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Processing parameters influencing energy efficient injection moulding of plastics and rubbers

UDK 678.027.7:678.4/5
Review / Pregledni rad
Received / Primljeno: 5. 3. 2012.
Accepted / Prihvaćeno: 20. 2. 2013.

Summary

Injection moulding is one of the most important processes of plastics and rubber compounds processing. It enables the production of very complex plastics and rubber parts, even parts made of different plastics and rubber compounds, in one cycle. The system for injection moulding of polymers consists of different elements such as the mould, injection moulding machine and device for mould temperature regulation (tempering), and additional elements: dryers, robots, etc. For successful injection moulding, optimisation of moulded part material selection as well as elements of the injection moulding system is necessary. All of the mentioned factors consume significant amounts of energy. The paper presents the analysis of energy consumption in injection moulding systems, as well as the possibilities of energy savings in injection moulding process, starting with material selection, in order to obtain a more energy efficient process.

KEY WORDS:
injection moulding
energy efficiency
moulded part material selection

KLJUČNE RIJEČI:
energijska učinkovitost
injekcijsko prešanje
odabir materijala otpreska

Utjecaj parametara prerade na energijski učinkovito injekcijsko prešanje plastike i gume

Sažetak

Injekcijsko prešanje jedan je od najvažnijih postupaka prerade plastike i kaučukovih smjesa te drugih organskih i anorganskih polimera. Postupak omogućuje proizvodnju vrlo kompleksnih proizvoda, katkad istodobno od više materijala, u jednom ciklusu. Sustav za injekcijsko prešanje polimera sastoji se od glavnih elemenata, kao što su kalup, ubrizgavalica i temperiralo, te dodatnih elemenata: sušila, robota itd. Za uspješnu proizvodnju injekcijskim prešanjem potrebno je optimirati izbor materijala otpreska i elemenata sustava za injekcijsko prešanje. Svi navedeni faktori utječu na potrošnju energije. Članak prikazuje analizu potrošnje energije u sustavu za injekcijsko prešanje te moguće načine uštede, počevši od odabira materijala otpreska, radi postizanja energijski učinkovitijeg procesa prerade.

Introduction

Injection moulding is the most important and the most widespread procedure of plastics and rubber compounds processing, even metals (MIM – metal injection moulding and die casting of metals melts or CIM – ceramics injection moulding). Injection moulding offers: production of very complicated product geometry in one cycle, possibilities of production of several identical or different products in the same cycle, production of multicolour or multi-component products, production of hollow products, production of macro and micro products, etc. A successful injection moulding process begins with adequate moulded part material selection. Furthermore, basic moulding equipment (system) is necessary. It consists of: mould, injection moulding machine and temperature regulation device. Modern injection moulding process also relies on additional equipment which mainly consists of dryers (for granulate drying), heat exchange systems, robots and manipulators. Each of the mentioned elements consumes energy, directly or indirectly (Figure 1). In recent years, decrease of energy consumption in the field of equipment for injection moulding is a general trend. Along with energy saving during injection moulding cycle (equipment), energy efficient injection moulding should be considered even in early phases of moulded part design, selection of moulded part material, and mould design. Energy efficient injection moulding has not only economically, but also environmentally positive impact. It is the fact that consumption of 1kWh of electric energy presents approximately equivalent of 0.43kg of CO_2[1]. The paper covers the systematization of energy saving possibilities from polymer moulded parts development to their production by energy efficient injection moulding.

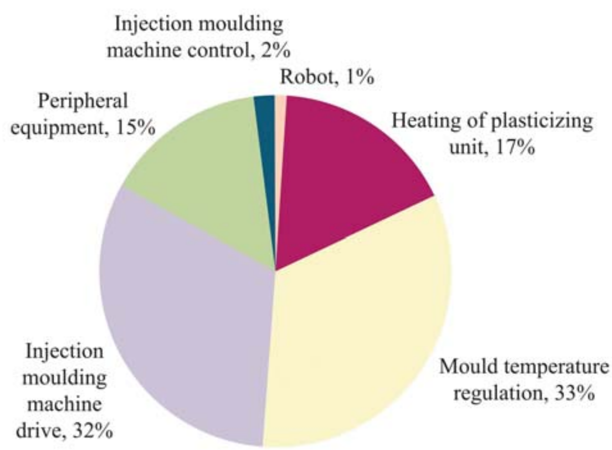

FIGURE 1 – Share of energy consumption in representative injection moulding system[1]

Moulded part design and selection of appropriate material

The approximate magnitude of the cost of energy in plastic processing, shown in Table 1[1], draws attention to the importance of the material selection for the moulded part.

