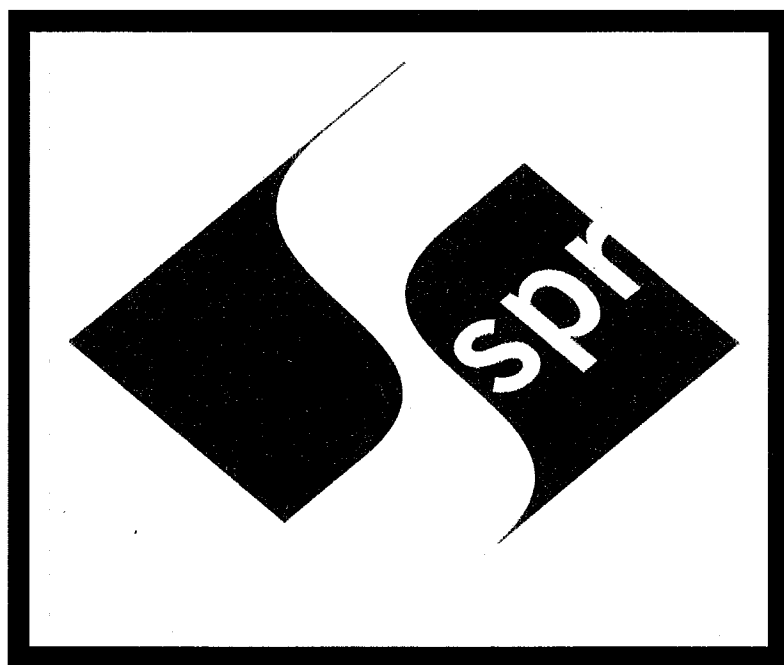


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# EFFECT OF THE OPERATING CONDITIONS ON THE PERFORMANCE OF PROFILE EXTRUSION DIES

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## 1. Introduction

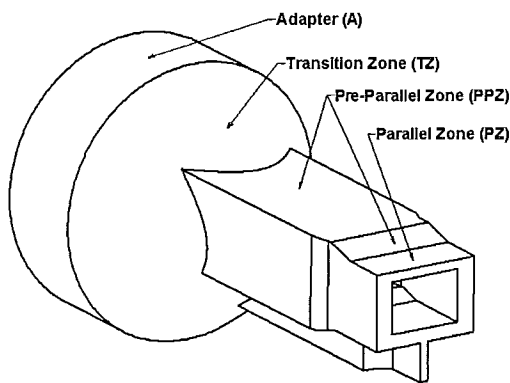
In the past, the design of profile extrusion dies was based on experimental trial-and-error procedures, that rely heavily on the designers experience and are usually very time, material and equipment consuming [1]. Currently, due to the development of software packages for the mathematical modelling of the flow of polymer melts [2-6] this trial-and-error procedure is being progressively transformed from experimental to numerical. However, the generation of the successive solutions, and the decisions involved in this process, are still committed to the designer [1]. Furthermore, only recently some relevant post-extrusion phenomena were included in the models. For example, in the particular case of post-extrusion swelling it is already possible to automatically define the contour of the final zone of the extrusion die (parallel zone) [7,8], but the first trial for the geometry of the extrusion head must be completely defined by the user and the automatic procedure only acts on the final parallel zone of the die. Anyway, the automatic design of profile extrusion dies is still incipient, since it ignores, amongst other things, the need for balancing the flow along the die exit contour. To match these objectives, especially for complex geometries, the flow should be ideally modelled in 3D [9]. However, this is usually not very attractive to designers since it requires unacceptable turnaround times for results, mainly due to the time required for calculation and for geometry and grid generation [9].

This work is a contribution towards the 'Automatic Extrusion Die Design' concept and it includes developments into an existing computational code [10] based on the finite volume method, namely the introduction of the energy equation for non-isothermal calculations. This option was induced by recent research efforts into 3D problems, which have shown that the modelling based on the finite volumes method should help to reduce the time required for calculation [11]. A routine for the automatic definition of the geometry was also developed.

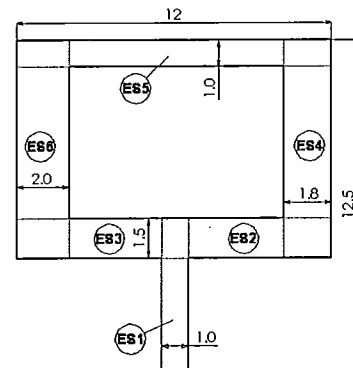
This will be used as input to the existing pre-processor of the computational rheology code, which generates the computational grid required for the numerical flow simulations. This routine allows the use of non-uniform, non-orthogonal grids mapping the flow area in order to predict complex flows and reduce computational requirements. The developed routine, the pre-processor and the computational code were integrated smoothly as part of the whole die design code.

