Applied Energy 136 (2014) 726–737

Contents lists available at ScienceDirect

Applied Energy

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

Investigation of the process energy demand in polymer extrusion: A brief review and an experimental study

Chamil Abeykoon [a,*], Adrian L. Kelly [a], Elaine C. Brown [a], Javier Vera-Sorroche [a], Phil D. Coates [a], Eileen Harkin-Jones [b], Ken B. Howell [a], Jing Deng [c], Kang Li [c], Mark Price [b]

[a] IRC in Polymer Science and Technology, School of Engineering, Design and Technology, University of Bradford, Bradford BD7 1DP, UK
[b] School of Mechanical and Aerospace Engineering, Queen's University Belfast, Belfast BT9 5AH, UK
[c] School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, Belfast BT9 5AH, UK

HIGHLIGHTS

- Energy consumption and losses in polymer extrusion are discussed.
- This compares energy consumption in polymer extrusion at different conditions.
- The role of power factor on energy efficiency in polymer extrusion is explored.
- Empirical models on extruder energy consumption are provided.
- Computer modelling of energy consumption of polymer extrusion is performed.

ARTICLE INFO

Article history:
Received 13 October 2013
Received in revised form 5 September 2014
Accepted 8 September 2014
Available online 17 October 2014

Keywords:
Polymer extrusion
Process monitoring
Energy consumption
Energy efficiency
Power factor
Modelling

ABSTRACT

Extrusion is one of the fundamental production methods in the polymer processing industry and is used in the production of a large number of commodities in a diverse industrial sector. Being an energy intensive production method, process energy efficiency is one of the major concerns and the selection of the most energy efficient processing conditions is a key to reducing operating costs. Usually, extruders consume energy through the drive motor, barrel heaters, cooling fans, cooling water pumps, gear pumps, etc. Typically the drive motor is the largest energy consuming device in an extruder while barrel/die heaters are responsible for the second largest energy demand. This study is focused on investigating the total energy demand of an extrusion plant under various processing conditions while identifying ways to optimise the energy efficiency. Initially, a review was carried out on the monitoring and modelling of the energy consumption in polymer extrusion. Also, the power factor, energy demand and losses of a typical extrusion plant were discussed in detail. The mass throughput, total energy consumption and power factor of an extruder were experimentally observed over different processing conditions and the total extruder energy demand was modelled empirically and also using a commercially available extrusion simulation software. The experimental results show that extruder energy demand is heavily coupled between the machine, material and process parameters. The total power predicted by the simulation software exhibits a lagging offset compared with the experimental measurements. Empirical models are in good agreement with the experimental measurements and hence these can be used in studying process energy behaviour in detail and to identify ways to optimise the process energy efficiency.

1. Introduction

Polymers are among the most important materials available today. Many conventional raw materials such as steel, glass and wood are being replaced by various types of polymeric materials or polymer composites which perform the same function while offering a number of advantages including low density and ability to form readily into complex shapes. As a result, the demand for polymeric materials has shown a rapid increase over the last few decades. Records show that the world total plastic production in the years 1950, 1976, 1989, 2002 and 2010 was 1.3, 50, 100, 200 and 304 millions of tonnes, respectively [1]. Moreover, world

* Corresponding author.
E-mail addresses: c.abeykoon@glyndwr.ac.uk, yabeykoon01@qub.ac.uk (C. Abeykoon).

http://dx.doi.org/10.1016/j.apenergy.2014.09.024
0306-2619/© 2014 The Authors. Published by Elsevier Ltd.

plastics production in volume surpassed that of steel in 1981 and the gap has been continuously increasing since then [2]. The demand for polymeric materials is forecast to further increase.

1.1. Polymer extrusion

Various types of polymer processing extruders are currently in use in industry including single/multi screw extruders and disk/drum extruders. Of these extruders, single screw continuous extruders are the most commonly used [3]. The screw is the key component of an extrusion machine and can be divided into three main functional/geometrical zones (i.e. feed or solids conveying, compression or melting, and metering or melt conveying) in the case of simple, single flighted screw geometries. The feedstock material fed into the machine through a hopper is conveyed along the screw while absorbing heat provided 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. More details on the process operation and mechanisms of polymer extrusion can be found in the literature [4,5].

