



ENERGY ANALYSIS IN THE EXTRUSION OF PLASTICS.

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<p>Abstract:</p> <p>An experiment was conducted to investigate the energy consumed during extruder runs using an amorphous polymer (polyamide) of grade grimaldi TR 55, in the Arcada plastic laboratory. During this process, energy was applied to the polymer by the heating and the drive systems, this energy was used to melt and transport the polymer to the extruder die. The energy in the product will then be transferred to the water or air which is often discarded after the process.</p> <p>The focus of this thesis is to quantify and qualify this stream of energy that is transferred in the cooling medium (air or water), by suggesting different methods which this energy can be valuable to the company. This energy may be extracted and converted in to different forms of energy (mechanical or electrical) using a heat exchanger, depending on the quality and quantity of the heat content in the stream, or may be used directly in heating the surroundings.</p>	
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List of symbols:

Q = the heat content in (kcal).

V = the volume flow rate of the substance in (m^3/hr).

ρ = density of the flue gas in (kg/m^3).

C_p = specific heat of the substance in ($\text{kCal}/\text{kg}^\circ\text{C}$.)

ΔT = temperature difference($^\circ\text{C}$).

$\Delta H = H_2 - H_1$ = enthalpy increase per unit polymer mass (J/kg).

ΔPE = potential energy increase per unit polymer mass (J/kg).

ΔKE = kinetic energy increase per unit polymer mass (J/kg).

ΔQ = net thermal input in to unit polymer mass (J/kg).

ΔW = net mechanical input in to unit polymer mass (J/kg).

G = mass output per unit time (kg/s).

Q_O = total thermal energy input by the heaters per unit time (J/s).

Q_C = total thermal energy removed by cooling per unit time (J/s).

Q_i = total thermal energy lost in the surrounding per unit time (J/s).

W = mechanical energy input by the motor per unit time = motor power (W).

W_O^* = theoretical motor power in the adiabatic operation (W)

$\bar{\sigma}$ = shear rate in screw channel, is given in per second (sec^{-1}).

d_{screw} = screw diameter in (mm).

n_{screw} = screw speed in revolutions/minute (rpm).

h = channel depth in (mm).

P_h = head pressure in Pascal (Pa)

ΔE = internal energy increase per unit polymer mass (J/kg)

V = specific volume, i.e. volume of unit polymer mass (m^3/kg)

C_p = specific heat measure at constant pressure ($\text{J}/\text{kg}^\circ\text{C}$).

C_v = specific heat measure a constant volume ($\text{J}/\text{kg}^\circ\text{C}$).

R = resistance of the heating element (Ω).

L = the length of the heating element (mm).

ρ_r = the resistivity of the heating element at 20°C (Ωm).

M = mass of polyamide process in (g).

C_p = heat capacity of polyamide in ($\text{J}/\text{g}^\circ\text{C}$).

ΔT = difference in temperature between room temperature and melt temperature ($^\circ\text{C}$).

Definitions of Terms Used in the Thesis:

Extrusion:

A shaping process in which melted plastic resin or other heated material is forced through an opening to produce a product that maintains a relatively consistent size and shape. It is often used in most manufacturing and food processing industries. (Toolingu, [8]).

Extruders:

A machine or device that forces ductile or semisoft solids through die openings of appropriate shape to produce a continuous film, strip, or tubing. Most of them takes in electrical energy and convert it to heat during the process. (Toolingu, [8]).

Heat Energy:

Heat energy is a form of energy that is transfer among particles in a substance (or system) by means of kinetic energy of those particles. In other words, under kinetic theory, the heat is transferred by particles bouncing into each other. As a form of energy, the SI unit for heat is the joule (J), though heat is frequently also measured in the calorie (cal). (Wikipedia,[9]).

Polymers:

Polymers are chemical compounds made of smaller, identical molecules (called monomers) linked together. Some polymers, like cellulose, occur naturally, while others, like nylon, are artificial. Polymers have extremely high molecular weights, make up many of the tissues of organisms, and have extremely varied and versatile uses in industry, such as in making plastics, concrete, glass, and rubber. (wikiPlastics, [10]).

Enthalpy:

This is the amount of heat content used or released in a system at constant pressure. Enthalpy is usually expressed as the change in enthalpy. The change in enthalpy is related to a change in internal energy (U) and a change in the volume (V), which is multiplied by the constant pressure of the system. Enthalpy (H) is the sum of the internal energy (U) and the product of pressure and volume (PV) given by the equation: $\mathbf{H = U + PV}$. The unit of measurement for enthalpy in the joule or calories. (wikipedia,[11])

Thermodynamics:

It is the study of how heat, work, and energy are related, though it is a physical phenomenon, it has a clear application in other sciences. They exist three fundamental laws of thermodynamics; each law leads to the definition of the thermodynamic properties which help us to understand and predict the operations of physical systems. (Wikipedia, [12]).

Adiabatic Systems:

A system in which there is zero transfer of heat to the surrounding and vice versa is known as an adiabatic system. This phenomenon is common in thermodynamic system in which physical and chemical processes are assumed as being closer to this concept. (Hyperphysics.phy, [12]).

Shear Rate:

Shear rate is the movement of a layer of fluid on another at different velocities, if a fluid is placed between two parallel plates that may be about some few centimeters apart, one of the plate moving at a velocity of 2.0 cm/sec and the other plate stationary. Midway between the plates, a layer is moving at 1.0cm/sec. The rate of change of velocity with distance from the plates can be expressed as $(V_a - V_b)/h$. Hence shear rate unit are the inverse of a second. (Wikipedia. [13]).

Heat capacity:

The ability of a compound or element to store or give out heat is often described as its heat capacity; it is also described as the amount of energy needed to raise the temperature of 1g of an element or compound by 1°C. (Wikipedia. [13]).

Introduction

1.1 Background

Today, plastic manufacturers are giving more attention to energy consumption than they had historically, due to the dramatic increase in energy cost. Understanding how energy is consumed by the two primary sources on an extruder, the motor and the heaters, is becoming a very important part of extrusion technology. It provides opportunities for making both hardware and operation improvements that may yield significant cost savings.

Because economic benefits provide sufficient motivation to evaluate extruder energy consumption, there are other reasons to do so. Processing of the polymer compound inside an extruder is primary an energy transfer phenomenon. Heat is added to the material through mechanical and conductive means and may be removed from the material by conduction through the barrel wall. Hence analyzing energy consumption by an extruder, most of which is transferred to the polymer for both heating and transporting it, provides a valuable assessment of how the material is being processed. (S Barlow, [1])

The aim of this thesis is to describe the results obtained from an experiment set-up to investigate the energy changes in the Arcada extruder under different sets of conditions. The extruder was run at different screw speeds, at three different scenarios. A focus is placed on analyzing the energy consumed across the profile barrel zones, which is highly dependent on screw speed and processing parameters. Also an analysis is made of the individual contributions of the heater energy and motor energy to the total energy consumed under varying conditions. And finally how this waste energy released during cooling can be reused for other industrial purpose.

1.2 Objectives:

There are three main objectives for the purpose of this thesis;

1. To analyze the total heat exchange during an extrusion process (calculating the total energy input versus energy output after the process).
2. To calculate the waste energy released during cooling process from the extruder.
3. To suggest a method in which this waste energy produced during cooling can be reused for different purpose.

2. LITERATURE REVIEW

2.1 History of Polymer Extrusion

The first machine for extrusion of thermoplastic material was built around 1935 by Paul Troester in Germany. (Rauwendaal, [1]), Before this time, extruders were primarily used for extrusion of rubber. These earlier rubber extruders were steam heated ram extruders and screw extruders, with the later having very short length to diameter (L/D) ratios, about 3 to 5. After 1935, extruders evolved to electrically heated screw extruders with increase length. Around this time, the basic principle of twin screw extruders was conceived in Italy by Roberto Colombo. He was working with Carlo Pasquetti on mixing cellulose acetate. Colombo developed an intermeshing co-rotating twin screw extruder. (Rauwendaal, [1]). He obtained patent in many different countries and several companies acquired the right to use these patents. Pasquetti followed a different concept and developed and patented the intermeshing counter rotating twin screw extruder. (Maddock,[2]).

2.2 Types of extruders:

There exist different types of extruders in the polymer industries. Extruders may be distinguished by their mode of function; continuous or discontinuous. Continuous extruders are equipped with rotating parts whereas discontinuous extruders extruded plastics in a recurrent manner and this type is suited for batch type processes such as injection molding. Extruders may be used in different type of industries such as food processing industries, plastics industries, metals and aluminum industries as well as different secondary manufacturing industries. The mode of operation of this machine is very simple; material enters the hopper of the extruder usually by gravity and is pushed down along the barrel by the rotation of the screw, this pushing generate friction between the barrel wall and the screw hence generating the heat energy required to melt the material.

