



Optimization of mold thermal control for minimum energy consumption in injection molding of polypropylene parts

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ABSTRACT

The environmental impact of the injection molding process is mostly due to electricity consumption. This is particularly significant for packaging products, which are the largest application sector for the plastics industry. In this work, electricity consumption measurements of the process were performed, considering a large production plant processing polypropylene packaging parts. In particular, the electricity consumption of mold thermal control was analyzed and minimized through a representative case study. The effects of alternative configurations of cooling channels and different process parameters were experimentally and numerically investigated, considering both the electricity consumption and the molded parts quality. The results indicated that the industrial common practice of maximizing the water flow rate and connecting the mold cooling circuits in parallel, to minimize the increase of coolant temperature, can be satisfactory in terms of part quality but not optimal when considering the energy consumption related to mold thermal control. By setting the hot runner and nozzle temperatures to the lowest suitable values, the coolant flow rate could be reduced significantly (–66%) without compromising the quality of the molded parts and reaching a minimum value of the energy consumption.

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1. Introduction

The increasing competitiveness of the current industrial environment has led to a shifting of the focus from the product to the integrated production system, making companies responsible also for the sustainability of the manufacturing processes (Ribeiro et al., 2013). Energy savings and emissions reduction related to manufacturing are crucial issues, especially considering large-scale processes, such as injection molding (Lucchetta and Bariani, 2010). Indeed, the higher the process diffusion the more significant the reduction of its environmental impact due to a slight increase in its overall efficiency (Thiriez and Gutowski, 2006).

The assessment of the environmental impact of the plastic industry started more than 40 years ago (Boustead, 1992), when manufacturing enterprises started implementing energy consumption evaluation in order to improve both their economic benefit and environmental performance (Wang et al., 2013). Since then the energy issue in injection molding has become more and more crucial (Givens and Jorgenson, 2013; Czap and Czap, 2010;

Mianehtrow and Abbasian, 2017; Zhang et al., 2017). Indeed, the continuously increasing cost of energy and the rising number of market competitors have been further pushing manufacturers towards new improvements and optimization of the injection molding process (Lucchetta et al., 2006). In this context of high-energy consumption, there is a great potential for increasing injection molding efficiency through process optimization (Park and Nguyen, 2014; Cellere and Lucchetta, 2008). Consequently, researchers have been aiming at improving injection molding environmental performance by providing the designers with solutions to optimize electricity consumption (Weissman et al., 2010; Elduque et al., 2015).

The energetic impact of the injection molding process is particularly important for the packaging industry, which is the leading injection molded plastics application segment and constitutes about the 40% of the demand for plastics, thus having a large impact on the plastic manufacturing economy (PlasticsEurope, 2015). In particular, among the commodity plastics used in this industry, polypropylene has emerged as the largest raw material segment and accounted for over 35% of total demand in 2014 (Grand View Research, 2015). Injection molding plants for packaging products commonly function on 24 h shifts for 7 days a week, thus being particularly intense in terms of electrical energy

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Abbreviations			
t_c	cycle time	Q	coolant flow rate
Q_m	flow rate in the cooling circuit of the mold	T_{hr}	temperature of the hot runner system
ΔT_m	temperature difference between inlet and outlet in the cooling circuit of the mold	T_b	nozzle temperature
Q_p	flow rate in the cooling circuit connecting the chiller to the mold	P_h	packing pressure
ΔT_p	temperature difference in the cooling circuit connecting the chiller to the mold	P_t	thermal power required to maintain the set mold temperature
P_e	electrical power absorbed by the injection molding machine	$P_{t,m}$	fraction of P_t required by the mold
<i>MFR</i>	Melt Flow Rate	$P_{t,p}$	fraction of P_t required for the function of the injection molding machine
<i>Re</i>	Reynolds number	P	density of the cooling water
<i>DoE</i>	Design of the Experiment	c_p	specific heat capacity of the cooling water
		E_e	energy consumption
		<i>SEC</i>	Specific Energy Consumption
		w	weight of the molded polymer (part and runners)

demand, because of the high-power absorption related to the functioning of main injection molding machines units (i.e. injection, clamping and cooling units) (Müller et al., 2014).