Being a fundamental method of processing polymeric materials, extrusion is used in the production of commodities in diverse sectors such as packaging; household; automotive; aerospace; marine; construction; electrical and electronic; and medical applications. Usually, polymer processes use energy carriers in two major ways as raw materials (petrochemicals) and for processing. Typically, extrusion is an energy intensive production method and it is well-known that these processes often operate at poor energy efficiencies [3,6–8]. Although process energy efficiency is good at higher processing speeds, it is difficult to run at these conditions as thermal fluctuations increase with increasing screw speed resulting in very poor melt quality. Details on the typical melt thermal variability with increasing screw speed was discussed by the authors' previously [5,9–14]. Therefore, the majority of extrusion processes are operating at conservative rates to control or avoid problematic thermal fluctuations and this leads to poor energy efficiency. Since, global energy prices are increasing rapidly, plastics based manufacturing companies are highly concerned about the energy efficiency of their production plants in order to maximise profit margins. A major current concern in the industry is therefore to determine how to optimise energy and thermal efficiencies simultaneously while achieving the required process output rate and melt quality. The aims of this work are therefore to explore process efficiency using a highly instrumented single screw extruder with commercial grades of polymers. Then, it is expected to develop models to predict the process energy consumption which can be useful in optimising the process energy demand. Initial results are presented in this paper.

1.2. Extruder energy demand and possible energy losses

Usually, extruders are supplied with electrical energy for their operation and this energy is converted into mechanical or thermal energy. Process energy losses occur in the various stages of the operation mainly as electrical, mechanical or thermal losses. A typical energy flow diagram for an extruder is shown in Fig. 1 (not drawn to scale). Usually, the drive motor is the component which consumes the highest portion of the supplied energy to an extruder. Currently, most extruders are driven by alternating current (AC) or direct current (DC) motors. In a typical AC motor, energy losses usually occur as electrical (or copper), core, mechanical and stray losses. In addition to these four types of losses, brush loss also occurs in DC motors which use brushes for supplying the power [15]. Usually, the losses related to the drive motor have accounted for approximately 14% for a medium scale extruder [7]. The maximum energy efficiency of a motor can be achieved when it is running at the rated speed. However, as mentioned earlier, most industrial extruders are operated at conservative rates to avoid undesirable thermal and throughput fluctuations, and hence achieving the rated motor speed may not be possible. Also, these are inductive loads (as they use magnetic fields) and the total power demand is related to the power factor as given in Eq. (1) [16].

$$Power = V \times I \times \cos\phi \quad (1)$$

where V is the supply voltage, I is the current drawn by the motor and $\cos\phi$ is the power factor which ranges from 0 to 1. Usually, the power factor relates the shape of the current waveform drawn by a load to the sinusoidal voltage waveform supplied by the power supplier. For purely resistive loads, the current drawn by the load is a sinusoid which is exactly in phase with the voltage waveform and hence the power factor is unity. This is the most energy efficient operating condition. For inductive loads, the current will lag behind the voltage in phase, and hence the power factor will be less than one. Therefore the energy supplied to the load will not be used optimally. As the mains voltage is fixed, a higher current is required from the power supplier (i.e. a high apparent power than usual) to compensate for the phase shift and deliver the same usable power to the load, bringing the active power back up to the level required to do the desired mechanical work. The power supplier must build additional infrastructure to deal with low power factor conditions and pay for the higher apparent power. Due to these issues, power suppliers may charge extra capital and operating costs to the industrial users who operate with a power factor below a certain level (e.g. below 0.95) [17,18]. Obviously, these low power factor conditions are quite common with electrical motors as these are inductive loads. As a result, extrusion companies may have significant impact on their energy efficiency as the electrical motors

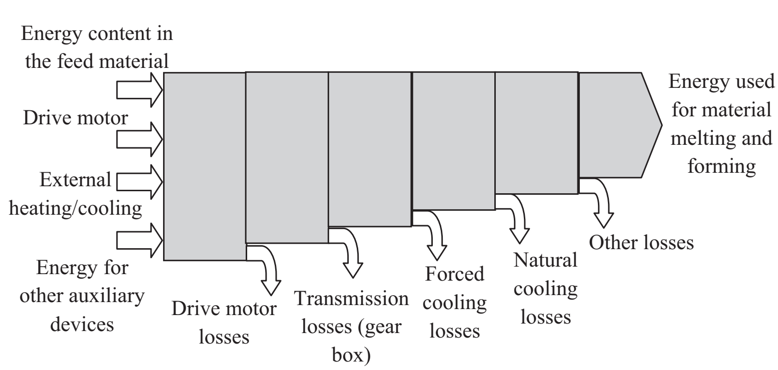

Fig. 1. A typical energy flow diagram for an extruder.