Minimizing Energy Consumption in Polymer Extrusion

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In the following work a correlation was inferred of the effects of material behaviour in different zones of the extruder screw channel with a number of process parameters. Calculus of the average temperature variation of the processed material with length and depth of the screw channel allows effective positioning of intense mixing zones, resulting in enhanced melt thermal homogeneity and product quality. Relationships for the flow-rate of the feeding zone, the specific power and the efficiency of the extrusion process allow the overall performance calculus of the extruder. To increase process efficiency one must reduce the heat loss, Q_l which results in energy savings and the decrease of thermal pollution of the environment. It becomes thus possible to replace a certain number z of actual extruders with diameter D, each with a total installed power $N_{t,1}$ and flow-rate $G_{m,1}$, with a single extruder of the same diameter D assuring a flow-rate $G_m = z \cdot G_{m,1}$ and whose total installed power is $N_t < z \cdot N_{t,1}$. Heat lost through the external surface of the heating system of z extruders $(z \cdot Q_{1,l})$ is higher than that of a single modern extruder. Consequently, process efficiency in the up-graded extruder is higher than that of the z extruders, resulting in diminished energy related expenses and cost of the mass unit of extruded product along with less environment pollution.

Keywords: extrusion process; extruder performance; output; extruder efficiency; thermal pollution; energy

Experimental research works of Maddock [1; 2], Marshal, Klein and Uhl [3], Tadmor, Duvdevani and Klein [4], Tadmor [5], later repeated in the work of Menges and Klenk [6] and Klenk [7, 8], showed the evolution of the physical state of the processed material and its temperature variation along channel length and with screw channel depth (fig.1, 2). A severe thermal non-uniformity of the polymer melt layer in the screw channel was noticed. To lessen the thermal non-uniformity, the screw was initially perforated centrally on its entire length, and heated to increase the temperature of the colder polymer melt layers being in contact with the screw surface. This way it became possible to increase the depth of the screw channel and consequently the extruder's flow-rate [9]. Later, with the introduction of various technical solutions to increase thermal homogeneity of the melt, the procedure of heating the screw was given up, due to its technical difficulty (screw had to be perforated when built, while it had to rotate when in function).

To further reduce the thermal non-uniformity in the screw channel depth an additional flight, barriers to retain the not melt solid particles, thermo-mechanical homogenization zones, as well as intense shear zones were introduced on the screw [10-14].

Based on Decker [15] initial research and on Darnell and Moll [16] theoretical and experimental work and the in-depth work of Schneider [17], a conclusion was reached that the output can be substantially enhanced by increasing the friction coefficient between the granules and the internal surface of the extruder barrel in the feeding zone.

As a result, grooved zones were designed (fig.3) on a length of (3...5)D. These resulted in an output increase along with improving the stability of the overall extrusion process.

Experimental research [18; 19] allowed determination of the friction coefficient between granules and grooves. These values were used to calculate the slipping coefficient of granules on the screw [20-23], based on which the extruder output is calculated from the conditions of the feeding zone [20-25], allowing the optimization of the extrusion process with respect to output [26].

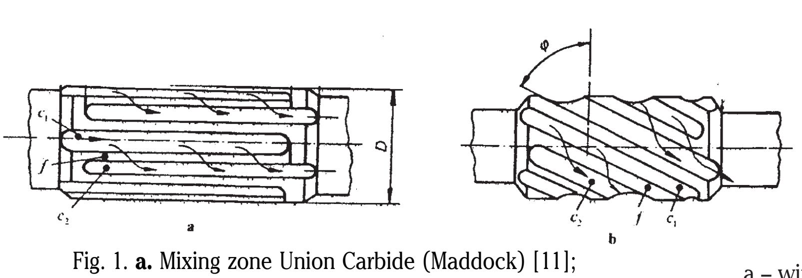

Fig. 1. **a.** Mixing zone Union Carbide (Maddock) [11]; **b.** Mixing zone Egan [13]. c_1, c_2 – channels; f – barrier flight; φ-channel inclination angle

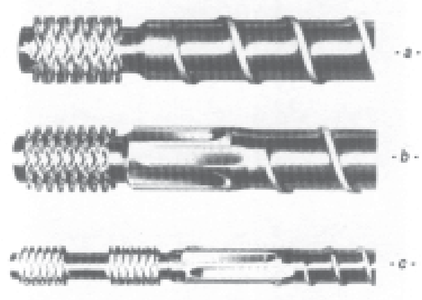

Fig. 2. Screw for polyolefin:
a – with a zone with rhomboidal elements at the end of the screw; b, c – with Union Carbide (Maddock) mixing zones and a zone with rhomboidal elements at the end of the screw

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the duration between the start and stop of the electrical heating system of the extruder barrel.

