

DEVELOPMENT OF A MULTI-PURPOSE TWIN-SCREW EXTRUDER

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the degree Master of Engineering at the
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Declaration

I, Werner van Niekerk, (ID NR:8211165108080) hereby declare that all the material incorporated into this project report is my own original unaided work, except where specific reference is made by name or in the form of a numbered reference. The work herein has not been submitted to any other university to obtain a degree.

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8 April 2009

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ABSTRACT

The extrusion market of South Africa has a smaller demand for products than most of the First World countries in which mainly single process twin-screw extruders are used. This leaves a void for the development for a multi-purpose twin-screw extruder. This will enable companies to manufacture a greater diversity of products with one machine, not only in South Africa, but in the rest of Africa as well.

Africa has one of the biggest rates of poverty and famine in the world. The famine crisis in Africa is mainly due to the lack of food with a high nutritional value. The conventional cooking method currently used, that of preparing food over an open fire, causes the loss of most of the vitamins and essential nutritional values in the food.

Extrusion is the process whereby high quality food is manufactured by using simple raw materials. The raw material goes through a process of heating, mixing and shearing to produce a high quality end product.

The main disadvantage of extruders currently available on the market is their cost. Extruders are currently manufactured in the First World countries. This causes that the machines are too expensive and unaffordable for most of the African markets. This creates the opportunity for an affordable extruder to be manufactured and maintained in Africa.

This study provides an introduction to extrusion. Chapter 2 contains a literature study on the various extruders and their respective available sub-components. It also discusses the differences between different extruders. In Chapter 3 a generic approach to the design and manufacturing of an extruder unit is formulated and discussed. Chapter 4 is dedicated to the explanation of basic screw geometry and designs. Chapter 5 contains case studies on two types of barrels designed and tested during this study. It also provides the best choices of

designs for various components. In Chapter 6, a case study of a fully operational twin-screw food extruder is discussed. This extruder was manufactured in Africa, and maintained in Africa. Recommendations and conclusions of this study are summarized in Chapter 7.

OPSOMMING

Suid-Afrika se ekstrusiemark het 'n kleiner aanvraag vir ekstrusieprodukte as die meeste van die Eerstewêreldlande, waarin daar hoofsaaklik enkelproses dubbelskroef-ekstrueerders gebruik word. Dit laat 'n gaping vir die ontwikkeling van 'n multi-proses dubbelskroef-ekstrueerder. Dit sal maatskappye in staat stel om 'n groter diversiteit van produkte met slegs een masjien te vervaardig. Dit geld nie net vir Suid-Afrika nie, maar ook vir die res van Afrika

Afrika is een van die wêreldlande met die hoogste armoedesyfer. Die hongersnood-krisis is hoofsaaklik die gevolg van 'n tekort aan voedsel met 'n hoë voedingswaarde. Die konvensionele metode van kook oor 'n oop vuur, wat tans gebruik word lei daartoe dat die meeste van die vitamines en noodsaaklike voedingswaardes van die voedsel verlore gaan.

Ekstrusie is 'n proses waardeur hoë-kwaliteit voedsel geproduseer kan word uit grondstowwe. Die grondstowwe gaan deur 'n proses van verhitting en vermenging om die finale produk te vorm.

Die grootste nadeel van beskikbare ekstrueerders tans, is hulle hoë koste. Ekstrueerders word in ongeveer elke Eerstewêreldland vervaardig. Dit veroorsaak dat hierdie masjiene baie duur en onbekostigbaar vir die Afrikamark is, wat die geleentheid daarstel vir die vervaardiging van 'n bekostigbare ekstrueerder in Afrika, wat ook in Afrika onderhou word.

Hierdie studie sal 'n inleidende beskrywing van ekstrusie bied. Hoofstuk 2 bevat 'n literatuurstudie van die beskikbare ekstrueerders en hulle onderskeie subkomponente. 'n Generiese aanslag op die ontwerp en vervaardiging van 'n ekstrueerder is in hoofstuk 3 geformuleer en bespreek. Hoofstuk 4 is toegewy aan die verduideliking van basiese skroefontwerp. Hoofstuk 5 bevat twee

gevalllestudies van twee lope wat ontwerp en vervaardig is gedurende hierdie studie en verskaf verder die beste keuse vir die onderskeie komponente.

