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Process efficiency in polymer extrusion: Correlation between the energy demand and melt thermal stability

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HIGHLIGHTS

- This paper discusses the energy conservation of an extruder.
- This describes the energy and thermal efficiencies in polymer extrusion.
- This explores the correlation between energy demand and thermal stability.
- This explores radial temperature fluctuations of the melt flow in extrusion.
- This models the total power demand in polymer extrusion empirically.

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ABSTRACT

Thermal stability is of major importance in polymer extrusion, where product quality is dependent upon the level of melt homogeneity achieved by the extruder screw. Extrusion is an energy intensive process and optimisation of process energy usage while maintaining melt stability is necessary in order to produce good quality product at low unit cost. Optimisation of process energy usage is timely as world energy prices have increased rapidly over the last few years. In the first part of this study, a general discussion was made on the efficiency of an extruder. Then, an attempt was made to explore correlations between melt thermal stability and energy demand in polymer extrusion under different process settings and screw geometries. A commodity grade of polystyrene was extruded using a highly instrumented single screw extruder, equipped with energy consumption and melt temperature field measurement. Moreover, the melt viscosity of the experimental material was observed by using an off-line rheometer. Results showed that specific energy demand of the extruder (i.e. energy for processing of unit mass of polymer) decreased with increasing throughput whilst fluctuation in energy demand also reduced. However, the relationship between melt temperature and extruder throughput was found to be complex, with temperature varying with radial position across the melt flow. Moreover, the melt thermal stability deteriorated as throughput was increased, meaning that a greater efficiency was achieved at the detriment of melt consistency. Extruder screw design also had a significant effect on the relationship between energy consumption and melt consistency. Overall, the relationship between the process energy demand and thermal stability seemed to be negatively correlated and also it was shown to be highly complex in nature. Moreover, the level of process understanding achieved here can help to inform selection of equipment and setting of operating conditions to optimise both energy and thermal efficiencies in parallel.

1. Introduction

Polymeric materials are widely used all over the world primarily due to their superior properties such as high strength to weight ratio; high temperature/chemical/corrosive resistance; non-conductivity; high clarity; re-processability; low cost and so forth.

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Nomenclature

a	the shift factor
C_1, C_2, T_s	empirical constants
C_p	the specific heat capacity of the material
$\overline{C}_p$	the average specific heat capacity of the polymer
D	diameter of the screw
E_{in}	the total energy supplied to the extruder
E_{losses}	the total amount of energy wasted without involving in any useful work
E_T	the theoretical energy required for melting and forming of material
E_u	the energy used for useful work
h_1	the specific enthalpy of the materials at the input
h_2	the specific enthalpy of the materials at the output
H_f	the enthalpy of heat of fusion of the materials
Δh	the changes of the enthalpy
$\dot{M}$	the mass flow rate
n	the power law index
P_1	the pressure at the input
P_2	the pressure at the output
T_1	the feedstock temperature at the input
T_2	the feedstock temperature at the output
T_r	a reference temperature
T_{mean}	the mean temperature across the melt flow
$f(T)$	the temperature function
T-IR	the temperature measured by the IR temperature sensor
$Trp - x, x = 0, 2.5, 5.0, 8.0, 11.0, 14.0, 16.5$	temperature of the melt at x mm away from the melt flow centreline (rp refers to radial position)
ΔT	the level of the melt temperature fluctuations across the melt flow
$\eta_{extruder}$	the extruder energy efficiency
ρ	the density of the material
$\bar{\rho}$	the average density of the material
$\eta_{extruder,thermo}$	the thermal efficiency of an extruder
μ	the viscosity
μ_0	the viscosity at zero shear rate
γ	the shear rate
λ	the relaxation time
ω_{sc}	screw speed

More importantly, polymeric materials are showing a great potential of saving energy consumption in aerospace, automotive, marine and transport sector. Moreover, they are quite easy to form into complex shapes compared to other conventional materials. Also, the energy requirement for processing of polymers is considerably lower than other conventional materials such as steel and glass. Perhaps, these may be among the major reasons for growing popularity of polymeric materials in diverse industrial sectors. Although the processing of polymers demands a less amount of energy compared to other materials [1], many polymer processes operate at poor energy efficiency. Usually, the specific energy consumption (SEC) in polymer extrusion reduces as processing speed increases [2,3]. However, the thermal fluctuations of the melt flow are increased as the process speed is increased [4–9]. Therefore, the majority of polymer processes are run at conservative rates to avoid thermal fluctuations at higher processing speeds. Currently, the polymer sector is under pressure to cut down excessive use of energy due to the gradual increase of energy prices in the world over the last few decades [10].

Usually, polymer extrusion is an unpredictable process and hence it is highly prone to fluctuations in nature. Moreover, the process parameters are complexly coupled each to other and hence difficult to set-up and control [7]. Therefore, the typical relationship between process thermal stability and energy efficiency may differ depending on the processing conditions; material and machine being used while the quality of the process monitoring and control also may have considerable effects. Among the polymer processing extruders, single screw continuous extruders are the most commonly used in industry [11] and that is mainly due to their low purchase and maintenance costs, simplicity of operation and the ability to generate the required pressure [12]. Therefore, this study is focused on single screw extrusion processes. More details on the process mechanisms, operational requirements, and the available process analytical techniques (PAT) of polymer extrusion can be found in the literature [13–16].

1.1. Efficiency of an extruder

An illustration of an extruder based on its energy conservation can be illustrated as shown in Fig. 1.

Then the energy used for useful work (E_u) from an extruder (i.e. the energy used for material melting and forming through the die) can be given as:

$$E_u = E_{in} - E_{losses} \tag{1}$$

where E_{in} is the total energy supplied to the extruder and E_{losses} is the total amount of energy wasted without involving in any useful work. Therefore, the extruder energy efficiency ($\eta_{extruder}$) is given by:

$$\eta_{extruder} = \frac{E_{in} - E_{losses}}{E_{in}} \times 100\% \tag{2}$$

Here, the energy inputs (E_{in}) are from the electrical energy supplied to the devices such as drive motor, motor cooling fan, barrel/die haters, barrel cooling fans, instruments in the control panel, and water pump. The energy losses which may occur in these devices and other mechanical/functional systems such as transmission, forced/natural cooling come under E_{losses}. Of the energy consuming devices, drive motor and barrel/die heaters are likely to consume more than 90% of the total energy supply while these are also responsible for the highest energy losses. In extrusion there is a little potential of useful recovery of rejected energy as these are largely released to air or water. Drury [17] argues that over 40% from the energy input to the small scale extruder is wasted through drive/transmission losses, radiation, convection, conduction losses, etc.

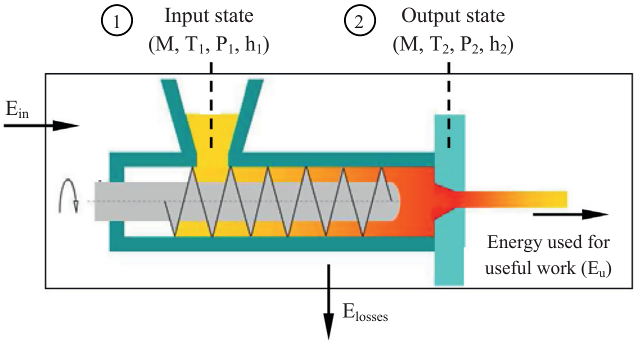

Fig. 1. An illustration of an extruder based on its energy.