Moreover, the energy efficiency of injection molding plants for packaging products is usually not properly controlled because of its common configuration, in which all of the molds and the injection molding machines are connected to a centralized chiller without dedicated thermal control equipment (Godec et al., 2012). In fact, in this high-throughput industrial sector, due to the markedly high consumption of a single commodity plastic (e.g. polyethylene, polypropylene or polystyrene), it is common practice to have only one material being processed in the whole plant. Consequently, each mold temperature is controlled by the temperature set in the water chiller, which is the same for all the molds. This configuration is economic, since dedicated temperature controllers are not needed, but it can be negative in terms of quality of the molded parts and overall energy consumption of the plant.

The reduction of the energy consumption in injection molding is usually pursued by following two different strategies: improvement of machinery (i.e. hardware and auxiliary equipment) or optimization of the processing parameters (Park and Nguyen, 2014). Despite intervening on machines can be demanding in terms of investments compared to the optimization of process parameters (Lu et al., 2012), most of the studies reported in the literature focused their analysis on the former, without considering the potential improvement offered by process optimization (Madan et al., 2015).

As far as the cooling equipment is concerned, the energy performance of the process can be improved in different ways. In particular, isolating the mold from the cooling network of the plant can lead to improved accuracy in the control of mold temperature, which ultimately allows for a reduced energy consumption (Godec et al., 2012). Indeed, the settings for the coolant flow (i.e. temperature and flow rate) can be accurately defined and set for each mold (Choi et al., 2012).

The complexity of the injection molding process and the interactions between auxiliary equipment, mold design and process parameters make the reduction of energy consumption by optimization of mold thermal control particularly complex (Mattis et al., 1996). Therefore, it is necessary to systematically monitor and analyze the electricity consumption of each injection molding machine and the temperature and flow rate of the coolant for each mold. The conventional trial-and-error approach applied in the industry can lead to quality issues in the parts, which are then difficult to control whilst aiming at reducing the energy consumption. Moreover, industrial common practice is usually inspired

by general guidelines, such as maximize the water flow rate and connect mold cooling circuits in parallel to minimize the increase of coolant temperature (Kazmer, 2007). Exalting these guidelines without measuring their energy impact in any specific case can lead to significant inefficiencies. A systematical approach to the optimization of process and cooling parameters should consider both energy consumption and the quality of the parts (Qureshi et al., 2012).

In order to support this consideration with experimental evidence, in this work the impact of mold thermal control on the injection molding energy consumption was investigated. This is the first work specifically focused on mold thermal control for minimum energy consumption in injection molding. The analysis of the efficiency of the mold cooling system adopted in a mono-material injection molding plant for packaging products was studied by carrying out an audit of the electrical consumption and the coolant heat flow rate for 86 monitored molds. Different configurations of cooling channels were analyzed considering the heat flow rate and the quality of the molded parts. The effect of process parameters was then analyzed and optimized considering the energy consumption of the injection molding machine, the chiller and the water circulation pumps.

Section 2 describes the injection molding plant for which the energy consumption was analyzed, the product and mold designs and the equipment used for monitoring the electricity consumption and the coolant heat flow rate. Section 3 discusses the injection molding setup considered for the optimization of the cooling phase. The results of the initial energy consumption audit and of the optimization are presented and discussed in Section 4. A cost analysis, described in Section 5, allowed the evaluation of the impact of optimization of mold thermal on possible economic savings. Concluding, Section 6 reports the main results indicating how the energy consumption related to mold thermal control can be evaluated and what are the possible approaches to its reduction.

2. Materials and methods

2.1. Description of the injection molding process

Injection molding machines consist of four key units: injection, clamping, drive and control units (Elduque et al., 2015; Park and Nguyen, 2014; Mianehrow and Abbasian, 2017). The sequence of events during the injection molding of a plastic part is shown in Fig. 1. The cycle begins when the mold closes, followed by the injection of the molten polymer into the mold cavity, which is cooled to force a rapid solidification of the part. Once the cavity is filled, a

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