Flow Balance Optimisation of Profile Extrusion Dies

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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. Therefore, to achieve this objective, the flow along a profile die channel must be accurately described, demanding a computational code able to predict the complex 3D flow patterns developed and the corresponding local fluid temperature variations promoted by viscous heat dissipation. In this work a methodology for flow balancing is implemented and illustrated. The software developed for this purpose encompasses a 3D computational code based in the finite volumes method, to perform the numerical non-isothermal flow computations, and two optimisation algorithms (one based on the simplex method for non-linear programming problems and other based on the conventional trial-and-error experimental procedure), both algorithms are associated to an objective function, to carry out the automatic search of a final solution. Three different strategies to balance the flow may be adopted (allowing for the use of both length and thickness of the die parallel zone to control the flow distribution).

1 Introduction

In the past, the design of profile extrusion dies was based on experimental trial-and-error procedures, relying essentially on the designers experience and usually being very time, material and equipment consuming [1,2]. Currently, due to the development of software packages for the mathematical modelling of the flow of polymer melts [3-7] this trial-and-error procedure is being progressively transformed from experimental to numerical. However, the generation of the successive solutions, and the decisions necessarily involved in this process, are still committed to the designer [1].

To achieve the specified geometry for an extruded profile together with a minimal degree of internal stresses, flow balancing of the die is required. This requisite depends essentially of the geometry of the flow channel and of the rheological properties of the polymer melt and its dependence of both shear rate and temperature. Therefore, to achieve this objective, the flow along a profile die channel must be accurately described, demanding a computational code able to predict the complex 3D flow patterns developed and the corresponding local fluid temperature variations promoted by viscous heat dissipation [8], especially in the case of thin complex cross section geometries involving different local flow restrictions. Flow balancing is one of the steps of a broader global profile extrusion die design methodology previously developed [9] and presented elsewhere [10,11]

This work is a contribution towards the *automatic extrusion die design concept* and it focuses on the improvements implemented in a profile extrusion die design methodology [9].

2 Methodology

For flow balance purposes the extrusion die flow channel is divided in four particular geometrical zones, namely, the die land or parallel zone (PZ), the pre-parallel zone (PPZ), the transition zone (TZ) and the adapter (A), as illustrated in Figure 1. The PZ and PPZ cross sections are divided in elemental sections (ES) [9], zones defined by adjustable geometrical parameters that enable the control of the local flow restriction, and zones corresponding to the intersections (I) of several ES, shown in Figure 2. The controllable geometrical parameters of the PPZ are those shown in Figure 1: distance to the die exit, or length of constant thickness, L, angle of convergence, α, and compression ratio, t_2/t_1. [9-11].

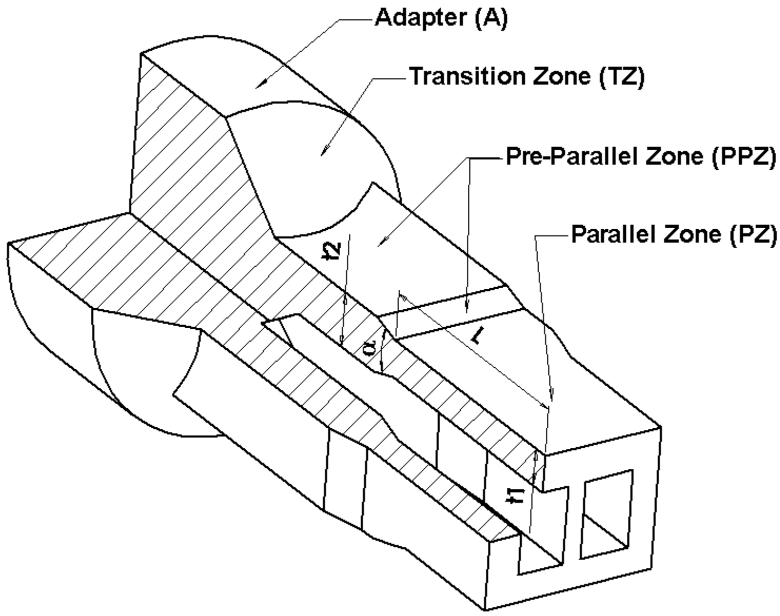

Figure 1 - Flow channel of a profile extrusion die. Identification of its main geometrical zones and geometrical controllable parameters considered in the definition of the PPZ.

