ACTA TECHNICA CORVINIENSIS – Bulletin of Engineering
Tome V (Year 2012). FASCICULE 1 [January–March]. ISSN 2067-3809

[1.] Damir GODEC, [2.] Maja RUJNIĆ-SOKELE, [3.] Mladen ŠERCER

ENERGY EFFICIENT INJECTION MOULDING OF POLYMERS

[1.] UNIVERSITY OF ZAGREB, FACULTY OF MECHANICAL ENGINEERING AND NAVAL ARCHITECTURE, IVANA LUČIĆA 5, ZAGREB, CROATIA

ABSTRACT: Injection moulding is one of the most important processes of cyclic polymer and other materials processing. It enables the production of very complex parts, in one cycle. For successful injection moulding, injection moulding system is necessary. It consists of main elements: the mould, injection moulding machine and device for mould temperature regulation (tempering), and additional elements: dryers, robots etc. All of the mentioned elements consume significant amounts of energy. The paper presents the analysis of the possibilities of energy savings in injection moulding process, starting with moulded part geometry, in order to obtain more energy efficient process.
KEYWORDS: injection moulding, energy efficiency

INTRODUCTION

Injection moulding is the most important and the most widespread procedure of polymer processing. It enables production of very complicated product geometry in one cycle, possibilities of production of several identical or different products in the same cycle. Advanced injection moulding processes enable production of multicolour or multi-component products, production of hollow products, production of macro and micro products etc. For successful injection moulding process, basic equipment (system) is necessary. It consists of: mould, injection moulding machine and temperature regulation device. [1] Modern injection moulding process also relies on additional equipment which manly consists of dryers (for granulate drying), water cooling systems, robots and manipulators. Each of the mentioned elements consumes energy, directly or indirectly (Figure 1).

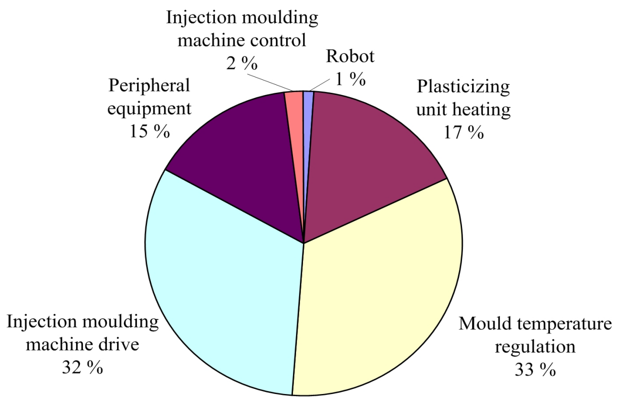


Figure 1 – The share of energy consumption in representative injection moulding system [2]

In recent years, decrease of the energy consumption in the field of equipment for injection moulding is 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 positive impact, but environmentally as well. It is the fact that consumption of 1 kWh of electric energy presents approximately equivalent of 0.43 kg of CO_2 [2]. The paper covers the systematization of energy saving possibilities from polymer moulded parts development to their production by energy efficient injection moulding.

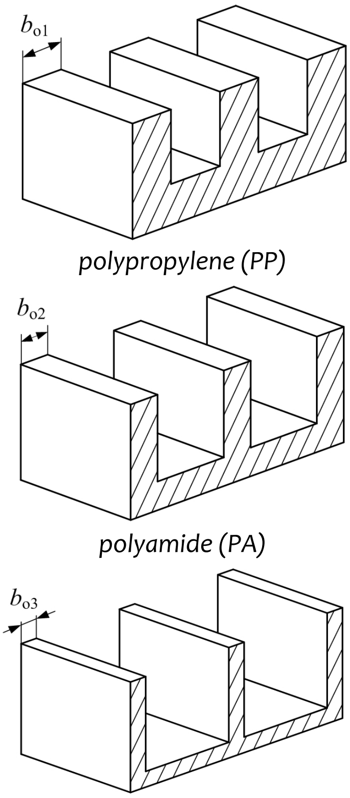
MOULDED PART DESIGN & MATERIAL SELECTION

The main activity of central moulded part development phase encompasses shaping, dimensioning and moulded part material selection where all activities are interconnected [3]. Based on set requirements on the product, it is possible to select adequate material (or more of them), and to perform a dimensioning of the moulded part. 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 polymer moulded parts development is achieving a uniform wall thickness while simultaneously conserving moulded part functionality.

At the polymer materials market, recently it is possible to witness the trend of growth of number of new materials with properties tailored to the specific applications. Naturally, any advanced material property additionally raises its price. Material with better properties, e.g. reinforced with glass fibers, will allow production of molded parts with thinner walls (Figure 2) [4]. Although these materials are generally more expensive, they enable the production of molded parts with reduced weight. The result is lower consumption of materials per unit of product.

