Sensitivity of Flow Distribution in Extrusion Dies: Influence of the Design Strategy

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Abstract

To achieve the specified geometry for an extruded profile together with a minimal degree of internal stresses, flow balancing of the die is required. To fulfil this requisite, a set of operating conditions/polymer rheological properties are assumed during the design step, which are particularly relevant in the definition of the extrusion die flow channel. However, fluctuations of the operating conditions and/or slight variations of the polymer rheological properties are expected to occur during long-term productions. The effect of these factors on the performance of an extrusion die will depend, among other factors, on its flow distribution sensitivity. In this work, four extrusion dies optimised (balanced) using different design strategies are evaluated in terms of their absolute quality (when used in the optimal conditions) and in terms of their stability to the operating factors considered. For this purpose, a computational code, based on the finite-volume method, is used to perform the required non-isothermal three-dimensional numerical simulations of the flow under conditions defined by a statistic Taguchi analysis.

1 – INTRODUCTION

There are two main strategies commonly adopted to balance the flow: i) *strategy 1* (ST1) - search the best set of flow channel lengths, in the final parallel zone of the extrusion die, in order to obtain in each channel a local average velocity equal to the average velocity of the profile [1-5]; ii) *strategy 2* (ST2) - search the best set of flow channel thickness, in the same zone of the extrusion die, in order 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 adoption of the first strategy results always in a final solution where cross flow is present. Therefore, this strategy demands 3D flow simulations and it is expected to generate a final solution particularly sensitive to fluctuations of the operating conditions/polymer rheological properties. However, the imposition of an equal average velocity will contribute to minimise the degree of internal stresses of the extruded profile, thus increasing its dimensional stability. These disadvantages are expected to be minimized by the inclusion of flow separators [3], but its use must be well pondered in order to minimise the risk of mechanical failure of the extrudate promoted by the weld lines formed.

On the other hand, when the second strategy is adopted the cross flow is minimised and, therefore, a 1D/2D flow simulation may probably be accurate enough to describe the correspondent flow field [2]. In this case, 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 the die, thus contributing for the development of differential stresses.

Despite their differences, both strategies implicitly consider that all the dimensions of the extruded profile have the same importance and must be satisfied within a pre-defined tolerance.

However, when the thickness of a specific wall is associated to a lower constraint, a third strategy, *strategy 3* (ST3), can be adopted: find the most appropriate flow channel thickness in order to obtain a local average velocity equal to the average velocity of the profile. This strategy is expected to combine the advantages of the previous ones but with a drawback on the profile dimensions since the profile thickness will not be controllable.

To perform the automatic optimisation of the die flow channel, a set of operating conditions/melt rheology is assumed. 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, which may reduce the performance of the extrusion die. The sensitivity of flow distribution to processing parameters will be studied using extrusion dies whose flow channel was optimised using different design strategies, namely *strategy 1* or *strategy 2* applied to all channels and a 'mixed design', i.e., simultaneous use of the three above mentioned design strategies. To complete this study, a fourth die will be optimised using a variant of the first strategy, *Strategy 4*, consisting of the optimisation of the flow channel lengths of a die having flow separators.

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 die parallel zone cross section in elemental sections [3], ES. 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 non-isothermal flow computations encompasses a 3D computational code based in the finite volumes method [7] and an optimisation algorithm associated to an objective function [3], to carry out the automatic search of a final solution (die channel geometry). This function has two terms, one accounting for the flow distribution and another relative to the length of the parallel zone. For optimisation purposes, this will be the objective function to be adopted. However, for sensitivity analysis purposes, the performance of the dies will only be assessed through the resulting flow distribution, since their geometry is maintained constant during the study. Therefore, the following equation will be considered:

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

where V_i is the average melt velocity in elemental section i, V_{target} is the average velocity required for the same section in order to guarantee a pre-defined thickness, A_i is the cross-section area of section I and A is the cross-section of the global flow channel. Considering this definition, an objective function value of zero will correspond to a die perfectly balanced.

3 - Optimisation

Figure 1 depicts the initial, before optimisation, cross section of the die, common to all case studies here presented, which is considered equal to that of the profile to be produced. The four dies used in the simulations performed to carry out the sensitivity study, were optimised using the method described elsewhere [6] under the fixed following conditions: temperature of the external die wall (T_w) and melt inlet temperature, 230ºC; flow rate corresponding to an average melt global linear velocity (V) of 0.1 m/s at the die exit; zero-shear-rate viscosity of the melt (η_0) of 55800 Pa.s and melt power-law index (n) of 0.30. All the simulations were performed

assuming fixed thermal boundary conditions: internal walls insulated (including the separators, when existing) and external walls (in direct contact with the heating elements, isothermal). The profile elemental sections considered, common to the four case studies, are illustrated in Figure 1.