The next step consists in the selection of the flow balance strategy adopted to balance the flow in each ES. There are three strategies available:

i) search for the best set of ES lengths in order to obtain a local average velocity in each ES equal to the global average flow velocity (ST1) [2,8-11];
ii) search for the best set of ES thickness in order to obtain a local ES flow rate that allows the attainment of the pre-established ES thickness after pulling (ST2) [2,8];
iii) find the best ES thickness in order to obtain a local average velocity equal to the global average flow velocity (ST3). This strategy combines the advantages of the previous ones but has a drawback, the thickness is not controllable.

The methodology proposed in this work will combine the three strategies. This would result in a final die channel geometry, which will minimise the internal stresses of the extruded profile while exhibiting a performance less dependent of the operating conditions.

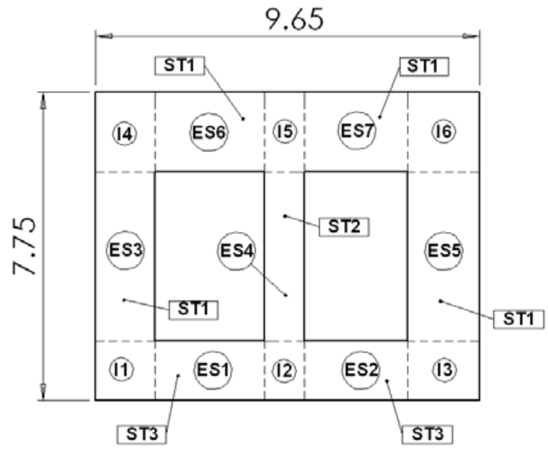

Figure 2 - Cross section of the parallel zone (PZ) of the profile die used as a case study (dimensions in mm): subdivision in elemental sections (ES), intersection (I) and identification of optimisation strategy (ST) adopted for each ES.

The most restrictive zones of the flow channel, pre-parallel zone (PPZ) and the parallel zone (PZ) illustrated in Figure 1, dominate the flow distribution [2,9]. Therefore, for flow balance purposes it will be sufficient to model the flow in the above-referred zones of the die (PPZ+PZ), not only because they dominate the flow distribution [2,8-10] but also because the flow occurring in upstream zones (adaptor and transition) has negligible contribution for viscous heating.

4 Optimisation process

The aim of the developed optimisation methodology is to automatically find the set of geometry parameters that results in the most balanced geometry. Figure 3 illustrates schematically the integration of the different routines needed for this purpose.