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 molding, productivity of the system is mainly determined with molded part cooling time.

From general equation of molded part cooling time [1] it is clear that the molded part wall thickness is the most influential factor on the molded part cooling time.



polypropylene (PP)

polyamide (PA)

PA + 30 % GF (glass fibres)

Figure 2 - Comparison of product wall thickness with different materials [4]

$$t_h = \frac{b_o^2}{a_{ef} \cdot \pi \cdot K_O} \cdot ln\left[K_U \frac{T_T - T_K}{T_{PO} - T_K}\right] \quad (1)$$

where: t_h - moulded part cooling time (s), b_o - moulded part wall thickness (mm), a_{ef} - effective thermal diffusivity of polymer material (mm^2/s), K_O - coefficient of moulded part shape, K_U - coefficient of moulded part interior, T_T - polymer melt temperature (K), T_K - mould cavity wall thickness (K), T_{PO} - deflection temperature under load (K).

Therefore, when using materials that enable the production of molded parts with thinner walls, not only are possible savings in the amount of material, but still provide even larger opportunities for savings in the shortening the injection molding cycle. For example, if necessary wall thickness can be reduced from 2.0 mm to 1.5 mm, it is possible, under identical processing parameters, to shorten molded part cooling time for more than 40 %. If the average cycle time is e.g. 25 seconds, possible saving per cycle is 10 seconds. In the 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 molding of polymers has to fulfill basic partial functions and possible special functions. One of the partial functions that have to be realized 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, moulded part cooling time can be influenced in two ways: by selection of appropriate material for elements of mould cavity and by appropriate cooling channels design. It should be aware that shortening of moulded part cooling time must be adjusted to the type of polymer material. For the majority of polymer 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 [1]

Influence of the mould cavity material on the molded part cooling time, and consequently injection molding 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 3).

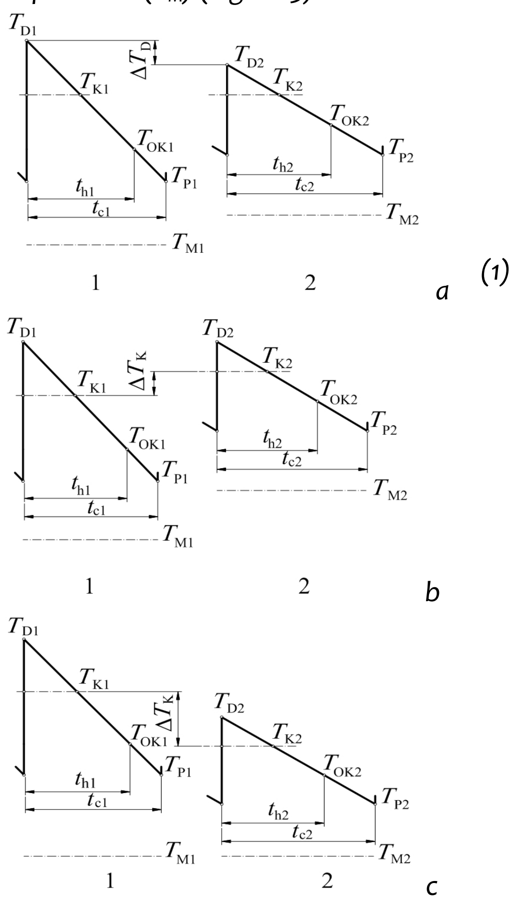
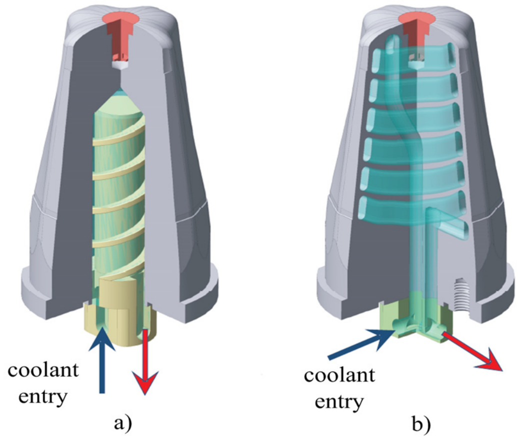


Figure 3 - Influence of mould material on moulded part cooling time: a) required cavity wall temperature, b) required contact temperature, c) required coolant temperature; 1 - material with lower thermal properties, 2 - material with higher thermal properties; T_D - contact temperature (K), T_{OK} - mould opening temperature (K), T_M - coolant temperature (K), T_P - start temperature (K), t_c - injection moulding cycle time (s) [1]

If the required mould cavity wall temperature is defined (Figure 3a) that has to be maintained during injection molding cycle (t_c), contrary to expectations, shorter cycle times can be achieved by 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 mould cavity. Therefore it is possible to achieve 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 molding machine. E.g., use of high alloyed steel can result in 10 % shortening of injection molding cycle, compared with the use of beryllium bronze. When the required coolant temperature is defined (Figure 3c), shorter cycles can be achieved with the use of materials with higher thermal properties.

