Experimental verification of computer model for polymer plastication process in injection molding

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Abstract: This paper is a continuation of the work on a comprehensive model of the plastication process in injection molding. The aim of this research is the analysis of the results generated by the proposed model by comparing these results with the wide experimental characteristics of real plasticating system of injection molding machine for two polymers — PE-LD and PE-HD, differing in rheological and thermal properties due to the different physical structure of both polymers. It was found that the model correctly determines the dynamics of changes of characteristics of the plastication process by changing the input parameters of the process. The average quantitative differences between the experimental and theoretical characteristics do not exceed 20 %. Computer model still requires minor changes to improve compliance of model results with characteristics of real unit of injection molding machine, primarily for determining more accurate values of melt pressure and torque.

Keywords: injection molding, injection molding machine, plasticating system, modeling.

Weryfikacja doświadczalna komputerowego modelu procesu uplastyczniania polimeru podczas wtryskiwania

Streszczenie: Artykuł stanowi kontynuację prac nad kompleksowym modelem procesu uplastyczniania polimerów podczas wtryskiwania. Porównano wyniki generowane przez proponowany model z szerokimi doświadczalnymi charakterystykami pracy rzeczywistego układu uplastyczniającego wtryskarki, w odniesieniu do dwóch polimerów o odmiennej strukturze fizycznej — PE-LD oraz PE-HD — różniących się właściwościami reologicznymi i termicznymi. Stwierdzono, że model poprawnie określa dynamikę zmian charakterystyk uplastyczniania przy zmieniających się parametrach wejściowych procesu, a średnie ilościowe różnice między charakterystykami teoretycznymi a doświadczalnymi nie przekraczają 20 %. Model komputerowy wymaga jeszcze dopracowania w celu poprawy zgodności charakterystyk wyznaczanych z charakterystykami pracy rzeczywistej jednostki uplastyczniającej wtryskarki, przede wszystkim w zakresie dokładniejszego wyznaczania wartości ciśnienia tworzywa w cylindrze oraz momentu obrotowego ślimaka.

Słowa kluczowe: wtryskiwanie, wtryskarka, układ uplastyczniający, modelowanie.

One of the elements that allow to minimize the production costs is the optimal choice of processing equipment and processing conditions. For a long time, optimization of geometry of plasticating systems and forming tools in processing machines have used the experience of designers and manufacturers. Since the last few decades, the theoretical approach has an increasing importance. It relies on using of mathematical models for plastication process on the basis of the law of mass, momentum and energy conservation and the characteristics of the material. These models combine the basic characteristics of the plastication process, like pressure and temperature distribution, output, power demand, *etc*., with the geometry of plasticating system, adjustable process parameters and material data, allowing thereby the optimization of the equipment design.

Theoretical approach to the plastication process through the creation of computer-based simulation models is widely used, mainly in the case of the extrusion process. Many models can be find in the literature, that describe, in less or more complex way, the plastication of polymers in single-screw extruders. They use commonly similar principles but differ in detailed assumptions. Thus, the extruder is divided into three main functional zones — zone of solid conveying, transient zone and zone

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of melting and melt conveying. The models of solid conveying zone are based on the mechanism of dry friction represented usually by the classic approach of Darnell and Moll [1] with subsequent modifications, *e.g.* [2—6]. They were also extended to describe the solid conveying in grooved barrels in isothermal an non-isothermal cases. In the last decade there appear also models describing the solid polymer conveying in terms of the behavior of granular systems. They are based on so called 3-D discrete particle simulations [7]. The existing models were also subsequently reviewed in various monographs on polymer extrusion, *e.g.*, [2, 8—10].

The existing models of polymer melting in screw systems can be roughly divided into two categories, *i.e.* the models of contiguous solid melting (CSM) and models of dispersed solid melting (DSM). For description of the melting process in single-screw systems, the Tadmor (CSM) model [2] and its various modifications are used most commonly [11—16]. The Tadmor model assumes that the melting occurs in a thin layer between the heated barrel and solid polymer bed, which moves with a constant velocity along the screw channel. Circulated melt pool, appearing at some critical thickness of the melting layer, accumulates at the active screw channel flight. Its relative width increases gradually dependent on process parameters and screw geometry. Modifications of the Tadmor model take into account such phenomena as the changes of solid bed velocity, solid bed break up or melting accompanied by circulating melt flow around the solid bed. Additionally, a flat screw channel shape and one- or two-dimensional, non-isothermal flow are usually assumed. Moreover, rheological properties of the polymer melt are described as a rule by the power law. It allows the calculation of typical characteristics of the process, depending on the channel geometry and operating conditions. The existing CSM models are also presented and discussed in extrusion monographs [2, 8—10] mentioned above or various books on polymer processing. The DSM melting mechanism is characteristic of so called starve-fed extrusion regime, which is more relevant of twin-screw extrusion. The starve-fed conditions in single-screw extruders can be obtained with controlled (volumetric) feeding, because for typical processes the flood feeding described by the CMS models prevails. Although the starve-fed in single-screw extruders is known for a long time [17, 18], its systematic study and modelling began in the last decade, especially due to the works of Wilczyński *et al*. [19—21]. Hence, the existing models require a further improvement.

In the last few decades, there has been also observed a significant development in the field of modelling of the plastication process in twin-screw extruders, both in the co-rotating systems [22—25], as well as (the last decade) in the counter-rotating systems [26—28].

Despite the significant development of extrusion simulation programs, only very few simulation models describe the plastication process in injection molding (called sometimes as reciprocating extrusion). The main cause of these disparities is much more complex dynamics of this process, resulting from a periodical nature of the injection molding. It involves with the existence of coupled static and dynamic melting phases (non-rotating and rotating screw) accompanied by axial screw movement with adjustable stroke. Model approach to melting mechanism in injection molding has been the subject of several relative old works [16, 29—32], without further continuation of the model development. However, in the last decade several new works have been published [33—43]. The paper concerning the calculation of power requirement in the plasticating systems of injection molding machines and extruders was introduced a few years ago by Potente [37]. Potente and coworkers also presented the new mathematical approach to simulate the polymer plastication in injection molding [38]. However, this model, verified experimentally on a few industrial plants, does not take into account the solid conveying and transient zones and uses some special modelling empirical constants. There are also reports on experimental study of the solid bed width in screw channel of injection molding machines [39, 40] with the use of „transparent windows" made in the barrel to observe the behavior of solid polymer. Probably the most comprehensive model of plastication process in injection molding, which reflects well the dynamics of a real reciprocating screw was presented a few years ago by Iwko and Steller [41, 42]. Some other details of the model were published elsewhere [44—47]. The created simulation model was also partially verified experimentally by measurements of the screw rotation time for several thermoplastics at different adjustable process parameters. This work presents a more comprehensive experimental verification of the model for its possible modifications and improvements. It supplies also many different experimental data on characterization of injection molding process which might be useful in other studies.

It follows clearly from the foregoing literature data, that the creation of adequate and comprehensive simulation model of plastication process in injection molding is still not fully completed. This confirms the fact that for the extrusion there exist at least several commercial software, such as EXTRUD, SSD, REX, SSEM and NEXTRUCAD, but for the analysis of plastication process in injection molding, there is probably available only one program — PSI.

The purpose of this article is the comparison of the results generated by the proposed model with comprehensive experimental characteristics of real plasticating injection molding system for two polyethylenes: PE-LD (MFR = 2 g/10 min) and PE-HD (MFR = 8 g/10 min) which differ not only in flowability and consequently in rheological behavior, but also in tribological and thermal properties as a result of various chemical and physical structures. On the background of these two different polymers, the differences in behavior of the model will be exposed.

COMPUTER MODEL

In order to introduce the model evaluated later in this paper, its main assumptions and key segments of its construction were presented below.

To create mathematical model of plasticization process during injection molding, the presence of four dynamical zones in the plasticating system was assumed:

— feed port and solid conveying zone,

— transient zone,

— melting zone,

— melt conveying zone.