In Hoofstuk 6 is 'n gevalllestudie van 'n volledig-vervaardigde dubbelskroef-ekstrueerder. Hierdie ekstrueerder is vervaardig in Afrika en word in Afrika onderhou. Aanbevelings en opsommings van hierdie studie word in Hoofstuk 7 verskaf.

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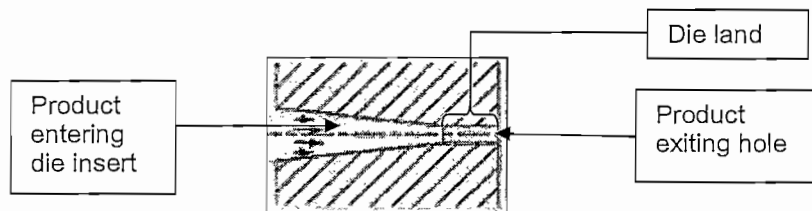
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Nomenclature

- 1) **Nitriding:** *is a process which introduces nitrogen in the surface of a material. It is used in metallurgy for surface-hardening treatment of the steel surface.*
- 2) **Co-extrusion additives:** *additives added to the die of the extruder to create the final product.*
- 3) **Repeatability:** *the extrusion process will run for several hours on end.*
- 4) **L/D Ratio:** *this is the length to diameter ratio of the extruder barrel. The diameter being the bore diameter and the length, the length of the barrel.*
- 5) **G-code:** *is a common name for the programming language that controls NC and CNC machine tools.*
- 6) **4D:** *is 4 times the bore diameter. For example: a 4D screw element for a 50mm extruder would be 200mm long. ($4 \times 50 = 200\text{mm}$)*
- 7) **Die land:** *the die land is the narrowest part in the die. This creates the compression/pressure needed to “puff” certain food stuffs. The length of the die land depends on the type of product and can easily be determined by a method of trial and error. For example: To create simple puffs from maize, a die land of between 2.5mm and 3mm will be needed.*



Chapter 1: Introduction

1.1 Introduction

To date extruders have mainly been custom-built to fulfil a specific purpose, i.e. to produce a single product, or in some cases, a few products with similar processing requirements. The designing aim with the extruders was not to simplify switchover between products or use the same extruder to produce a number of different products. One of the main reasons for this is the fact that twin-screw extruders are expensive and were consequently mostly being used by large international companies with large markets for their products. The tendency therefore was to use a number of extruders, each dedicated to a specific product, rather than a multi-processing modular twin-screw extruder (Vorster, 2005).

The high cost of the extruders made the acquisition of a twin-screw extruder difficult for processing companies with smaller markets, such as companies in South Africa and other developing countries. The inability of current extruders to switch over quickly between products further hampered the wide-scale use of twin-screw extruders by smaller companies.

Subsequently, there is also a need for a local manufacturer of high quality extruders. The advantages of this are that the extruder can be maintained locally and that technical support is always available. These advantages are necessary, because personal interaction between the end-user and the original equipment manufacturer (OEM) is very important, since it enables the end user to do product switchovers much quicker, thus reducing downtime.

1.2 *The need for a modular twin-screw extruder*

The development of this extruder will benefit smaller companies, with smaller markets, in that they will be able to buy an extruder and use it for a variety of different products. Thus, it will be possible for the company to cater for any change in the market without buying a new extruder. The modularity will also assist in lowering maintenance costs because only the worn parts and components will have to be replaced. The modularity and multi-process abilities will result in the standardization of extruder components, thus opening the opportunities for the introduction of more effective production lines.

1.3 *Aims of this study*

The aim of this study is to develop a multi-process modular twin-screw extruder in order for the same extruder to be used to process different products, with quick configuration-switchover capabilities between products i.e. polymers food etc. This will result in minimal plant downtime and machinery that can be serviced easily. Cost of various components also plays a major role in the design process.