For thermally sensitive polymers (e.g. polyvinylchloride) one must take into consideration the duration the polymer melt is kept at a certain temperature to avoid its degradation.

To this end, calculus of the melt retention time along geometrical zones of the screw [55] and on the succession of nozzles in the extruder head [56] might prove itself useful.

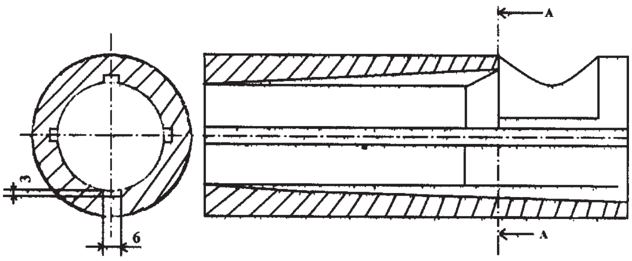


Fig. 3 Grooved feeding zone

Towards increasing the flow-rate of the feeding zone the dependence of bulk density, ρ_v on the ratio between the screw channel depth, h and the average diameter value of the fed granules [27, 28], as well as the possibility to increase the value of ρ_v, hence the output, through vibration [28-30] have been shown.

After the invention of intense homogenization zones, the need for their calculation became apparent. Various theories were proposed, among them those presented in the papers [31-34], analyze this problem from the thermo-mechanical point of view completely: the variation of pressure and temperature between the entry and exit from this zone, the efficiency of the homogenization process [35; 63] and the calculus of the geometry of the intense homogenization zone [36, 63]. To determine the position of the homogenization zone along the screw, the relationships for temperature and pressure variation of the non-Newtonian melt in the screw channel were inferred [33; 37-39].

The overall performances of the extruders are analyzed through [40-41]:

- efficiency of the extrusion process;
- total efficiency of the extruder;
- specific power, as ratio between the total power necessary for the extruder and its output, for a given polymer.

The greater the quantity of mechanical energy transformed into heat through internal and external friction, the greater the process efficiency. The issue of mechanical energy transformed into heat through friction was addressed for a non-Newtonian polymer melt in paper [42].

After understanding the extrusion process in correlation with the geometry of the screw channel, with process parameters (pressure, temperature, screw speed), with the characteristics of the extruder head, and all these correlated with the thermal, rheological and tribological behaviour of the processed polymer, it became possible to establish the relationships and methods of calculus for the screw [43-45], for the extruder head [46, 47] and for the extrusion process as a whole [41].

All these results that were obtained before must be correlated between them. For the method of calculus of the screw channel profile, of variation of the channel depth along the screw length, one must introduce the calculus of temperature variation with screw channel depth, along with establishing the position of the homogenization and/ or intense shear zone(s) followed by their design. When calculating the extruder head, one must consider the dependency between the critical velocity gradient and the end channel pressure [48].

When calculating the flow-rate of the feeding zone and the pressure variation along the screw channel, one must consider the dependence of the granular or powdery material bulk density in the feeding zone on pressure [49-52].

The variation of the bulk density determines temperature variation of the processed material [53-55]. This influences

Practical consequences of some theoretical and experimental research

Over time, especially in the last 60 years, in different stages, were evidenced separately, experimentally or/ and theoretically, some important aspects of the extrusion process of plastic materials.

In the following work, a correlation of the effects of material behaviour in different zones of the screw channel, with the screw channel geometry, the temperature variation along the screw length and on the depth of the material layer in the screw channel, with pressure variation along the screw and with the melt thermal non-homogeneity, especially in the poly-tropic regime at rather modest screw speed was inferred.

