EXPERIMENTAL STUDY ON ENERGY CONSUMPTION IN THE PLASTICIZING UNIT OF THE INJECTION MOLDING MACHINE

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Abstract: *Injection moulding is a widespread method of polymer processing. The annual, global energy consumption for injection moulding is comparable to the annual energy production of different European countries. The most energy-consuming stage of the injection moulding is the plasticization process, which needs the energy mainly for the rotational and reciprocating screw motion as well as the heating of the barrel. Both issues were examined by changing various parameters of the injection moulding process, measuring the process characteristics and calculating the corresponding values of SEC (specific energy consumption). Various thermoplastic polymers were examined. It was found that the optimal conditions from the energy consumption point of view is low value of rotational velocity of the screw. Changes of back pressure do not affect the energy consumption of the plasticizing system of the injection moulding machine. Furthermore, an increase of the SEC value with increasing barrel temperature was shown. It was ca. 15% for the average barrel temperature rise of 20°C.*

Keywords: INJECTION MOLDING, PLASTICIZATION, POWER DEMAND, ENERGY CONSUMPTION, SEC

1. Introduction

Energy consumption is one of the most important parameters associated with the analysis of technological processes. Energy efficiency of technological processes is one of the critical issues for the manufacturing industry, mainly due to increasing cost of energy and the impact on the environment. Reducing energy consumption is therefore relevant not only for the economic benefits to producers, but also because of the improving of environmental performance of the products manufacture [1-7]. This can be done only with precise knowledge of the production process and its energy characteristics, as well as knowledge of effect of processing parameters on energy consumption per mass unit (called SEC - specific energy consumption).

Injection molding of plastic is now one of the most widely used manufacturing processes. With this technique, millions of parts of various types and sizes, ranging from electronic and electrical components, toys, packaging, through elements of automobile and pharmaceutical industry, until precise microdetails for technology or medicine are produced. Injection molding process is often preferred by designers because of the possibility of applying different polymeric materials and very short process time, as well as the repeatability and accuracy of obtained products. Although polymer materials are characterized by substantial value of SEC at their production stage [8] (Fig. 1), the energy consumption of manufacturing processes of polymeric materials per unit volume of product are extremely low in comparison with other processes [9]. This issue indicates that polymers are one of the most energy-saving materials, taking into account the full life cycle of the products.

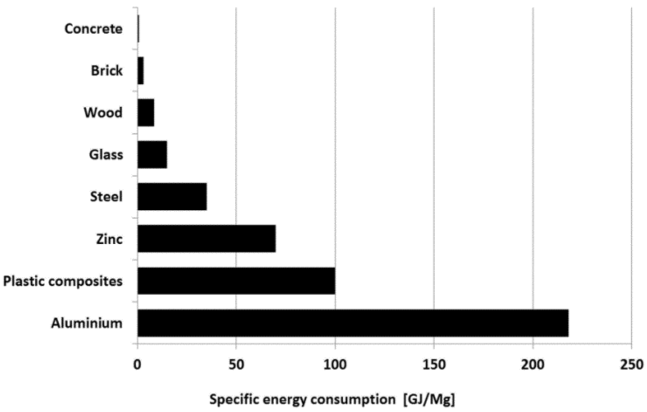

Fig. 1 *Approximate amount of energy needed for production of different materials [8]*

Because the injection molding process is one of the most energy-efficient manufacturing processes (per unit volume of material), it might seem that it should not require greater attention from the energetic point of view. However, this is the misleading approach, mainly due to the extremely frequent use of injection molding process in the world, and hence the massive amount of polymeric materials processed with this technique. In order to illustrate how large is the consumption of energy in the area of injection processing on a global scale, it is worth to present some literature data [5,9-12]. A life cycle inventory (LCI) of injection molding process indicates that the largest energy expenditure is characterized by the first stage of the cycle - the production of the polymeric material. Figure 2 shows the average values of the LCI for injection molding process of a typical large-scale thermoplastics. The value of the LCI for the polymer production stage is also averaged (PE-LD -73 MJ/kg, PE-HD - 89 MJ/kg, PP - 83 MJ/kg, PS - 87 MJ/kg) [9].