A twin-screw food extruder has been successfully developed over recent years at the North-West University. The extruder is currently operating in a production environment and it demonstrates high levels of performance and reliability. There are still a few problems with the extruder. A further aim of this study is to identify and solve those problems. Selecting the following items will provide this information:

- The right screw configuration
- The correct barrel type
- Material choice and type (shape etc.) for the various components
- Heating and cooling methods
- Selection of the correct feeder

- Reduction of maintenance cost

1.4 Scope of this study

Through an examination of a projection of what the scope of the study might comprise of, the following came to the fore:

- The first step was to determine what previous work had been done on modular twin-screw extruders and to determine the basic components of an extruder. The results of this examination can be found in Chapter 2, in the literature study
- Thereafter a generic design tree for the design of a twin-screw extruder was developed
- Investigate and discuss basic screw design
- Investigate various case studies and explain the findings of these investigations
- Design and manufacture a modular twin-screw extruder
- Test the extruder and evaluate the findings
- Recommendations and conclusions

1.5 Summary

This chapter provides an introduction to the current main uses of extruders and needs and goals of this study. The project aims are also formulated and briefly explained to provide a background on this study. The main focus areas for this study were also identified and are the following:

- Selecting the correct screw configuration
- Selecting the correct barrel type
- Selecting the correct materials and type (shape etc.) for the various components
- Choosing relevant heating and cooling methods
- Selection of the correct feeder

- Reduction of maintenance cost

The scope of this study was also formulated and the method that will be employed in this study is also explained.

Chapter 2: Literature survey

2.1 Introduction

In this chapter a literature survey will be executed to determine the definition of an extruder, determine the advantages of extruders, provide a detailed description of the different types of extruders, define and explain the function of the extruder screw, define and explain the function of the extruder barrel and explain the heating and cooling of the barrel, provide an explanation on the functioning of dies, cutters and feeders, define and explain the extruder scale up and provide an explanation of the chemical changes that the product undergoes during operation.

2.1 What is an extruder?

The definition of an extruder needs to be discussed so that there is clarity on what the basic operation of an extruder entails:

“Extrusion is basically a process of pushing a ductile material through a die to obtain a desired shape. Various types of products can be extruded, e.g. polymers, food, metals etc” (Rauwendaal, 1998).

2.2 Advantages of extrusion

Depending on the type of product to be extruded, extrusion has many advantages. The following are just a few advantages related to food and plastic extrusion:

1. *Adaptability*: Changing minor ingredients and operating conditions can produce a large number of products
2. *Energy efficiency*: Extruders operate at relatively low moisture content. Thus not much drying is required after extrusion

3. *High Productivity*: The continuous nature of the extrusion process ensures high productivity
4. *High quality product*: Extrusion is a High Temperature/Short Time (HT/ST) process. The short exposure time to heat minimizes the degradation of food nutrients. It also improves the digestibility of protein through denaturing, and starches through gelatinizing
5. *Low cost*: Extrusion has a lower processing cost than other cooking and forming processes. Darrington (1987) reported savings of raw material (19%), labour (14%) and capital investment (44%) when using the extrusion process and less space is required per operating unit

2.3 Different types of extruders

Extruders have been developed over the years to address every shortcoming that its predecessor might have had. This led to the development of multi-screw extruders that has up to eight rotating screws. The three types of extruders that gained the most ground were the single screw extruder (SSE), the counter- and the co-rotating twin-screw extruders (TSE). These types are used most commonly in the various industries.

Each one of these types of extruders has advantages and disadvantages. A more detailed explanation of each follows (White, 1990).

- ***Single screw extruder (SSE)***: A SSE has only one screw with which to generate the required pressure to force the product through the die. They rely on drag flow to develop die pressure. This causes a SSE to be classified as a drag flow device rather than a positive displacement pump, it drags the material down the barrel. Liquorice is an example of a product that cannot be extruded by an SSE. The reason for this is that liquorice is a very sticky product in the molten state and because an SSE relies on the drag flow in the barrel, the liquorice sticks to the screw and resists being conveyed forward (White, 1990)

- **Twin-screw extruder (TSE):** In Figure 1, the basic components of a twin-screw extruder can be seen. Two types of twin-screw extruders are available: Co-rotating and Counter-rotating TSEs. The co-rotating TSE is the more popular one of the two as can be gathered from Table 1

