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# Single screw extrusion control: A comprehensive review and directions for improvements

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A R T I C L E I N F O

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A B S T R A C T

Polymer extrusion is usually a complex process, particularly due to the coupled nature of process parameters, and hence highly prone to fluctuations. Although a number of different approaches have been attempted in research/industry over the last few decades for extrusion control, it is still experiencing some problems in achieving consistent product quality. Presently, most of the polymer processing extruders are equipped with PID controllers mainly for the control of the screw speed and barrel temperatures in their set limits. It seems that only both of these controllers are commonly used as the major aids of process control to achieve the required melt quality. Although, the quality of the melt output (i.e., a thermally homogeneous melt output which is constant in quantity and quality over the time) is the key variable in polymer extrusion, only a few control techniques are available which make control decisions by observing the actual melt flow quality. Therefore, the development of new control strategies which consider the actual melt quality, perhaps incorporating industrially popular nonlinear techniques such as artificial intelligence, should be highly valuable. In this work, a critical evaluation is made on the state-of-the-art of the previous control approaches in polymer extrusion in industry and research while identifying their limitations. Then, some of the possible directions for future research and also to develop an advanced process control strategy are presented by eliminating a few of the existing limitations.



## 1. Introduction

It is obvious that the global energy demand has been increasing rapidly over the last few decades. Meantime, it has been predicted that there will be a scarcity of available energy sources in the world within the next few decades and hence the energy prices are continually increasing (The global energy crisis, 2014). In general, it is well-known that a significant portion of the global annual energy production is consumed for the transportation purposes (Bredenberg, 2014) and hence scientists are exploring ways and means to cut down the energy usage particularly in the transport sector. Here, the replacement of the conventional raw materials such as metal, glass, wood, etc. with the advanced polymeric materials with a high strength to weight ratio has been becoming one of the potential solutions. In addition to the significant reduction of weight, polymeric materials offer a number of other advantages such as ease of forming into complex shapes, high temperature/chemical/impact resistance, high clarity, reprocessability, low cost, etc. over other materials. Therefore, polymeric materials have become widely popular not only in the transport sector but also in construction, medical, electrical and electronic, household applications as well. Under these circumstances, polymer processing techniques are becoming highly important production methods in the industry. Among the polymer processing techniques, extrusion can be recognised as one of the fundamental methods and hence the improvements of the process monitoring and control will be highly useful for catering the growing demand with good quality products at low unit cost. Moreover, such improvements should help to minimise the process related common problems such as long downtimes, waste of material, energy, labour, etc. which offer several economic benefits.

Polymer extrusion is usually involved in the final production of many polymer products such as pipes, films, sheets, tubes, rods, etc. It is also an intermediate processing stage in injection moulded, blown film, thermoformed, and blow moulded products. An extruder is a machine which processes material by conveying it along a screw and forcing it through a die at a certain pressure. The screw is the key component of an extruder and it has been divided into three main functional/geometrical zones (i.e., solids conveying or feed, melting or compression, and metering or pumping) which are generally based on the primary operations of an extruder as shown in Fig. 1.

The feedstock material fed into the machine through the hopper is conveyed along the screw while absorbing the heat provided

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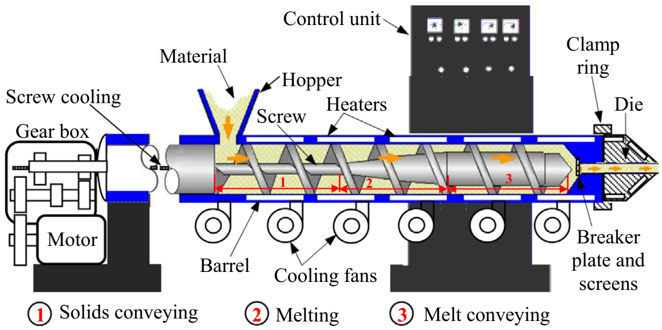


**Fig. 1.** Basic components of a single screw extruder.

by the barrel heaters and through process mechanical work. Eventually, a molten flow of material is forced into the die which forms the material into the desired shape. In general, the main function of an extruder is to deliver a homogeneous, well mixed polymer melt at specified uniform temperature and pressure. In order to accomplish this requirement, extruders are generally equipped with an efficient drive and a feed system, a screw designed to melt and convey the polymer and devices such as temperature and pressure sensors which are required to monitor the system for troubleshooting and control. More details on the process operation and mechanisms of polymer extrusion can be found in the literature (Abeykoon, 2012a; Rauwendaal, 2001; Stevens & Covas, 1995).