TABLE 1 – Manufacturing costs for thermoplastic parts[1]

Factors	*Volume, %*
Material	80
Machine	10
Mould	5
Labour	2
Packing etc.	3
Total	*100*

The plastic processing industry in the developed world is highly focused on the cost labour, but the cost of materials and overheads are far more important in the total product cost.[1] Good injection moulding process means conversion i.e. plastification of the solid material into liquid melt. Upon producing the required shape, such energy has to be removed to achieve effective solidification of the molten core.

For plastification, the correct use of the two main heat energies, conductive and frictional, needs to be effective. The lack of frictional energy for most of amorphous materials such as polystyrene (PS), high-impact polystyrene (PS-HI), polycarbonate (PC), polysulfone (PSU) and acrylonitrile/butadiene/styrene (ABS) is usually compensated by conductive energy, i.e. heating. Processing of semi-crystalline materials, such as polyamide (PA), are not so simple; very often some amount of unpractised materials leads to very poor quality of final parts. To avoid such issue, various options are available, all requiring more energy consumption; increasing barrel temperature or increase screw back pressure to achieve the required flowability of the melt.[2] Both options increase the total costs. Control of the surface temperature of each mould cavity within the defined limits forms the basic of efficient melt solidification and economic part manufacture.[3.]

The melt, when injected into a mould, is forced along the gap and outer layer of the mould, mostly metal surfaces. This contact stops the melt flow of outer, peripheral melt layers. The resultant flow of molten inner core fronts in the form of a parabolic curve, in which the maximum flow velocity is in the centre of the melt and the minimum velocity is at the interface with the metal surface. The frictional energy quantity is determined by the velocity of the molten material through the gap and the injection speed. The velocity of the melt flow needs to be optimised in accordance with the thickness of the wall section, the flow length and the type of processed materials and its related melt viscosity. Different material grades have varying flow length capabilities (Figure 2)[4] for processing of thermoplastics. Understanding of the materials flow behaviour provides invaluable information for selecting the correct process parameters and costs.

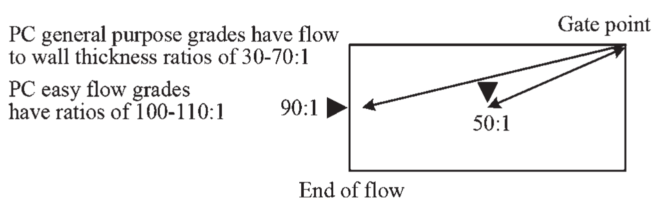

FIGURE 2 – Flow length – wall ratio for two grades of PC with equal wall thickness (1mm)[4]

Some of thermoplastics materials are hygroscopic, i.e. they absorb water readily into the bulk materials. This type of thermoplastics, such as PA, poly(ethylene terephtalate) (PET), ABS and PC, has a natural moisture content of up to 3% and will always require drying to be processed. If such materials are not dried, moisture in and on the surface of the plastic granules will be converted to steam during processing and this may show as an internal void, as a surface imperfection or create a plane of weakness in the product. Drying accounts for approximately 15% of the total energy used in plastic processing. Using the optimised process and new technologies this can be reduced by up to 50%.[1] Selection of non-hygroscopic thermoplastics, when possible, represents considerable savings in energy usage and cost.