In order to create a mathematical model of the plastication process in injection molding it was assumed the flat (rectangular) screw channel model and the starting point for such model will be the model of steady-state extrusion, that is similar to the classical extrusion model of Tadmor and Klein [2]. However, in contrast to the steady conditions (characteristic for extrusion), the lengths and positions of dynamical zones change in time within the injection cycle. To describe these time changes it was adopted, that during the cycle two coupled states (appearing at two characteristic moments of time) are valid:

— at the moment of the end of screw rotation (the beginning of static melting),

— at the moment of the beginning of screw rotation (the beginning of dynamic melting).

It was assumed that the dynamic equilibrium in the solid conveying zone is established fast enough. Hence, its operating characteristics can be adequately described by means of relations, that are valid for the steady-state conditions [2]. However, the axial velocity component U of rotating and withdrawing screw should be additionally taken into account. It changes significantly the resulting flow equations in comparison with steady-state conditions.

Assuming the flow continuity, the mass flow can be calculated both from the solid bed velocity and from the screw withdraw velocity as:

$$\dot{G} = H\, W\, V_{sz}\, d_s \tag{1}$$

where: H — channel height, W — channel width, V_{sz} — solid bed velocity along the screw channel (in z-direction), d_s — density of solid polymer.

If the mass flow $\dot{G}$ is known, the values of V_{sz} and U can be calculated and it makes possible to calculate the solid conveying angle. If this angle is known, the pressure profile in the solid conveying zone can be determined using the force and torque balance [1]. A general equation describing the pressure changes over the zone length has the form:

$$p_2 = p_1 \exp(k \cdot z) \tag{2}$$

where: k — constant [1], z — length of one computational step in z-direction.

The initial pressure p_0 in the feed port region can be calculated according to the simple formula proposed in [32]:

$$p_0 = d_0\, g\, D \tag{3}$$

where: d_0 — bulk density, g — gravitational acceleration, D — outer screw diameter.

For a given pressure profile it is possible to determine the power demand in the solid conveying zone as the sum of power dissipated at the barrel, screw root and screw flights and the power used to increase the pressure in the solid bed.

The transient zone in the model starts at a point, where melt layer appears at the solid bed surface. We adopted, that it is the place of the screw channel, that at a given moment of time corresponds with the beginning of the barrel heating zone. The end of the transient zone in screw channel corresponds with that point, where the melt film thickness reached a critical value δ_w [2]. In contrast to the solids conveying zone, the total length of the transient zone is variable and it depends on the process conditions. According to [2] it was assumed that the melt film thickness changes linearly between 0 and δ_w over the zone length. These changes depend on the rate of dynamic melting, that can be calculated from [2], assuming additionally the axial screw velocity U.

The calculations of the pressure changes in the transient zone base on the assumption that the pressure gradient in this zone can be determined as a weighted average of the pressure gradient at the end of the solid conveying zone and the pressure gradient at the beginning of the melting zone:

$$\left(\frac{\partial p}{\partial z}\right)_t = \left(\frac{\partial p}{\partial z}\right)_s (1-x) + \left(\frac{\partial p}{\partial z}\right)_m x \tag{4}$$

where: subscripts t, s and m — transient, solid conveying and melting zone, respectively, x — weight, changing on the length of the transient zone from 0 to 1.

This semiempirical approach, that provides a smooth pressure profile at the zone boundaries was introduced, because there is no exact method of pressure calculation in the case, if the flow is determined by both dry and viscous friction.

The melting process during injection molding is more complicated in comparison with extrusion, mainly due to the existence of the static melting phase (for stationary screw). Moreover, the phase of dynamic melting is additionally connected with the axial screw motion. Both phases are coupled. The final conditions for one of them are the initial conditions for the other.

Static melting begins after the stop of rotational screw motion. Solid polymer is molten in the certain time interval (approximately equal to cooling time), and then the screw is shifted forwards of the distance of screw stroke and in this position polymer is molten in the time approximately equal to hold time. According to the known theories of static melting [30—32] it was assumed that the time dependent melt film thickness δ_t coming from the solid polymer (of the mean temperature T_s) molten in contact with the hot barrel surface is given by the equation:

$$\delta_t = \delta_0 + k\sqrt{t} \tag{5}$$

where: δ_0 — the initial thickness of the melt, k — the root of the algebraic, non-linear, complex equation [31].

Assuming that the state after dynamic melting A_0 is the initial state for the phase of static melting, the solid bed profile after static melting can be determined as follows:

$$A = A_0 \frac{H - \delta_t}{H - \delta_0} \tag{6}$$

where: A — ratio of the cross-sectional area of the channel occupied by solid bed to the total cross-sectional area of the channel (after the melting process), A_0 — initial value of A (before the melting process).

Dynamic melting starts in the moment of the screw rotation beginning. The calculation of the solid bed profile after the screw rotation period was done based on the theory of dynamic extrusion [31]. The basic equation, that describes the differential mass balance in solid bed under unsteady conditions, can be presented in the following way:

$$\frac{\partial A}{\partial t} + \frac{\partial A}{\partial z} = -\frac{\Phi}{V_{sz} d_S \sqrt{H}} \sqrt{\frac{A}{H(z)}} \tag{7}$$

where: Φ — auxiliary variable associated with the rate of dynamic melting [2, 48], $H(z)$ — relative height of screw channel.

Expression (7) is a non-linear partial differential equation of first order, that describes the evolution of relative cross-section area of solid bed in time and space during the screw rotation. The equation (7) was solved analytically for the purposes of the model with the assumption of 3-zones screw.

Equilibrium values of A after static and dynamic melting can be calculated using the method of iteration. As the first approximation of A, the steady-state profile can be assumed (theoretically any profile could be taken into account). Hence, the approximated A profile after static melting can be determined. It is the initial value for the new profile of solid bed A calculated for dynamic melting. The iteration is repeated until A profiles (after static and dynamic melting) are established.

If the solid bed profiles are known, the pressure and temperature profiles in screw channel can be calculated. Knowing of these profiles makes possible to calculate other quantities, *e.g.*, power requirement, screw torque and energy consumption, that are important for the detailed characterization of plasticization process. All quantities were calculated for the A profile after dynamic melting, that is characterized by maximal filling of the screw channel with solid polymer.

For the pressure calculation we have assumed that the pressure is stabilized fast enough, and for its calculations the same methods can be used as for the steady-state conditions. Pressure was calculated according to the own method based on the results of analysis of the two-directional, non-isothermal flow of Ellis fluid in rectangular channel [49].

In contrast to the pressure profile, the temperature profile is the result of thermal processes during the whole screw rotation phase. For this reason the methods, that are valid for the steady-state conditions, cannot be applied for calculation of the temperature profile. In this case, the temperature profile was determined by an approximated method described in [32], that was adapted to the model requirements.

The averaging equation of energy for the melt region is represented by the expression:

$$d_m c_m \frac{\partial T}{\partial t} = k_m \overline{\frac{\partial^2 T}{\partial y^2}} + \overline{\left(\tau_{xy} \frac{\partial v_x}{\partial y} + \tau_{zy} \frac{\partial v_z}{\partial y} \right)} - \\ - d_m c_m V_{mz} \frac{\partial T}{\partial z} - d_m c_m V_{im} (T - T_b) \tag{8}$$

where: d_m — density of molten polymer, c_m — specific heat capacity of polymer melt, V_{im} — the mean inflow rate of melt from the melting layer, V_{mz} — mean flow rate of the melt along the screw channel.

The respective terms in equation (8) represent the following quantities: heat accumulation rate, heat conduction rate, rate of heat generation by viscous friction, heat convection rate and rate of heat input from the melt film. The mean values of terms describing the energy conduction and dissipation can be calculated in similar way as presented in [51] for the steady-state extrusion. Assuming the constant barrel temperature and neutral screw, after several transformations equation (8) takes the following dimensionless form:

$$\frac{\partial \theta}{\partial \tau} + \frac{\partial \theta}{\partial l} = -B(l, \tau)\theta + C(l, \tau)\exp(-a\theta) \tag{9}$$

where: θ, τ, l — dimensionless values of T, t and z, respectively; B, C — complex variables [41], a — temperature coefficient.

Equation (9) is a nonlinear, partial differential equation. It was solved numerically (by the similar method presented in [51]).