Counter rotating TSE	Co-rotating TSE
1) Higher pressures can be achieved because of separate channel conveying action	1) Higher screw speeds can be achieved because radial forces are more uniformly distributed
2) Has poor mixing characteristics	2) Offer more flexibility for producing a wider variety of products
3) Higher wear on components because of uneven distribution of forces	3) Less wear on the barrel components
4) Application tends to be limited to low viscosity systems which require positive displacement	4) Product quality and output are constant

Table 1: Comparison of a Counter and Co-rotating TSE
(Rauwendaal, 2001)

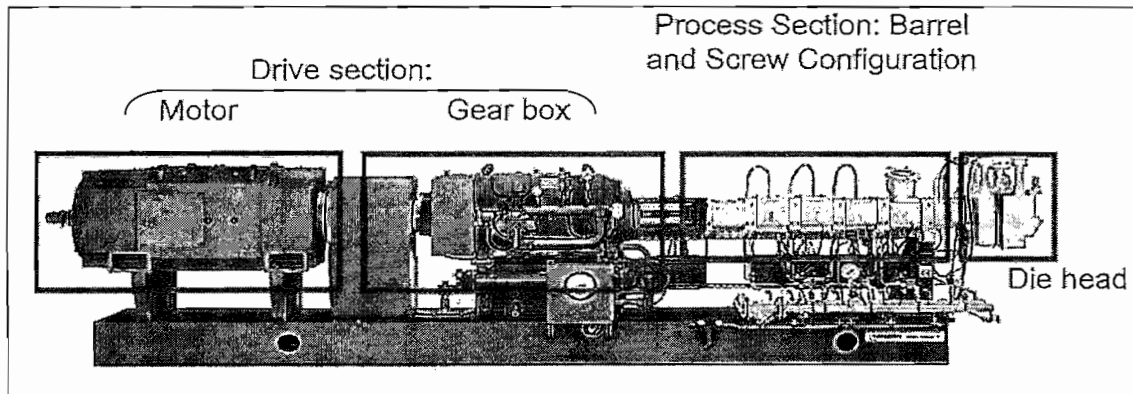


Figure 1: An Extruder Unit (Society of Plastic Engineers, 2002)

The twin-screw extruder was developed to overcome the limitations of the SSE, and can be compared to the "next generation" of the single screw unit. The main

difference between the single and twin-screw extruder is that in a twin-screw extruder the dual screw action conveys the product through the barrel.

The twin-screw extruder has the following advantages:

- The TSE is self-cleaning. This self-cleaning action is obtained by the way the screws mesh into each other (See *Figure 2*). The clearance between the screws are determined by two factors:
 1. The shaft centre distances
 2. The root diameter of the screw

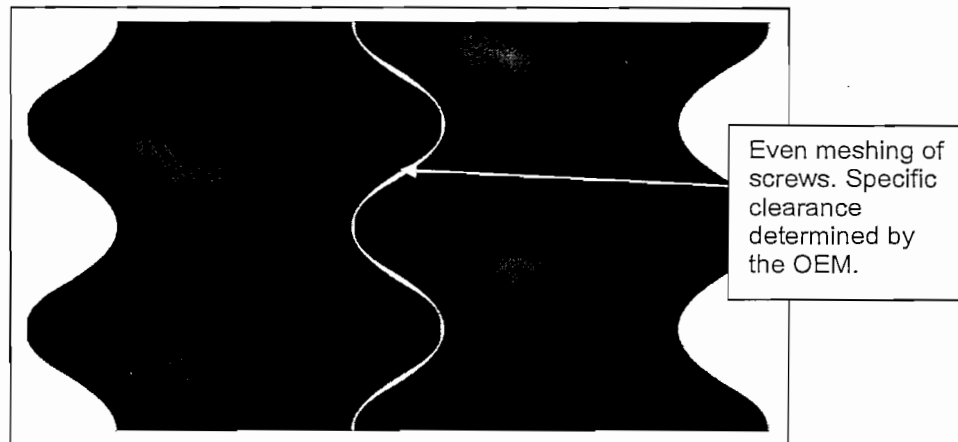


Figure 2: Even meshing between two screw elements

- A wider range of products can be produced with a quicker product switchover. Almost all products produced on an SSE can be produced by a TSE
- The quality of the product is easily reproduced
- High input of mechanical energy is possible because of the big variety of screw configurations that is possible
- The processing parameters (temperature, pressure, etc) can be varied independently on a TSE and can consequently be better controlled. In an SSE it can be controlled to a lesser degree
- The mixing ability of a TSE is a lot more effective than that of a SSE. The reason for this is that the TSE mixes in a “figure 8” mixing style. This

