Abstract

Energy efficiency of injection molding is critical to increase the sustainability indexes of this process and to reduce production cost. The Energy Gap Methodology (EGM) is presented as a valuable tool to prioritize the interventions to increase the energy efficiency in injection molding and other polymer processes. This methodology identifies four gaps: production, process, technological and R&D gaps. Three industrial successful case studies reducing energetic gaps in injection molding are presented, obtaining specific energy consumption (SEC) reductions between 9 and 15%.

1. Introduction

Sustainable energy security is a global priority. Energy efficiency of productive processes is one of the most important strategies to achieve it [1]. The market demands products made with lower carbon footprint and with environmentally friendly materials. The reduction of energy and resource consumptions is relevant for the plastic industry, not only from the environmental point of view, but also for production cost reduction. The plastic processing sector is an intensive consumer of electrical energy. It is estimated that the cost of energy represents between 4% and 10% of the operational costs in a processing plant [2].

The energy consumption of the Colombian plastic and rubber industry is well above the average consumption of the whole manufacturing industry. As shown in Figure 1, the plastic industry historically requires around twice the energy to obtain the same production (given in Colombian pesos) than the whole Colombian manufacturing industry.

Injection molding is one of the most important processes in the plastic industry. For this process, the share of the energy cost in the total cost of a plastic part varies between 3% for industrial parts and 10% for packaging parts. This share of the cost of energy is significant, taking into account that the margins of utility of plastic parts are usually lower than 10%[2].

Different approaches have been developed to diagnose and increase the energy efficiency in injection molding processes. Thiriez and Gutowski analyzed the environmental impact of the injection molding process taking into account the specific energy consumption [4]. Yao proposed an approach that integrates injection molding machine controls and settings in order to improve the process energy efficiency [5]. Ribeiro et al. proposed a thermodynamic-empirical model to estimate the energy consumption in the injection molding process [6]. Qureshi et al. presented an empirical approach to relate processing variables and energy consumption [7]. Chien and Dornfeld presented a semi-empirical model to estimate the energy consumption of an injection molding machine, based on the energy profile of the injection molding process Spiering et al., presented methodologies to estimate the expected energy consumption in injection molding plants, addressing the impact of the mold [8]. Müller et al, used the energy value stream mapping method (EVSM) [9], which considers lead times.

In industry, energy improvements are usually focused on the methodology of monitoring and targeting (M&T) [10].
This methodology is very useful to determine if a plant is constantly improving from the energetic point of view. However, it does not give information about the energetic intervention priorities. Therefore, M&T information must be correlated with the process behavior and quality criteria, to obtain tools to apply effective energy enhancements.

Since 2008, ICIPC has been working on energy consumption in polymer processing. Some ICIPC publications about this subject can be found in [2], [11]–[13]. ICIPC has developed a methodology to diagnose and prioritize the interventions to improve the energy efficiency of a polymer processing production line, taking into account the specific energy consumption, the productivity of the line and the return of the investment. This methodology is called the Energy Gap Methodology (EGM). EGM has been applied in more than twenty production lines in Colombia, reducing in more than 10% the specific energy consumption in injection molding, sheet extrusion, twin screw extrusion, blow molding, rubber injection and extrusion, among others (sometimes reductions of 50% have been reached). This paper introduces the methodology and presents some successful cases of implementation in injection molding plants.

2. Energy Gap Methodology (EGM)

EGM is based on different definitions of the specific energy consumption (SEC) (See Figure 2). SEC is the relation between energy consumption and production. Depending on several considerations, different SEC values can be defined. The effective specific energy consumption (SECe) represents the production performance and it is the ratio between the processing line energy consumption during a specific period divided by the amount of conforming production obtained in the same period. The apparent specific energy consumption (SECa) reflects the performance of the process, and it is the ratio between the energy consumption of the process working in stable conditions divided by the production obtained under said conditions. The technological specific energy consumption (SECtec) is the best SEC value that can be obtained with the current production line technology. The state of the art specific energy consumption (SECsa) is the minimum value of SEC that is offered by the most efficient commercially available technology. Finally, the thermodynamic specific energy consumption (SECthe) is the theoretical minimum value to heat up and cool down the polymer in order to obtain a conforming production.

SECe can be estimated after measuring the energetic performance of a production line for a long period of time. SECa can be measured and calculated using monitoring techniques during short time lapses. SECtec is unknown a priori, but it can be estimated if the energetic class of the injection molding machine is known (for example, under Euromap 60.1 [14]) or after applying a Design of Experiments (DoE) on the process variables [11], [12].