One of the most fundamental questions in the model is determination of the screw retraction velocity U and the pressure profile, where the last value is equal to the known back pressure at the screw end. Both quantities are strictly coupled, and their determination closes the computation cycle. It makes possible the calculation of the most important final process characteristics, such as plastication rate, power requirement, screw torque, mean melt temperature and energy consumption. The choice of the proper backward velocity U for a given back pressure was done with the iteration method using a special control algorithm. It increases or decreases the U value depending on the calculated pressure on the screw end and the assumed back pressure, until both pressures become equal with a desired accuracy.

In summary, some earlier formulated concepts of the modeling of dynamics in plasticating injection molding systems for the developing model have been taken into account. The main of them is the coupling between the dynamic melting (rotating screw) and static melting (non-rotating screw) [16, 30—32]. Due to a partial similarity between extrusion and reciprocating extrusion some solutions from existing extrusion models have also been applied. The most important of them are the pressure calculation and solid conveying (generalized for backward screw motion) [2, 48]. However, many other issues are the original solutions, such as: the generalization of the static and dynamic melting process for the three-zone screw, description of reciprocating screw motion with adjustable stroke, description of two-dimensional, non-isothermal and non-Newtonian (power-law) melt flow in the channel, solution for time dependent (transient) mass balance during dynamic melting and description of instant melt temperature changes [42, 43, 49, 50].

The simulation model of polymer plastication in injection molding uses four groups of input data, *i.e.*,: geometric parameters of the three-zone screw and the barrel (*e.g.*, lengths of feed, compression and metering sections, screw pitch and diameter, channel depths in feed and metering sections, radial clearance, flight width, *etc.*), adjustable operating parameters of the injection molding machine (*e.g.*, screw rotation velocity, downtime of the screw in front and back position, barrel temperature, back pressure, injection stroke, *etc.*), material data (density, heat capacity, thermal conductivity of solid and melt, melting temperature, heat of fusion, power law constants, *etc.*) and numerical data (rate and accuracy of calculations). Dependent on above input data, the following characteristics of the plastication process can be determined: relative solid bed width, pressure and temperature profiles along the screw, torque and rotation time of the screw, power requirement, throughput, *etc*.

For evaluation of prediction accuracy and possible improvements, the simulation model requires a full experimental verification based on the comparison of its output characteristics mentioned above with the experimental characteristics of a real plasticating unit. For this purpose, the measuring system as special equipment of the conventional injection molding machine was designed and built.

EXPERIMENTAL PART

The test stand for measurements of output parameters of the plastication process during injection molding consists of suitably instrumented injection molding machine linked to the collecting and processing data module and the computer for imaging and saving of collected data. The test stand shown in Fig. 1 consists of:

— injection molding machine Battenfeld Plus 350/70;

— four pressure/temperature sensors [analog CDTAI200-1/2-1500-1-1-1J (Bagsik Sp. z o.o.), range 0—150 MPa, 0—300 °C, OE: ± 0.5 % FS];

— torque — measuring coupling [analog sensor DMF2X-250 (MEGATRON Elektronik GmbH & co. KG), range 0—250 Nm, OE: ± 1 % FS];

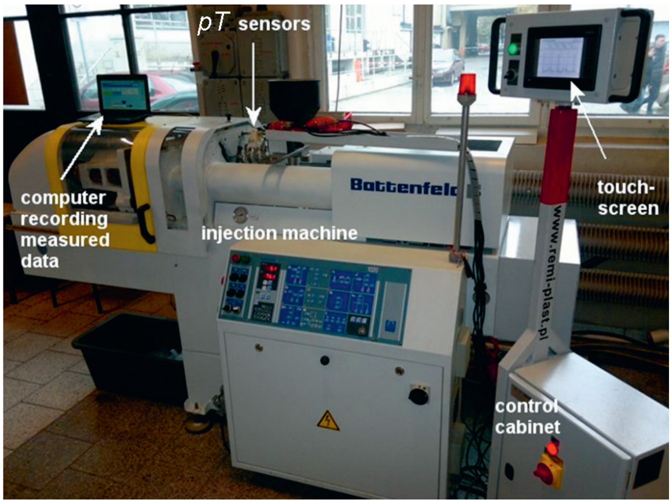

Fig. 1. The test stand of plastication process in injection molding

T a b l e 1. Characteristics of the screw and injection molding machine

Screw diameter, mm	25
Relative screw length (*L/D*)	17
Length of feed/melting/metering zone, turns	14 / 4 / 4
Channel depth in feed/metering zone, mm	4.1 / 1.9
Screw pitch, mm	19
Flight width, mm	3.7
Max. clamping force, kN	350
Max. injection volume (PS), cm^3	49
Max. injection pressure, MPa	157.5

T a b l e 2. Material data for polyethylenes

Property	PE-LD	PE-HD
Melt flow rate[b] (*MFR*), g/10 min	2.2	8
Bulk density[a], kg/m^3	598	596
Coefficient of dry friction[c] (polymer-barrel)	0.4	0.4
Coefficient of dry friction[c] (polymer-screw)	0.3	0.3
Density of solid[b], kg/m^3	920	960
Specific heat of solid[a], J/(kg · K)	1.96	1.82
Thermal conductivity of solid[c], J/(m · s · K)	0.32	0.43
Melting temperature[a], °C	114	137
Melting enthalpy[a], kJ/kg	113	202
Density of melt[a], kg/m^3	757	755
Specific heat of melt[a], J/(kg · K)	2.12	2.45
Thermal conductivity of melt[c], J/(m · s · K)	0.23	0.42

[a] Self-experimentally determined; [b] data from TDS; [c] averaged data from various literature sources.

— inductive sensor for screw rotation velocity measurements (induction detector E2A-S08KS02-WP-B1, Omron Corp.);

— screw linear displacement sensor (analog sensor LWH 0150 (Novotechnik U.S. Inc.), range 0—150 mm, LE: ± 0.08 %);

— control cabinet with touch screen.

Table 1 shows the main features of the injection molding machine used in the study. Measurements were made with two polyethylenes (PE-LD and PE-HD) characterized in Table 2. Adjustable (variable) parameters of the process were the following:

— back pressure (changed in range 4—24 MPa),

— screw velocity (changed in range of 30—70 % of the maximal screw velocity),

— dwell time (changed in range of 8—50 s).

Table 3 shows the values of adjustable parameters used in experiments.

Studies on the plastication process in injection molding were carried out by changing on given levels only one of the parameters listed in Table 3, and keeping constant the values of other parameters. They were always equal to the median (the third) value in Table 3. Back pressure, screw velocity and dwell time were the same for both polymers. The symbols of *T*1—*T*5 were introduced due to different median barrel temperatures of both polymers. During experiments all three heating zones of the barrel were kept at the same (constant) temperature. Constant process parameters are shown in Table 4.

T a b l e 3. Adjustable parameters of injection molding process

	Back pressure, MPa				
PE-LD PE-HD	3.5	6.5	10	16	24
	Screw rotation velocity, rpm				
	154	200	240	286	333
	Dwell time, s				
	8	12	20	30	50
	Barrel temperature, °C				
	*T*1	*T*2	*T*3	*T*4	*T*5
	140	160	180	200	220
	150	170	190	210	230

T a b l e 4. Constant parameters of injection molding process

Parameter	PE-LD	PE-HD
Injection pressure, MPa	70	80
Hold pressure stage I / II, MPa	40 / 32	42 / 34
Hold time stage I / II, s	2 / 2	2 / 2
Mold temperature, °C	35	35

There were 16 holes made in the barrel for *pT* sensors. The locations of these holes are shown in Fig. 2a. Four sensors, numbered from 1 to 4 in positions 4, 8, 12 and 16, respectively were placed in the barrel, as shown schematically in Fig. 2b. The location of sensors in these positions

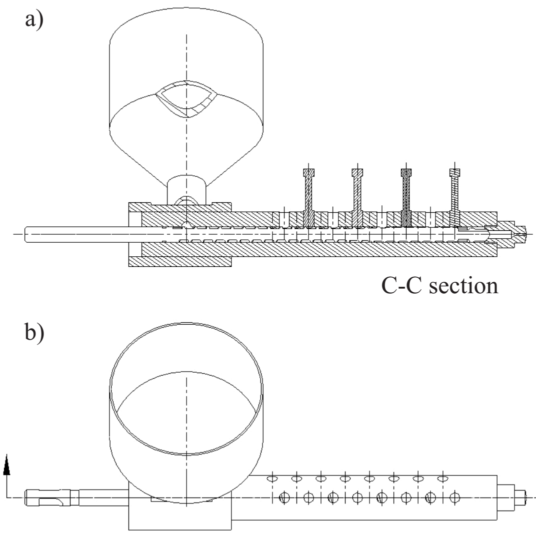

Fig. 2. The arrangement of: a) the holes in the barrel for *pT* sensors, b) view of four *pT* sensors location in the barrel

makes possible the pressure and temperature measurements over the maximal barrel length. In the maximal front position of the screw, the sensors 1—4 are located over the 10, 14, 18 and 22th screw turn, respectively. During the screw rotation phase, the screw moves back by constant value of the screw stroke, which is equal to 2.5 turns.