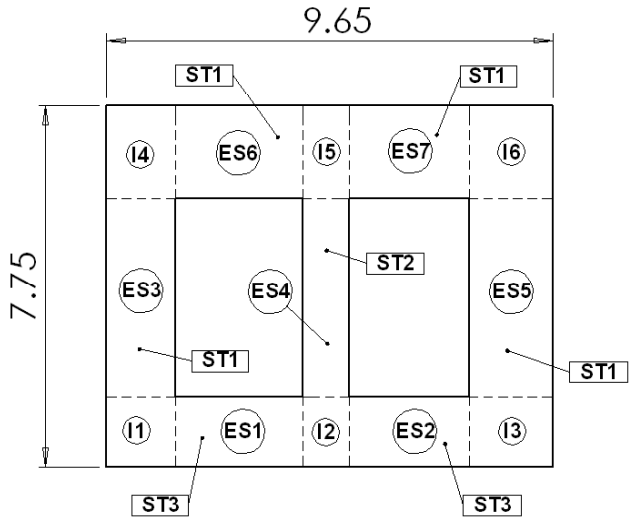


Figure 1 – Cross section of the profile to be produced, elemental sections (ES) and intersection zones (I) considered for optimisation purposes and strategies (ST) adopted in Design Methodology 3.

In terms of design strategies, the following was considered:

i) Design Methodology 1 – exclusive use of design *strategy 1* (ST1), applied to all ES;
ii) Design Methodology 2 – exclusive use of design *strategy 2* (ST2), applied to all ES;
iii) Design Methodology 3 – three design strategies (ST1, ST2 and ST3) are applied, as summarized in Figure 1;
iv) Design Methodology 4 – exclusive use of design *strategy 4* (ST4), applied to all ES. The location of the separators (axial walls) considered is illustrated in Figure 2.

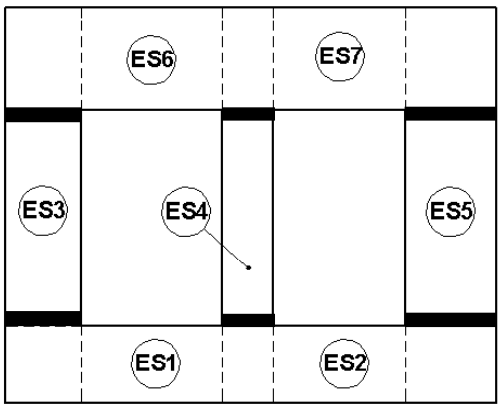


Figure 2 – Separators used and elemental sections (ES) considered in Design Methodology 4.

4 Sensitivity Study

The parameters (factors) considered 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 external die walls temperature, T_w; ii) melt rheological

properties, such as zero-shear-rate viscosity, η_0, and power-law index, n, which are not directly controllable during extrusion.

The experiments (simulations) to be performed were defined by a statistics Taguchi technique [8,9], considering three levels for each factor. The main objective of this study is to analyse the flow distribution, through the objective function (F_{obj}) defined by equation 1. However, the discussion will be extended to other potentially important results, namely: total pressure drop, maximum shear rate, average melt temperature and its standard deviation at the die exit.

5 - Results and discussion

After optimization some of the ES optimized via Design Methodologies 1 or 4 have very low length-to-thickness ratios (ES 1 to 4 in die 1 and ES 3 to 5 in die 4).

The relative performance of the dies used in each design methodology can be assessed in terms of the results generated, shown in Table 1, by the flow simulation under the conditions used in their optimization (common to all). In terms of the flow distribution, which is the most important result here considered, it can be concluded that the die originating the most equilibrated flow is that corresponding to Design Methodology 2, optimized with ST2, which have the lower objective function value (circa 0.019). The remaining dies have objective function values of the same order of magnitude (0.0047, 0.050 and 0.042 for Design Methodologies 1, 3 and 4, respectively). The best performance of die 2 was expected since the main objective of strategy 2 is to diminish the local differences in flow restriction through minimization of the differences in ES thickness. In fact, this difference changed from an initial value of 2 (2.000/1.000) to a final value of 1.4 (1.750/1.250).