Along the screw length, material pressure and temperature vary continuously. The temperature of the processed material varies continuously, having in a given section of the material layer in the screw channel values between a minimal value, T_{min} and a maximal value T_{max}. Therefore, two distinct extreme temperature curves can be noticed in the material layer, along the length of the screw channel. Temperature increases from T_o, at the entry in the feeding zone, up to temperature T_e at the exit from the screw channel, at the entry in the extrusion head, respectively. In a given section, between the maximum and the minimum temperature the difference is $\Delta T_{M,m} = T_{max} - T_{min}$. On the other hand, the melt with a given temperature, e.g.T_1, is to be found on a length ΔL_1 along screw length.

Based on the variation curves of the material temperature the screw thermal characteristic zones can be established [22; 41]:

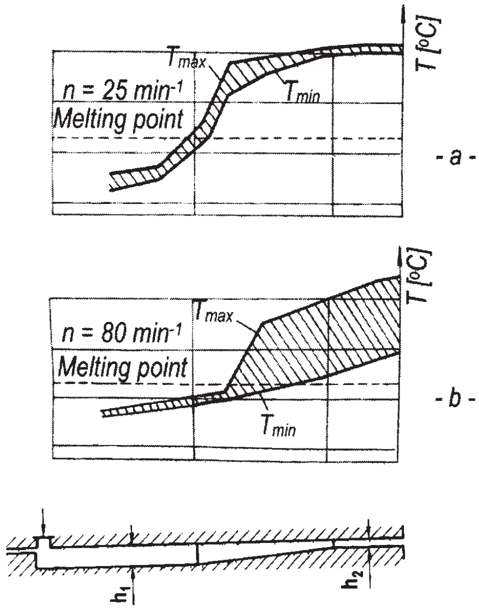
- zone where the material (granular or powdery) is found in a *solid non-cohesive* state (feeding zone);
- zone of the *cohesive solid* material (particles begin to adhere among them);
-transition zone between the temperature of the beginning of change of state, $T_{s,i}$ on curve T_{max} and the temperature of the beginning of change of state (or flow) on curve T_{min}, in this zone the material passes from solid granules 100% to melt 100%;
-melt zone, where melt temperature on curve of T_{min}, is higher than the temperature of the beginning of change of state.

This zone separation is necessary for the calculus of the extrusion process [41].

With the increase of the screw speed, increases the temperature difference $\Delta T_{M,m} = T_{max} - T_{min}$ at the exit of the screw channel (fig. 4).

Pressure generation is necessary for product formation when exiting the extruder head. Pressure variation along screw length (fig. 5) depends on the shape and size of the screw channel, but also on the existence of grooved channels on the internal surface of the barrel in the feeding zone.

For a screw with three geometrical zones without zones of intense shear or homogenization, pressure varies either continuously up to the screw exit pressure, p_c - $p_{max,1}$(1), or reaching initially a maximum,$p_{max,2}$ at distance $L_{pM,2}$ from



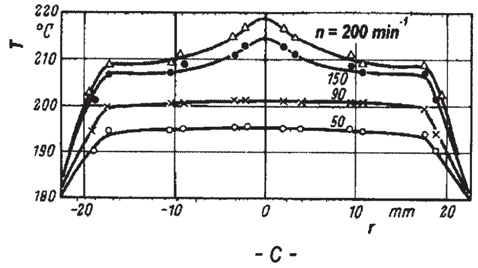


Fig. 4. Material (HDPE) temperature variation along screw length: *a*, *b* – at two different rotational speeds *a* – 25 min^{-1}; *b* – 80 min^{-1}; *c* – beyond screw end, function of the radius for an extruder with D = 45 mm and L / D = 30 at rotational speed n=200min^{-1} [57]

the beginning of screw, after which it decreases to $p_{c,1}$. For this screw, the portion of length (L_1 - $L_{pM,2}$) can assure a certain thermal homogenization of the melt.

For the screw with shear and homogenization zones mounted at the screw end, which do not impose the increase of pressure (consumes the pressure energy), the maximum pressure, $p_{max,3}$ is reached before these zones (3), at length $L_{p,M,3}$ (fig. 5).