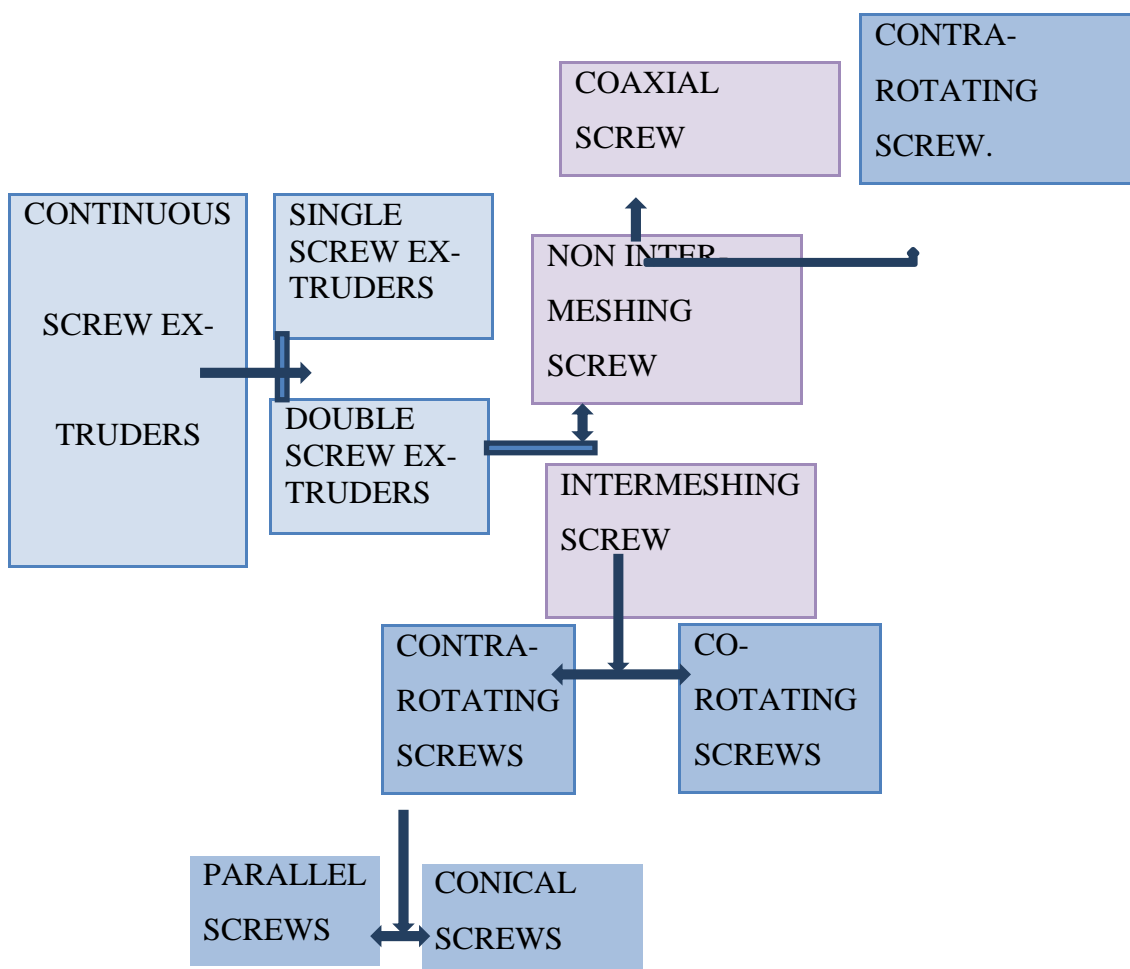


Figure 1 Classification of the different types of extruders (Author)

2.2.1 Single Screw Extruders:

Most extruders are equipped with screw as their main mixing component. Screw extruders are classified as single or multiple screw extruders. Single screw extruders are the most common type of extruders used in the polymer industry, because of its straight forward design, relatively low costing, and its reliability, they are most often used. (Maddock, [2]). Their screw has only one compression section, even though the screw has three distinct geometrical sections; the first section (closest to the feed opening) generally has deep flights. The material in this section will be mostly in the solid state. This section is referred to as the feed section of the screw. The last section usually has shallow flights, the material in this section will be mostly in the molten state. This screw section is referred to as the metering section. This section is called the transition section or compression section. In most cases, the depth of the screw channel reduces in a linear fashion, going from the feed section towards the metering section, thus causing a compression of the material in the screw channel. (Rauwendaal [1]).

Table 1. Different Types of Extruders (Maddock[2]).

Screw extruders (continuous).	Disk or drum extruders (Continuous).	Reciprocating single screw extruders(discontinuous)
Single screw extruders	Spiral disk extruders, Drum extruders, Disk pack extruder, Stepped disk extruder	Ram extruders
Melt fed, Plasticating, Single stage, Multiple stage Compounding.	Viscous drag extruders	Melt fed extruder, Plasticating extruders, and Capillary rheometer.
Multi screw extruder	Screw less extruder, Screw or disk type melt extruder	Plasticating unit injection molding machines. Compounding extruders such as the Kneader
Twin screw extruders, Gear pumps, Planetary gear extruders, Multi (<2) screw extruders.	Ram extruders	Reciprocating single screw extruders.
Elastic melt extruders		

2.2.2 Double Screw Extruder:

The double or twin screw extruders function similarly like a single screw extruders, apart from the fact that they are more effective due to the presence of two screws that generate and mixed the polymers more efficiently. The screw function in generating heat when it rotates, this heat generation process is achieved by friction between the barrel walls and the screw. In some extruders, the screws rotate in the same direction while in others they rotate in opposite direction. The way the twin screw extruder is designed makes it possible to be used for specific operations. (Rauwendaal [1]).

2.2.3 Vented Extruders:

In vented extruders, there are one or more openings (vent posts) in the extruders' barrel, through which hot gases can escape. Thus the vented extruders can extract hot gases from the polymer in a continuous manner. This extraction of hot gases adds a functional capability not present in non-vented extruders. In addition to the extraction of gases, one can use the vent port to add certain component to the polymer, such as additives fillers reactive components. This clearly adds to the flexibility of vented extruders, with the additional benefit that the extruders can be operated as a conventional non vented extruder by simply closing the vent port and, possibly, changing the screw geometry. (Womer, [3]). The design of the extruder screw is very critical to the proper functional of the vented extruder. One of the main problem is that vented extruders are afflicted with is vent flow. This is a situation where not only the volatile are escaping through the vent port, but also some amount of polymer. Thus the extruder screw has to be designed in such a way that there will be no positive pressure on the polymer under the vent port (extraction section). This has led to the development of the two stage extruder screw, especially designed for eliminating gases during extrusion. Two stage extruder screws have two compression sections separated by a decompression /extraction section. Because of the limited gas remover capacity of single screw extruders of conventional design, they are something equipped with two or more vents ports. A drawback of such a design is that the length of the extruder can become a problem. Some of these extruders have an L/D ratio of 40 to 50. This create a problem in handling the

screw, for instance when the screw is pulled, and increases the chance of mixing problems in the extruder. If substantial amount of gases need to be removed a twin screw extruder may be more cost effective than a single screw extruder improved gas elimination capability and deserve equal consideration. (Rauwendaal [1]).

3.0 EXTRUDER MACHINE COMPONENTS

The extruder is a very important machine in the plastic industry, as compared to injection molding machines, they are used to produce product of continues profile. Extruder's main components are a hopper at one end from which the material to be extruded is fed, a tubular barrel, usually electrically heated; a revolving screw, ram or plunger within the barrel, and a die at the opposite end for shaping the extruded mass. Extruders may be divided into three general types—single screw, twin or multiple screw, and ram—each type has several variations. The different parts that makes up an extruder are reviewed below.

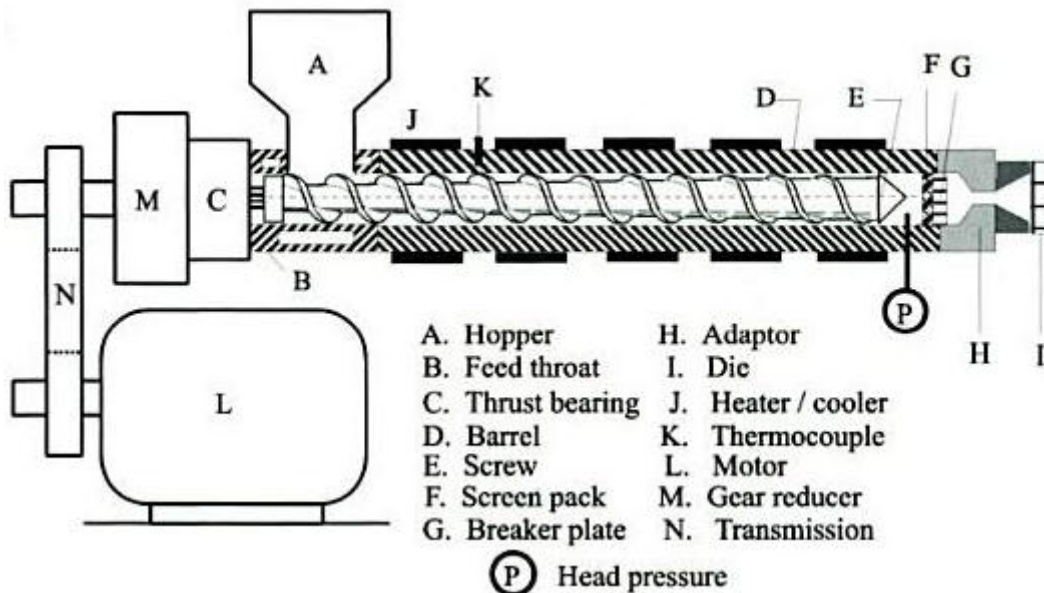


Figure3. Component of a typical single screw extruder. (Chung, [5]).

3.1 Screw:

The extruder screw is one of the most important component of the machine, its design is crucial in the mixing and processability of the polymer in question, with respect to the type of polymer to be processed. The screw is designed into five different sections known as zones. Different types of polymer may have different screw designs; some designs may not have the entire zone. (Rauwendaal [1]).

Three zones are usually identified in most screws which are;

Feed zone- The feed zone is the point where the resin enters the extruder. In this zone, the width of the flight is the same, and the channel distance is usually the same all over the zone.

Melting zone- This is where the melting begins, as the screw rotates, more and more resins are being melted and the channel depth gets more and more reduced.

Metering zone- In this zone, the channel depth is again the same throughout the zone, melting of the last particles and mixing of the polymer to a uniform temperature and composition occurs in this zone, here, barrel heaters may contribute some energy needed to complete the melting.

Furthermore, a vented (two-stage) screw will have:

Decompression zone. In this zone, about two-thirds down the screw, the channel unexpectedly gets deeper; the pressure is released and allows any stuck gases (usually moisture or air) to be removed out by vacuum. (Chung, [5]).

