FLOW BALANCING OF PROFILE EXTRUSION DIES

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Abstract

In this work a methodology to automatically balance the flow in profile extrusion dies is used. For this purpose a computational code, based on the finite-volume method, was developed and used to perform the required three-dimensional numerical simulations of the flow.

The methodology is illustrated using two case studies, each one leading to the adoption of a different constructive solution (with and without flow separators).

In order to evaluate the quality of the automatically generated die geometries, an objective function, that takes into account the flow balancing and the ratio L/t of the parallel zone, is proposed.

Introduction

The performance of an extrusion die depends, amongst other things, on the rheological design of the flow channel and on the operating conditions adopted during extrusion. An adequate design must guarantee the production of the required profile (in terms of geometry and dimensions) at the highest possible speed and quality. This requires the minimum possible level of internal stresses and the avoidance of rheological defects (e.g., shark skin and melt fracture) and thermal degradation of the melt.

The viscoelastic behaviour of the polymer melts and the large number of phenomena and restrictions involved makes this a very complex task, which is strongly dependent on the designer knowledge/experience and often requires several trials. Considerable gains are to be expected from the use of adequate computational tools, but despite the availability of some commercial software for the numerical prediction of polymer melt flows through extrusion dies (1-5), its application still requires the user to take decisions in order to generate the successive trial geometries until a final reasonable solution is achieved. Furthermore, the commercial codes usually do not include all the relevant phenomena: for example, it is already possible to solve the inverse problem in die-swell, i.e. to guess the contour of the die land required to produce a given profile (6,7), but without considering the need of flow balancing, which only recently has been addressed in the literature (8-11). At the same time these computational tools are usually not user-friendly and require large CPU times, which are incompatible with the industrial need of swift calculations. The global automatic optimisation of extrusion die design still remains a challenge (11) and it is the purpose of this work to contribute to further developments of automatic die design tools.

This work presents a scheme to balance the flow in the die channel and is part of a global methodology, currently being developed, for the rheological design of profile extrusion dies. The structure adopted is adequate for a future inclusion in an automatic process of optimisation of the flow channel geometry. A 'first guess' is based on analytical calculations, and is followed by numerical simulations aimed at refining the solution, in order to increase the efficiency of the optimisation process.

The numerical calculations of the flow field are based on a finite-volume code for the solution of the mass, momentum and rheological constitutive equations (12). This code solves the three-dimensional flow of Newtonian, generalised Newtonian or viscoelastic fluids and it significantly contributes to reduce the time required to perform all the simulations needed to achieve the geometrical solution.

Methodology

In order to balance the flow the extrusion die is divided on 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), all illustrated in Figure 1.

The parallel, transition and adapter zones are present in almost all conventional dies. Since the flow balancing cannot be attained by modifications performed in the die land cross section, as that would change the extrudate dimensions, in the present methodology a pre-parallel zone was inserted between the transition and the parallel zones. The pre-parallel zone is convergent and, as the parallel zone, it is very restrictive to the flow. The insertion of that zone facilitates the local control of the flow resistance and will not influence the final extrudate dimensions if a sufficiently long parallel zone is provided. The controllable geometrical parameters of the pre-parallel zone are those

shown in Figure 2: distance to the die exit, or length of parallel zone, L, angle of convergence, α, and compression ratio, t_2/t_1.

The design algorithm begins with the division of the cross section of the parallel and pre-parallel zones in elemental sections (ES). As a first attempt, the constructive solution adopted is the conventional, i.e., flow channel without separating walls to avoid the formation of weld lines.