motion mixes the product much better than the single twist mixing of the SSE. The TSE offers a wider range of mixing elements than the SSE so that products with a bigger particle size than a SSE can be extruded

- Start-up and shutdown can be handled quickly on a twin-screw extruder
This saves time and money, especially on high volume production lines

The only disadvantage of the TSEs in comparison with the SSEs is their significantly higher capital cost.

Figures 3 and 4 show in what way the abovementioned extruders compare to one another.


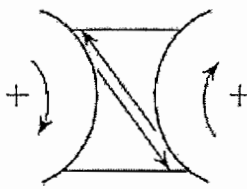
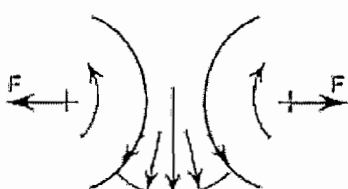
Single screw extruder	Twin-screw extruder	
	Co-rotating	Counter-rotating
 <p>No self wiping effect. Product can stick to the screw without being transported forward.</p>	 <p>Velocity difference between the two screws. One screw wipes the other one without creating high forces towards the barrel wall. This allows high screw speed without the risk of wear.</p>	 <p>No velocity difference between the two screws. The product is squeezed out of the gap between the screws. This "calender effect" causes high forces towards the barrel wall (= risk of wear). These forces are limiting screw speed of this extruder system.</p>

Figure 3: Schematic comparison of product flow in the different screw extruders (Society of Plastic Engineers, 2002)







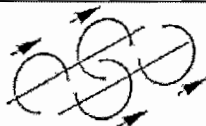
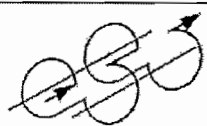
Single screw extruder	Twin-screw extruder	
	Counter-rotating	Co-rotating
Axial open system 	Axial closed system  	Axial open system  
		
Product conveying depends on the difference of friction of the polymer to the screw and polymer to the barrel wall. • low friction to the screw (chrome plating) • high friction to the barrel wall (grooved inner surface) Melt conveying by drag flow.	Closed chamber in the Intermeshing area of the screws. "Single screw conveying" in the other parts of the screw. Good conveying Good pressure build-up Reduced longitudinal mixing	Open intermeshing area of the screws. "Single screw conveying" in the other parts of the screw. Reduced conveying Reduced pressure build-up Good longitudinal mixing

Figure 4: Schematic comparison of the different screw extruders
(Society of Plastic Engineers, 2002)

2.4 The extruder screw

The heart of the extruder is the extruder screw. This is a long cylinder with a helical flight wrapped around it. *Figure 5* shows a typical extruder screw with its various processing sections. An extruder screw normally consists of three sections or zones (Clextral Group, 2005):

- Feeding zone: Typically feed screws with a large pitch
- Mixing/cooking zone: Medium to small pitch feed screws and kneading elements
- Metering zone: Depending on the die and product type, but this zone normally consists of feed screws with varying pitches

These sections have various other names depending on the type of product. In food extrusion for instance, the zones have names like compression, melting, reacting, amorphousing, and texturizing zones.

A more in depth description of basic screw design and configuration will follow in Chapter 4.

