Journal of Cleaner Production 148 (2017) 804–810

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Energy monitoring of plastic injection molding process running with hydraulic injection molding machines

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ARTICLE INFO

Article history:
Received 11 June 2015
Received in revised form
11 January 2017
Accepted 7 February 2017

Keywords:
Injection molding machine
Specific energy consumption
Energy efficiency
Energy consumption profile
Process related parameter
Machine related parameter

ABSTRACT

With respect to the importance of energy consumption reduction in industrial plants, an attempt has been made to specify the most important parameters affecting energy consumption of plastic injection molding process as one of the most energy intensive processes in plastics industry. In this regard, the specific energy consumption of six hydraulic injection molding machines and the profile of their energy consumption over one cycle of injection molding process were measured to assess the effect of different machine related and process related parameters on energy consumption and realize energy saving opportunities in the injection molding process. Results showed that among all quantitative parameters, throughput and total cycle time, which are process related parameters, have the most important impact on the specific energy consumption of the process. Whereas, the most important effect of machine related parameters were found to be on the peak power of energy consumption, which gives an insight to industrial plants how to reduce the maximum electrical demand of the plant. In addition, it was proved that each hydraulic injection molding machine has a unique profile of energy consumption depending on the design of the machine and process, and then according to these profiles, three types of process designs were identified.

1. Introduction

Energy saving is one of the most important concerns in industrial plants. Among different industries, the plastics industry is one of the biggest energy consumers (Elduque et al., 2015; Pun et al., 2003), and injection molding process, which produces a very high portion of plastics parts in the market, counts as the most energy intensive process in this industry (Elduque et al., 2015; Park and Nguyen, 2014; Pun et al., 2003; Spiering et al., 2015). Therefore, investigating the energy saving opportunities for this process seems to be quite important, and any reduction in its energy consumption will result in a significant amount of energy saving in the whole plastics industry.

Generally, the injection molding process works with three basic types of injection molding machines (IMMs): hydraulic, all-electric and hybrid ones that mainly differ in the actuation method used for screw rotation, injection, and clamp motions (Socks, 2005). Although all-electric and hybrid IMMs consume considerably lower energy than hydraulic ones, they have some operational limitations in the production of parts that require high screw velocity or high clamping pressure (Kanungo and Swan, 2008). Therefore, understanding the energy saving opportunities in hydraulic IMMs, as the most energy consumer machines in the plastics industry, seems to be an important concern (Madan et al., 2015; Park and Nguyen, 2014; Spiering et al., 2015).

Energy saving methods developed for hydraulic IMMs are based on two general approaches. One approach is changing the machine design and the other one is related to the optimization of process settings (Lu et al., 2012; Madan et al., 2015; Park and Nguyen, 2014). To apply each of these approaches, it is necessary to have a comprehensive understanding about the importance of machine related and process related parameters listed in Table 1.

It is worth noting that unlike the importance of energy efficiency improvement in hydraulic IMMs, less attention has been paid to this matter and sparse studies have been published on this subject up to now. Most of the published researches on injection molding process are more focused on parameter optimization and

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http://dx.doi.org/10.1016/j.jclepro.2017.02.053
0959-6526/

life cycle assessment (Elduque et al., 2015; Ferreira et al., 2010; Lu et al., 2012; Madan et al., 2015; Park and Nguyen, 2014; Pun et al., 2003; Spiering et al., 2015), whereas, a few of them tried to investigate the effect of machine or process related parameters on energy consumption of this process. Among them, Muller et al. (Müller et al., 2014) assessed potentials for energy efficiency improvement in the injection molding process by considering two approaches: reducing the process time and decreasing the power level, and showed by considering these two approaches, respectively 15% and 60% reduction in energy consumption is reachable. Ambs and Frerker (1998) and Englander and Remley (1994) in separate studies investigated the effect of motor and pump types on energy consumption of hydraulic IMMs and reported that the change in the type of motors and pumps respectively resulted in 60% and 20% of energy consumption reduction for the whole process. In another work, Taylor et al. (2007) investigated the relative energy consumption of induction barrel heating and band heaters during injection molding process and reported by changing the type of barrel heaters, the efficiency of heating increases up to 60%, which has a direct effect of energy consumption of the whole process. Ruberg et al. (2008) investigated the role of screw design on energy consumption of IMMs and reported a screw with efficient design could result in the energy consumption reduction of up to 3%. In a completely different work, Kelly et al. (2006) investigated the effect of the age of hydraulic IMMs on their energy consumption and showed that newer machines consume less energy than the older ones.