Second metering zone. It is similar to the first metering zone, but with larger channel depth, this forces the melt to get out through the resistance of the screens and the die.

The L: D ratio of an extruder screw is defined as the length of an extruder screw with respect to its diameter. An L: D ratio of 24:1 is common, but some bigger machines go up to 32:1 for faster mixing and additional output with no change in the diameter of the screw. Twin screws usually can measure about 36:1 to account for the two extra zones. (Chung, [5]).

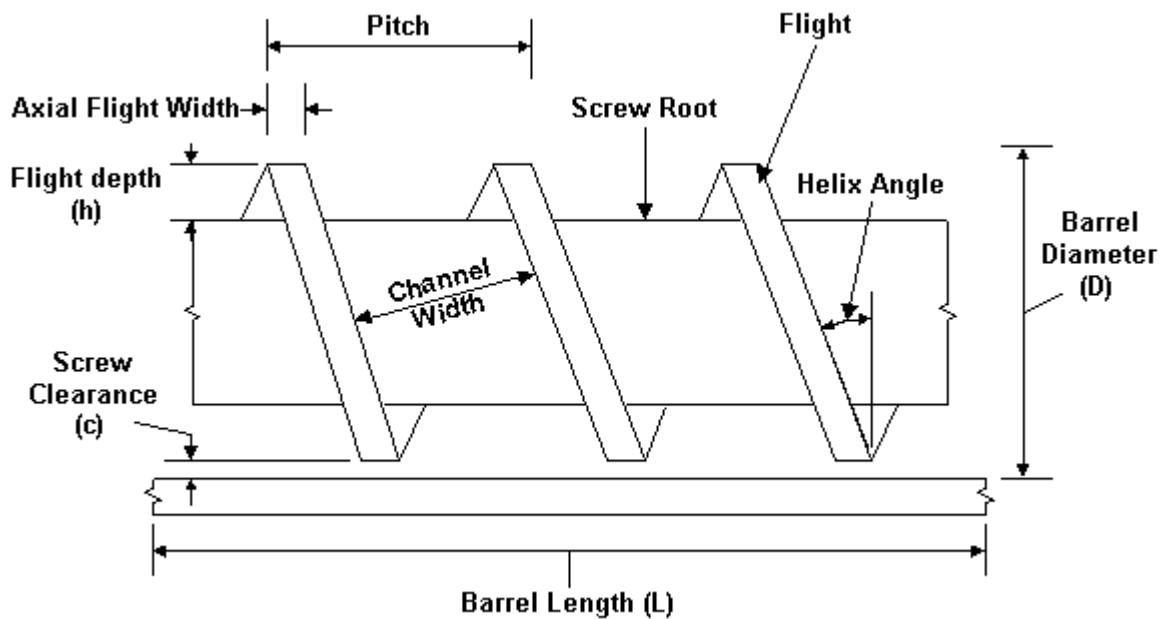


Figure 4. Extruder screw (Extrusion of Polymers) (Chung [5]).

Screw dimensions are commonly addressed by its L/D ratio which can range from 1 to 20, and by its compression ratio which is usually 2.5:1 to 4:1. (Crawford [4]).

3.2 Barrel:

The extruder barrel hosts the screw internally and the heater and other components externally. In the feed section is equipped with a hopper design to prevent premature melting of the polymer resins. Along the length of the extruder barrel is covered a layer of protective material to prevent heat losses from the inlet. There may be several zones of heater bands to each section of the barrel wall. The change in temperature of each zone is detected by a sensor mounted beneath the barrel. There are two types of barrel heaters; band and cast. The band type is used for heating while the cast type has passages to house a flow of a cooling medium, and thus it can be used for both heating and cooling. The cooling medium is usually water but at time oil can be use to prevent thermal shock to the barrel. (Rauwendaal [1]).

Since the extruder barrel is the main component where the plastic is being process, they are designed to be large enough to hold the maximum possible amount of material, and also designed to prevent the screw from scraping the walls of the barrel that may cause damage to the barrel wall. (Rauwendaal [1]).

3.3 Die:

The extruder die is the component of the machine that gives the final shape of the product, so its design is crucial both for specification and accuracy. The extruder die create a passage through which molten polymer exit the extruder with the help of pressure built up in the barrel during processing. The molten polymer coming out of the die has a constant exit velocity across the entire die exit. Streamline the flow to avoid abrupt changes in the flow passage that may cause stagnation areas. If the flow of the polymer is not constant it may result to the degradation of the stagnated polymer along the barrel channel after a considerable period of time. (Rauwendaal [1]).

3.4 The Drive Systems

The Drive – Historically the extruder uses the DC motor as the main driving component, but this system had been replaced by an AC motor. This AC drives are digital and brushless. The AC motor can easily be optimized in to a 3-phase motor when need arise. AC motors are rated between 25 kW to 85 kW and is controlled by drives with parallel ratings; depending on the extruder model. The rotation of the motor is transferred to the screw with the help of the shaft and pulley system to get maximum transmission efficiency even under adverse high-torque conditions. The performance of a drive system is also very important to the extruder machine and should be thought of when considering the type of machine to purchase. (Rauwendaal [1]).

The bearings - The extruder bearing system consists of a distinct permutation of circular and axial bearings to provide best resistance-support for the screw even at extraordinary load at high speed situations. (Chung, [5]).

Cooling – The extruder has a water cooling mechanism that circulates around the barrel cooling mechanism. The water cooling system is controlled automatically by a sensor that picks the temperature at a predefined point in the processing zone. (Chung, [5]).

Material - The material feeding is carried out by gravity, other feeding mechanisms are the volumetric double-screw feeding systems driven by variable speed drives. Gravitric feeding systems are offered optionally.

Product cutting – The cutting mechanism is located after the cooling tank. The distinct cutter unit provides flexibility of use with different die-systems and prevents problems due to variance expansion between cutter and die. The cutter is driven by an adjustable speed drive.

The Control - In the extruder, control of the machine is done with the help of a programmable logical control based system with a mutual operator consol on the panel showing all relevant task parameters and providing all essential control elements for monitoring the process of the different mechanisms of the machine.

4.0 HEATING AND COOLING SYSTEMS IN EXTRUDER

To bring the extruder machine to a functioning temperature, heat is required; this heat brings the machine to a proper temperature for startup and for maintaining the desired temperature under normal operations. There are three methods of heating the extruder: electric heating, fluid heating, and steam heating. The electric heating is the most common method of heating the extruders. (Rauwendaal, [1]).

4.1 Electric Heating.

Electric heating has dominated steam and fluid heating in extruder because it can cover a much larger temperature range, it is low cost and easy to maintain as compared to steam and fluid heaters. On the extruder barrel walls they are placed in zones. Small extruders usually have fewer heaters as well as zones while larger extruders have more heaters and more zones. Each zone is controlled autonomously, so that a temperature profile can be maintain along the extruder. This can be an even profile of temperature, increasing or decreasing profile or a combination of both depending on the particular polymer and operation in question. (Rauwendaal,[1]).

Electric resistance heaters are widely use in extruder machines. The heat generated by the extruder heaters is made possible by passing a certain amount of current through a conductor of certain resistance, as the resistance creates barrier to the flow of electrons, heat is generated. The amount of heat generated is given by the equation below:

$$Q_c = I^2 R = VI = V^2 / R \quad (\text{Eqn1})$$

Where I is the current, R is the resistance, and V is the voltage. This equation is valid for direct current (DC) as well as single phase alternating current (AC), provided the current and voltage are expressed as root mean square (rms) values and the circuit being purely resistive (phase difference zero). With three phase circuit the heat generation is; (Rauwendaal,[1]).

$$Q_c = 3VI \quad (\text{Eqn2})$$

Mica strip are usually used to insulate resistance band heaters. These heaters are low cost but not quite durable and are not very reliable. They can withstand temperatures of up to 500°C and have a loading capacity of about 50kW/m². Recent types of mica heaters can handle power densities up to 165 kW/m². The durability of a heater depends on the usage and the contact between the barrel and the surface of the heaters. Inadequate surface contact will cause overheating and the outcome will reduced heater life or even premature burnout of the heater element. Commercially, are available special paste to improve the heat transfer between the heater and the barrel. (Rauwendaal, [1]).

Generally, ceramic band heater has longer life span than the mica insulated heaters and they can tolerate greater power densities, up to 160 kW/m² or more and block temperatures of up to 750 °C. The only disadvantage of ceramic heaters is that they are not flexible and tend to be huge. Though some ceramics band heaters have a thin-line design with negligible space requirements.

Beside the mica and ceramic heaters is also available is the cast in aluminum heaters. The heating element in this type of heater is the cast in semicircular or flat aluminum blocks. The heat transfer in this type of heater is good and uniform; these heaters are reliable and give a good service life. These heaters have a service temperature of up to 400 °C with a watt density of about 55kW/m². (Rauwendaal, [1]).

The Heating of the extruder normally reduces the overall power consumption of the motor as well as the overall power requirement of the process. Though cooling is necessary, it does not consumed energy thus do not contribute to the overall power requirement of the process, and the energy extracted by cooling is wasted. If an extrusion process requires a substantial amount of cooling, this is usually a strong indication of improper process design. This could mean improper screw design, excessive length to

diameter ratio, or incorrect choice of the extruder; for instance single screw versus twin screw extruder. The extrusion process is generally designed in such a way that most part of the energy requirement is supplied by the extruder drive. The rotation of the screw causes friction and viscous heating of the polymer, which constitutes a transformation of mechanical energy for the drive into the thermal energy to raise the temperature of the polymer. The mechanical energy generally contributes to 70 to 80% of the total energy. This means that the barrel heaters contribute only 20 to 30 %, discounting any losses. (Rauwendaal [1]). If the majority of the energy is supplied by the screw, there is a reasonable chance that local internal heat generation in the polymer is higher than the required to maintain the desired process temperature. Thus, some form of cooling is usually required. Many extruders use forced air cooling by blowers mounted underneath the extruder barrel.