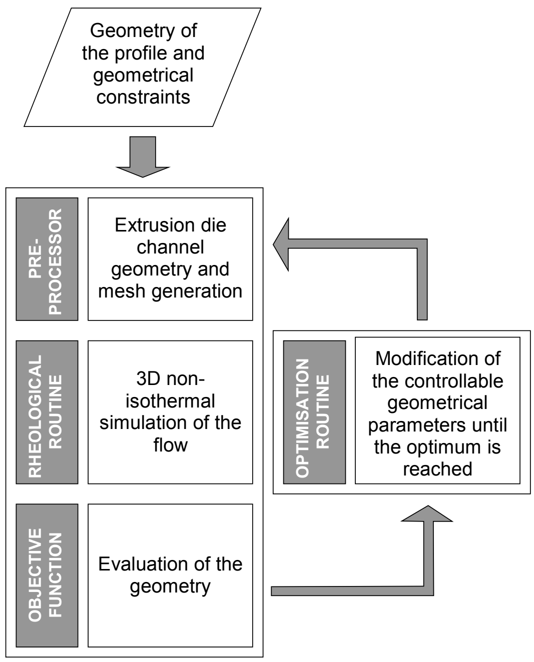

Figure 3 – Optimisation procedure flowchart

The process begins with the definition of an initial trial geometry for the flow channel. The geometrical constraints are also established at this stage. The maximum and minimum admissible values for the ratio length/thickness (L/t) are considered to be 15 and 1, respectively, being independent of the geometry of the profile to be produced, but a penalty function is applied to L/t values below 7, as these values are not recommended [12]. To guarantee a final realistic solution for the extrusion die, conditions of equality of thickness may be imposed to different elemental sections, in the cases they are supposed to be machined in a same step. This restriction is thus dependent of the particular profile under study.

Two optimisation algorithms were implemented. One based on the non-linear SIMPLEX method (SM) [13] and other that mimics the conventional trial-and-error experimental procedure of an extrusion die manufacture (EM), i.e., it proposes changes in the geometry in order to facilitate the flow in sections where the melt flow rate is lower than the required, and vice-versa.

During the calculations, the quality of each trial geometry automatically generated is assessed by an objective function (F_{obj}), which combines two criteria affected by different weights - flow balance and ratio L/t – weighted by the area of each zone:

$$F_{obj} = \sum_{i=1}^{n} \left\{ \left\{ \alpha \left(1 - \frac{V_i}{V_{obj,i}} \right)^2 + k(1-\alpha) \left[1 - \frac{(L/t)_i}{(L/t)_{\min}} \right]^2 \right\} \frac{A_i}{A} \right\} \qquad (8)$$

with k = 0 for all I zones and for ES zones with $(L/t)_i \geq (L/t)_{\min}$ and k = 1 for ES zones having $(L/t)_i < (L/t)_{\min}$

where:

n – total number of ES and I zones

$V_{obj,i}$, V_i – objective and actual average velocities of the melt flow in each zone, respectively

$(L/t)_i$ - ratio between the length and thickness of each ES

$(L/t)_{\min}$ - minimum value recommended for the ratio L/t (considered to be 7)

α - relative weight

A, A_i – cross section areas of the global flow channel and of each zone, respectively

The value of the objective function decreases with increasing performance of the die, being zero for a balanced die with all the ES lengths in the advisable range. In this work α was considered to be 0.75, in order to give a higher relative importance to the flow balance when compared to the ratio L/t.

During the optimisation process a mesh generator, which is also under development, is used to generate automatically the grid corresponding to each geometry proposed by the optimisation

algorithm. In order to improve the efficiency and/or accuracy of the numerical simulations these routines are programmed to generate smooth grids, with cell size continuity, and to refine the mesh along the flow channel thickness, particularly near the wall, where severe gradients of the flow field are expected (see Figure 4).

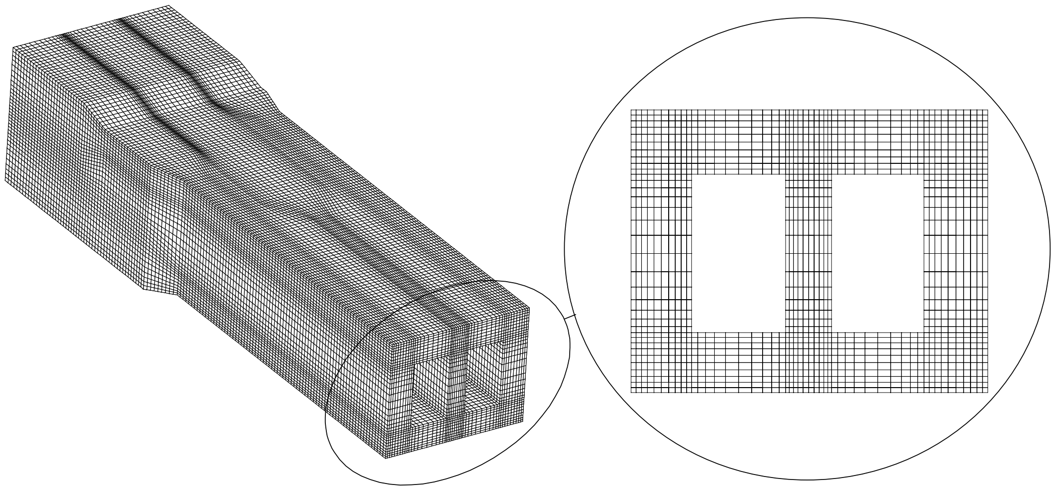

Figure 4 – Typical mesh used in the calculations.