Table 1 – Results obtained for each die (design methodology) corresponding to the conditions used in their optimisation (reference results).

Design Methodology	F_{obj}	Pressure (Pa)	Shear rate (s^{-1})	T average (ºC)	T std dev (ºC)
1	0.047305	4710428	991.7237	231.1123	1.03449
2	0.019092	6261744	1073.124	231.5287	1.642116
3	0.049691	5480660	857.5959	231.3157	1.318759
4	0.042365	7307081	1152.136	231.8186	1.910156

Considering the remaining results shown in Table 1, it can be concluded that die 1 has the best performance since it has associated the minimum total pressure, melt average temperature and differential melt temperature. These results are a consequence of their lower ES lengths, the controllable variable used in its optimization. Therefore, a similar performance could be expected for die 4 (in which the ES lengths were also the controllable geometrical parameter). However, the thickness (0.5 mm) of the separators included in this die promoted a decrease in its cross section flow area thus leading to undesirable increases in pressure drop, shear rate and temperature.

The objective function value computed with equation 1 considers the cross-section areas of the elemental sections, thus given a global idea of the (weighted) equilibrium of a die. However, if the limits of the average absolute melt velocities are considered, the panorama changes. In Table 2, the variations of the average absolute melt velocity are presented. These values were computed using the maximum average velocity (among all the ES and I sections) as reference, since in practice it is expected that the pulling velocity will be, at least, of this order of

magnitude. Using this point of view, the best solution seems to be now die 4, in which the maximum draw ratio imposed to the extrudate is circa 49%. It must be mentioned that these maximum draw ratios represent a limitation for Design Methodologies 1 and 4 (draw ratios of 1 would result for all section in the ideal case) whilst for the other two Design Methodologies are inherent to the strategy adopted.

Table 2 – Maximum variation of the melt average velocity.

Design Methodology	Variation (%)
1	67
2	59
3	69
4	49

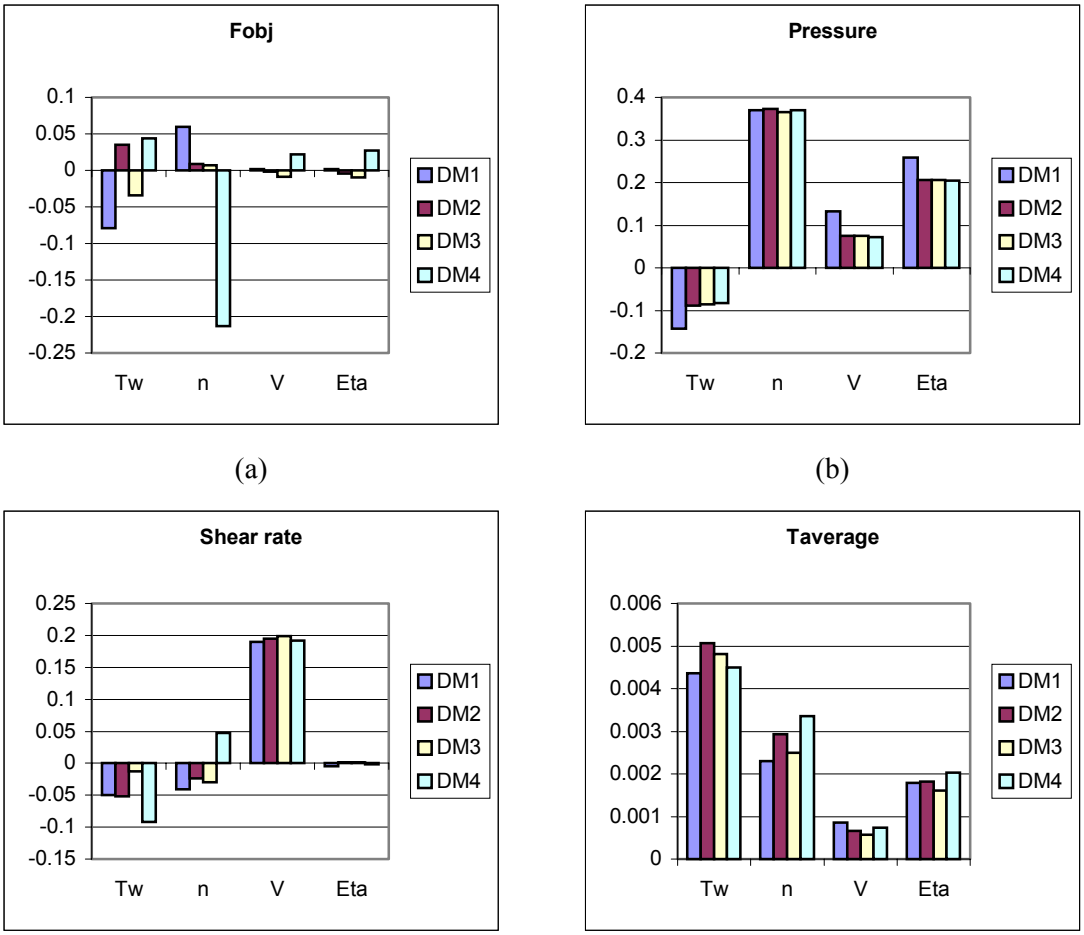
Generally, the Taguchi analysis performed for each design methodology, using the corresponding set of nine experiments, enabled to conclude that all the factors considered are independent, i.e., there are not interactions between them for all the results considered. The factors with statistical significance are shown in Table 3, for each design methodology and result considered. 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 the dies included in the study and that the standard deviation of the melt temperature at the die exit is not affected by any factor.