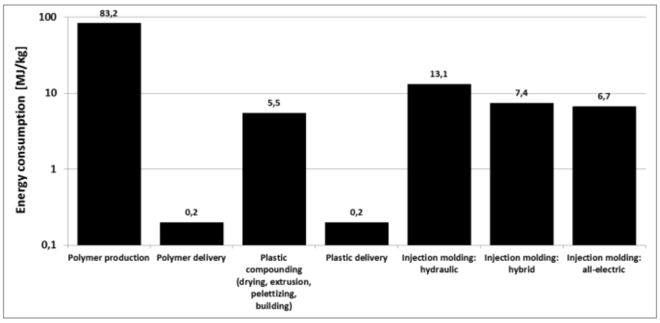

Fig. 2 *Energy consumption in the LCI for injection molding [12]*

Tab. 1 shows the amount of energy consumed annually in the world by injection molding industry (for LCI, without the polymer production stage – see Fig. 2). In accordance with the recommendations [12] it was assumed that 70% of injection molding machines used in the world industrial production are hydraulic, 15% are hybrid and 15% are full-electric machines. Tab. 2 shows the annual energy production in 2011 in selected countries of the world. In the last few years, energy production in those countries remained substantially constant.

Comparing the data in Tab. 1 and Tab. 2 we can see that the annual energy consumption in injection molding industry around the world is comparable to the order of magnitude with the annual production of energy in different countries. The amount of energy of approximately 10^8 GJ per year is significant on a national scale. Therefore, the problem of energy consumption in injection molding process of polymeric materials seems to be very important. Appropriate control of injection process can result in considerable energy savings while maintaining the suitable properties of the product.

Table 1: *Total energy used in injection molding, without material production [12]*

Specification	Global [GJ/yr]
4 thermoplastics (PE,PP,PS,PVC)	4.0E+8
all plastics	6.7E+8

Table 2: *Annual electricity production in 2011 [13]*

country	total electricity net generation [GJ/yr]
U.S.	1,5E+10
Germany	3,0E+09
Italy	1,0E+09
Spain	1,0E+09
Australia	8,6E+08
Turkey	7,9E+08
Ukraine	6,6E+08
Poland	5,5E+08
Sweden	5,3E+08
Norway	4,5E+08
Argentina	4,4E+08
Netherlands	3,8E+08
Czech Republic	2,9E+08
Finland	2,5E+08
Austria	2,2E+08
Romania	2,1E+08
Portugal	1,8E+08

The aim of this work is the analysis of the specific energy consumption (SEC) in injection molding process for five commonly used thermoplastic polymers (PE-LD, PE-HD, PP, PS and POM) at various operating parameters of the injection molding process. The study involved only the plasticizing system of an injection molding machine. It is known that the power demand during the injection molding process is dominated mainly by the plasticizing system, i.e. by a hydraulic motor of the injection molding machine (working during a reciprocating motion of the screw, around 50% of the total power demanded during working of the injection machine) and the heating elements of the barrel (approx. 30% of the total power) [10,11]. More precise analysis of power demand during various stages of injection cycle are presented in [10-12,14]. It follows that a phase of plasticization (rotation and reverse movement of the screw) is the most critical stage of the entire injection cycle from the energy consumption point of view. The effect of the screw rotation stage of injection molding process on the entire average energy consumption is even greater for full-electric injection molding machines than for hydraulic ones [12].

This work concerns study of the impact of most important factors affecting the power demand by the injection molding process. These are power demand by a hydraulic motor (back pressure and rotational speed of the screw) and the heating elements (temperature of the barrel). In the analysis, some less quantifiable factors, such as the energy dissipated in the gear system, have been neglected.

2. Experimental Procedure

In order to estimate the Specific Energy Consumption (SEC) during plasticization phase of the injection molding process, first we have to calculate a power demand by the plasticizing zone of injection machine. Then we can calculate the SEC value as a ratio of the power and the mass rate of plasticization from the formula:

$$SEC = \frac{\bar{P}}{\dot{Q}} \quad \left[\frac{kWh}{kg}\right] \qquad (1)$$

where $\bar{P}$ is the average power demanded by plasticizing system [kW] and $\dot{Q}$ is the mass yield of the injection process [kg/h].