The next step consists on the iterative definition of the geometry of the pre-parallel zone required to balance the flow. In previous works (13,14) it was concluded that the parameter that most influences the flow balance is the length of the parallel zone (L). As a consequence, in this work, the other dimensions of the PPZ, shown in Figure 2, were considered fixed. Therefore, only the lengths L_i of each ES of the parallel zone needed to be determined. For this purpose an iterative search algorithm was implemented. On each iteration the correction of each ES length was based on the ratio between the computed and required average velocities: when the calculated velocity was higher than the required, the ES length was increased in order to augment the flow restriction, and vice-versa. The maximum and minimum admissible values for ratio L/t were considered to be 15 and 1, respectively. The algorithm makes use of a routine developed for the automatic generation of both the geometry and the corresponding computational grid required for the numerical simulations.

If the final balanced geometry results in parallel zones that are too short to allow the relaxation of the stresses developed in upstream convergent zones, another constructive solution must be sought with the allocation of separating walls between the most critical elemental sections. These flow separators start at the entrance of PPZ and end some millimetres before the die exit (15). This second constructive solution enables the independent control of each elemental section (9,10), but it shall be avoided whenever possible as it induces the formation of weld lines close to the die exit, which may affect the mechanical performance of the extruded profile.

During the calculations, the quality of each trial geometry was assessed by the following objective function

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

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)

α - relative weight

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.

The value of the objective function decreases with increasing performance of the die, being zero for a balanced die having all the ES lengths in the admissible range.

Case studies

The polymer used in the simulations was a polypropylene homopolymer extrusion grade. Its rheological behaviour was experimentally characterised by capillary and rotational reometries, at 200ºC, and its viscosity was least-squared fitted by a Bird-Carreau constitutive equation.

The performance of the methodology proposed for flow balancing was assessed by testing the design of two similar extrusion dies for the production of cross shaped profiles, called Cross-B die and Cross-U die. The profiles have the parallel zone cross-section depicted in Figure 3(a) with three legs having a thickness of 2.0 mm and a thinner fourth leg. The different thicknesses of the legs result in an unbalanced flow because the thinner leg is more flow restrictive. The difference between the two dies concerns the thickness of the thinner leg (t in Figure 3(a)), which has the value of 1.8mm for Cross-B die and 1mm for Cross-U die. From a flow-balance point of view, the former is expected to be almost balanced (Cross-B), and the latter strongly unbalanced (Cross-U).

The flow rate imposed corresponds to an average velocity of 100 mm/s at the die exit and the flow was considered isothermal. Considering the objective of these case studies, the simulations of the flow were only performed in the die zones relevant for this purpose, i.e., PPZ and PZ. The geometry of the die was considered similar to the one shown in Figures 1 and 2.

Results and discussion

Initially, the parallel zone cross-section was divided in four elemental sections, ES1 to ES4, as shown in Figure 3(a). Note that the region defined by the intersection of the four legs was not considered as an independent zone due to the impossibility of controlling independently its geometry. However, this zone will also become balanced when the average flow velocity in all the elemental sections, ES1-4, is equal to the extrusion average linear velocity. Given the symmetry of the cross-section, the flow through ES3 and ES4 is similar and the corresponding results are presented together.

As mentioned before some dimensions of the PPZ, defined in Figure 3(b), were fixed (entrance thickness of 3 mm for all legs; convergence angle of 30º).

The results obtained for the Cross-B die are illustrated in Figure 4 in terms of objective function (a), ratio L/t (b) and relative average velocity (c). As indicated by the objective function the best solution is obtained around iteration 4, with a value of just under 0.1. However, it must be noted that even in this case the best solution for the flow balance is a geometry having very small L/t ratios (iteration 20 in Figure 4(c)), which corresponds to a high value of the objective function. That is a consequence of the small restriction imposed by the intersection zone, which induces the progressive reduction of the length of all neighbouring ES in order to deviate the fluid from that zone.

For the Cross-U die, Figure 5 plots the same information that was presented in Figure 4, for Cross-B. It can be concluded that for the Cross-U die the algorithm was unable to reach a realistic geometrical solution, as shown by the relatively high (0.3) minimum value of the objective function. In fact, the thinner section (ES1) remains too restrictive even when an unacceptable low value of L/t is considered. As a consequence, another constructive solution, involving the allocation of flow separators, was tried and the geometry shown in Figure 6 was considered. On Cross-U1 three separators are used to isolate all the ES and to eliminate the intersection region along the paths defined by the separators.