## 2. Methodology

The first task to be considered in the die design procedure is the flow balance [12,13] in which the flow channel is divided into four main geometrical zones [13], namely the die land or parallel zone (PZ), the pre-parallel zone (PPZ), the transition zone (TZ) and the adapter (A), all shown in Figure 1. The cross section of the parallel and the pre-parallel zones is divided into elemental sections (ES) [13], shown in Figure 2, which have independent controllable length with constant thickness ( $L_i$ ). For flow balance purposes it will be sufficient to model the flow in the pre-parallel and parallel zones of the die (PPZ+PZ), since the two final sections of the die dominate the flow distribution [9,13,14].



**Figure 1** - Flow channel of a profile extrusion die split in its main geometrical zones.



**Figure 2** - Cross section of the parallel zone (PZ) and elemental sections (ES) considered (dimensions in mm).

The objective of the algorithm is to find the set of lengths ( $L_i$ ) that results in the most balanced geometry. The maximum and minimum admissible values for the ratio length/thickness ( $L/t$ ) were considered to be 15 and 1, respectively. As stated in the literature  $L/t$  values below 7 are not advisable [15]. However, it would not be prudent to reject a trial geometry perfectly balanced having an  $L/t$  slightly lower, since the limit values are purely empirical, resulting from industrial practice. Therefore, in this work the quality of each trial

geometry is assessed by an objective function ( $F_{obj}$ ), which combines two criteria affected by different weights: flow balance and ratio  $L/t$ :

$$F_{obj} = \sum_{i=1}^4 \left\{ \alpha \left( 1 - \frac{V_i}{V_{av}} \right)^2 + k(1-\alpha) \left[ 1 - \frac{(L/t)_i}{(L/t)_{opt}} \right]^2 \right\} \quad (1)$$

with  $k = 0$  for  $(L/t)_i \geq (L/t)_{opt}$  and  $k = 1$  for  $(L/t)_i < (L/t)_{opt}$

where:

$V_{av}$ ,  $V_i$  - average velocities of the extrudate and of the flow in each ES, respectively

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

$(L/t)_{opt}$  - optimum value for the ratio  $L/t$  (considered to be 7)

$\alpha$  - relative weight (considering the higher relative importance of the flow balance criterion,  $\alpha$  was considered to be 0.75)

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 admissible range.

The flow balance methodology tested here is based on a previous method developed in [12,13] with two additional improvements: 1) The search process used to find the best geometry is based on the value of the objective function; 2) The process starts with coarse meshes and progressively performs mesh refinements as the final solution is approached.

### 3. 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 reometers, at 210°C, 230°C and 250°C. The shear viscosity was least-squared fitted by a Bird-Carreau constitutive equation and combined with the Arrhenius law (equations 7 and 8), that produced the following parameters:  $\eta_{\infty}$  (Pa.s)=0,  $\eta_0$  (Pa.s)= $5.58 \times 10^4$ ,  $\lambda$  (s)=3.21,  $n=0.3014$ ,  $\alpha$  (°C)=  $2.9 \times 10^3$  and  $T_0$ (°C)=230.

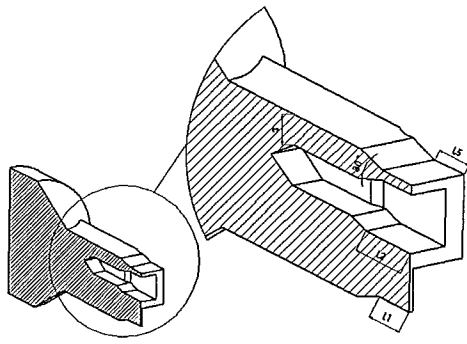
The flow balance methodology was used to design the flow channel of the extrusion die shown in Figure 1, adopting the division in elemental sections (ES) illustrated in Figure 2.