Measurement of power demanded by the plasticizing system was made on a research position, consisting of suitably instrumented injection molding machine linked to a collecting and processing data module and a computer for imaging and saving data. An injection molding machine Battenfeld Plus 350/70 was used. The research position was described in more detail in [15]. Five different thermoplastic polymers used in this study are described in Table 3. The product obtained in this study is shown in Fig. 3.

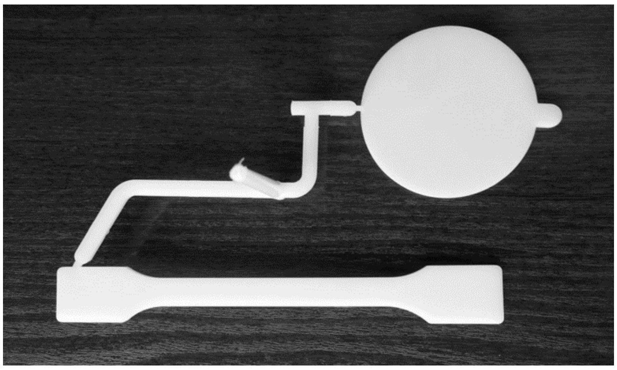

Fig. 3 *The element obtained in the study*

Table 3: *Polymers used in the experiment*

polymer	type	MFR [g/10 min]
PE-LD	Malen E FABS 23D022	2,2 (190/2,16)
PE-HD	Hostalen GC 7260	8,0 (190/2,16)
PP	Moplen HP548R	23 (230/2,16)
PS	Krasten 154	10 (200/5)
POM	Schulaform 9A	10 (190/2,16)

The average power $\bar{P}$ demanded by the plasticizing system has been related to the time of one whole injection cycle. It was assumed that the total, average power $\bar{P}$ is equal to the ratio of an average energy $\overline{Ec}$ consumed by the plasticizing system during one injection cycle, to an average cycle time $\overline{tc}$. The energy $\overline{Ec}$ consumed by the plasticizing system during one injection cycle is the sum of an average energy $\overline{E_h}$ consumed by heating elements placed on the barrel at the average cycle time $\overline{tc}$ ($\overline{E_h} = \overline{P_h} * \overline{tc}$) and an average energy $\overline{E_s}$ consumed by the injection screw during its rotational movement ($\overline{E_s} = \overline{P_s} * \overline{tr}$), where $\overline{tr}$ is an average time of rotation of the screw. So, we can therefore assume:

$$\bar{P} = \frac{\overline{Ec}}{\overline{tc}} = \frac{\overline{P_h} * \overline{tc} + \overline{P_s} * \overline{tr}}{\overline{tc}} \quad [kW] \qquad (2)$$

The power $\overline{P_h}$ demanded by the heating elements was determined by the precise measurement of switch-on time of each heater (all three heaters are powered in discreet way) during the whole time of the experiment. Data of power demand for each heater were collected in 16s-cycles, as it was presented in Fig. 4. Then instantaneous values of power demand Ph for heaters 1-3 were averaged and added together to give the average power demand $\overline{P_h}$.

The average power $\overline{P_s}$ demanded by the screw during the screw rotation time was determined indirectly by measuring the torque (using the device for measurement of torque, mounted directly on a drive system of screw), which was then converted to power by using the known formula:

$$\overline{P_s} = \frac{\bar{M} * v}{9550} \quad [kW] \qquad (3)$$

where $\bar{M}$ – an average value of torque on the screw during screw rotational movement [N*m], v – a rotational speed of the screw [rpm].

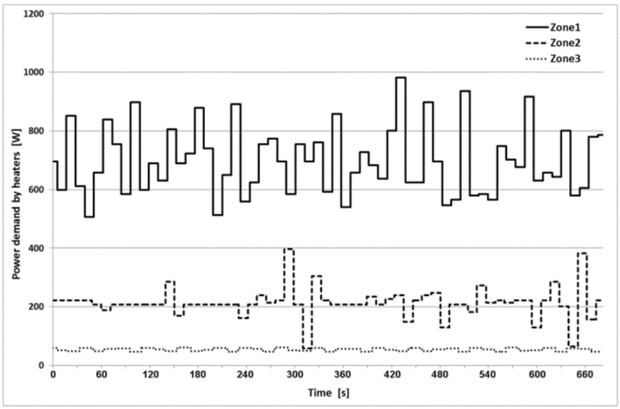

Fig. 4 *Sample graph plotting changes of power demand by the barrel heaters during injection molding of PP*