The external surface of the heater or spacers between the heaters is often made with the cooling ribs to increase the heat transfer area and thus, the cooling efficiency. Small extruders can often do without forced air cooling because their barrel surface area is quite large compared to the channel volume, providing a relatively large amount of convective and radiative heat losses. (Rauwendaal, [1]). Some extruders operate without any forced cooling or heating. This is the so called “auto-genous” extrusion operation, not to be confused with adiabatic operation. An autogenous process is a process where the heat required is supplied entirely by the conversion of mechanical energy into thermal energy. However, heat losses can occur in an autogenous process. An adiabatic process is one where there is absolutely no exchange of heat with the surroundings. Clearly, an autogenous extrusion operation can never be truly adiabatic, only by approximation. In practice, auto-genous extrusion does not occur often because it requires a delicate balance between polymer properties, machine design, and operating conditions. A change in any of these factors will generally cause a departure from the auto-genous conditions. The closer one operates to auto-genous conditions, the more likely it is that cooling will be required. Given the large differences in the thermal and rheological properties of various Polymers, it is difficult to design an extruder that can operate in an auto-genous fashion with several different polymers. Therefore, most extruders are designed to have a reasonable amount of energy input from external barrel heaters. (Rauwendaal, [1]).

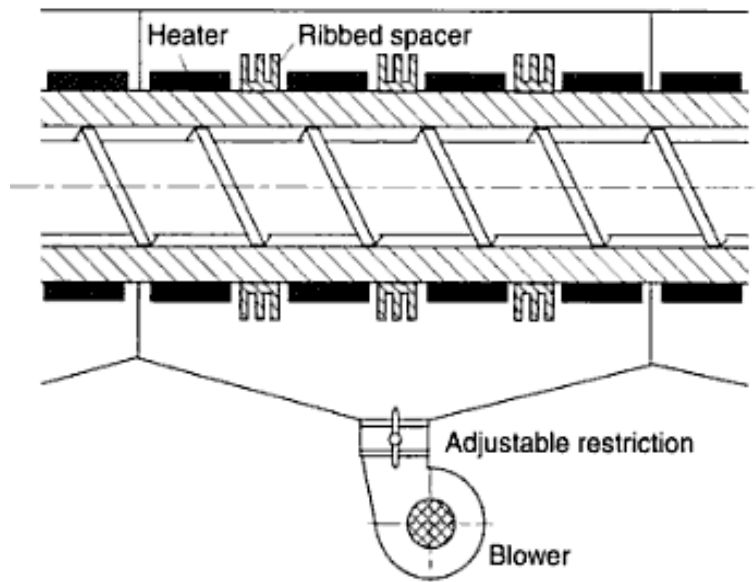


Figure 7. Extruder cooling by forced air. (Rauwendaal, [1]).

On the other hand, the energy input from the barrel heaters should not be too large. The problem with the external heating is that this is associated with relatively large temperature gradients. In materials with low thermal conductivity, large temperature gradients are required to heat up the material by external heating at a reasonable rate. Since polymers have a low thermal conductivity, raising the polymer temperature by external heating is a slow process and involves large temperature gradients. Thus, locally high temperatures will occur at the metal/polymer interface. The combination of the high temperatures and long heating times makes for high chance of degradation. The heating by viscous heat generation is much more favorable in this respect, because the polymer is heated relatively uniformly throughout its mass. Thus, one would generally want the mechanical energy input to be more than 50% of the total energy requirement, but less than about 90%. (Butler, [9]).

4.2 Air Cooling:

Air cooling is a fairly gentle type of cooling, because the heat transfer rates are relatively small. This is not good if intensive cooling is required. On the other hand, there is advantage in that when the air cooling is turned on, the change in temperature occurs gradually. With water cooling, a rapid and steep change in temperature will occur as soon as the water cooling is activated. From a control point of view, the latter situation can be more difficult to handle. (Rauwendaal, [1]).

4.3 Water Cooling:

In fluid cooling, water is the most common heat transfer medium. In most cases, water is used to cool the grooved barrel sections which often require intensive cooling for the process to be effective. One of the complications with water cooling is that evaporation can occur if the water temperature exceeds boiling temperature. This is an effective way to extract heat, but causes a sudden increase in cooling rate. From a control point of view, this constitutes a non-linear effect and it is more difficult to properly control the extruder temperature if such sudden, non-linear effects occur. Thus, water cooling may place much higher demands on the temperature control system as compared to air cooling. The cooling efficiency of air can be increased by wetting the air; however, this requires cooling channels made out of corrosion-resistant material. This technique is used in patented vapour cooling system. The latent heat of vaporization which circulates around the extruder barrel is extracted by a water cooling system that surrounds a condensing chamber located away from the barrel. A schematic of this vapour cooling system is shown in the figure below; (Rauwendaal, [1]).

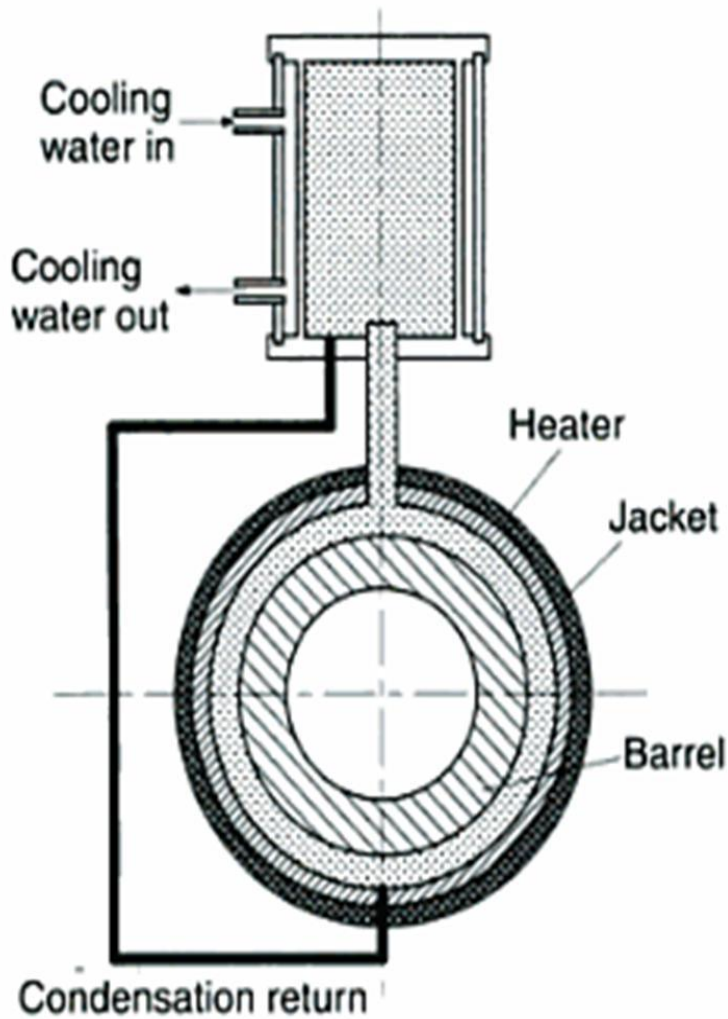


Figure 8. Extruder vapor cooling system. (Rauwendaal, [1]).

Oil or air cooled extruders can use step less cooling control, using a proportional valves and positioning motors. These systems are relatively expensive, but they are reliable and require little maintenance. With water cooling, the cooling power is generally controlled by energizing a solenoid valve. For low temperatures, usually a constant cycle rate is used with variable pulse width system. The pulse varies in proportion to the cooling power required. (Rauwendaal, [1])

At high temperatures, where water is flashing to steam, more intensive cooling is possible. In these cases, a different cooling control can be used, known as a constant pulse width system. When cooling is required, the solenoid is energized by pulse signal of predetermined length. The frequency of the pulse is varied in proportion to the cooling

power required. Finally it should be noted that cooling is a waste of energy and should be minimized as much as possible.

4.4 Screws Heating and Cooling.

It is also important to note that the barrel-polymer interface constitutes only 50% of the total polymer-metal interface. Thus, with only barrel heating and/or cooling; only about 50% of the total surface area available for heat transfer will be utilized. The screw surface, therefore, constitutes a very important heat transfer surface. Many extruders do not use screw cooling or heating; they run with a so-called “neutral screw”. If the external heating or cooling requirements are minor, then screw heating or cooling is generally not necessary. However, if the external heating and cooling requirements are substantial, then screw heating and cooling can become very important, sometimes a necessity.

Heating or cooling of the screw is slightly more difficult than barrel heating or cooling, because the screw is in motion. This means that it is necessary to use rotary unions, slip rings or other devices to transfer energy in or out of the extruder screw. These devices, however, have become rather standard in industry, and they are commonly available. Water cooling can be done even without the use of a rotary union. This is done by running some copper tubing down in to the bore of the extruder screw and connecting a water supply to the copper tube. The water will flow towards the end of the screw through the tube and will then flow back in the angular space between the tube and the screw. As the water reaches the shank end of the screw, it will simply drain away. This is a crude, but effective type of screw cooling.