In spite of the significant improvements in polymer extrusion field over the last few decades, process thermal monitoring and control still remain an issue. Process operators have to face challenges in achieving the required quality of the melt output (e.g., melt flow thermal stability/homogeneity, consistency of the flow rate, etc.) with prevailing knowledge and technology. For example, achieving good thermal stability is a key to form high quality extruded products as thermal fluctuations may cause to generate problems in physical and mechanical properties of the products. Therefore, continuous and accurate monitoring of the major process variables and also the use of advanced process control strategies are highly invaluable to form good quality melt output.

### *1.1. Importance of improved process monitoring and control*

The key idea behind the process monitoring is to identify inherent process problems and to develop strategies to control them, both through machine design and process operation. Obviously, the performance of the process control strategies depends on the accuracy and the quality of the process monitoring techniques (i.e., depends on how good process problems are identified and understood). An accurate control cannot be achieved if the process cannot be monitored accurately (Coates, 1995). Overall, process control relates to the selection and tuning of processing conditions to maintain the process efficiency and product quality for a specific material and a machine. In fact, the main objective of any process controller is to achieve good quality products while achieving a better process efficiency in terms of the use of material, energy, labour, time, etc.

In polymer extrusion, melt output from the machines should be uniform throughout the process (i.e., the uniformity of the melt temperature over the time and temperature homogeneity across the melt flow) to achieve good quality products. Temporal thermal variations of melt output may cause to generate variations of melt pressure resulting in output rate variations, non-uniformities of optical/mechanical/chemical properties of the extruded parts, extrudate with un-melted particles, etc. (Squires & Wolf, 1971). In fact, process problems can occur due to the variability of processing materials (Brown, Kelly, & Coates, 2004a; Fenner, 1979; Gogos & Kim, 2000), machine geometry (Béreaux, Charmeau, & Moguedet, 2009; Kelly, Brown, & Coates, 2005, 2006; Rauwendaal & Sluis, 2004; Wilczyñski, 1989) and process settings (Brown et al., 2004a; Gitschner & Lutterback, 1984; Kelly, Brown, & Coates, 2006; Rauwendaal, 2001; Wood & Rasid, 2003). Obviously, the processing problems attributed to the machines' functionality (e.g., screw misalignments, vibrations of machine parts, inaccuracies of screw design) have to be addressed at the stage of machine design and the selection of optimum operating conditions may be the most important factor to achieve process requirements for a given machine and a material. In such a situation, having a process controller which can accurately detect and control process problems is invaluable.

Although the quality of the melt output seems to be the major consideration in polymer extrusion, it seems that not many control techniques are available which make control decisions by observing the actual melt flow quality. This may be due to the practical difficulties of monitoring the melt quality across the flow cross-section without disturbing the melt flow. Presently, most of the polymer processing extruders are equipped with speed controllers (i.e., to maintain the screw speed within set limits) and temperature controllers (i.e., to maintain the barrel zone temperatures within their set limits). Both of these controllers are commonly used as the major aids of process control to achieve the required melt quality. The feedback for speed control is obtained via instruments such as tachometer generators (i.e., a device which can convert the measured speed into an analogue voltage signal) while temperature feedback is usually obtained from the thermocouples attached to the extruder barrel/die wall. In fact, the availability of a controller which makes necessary control decisions by observing the actual quality of the melt (by using an appropriate measurement technique) would be highly useful rather than maintaining the barrel set temperatures and/or screw speed within their set limits without obtaining any feedback on the actual melt quality. Based on this background, further research to improve the process control in polymer extrusion was timely and hence this study was mainly focused on exploring possible directions for possible improvements. Initially, a critical evaluation of the previous extrusion control approaches are presented while identifying their capabilities and limitations. Then, the current limitations relating to the extrusion control are discussed while proposing possible directions for developing advanced control approaches for polymer extrusion control.

### *1.2. Approaches in polymer extrusion control*

#### *1.2.1. Melt temperature and/or pressure control*

Control schemes based on temperature and/or pressure have been prevalent since the late 1970s. Several researchers attempted to control the melt temperature and pressure as an indirect approach of controlling the melt viscosity due to the difficulties encountered in real-time viscosity monitoring. Melt temperature control helps to avoid viscosity fluctuations (for a consistent feed material) and thermal degradation of the material. Stable pressure generation ensures a consistent mass flow rate. Initially, several researchers used linear Laplace transform techniques to develop control schemes relating to extrusion melt temperature and pressure via proportional-integral-derivative (PID) algorithms. Later, some other researchers used time series techniques for temperature and pressure control, which are capable of developing more sophisticated models allowing identification and control of process disturbances.

*1.2.1.1. Control schemes based on Laplace transform or time series models.* The first study on the dynamic extruder pressure was carried out by White and Schott (1972) in early 1970s. Step and