As it is stated in previous paragraph, each of these studies explored the effect of one or two of the important parameters affecting energy consumption of hydraulic IMMs, and it seems that the interaction between machine and process related parameters and the explanation of their energy consumption profile are left behind. In addition, it is obvious that there are possibilities to reduce the energy consumption of an old machine by changing the process parameters or retrofitting its motors and pumps, but it is not clear that change in which item is more efficient: process parameters or machine design.

It is worth noting that in real working condition, it is difficult to investigate the effect of all above mentioned parameters at the same time. However, to compare the energy efficiency of different IMMs with different process settings, the specific energy consumption (SEC), which is defined as the energy consumed per one kilogram of processed polymer (kWh/kg), can be used as a comparison measure (Thiriez and Gutowski, 2006) (Giacone and Mancò, 2012), because, all the process and machine-related parameters show their effects on the SEC.

In this work, the effect of process related and machine related parameters on SEC of hydraulic IMMs, in a real working condition, is investigated to provide a general insight about more influential parameters and energy efficiency improvement opportunities. In addition, the energy consumption profile of the tested machines, during one cycle of injection molding process, has been assessed in details to understand the effect of the energy consumption profile on SEC of hydraulic IMMs.

2. Description of 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; Pun et al., 2003; Spiering et al., 2015). Generally, in an injection molding process, the injection unit receives the raw material through the hopper, heats it up by heater bands, screw rotates until it melts, and injects the molten plastic into the mold; then the clamping unit holds the part under pressure until the produced plastic part cools down and solidifies. In addition, the mechanical force for closing, clamping and opening the mold is provided by this unit. The drive unit provides the required energy for mechanical components and varies between different types of IMMs and the control unit controls the process parameters, e.g. oil level (in the case of hydraulic machines), barrel temperatures, clamping forces and flow rates of the pumps (Kanungo and Swan, 2008).

Therefore, an injection molding cycle can be described in eight steps: mold closing, clamping, injecting, holding, plastification, cooling, mold opening, and ejecting (Ambs and Frerker, 1998; Kanungo and Swan, 2008; Socks, 2005). It is worth noting that plastification, clamping and injecting phases are the most energy consuming stages in an injection molding cycle (Thiriez, 2006). Moreover, if the plastification of the polymer for the next cycle is completely finished but the part in the mold still requires more cooling time, there will be also an idle period in the injection molding cycle, in which the least hydraulic power is required, whereas the machine power supply doesn't change (Ambs and Frerker, 1998; Socks, 2005).

3. Test methods

The product related SEC of six hydraulic IMMs was measured according to the Euromap-60.2 recommendation as a standard test method (EUROMAP 60.2). The cumulative power usage of each machine was measured by TES-3600 power analyzer instrument (with five second time interval of sampling record) over a period of two hours. Then, the cumulative power usage was divided by the weight of the processed polymer over the mentioned time, and each measurement was done for three times. It is worth noting that these machines, which all were from famous machine manufacturers, were chosen according to their clamping force and their processed material. In addition, the experiment was done in the summer of 2014 in Mehr Cam Pars industrial plant, Tehran, Iran.

For investigation of energy consumption profile per one cycle of injection molding process, energy usage of each machine was recorded in 5-s intervals by the same instrument. The acquired data was plotted as graphs of energy usage versus time for each machine.

The tested machines were placed in two groups depending on their clamping force (a force that holds the mold closed during injection and cooling stages). It is obvious that high clamping force machines (clamping force around 3000 tonne) consume significantly more cumulative energy than low clamping force ones

Table 1
List of machine related and process related parameters.

Machine related parameters	Product related parameters
Type of motors and pumps (Ambs and Frerker, 1998; Englander and Remley, 1994; Socks, 2005; Thiriez, 2006)	**Total cycle time** (Brincat and Speight, 2009; Krishnan et al., 2009; Thiriez, 2006)
Control system (Anguita et al., 2002; Wei and Horowitz, 1999)	**Injection pressure** (Ambs and Frerker, 1998; Socks, 2005)
Screw design (Ruberg et al., 2008)	**Injection speed** (Ambs and Frerker, 1998; Socks, 2005)
Type of barrel heaters (Taylor et al., 2007)	**Throughput** (Elduque et al., 2015; Spiering et al., 2015; Thiriez and Gutowski, 2006)
Age (Kelly et al., 2005)	