Explanation of selected phrases occurring later in this paper: back pressure — pressure on the head of the screw encountered during its rotation, dwell time — downtime of the screw in the rear position, counted from the end of the rotation of the screw to the start of the injection stage, recovery time — the time the rotation of the screw.

EXPERIMENTAL RESULTS

In order to compare the results generated by the model with the characteristics of a real injection molding machine, four test series of experiments were carried out:

— test at variable back pressure,

— test at variable screw rotation velocity,

— test at variable dwell time,

— test at variable (average) barrel temperature.

The comparison of the model characteristics of the plastication process with measured characteristics of the real injection molding machine for PE-LD and PE-HD is discussed below. The tests, which are not discussed in details, were also carried out for PP and POM. Hence, brief references to these studies are also included if necessary, and for generalization, some results for PP and POM were also taken into account.

Because of periodical (*i.e.*, unsteady) process character, the results refer to the moment just before the end of screw rotation. This moment corresponds to the maximum filling degree of the screw channel with solid polymer, and it is critical from the point of view of the main plastication characteristics. It is of fundamental importance for such quantities as the pressure and temperature profiles along the screw length, the power demand by the screw, the screw torque, *etc*.

Pressure and temperature profiles for variable input parameters, *i.e.*, back pressure, screw rotation velocity, dwell time and barrel temperature are presented mainly for two extreme values of these parameters. The results for intermediate values of the input parameters are not shown to keep the readability of pictures. For these values, the obtained characteristics have commonly changed linearly with respect to the characteristics for extreme values.

In order to standardize the charts, the results for PE-HD are represented by solid lines, and for the PE-LD by dashed lines. The characteristics obtained from the model are shown as thick lines without markers, while the experimental profiles represent thin lines with markers indicating the measurement points.

The first part of the study involved the effect of variable back pressure. Figure 3 shows the comparison of the pressure and temperature profiles along the screw length for PE-LD and PE-HD, which were determined experimentally and generated by the model for back pressure equal to 3.5 and 16 MPa, respectively.

The comparison of the pressure profiles shows a very good agreement between model predictions and experimental characteristics for PE-HD (MFR = 8), while in the case of PE-LD (MFR = 2), the model overestimates the pressure value by *ca.* 30 % (in pressure maximum) regardless of the back pressure value.

In general, the differences in simulated and measured pressure profiles seem to be dependent on polymer flowability (MFR). For other polymers mentioned above, the results are also different, *e.g.*, for PP (MFR = 23) which is characterized by very high flowability, the model underestimate the pressure profile. For POM (MFR = 10) the model predicts correct pressures along the screw length (as for PE-HD). The strong sensitivity of model predictions to rheological properties of the melt may result from different reasons. One of them results from the fact that a real injection screw works partially in a starve-fed regime, because at the initial stage of screw rotation the polymer from hopper is inserted into an empty screw channel of the length equal to the injection stroke. It may somewhat change the melting mechanism from contiguous (CSM) to dispersed (DMS) one. Moreover, the solid polymer in the feed zone may not be fully compacted (its density corresponds probably to the maximum packing fraction of a granular material), which may results in a faster solid bed break up and creation of solid polymer suspension in its own melt. Such behavior, which can change the true flowability of melted polymer, is at least partially

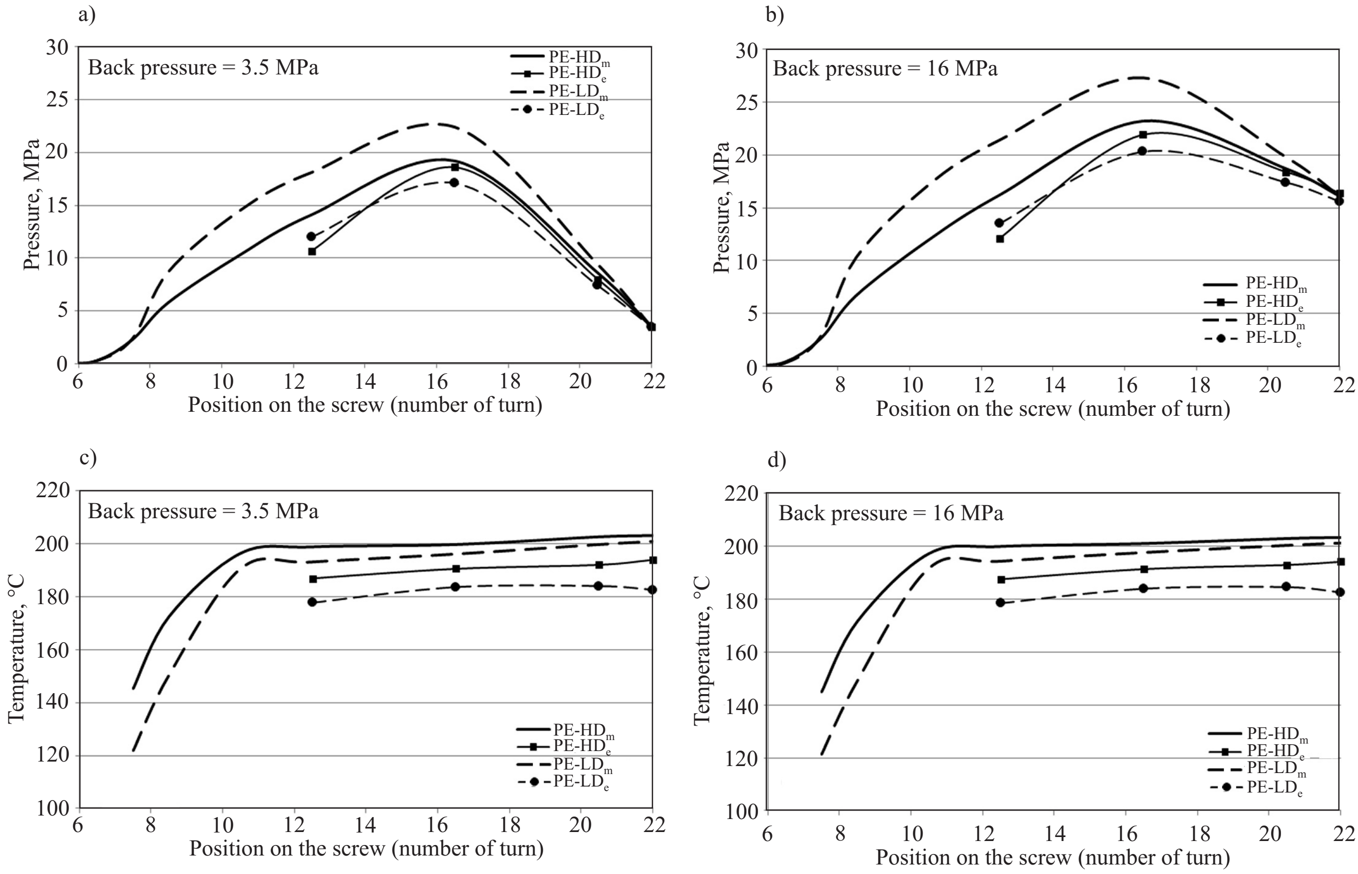

Fig. 3. a, b) The pressure profiles; c, d) temperature profiles of plastication process for PE-LD and PE-HD at different back pressures; subscript designation: m — data from model, e — data from experiment

confirmed by observations presented in refs. [39, 40]. It should be noted that the simulation model is based on the power law equation of viscosity, and the real power law constants of such „suspension" may be quite different from those measured directly on melt. This issue will be the subject of further analysis in order to improve the agreement of model predictions with experimental pressure profile.