The main activity of central moulded part development phase encompasses shaping, dimensioning and moulded part material selection where all activities are interconnected (Figure 3)[5]. Based on the set requirements on the product, it is possible to select adequate material (or several of them), and to perform dimensioning of the moulding. Even at the stage of moulded part development, it is possible to contribute to energy savings that will be realized later in the moulded part production. First of all, general guideline for plastics moulded parts development is achieving a part with as uniform wall thickness as possible while simultaneously conserving the moulding functionality.

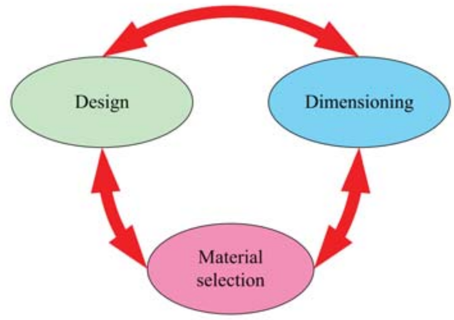

FIGURE 3 – Relationship among the main phases of the moulded part development[5]

On the plastics materials market, it has been possible recently to witness a trend of growth of the number of new materials with the properties tailored to specific applications. Naturally, any advanced material property additionally raises its price. Material with better properties, e.g. thermoplastics reinforced with glass fibres, will allow production of moulded parts with thinner walls, favourable thermal properties and thus in shorter cycles (Figure 4)[6]. Although these materials are generally more expensive, they enable the production of moulded parts with reduced weight. The result is lower consumption of materials per unit of product.

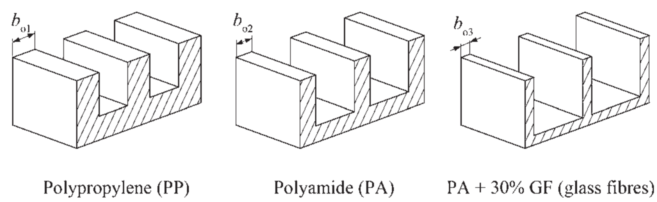

FIGURE 4 – Comparison of moulded parts wall thickness with different materials[6]

In adequate material selection process, the most common criterion is the cost of material, while processing costs are often out of consideration. In the case of injection moulding, productivity of the system is mainly determined with moulded part cooling time. From the general equation of thermoplastics moulded part cooling time[7,8] it follows that the moulded part wall thickness is the most influential factor on the moulded part cooling time.

Therefore, the use of materials that enable the production of thinner walls of the moulded parts, the savings in the amount of material quantity as well as the opportunities for shortening the injection moulding cycle are possible. For example, to reduce the wall thickness from 2.0mm to 1.5mm (reduction of moulded part wall thickness of 25%), it is possible, under identical processing parameters, to shorten the moulded part cooling time by more than 40%. If the average cycle time is e.g. 25 seconds, the possible saving per cycle is 10 seconds. In case of mass production, these 10 seconds can turn into months, which results in large energy savings.

Mould for injection moulding

Each mould for injection moulding of polymers has to fulfil the basic partial functions and possible special functions. One of the partial functions that have to be realised in every mould is mould cavity wall temperature regulation, respectively reaching and maintaining the requested temperature field. This means that the mould is a heat exchanger in which efficiency of heat exchange directly influences the moulded part cooling time.

By means of the mould, the moulded part cooling time can be influenced in two ways: by selection of appropriate material for elements of mould cavity and by appropriate heat exchange channels design. One should be aware that shortening of the moulded part cooling/heating time must be adjusted to the type of material. For the majority of thermoplastic materials there is prescribed maximum cooling rate, which results in satisfactory properties of the final product. This is particularly important in the processing of semi-crystalline thermoplastics.

Influence of the mould cavity elements material

Influence of the mould cavity material on the moulded part cooling time, and consequently injection moulding cycle time is not simple. It depends on determined processing parameters such as mould cavity wall temperature (T_K), contact temperature (T_D), or coolant temperature (T_M) (Figure 5)[7]. If the required mould cavity wall temperature is defined (Figure 5a) that has to be maintained during the injection moulding cycle (t_c), contrary to expectations, shorter cycle times can be achieved by the application of materials with lower thermal conductivity.

