Thermal Aspects of the Calibration of Extruded Profiles

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Abstract

The cooling stage in profile extrusion is a very important process step, as it affects the final dimensions of the profile, its dimensional stability and its mechanical performance. Unfortunately, heat removal during the cooling stage is very difficult to anticipate, especially in the case of complex profiles. Therefore, the ability to numerically model the profile cooling is an important tool to assist the extrusion designer. In the present work, a 3D finite volume method based numerical code of profile cooling is developed, results being presented for calibrators with different geometries.

1- Introduction

Calibration of the cross-section of a profile before intensive cooling of the material is an important step of profile extrusion. The viscoelastic behaviour of the melt upstream, together with the operating conditions and die design, make it very difficult to produce the required cross-section. Moreover, as the profile progresses along the line is subjected to a variety of external forces, such as friction, buoyancy and compression. Hence, the calibration stage must ensure that the incoming melt is properly shaped, and that the outgoing profile is strong enough to withstand the external forces.

From a thermal point of view, the calibrator(s) must also ensure fast rate uniform cooling of the extrudate, in order to induce the appropriate morphology and a uniform level of thermal induced residual stresses. In practical terms, the temperature gradient along the profile contour must be minimized and the average profile temperature at the calibration outlet must fall bellow the solidification temperature. The parameters influencing the thermal performance of the calibrating unit include the system geometry (number of calibration units, their length and distance separating them, the layout of the cooling channels - number, diameter, orientation relative to the extrusion direction, distance to the extrudate surface), the cooling conditions (temperature of the inlet water, flow rate, flow direction), location of the vacuum holes and the extrusion conditions (flow rate, cross-temperature profile at the die exit).

The above parameters, together with the relative complexity of some profiles, require the use of numerical methods to determine the time evolution of temperature profiles. Menges *et al.* [1] developed a 2D FEM approach, which was later extended to take into account the axial heat fluxes within the calibrator [2]. One additional difficulty is the selection of the proper heat transfer coefficient, *h*, that accounts for the heat transfer between the plastic profile and the calibrator. It was experimentally shown that this coefficient might vary between 10 and 1000 W/m^2K [3], depending on the location along the calibrator. Other researchers [4] used their practical experience to select different constant *h* values for each profile wall, depending on the nature of the contact with the cooling medium (calibrator or water).

In this work, a 3D code is used to model the calibrating/cooling stage of profile extrusion, with a view to designing calibration systems.

In this code the numerical calculations of the temperature field are based on a finite-volume code for the solution of the energy equation, which is transformed into a general, non-orthogonal coordinate system for calculating the temperature. The resulting differential equations were then discretised following the finite-volume approach of Patankar [6], but adapted for collocated, non-orthogonal grids, as described in Oliveira [7].

The code is sufficiently general to take into account all the above-referred relevant parameters. This will be illustrated in the following sections considering different geometries and layouts for a constant cooling length. The aim of the project is to develop a design tool for calibrators using an optimisation approach.

2- Case Studies

Cooling of a hollow rectangular profile was modelled using four different calibrators denoted as A, B, C and D in Figure 1. Calibrator A is 750 mm long and contains four cooling channels. Two are rectilinear and run parallel to the lateral walls of the profile. The other two are placed on the top and bottom of the profile, respectively, and progress as a square wave. Calibrator B is similar to A, but now three individual calibrating units, 250 mm long, are used. Calibrators C and D are single bodied as calibrator A, the four and six straight channels used, respectively, being positioned as illustrated in Figure 1.
The general conditions considered for the simulations performed are shown in Table 1.

Table 1 – General conditions used in the simulations.

Polymer	HDPE
Linear extrusion velocity	1.2 m/min
Profile thickness	3 mm
Cooling channels' diameter	8 mm
Melt inlet temperature	210 ºC
Room temperature	20 ºC
Cooling water temperature	13 ºC
Profile/Air convection heat transfer coefficient (free convection)	5 W/m^2K
Profile/Calibrator convection heat transfer coefficient (contact resistance)	5000 W/m^2K
Inner profile boundary	Insulated

3- Results and discussion

The evolution of the profile temperature along the extrusion axis, for Calibrators A and B, is illustrated in Figure 2. As expected, Calibrator B induces a more homogeneous final temperature distribution. This is due to the reversal heat transfer occurring in-between two consecutive calibrators, which increases both the temperature distribution homogeneity (thus reducing the thermal stresses) and the effectiveness of the subsequent cooling, due to the increase of the profile surface temperature. The improvement is more evident in Figure 3, where the final temperature fields for the different examples are compared (some quantitative data is also shown in Table 2).
As shown in Figure 3 and Table 2, Calibrator D has the best performance both in terms of average temperature and temperature homogeneity. The minimum temperature was reached with Calibrators B and D as the layout of their cooling channels promotes the intensive cooling of the profile corners. However, Calibrator B is less efficient than D in the removal of the heat at the top and bottom sides.

Table 2 – Results obtained for the profile temperature distribution at the exit of the calibration system.