For SECsa estimation, local and global scopes can be used. In the local scope, SECsa can be calculated using the minimum historical value obtained to produce a part in the plant, similar to the one that is going to be analyzed. This approach is recommended for large injection molding plants. A global scope considers the best commercially available technology, for example the Class 10 in EUROMAP 60.1 [14].

Based on the five SEC definitions, four different gaps can be considered:

- The production energy gap is related to the difference between the effective and the apparent SEC values. This gap can be reduced by improving the production program, reducing the lead times, maximizing the utilization of the installed capacity, reducing reference time changes, etc.

- The process energy gap is related to the differences between the apparent and technological SEC values. This gap can be reduced by optimizing the processing parameters, in order to reduce energy consumption and/or increase the productivity of the injection molding process.

- The technological energy gap is related to the difference between the technological and the state of the art SEC values. This gap can be reduced by investing in more efficient technologies (chillers, hot runner systems, molds, injection molding machines, screws, dryers, etc.)

- The R&D gap is related to the difference between the state of the art and the thermodynamic SEC values. The reduction of this gap is the challenge of machine and processing technology developers.

Based on the gap value and the required investment, the intervention priority can be defined. This methodology has been successfully used in several injection molding production lines.
3. Energy Gaps Methodology in Injection Molding

Three industrial successful interventions for production, process and technology gaps are presented.

3.1. Reduction of the Production Energy Gap

A good production schedule is key to reduce the production energy gap. A company with eleven machines to produce containers of weights between 3 and 26 g was intervened. Energy consumptions and production rates were measured in each machine and mold. The energy consumption during the machines starting-up was measured. The machines were turned on every morning.

A process capability analysis was applied showing it was possible to use less machines to satisfy the production demand. As can be seen in Figure 3, machines 1, 2, 7, 9 and 10 presented low occupancy. The study concluded that the production can be supported with nine machines as can be seen in Figure 4.

Therefore, without using the machines 1 and 2, an energy demand reduction of 12 kW was expected. The energy consumption before the changes was 1669 kWh/day, with 560 kg/day (SEC =2.98kWh/Kg). The energy consumption after the changes was 1591 kWh/day with 560 kg/day (SEC =2.84kWh/Kg), reducing by 4.7% the specific energy consumption per month.

On the other hand, the starting-up process was improved. Before the intervention, the company turned on the machines without any schedule (sometimes they were turned on a couple of hours before production). By defining that the machines should be turned on 30 minutes before the production starts, machine 5 reduced the starting-up energy consumption by 57.4% and machine 8 by 41.13%.

3.2. Reduction of the Process Energy Gap

The reduction of the process energy gap is related to the optimization of the processing parameters to reduce energy consumption, increase productivity and reduce non-conforming products. The energy distribution in injection molding must be analyzed in different ways because each part of the cycle has different levels of consumption.

There is no general rule to optimize an injection molding cycle. For example, for large parts, the plasticizing stage may have an energy consumption between 35 and 45% of the total cycle consumption, and the remaining cooling time can represent between 20 and 30%. On the other hand, the most critical energy consuming stages in small parts can be the mold filling and the mold movements.

Because machine, mold, and material, work together the behaviors, limitations and capabilities of each one should be taken into account in order to improve the system.
efficiency. The understanding of the injection molding process, machine capabilities, mold limitations and the product quality requirements (weight, dimensions, etc.) is critical to reduce the process energy gap. The strategy is to change cycle parameters (temperatures, reduce cooling, optimize plasticization, etc.), without affecting the quality of the product.

In this case study, an injection process of an automotive part with 1.3 kg of weight was improved. The part was made of PP reinforced with glass fiber. The product was manufactured in a hydraulic machine with two drives and with 800 tons of clamping force. For the study, one drive (blue line in Figure 5) and the total machine consumption were analyzed. Hot runner bands and chiller system were not considered. Figure 5 shows the energy demand vs time of the initial injection molding cycle. Each vertical line represents the end of each stage.

The energy consumption distribution in the cycle can be presented in two ways. In Figure 6, the distribution is presented per cycle stage. In this way, it is possible to identify the stages that consume more energy in order to prioritize the solution. Figure 7 shows the distribution per groups: mold movements, filling and packing, plasticizing and base consumption.

Base consumption (red area in Figure 7) is the energy required by the machine to keep the material inside the plasticizing unit at the melt temperature without machine movements. This consumption depends on the heating bands and the hydraulic drive motor. In the filling and plasticizing stages (green and yellow areas in Figure 7), a different behavior of the base consumption is expected, since viscous dissipation generates heat, heater energy demand is reduced. For this reason, base consumption is not considered during these stages.