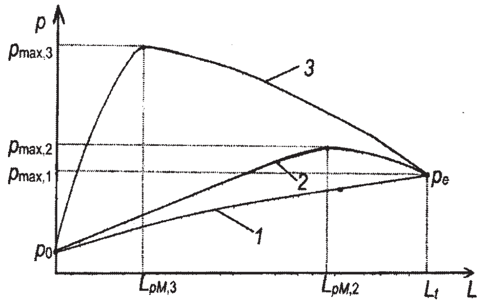


Fig. 5. Material pressure variation along screw length

Figure 6 presents pressure variation along a screw length with diameter D = 45 mm, with intense shear and homogenization zones mounted on a length of 8D and 6D, respectively, towards screw end. Before those, over a length of 10D the screw channel has a constant depth and the feeding zone is axially grooved [58]. It can be noticed that the shape of the pressure variation curve is similar. Increasing the exit pressure, maximum pressure increases also.

The mass flow-rate of the extruder in kg/s, is established in the feeding zone and is given by the relationship,

$$G_m = \rho_v \cdot k_G \cdot C \cdot \omega , \qquad (1)$$

where ρ_v is the material bulk density at the entrance in the screw channel, $\omega = \pi . n / 30$ – screw angular velocity, kG= k_{w1}. k_{w2} - flow-rate coefficient; k_{w1}- sliding coefficient between the processed material and screw in the feeding zone; k_{w2}- mean speed coefficient of particles in the cross-section of the screw channel; n - screw speed, rot/min; C - geometrical constant, dependent on screw diameter, D, on channel depth in the feeding zone, h_1, on average axial width of screw flight, $\bar{e}_b$, and on the number of screw flight beginnings, i_b;

$$C = \frac{\pi}{4} \cdot h_1 \cdot D^2 \cdot \left(1 - \frac{h_1}{D}\right) \cdot \left(1 - \frac{2h_1}{D}\right) \cdot E_s \cdot \sin 2\varphi_s ,$$

where

$$E_s = 1 - i_b \frac{\bar{e}_b}{\pi(D - h_1)\sin\varphi}$$

$\varphi = arc\left[\tan\left(\frac{S}{\pi \cdot D}\right)\right]$- screw flight inclination angle with screw diameter;

S= pitch of screw flight;

$\varphi_s = arc\left[\tan\frac{S}{\pi(D - 2h_1)}\right]$, screw flight inclination angle, with screw surface, at diameter (D - $2h_1$).

Modeling of melt movement in the screw channel [59], along with the correlation of the screw channel geometry with the processing conditions and the flow-rate, allow the determination of the melt retention time in the extruder [60].

Fluctuation of the bulk density value ($\rho_v \pm \Delta\rho_v$) determines fluctuations of the flow-rate and periodical instability of the extrusion process [52 - 55], to which, sometimes, adds up, by example the instability of sheets at extruder head exit [61].

Total power used for material extrusion,

$$N_t = N_m + N_{th} , \qquad (2)$$

where N_m is the mechanical power used for material transportation and pressure generation, whereas N_{th} is the exterior heating system power.

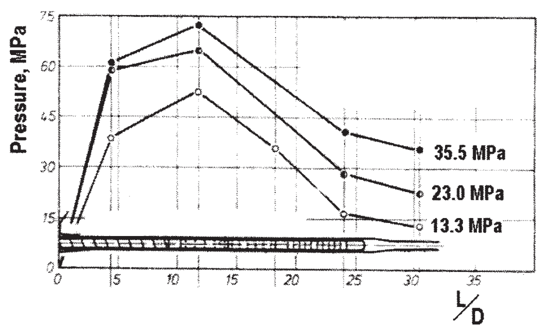


Fig. 6. Pressure variation along screw length (D = 45mm) when processing a plasticized polyvinylchloride, at three processing pressures p_c = 13.3, 23.0 and 35.5 [MPa] and a screw rotation speed of 66 min^{-1} [57].