In order to reduce the time required for the computation the process starts with coarse meshes and progressively performs mesh refinements as the algorithm move towards to the final solution.

4 Case Study

The polymer used in the simulations was a polypropylene homopolymer extrusion grade, Novolen PPH 2150, from Targor. Its rheological behaviour was experimentally characterised by capillary and rotational reometries, at 210ºC, 230ºC and 250ºC. The shear viscosity was least-squared fitted by a Bird-Carreau constitutive equation combined with the Arrhenius law, producing the following parameters: η_∞ (Pa.s)=0, η_0 (Pa.s)=5.58x10^4, λ (s)=3.21, n=0.3014, α (ºC)= 2.9 x10^3 and T_α (ºC)=230.

The proposed flow balancing methodology was used to design the flow channel of the extrusion die shown in Figure 1, adopting the division in elemental sections (ES) illustrated in Figure 2. In this example strategy ST3 was selected for ES1 and ES2, as they are both supposed to be part of a profile wall without pre-defined thickness. It was also considered that ES3, ES5, ES6 and ES7 must have pre-defined thickness and high dimensional stability in use; therefore, for these sections strategy ST1 was selected. Finally, the inner wall of the profile must have a pre-defined thickness (to avoid differential cooling in the calibrator), but it can support internal stresses without promoting the distortion of the

profile; in this case, strategy ST2 was selected. The optimisation strategies adopted for each ES are illustrated in Figure 2.

The geometry was optimised using both the '*experimental method*' (EM) and the SIMPLEX method (SM).

The cross section of the flow channel had sections of different thickness (shown in Figure 2), in order to enforce an unbalanced geometry.

The initial/reference dimensions of the die flow channel are shown in Table 1. For the other dimensions of the PPZ, defined in Figure 1, were used an entrance thickness (t_2) equal to 3 mm and a convergence angle (α) of 30º for all the ES.

Table 1 – Initial flow channel dimensions

ES	1	2	3	4	5	6	7
t_i[mm]	1.5	1.5	1.5	1.0	1.8	2.0	2.0
L_i [mm]	22.5	22.5	22.5	15.0	27.0	30.0	30.0

Independently of the methodology adopted for optimisation the algorithm encompasses 5 controllable variables, namely: Opt1 for ES1 and ES2 thickness, Opt2 for ES3 length, Opt3 for ES4 thickness, Opt4 for ES5 length and Opt5 for ES6 and ES7 length. Due to machining requirements ES1 and ES2 thickness and ES6 and ES7 length were considered to be equal.

The operating conditions used in the calculations are defined in Table 2.

Table 2 – Operating conditions

Flow rate*	16.7 kg/h
Melt inlet temperature	230 ºC
Outer die walls temperature	230 ºC
Inner (mandrel) die walls	Insulated

* Corresponding to an average velocity of 100 mm/s at the die e

As mentioned before at the beginning of the calculations the computational grid was coarse, representing the ES with only 2 cells along the thickness. A typical grid used in the final stages of the calculations, with 10 cells along the thickness (comprising a total of 160,000 cells for the whole geometry), is shown in Figure 4. The typical calculation time required for each iteration of the optimisation code using this mesh, including the time required for grid generation and flow field calculation, is 1.25 hours using a Pentium III computer running at 933MHz.

5 Results and discussion

The results obtained through the flow distribution optimisation are illustrated in terms of the variations of the objective function, the ratio Opt/Opt_{ref} and the ratio V/V_{obj} in Figures 5 and 6, for the EM and SM, respectively.