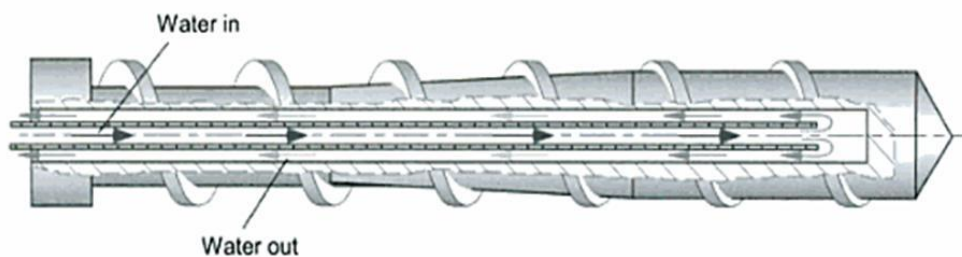


Figure 9. Simple screw cooling system in cross section. (Rauwendaal,p [1]).

5.0 Heat Recycling in Extrusion:

In extrusion processes, waste heat refers to energy that is generated by the extruder machine without being put to practical use. Sources of waste heat in extrusion include; heat absorbed by the cooling medium during product stabilization, heat from the surface of the equipment's by radiation. The exact amount of extrusion waste heat is poorly quantified, but research has estimated that as much as 30% of extruder energy consumption is eventually train down the sink as waste heat. (Builder, [9]). Some wasted heat losses from plastic processes are unavoidable, but improving equipment efficiency or installing waste heat recovering systems can reduce this loses. Waste heat reclamation means capturing and reusing the waste heat in extrusion processes for heating or for generating mechanical or electrical work. Example of waste heat uses include generating electricity, preheating combustion air, preheating furnace loads, absorption cooling, and space heating.

To be profitable in a plastic extrusion industry, cost need to be cut, and one way of doing this is to apply heat regaining knowledge which can help to drastically reduces energy consumption either by reusing the waste heat in other processes within the industry. Though it is still difficult to reused waste industrial heat due to a combination of cost and practical obstacles, numerous applications are already adopting this process in different industrial plant. An understanding of waste heat losses, recovery practices, and barriers during extrusion process is necessary in order to better identify heat recovery opportunities and technologies needed in the plastic industry. Such findings can help plastic manufacturers in identifying research priorities for endorsing plastic industrial energy efficiency in feature.

6.0 HEAT ANALYSIS OF POLYMER EXTRUSION

In all extrusion processes, the first law of thermodynamics, that is, the conservation of energy must be satisfied. During the extrusion process of polyamide (PA), the energy needed for processing is provided by the motor and the barrel heaters, usually a very small negligible portion of the motor energy is lost through the drive chain as frictional heat in the coupling and the gear box. Most of the mechanical energy (M_o) of the motor consumed in other to rotate the screw is converted in to heat by shearing the

polymer melt, a large amount of heat is generated in the melt by viscous dissipation as the melt is shear by screw rotation (Chung, [5]). A very small portion of the mechanical energy is used to compact the polymer feed, to develop the melt pressure, and to move the melt out of the screw. The melt pressure developed at the end of the screw drops to ambient pressure as the melt comes out of the die, converting the mechanical energy associated with the melt pressure in to heat. Virtually about 80% of the mechanical energy of the motor is converted in to heat. The heat generated in the melt is the main source of heat used to melt the polymer feed. The thermal energy (Q_o) provided by the barrel heaters is conducted to the polymer through the barrel. When the melt overheats above the set point of the barrel heater, the cooling system on the barrel takes away heat (Q_c) from the melt. Some reasonable amount of heat (Q_l) is lost to the ambient through the barrel and the screw shaft. The balance of the total mechanical and thermal energies is equal to the increased heat content of the polymer from the feed temperature to the melt temperature.

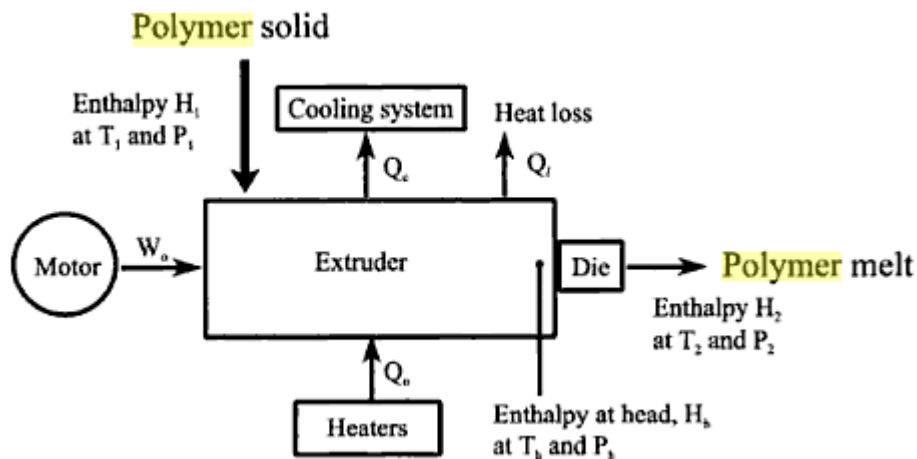


Figure11. Energy balance in polymer extrusion (Chung, [5]).

A typical polymer extruder takes in resins in the solid form at a temperature T_1 and pressure P_1 with enthalpy H_1 and extrudes the melted polymer at a temperature T_2 and pressure P_2 with enthalpy H_2 . It is noted that enthalpy is a function of both temperature and pressure. At a constant temperature enthalpy increases with increase pressure.

As seen above from figure 11, the energy balance for unit polyamide mass going through the extruder is given by the first law of thermodynamics; (Chung),[5]).

$$\Delta H + \Delta PE + \Delta KE = \Delta Q + \Delta W \quad (\text{Eq3}) \text{ (Chung), [5]}.$$

Where;

$\Delta H = H_2 - H_1 =$ enthalpy increase per unit polymer mass. (J/kg)

$\Delta PE =$ potential energy increase per unit polymer mass. (J/kg)

$\Delta KE =$ kinetic energy increase per unit polymer mass. (J/kg)

$\Delta Q =$ net thermal input in to unit polymer mass. (J/kg)

$\Delta W =$ net mechanical input in to unit polymer mass. (J/kg)

Because ΔPE and ΔKE are negligible in comparison to ΔH in extrusion, Eqn (3) is reduce to $\Delta H = \Delta Q + \Delta W$ (Eq4). (Chung),[5]).

Referring to fig. 11 above, ΔQ and ΔW can be express as

$$\Delta Q = (Q_o - Q_c - Q_l) / G \quad (\text{Eqn5}). \text{ (Chung),[5]}.$$

$$\Delta W = W_o / G \text{ (neglecting mechanical losses)}$$

Where G ; = mass output per unit time = mass output rate (kg/s).

$Q_o =$ total thermal energy input by the heaters per unit time (J/s).

$Q_c =$ total thermal energy removed by cooling per unit time (J/s).

$Q_l =$ total thermal energy lost in the surrounding per unit time (J/s).

$W =$ mechanical energy input by the motor per unit time = motor power

Combining equation (3), (4) and (5), the required motor power can be obtained, i.e.

$$W_o = G. \Delta H - (Q_o - Q_c - Q_l) \quad (\text{Eqn6}). \text{ (Chung),[5]}.$$

In situations where there is no heat exchange between the extruder and the surroundings (adiabatic systems) i.e. $\Delta Q = (Q_o - Q_c - Q_l) = 0$, the theoretical motor power in the adiabatic operation becomes $W_o^* = G \Delta H$ (W) (Eqn7)

Where W_o^* = theoretical motor power in the adiabatic operation.

Most modern extruders running at high screw speeds generate excessive heat and utilize barrel cooling. Therefore, the motor power of an extruder must be substantially more than the value predicted by (Eq7). The mechanical energy efficiency of an extruder defined by the ratio of the theoretical motor power consumed in the operation, (W_O). (Chung) [5]).

$$\% \text{ Mechanical energy efficiency} = 100. [(W_O^*) / (W_O)] \quad (\text{Eqn8})$$

Thus the minimum motor power of the extruder should be;

$$W_O = (W_O^*) \cdot [100 / (\% \text{ Mechanical energy efficiency})] \quad (\text{Eqn9})$$

In reality, adiabatic systems give the maximum mechanical energy efficiency at high screw speeds, consuming the minimum motor power express by equation (7). Polymers require about 95-165 Kcal/Kg to be heated from room temperature to a desired melt temperature of about 175-300 °C. Thus the maximum mechanical energy efficiency ranges from about 5 to 9 kg/ (kWh). The actual fact is that the mechanical energy efficiencies of modern extrusion operations at high screw speeds are substantially lower than the above values by as much as 40%. Mechanical energy efficiencies at low screw speeds can be higher than the above values because barrel heaters add heat to the polymers. Mechanical energy efficiency always decreases with increasing screw speed because more heat is generated in the melt and less heat is conducted from the barrels heaters to the polymer. A polymer with higher heat content usually has lower mechanical energy efficiency. Crystalline polymers usually have higher heat contents than amorphous polymers, and they have lower mechanical energy efficiencies than amorphous polymers Chung [5].

6.1 Approximating the Temperature Change through the Die

In fig.11, the theoretical exit temperature of polyamide (PA) can be found using (Eqn10) below, the melt pressure at the end of the screw, that is the head pressure P_h is assumed to be about 450 Mpa (processing pressure of polyamide taking from the polymer data sheet). (Arcada). The melt pressure drops to $P_2 = 0$ as the melt is extruded in to the surrounding through the die. If there is no heat exchange between melt and the die, the enthalpy of melt at the head, H_h at T_h and P_h , should be equal to the enthalpy of the melt exiting the die H_2 at T_2 and P_2 . The pressure drop through the die from P_h to P_2

is converted in to heat, raising the melt temperature from T_h to T_2 . Assuming no heat exchange through the die and negligible compressibility of the melt ($\Delta V = 0$), the temperature rise through the die can be approximated as follows;

$$\Delta V = 0$$

$$C_p = C_v$$

$$\Delta H = \Delta E + \Delta (P.V) = \Delta E + V. \Delta P + P. \Delta V = \Delta E + V. \Delta P = 0 \text{ (Chung) [5]}.$$

$$\Delta E = -V. \Delta P = -V. (P_2 - P_h) = V. (P_h - P_2) = C_v. \Delta T = C_p. (T_2 - T_h)$$

$$\text{Therefore; } \Delta T = (T_2 - T_h) = V. (P_h - P_2) / C_p \quad (\text{Eq.10}).$$

Where;

ΔE = internal energy increase per unit polymer mass (J/kg)

V = specific volume, i.e. volume of unit polymer mass (m^3/kg)

C_p = specific heat measure at constant pressure C_v = specific heat measure a constant volume.