The reason lies in the fact that when using such materials the heat is accumulated under the surface of the mould cavity. Therefore it is possible to achieve the required cavity wall temperature with lower polymer melt temperature, which shortens the cycle time, and thus reduces the electrical energy consumption which is required for maintaining the necessary melt temperature in injection unit of injection moulding machine. E.g., the use of high alloyed steel can result in 10% shortening of injection moulding cycle, compared with the use of beryllium bronze. When the required coolant temperature is defined (Figure 5c), shorter cycles can be achieved with the use of materials with higher thermal properties.

In order to be able to produce high quality moulding in optimised process of injection moulding, the maximum possible uniform temperature field at the mould cavity has to be realised. Today it is possible to achieve such uniform (conformal) cooling by applying Rapid Tooling processes for the production of critical mould inserts (cores and cavities).

Influence of the system for mould temperature regulation

Mould for injection moulding is a heat exchanger in which heat exchange occurs between the melt, the coolant that flows through the system for mould temperature regulation and the environment (Figure 6). Many studies have shown that the use of innovative methods of mould temperature regulation can shorten the injection moulding cycle times in the range of 20 to 40%, thus saving nearly the same amount of energy.[9]

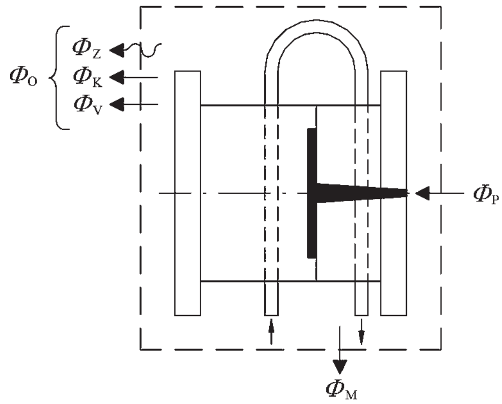

FIGURE 6 – Mould – heat exchanger: Φ_P – heat that thermoplastic melt brings to the mould, Φ_O – heat exchanged between mould and the environment, Φ_Z – heat exchanged by radiation, Φ_K – heat exchanged by convection, Φ_V – heat exchanged by conduction, Φ_M – heat exchanged between mould and coolant[7]

Additive manufacturing processes (AM) can offer additional advantage in optimising the injection process by manufacturing of key mould elements with the design of cooling channels in such a way that they optimally follow the contour of the mould cavity walls – so-called conformal cooling (Figure 7).[8] AM is a group of manufacturing processes in which mould inserts can be manufactured mostly from metal powders layer-by-layer to the final mould insert. Manufacturing is performed by the application of laser beam or other sources of heat, necessary to connect powder particles on each layer, as well as to connect the neighbouring layers.

Classic mould manufacturing processes (milling, turning, electro-erosion, etc) do not allow this possibility. The application of conformal channels results in uniform mould cavity wall temperatures, shorter cycle times and higher moulded part quality.[9,10]

