Verified model of plasticization of polymers during injection moulding as a tool optimizing the design of injection moulding machine components

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Abstract: The article briefly presents the possibilities of the created and verified model of polymer plasticization during injection moulding. Exemplary characteristics generated by the model are presented and examples of applications of the described model for supporting the design of plasticizing systems of injection moulding machines are indicated.

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1. Introduction

One of the elements enabling the reduction of the production costs of polymer products is the optimal selection of the design of processing machines and processing conditions. This statement also applies to processing methods using screw transport processes. These methods include, in particular, extrusion and screw injection moulding, which are definitely leading among all methods of polymer processing. Both extrusion and injection moulding include two stages, i.e. plasticizing and shaping of material, which have a decisive impact on the quality of polymer products and the costs of their production. The main task of the plasticizing stage is obtaining a plasticized material with high material and thermal homogeneity, as well as high efficiency and low energy consumption.

Differences in the plasticization process during extrusion and injection moulding are mainly visible in the different geometry of plasticizing systems, especially screws in injection moulding machines and extruders. The experience of designers and technologists was used to optimize the geometry of these systems for a long time. In recent years, the theoretical approach has gained more importance. It is related to the creation of mathematical models of the plasticization process based on the laws of conservation of mass, momentum and energy, as well as knowledge of the characteristics of materials. These models link the basic plasticization characteristics of a given material with the geometry of the plasticizing system, thus enabling the optimization of design solutions.

Based on the bibliographic analysis carried out by the authors in the work on the model, it can be shown that, in principle, there were no comprehensive models of the polymer plasticization process during injection moulding, including the analysis of the solid material transport zone, melting and melt transport, which would be widely experimentally verified, available in the literature. Existing models usually describe the plasticizing process in a partial way, excluding some dynamic zones of the injection moulding machine, and they have not been verified or their verification was fragmentary.

A few years ago, the authors created the first, full model of the polymer plasticization process during injection moulding, which was widely experimentally verified on a specially designed test stand. This paper presents very briefly selected characteristics of the experimentally verified model of polymers plasticization during injection moulding, then some practical applications of this model are presented.

2. The simulation model

The full model of the plasticization process during injection moulding was developed [1-3]. It allows to predict all the most important output values of the injection plasticization process, such as:

1. profile of the relative width of the solid material bed along the length of the barrel,
2. material pressure profile along the length of the barrel,
3. material temperature profile along the length of the barrel,
4. average torque on the screw during its rotation,
5. mass yield of the plasticization process,
6. specific energy consumption by the plasticizing system,
7. screw rotation time and injection cycle time.

The model includes the analysis of the transport of solid material, starting from the hopper, then the transport of granules in the screw channel, next the process of melting the material (dynamic and static melting), and finally the process of transporting the polymer melt.

Examples of model characteristics for POM injection are presented below (operating parameters: $T_b = 210^\circ$C, $v_s = 240$rpm, $t_p = 20$s, $t_h = 4$s, $p_h = 10$MPa).

![Fig. 1. The relative width of solid bed of POM in screw channel during injection molding](image-url)

Figure 1 shows the relative width of the POM solid bed during injection moulding. We can see (red line) that its channel would be half filled with solid polymer if the screw continued to rotate (extrusion process). However, the presence of a static melting phase in injection moulding causes the polymer to melt faster. Hence, injection screws are shorter than extruder screws.
Figure 2 shows the relative width of the POM solid bed during injection molding with different screw stroke values for injection process. It is possible to observe the expected shift of the end of polymer melting towards the end of the screw as the value of the stroke NS increases. The generally recommended injection screw stroke is in the range of 1-3D.

Figure 3 shows the POM temperature during injection molding at various values of the screw rotational velocity \( v \). The expected slight increase in the temperature of the polymer melt above the barrel temperature \( T_b = 210^\circ C \) is observed. Increasing the velocity of the screw causes a slight increase in the temperature of the molten material at the end of the screw, in this case by about 5°C for each additional 100 rpm.

Figure 4 shows the POM pressure during injection at various values of the rotational speed of the screw \( v \). The observed course of the pressure curves results from the dynamics of the process and the properties of the transported material: solid at the beginning, then melted. In the vicinity of 6-8 turns, the exponential pressure increase is visible, characteristic of the transport of solid materials. Then we observe the deceleration of the exponential pressure increase related to the melting of the polymer. In the further part of the screw, the pressure changes in the material are linear, characteristic of melted polymers. The observed pressure maximum is characteristic for the correct course of the process and in this case it occurs around the 19th turn.