The average value of torque $\overline{M}$ was calculated as arithmetic averaging of instantaneous values of measured torque M during the screw rotation movement. Measurements of the torque were performed with a frequency of 50 Hz. The above approach to determining of power demand on the hydraulic motor was made, because other methods (e.g. power demand measurement by assessing the hydraulic pump capacity and its rotational speed or measurement of the power demand by the electric motor, which drives the hydraulic motor) introduce additional errors. In this experiment these errors could be avoided.

The studies of the injection molding process were carried out by varying of selected controllable parameters of the plasticization process in a relative wide range, as shown in Table 4. If one parameter was varied, the other parameters were kept constant, with value equal to the middle (third) of five ones listed in Table 4. For example, for changing the back pressure parameter during the injection process of PP polymer, the other parameters had constant values equal vr=240rpm, td=20s and Tb=230°C. Others, invariable parameters of the injection process are presented in [15]. No tests for POM at variable barrel temperature were carried out because of a narrow processing window for this polymer [16]. Moreover, tests for PS at variable screw velocity were also not carried out for technical reasons. The viscosity of melted PS was high and overload of the screw drive system had occurred at higher values of screw velocity.

Table 4: *Values of controllable operating parameters of plasticization process*

	back pressure [MPa]				
PE-LD,PE-HD,PP, POM, PS	4	7	10	16	24
	screw rotation velocity [rpm]				
PE-LD,PE-HD,PP,POM	154	200	240	286	333
	dwell time [s]				
PE-HD,PE-LD,PP,POM,PS	8	12	20	30	50
	barrel temperature [°C]				
PE-LD	140	160	180	200	220
PE-HD	150	170	190	210	230
PP	200	215	230	245	260
PS	-	180	200	220	240

3. Experimental results and discussion

Four series of experiments were performed: the first group of experiments took into account variable back pressure, the second one was for variable screw speed, the third one was for variable dwell time and the last one was for variable barrel temperature. Due to space constraints, the results for the variable rotational speed of the screw and for the variable dwell time only are shown below.

In the first series, the average power demanded by the heaters placed on the barrel and the average power demanded by the rotating screw for variable back pressure during plasticization of different thermoplastic polymers were determined. Obtained results, along with the throughput of the injection molding process, are shown in Fig. 5-8. The SEC values for the injection process of different polymers, defined accordingly to the formula (1), are shown in Fig. 9.