The results obtained with the Cross-U1 are shown in Figure 7. In this particular case it was possible to generate successive better geometries and to reach a well balanced final solution, within the pre-defined L/t limits, with the lowest value of the objective function (around 0.01).

Contours of the axial velocity are shown in Figure 8 for two cases: the initial iteration used with Cross-U die and the best results obtained for Cross-U1. The progression from a strongly unbalanced situation (Cross-U) to an almost balanced case (Cross-U1) is well shown.

It should be noted that the Cross-U1 alternative, despite being the most balanced case, does not guarantee the best solution from the mechanical point of view, as it promotes the formation of several weld lines. The lateral flow that takes place after the junction of the independent streams, just before the die exit, will contribute to enhance the strength of the weld lines, but it may be insufficient to guarantee the adequate mechanical performance of the extrudate.

Conclusions

In this work a methodology for the automatic flow balance of profile extrusion dies was tested. It was shown that the insertion of a pre-parallel zone facilitates the search of a flow balanced geometry.

The methodology does not yet include an optimisation algorithm but already uses a 3-D computational code to perform the numerical simulations of the flow.

To assess the quality of the calculated geometries an objective function that takes into account the flow balancing and the ratio L/t of the parallel zone was tested. This function has shown to be adequate to evaluate the performance of the extrusion dies used in this work.

It was verified that accentuated differences in thickness among the elemental sections of a die demand unacceptable short parallel zones, therefore requiring the allocation of flow separators between the more restrictive sections. This practice may be needed even for apparently balanced geometries that have low flow restriction (intersection) zones.

The insertion of flow separators was shown to be a good solution in terms of flow balancing, but it must be well pondered in order to minimise the risk of mechanical failure of the extrudate.

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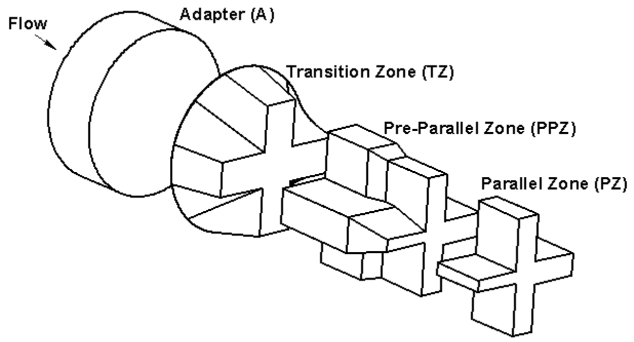


Figure 1 – Flow channel of a profile extrusion die split in the main geometrical zones.

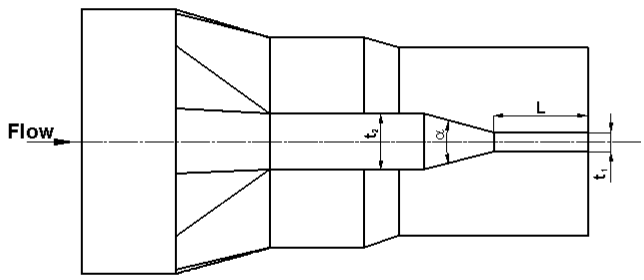
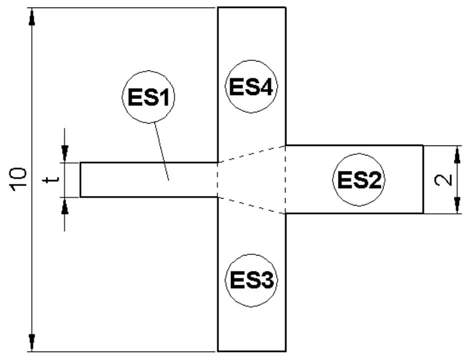
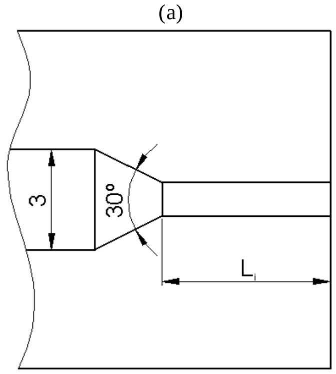


Figure 2 – Side view of the flow channel illustrated in Figure 1 showing the geometrical controllable parameters considered in the definition of the pre-parallel zone.