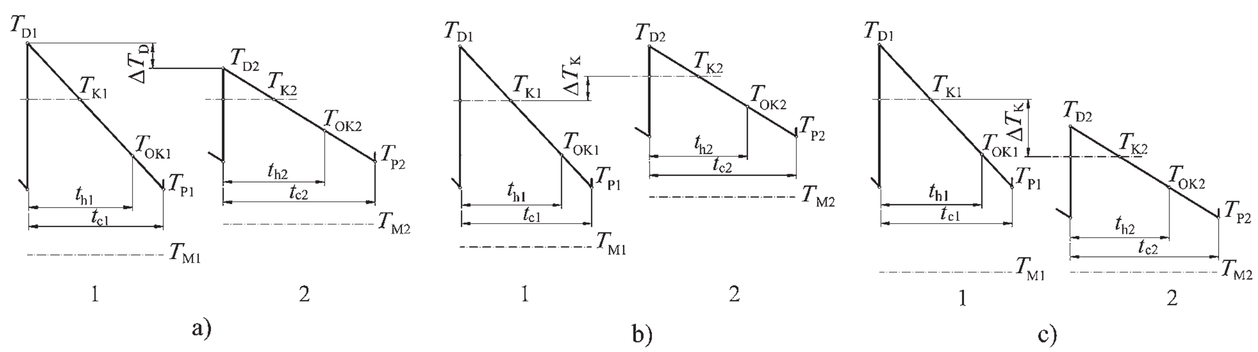

FIGURE 5 – Influence of mould material on moulded part cooling time: a - required cavity wall temperature, b - required contact temperature, c - required coolant temperature; 1 - material with lower thermal properties, 2 - material with higher thermal properties; T_D - contact temperature (K), T_{OK} - mould opening temperature (K), T_M - coolant temperature (K), T_P - start temperature (K), t_c - injection moulding cycle time (s)[7]

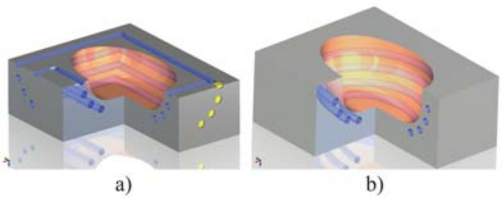

FIGURE 7 – Example of mould plate cooling: a - classic, b – conformal[8]

Apart from their configuration, such cooling channels can additionally enhance the intensity of heat exchange in the mould, and therefore additionally shorten the moulded part cooling time by channel cross-section. If such a channel is produced in a hexagon shape of the cross-section instead of a circular shape, the cooling channel surface through which the heat is exchanged in a mould can be increased to 30% (Figure 8)[11]. In that case two approaches are possible. The first approach is based on maintaining the same cooling time, while thermal load of the system for temperature regulation is reduced, as well as the energy consumption. In the second approach, it is possible to shorten the cooling time.[9,10]

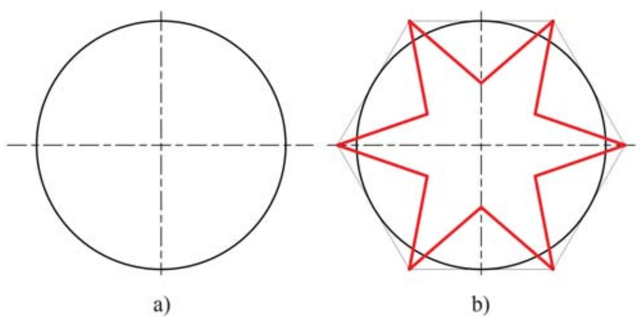

FIGURE 8 – Cross-sections of cooling channels: a - classic shape, b - shapes achievable by AM[11]

Some of the companies in the field of additive manufacturing of metal products develop different means of mould temperature regulation. Instead of single cooling channels, whole surface hollow structures are designed under the cavity wall surface.

The first structure is made of a number of consecutive nodes that are wriggling into a larger inlet and outlet holes. Consecutive nodes in this configuration ensure a sufficiently large volume flow of the coolant. The second structure does not consist of nodes, but of the net surface structure which is only 2mm below the cavity wall, and ensures large coolant flow. Small net distance to the mould cavity wall enables very efficient temperature regulation, even in the case of using high alloyed steels for cavity elements. Next advance of application of such a system is in the possibility of temperature regulation adaption to specific mould cavity areas. Thus, it is possible to reduce the unwanted thermal deformations of the moulded parts and to accomplish target value of shrinkage compensation. Net-like structure is combined with insulation layer which enables fast temperature changes in the phase of moulded part cooling in the cavity[12].

Another approach in optimization of injection moulding process is the application of the so-called *gradient materials*. The approach is based upon the principle in which the outer layers of mould inserts are made of hard materials (for example high alloyed steels with high hardness), while the inner area of the insert is made of materials with high thermal conductivity (for example copper alloys). The solution with copper core and classic, straight cooling channels can result in 15 to 25% shortening of the moulded part cooling time. The combination of such approach with conformal channels results in shorter cycle of approximately 30%.[13]

On the market there is also the so-called *Contura* system (Figure 10) of mould temperature regulation. Similar to the application of AM procedures, *Contura* system of mould temperature regulation enables optimal following of the cavity wall contour. The result is up to 30% shorter injection moulding time.