The theoretical exit temperature of polyamide exiting the die can be approximated and compared with the experimental value;

$$\text{From Eqn8 above; } \Delta T = (T_2 - T_h) = V. (P_h - P_2) / C_p.$$

$$V = \text{specific volume} = \frac{1}{\text{density}} = \frac{1}{1.06} = 0.9433 \text{ m}^3/\text{kg}.$$

Head pressure $P_h = 450 \text{ Mpa}$ (Arcada)

Exit pressure $P_2 = 0$

$C_{PA} = 1.80 \text{ J/g}^\circ\text{C}$. (Arcada polymer data sheet).

$$\text{Therefore } \Delta T = (T_2 - T_h) = V. (P_h - P_2) / C_p = \frac{0.9433(450 - 0)}{1.80} = 235.9 \text{ }^\circ\text{C}$$

6.2 Experiment to Analyze the Energy Changes during Extrusion of Polyamide (PA).

Requirements:

The Arcada extruder machine model **Eco Ex Extruders No: 04-001E**

Machine type: Eco EX 18 25xD CE

Manufacturer: KFM AB OLOFSSONS EL SWEDEN

Model year: 2008

Machine weight: 150 kg

Machine power: 400V AC 3-FAS 50/60HZ

Maximum load: 19.1A

Maximum fuse: 25A

Maximum motor load: 7.2A

Reinforce polyamide (PA) of the grade PA/Grilamid FE 5599/EM- Grivory

A dryer to pre-dry the polymer

A thermometer to monitor the change in water temperature

A balance scale to weight the polymer before processing

About 7000g (7kg) of fresh water at about 10°C use for the cooling process

Stop watch to record the variations in the temperature of the cooling water

An energy source mainly electrical energy to heat up and melt the polymer

A wattmeter to measure the power intake of the drive system.

6.2.1 Extruder:

The KFM Eco Ex extruder was used for all runs. It has a 25:1 barrel L/D consisting of 2D feed throat and six 7.3D temperature control zones. It is equipped with flush mounted temperature and pressure sensors located just downstream of the screw tip. Head and die hardware remained constant throughout the experiment.

The table below shows the drive system ratings for the extruder. These values were used to calculate the motor energy consumption.

Table 2: The KFM Eco Extruder drives system rating. (Arcada)

Maximum Motor Power (HP/kW)	25 /18.64
Maximum Motor Speed (rpm)	1750
Reduction Ratio	2.5
Maximum Screw Speed (rpm)	125
Maximum Motor Current (A)	12.50

A PLC-base temperature controller monitoring system was used to record “on” time for each heater. These data were used to calculate the amount of energy consumed by the heater in each temperature control zone.

6.2.2 Material:

The material used in this experiment was a family of polyamide of the grade Grilamid TR 55 base on nylon 12. It is an amorphous thermoplastic; it has a combine excellent transparency with superior chemical resistance, strength, stiffness, toughness and outstanding processability. Below is a table showing the material properties s provided by the supplier.

Table 3. Material properties as provided by supplier. (lab.arcada.fi)

Polymer	Solid Den- sity (g/cm ³)	Melt Flow Rate(g/10min)	Heat Ca- pacity@ 20°C(J/g°C)	T _g (°C)	Mass flow rate g/sec
PA	1.06	7.5	1.80	155	50

Figure 12 below shows rheological data for polyamide (PA). This data was measured with a Rosand RH10 capillary rheometer. It is clear that the PA has more than twice the viscosity at all shear rate. (Arcada).

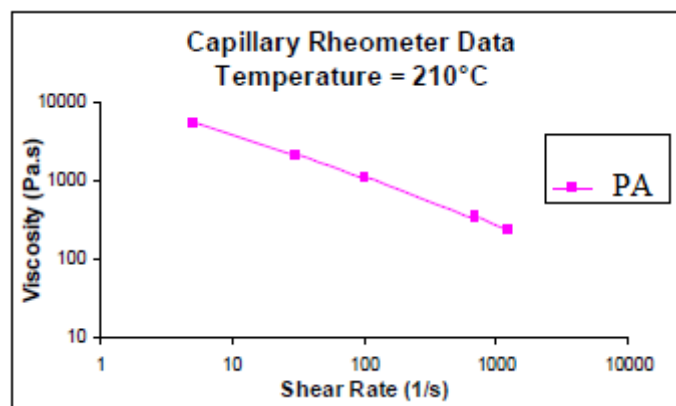


Figure 10. Capillary rheometer data for Polyamide. (Arcada)

6.2.3 Material Preparation:

The material was first dry. Drying was done following the recommen- dation from the supplier; oven was used for the drying. The drying temperature was 80°C and the drying time was approximately 6 hours.

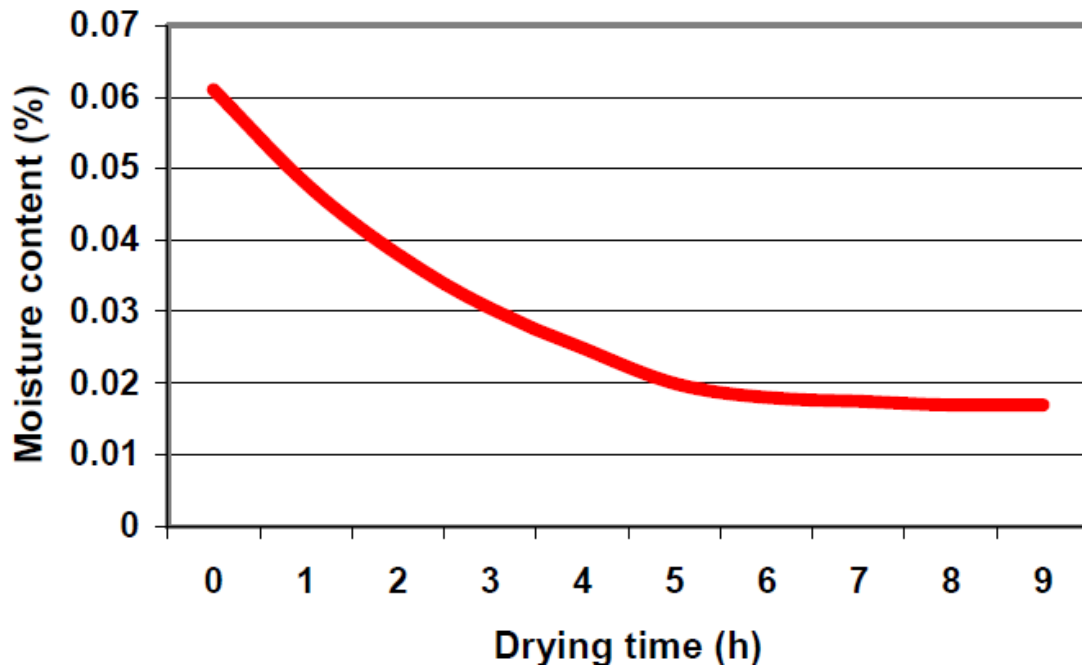


Figure 11. The relation between moisture content and drying time. (Arcada).

Grilamid TR 55 is dried and packed with a moisture content of less than or equal to 0.08%. If the packaging becomes damaged or is left open for too long, then the material must be dried. Too much high moisture content is realized by some inconsistency on the material surface.

6.2.4 Machine Settings during Processing:

The table below shows the temperature zones set points utilized for all extruder runs. The six temperature control zones will be referred to as Z1 through Z6 in this work. Z1 through Z3 include cooling channels, however, none of these came on at any point during the experiment.

Table 4. Temperature profiles used for all the extruder runs. (Author)

Temperature Control Zone	Temperature (°C)
Barrel zone 1 (Z1)	290
Barrel zone 2 (Z2)	300
Barrel zone 3 (Z3)	300
Barrel zone 4 (Z4)	300
Barrel zone 5 (Z5)	300
Barrel zone 6 (Z6)	300

7.0 METHOD:

This experiment was carried out in the Arcada plastic laboratory at standard conditions (room temperature and atmospheric pressure). The material selected for this process is polyamide of the grade PA/Grilamid FE5599/EM-Grivory, the reason for selecting this material was due to its high melting point. After pre-drying of the polymer at 80°C for four hours, the polymer was transfer to the hopper of the extruder machine with the temperatures of the six zones set at 300°C. The heat input in to the system came from two sources; the first source was the heat introduced through the extruder barrel walls with the barrel heater system. The second source was the heat that is converted from the mechanical drive of the shaft work. Before the process started the initial temperature of the cooling bath was recorded at 10°C and the cooling bath was modified to keep the water stagnant for the whole process, so that a significant rise in the temperature of the water can be observed. The heat flows are also different during the start up and stabilization process. As the process is adjusted to running conditions with higher screw speed set at 50 rpm, a substantial amount of heat is generated through friction in the polymer and less heat is added by the barrel heater since it temperature is still set at 300°C. The residual energy in the melt, in the form of pressure potential energy is converted in to heat by pressure drop in the die.