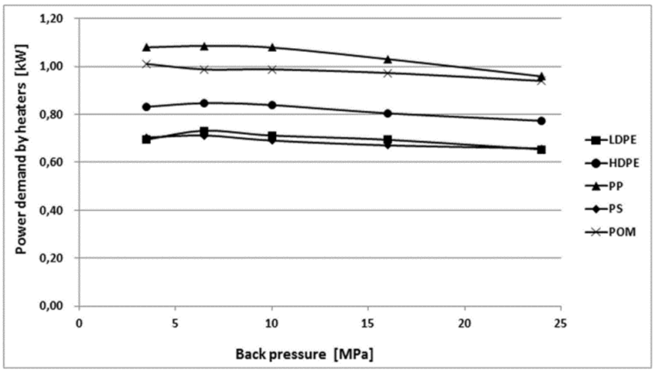

Fig. 5 *Power demand by heaters at variable back pressure*

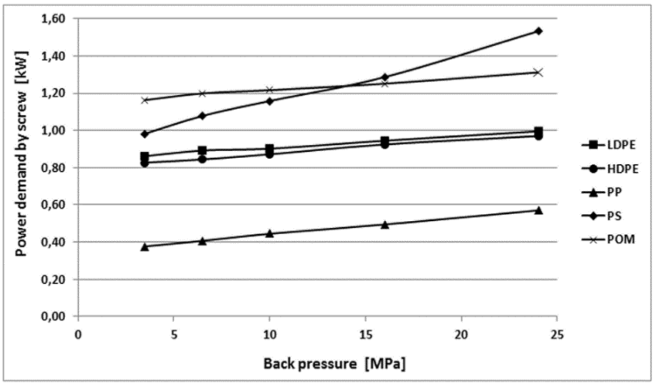

Fig. 6 *Power demand by the screw at variable back pressure*

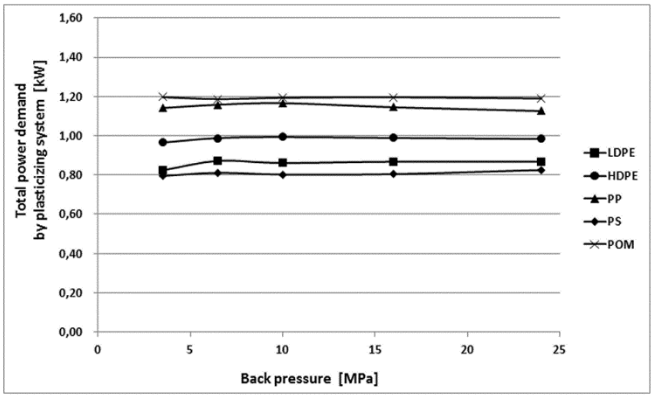

Fig. 7 *Total power demand by plasticizing system at variable back pressure*

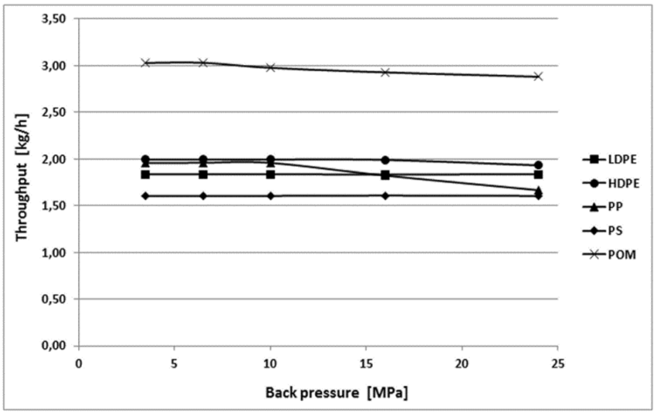

Fig. 8 *Throughput of the injection process at variable back pressure*

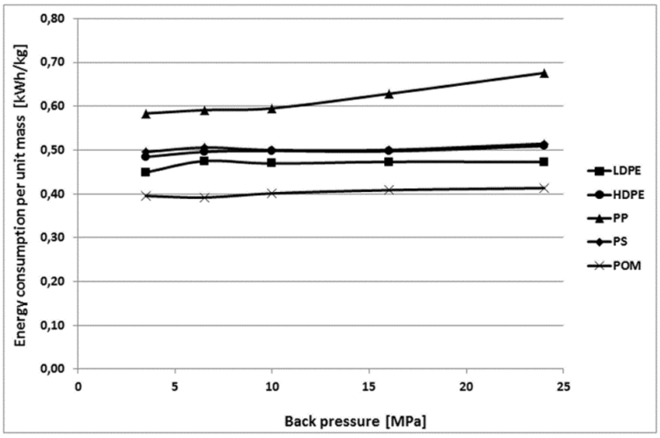

Fig. 9 *SEC for the injection process at variable back pressure*

Figs. 5-8 show very similar behavior for all tested thermoplastics. By changing back pressure values in the range of 3.5-24 MPa, slight maximum of the power demand by the heaters and slight increase of the average power demand by the screw can be observed. Only for amorphous PS, the power demand by the screw increases quite rapidly with increasing back pressure. Assuming that there are two most important power components mentioned above, i.e. the average power demanded by the screw and the average power demanded by the heaters, the approximate total power demanded by the plasticizing system of injection molding machine does not practically change with increasing back pressure. On the other hand, due to the constant throughput of the injection molding process for the whole range of back pressure values it can be seen in Fig. 9, that the SEC remains constant with the exception of PP, where the SEC grows about 20% for back pressure changes in the range of 3.5-24 MPa as a result of throughput decreasing. However, the different behavior of PP may be associated with the different melting mechanism. It could be related to high degree of crystallinity of solid PP and/or with crystals rearrangement during fusion [17,18]. The different behavior of PP during the melting process could be also observed in work concerned with starve feeding in extrusion process [19].