Table 3 – Factors with statistical significance.

Design Methodology	Results				
	F_{obj}	Pressure	Shear rate	T average	T std dev
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

Concerning flow distribution, results shown in Figure 3(a) point out that for Design Methodology 1 the processing conditions assumed to perform its optimization are not those that result in its maximum performance. In fact, a decrease in the wall temperature, T_w, will decrease the objective function value. This is a consequence of a more favorable flow distribution, and does not invalidate the optimization methodology used, which is merely based on geometrical parameters. However, as T_w is a controllable factor, it may be included, in future, in ST1 to improve its optimization capability. Results shown in Figure 3(a) also indicate that V and η_0 factors have almost no influence on flow distribution, for all the design methodologies considered.

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



(a) (b)

(c) (d)

Figure 3 – Sensitivity of the results to the factors considered.

As shown in Figure 3(c), the maximum shear rate clearly increases with the flow rate, as expected. The decrease of this value with the increase in power-law index is also an expected result, as the velocity profile changes progressively to a plug-flow type. However, the increase is not so 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 promoted by variation of T_W can be attributed to flow redistribution. On the other hand, the variation of η_0 almost does not affect the flow distribution, as can be seen in Figure 3(a), and, hence, in this case the shear rate field is maintained.

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

The maximum magnitude of the variation promoted by the factors considered in the study is listed in Table 4. It can be concluded that in terms of flow distribution the performance of die 2 is only sensitive to the factor T_w, being also the less sensitive to variations of the factors considered, showing a maximum variation of 10%. The advantage of using 'mixed strategies' in Design Methodology 3 is now apparent. In fact, die 3 despite having an objective function value similar to that of die 1, when used in the reference conditions (circa 0.050, as shown in Table 1), is much less sensitive to variations of the factors considered, showing a maximum variation of 12%, whilst die 1 shows a corresponding value of 28%.

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

Design Methodology	F_{obj}	Pressure (Pa)	Shear rate (s^{-1})	T average (ºC)
1	28	195	57	2
2	10	154	54	2
3	12	152	49	2
4	64	152	66	2

6 - Conclusions

In this work several die design methodologies are compared in terms of the performance of the dies they generated, when operated under the reference optimization conditions, and in terms of their sensitivity to several factors. The most important result considered is the flow distribution, but other potentially relevant results are 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 optimization purposes. In fact, the die generated through its use is simultaneously the more balanced and less sensitive to variations of the operating parameters.

ii) The use of separators slightly improves the flow distribution when the reference optimization conditions are considered, but turn this result more dependent on the operating conditions. The remaining results considered are generally worse when the separators are included. However, the minimum average draw-ratio experienced by the extrudate occurs in this die.

iii) Strategy 1 may be improved through the inclusion of the wall temperature as an additional controllable parameter of the optimization scheme.

iv) As expected, the simultaneous use of several strategies combines their advantages. Consequently, die 3 (optimized via Design Methodology 3) shows ES lengths higher then those of die 1 being, at the same time, less sensitive to variations of the factors considered.

v) For all the cases considered, the flow rate and the zero-shear-rate viscosity do not affect the flow distribution.

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