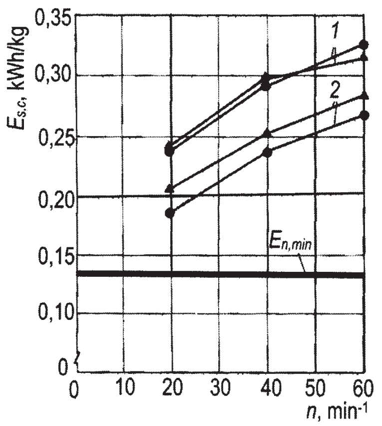


Fig. 7. Variation of the used specific energy, $E_{s,c}$ with the screw rotational speed, n. When processed on an extruder with diameter D = 90 mm and L / D = 25, of a high viscosity polyethylene fed as granules (•) or as powder (▲).$E_{n,min}$ -necessary minimum specific energy

Specific power represents the ratio of power used to process mass flow-rate,

$$N_{sp} = N_t / G_m \tag{3}$$

From experimental data processing result flow-rate and the specific energy used are directly proportional to rotational speed (Gm ~ n) and ($E_{s,c}$ ~ n). By example, when processing a high viscosity polyethylene fed either as granules or powder, $E_{s,c,}$ increases with the increase of rotational speed for a classic screw with three geometrical zones (*1* – in fig. 7), as well as in the case of a screw with five geometrical zones, the last one being built with homogenizing pins (*2* – in fig. 7) [40].

One can notice that $E_{s,c}$ depends very little on the state of the fed polymer (granular or powdery), but is influenced by screw geometry; it is smaller for the screw with homogenizing zone (*2* – in fig. 7) compared to the screw without it (*1* – in fig. 7). Necessary minimal specific energy for the extrusion process is $E_{n,min}$ being calculated with relationship (6).

· The concept of specific power, together with the variation of processed material enthalpy between the exit of the screw channel H(p_c, T_e) and the entrance in the screw channel H(p_o, T_o), allow calculating the extrusion process efficiency,

$$\eta_p = \frac{\Delta H}{N_{sp}}, \tag{4}$$

where ΔH = H(p_c; T_c) - H(p_o; T_o)

Otherwise put, the process efficiency has the following expression [40],

$$\eta_p = \frac{E_{n,\min}}{E_n + Q_l}, \tag{5}$$

where:

$$E_{n,\min} = 0.5 \cdot \overline{w}_e^2 + \Delta H\,, \tag{6}$$

is the minimum specific energy (J/kg) necessary to accomplish the extrusion process;

E_n -specific energy effectively used in the extrusion process;

Q_l -specific energy lost to the environment (lost heat);

$\overline{w}_c$- mean velocity of the melt in the exit cross-section of the screw channel. Term $0.5\overline{w}_c^2$ is negligible for extruders functioning in the poly-tropic regime, but has to be considered for the auto-term extruders, where screw peripheral velocity is relatively high.

At extruders with auto-term regime, the mechanical energy (N_m . t, where t is time) transforms mostly in heat, through internal and external friction, by which the processed material is melt and brought at the extrusion temperature T_c. In this case N_t and N_{sp} values are minim and consequently process efficiency η_p reaches its maximum value.

If the extruder barrel is very well isolated, so that the thermal loss towards the environment $Q_l \rightarrow 0$, then at an extruder with an auto-term regime $\eta_p \rightarrow 100\%$.

Bringing the extrusion process as close as possible to an auto-term regime increases the process efficiency η_p, as compared to an extruder in a poly-tropic regime.

Calculus of the material temperature in a given point along the length of the screw channel can be done by the general relationship (fig. 8),

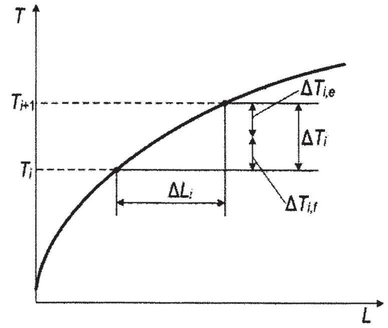


Fig. 8 Evolution of the average material temperature in the screw channel over an incremental length, ΔL_i

$$T_{i+1} = T_i + \Delta T_i\,, \tag{7}$$

written for the increment of length ΔL_i where

$$\Delta T_i = \Delta ST_{i,e} + \Delta T_{i,f}$$

with $\Delta T_{i,e}$ - temperature increase due to heat transfer, and $\Delta T_{i,f}$- temperature increase due to internal and external friction.