The results show that the injection molding process on the research position should be performed at the higher back pressure values, because on the one hand, it promotes improvement of material and thermal homogenization of molten polymer in the barrel. On the other hand, the increase in back pressure does not practically affect throughput and power demand by the plasticizing system, that is crucial in the entire LCI for the injection molding process.

The next experiment involved measurements of characteristics of the injection molding process at variable screw rotation velocity. Measurement results of power characteristics and process yield are shown in Figs. 10-13. The SEC for the injection molding process for various thermoplastic polymers at different values of screw rotation speed is shown in Fig. 14.

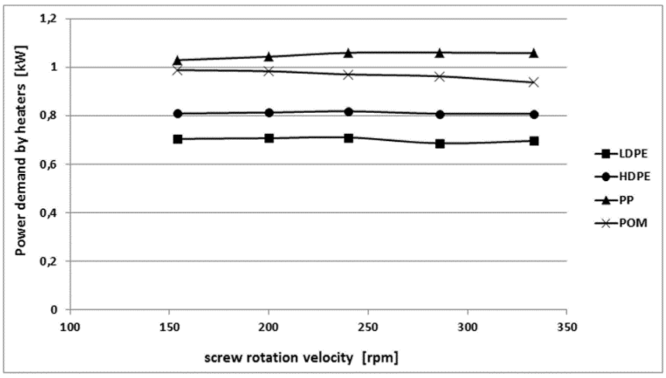

Fig. 10 *Power demand by heaters at variable screw rotation velocity*

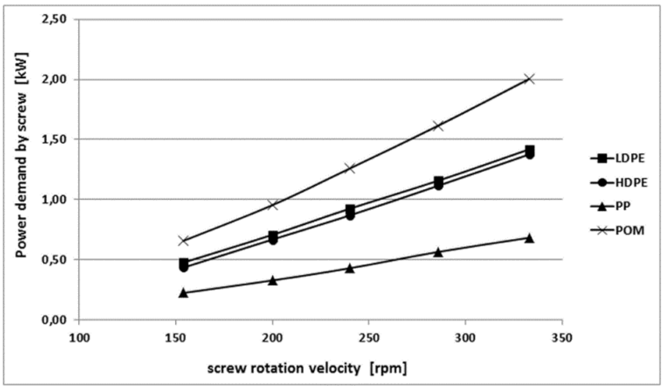

Fig. 11 *Power demand by the screw at variable screw rotation velocity*

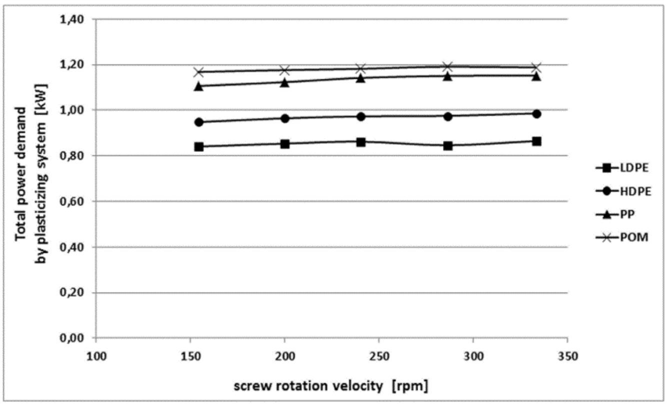

Fig. 12 *Total power demand by plasticizing system at variable screw rotation velocity*

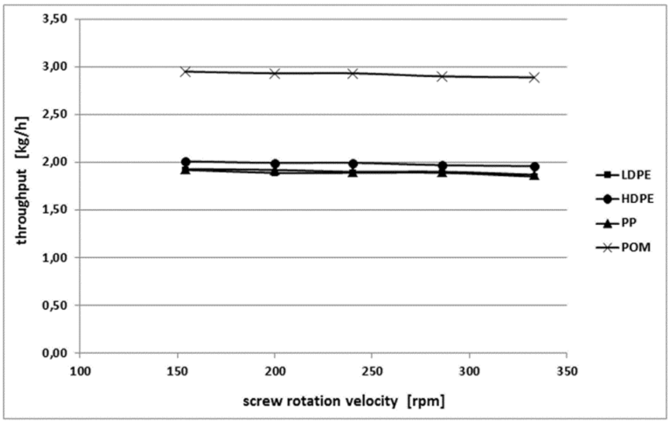

Fig. 13 *Throughput of the injection process at variable screw rotation velocity*

