Extruder Performance based on a Correlated Extruder Head-screw-barrel Unit Working Field

COSMIN V. JINESCU*, NICOLETA TEODORESCU
Politehnica University of Bucharest, Department of Industrial Process Equipment, 313 Splaiul Independentei, 060042, Bucharest, Romania

A number of inventions, and theoretical and experimental research allowed to increase the thermal homogenous melt flow-rate delivered by the screw. On the other hand, quality of the extruded product depends on geometrical considerations of the extrusion head and on a large scale on the rheological behaviour (viscous and elastic) of the polymer melt. Non-harmonizing the design of the screw-barrel unit with the construction of the extrusion head can lead to low-quality products. In this paper, the extrusion head working field was drawn based on limitations imposed by the screw-barrel unit, i.e.: maximum flow-rate assuring required melt thermal homogeneity; - maximum flow-rate for which the heating system on the barrel (and screw, eventually) assures the extrusion temperature; -minimum flow-rate corresponding to screw diameter.

Keywords: extruder head working field, extruder performance, rheological behaviour, screw-barrel unit

In the case of plastic materials extrusion, the non-harmonizing of the screw-barrel unit design with the extrusion head, leads to products loaded with internal stresses and cross-sectional non-homogeneity.

The life span of these products is relatively small. For pipes, for example, fracture before due time leads to environment pollution with the transported substances.

To avoid such situations, the analysis of the extrusion head working field is necessary, in accordance with the extrusion process parameters, rheological behaviour of the polymer melt, product quality conditions as well as economic considerations.

Extruders have been improved especially after 1953, when the first in-depth theoretical analyses of the extrusion process have been published [1-19]. The main objective consisted in the design and construction of the extruder screw so that it allows the maximum flow-rate of thermally homogenous melt.

The screw with barrier flight was designed [15, 20] and then the intensive mixing zones mounted on the screw [21 - 24]. To increase the flow-rate, grooved zones on the barrel were added in the feeding zone, which enhancing the friction coefficient between the polymer granules and the barrel led to a higher extruder flow-rate [25 - 30].

Experimental and theoretical research concerning the extruder flow-rate, the established flow-rate calculus relationships [31 - 40], constructive solutions and the corresponding relationships of the intensive homogenizing zones [41 - 47], as well as those referring to thermal non-homogeneity and temperature variation of the melt in the screw channel [48 - 51] led to an increase in the screw capable flow-rate. This advantage, created by the results of research and inventions related to the screw-barrel unit, was limited due to conditions imposed by the flow pattern in the extrusion head, especially in the entry zone and by the end channel at the extrusion head exit, for viscous-elastic polymer melts.

To address these issues the spiral mandrel before the end channel was invented, allowing the cross-flow of the melt currents and avoiding the effect of melt currents separation, characteristic to „classic" extrusion heads, with spider mandrel [24].

To optimize the extrusion process, the extruder optimization diagram was drawn initially with coordinate flow-rate – pressure at screw channel exit [52; 53]. Later on, the working field of the extruder head was defined and drawn, with coordinate flow-rate – pressure at extrusion head entry [54 - 57]. In this paper is proposed an enhanced and completed solution of the method developed in papers [54; 55] for the drawing of the extrusion head working field.

Extruder head-screw-barrel unit correlated working field

In the extrusion head the melt pressure decreases from p_e, at extrusion head entry, to a value p_f in the cross-section at the end channel exit. Pressure p_f can be greater or equal to atmospheric pressure, p_0; this depends on the extrusion head geometry, flow velocity and elastic properties of the melt. Melt temperature in the extrusion head is considered constant and equal to the extrusion temperature, T_e, characteristic for each polymer.

Extrusion head working field (in the semi-plane limited by the coordinates G_m – flow-rate – and p_e) is obtained at the interior of the contour determined by the intersection of the following curves (fig. 1.a) [54; 55]

1. minimum pressure curve, $p_{e,min}$(T) at a given processing temperature, conditioned by the product minimum quality requirements;
2. maximum pressure curve, $p_{e,max}$(T) at a given processing temperature, conditioned by the minimum value of total efficiency;
3. extrusion head characteristic G_m - p_e corresponding to maximum temperature, $T_{e,max}$ for which the extrusion of that material is possible;
4. extrusion head characteristic G_m - p_e corresponding to minimum temperature for which the extrusion of that thermo-plastic material is possible;
5. allowable maximum flow-rate curve, $G_{al,max}$ corresponding to maximum allowable velocity of the melt through the extrusion head end channel.