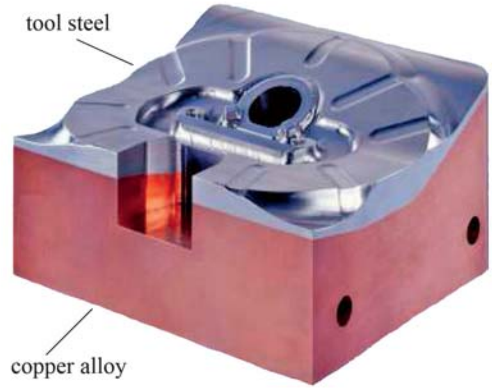

FIGURE 9 – Example of gradient mould insert[13]

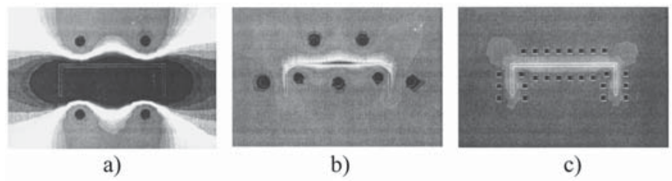

FIGURE 10 – Comparison of mould temperature fields: a - classic channels, b - optimized classic channels, c - *Contura*-system channels[14]

The so-called *pulse* approach to the mould temperature regulation is a very interesting approach as well. Pulse temperature regulation enables that in the phase of melt injection into the mould cavity, the flow of coolant is stopped. This directly increases the contact temperature of the mould cavity wall. After cooling the melt beyond the temperature of glass transition, the system opens the valve, and intensive flow of the coolant through the mould is established. The pulse cooling senses the mould surface temperature and applies a pulse of coolant at maximum flow rate directly from the chiller or cooling tower during each moulding cycle for maximum heat removal. Each cooling pulse equals the excess heat from each moulding cycle and compensates for the cycle time, melt and ambient temperature and coolant pressure changes (flow). The consequence is very fast mould cooling. Among many advantages of such principle of mould temperature regulation, it is also possible to recognize the shortening of the moulded part cooling time.[15]

Injection moulding machines

In previous efforts to save energy during injection moulding, maximum attention and research was focused on the injection moulding machines. In order to be able to compare the injection moulding machines, the *German Federation of Engineers* (*VDMA*) developed a protocol *EUROMAP 60* with the purpose of comparing the electrical energy consumption between injection moulding machines of the same size. The present state of the injection moulding machines market is characterized by the existence of three basic groups of injection moulding machines: hydraulic, hybrid (partly hydraulic and partly electric) and all-electric.[1]

Although all-electric injection moulding machines (Figure 11) are on the average about 10% more expensive than other two groups, higher initial investment can be returned very quickly because of the reduced energy consumption of all-electric machine and the possibilities of faster operation, which indirectly shortens the injection moulding cycle. The basic advantage of all-electric injection moulding machines lies in the fact that during the phase of the moulded part cooling in the mould, apart from energy needed for polymer plasticizing in the unit for plasticization, there is no need for additional energy.[1,16]

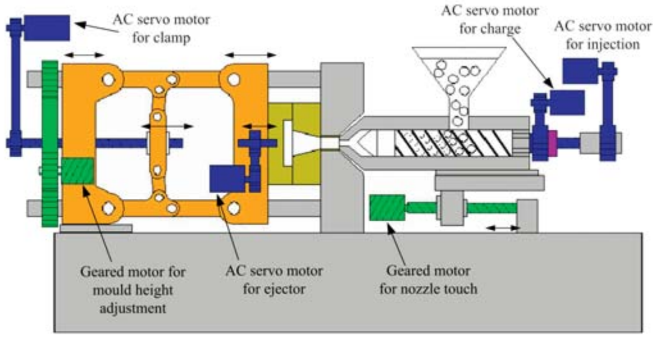

FIGURE 11 – Cross-section of all electric injection moulding machine[16]