INFLUENCE OF THE SYSTEM FOR MOULD TEMPERATURE REGULATION

Mould for injection molding is a heat exchanger in which heat exchange occurs between polymer melt, coolant that flows through the system for mould temperature regulation and environment. Many studies have shown that the use of innovative methods of mould temperature regulation can shorten the injection molding cycle times in range of 20 to 40 %, as thus save nearly the same amount of energy. One of the main advantages of applying modern additive manufacturing processes (AM) in the production of key mould elements is the possibility of design the cooling channels in these elements in such a way that they optimally follow the contour of mould cavity walls - so called conformal cooling (Figure 4) [5]. Classic mould manufacturing processes (milling, turning, electro-erosion etc.) do not allow this possibility. Application of conformal channels results with uniform mould cavity wall temperatures, shorter cycle times and higher molded part quality. [6,7]



Figures 4 - Example of mould insert cooling: a) classic, b) conformal [5]

Apart from their configuration, such cooling channels can additionally enhance intensity of heat exchange in the mould, and therefore additionally shorten of molded part cooling time by channel cross-section. If such a channel is produced in a six-pointed star shape of cross-section instead of a circle shape, cooling channel surface through which heat is exchanged in a mould, can be increased to 30 %. In that case two approaches are possible. 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. [6,7]

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 large enough volume flow of coolant. Second structure does not consist of nodes, but of the net surface structure which is only 2 mm 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. Net-like structure is combined with insulation layer which enables fast temperature changes in the phase of molded part cooling in the cavity (Figure 5). [8]

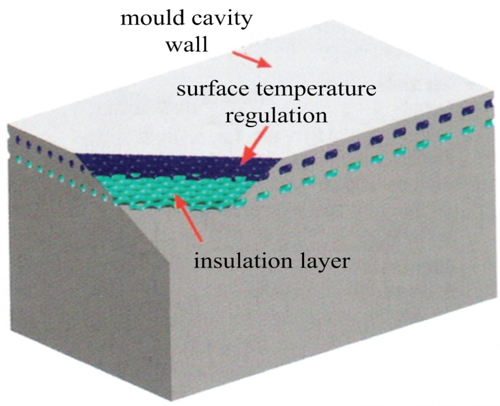


Figure 5 - Mould insert surface temperature control [8]

Another approach in optimization of injection molding process is application of so-called gradient materials. 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 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 molded part cooling time. Combination of such approach with conformal channels results in the shorter cycle of approximately 30 %. [9]

So-called pulse approach to the mould temperature regulation is very interesting approach as well. Pulse temperature regulation enables that in the phase of polymer 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, system opens the valve, and intensive flow of the coolant through the mould is established. 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 molding cycle for maximum heat removal. Each cooling pulse equals the excess heat from each molding cycle and compensates for 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 shortening of the molded part cooling time. [10]

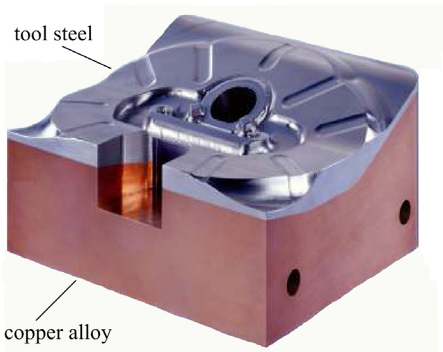


Figure 6 - Example of gradient mould insert [9]

INJECTION MOULDING MACHINES

In previous efforts to save energy during injection moulding, the maximum attention and research was focused on injection moulding machines. In order to be able to compare injection moulding machines, German federation of engineers VDMA developed a protocol EUROMAP 60 with the purpose of comparison of 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 existing of three basic groups of injection moulding machines: hydraulic, hybrid (partly hydraulic and partly electric) and all-electric. [2]

Although all-electric injection moulding machines (Figure 7) are in 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 possibilities of faster operation, which indirectly shortens the injection moulding cycle. 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. [2,11]