Analyzing the temperature profiles in the screw channel it should be noted that the model assumes a constant barrel temperature that was also assumed in experiments. It can be seen that the calculated temperature in screw channel overestimates as a rule the measured values in the barrel. For PE-HD, the overestimation is around 10 °C, and for PE-LD it is slightly larger, *ca*. 15 °C. The differences in temperature profiles for other polymers are of the order 8—10 °C (POM), and for PP there is a good agreement of model values with the measured ones. The differences are of 2—3 °C, regardless of the value of the back pressure.

It can be seen that both the differences in temperature profiles and the differences in pressure profiles are also dependent on the polymer viscosity. These differences become larger, the higher is the polymer viscosity (lower flowability). The reasons of such behavior are probably similar as for pressure. It is noteworthy, that there is only a relative small increase in melt temperature over the barrel temperature observed in measurements. Regardless of the polymer and process parameters, this increase is always 2—6 °C. However, it is very important to note that the measured temperature of the polymer refers probably to the temperature of the molten polymer layer at the barrel, where the *pT* sensor is mounted, while the simulation program generates an average temperature in the cross-section of the screw channel. This can be a source of discrepancies especially at low flowability, when viscous friction increases.

Figure 4 shows the comparison of other characteristics of plastication process in injection molding at variable back pressure. A good agreement of theoretical and experimental profiles for PE-LD can be seen and the quantitative differences do not exceed 20 %. For PE-HD these differences are larger almost twice mainly for torque. In general, a good prediction of the process dynamics the model at variable back pressure can be seen. It is reflected by similar shapes of both curves. The model determines somewhat too small screw torque and screw rotation time and slightly overestimates the output.

Pressure and temperature profiles for different screw rotation velocities are shown in Fig. 5. The charts are similar to those of Fig. 3. The model predicts well the pressure values for PE-HD especially at lower screw velocities, and at higher velocities *ca*. 10 % overestimation of pressure at its maximum can be seen. In the case of PE-LD, the pressure overestimation by the model is slightly larger and *ca*. 40 % for large screw velocities.

Analyzing the temperature profiles in Fig. 5 it can be seen, similar as in Fig. 3, a better agreement of tempera-

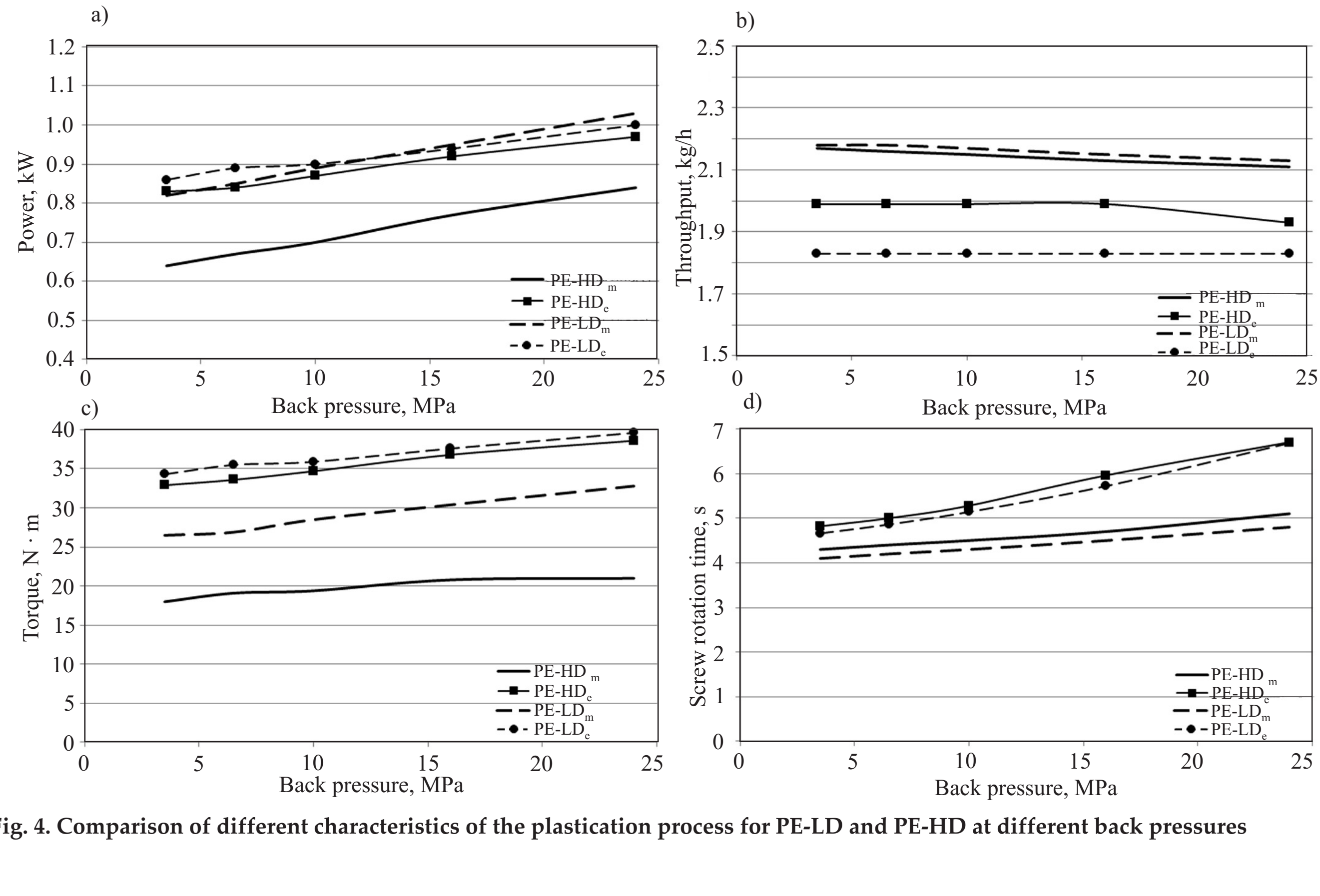

Fig. 4. Comparison of different characteristics of the plastication process for PE-LD and PE-HD at different back pressures