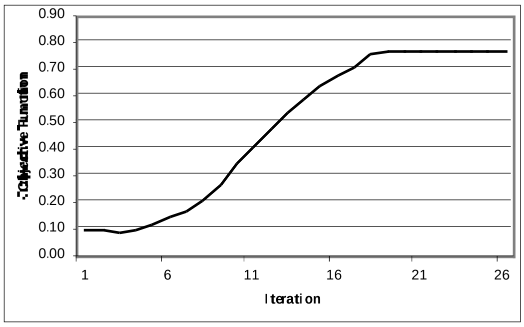


(a)

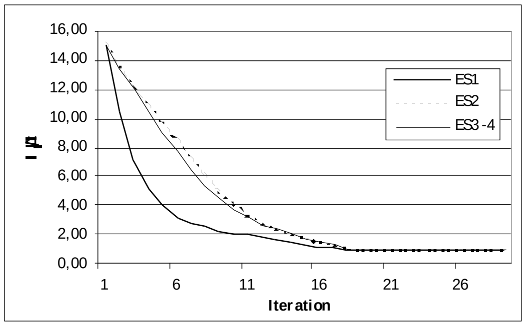


(b)

Figure 3 – Flow channel of the profile die used as a case study (dimensions in mm): (a) cross section of the parallel zone (PZ) and elemental sections (ES) considered; (b) side view.



(a)



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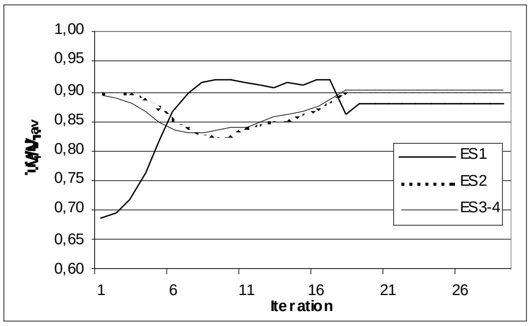
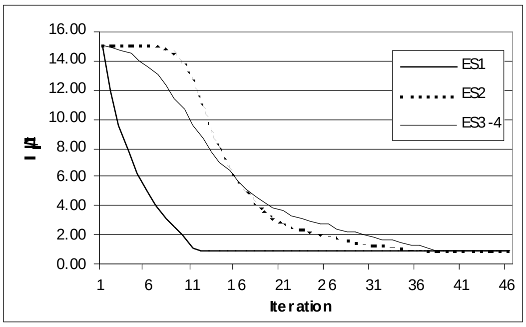


(c)

Figure 4 – Results of simulations performed in successive iterations for Cross-B die: (a) objective function; (b) ratio length/thickness of the parallel zone of each elemental section; (c) relative average velocity in each elemental section.

(a)



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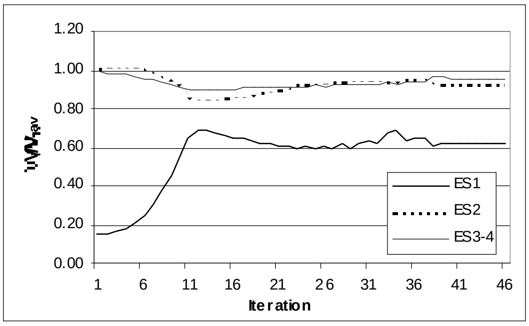


(c)

Figure 5 – Results of simulations performed in successive iterations for Cross-U die: (a) objective function; (b) ratio length/thickness of the parallel zone of each elemental section; (c) relative average velocity in each elemental section.