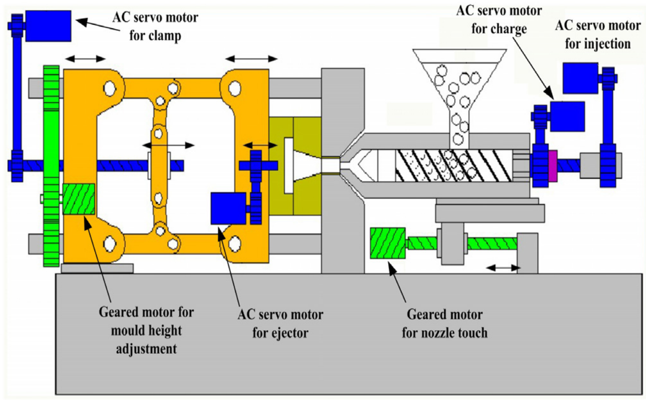


Figure 7 – All-electric injection moulding machine (cross section) [11]

Although in the domain of energy savings dominate all-electric injection moulding machines, 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 demolding from the cavity.

In addition, the energy on the injection molding machines can be saved even with very common actions, 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). [2]

PERIPHERAL EQUIPMENT - DRYER AND COOLING SYSTEMS

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

Drying of polymer 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 moulded parts. Therefore, as additional equipment in the system for injection moulding of polymers, 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 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 [12] and ETA process [13].

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, inorganic polymer) 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, a 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 8). [12]

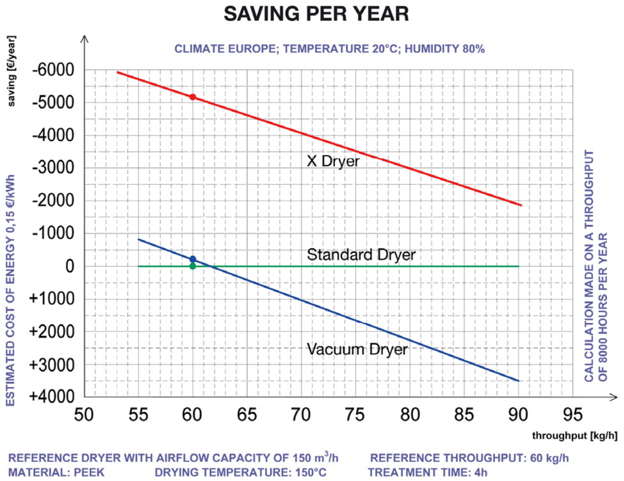


Figure 8 - X Dryer energy savings [12]

In the second case, the ETA drying process allows energy savings up to 40 %. 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 9 shows the energy consumption for drying using the ETA process, depending on the type of dried polymer. [13]

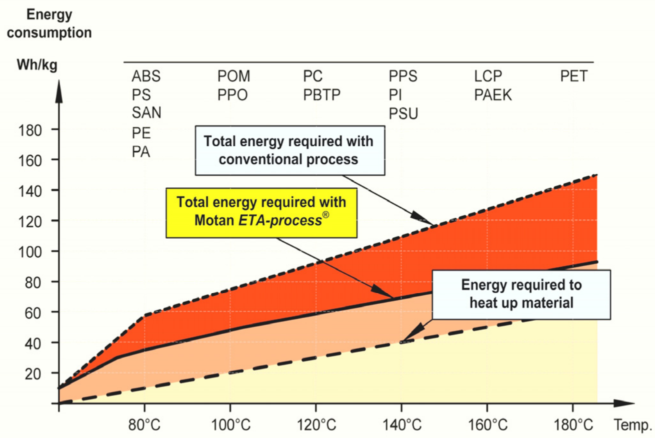


Figure 9 - ETA process energy consumption [13]

Suitable chilling equipment has a primary importance in all the plastic processing. In the past, regardless of the temperature level, the cooling of these processes has 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 in the market, in the past years pushed all the polymer processing industries to improve and optimize the whole production process.

As far as concerns the cooling equipment, 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 a traditional water chiller, 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 (Figure 10). [2,14]

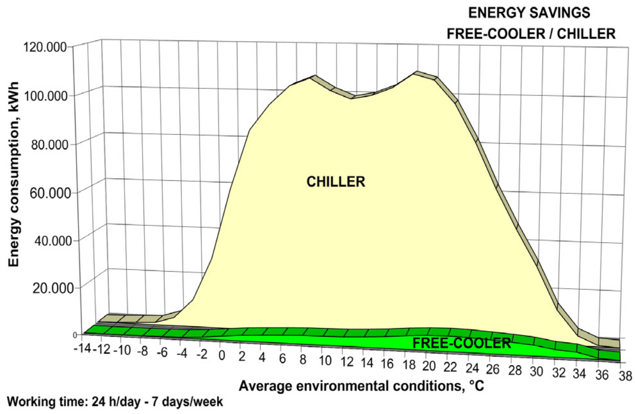


Figure 10 - Possible energy saving in application of Free Cooling (FC) system [14]

The Free Cooler permits the 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 into the circuit itself, with no contact with 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 alga and bacteria, high evaporation or water loss with consequent increase of the 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.