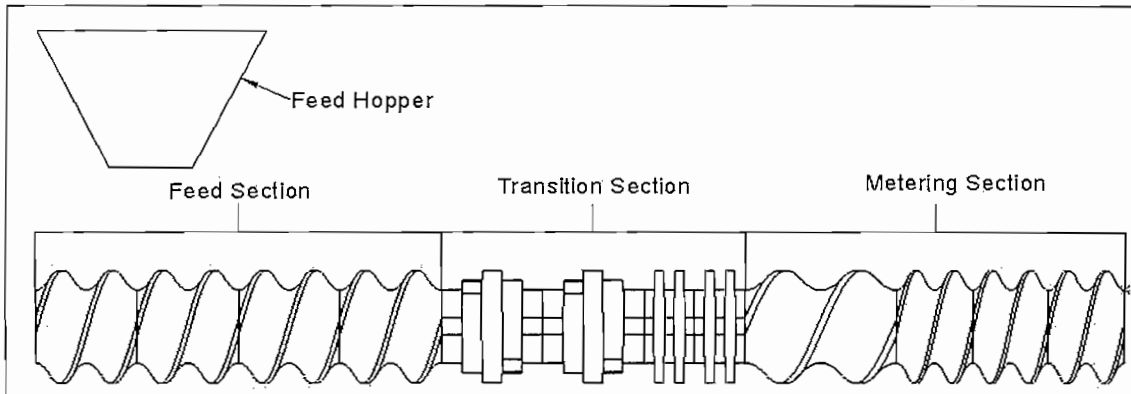


Figure 5: Schematic presentation of various processing sections of an extruder screw

2.4.1 The feed zone/section

The feed zone is located in the rear cylinder (hopper) zone. Pitch length of the screws is longer than in the rest of the configuration to allow for maximum free volume to convey the raw product fed into the hopper. Variations on normal feed screw segments have been developed to increase the free volume in the feed section. More detail on this will be provided in Chapter 4. The feed screws “force” the product forward in the barrel to acquire adequate pressure. The OEM determines the amount of feed screws needed to process certain products. This process is normally completed through experience and trial and error methods.

In food applications, moisture is normally added in this zone. This is done by simply pumping water through a hole in the barrel by means of using a dosing pump. Steam may also be added instead of water in liquid form.

2.4.2 The transition zone

The transition zone is the part of the process where the granules get mixed and cooked (food applications). It is also referred to as the transition section in which the product “changes”. In polymer extrusion, this is the section where the polymer melts and is mixed with any extra additives.

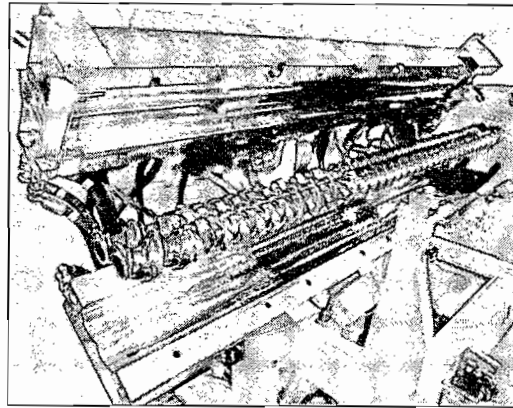
This zone normally consists out of kneading elements, medium pitch reverse elements (to promote melting and cooking) and forward conveying screws. A large amount of mechanical energy goes into the product in this zone. As the product flows through this section, it begins to form a more dough like structure, therefore the product will typically reach maximum compaction in this section.

2.4.3 The metering section

In a polymer extrusion process the metering section provides melt stability and helps to ensure a uniform delivery rate. In food extrusion this is the zone where amorphousing and/or texturizing of the product occur. The shear rates and compression of the product is at its highest in this region. This is achieved by the extruder screw configuration. More kneading blocks and compression elements will also be present in this area, to further knead and compress the product. Thereafter the extrudate is finally forced through a die at the end of the extruder to acquire the desired shape of the product.

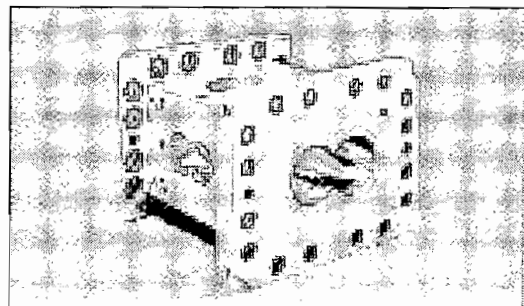
2.5 *The extruder barrel*

The casing in which the screw turns is called the barrel. There are two types of barrels, clamshell and solid barrels. A segmented clamshell barrel as seen in *Figure 6* uses a splitting motion for opening. The barrels and screws can easily be inspected and cleaned using this type of barrel.