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

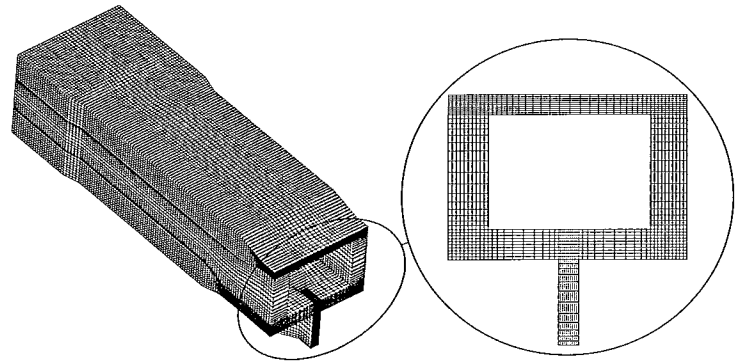
The conditions used in the calculations are defined in Table 1.

**Table 1 – Operating conditions**

Flow rate*	16.5 kg/h
Melt inlet temperature	230 °C
Outer die walls temperature	230 °C



**Figure 3** – Side view cut of the flow channel illustrating the constructive solution adopted and showing some relevant dimensions (mm).



**Figure 4** – Typical mesh used in the calculations.

Inner (mandrel) die walls	Insulated
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\* Corresponding to an average velocity of 100 mm/s at the die exit

As stated above the simulations of the flow were only performed in the die zones relevant for this purpose, i.e., PPZ and PZ. In a previous work [16] it was concluded that the parameter that most influences the flow balance is the length of PPZ+PZ having a constant thickness ( $L$ ). As a consequence, the other dimensions of the PPZ, defined in Figure 3, were fixed (entrance thickness of 3 mm and convergence angle ( $\alpha$ ) of  $30^\circ$  for all the ES), i.e., only the lengths  $L_i$  of each ES needed to be determined.

At the beginning of the calculations the ratio  $L/t$  for all ES was considered to be 15.0, and the computational mesh was coarse representing the ES with 2 cells only. A typical grid used in the final stages of the calculations, with 10 cells along the thickness (a total of 162,840 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 2 hours using a Pentium III computer running at 933MHz.

## 4. Results and discussion

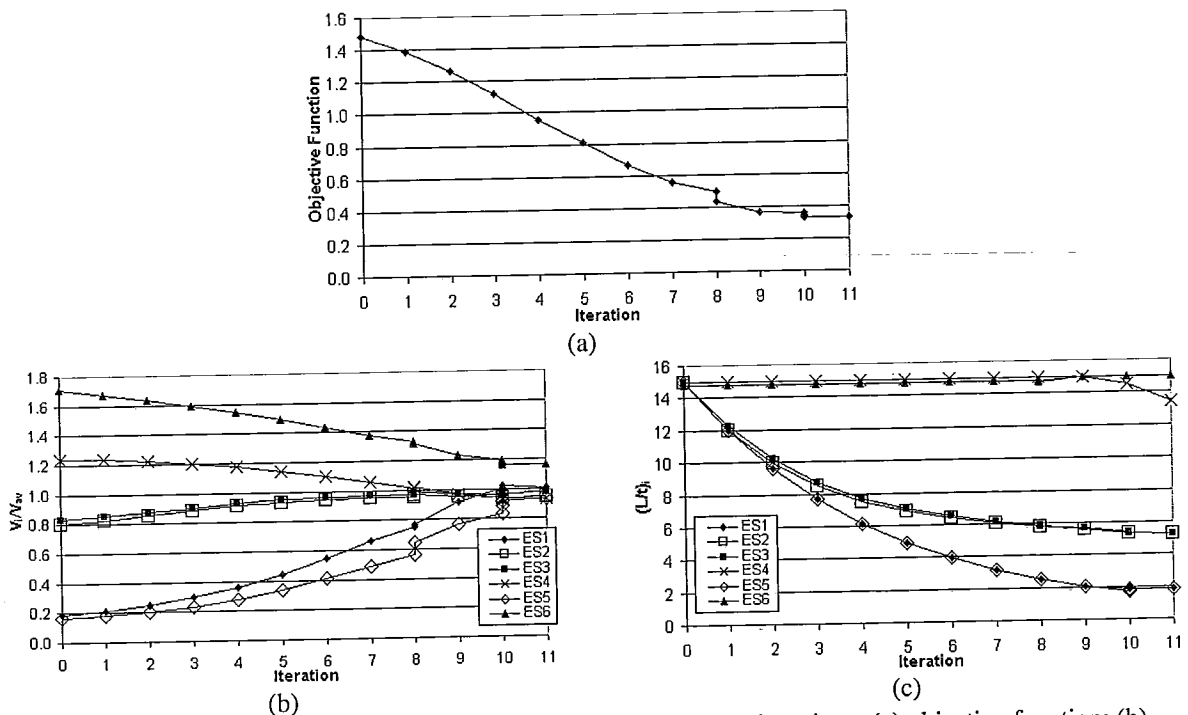
### 4.1 Performance of the methodology

The results obtained through the use of the flow balance methodology are illustrated in terms of the variation of the objective function, the ratio  $L/t$  and the average velocity ratio in Figures 5(a), (b) and (c), respectively. As expected, in the first iteration, there are significant differences