Different Energy Transformation during the Process

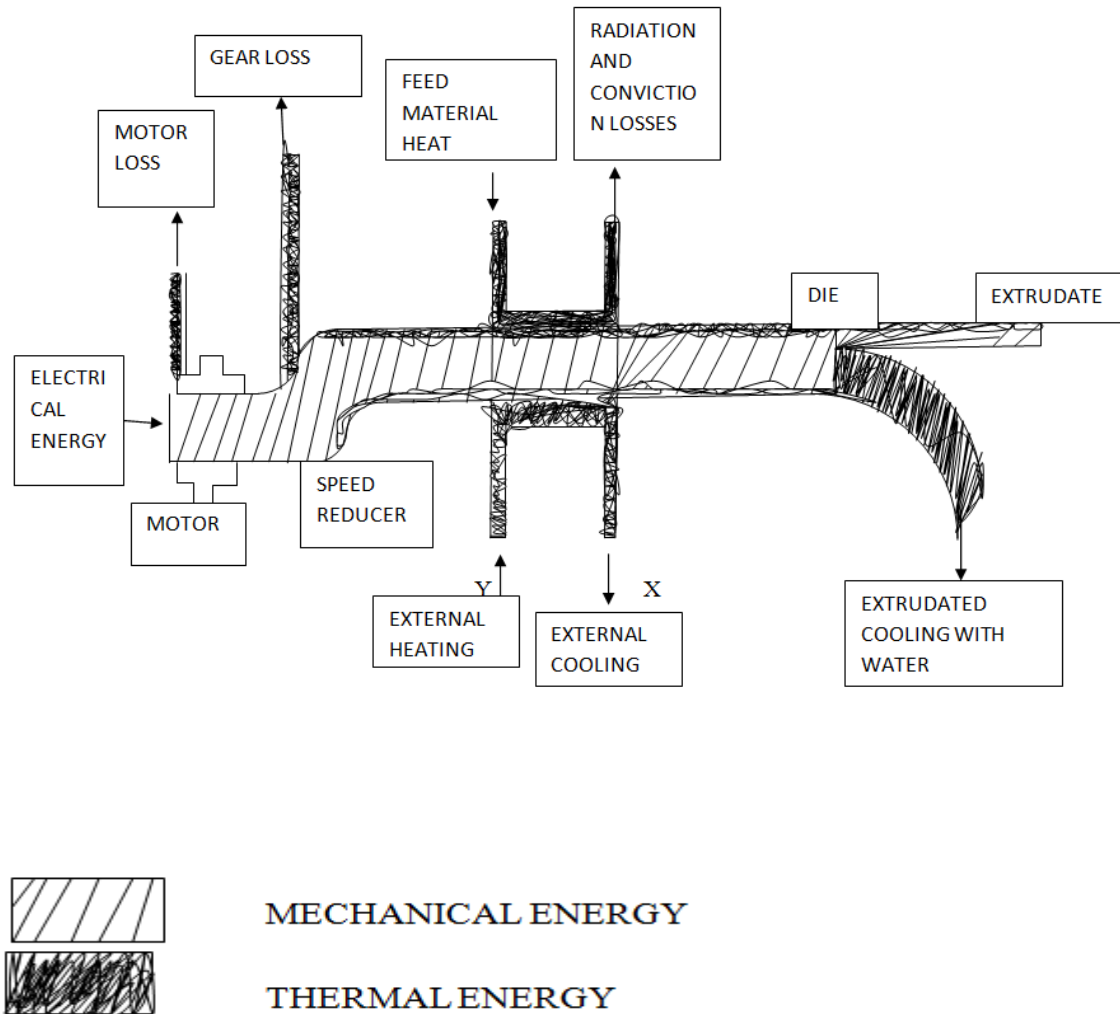


Figure12. Energy flow diagram for the extrusion process showing inputs of mechanical and electrical energy and output of thermal energy. (Author)

A total of three extrusion runs were conducted. The same material was run at three different screw speed (30, 40, 50 rpm). Each run was allowed to equilibrate for ten minutes before any data was collected. Once a run had stabilized, the following measurements were made; melt temperature ($^{\circ}\text{C}$), maximum and minimum head pressure (MPa), motor current (A), throughput (kg/hr), and heater-on time (s) for each run.

Table5. Changing in temperature with time, mass of polyamide (PA) extrudated.

Running time in minutes	(rpm)	Mass of PA in /g	Initial temp of water / °C	Δ in temp.of water /°C
0	30	50	10	10
15	30	100	13.5	15
30	30	150	15	20
45	40	200	20	25
60	40	250	25	30
75	50	300	30	36
90	50	350	36	42

7.1 Calculations:

In order to determine the exit temperature of the extrudate in this experiment, the shear rate has to be determined, shear rate which is given by:

$$\text{Shear rate } (\dot{\gamma}) = \frac{\pi \times d \times n}{60 \times h} \quad (\text{Eqn9}). \text{ (Harold F. Giles, p161[5].)}$$

Where $\dot{\gamma}$ = shear rate in screw channel, is given in secs^{-1}

d_{screw} = screw diameter in mm

n_{screw} = screw speed in revolutions/minute

h = channel depth in mm.

In this experiment, the Arcada extruder barrel diameter was taken from the extruder manual to be $d = 18$ mm, the screw speed n set at 50 rpm and the channel depth in mm was measured to be $h = 9.5$ mm.

Then the shear rate at the barrel zone is given by (Eqn9);

$$\text{Shear rate} = \dot{\gamma} = \frac{\pi \times d \times n}{60 \times h} = \frac{3.14 \times 0.018 \times 50}{60 \times 0.0095} = 4.957 \text{ s}^{-1}$$

The rate at which polymers sheared between the end of the screw tip and the barrel wall is computed using (Eq9) above. The shear rates between the end of the screw flight and the barrel wall are high because the height is small, and low between the lowermost end of the screw channel and the inner barrel walls because the distance between them is large there.

The rate at which polymers shear at the end of the screw area depends on the die shape. Since the Arcada extruder had a round die lip channel, the shear rate is computed using the equation below;

$$\text{Shear rate at the end of the die } (\bar{\sigma}) = \frac{4x q}{\pi x r^3} \quad (\text{Eq10}) \text{ (Harold F. Gile, p161 [14]).}$$

Where $\bar{\sigma}$ = Shear rate in round channel

r = Radius of the whole

q = Volumetric flow rate calculated given by;

$$q = k x \frac{\Delta P}{\eta} = \frac{\pi x r^4}{8 x L} x \frac{\Delta P}{\eta} \quad (\text{Eq11}). \text{ (Harold F. Giles, p61 [14]).}$$

Where $k = \frac{\pi x R^4}{8 x L}$ (opposing factor)

L = channel length

ΔP = Pressure drop across the channel

η = polymer Viscosity

Therefore the pressure fall in the channel can be establish from

$$\Delta P = \frac{2 x \phi x L}{r} \quad (\text{Eq12}). \text{ (Harold F. Giles, p161,[14])}$$

Where ϕ = Shear stress = F/A = Force applied per unit area.

7.2.1 The energy contribution by the drive system:

Power of the drive system can be approximated using the relationship;

Power $\approx 0.9 \frac{N_{act}}{N_{max}} IV$, (where N_{act} the actual rpm and N_{max} is the maximum rpm and I and V are the respective current and voltage measured across the motor).

This implies the approximate power consumed (taken in by the motor is ;)

$$P \approx 0.9 * \frac{50}{125} * 12.50 * 400 \approx 1800 \text{ watts. (Rauwendaal, [1]).}$$

The energy supply during 1 hour of processing 1200 g of PA is;

$$\text{Energy} = \text{Power} * \text{time in seconds} = 1800 * 3600 = 6480 \text{ kJ}$$

Part of this energy is used to drive the shaft and bearings of the extruder while the rest is converted in to heat energy by friction and shear between the extruder screw and the barrel wall.

7.2.2 The energy contribution by the heaters:

There are six ban heaters on the extruder, made up of nichrome alloys, the energy contribution of one of the heater was computed and multiplies by six to get the total contribution of the heating system.

Heater type: Aluminum band Heater Heating element: nichrome; (nickel and chromium alloys) Heater diameter is approximately 102 mm, Heater width is approximately 38 mm, Maximum lead amperes is approximately 12.5A, Voltage supply was 240V.

The watt density for this heater type is rated at (50W/ sq. inch) which are approximately (7 W/cm^2):

Surface Area of each heater is given by;

Area = $\pi * D * W = (3.1415 * 1.02 * 0.38) = 1.22 \text{ m}^2$. Surface Area of each heater is given by **Length (circumference) = $2\pi r = 2 (3.1415) (0.51) = 3.20 \text{ m}$**

The resistance of each of the heater is given by;

$$\mathbf{R = \rho_r L/A} \quad (\text{Kramer, W. A, [6]}).$$

Where R = resistance of the heating element.

L = the length of the heating element (in this case its circumference since it is cyclic in shape).

ρ_r = the resistivity of the heating element at 20 °C which is = $1.1 * 10^{-4} \Omega\text{m}$.

$$\therefore \mathbf{R = \rho_r L/A = 1.1 * 10^{-5} * 3.20 / 1.22 = 2.9 * 10^{-5} \Omega}$$

The power dissipated by one heater is then given by;

$$\mathbf{Power = VI = I^2/R = (12.50)^2/2.9 * 10^{-5} = 5.4 * 10^{-4} \text{W}}$$

Then the energy produced by one of the heater during processing in one hour is given by:

$$\mathbf{Energy = Power * Time = P * t \text{ (sec)} = 5.4 * 10^{-4} * 3600 = 16.3125 \text{ J}}$$

Therefore, the total energy produce by six of the heating system in 1 hour is;

$$\mathbf{Energy \text{ produce by 1 heater; } (16.3152 * 6) = 97.875 \text{ J}}$$

7.2.3 Energy for phase transformation

The energy required to heat solid polymer resins (Polyamide) from when the experiment begins to when the polymer became melted is given by the equation below;

Energy = Heat to melt (PA) from room temperature to its melting point.

$$\mathbf{E = (M \times C_p \times \Delta T)} \quad (\text{Eq13})$$

Where E = Energy

M = mass of polyamide process in one hour

C_p = heat capacity of polyamide in J/g°C

ΔT = difference in temperature between room temperature and melt temperature in °C and is given by $(300-25) = 275$.