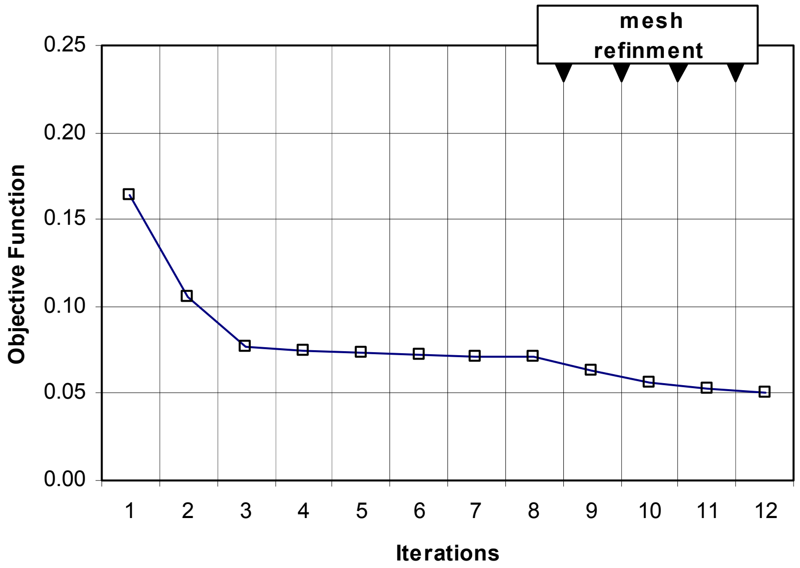

Figure 5 – Objective function values obtained for the simulations performed during the optimisation process for the Experimental Method (EM).

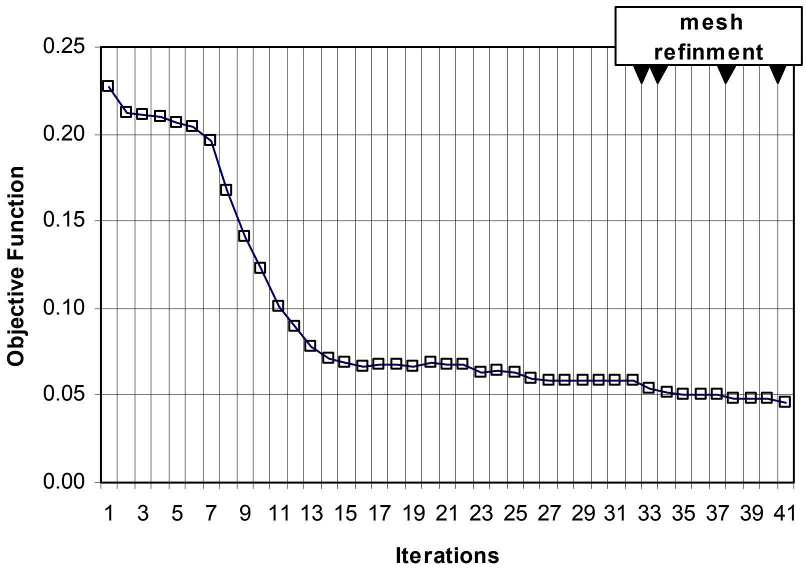

Figure 6 – Objective function values obtained for the simulations performed during the optimisation process for the SIMPLEX Method (SM).

The solutions obtained by both optimisation techniques are similar in terms of optimum value obtained for the objective function. Since the EM requires less iterations than SM (as shown in Figures 5 and 6) the total time consumed in the calculations in EM is 1/3 of the time consumed in SM (see Table 3).

As expected from the profile geometrical unbalance, in the first iteration there are significant differences in the average ES velocities (and consequently the objective function has a high value), but, after optimisation, a reasonable improvement was obtained.

Table 4 – Maximum difference of each variable to the respective final result and time consumed in calculations, at each mesh refinement stage.

