Contribution to Single Screw Extruder Design

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For the optimization of the screw and extrusion process design one need to address issues such the interdependence between the geometrical, hydrodynamic, thermal parameters and material behaviour in each screw zone along with the correlations between successive screw zones. For that purpose, the process parameters (material temperature, barrel temperature, screw speed, pressure development in the screw channel), the screw geometry (flat and compression zones) and the matter behaviour (tribological, thermal and rheological) as a function of temperature and pressure were analyzed. The interdependence between the screw design and the extrusion process parameters from a practical point of view, with the aim of designing the most suitable screw with optimal process parameters for a given processed material, was established.

Keywords: extrusion; screw design; optimization; process parameters

When one designs a screw some of the process and geometrical parameters must be chosen while the others will be calculated based on theoretical relationships. The first question is how many and which parameters are to be chosen. And secondly, what relationships should be used for mechanical, geometrical and process design.

The output limitation introduced by the extrusion die and the screw mechanical resistance is evidenced with the calculation of the allowable screw speed.

Establishing the interdependence between screw design and the extrusion process parameters from a practical point of view, one may find a solution for the following two problems:

-establishing processing conditions for a given screw geometry, processed material and end product;

-designing the most suitable screw and establishing optimal process parameters for a given processed material and end product.

Extrusion process characteristic parameters

One distinguishes geometrical parameters as well as process parameters such as screw and extrusion die geometrical parameters or thermal and dynamic parameters of the extrusion process. For instance, screw geometrical parameters are the following: -screw diameter, D; - total axial length of screw, L_t; - length of screw zone *j* of constant depth, L_{pj}; - length of compression zone *j* of screw, L_{cj}; - length of the shearing zone, L_{sh}; - length of the mixing zone, L_0; -channel depth in the L_{pj} zone, h_{pj}; - total compression ratio, ε_c; - screw pitch, t (or φ – helix angle at the outer diameter of the screw); -flight width in the axial direction, e; - number of flight starts, i_f; - clearance between the flight and the barrel, δ.

Process parameters include: screw speed, n; -die pressure drop, Δp_d ; - mass flow rate, G_m; - maximum pressure in the screw channel, p_M; - barrel L_{thj} thermal zone temperature T_{bj}; - die *j* thermal zone temperature, T_{dj}; - average temperature variation of the processed material along the screw, T(L); - average melt temperature at the end of the screw, T_e; - melt temperature variation on the channel depth, $\Delta T(h)$; - quality of the extruded product.

Some of the process parameters are imposed parameters (IP) such as the average temperature variation of the processed material temperature along the screw or the product quality, while the other result by calculation from suitable relationships. The values of the calculated parameters, for a given screw geometry, depend on the physical properties of the processed material (tribological, rheological and thermal) and on the imposed process parameters (fig. 1).

From the design point of view one needs to establish:

- the processed material average temperature variation along the screw;

- the correlation between the screw geometry, dynamical and thermal process parameters and physical properties of the processed material, in each geometrical zone, L_j, of the screw;

-the correlation between two successive zones of the screw from the hydrodynamics, thermal, rheological and geometrical point of view;

With the aid of such correlations it is possible to design and calculate the extrusion process.

Limitations in the extrusion process

The mass flow rate is limited by:

-channel depth in the feeding zone, h_1, smaller than $h_{1,max}$ whose value depends on the allowable stress of the screw building material;

-quality condition (e.g. with reference to the uniformity of the melt temperature in the exit section of the die or to the quality of the product surface).

To assure the temperature uniformity on the product thickness, the maximum temperature difference over thickness should be less than the allowable temperature difference.

On the other hand, to assure the product surface quality, the shear rate at the wall at the die exit should be less than the allowable shear rate at the wall, which is a melt characteristic.

Generally, for a channel depth in the feeding zone which equals the maximum permitted value of $h_{1,max}$, the maximum temperature difference over thickness is greater than the allowable temperature difference, hence imposing a thermal homogenization zone on the screw.