	Calibrator			
	A	B	C	D
T_{min} (ºC)	21.5	21.0	24.5	21.0
T_{max} (ºC)	55.3	53.1	54.4	49.5
$\overline{T}$ (ºC)	42.2	40.3	42.6	38.8
σ_T (ºC)	7.5	7.3	6.4	6.1

4- Conclusion

The examples illustrated above demonstrated the importance of the layout of the cooling channels in profile calibrators. Having in mind that other process parameters not considered here are also important, and also that the geometrical complexity of some profiles can be significant, it becomes clear that the availability of a 3D numerical modelling code of the cooling stage is an important tool for the extrusion designer.

References

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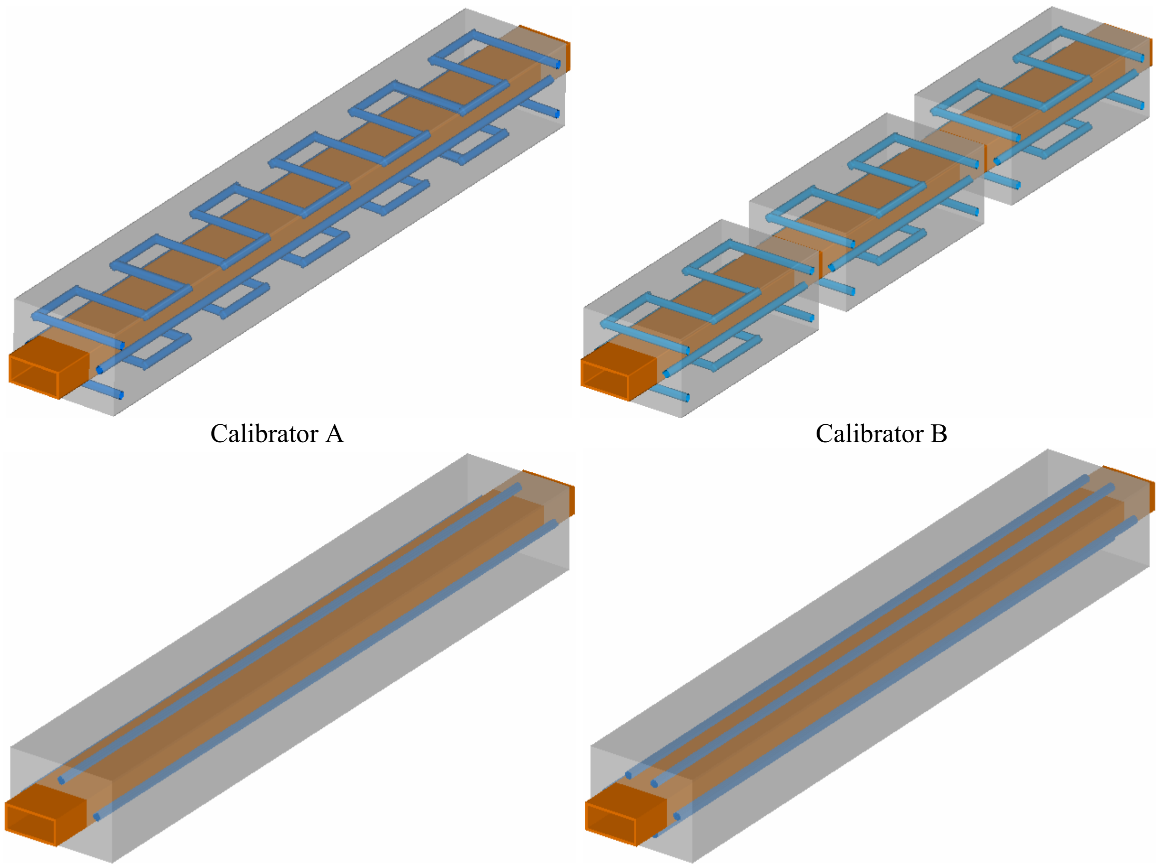

Calibrator A

Calibrator B

Calibrator C

Calibrator D

Figure 1- Geometry of the calibrators tested.