In a given cross-section, along the screw channel length, (fig. 9), the temperature at a given depth of the material layer, y can be calculated with the general relationship

$$T_i(y) = T_{s,i} + \Delta T_i(y), \qquad \Delta T_i(y) = \Delta T_{i,e}(y) + \Delta T_{i,f}(y), \tag{8}$$

where $T_{s,i}$ is the material temperature at the screw surface in cross-section i (fig. 9); $\Delta T_{i,f}(y)$ = ($T_{b,i}$ - $T_{s,i}$)(1 - ξ) - temperature variation in cross-section i, due to external heating; $\Delta T_{i,f}(y)$ -temperature variation in cross-section due to internal and external friction; $T_{i,b}$ -material temperature at barrel inner surface in cross-section i; ξ = y / h, where h is channel depth, and y ∈ [0; h] is a coordinate

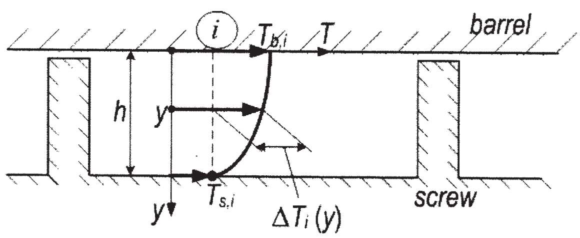


Fig. 9. Temperature variation of processed material on screw channel depth, in cross-section i

measured from the barrel internal surface towards the screw channel surface. The temperature variation due to internal friction, for example, can be calculated with the method presented in paper [42].

From the flow-rate general relationship (1) can be calculated the depth of the screw channel in the feeding zone and/ or the necessary screw rotational speed.

Using the results presented in the paper and the processed material behavior (rheological, thermal, tribological), the determination of the maximum pressure cross-section, L_{pM} becomes possible, through performance harmonization of screw characteristic zones [62].

Based on the general relationships (7) and (8), the position of the cross-section starting from which the intense shear and/ or homogenization zones must be mounted, can be established. From the process efficiency relationships (4) and (5) results the necessity of reducing the heat loss, Q_t which results in process efficiency increase. It becomes thus possible, the replacement of *z* actual extruders with diameter D, each with a total installed power $N_{t,1}$ and flow-rate, $G_{m,1}$, with a single extruder of same diameter *D* but calculated and equipped with performance elements assuring a flow-rate $G_m = z \cdot G_{m,1}$ and whose total installed power is $N_c < z \cdot N_{t1}$.

The specific power of this single extruder will be less than the sum of the specific powers of the extruders,

$$N_t / G_m < (z \cdot NG_m t,1) / (z \cdot G_{m,1})$$

On the other hand, heat lost through the external surface of the heating system of *z* extruders $(z \cdot Q_{l,1})$ is higher than that for a single modern extruder. Consequently, process efficiency in the new extruder is higher than that for the z extruders.

All these will result in diminishing the energy related expenses and reducing the cost of the mass unit of the extruded product.

Conclusions

Relationships for the flow-rate of the feeding zone, the specific power and the efficiency of the extrusion process allow the overall performance calculus of the extruder. On the other hand, the calculus of the average temperature variation of the processed material along the length of the screw channel and the variation of its temperature on the depth of the screw channel, allow determining the extreme curves for temperature variation, based on which one can establish where must be positioned the intense shear and/ or dispersive mixing zones. Thus, the thermal homogeneity of the melt is increased, leading to an enhanced product quality.

Increased process efficiency results in energy savings and the decrease of thermal pollution of the environment. It becomes therefore possible to replace a certain number z of actual extruders with diameter D, each with a total installed power $N_{t,1}$ and flow-rate $G_{m,1}$, with a single up-graded extruder of the same diameter D assuring a flow-rate $G_m = z \cdot G_{m,1}$ and whose total installed power is $N_{t,t} < z \cdot N_{t,1}$. Heat lost through the external surface of the heating system of *z* extruders $(z \cdot Q_{i,1})$ is higher than that of a single modern extruder. Consequently, process efficiency in the up-graded extruder is higher resulting in diminished energy related expenses and cost of the mass unit of extruded product.

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