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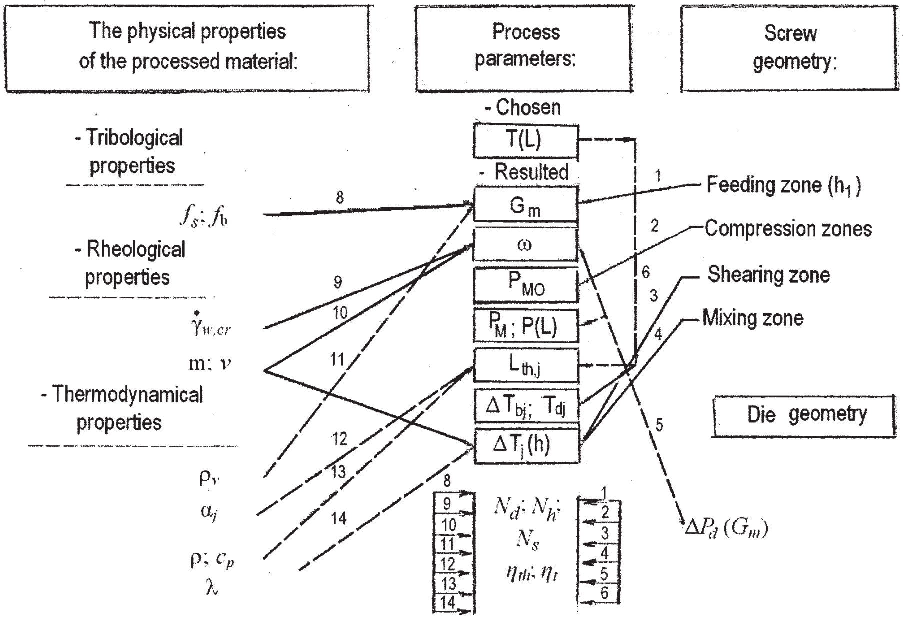


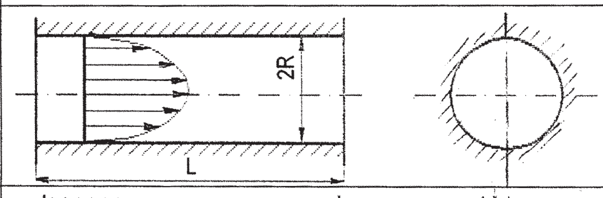
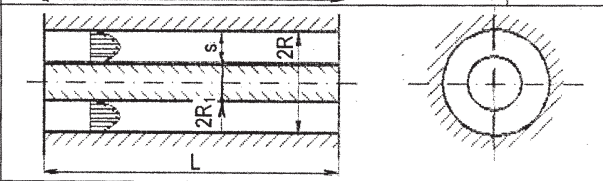
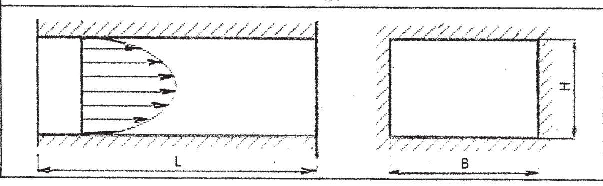
Fig. 1. The interdependence between the process parameters and the physical properties of the processed material, the screw geometry and the die geometry. G_m – flow rate; P – pressure; ΔP – pressure variation; T – temperature; ΔT_b – barrel temperature variation; ΔT_d – die temperature variation; $\Delta T(h)$ – material temperature variation on the channel depth; N_h – heating power; N_d – driving power; N_s – specific power; η_{th}, η_t – thermal and total efficiency; f_s; f_b – friction coefficients between processed material and screw and processed material and barrel, respectively; m, í – rheological constants; $\dot{\gamma}_{w,cr}$ – critical value of the strain rate at the wall; ρ_v – bulk density; ρ – melt density; λ – coefficient of thermal conductivity; c_p – specific heat; α - partial coefficient of heat transfer.