		Number of cells along thickness					
		2	**4**	**6**	**8**	**10**	**Total**
Maximum difference to final solution	**EM**	0%	0%	0%	0%	0%	
	SM	15%	15%	17%	2%	0%	
Calculation Time [h:m]	**EM**	0:06	0:10	0:53	2:39	5:03	**8:53**
	SM	0:32	0:23	3:48	8:37	16:45	**24:45**

Table 3 shows the evolution of the greatest difference (taken among all the controllable variables used) between its value at the end of each mesh refinement stage and its corresponding final value; the time consumed in the calculations at each stage is also shown. These results show that the meshes with 2 cells along the thickness were able to predict quite accurately the flow distribution (the EM the algorithm reached the final solution at this stage). Therefore, the subsequent mesh refinements applied were only useful for assessment purposes. However, it is important to mention that the use of the more refined meshes may be essential if accurate absolute values of velocity, pressure and temperature fields are required. Despite of the hours required to finish the calculations, for this case study, the algorithm achieved the final solution in just a few minutes.

The improvement obtained for the velocity fields is shown in the contours of Figure 7.

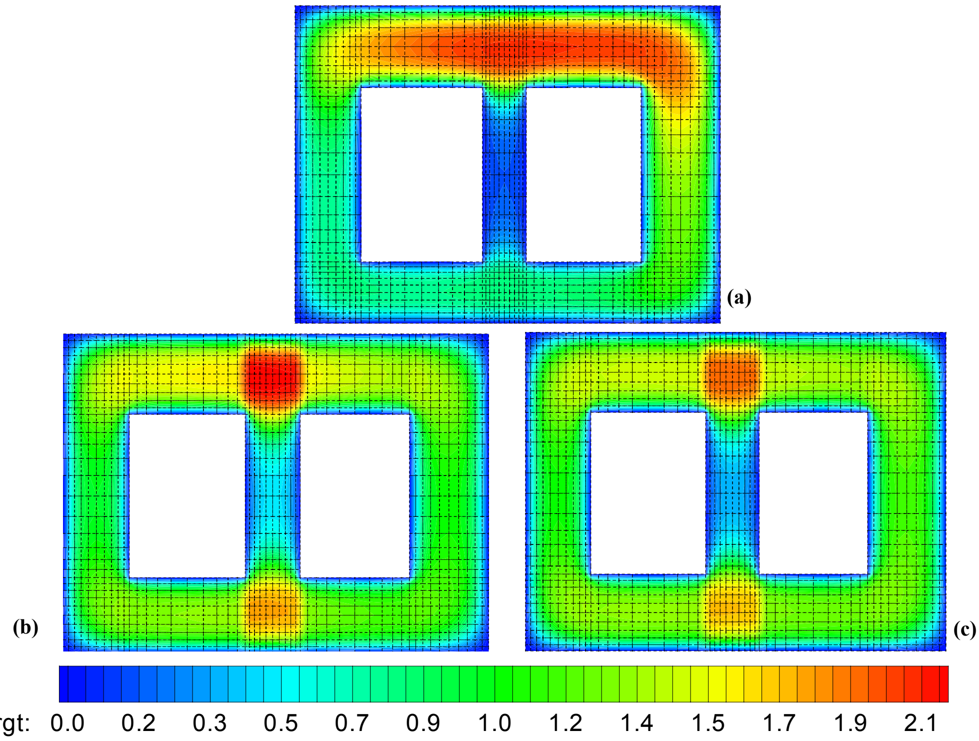

Figure 7 - Contours of the ratio axial velocity per objective velocity computed for: (a) initial trial geometry; (b) best result obtained by the Experimental Methodology and (c) best result obtained by the SIMPLEX Methodology.

6 Conclusion

The automatic die design methodology used in this work has shown great potential since it performed well and quickly in a complex profile geometry, without any user intervention during the search/optimisation procedure.

When coupled with the developed progressive mesh refinement technique, it resulted in a reasonable solution of the problem in just a few minutes of calculation.

The two optimisations algorithms tested reached a similar result, but the algorithm based on the '*experimental methodology*' performed swiftly than the one based in the non-linear SIMPLEX method.

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