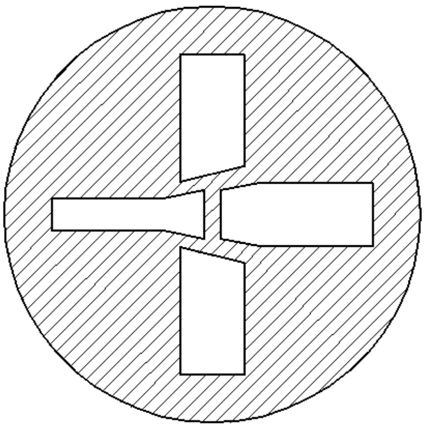
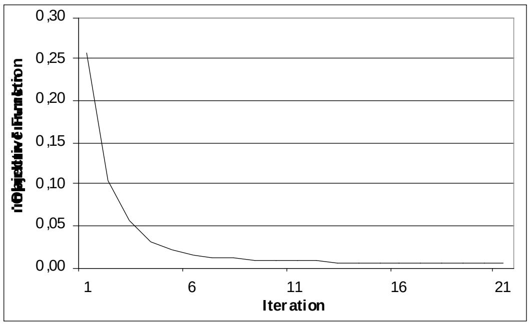
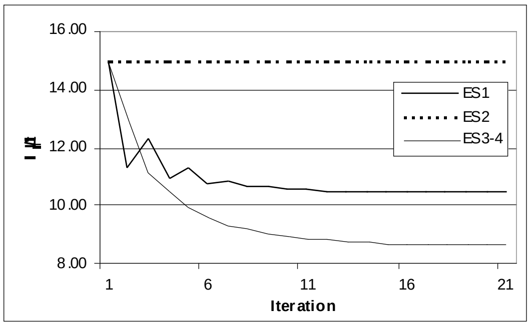


Figure 6 – Cross section of the parallel zone upstream of independent streams junction, showing the three flow separators used (Cross-U1).



(a)



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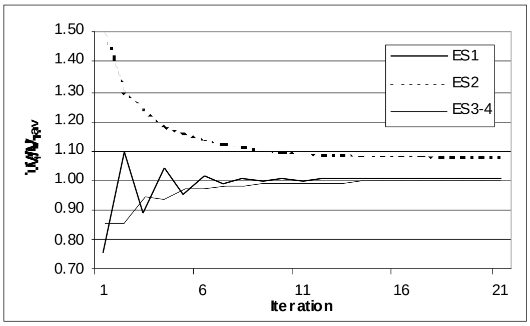
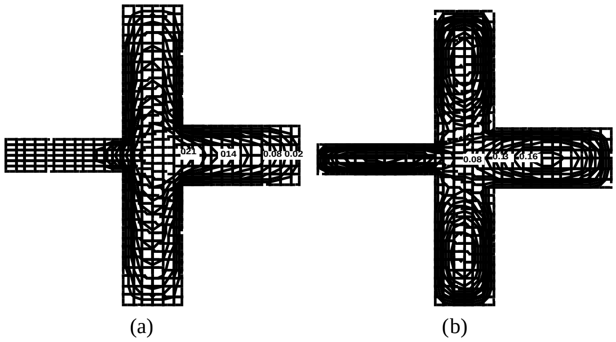


(c)

Figure 7 – Results of simulations performed in successive iterations for Cross-U1 solution: (a) objective function; (b) ratio length/thickness of the parallel zone of each elemental section; (c) relative average velocity in each elemental section.



(a) (b)

Figure 8 – Contours of the axial velocity (m/s) computed for: (a) initial trial geometry (iteration 1) of Cross-U die; (b) final geometry (iteration 21) of Cross-U1 solution.

Keywords: extrusion die design, profiles, flow balancing, finite-volume