Although all-electric injection moulding machines dominate in the domain of energy savings, the injection moulding producers strive to achieve energy efficiency on all types of machines. First of all, energy saving can be achieved by means of servo-motors as drives for hydraulic pumps. Servo-motor has the capability of optimal adjustment of rotation according to real needs from the process (cycle) of injection moulding. Therefore, in the phases in which there is no need for pump function, motor is in idle mode and saves the energy. Next are the machines with electric units for preparation and injection of polymer melt as well as electrical units for mould opening and closing, and moulded part demoulding from the cavity.

In addition, the energy on the injection moulding machines can be saved even with very common activities such as additional insulation to the heaters of cylinder for polymer melting and proper selection of screw (enables processing of some polymer materials at lower temperatures than prescribed).[1]

Peripheral equipment – dryers and cooling systems

Although the peripheral equipment includes a large number of devices, regarding energy consumption, there are two subsystems: systems for the drying of polymer materials and water cooling systems in large facilities for plastics processing.

Drying of plastics materials before processing is one of the most important preconditions for achieving high quality of finished moulded parts, efficient production and processing without problems and faults on the moulded parts. Therefore, as additional equipment in the system for injection moulding of polymers, the application of dryers is recommended. However, the dryers are one of the largest consumers of energy. Therefore, manufacturers of the drying equipment permanently improve drying to reduce energy consumption for drying of polymers to the minimum level. In the drying of polymer materials, it is possible to apply several approaches: drying in the oven, drying using hot air, drying using desiccants, drying using compressed air, low-pressure drying and infra-red drying.

In the available literature, it is possible to find a large number of innovative systems and processes. The paper will shortly present only two systems based on drying using desiccants: *X Dry* process[17] and *ETA*-process[18].

X Dry process of drying is based upon zeolitic technology that operates without compressed air or cooling water. The basic concept is the use of zeolites (volcanic mineral) as a filter, whereby the device does not consume power when it is not necessary, but use only the power required for the proper treatment of materials, all in accordance with the adjusted material flow. Variable air flow, uniform operation, high dew point, the lack of use of cooling water and compressed air, finally result in very high energy savings of up to 72% (Figure 12).[17]

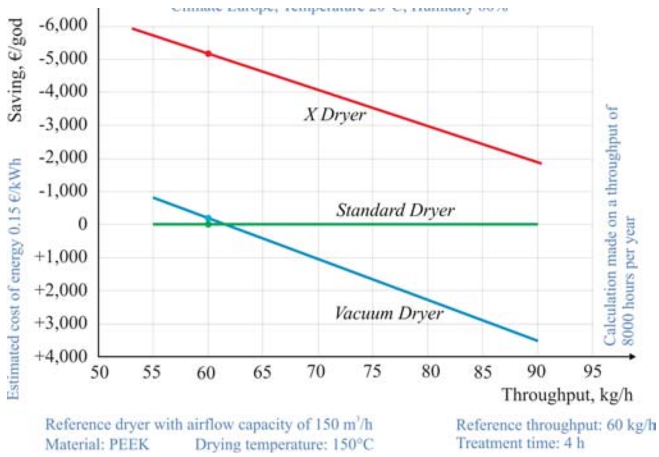

FIGURE 12 – *X Dryer* energy savings[17]

In the second case, *ETA-drying process* allows energy savings of up to 40%. The main characteristic of this process is the return of unused heat, i.e. hot air for material drying that is directly returned through heat exchanger system. Figure 13 shows the energy consumption for drying using *ETA-process*, depending on the type of dried polymer.[18]