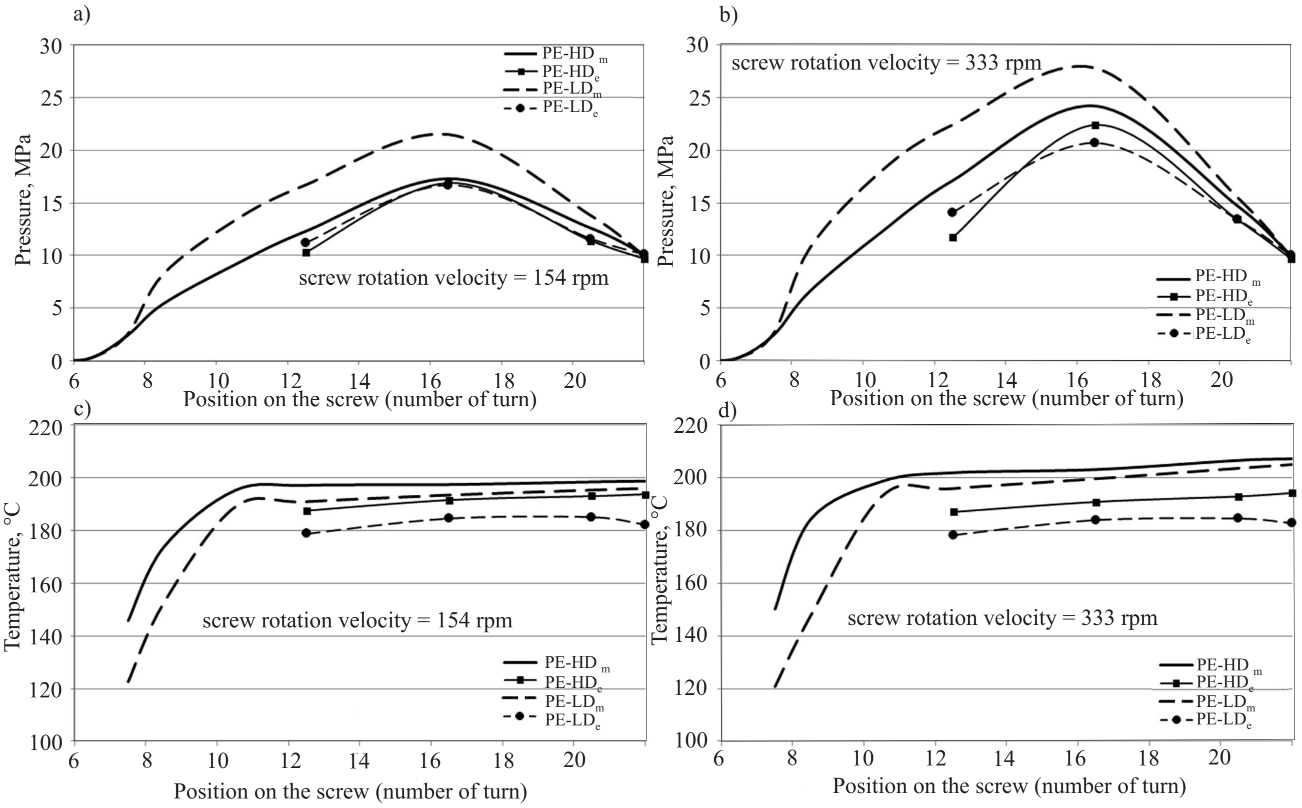

Fig. 5. The pressure profiles (top) and temperature profiles (bottom) of plastication process for PE-LD and PE-HD at different screw rotation velocities

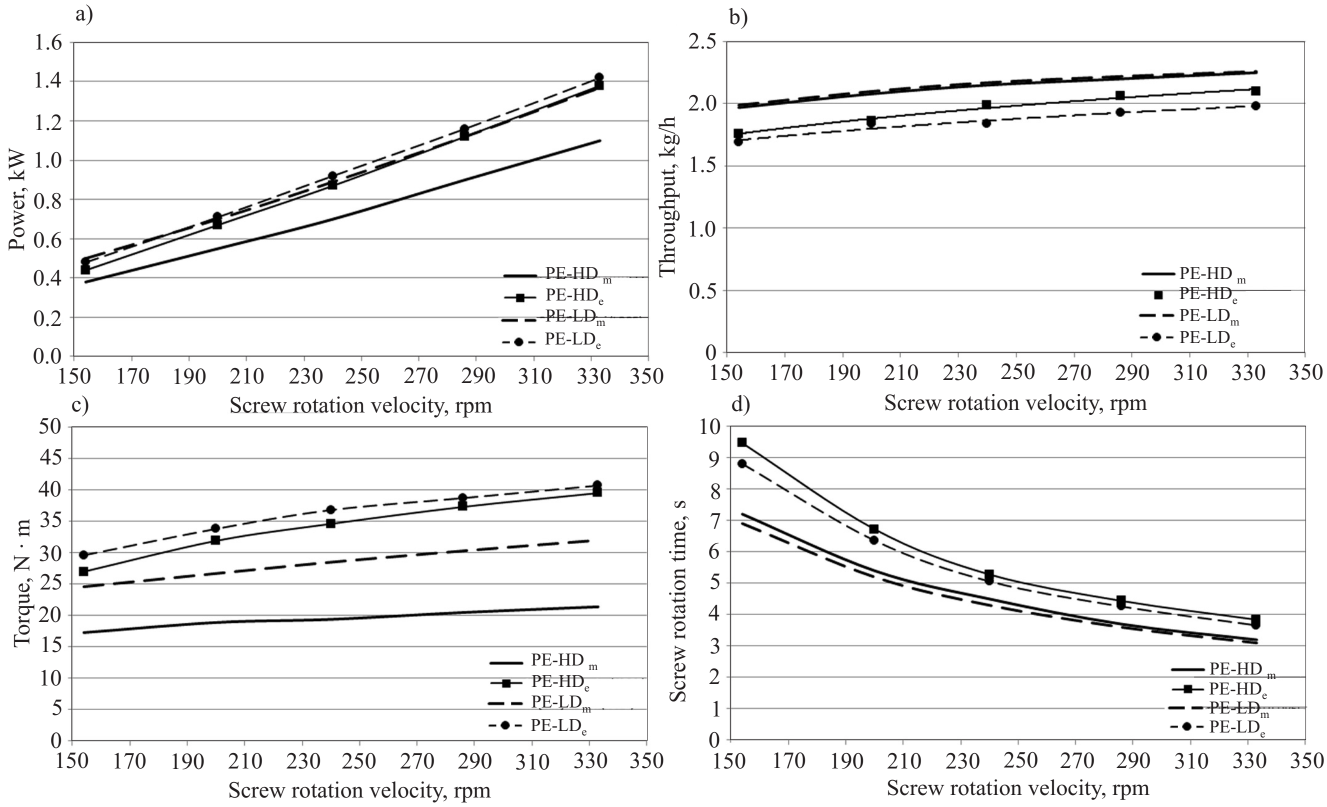

Fig. 6. Comparison of different characteristics of plastication process for PE-LD and PE-HD at different screw rotation velocities

ture values for PE-HD than for PE-LD. Temperature differences are smaller for lower screw velocities, while for higher velocities these differences rise, and reach for PE-HD the values of *ca*. 10 °C and for PE-LD *ca*. 18 °C.