When the main consumer group is the base consumption, efforts must be oriented to reduce melt temperature, cooling times and mold movement times. When the main consumer group is the plasticizing, an optimization of temperature melt, plasticizing velocity and counter pressure is required. If the main consumer is the filling/packing stage, filling velocity profile, melt temperature, mold temperature, packing pressure and packing time must be optimized. As can be seen in Figure 8, the opportunities for the study case of energy consumption reduction are first in the plasticizing group, followed by the base and filling/packing groups.

As can be seen in Figure 5, the initial cycle time was 91.5s, with a total cooling time of 33s (20s plasticizing plus 13s of remaining cooling time), obtaining a SEC of 0.48 kWh/kg. Considering that the average part thickness is 3 mm, the melt temperature is 210°C, the wall temperature is around 50°C and that the part can be demolded at 80°C, the cooling time can be theoretically reduced to 23 s.

In order to reduce the energy consumption during plasticizing, the plasticizing unit was evaluated at different temperatures and speeds (Figure 8, S2 PP Screw). The best performance was obtained with speeds around 50% and temperatures below 215°C. At this speed, the plasticizing time is much longer than the cooling time. Productivity (short cycle time) is usually economically more important than energy consumption. Therefore, the plasticizing velocity was defined at 80%.
Based on simulation results, the switchover point, the injection velocity profile and packing pressure were adjusted. The mold movement parameters were selected based on the most energy efficient case registered during the intervention.

At the end, the SEC was reduced from 0.48 kWh/kg to 0.33 kWh/kg, achieving 15% reduction on energy consumption and 13s of cycle time reduction, with changes only in processing parameters. The impact is even larger taking into account that the hot runner temperatures were reduced.

### 3.3. Reduction of the Technological Energy Gap

Most of the machine producers are concerned for energy performance. In plastic fairs, machine SEC values are usually reported. The reduction of the technological gap requires investment and/or suitable selection of technologies.

In this case study, the impact of the right technology selection is illustrated. A company had two machines with the same characteristics, but with different screws, one for PA (S1), and the other for PP (S2). Due to the production demand, they began to produce PP parts with the S1 screw, which was designed for PA products. Near 80% of their products are made of PP.

A Taguchi DoE with 3 levels, 2 factors and 3 runs for each point, was applied in order to evaluate the plasticizing performance of every screw. PP with glass fiber was used, considering values of 40%, 60% and 90% of screw speed, and melt temperature of 215°C, 230°C and 245°C.

Figure 8 shows a surface comparing the energy consumption of both screws. At any condition, the performance of S2 is better than the performance of S1, obtaining an energy reduction between 15 and 29%.

Similarly, plasticizing times are shorter for S2, obtaining time reductions between 2 and 7.9 s, as shown in Table 1.

Assuming that the plasticizing stage represents around 40% of the cycle energy consumption, only by using screw S2 instead of S1, the plant can reduce between 5 and 9% the energy consumption in their PP products (80% of the portfolio).

### 4. Conclusions

The reduction of energy consumption in injection molding is related to the technology (injection molding machine, mold, chillers, etc.), production (lead times, capabilities, and reference changes) and process conditions. In order to prioritize the interventions, the methodology of energy gaps is proposed, which takes into account energy consumption, productivity and quality.

The reduction of the process and production gaps usually does not require investments, but it needs a deep knowledge of the process and an important plant effort to lift and analyze information. The technological gap requires investments and therefore financial analysis.

In order to successfully apply the Energy Gaps Methodology, management, cultural and technical efforts are required to obtain a better energy performance within a productive plant.

### 4. Acknowledgments

The authors gratefully acknowledged the technical and financial support of the following organizations and companies in the region: ICIPC- (Instituto de Capacitación e Investigación del Plástico y del Caucho), EAFIT University, Colciencias (Administrative Department of Science, Technology, and Innovation of Colombia), Acoplasticos, Día S.A.S., Colauto S.A., Sofasa S.A., Tecnoplast S.A., Intecplast S.A.S., Lapetco S.A., Haceb S.A., Formacol S.A., Sumicolor S.A., and Extrusiones S.A.

**Table 1. Performance comparison between plasticizing units S2 and S1.**

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Plastication Speed [%]</th>
<th>Time Difference [s]</th>
<th>Energy Consumption Difference [%]</th>
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5. References


