.6
3	0.049691	5 480 660	857.6	231.3	1.3
4	0.042365	7 307 081	1152.1	231.8	1.9

Table 3. Results obtained for each die (design methodology) corresponding to the conditions used in their optimisation (reference results)

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 3 summarizes the main results of the optimisation of the dies. 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 Design Methodology 2, optimised with ST2, which has the lowest value of the objective function (circa 0.019). For the other dies the objective function has higher values but of the same order of magnitude: 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 through minimization of differences in ES thickness and the objective function in Equation 1 is totally based on flow distribution. In fact, the thickness ratio changed from an initial value of 2 (2.00/1.00) to a final value of 1.4 (1.75/1.25), as shown in Table 2. 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 3, it can be concluded that die DM1 has the best performance since it has the minimum total pressure drop, showing a melt average temperature and melt temperature standard deviation similar to those of the remaining. 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.

The value of the objective function computed with Eq. 1 considers the cross-section areas of the elemental sections, thus giving a global idea of the (weighted) equilibrium of a die. However, if the maximum and minimum values of the average absolute melt velocities are considered, the picture changes. In Table 4, the maximum draw-ratios experienced by the extrudate are presented. These values were computed dividing the maximum average section velocity (from the set of all ES and

Design Methodology	Maximum draw-Ratio
1	3.1
2	2.4
3	3.3
4	2.0

Table 4. Maximum draw-ratio experienced by the extrudate

I zones) by the corresponding minimum, since in practice it is expected that the pulling velocity will be, at least, of the order of magnitude of the former value.

From this point of view, the best solution seems to be the die DM4, for which the maximum draw ratio imposed to the extrudate is just about 2.0. It must be mentioned that these maximum draw ratios represent a limitation of the Design Methodologies 1 and 4 (draw ratios of 1 would result for all sections in an ideal case) whilst for the other two Design Methodologies they are inherent to the strategy adopted. Surprisingly, the value of the maximum draw ratio for die DM2 is lower than that corresponding to die DM1. From a theoretical point of view, this result was not expected and must be attributed to the large differences in thickness required for the extruded profile, which limited the efficiency of ST1. In other words, the reduction of the length of the most restrictive sections, in DM1, was insufficient to compensate for their higher restrictions.

5.2 Sensitivity Analysis

The set of nine experiments carried out for each design methodology, following the Taguchi technique, enabled us to conclude that the factors with statistical significance for each design methodology and result considered are those shown in Table 5. 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.

Fig. 4 shows the percent variation of each result corresponding to the maximum variation considered for each factor in the analysis performed. Therefore, using Fig. 4A as an example, an increase of T_w from 230 °C (reference value) to 250 °C (maximum value) promotes a decrease of 8 % and an increase of 4 % in the objective function value of the dies optimised with DM1 and DM2, respectively.

Concerning the flow distribution, the data in Fig. 4 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 Fig.4A also indicate that the factors V and η_0 have a negligible influence on flow distribution, for all the design methodologies considered.

Design Methodology	Results				
	F_{obj}	ΔP	$\dot{\gamma}_{max}$	$\bar{T}$	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 5. Factors with statistical significance

Generally, pressure drop decreases with increasing temperature, decreasing value of the power-law index and decreasing limit viscosity (see Fig. 4B), 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 Fig. 4C, 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

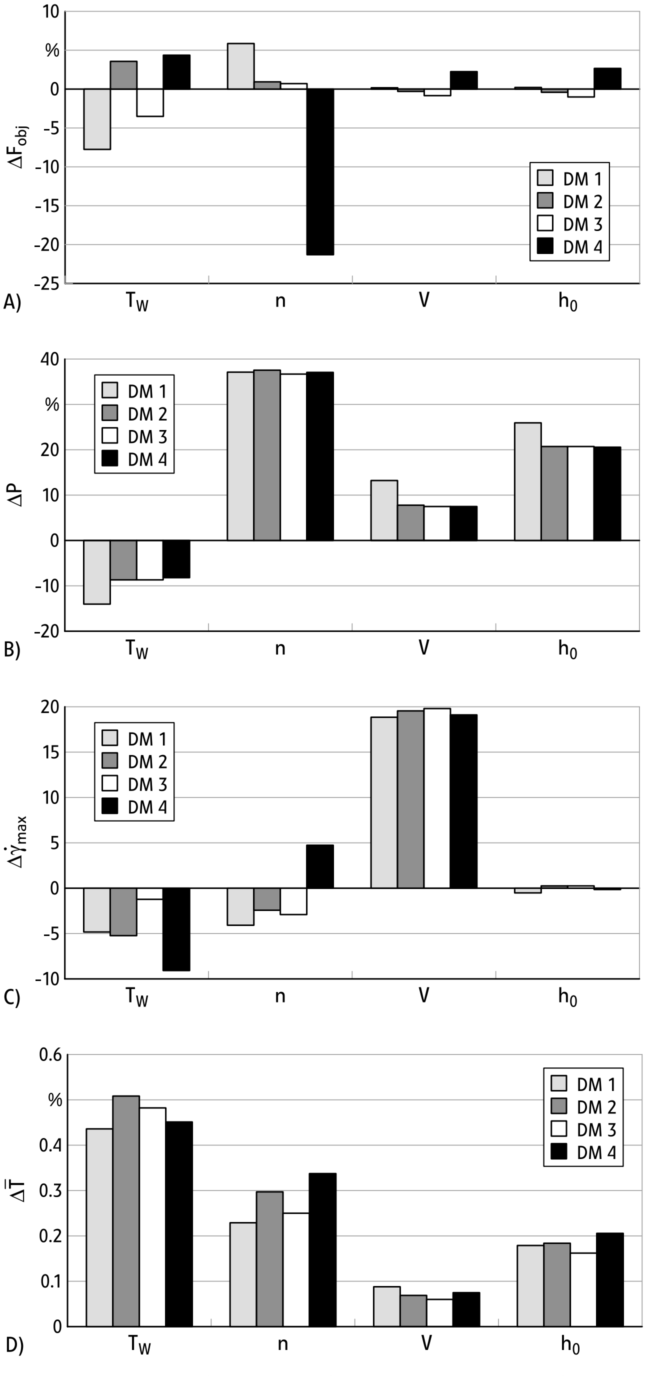

Fig. 4. Sensitivity of the results to the different factors considered: (A) objective function; (B) pressure drop; (C) maximum shear rate; (D) average melt temperature at the die exit

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 Fig. 4A, 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 Fig. 4D) 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 $\bar{T}$ due to the factors considered in the study are listed in Table 6. These values were computed dividing the difference between the maximum and minimum values by the corresponding reference value. Taking into consideration this information and that contained in Table 5, 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 3), 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 6). 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.

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

Table 6. Sensitivity (percentual variation) of each result to the factors considered

Taking into account the remaining information contained in Table 6, it can be said that there are no significant differences concerning the melt average temperature and that the most sensitive dies in terms of total pressure drop and maximum shear rate are dies obtained with DM1 and DM4, respectively.

6 Conclusions

In this work several die design methodologies are compared in terms of performance when the generated dies were 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, except that the minimum average draw-ratio experienced by the extrudate occurs with this die.

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.

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