*Figure 6: Clamshell barrel
(APV, 2000)*

In *Figure 7* a segment of a bi-metallic solid barrel can be seen. A solid barrel's lining is normally bi-metallic and can handle higher processing pressures than a clamshell barrel. Various other surface hardening methods are also used, like nitriding¹, but bi-metallic barrels are the most commonly used.



*Figure 7: Bi-metallic solid barrel
(Xtrutech, 1995)*

2.6 Extruder barrel heating and cooling

An extruder barrel normally has both heating and cooling abilities. Heating is usually done by cartridge elements, cast slab heaters or electrical band heaters, depending on the design and shape of the barrel (Rauwendaal, 1998). Heat is also generated due to friction (mechanical energy) in the barrel. Kneading elements generate higher friction than regular feed screws. More information on this topic will be provided later in the study. The temperature of the barrel is measured by using a thermocouple, resistance temperature detector or infrared

detectors. The thermocouple is based on the principle that if two different metals are connected and the temperature T of the joint, differs from a reference junction, say at T_0 , a voltage is generated across the two metals related to the temperature difference $T - T_0$. A resistance temperature detector works on the principle that metals' electric resistance vary with temperature. Thus, by measuring resistance, the temperature can be calculated. A platinum element is used to achieve high accuracy. There is also a linear relationship between temperature and resistance. Infrared temperature detection works on the principle that an object emits a changing radiation that is related to temperature. The amount of radiation emitted by the object is measured and the unit can then calculate the temperature (Rauwendaal, 1998).

Cooling on the extruder barrel is achieved by running chilled water through ports in the barrel. The OEM determines the position, size and amount of cooling ports. The placement of the ports normally depends on the number of zones, the zone positions and the positions of the cartridge elements.

2.7 The die and cutter

The die is placed at the exit end of the extruder where the product is discharged. Dies are designed to be highly restrictive in order to increase barrel fill, residence time and energy input (Huber, 1989). *Figures 8 and 9* show a few examples of extruder dies. A die normally consists of a transition or breaker plate and a die plate into which the die inserts fit, if necessary.

In an extrusion process, the cutter type depends on the type of product. In *Figure 9* a face cutter used to cut "puffs" and other food products can be seen.