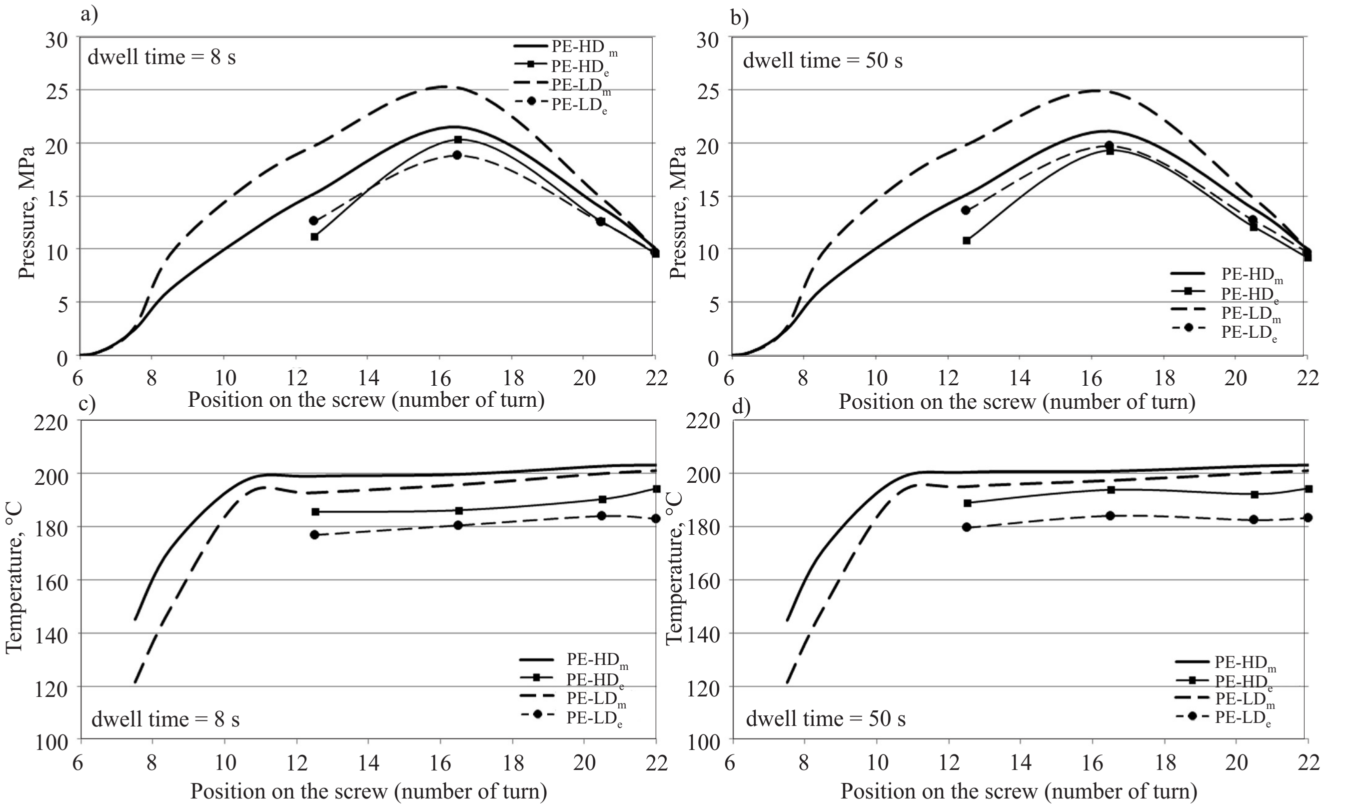

Fig. 7. The pressure profiles (top) and temperature profiles (bottom) of the plastication process for PE-LD and PE-HD at different dwell time

Experimentally determined temperature profiles are almost constant for both screw velocities applied. It means that the model somewhat overestimates the amount of heat generated by viscous friction. Similar behavior can be observed also in the case of other polymers studied, *i.e.*, PS, POM and PP. Melt temperature over the length of the screw channel in the same places is practically independent of the screw rotation velocity and the back pressure as shown in Fig. 3. However, it should be reminded that the temperature measured by the sensor is the temperature of wall-layer of molten polymer, while the calculated temperature is the average temperature of the melt in a cross-section of the channel. According to various sources [32, 49], the temperature of melt in cross-section of the channel for different places of this cross-section may differ by 15—20 °C.

The comparison of other characteristics of PE-HD and PE-LD plastication process at different screw rotation velocities is shown in Fig. 6. A good agreement of experimental and model profiles with differences below 20 % can be seen. Only the torque for PE-HD is determined by the model with larger error reaching 50 %. The model underestimates the screw torque, the power demand by the screw and the screw rotation time, similar as in the case of variable back pressure.

Figures 7 and 8 show the characteristics of the plastication process of both polymers at variable dwell time. It can be seen that the dwell time affects in a very small extent the changes in these characteristics. The model is almost insensitive to dwell time changes. Differences in experimental and theoretical profiles do not exceed 20 %, with the exception of torque for PE-HD, where differences are *ca*. 40 %.

The only characteristics that change with dwell time variations are the throughput and the melt temperature. The throughput clearly decreases with increasing dwell time as a result of increasing the injection cycle time. The study of polymer temperature for shorter dwell times indicates the fact of fast imposition of cooler polymer portions from the initial part of the barrel. The slightly lower temperature of the molten polymer than the barrel temperature can be observed for almost entire length of the barrel. The model does not predict such behavior, assuming that the minimal temperature of the melt layer is equal to the barrel temperature. This problem requires adjustments in the model.

Figures 9 and 10 show the comparison of the characteristics of plastication process for PE-HD and PE-LD at variable barrel temperatures shown in Table 3.

Figure 9 shows that for lower barrel temperatures, the model overestimates significantly the pressure values, while for higher temperatures ($T3$ and $T4$), there is a good similarity in theoretical and experimental profiles. It is worth noting that in a given point of the screw, the experimental pressure value is almost constant, regardless of the barrel temperature. The model is too sensitive to the barrel temperature, and it predicts significant rise of the melt pressure with decreasing barrel temperature, which

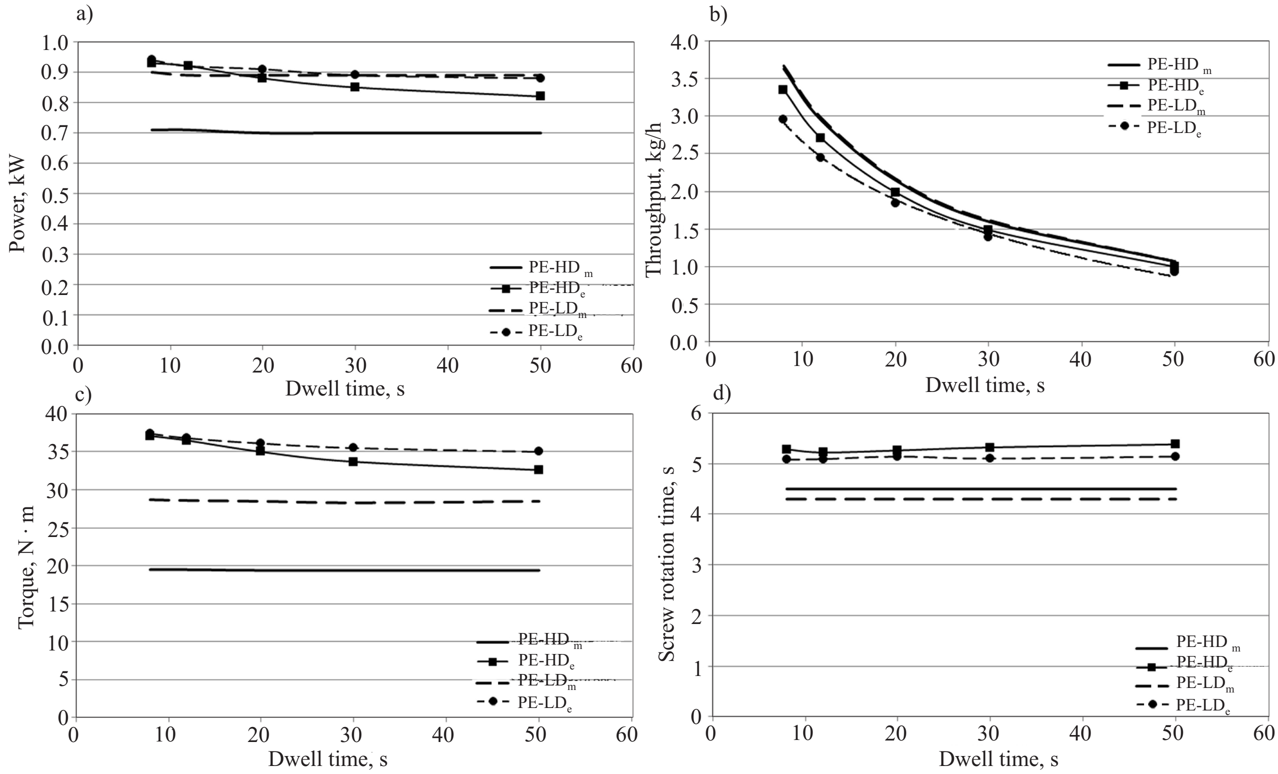

Fig. 8. Comparison of different characteristics of the plastication process for PE-LD and PE-HD at different dwell time