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* email:cosmin.jinescu@yahoo.com; Tel.: +40731306908

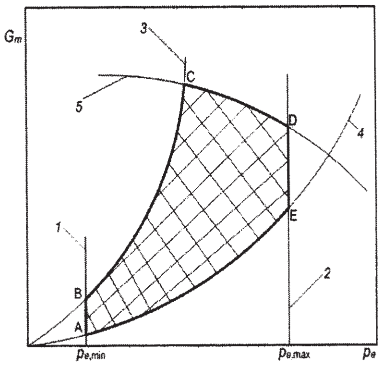

Fig. 1.*a*. Working field of the extruder head (ABCDEA)

The drawn curves limit the working field of the extruder head. The working field of the extruder head (ABCDEA, fig. 1.a) must be adjusted taking into account the following (fig. 1.b):

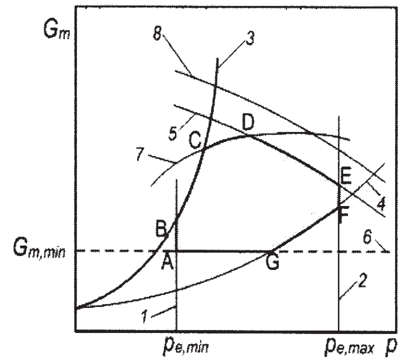

Fig. 1.*b*. Extrusion head working field with limitations imposed by the screw-barrel unit

6. extrusion head is attached to a screw-barrel unit characterized by a given value of the barrel internal diameter *D* (45; 63; 75; 90; 100 etc. mm), to which corresponds a certain economic minimum flow-rate $G_{m,\min}$ (curve 6).

Additionally, one must consider restriction curves ***7*** and ***8*** when drawing the extrusion head working field as limitations imposed by the screw-barrel unit:

7. screw-barrel unit assures a certain maximum masic flow-rate of a thermally homogenous melt, $G_{m,\mathrm{om}}$ (curve 7);

8. heating system of barrel (and screw, eventually) allows reaching the melt extrusion temperature, T_e, up to a certain maximum value of the flow-rate, $G_{m,th}$ (curve **8**). The corrected working field based on the limitations imposed by the screw-barrel unit becomes ABCDEFGA in figure 1.b.

The extrusion head working characteristics $G_m(\mathrm{p})$ are drawn at extrusion temperature, T_e, with possible working temperatures $T_e - \Delta T_e$ and $T_e + \Delta T_e$ where $\Delta T_e \leq \Delta T_{ad}$ represents temperature fluctuation amplitude, the allowable value of temperature fluctuation amplitude ΔT_{al} depending on the way temperature influences the rheological behaviour of the thermo-plastic melt. At materials for which a small variation of temperature yields a big viscosity variation, one admits correspondingly small values for ΔT_{al}.

Practical case

The extrusion head-screw-barrel unit correlated working field can be drawn as follows:

-Curves *1* and *2* result based on practical knowledge;

-Curves *3* and *4* represent extrusion head characteristics G_m - p_e at minimum and maximum extrusion temperature and are drawn based on the relationship:

$$\Delta p_T = \mathrm{K}_\tau \cdot \left[\left(\frac{(2\nu+1)}{\pi\nu\rho}\right)\right]^\nu C_T G_m^\nu \tag{1}$$

where:

K_τ and ν are rheological constants whose values for a given polymer depend on temperature and pressure;

ρ - melt density;

G_m – mass flow rate through the die;

C_T comprises the geometrical constants of all the dies in the series [55]. In general, pressure loss along the length of the extrusion head depends on the channel geometry, rheological behaviour of the polymer melt, nozzle entry effect and the melt elastic and sliding at the wall effects [58];