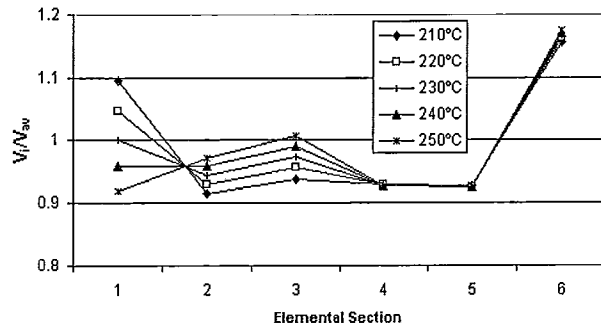
in the average velocities as a consequence of the previously mentioned cross section unbalance. The best solution is attained at iteration 11 for which the average velocities in all but ES6 are within 10% of the global bulk velocity. At ES6 the difference is 20% because the relative flow restriction is very low. A possible solution would be the inclusion of a local flow separator, to isolate the section [13].

#### 4.2 Influence of process parameters

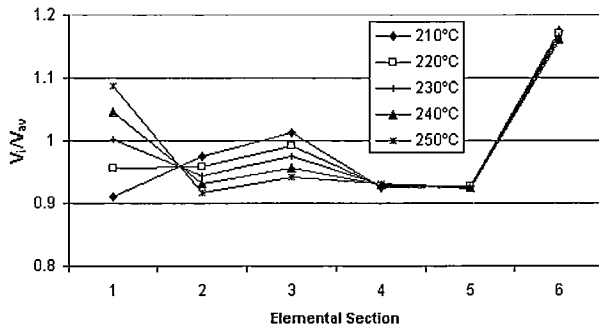
The influence of the inlet temperature, flow channel wall temperature and throughput (die exit average velocity) on flow balance is shown in Figure 6. As can be observed, the flow distribution is not very sensitive to the variations imposed. The most sensitive elemental section is ES1, showing a maximum variation of circa  $\pm 10\%$  in the average velocity when varying the temperature parameters. This is a consequence of its low thickness and high relative area for heat exchange with the outer wall. In order to compensate for that variation, the neighbouring elemental sections (ES2 and ES3) are also affected.



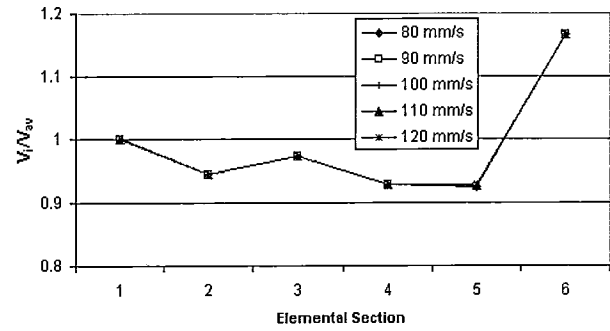
**Figure 5** - Results of simulations performed in successive iterations: (a) objective function; (b) ratio length/thickness of the parallel zone of each elemental section; (c) relative average velocity in each elemental section. Note: the discontinuities observed in the curves correspond to iterations at which the mesh was refined.



(a)



(b)



(c)

**Figure 6** – Influence of some operating parameters in the flow distribution: (a) melt inlet temperature; (b) channel wall temperature; (c) throughput (die exit average velocity).

## 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.

The three-dimensional computational code developed for performing the numerical simulations of the flow by [10] was here successfully extended to account for non-isothermal flow. When coupled with the developed progressive mesh refinement technique, it resulted in a reasonable solution of the problem in just 1 hour of calculation.

The effect of some process parameters on flow distribution was assessed in this work. The flow distribution was found to be essentially affected by the melt inlet temperature and the flow channel wall temperature in regions of low thickness, and neighbouring sections, whereas, throughput and viscous dissipation have negligible effects. However, note that flow distribution is assessed via a relative parameter, but in terms of absolute quantities these process parameters have a non-negligible effect. It is thus advisable to perform accurate non-isothermal calculations in order to account, amongst other things, for possible existence of hotspots.

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