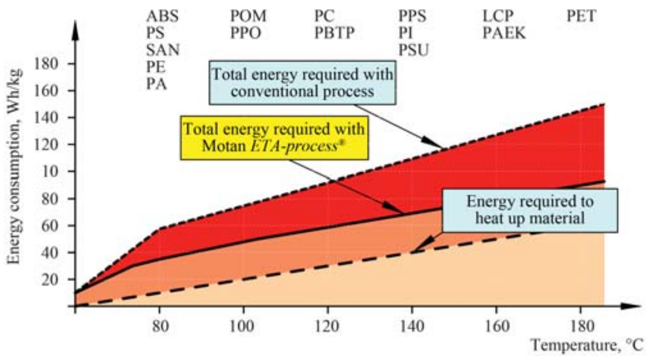

FIGURE 13 – *ETA-process* energy consumption[18]

Suitable chilling equipment has primary importance in all the plastic processing. In the past, regardless of the temperature level, the cooling of these processes had always been in charge of traditional water chillers. The continuous rise of the costs, the reduction of the margins due to the rising prices of the main materials and the growing number of competitors on the market, in the past years pushed all the plastics processing industries to improve and optimize the entire production process.[18]

As far as the cooling equipment is concerned, it is possible to improve the performances of the system by distinguishing the process temperature levels. It is possible to reach great energy savings by separation of the cooling of the low temperature utilities (0 to 20°C), usually served by traditional water chillers, from the high temperature utilities (25 to 40°C) that can use the ambient temperature for the cooling of the process water. Using the ambient air for the cooling of all the high temperature utilities enables obtaining relevant energy savings with a consequent short return to investment time.[19]

The *Free Cooler* permits complete separation between the process water and the ambient. The heat exchange happens through one finned coil battery made of copper and aluminium, crossed by an adequate air flow.

So the process water remains bounded in the circuit itself, with no contact with the ambient. In this way it is possible to avoid all the faults due to this: high impurities content, high oxygenation of the water with consequent high formation of rust along the circuit, high proliferation of algae and bacteria, high evaporation or water loss with consequent increase of hardness and necessity of continuous water refill, and so on. Moreover, the running costs of this kind of unit are surely lower. The main disadvantages are: higher water temperature (related to the ambient dry bulb temperature), higher floor space needed and higher investment.[19]

Free Cooler system is able, under the same operating conditions, to produce water at 29 to 30°C. The main improvement that permits this result is a new high efficiency adiabatic spraying system (SSS). This system can, through one high pressure pump, increase consistently the quantity of water sprayed really adsorbed by the air: in this way it is possible to have the air around the Free Cooler in condition of saturation by water. Over 80% of the water sprayed is adsorbed by air, against the 20 to 30% of one traditional spraying system, avoiding puddles below the *Free Cooler* and waste of water.[19]

Moreover, this system is automatically switched on only when the *Free Cooler* is not able to maintain the set temperature. In the end, the particular disposition of the nozzles together with the polyurethane filters avoid any direct wetting of the finned coil battery, eliminating the problem of scaling. Another improvement that gives high results in terms of energy saving is the continuous variation of the speed of the fans through an electronic control (EC fans). This system, compared to the traditional on/off adjusting system, permits huge energy saving (around 80 to 90%) and higher accuracy of the process water temperature.[19]

Conclusion

Continuous increase in costs, narrowing margins due to increasing prices of most of of the materials on the market and a growing number of competitors on the market in recent years have encouraged all the polymer processing industries to improve and optimize the entire production process. By applying a systemic approach to reducing energy consumption on every place possible, from material selection, the geometry of the moulded part, over the basic equipment for injection moulding, to additional equipment, it is possible to achieve multiple energy savings. In each of these segments, partial energy savings of 10 to 80% are possible. If possible savings of modern systems for injection moulding are compared to the systems from the year 1996, these values are additionally increased. For example, only the hydraulic and all-electric injection moulding machines in the past 15 years have achieved reductions in energy consumption ranging between 75 and 80%. Besides the positive economic impact, one should note a no less important positive impact on the environment in the form of reduced production of greenhouse gases that are directly related to the energy consumption in kWh.

Acknowledgement

The work is part of research within the project Increasing efficiency in polymeric products and processing development *funded by the* Ministry of Science, Education and Sports of the Republic of Croatia*. The authors would like to thank the Ministry for supporting this project*.

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