-Curve 5 represents the allowable maximum flow-rate curve, $C_{al,max}$ corresponding to maximum allowable velocity of the melt through the extrusion head end channel and it is drawn with relationship

$$G_{ad,\max} = \frac{G_{cr}}{c_n} \tag{2}$$

where:

$$G_{c_r} = \frac{\pi}{2(2+1/\nu)} \cdot d_f \cdot s_f^2 \cdot \dot{\gamma}_{p,cr}(p_f) \tag{3}$$

with G_{cr} is the critical flow-rate and $c_n > 1$ is a safety coefficient with respect to the critical state at the end channel wall [55] and the critical shear strain rate for normal stresses $\sigma = \sigma(p_f)$ due to melt internal pressure p_f [59]

$$\dot{\gamma}_{p,cr}(p_f) = \dot{\gamma}_{p,cr}(0) \cdot \left[1 - \left(\frac{\sigma(p_f)}{\sigma_{cr}}\right)^{\alpha+1}\right]^{\frac{1}{\nu}} \tag{4}$$

where $\dot{\gamma}_{p,cr} = \dot{\gamma}_{p,cr}(0)$ is the critical shear strain rate at the wall, corresponding to $p_F = p_o$ or $\sigma = 0$; σ_{cr} is the critical normal stress; ν is the exponent in law (1), and $\alpha = 1/k$, where *k* is exponent deriving from the law describing melt behavior under normal stresses,

$$\sigma = K_\sigma \cdot \varepsilon^k, \tag{5}$$

where:

K_o and k are melt constants at temperature T_c, while ε –strain under normal stress σ. It has to be mentioned that σ and ε for the melt are defined by natural concepts (after Hencky) and not by engineering concepts, given the large deformations involved.

Generally, $\sigma(p_f)/\sigma_{cr} = p_f/p_{cr}$, where p_{cr} is the critical pressure inside the melt. It can be noticed that for $p_f > p_o$ results $\sigma(p_f)/\sigma_{cr} = 0$ so, generally,

$$\dot{\gamma}_{p,cr}(p_f) < \dot{\gamma}_{p,cr}(0). \tag{6}$$

Consequently, to obtain a maximum value of $\dot{\gamma}_{p,cr}(p_f)$, it is necessary that normal stresses $\sigma(p_f)$ to relax completely before the end channel exit. It is therefore useful that $\gamma_{p,cr}(p_f)$ be as large as possible, because critical flow-rate through the end channel depends on it [7]. Increasing the value of clearance also determines the move of allowable maximum flow-rate curve towards greater values, because of $G_{al,max} \sim s_f^2$.

-Curve *6* represents a certain economic minimum flow-rate $G_{m,min}$ determined by the screw-barrel unit through the value of the barrel internal diameter;

- Curve *7* represents a certain maximum mass flow-rate of a thermally homogenous melt, $G_{m,om}$ the screw-barrel unit produces and is drawn considering the homogenization areas on the screw;

- Curve *8*: The heating system of the barrel (and screw, eventually) allows reaching the melt extrusion temperature, T_e, up to a certain maximum value of the flow-rate, $G_{m,th}$; therefore, the curve is drawn based on the heat balance between the heat provided by both the heating system and that generated through internal friction, and the quantity of heat taken away by the processed material at mass flow rate G_m.

Generally, to enlarge the working fields towards higher flow-rate values it is necessary to move vertically the curve of the allowable maximum flow-rate $G_{al,max}$. This is possible by increasing the critical shear strain rate $\dot{\gamma}_{cr}(p_f)$ or/ and by decreasing of the safety coefficient c_n towards values closer to 1.2.

Conclusions

An extrusion head-screw-barrel unit correlated working field was drawn based on the analysis of flow through the extrusion head and taking into account process parameters, rheological behaviour of polymer melts and its elastic behaviour influence on the extruded product quality.

The resulted working field took into account the flow-rate limitations imposed by the screw-barrel unit through the following: -minimum flow-rate related to screw diameter; - maximum flow-rate for which the screw can assure necessary thermal homogeneity of the melt; - maximum flow-rate for which the heating system on the barrel (and screw, eventually) can assure the required extrusion temperature.

It was evidenced the interdependence between the critical shear strain rate and the melt normal internal stress at the end channel exit. It was also noticed the dependence of the extrusion head-screw-barrel unit correlated working field size on the rheological behaviour of the polymer melt.

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