The mass of polyamide (PA) process during the experiment in one hour is 250 g.

Heat capacity of polyamide (PA) at room temperature;

$$C_{PA} = 1.80 \text{ J/g}^\circ\text{C} \text{ (Arcada)}$$

$$\Delta T = (\text{processing temp.} - \text{room temp.}) = (300 - 25) = 280^\circ\text{C}$$

Therefore the energy requirement for phase change of granular (PA) to molten PA is calculated from (Eq13);

$$\begin{aligned} E &= (M \times C_p \times \Delta T) \\ &= 250 * 1.80 * 275 = 12240 \text{ J} \end{aligned}$$

The energy of the cooling water in the tank before the extrusion process begins was also calculated as;

$$E_w = M_w * C_w * \Delta T = 700 * 4.2 * 15 = 44100 \text{ J.}$$

Where; E_w is the energy stored in the water before the process.

M_w is the mass of cooling water in the tank before the process begins.

C_w is the heat capacity of water.

ΔT is the temperature of the water before the process begins.

The energy of the cooling water in the tank after the machine has been run for an hour and extruded about 1200 g of plastics was also calculated. The only difference in this energy was due to the steady raise in the temperature of the cooling water from 15°C to 45°C in one hour after about 1200 g of the plastics material has been process. The change in energy of the water in the tank is then computed as; Energy of the water after one hour is $= 700 * 4.2 * 30 = 88200 \text{ J}$. This means that the energy of the water used in cooling has been double in one hour due to the steady raise in the temperature of the water used to cold the hot polymer coming out of the die, this energy is at time consider as wasted energy since it is only discard or allowed to cold down and wait for another extrusion cycle to begins.

Table 6: Summary of the energies in and out of the extruder

Energies in the extruder	Derivation of the energies	Calculated values of the energies in joules
Energy from the drive	$E = P * t, E = V * I * t.$ Where; P = power, V =voltage rating of the motor and I = current flowing in the motot.	$P \approx 0.9 \frac{50}{125} 12.5 * 400 \approx 1800$ W. Energy =Power * time in seconds = 1800* 3600 = 6480 kJ
Energy contribution from the heaters.	$R = \rho L/A, P = I^2/R,$ Energy = Power * time	Energy produce by 1 heater * 6 = 97.875 J
Energy to raise the PA temp. from room temp. to 300 °C.	$E_{PA} = (M_{PA} \times C_{pA} \times \Delta T)$	250 * 1.80 * 275 = 123750J
Energy of the cooling water in the tank before processing	$E_w = (M_w * C_w * \Delta T)$	700*4.20*15°C = 44100 J
Energy of the cooling water after 1 hour	$E_w = (M_w * C_w * \Delta T)$	700 * 4.20 * 30 = 58800J

8.0 Discussion:

This thesis investigates how energy is consumed by an extruder, made possible by processing polyamide resins by an extruder in the Arcada laboratory. The analysis was performed for three screw speed operating at the same environmental conditions with an amorphous polymer (polyamide) (PA).

Since there had been a steady rise in energy cost in the past decade, minimizing energy usage had been a priority for most plastic manufacturing companies. The extruder consumed a lot of energy, the ease at which this machine convert the electrical power in to heat energy had to be carefully monitored. In other to successfully minimize this energy consumption required us to understand how this machine uses it energy.

There are three main gate ways through which power enters the extruder; the screw drive, the barrel heaters, and the digital PLC control system. The power that enters the screw drive is what is use to rotate the screw and causes friction for polymers between the barrel wall and the screw itself, this constant rotation of the screw generate heat via friction, and this heat is the energy that is use to melt about 80% of the polymer during the processing.

The extruder take in energy in the form of electricity and convert it in to heated energy by the screw, and the energy leaves the extruder practically as heat in the polymer melt, the cooling medium in the barrel, entrance cooling fluid, gearbox cooling fluid, or lost to the surrounding. By knowing where and how this heat is leaving the extruder it is possible to minimize these losses and thereby improving the energy efficiency. This is called constructing an “energy balance.”

During this experiment, the total power usage of the extruder was obtain by connecting a voltmeter and an ammeter to the main distribution to get the voltage and the current supply to the motor and their product gives the power which was **5000 W**. Extruders melt polymers primarily by viscous dissipation. Imagine the amount of work it would take to rapidly stir a pot of heavy oil or grease with a spoon. That’s approximately what an extruder has to do to melt polymer. Almost all melting results from the rotation of the screw in the barrel. The turning screw causes the melt film adhering to the barrel to be stretched, or sheared. The extruder drive powers the screw rotation, overcoming the resistance required to stretch the melt film. The drive energy is

thus transferred into the melt film. This energy increases the film temperature and melts some of the adjacent unmelted material by transferred heat. Approximately 80% of the input power in the extruder is use for the melting process.

Referring to the calculation, it is obvious that the barrel heater contribute just about **15% to 20%** of the total energy needed to melt the plastics. Barrel heaters contributes just about one third of the energy required during melting, two third of the melting occurs through the shearing of the polymer by the screw which result in by the conversion of the mechanical energy of the screw in to heat energy. Extruder's heaters are used mainly to melt the polymer that remains in the barrel just before the process begins, to help in forming the initial melt, and to "balance" the barrel temperatures for specific purposes such as improving feed rate. Extruders with smaller capacities had more barrel heating capacities than those with larger capacities, because their barrel surface area with respect to their output is larger. Electrical energy in take in a single screw extruder comes in at the screw drive, when the screw rotates; it produces friction which in turn generates heat that helps to melt the polymer. Polymer shearing, pressurization, and mixing consumed little amount of energy. As plastic manufacturer, the transferred of energy from the screw drive to the product is critical because it plays a bigger rule in minimizing energy consumed by the extruder. Since energy cannot be created nor destroyed, the kilowatt hours (kWh) taking in by the drive system to the energy transferred to the polymer must be balance. For amorphous polymers, this is simply the temperature increase in the polymer from the feed temperature to the melt temperature.

There were important findings that were observed during the experiment, although the extruder in the lab has a smaller output, running it at higher speeds in other to boost productivity is an added advantage to save energy per kilogram of output. When the machine is running at elevated speed it also reduces the heater power consumption because the machine will produce enough heat for metering the polymer.

After the polymer had been melted in the barrel, it is then driven by pressure towards the die; this movement is caused by the shearing effect of the screw and the barrel wall. The molten polymer coming out of the die need to be cool in other to stabilize it shape.

The heat need to be removed faster to keep the production line moving. The faster the plastic can be cooled and stabilize it shape the faster more polymers are extruded, rapid heat transfer is a crucial factor in the production line at this point.

In big companies, with many extrusion lines with similar temperature profile, a central cooling system is more cost effective than operating individual cooling systems for each extruder, a central cooling will means reducing space for many cooling tanks and will required less maintenance as compared to many cooling tanks.

It is obvious that a central cooling system may be necessary in circumstances in which about 50% of the plants machines are operating within similar temperature range, in this case the cooling system must be sized to provide the lowest temperature possible. If the temperature between one material to the other varied by ($\pm 2^{\circ}\text{C}$), the system must be size to give room for this variation in temperature.

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8.1 Conclusion:

To stabilize the product to it require shape need a cooling medium, water was used in this experiment as a cooling fluid, the temperature of water was controlled at regular intervals and the raise in temperature of water was also recorded, it was noted that the temperature raises steadily as more and more polyamide is being extruded in to the tank of water, the difference in the raise of temperature before and after the experiment was used to computed the energy of the water in the tank before and after the experiment. The result shows that the energy of the water in the tank double after one hour due to the raise in the water temperature.

The amount of energy that is drain down the sink (wasted energy) is the energy that is transferred from the molten plastic coming out of the die to the cooling medium (water) in the tank. This energy is calculated from the change in the temperature of the cooling water in the tank after about 1kg of the plastic resins was extruded. This was done by keeping the mass of water in the tank constant and stationary, after about 1 hour of extrusion the change in temperature of the water in the tank was then multiply by the mass of water in the tank and it`s heat capacity to give **88200 J**. The energy of the water before the experiment was **44100 J**.

This means the energy of the cooling water doubles by extruding 1kg of plastic in 1 hour, if this energy is converted in to watt, it means the power consumed in one hour will be; power (watt) = $29400/3600 = 8.1$ watt = **0.0081 kW**.

This figure 0.0081 kW gives an approximation of the amount of energy that is drain down the sink. In a typical plastic manufacturing industries where the extruders are operating all-round the clock, the amount of energy that is drain down the sink is significant, in this case the heated water resulting from the cooling of the plastic from the die can then be consider for reused either by passing it through the radiators to heat the environment or by conveying it over the drier for drying of the resins before processing.

In addition to the energy study, performance characteristics were also considered. Major findings from this work are as follows:

- The extruder takes in large amount of power, and utilizes this energy during processing, 20% of the intake powers go to the drive and screw system while about 80% is transfer to the polymer by friction and conduction in the barrel.
- The barrel heaters are used mainly for startup and for the temperature stabilization, it contribute just about 20% for the total energy needed for the melting of the polymer.
- Screw mixing elements produce a melt with lower effective viscosity, resulting in lower head pressures and lower pressure variation compared to a general purpose screw.
- Barrel Zone 1, when not insulated from a cooled feed throat, consumes (wastes) significantly more energy than the other barrel zones.

Running at higher screw speeds is not only advantageous from a productivity standpoint, but provides significant energy benefits as well, including reduction in the percentage of energy required from heaters, much of which may be lost to the surrounding environment.

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