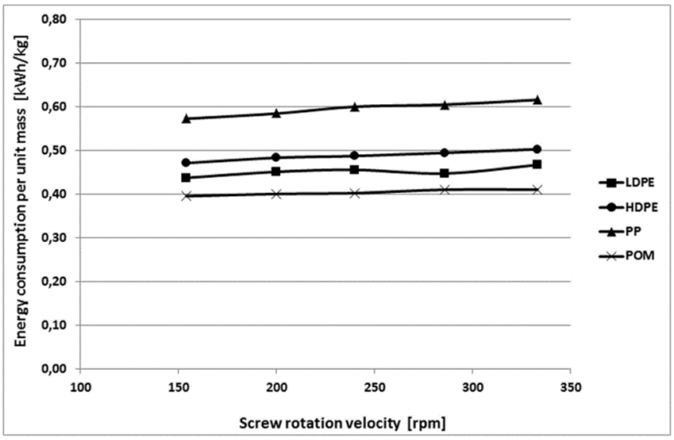

Fig. 14 *SEC for the injection process at variable screw rotation velocity*

There is practically no impact of variable rotational velocity of the screw on the power demand by heating elements (Fig. 10) for all investigated polymers. At the same time, a significant increase of the average power demand by the screw can be seen (Fig. 11). This leads to a mild growth of the total power demand by the plasticizing system with increasing rotational velocity of the screw, regardless of the type of polymer. Because of the constant yield characteristics (the rotation time of the screw is a part of the cooling time and has no impact on the yield of the injection molding process) with rising screw velocity, it can be seen in Fig. 14 that the SEC increases slightly. It follows that the injection molding process should be carried out at the low to medium values of the rotational screw velocity. High values of the screw speed result in the increased SEC till approx. 10% for the highest screw speed. Of course, the increasing power demand values by the screw for increasing rotational speed are compensated by the decreasing rotation time of the screw. It is result of the (Ps * tr) term in formula (2). Hence, the effect of the power demanded by the screw on the SEC is very small.

In conclusion, lower screw velocity values give less power demand by plasticizing process and, due to the constant throughput values, lower SEC values. These differences in the SEC values, however, are small. At the same time it is worth noting that it is not recommended to perform the injection molding process with high values of the rotational velocity of the screw. In this case, the circumferential speed is rather more important than the rotational one. With the large circumferential speed, a probability of a thermal decomposition of some polymer materials grows especially for the processing of more thermally sensitive materials such as PVC, polymer blends, thermosets and elastomers [20].

4. Conclusions

The injection molding process is a very widespread method of polymer processing, for which the annual, global energy consumption is comparable to the annual energy production of different European countries. The most energy-consuming stage is the plasticization process which needs the energy for reciprocating screw motion and heating of the barrel. In this work both the issues were examined by changing various working parameters of the injection molding process, measuring the corresponding process characteristics and calculating relevant values of the SEC (specific energy consumption). Five thermoplastic polymers (PE-LD, PE-HD, PP, PS and POM) were examined. It was found that the optimal conditions to perform the plasticization of thermoplastic polymers on the research position [15] were obtained when the low rotational screw velocity was applied. An increase of the SEC value with increasing barrel temperature was shown. It was ca. 15% for the barrel temperature rise by 20°C. It was also found that back pressure changes do not affect the power demand by the plasticizing system of the injection molding machine.

The strength measurements were not performed in this study. We focused only on power demand. The range of variable process parameters was assumed to obtain the correct quality of the moldings without shrinkage and other visible defects. It is worth to compile the proposed directions of changes in the values of technological parameters of the injection molding process with the mechanical properties of the received products. Then we can make a full analysis of the profitability of changes of technological parameters mentioned above.

Summarizing, it has been shown that the process of injection molding for thermoplastics should be performed at relatively low values of screw rotational velocity and large values of back pressure, as well as short values of dwell time for minimizing the energy consumption under the above experimental conditions. It is worth to perform similar research for larger injection molding machines and geometrically various moldings to generalize or detail the results presented in this work.

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