Figure 5 shows other characteristics of injection molding of POM as curves as a function of rotational screw velocity of screw. We can see significant increase in power demand and torque on the screw with increased velocity of screw. Yield of plasticization process, as well as SEC increase slightly. One can see expected reduction of recovery time and cycle time.

This model has been widely experimentally verified on a specially made research office, consisting of a Battenfeld 350/70 injection molding machine with appropriate equipment and software. This office and the results of experimental tests are described in various articles [3-6]. The results obtained in the model verification process resulted in the modification of the model in many segments in order to increase the accuracy of its indications. After the required corrections, the model of polymer plasticization during injection is characterized by a good prediction of the above-mentioned characteristics of the plasticization process, with average errors between the model results and the experimental characteristics up to 10% [3].

3. Application of the modelling results in the optimization of design of injection screws

The results generated by the experimentally verified model of plasticization of polymers during injection molding provide a lot of information that can be used in practically many ways. In addition to purely cognitive and educational knowledge of the course of characteristics, they can also be used in the design of plasticizing systems of injection molding machines, in particular injection screws.

As an example, we will simulate HDPE injection process. The geometrical parameters of the screw are shown in Fig. 6, the working parameters of the injection molding machine are shown in Fig. 7, and the properties of the polymer we can see in Fig. 8. The melting characteristics (solid bed profile) in the HDPE injection process with such geometrical, working and material parameters are presented in Fig. 9. Fig. 10 shows the pressure characteristics, while Fig. 11 shows other, determined by the model of the HDPE plasticization process characteristics. It can be seen that the solid bed is practically completely melted (solid bed profile \( A = 0 \), blue line) at the height of \( L = 12.5 \) (L - position along the length of the screw channel). Note that the total working length of the screw is 22D (total number of turns in all three zones). The maximum pressure is just over 18 MPa, and the energy consumption per unit mass of the material in the plasticizing process (SEC) is 189.1 kJ / kg.
Let’s see how the SEC of the process will change with a slight change in the geometry of the screw. We will reduce the compression ratio of the R screw ($R = \frac{H_{feed}}{H_{metering}}$) by increasing the height of the channel in the metering zone from 1.9mm to 2.8mm. Then the compression ratio $R$ will change from $R = 2.2$ to $R = 1.5$ (Fig. 12). Plasticization, pressure and other characteristics will change as shown in Figures 13, 14, 15.
It can be seen that the change of the screw compression ratio $R$ from the value of $R = 2.2$ to $R = 1.5$ caused that the maximum pressure decreased from the value of 18 MPa to approx. 11.5 MPa, which in turn resulted in the reduction of energy consumption by the plasticizing system (SEC) by $(189.1-163.3) / 189.1 = 14\%$. It should be noted that the material was completely plasticized in the screw in practically the same $L$ position ($L = 13$ vs. $L = 12.5$).

Reducing energy consumption by the screw by 14 percent is a very significant value, knowing that the most energy in the injection process is consumed by the plasticizing system [7]. The analysis of other characteristics also shows that the mass efficiency of the process also increased by approx. 3%, because the cycle time was shortened by almost 1 second.

Another example shows that when the number of turns in the metering zone was reduced from $N_3 = 4$ to $N_3 = 2$, SEC dropped to 174.3 kJ/kg, so it decreased by almost 8% (the number of turns in individual zones changed from 14/4/4 to 14/6/2, where the following numbers indicate the number of turns in the feed, compression and metering zone, respectively). The authors are not able to present the results graphically due to the limitations of the size of the article. We will gladly send such results (or any others) by e-mail on request.

It can therefore be seen that by controlling certain geometrical parameters of the screw, such as the height of the screw channel or the number of turns in individual zones, we can reduce the energy consumption of the screw by up to several percent. At the same time, we can observe the other characteristics of the process, taking care that the mass efficiency of the process does not decrease too much or that the point of complete melting of the material in the screw channel does not shift too much towards the end of the screw. This could cause a reduced material and thermal homogenization of the molten material, which would have a significant impact on the mechanical and visual properties of the product.

4. Summary

The tool for predicting with good accuracy various output characteristics of the polymer plasticization process during injection molding has been developed as a result of work on a mathematical model of the polymer plasticization process during injection molding. The knowledge of these characteristics is important not only from the cognitive and didactic point of view, but also allows to estimate the parameters of the plasticizing process important from a practical point of view, such as power consumption by the plasticizing system or plasticizing efficiency. It is also the tool for computer-aided analysis and design of injection screws, consequently enabling lower energy consumption by the plasticizing system of the injection molding machine or increased process efficiency.

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6. References