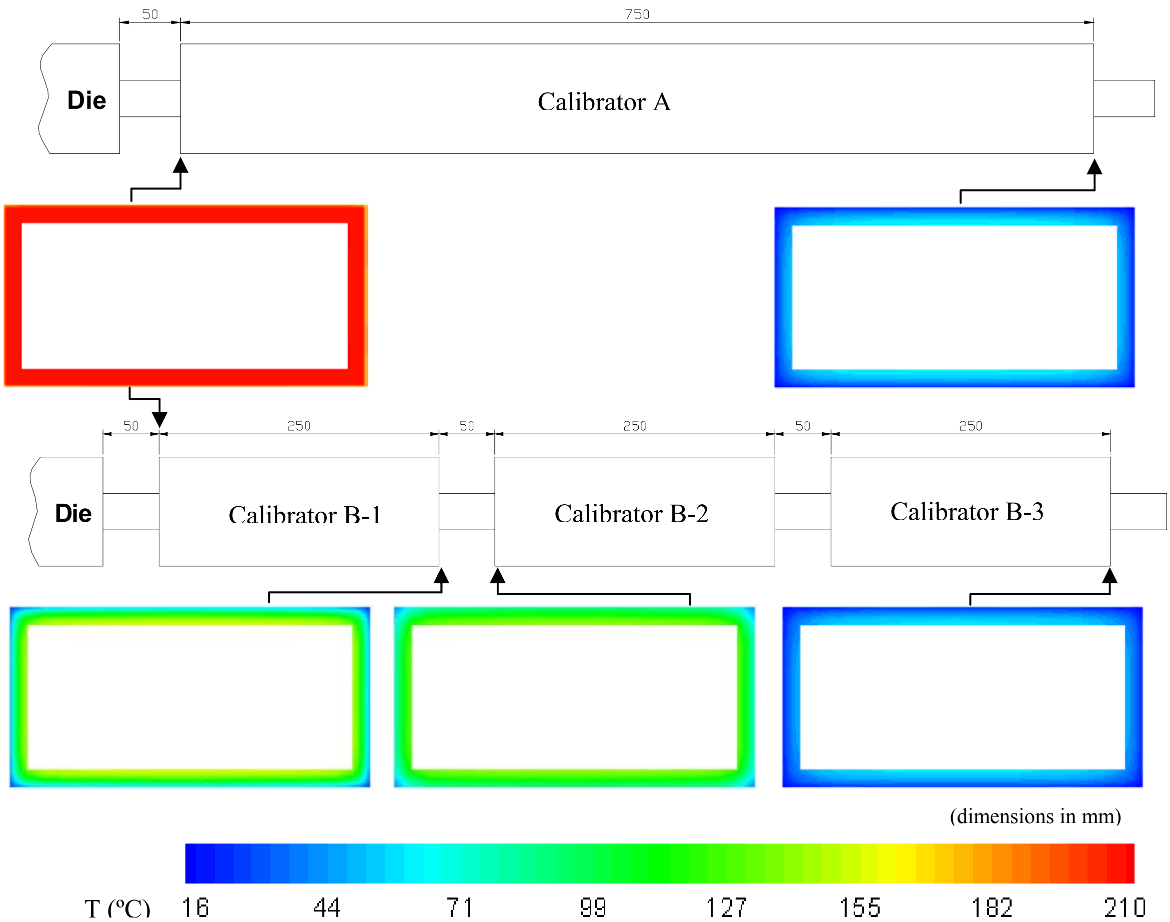

Figure 2 – Profile cross-temperature field at several locations along the calibration system, for calibrators A and B.

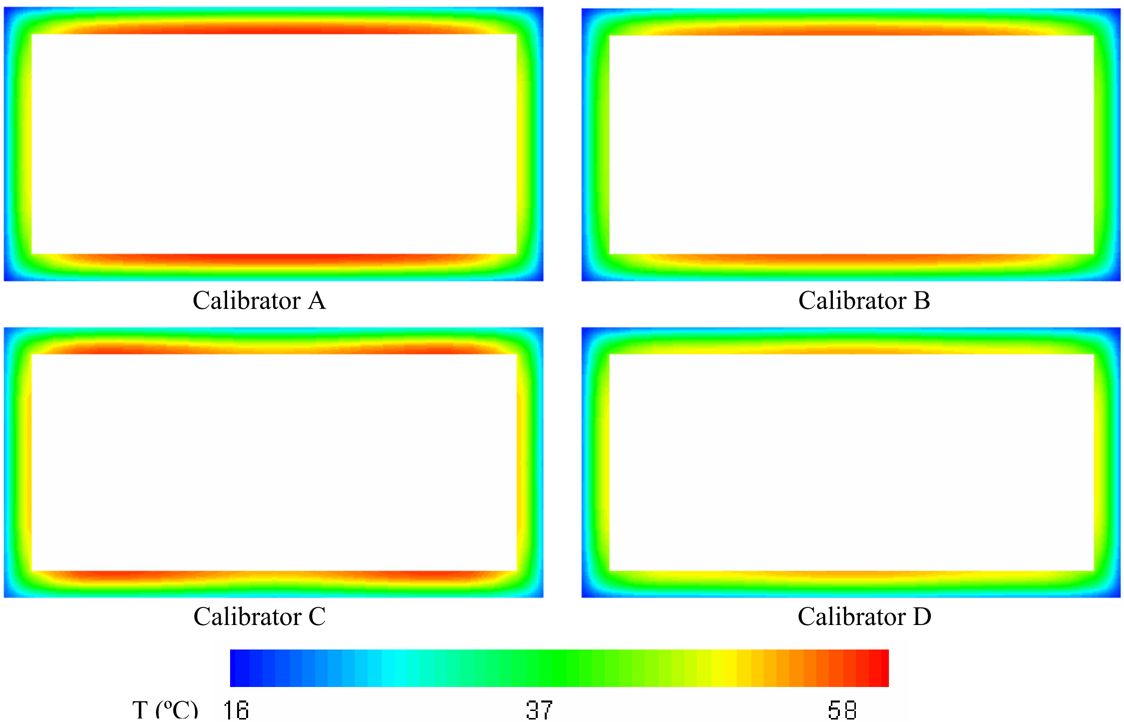

Figure 3 – Profile cross-temperature field at the calibration system exit for the four calibrators tested.