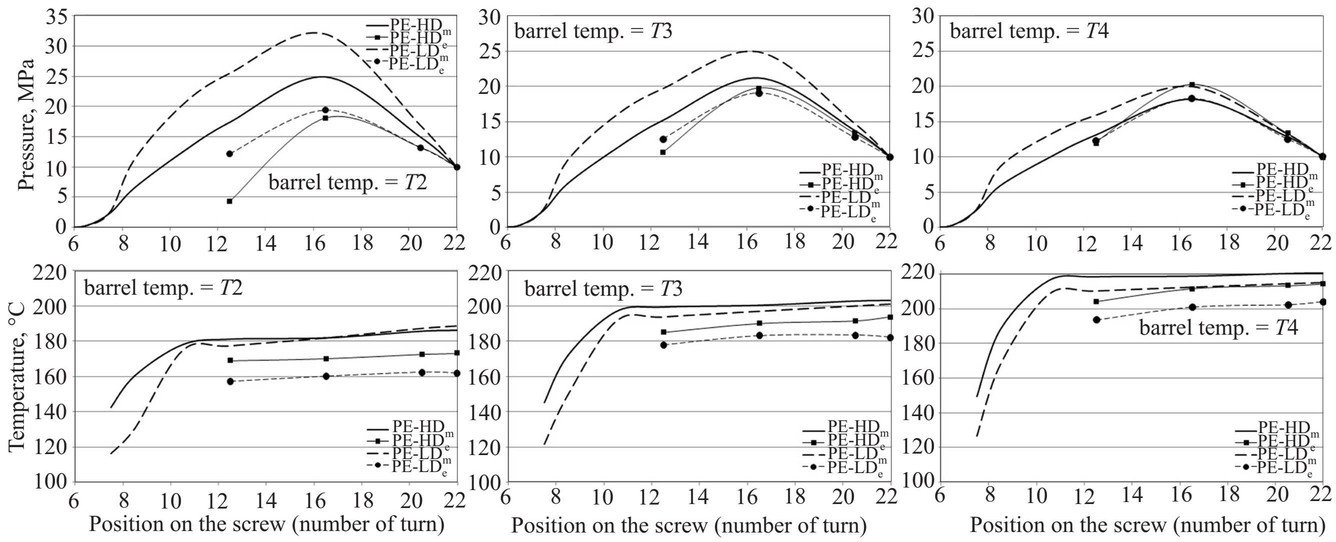

Fig. 9. The pressure profiles (top) and temperature profiles (bottom) of the plastication process for PE-LD and PE-HD at different barrel temperatures

is not observed in practice. This issue will be the subject of analysis in order to make changes in the model, to improve the agreement of theoretical and experimental pressure characteristics.

Similar differences are observed in the temperature profiles of the polymer melt. For barrel temperature *T*2, temperature differences between experimental values and model predictions are *ca*. 10 °C for PE-HD and 20 °C for PE-LD. For barrel temperature *T*4, these differences are half smaller. The probable reason for such behavior is the increasing effect of higher melt viscosity at lower barrel temperature on the heat generated by viscous friction. In fact, there are no observed effects of increased polymer viscosity on the melt temperature rise. Regardless the value of the barrel temperature, the melt temperature on the sensor 1 is slightly lower, on the sensor 2 is almost equal, and on the sensors 3 and 4 — slightly higher of about 2 to 4 °C than the temperature of the barrel.

Analyzing the other characteristics of the plastication process, it can be stated that an increase in the barrel temperature leads to a small decrease in the power demand by screw and the torque on the screw. It is accompanied

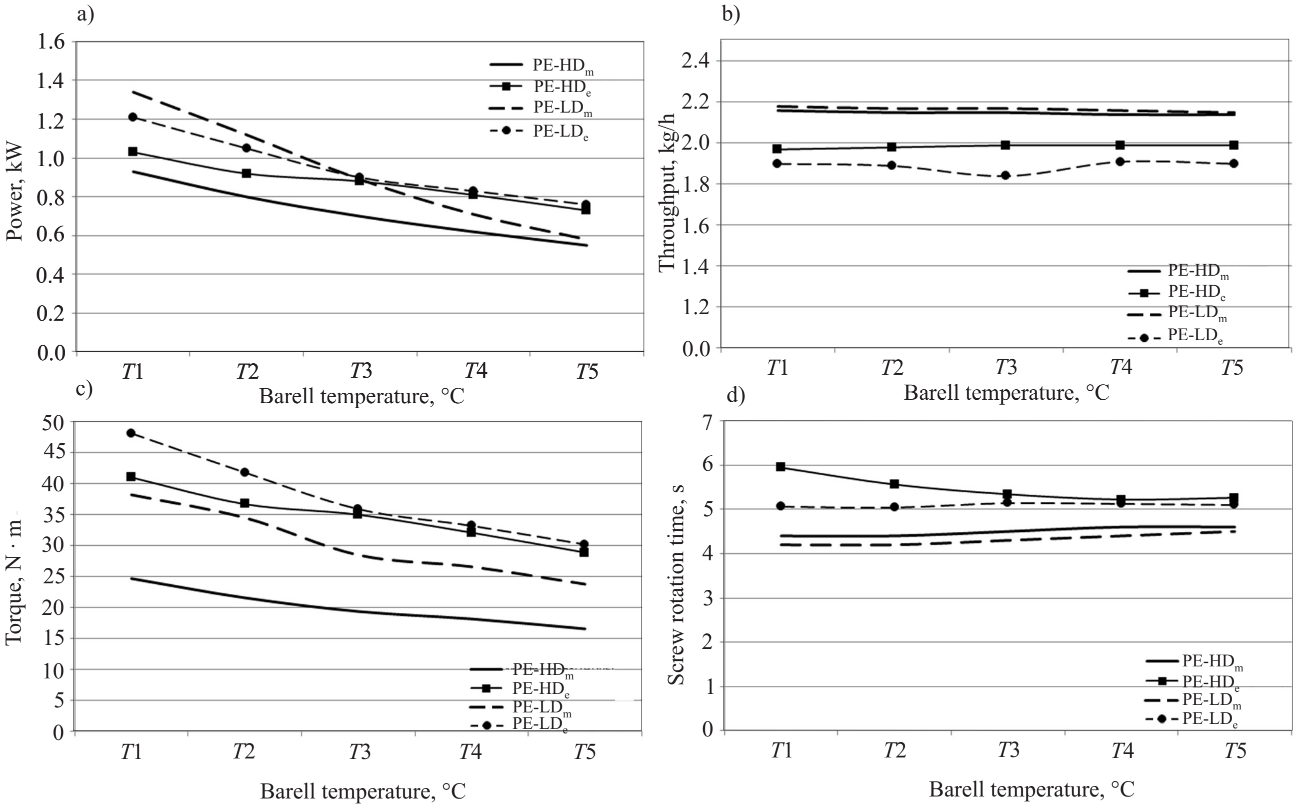

Fig. 10. Comparison of various characteristics of the plastication process for PE-LD and PE-HD at different barrel temperatures

by slight changes of the throughput and the screw rotation time. The model well estimates these characteristics and quantitative changes do not exceed 20 %. The only exception is, as in the previous cases, the torque for PE-HD. Quantitative differences in this case are *ca*. 40 %.

Very important parameter in studies of the plasticizing system of injection molding is solid bed profile (SBP), which determines the amount of non-plasticized material in the cross-section of the screw channel. We had also attempt to determine the SBP by Screw Pulling-out Technique. This technique allows relatively easy removal of the screw of the extruder. However, studies have shown that there is very difficult to pull out the screw of the injection molding with using this technique. The presence of the injection nozzle and the structural elements of the clamping unit caused the time to pull out the injection screw was too long. The minimum time to pull out the screw, obtained in the studies was 3 minutes. Such a long time caused that the polymer present in the screw was completely plasticized. Because the measurement of SBP is very important in the comprehensive assessment of plasticization in injection molding process, it was decided to perform in the cylinder glass windows, as described in [39, 40]. This work is currently in progress.

CONCLUSIONS

The paper deals with the plastication of PE-HD and PE-LD during injection molding with variable back pressure, screw rotation velocity, dwell time and barrel temperature. The values of the experimental process characteristics with characteristics generated by the simulation model were compared. It was found that the model correctly determines the dynamics of plastication process under the changes of the input parameters. The average quantitative differences between measured and simulated characteristics do not exceed 20 %.

Computer model requires some changes to improve agreement of some characteristics generated by the model with real characteristics of plastication process in injection molding. The presented data suggest that the appropriate rheological characterization of polymers plays very important role for determination of the heat generation intensity, especially in thin layers under large filling of the screw channel with solid polymer. An important role can also play a (transient) heat transfer character at the contact boundaries polymer melt with screw, barrel and solid material, because typical injection screw rotates much faster than a screw in the extruders. It is known, that an increase in the process intensity usually results in a change of process character from more isothermal to more adiabatic. The study has also allowed to determine several other potential sources of differences of theoretical and experimental data. This study will allow the introduction of improvements in the existing simulation model.

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