Table 1

THE SHEAR RATE AT THE WALL $\dot{\gamma}_w$, AND THE CRITICAL MASS FLOW RATE $G_{m,cr}$ by FLOW OF NONNEWTONIAN MELTS

$$(\tau = m \cdot \dot{\gamma}^{\nu})$$

$$\dot{\gamma}_w = \frac{G_v}{f_m \cdot f_G};\ G_{m,cr} = \rho \cdot f_m \cdot f_G \cdot \dot{\gamma}_{w,cr}$$

		f_m	f_G
1		$\frac{\nu}{1+3\nu}$	$\pi \cdot R^3$
2		$\frac{\nu}{1+2\nu}$	$\frac{\pi \cdot (R_1 + R) \cdot s^2}{2}$
3		$\frac{\nu}{1+2\nu}$	$\frac{BH^2}{2}$

To obtain high mass flow rates the two limitations must be correlated. The mass flow rate relationship of the feeding zone is given by the relationship [1-3].

$$G_{mf} = \rho_b k_G F_G \omega \qquad (1)$$

where ω = π n/30 with n in rev/min; ρ_b – bulk density; k_G – flow rate factor which depends on the friction coefficients between the processed material and the screw and the processed material and the barrel surface [4-8]; F_G – function depending on the screw feeding zone geometry ($F_G = E\, i_f D\, b_1\, h_1$ with $E = 1 – h_1/D$ and b_1 -screw channel width).

The mass flow rate relationship of the die exit zone is [9; 10]

$$G_{md} = \rho \cdot f_G \cdot f_m \cdot \dot{\gamma}_w \qquad (2)$$

where $\dot{\gamma}_w = \dot{\gamma}_{w,cr}$.(table 1).

Equaling these two mass flow rates one obtains the critical value for the screw angular velocity

$$\omega_{cr} = \rho \cdot f_G \cdot f_m \cdot \dot{\gamma}_{w,cr} / (\rho_b \cdot F_G) \qquad (3)$$

where f_m is a function of the rheological behaviour and f_G depends on the geometry of the die exit zone; ρ is the melt density at the die exit zone temperature.

Practically, we accept

$$\omega \leq \omega_a \qquad (4)$$

where

$$\omega_a = \omega_{cr} / c_s, \qquad (5)$$

with c_s >1 is a safety coefficient.

Calculation of the extrusion process

A given screw may yield an optimal extrusion process for a given processed material and die. When the die or the materials are changed, new operating conditions must be considered.

The calculation of the extrusion process is performed in the following order:

- extrusion die and extrusion die working field [9; 10];
- maximum channel depth in the feeding zone [11; 12];
- total compression ratio and compression ratios of the screw compression zones [11, 2];
- channel depth in the constant depth screw zones [11, 12];
- critical flow rate through the die, G_{cr} [10];

- allowable flow rate, $G_{al} = G_{cr}/c_s$ [13];
- maximum allowable screw rotational speed, $\omega_{al} = \omega_{cr}/ c_s$;
- processed material curve of average temperature variation with screw length;
- maximum pressure in the channel;
- thermal fluxes, barrel and die temperature in each thermal zone [11; 12];
- temperature variation curve with screw channel depth [14; 15];
- the curves of material minimum and maximum temperature variation with screw length [14, 15];
- coefficient of temperature non-uniformity [16];
- verification of thermal homogeneity and the need of a mixing zone /mixing and shearing zone [17-23];
- verification of the melting screw length;
- screw characteristics [23-25];
- retention time in the screw channel and extrusion die;
- driving and heating power [26];
- thermal efficiency and total efficiency [16] and specific power;
- product quality [27-29].

Application of the established method

By applying the proposed method of calculus of the extrusion process parameters for a single screw extruder with a diameter D = 90 mm and a L/D ratio of 28 in which LDPE is processed for pipes with outside diameter of d_e = 62 mm and inside diameter of d_i = 48 mm, in the case of a required flow rate of G_m = 326 kg /h, the resulted thermal efficiency was η_{th} = 59 % with a total efficiency of η_t = 52 %. The barrel temperature variation from the feeding zone outlet to the end of the barrel resulted 120°C; 169°C; 210°C and 244°C.

Conclusions

It can be seen that the established method provides information on whether it is necessary to introduce thermo-mechanical homogenizing zones (e.g. Maddock or Egan).

In the same time it provides values for the following: extrusion working field; length of thermo-mechanical homogenizing zone; material temperature variation on the screw length and over the channel cross-section; barrel zones temperature; residence time; effective flow rate; screw characteristics; screw speed; driving power; external heating power; thermal efficiency and total efficiency; specific power.

The proposed method allows optimization of the extrusion process as well as of the screw geometry.

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