Free Cooler system (Figure 11) is able, at 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 the 80 % of the water sprayed is adsorbed by the air, against the 20 to 30 % of one traditional spraying system, avoiding puddles below the Free Cooler and waste of water.

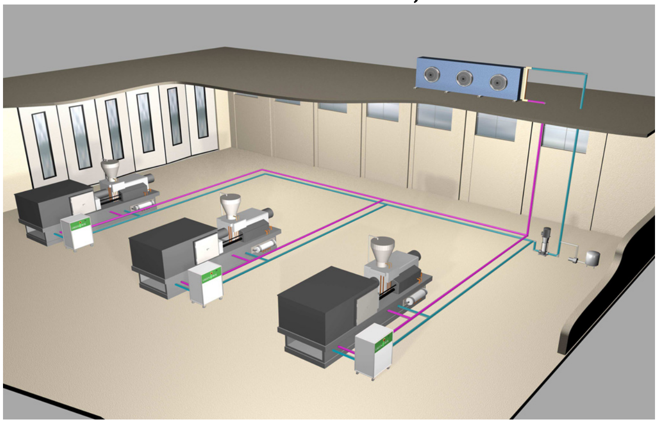


Figure 11 - Installation scheme of FC system in injection moulding facility [14]

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 wet of the finned coil battery, wiping out 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 a huge energy saving (around 80 to 90 %) and a higher accuracy of the process water temperature.

CONCLUSIONS

Continuous increase in costs, narrowing margins due to increasing prices of most of and a growing number of competitors in 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 the geometry of the molded part, over the basic equipment for injection molding, to additional equipment, it is possible to achieve multiple energy savings. In each of these segments, partial energy savings of 10 do 80 % are possible. When these savings are summarized, total savings can exceed 200 % when compared with systems in which energy saving are not considered. If possible savings of modern systems for injection molding are compared to the systems from the year 1996, these values are additionally increased. For example, only the hydraulic and all-electric injection molding machines in the past 15 years have achieved reductions in energy consumption ranging between 75 and 80 %. Besides the positive economic impact, it should be noted 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.

ACKNOWLEDGEMENT

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

REFERENCES

[1] ČATIĆ, I.: Izmjena topline u kalupima za injekcijsko prešanje plastomera, Društvo plastičara i gumaraca, Zagreb, 1985.

[2] KENT, R.: Energy Management in Plastics Processing, Plasticx Infomratio Direct, Bristol, 2008.

[3] RAOS, P., ČATIĆ, I.: Razvoj injekcijski prešanih polimernih tvorevina, Društvo plastičara i gumaraca, Zagreb, 1991.

[4] MALLOY, R.A.: Plastic Part Design for Injection Molding, Carl Hanser Verlag, München, 2010.

[5] ČATIĆ, I.: Izmjena topline u kalupima za injekcijsko prešanje plastomera, Društvo plastičara i gumaraca, Zagreb, 1985.

[6] N.N.: EOS, K2010 Press release, 2010.

[7] XU, X., SACHS, E., ALLEN S.: The Design of Conformal Cooling Channels in Injection Moulding Tooling, Polymer Engineering and Science, 41(2001)7, 1265-1279.

[8] SACHS, E. at al: Production of Injection Moulding Tooling Conformal Cooling Channels Using the Three Dimensional Printing Process, Polymer Engineering and Science, 40(2000)5, 1232-1247.

[9] N.N.: Hofmann Innovation Group - Press Release 2009

[10] NOBLET, V.: TRUMPF Laser Forming, Presentation at AFPR conference, Paris, 2005.

[11] N.N.: Pulse cooling, www.pulsecooling.com, 2011-04-11

[12] EDDISON, J.B.: Injection Moulding Machines Energy Efficiencies, www.consultekusa.com, 2011-02-23.

[13] N.N.: EUREKA – MORETTO introduces innovative approach to material drying, www.k-online.de, 2011-03-01.

[14] N.N.: ETA process, www.motan.co.uk, 2011-03-01.

[15] www.greenboxamerica.com, 2011-03-01.

ACTA TECHNICA CORVINIENSIS – BULLETIN of ENGINEERING

ISSN: 2067-3809 [CD-Rom, online]