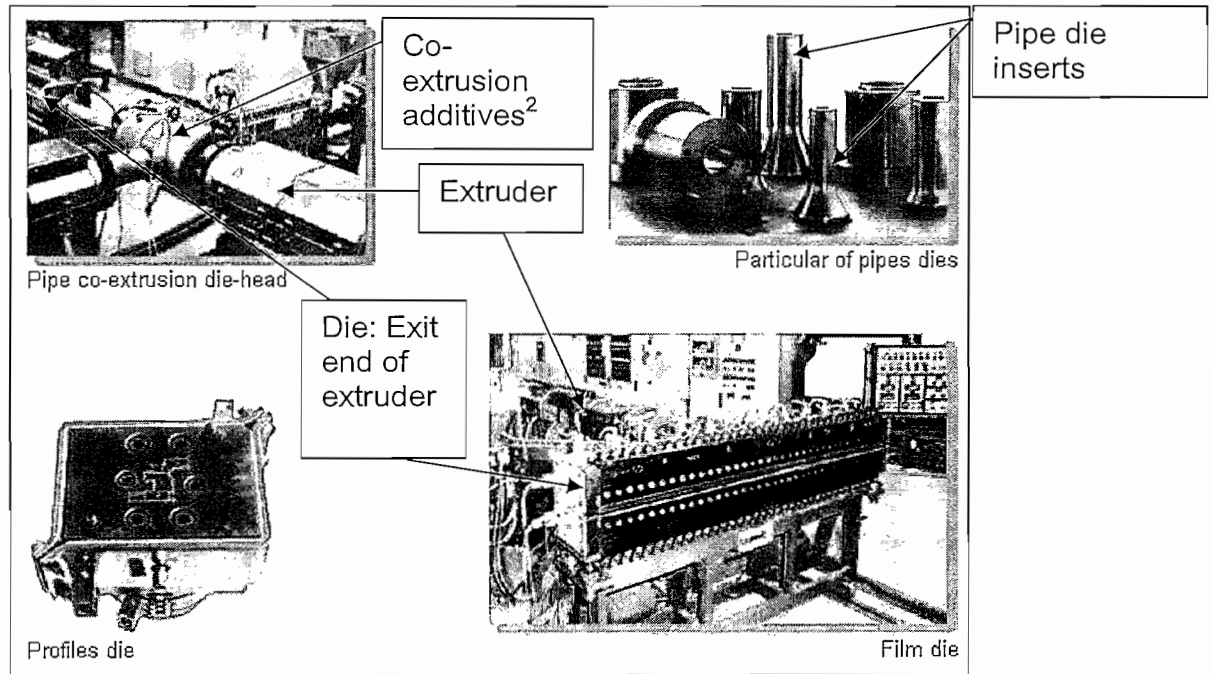


Figure 8: Different extrusion dies (Bausano, 2005)

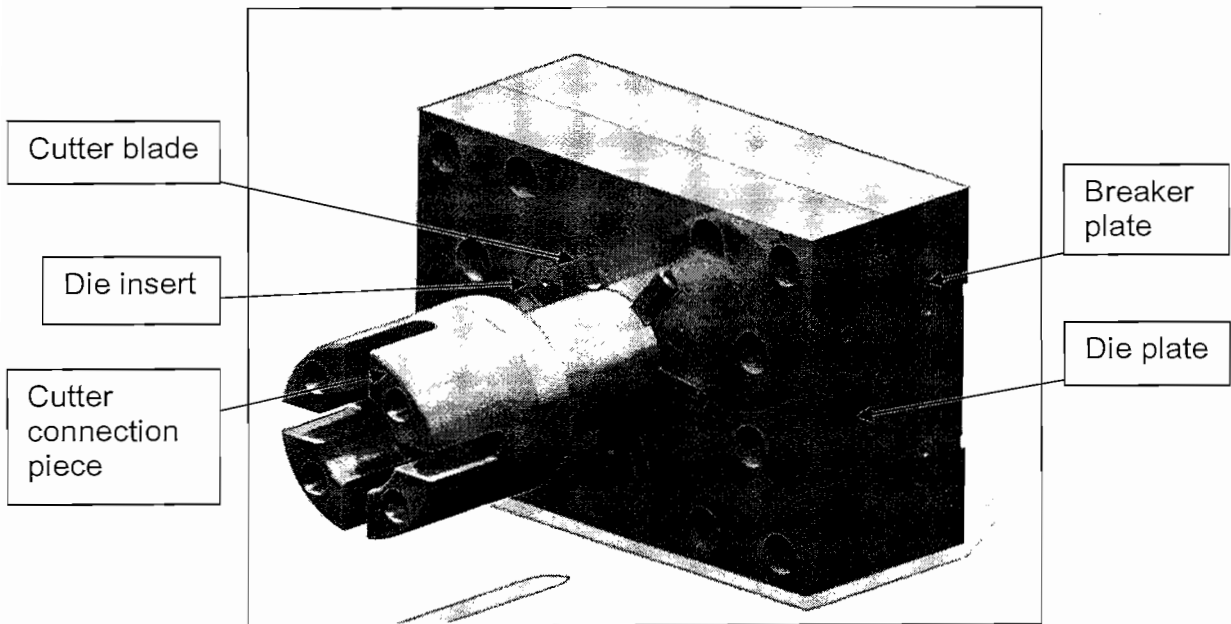


Figure 9: Die and cutter assembly

2.8 Feeders

There are two basic types of dry feeders used to feed extruders: volumetric and gravimetric feeders (Mercier *et al*, 1998). A feed port is located just above the feeding section in the extruder barrel. The feeder is mounted above the feed zone to feed the raw material into the feed hopper. The feed hopper is visible in *Figure 5*.

2.8.1 Volumetric feeder

A wide variety of volumetric feeders are currently available. The single-screw feeder is the one most commonly used, with a feed rate that is proportional to the screw speed (Mercier *et al*, 1998). A single screw volumetric feeder can be seen in *Figure 10*.

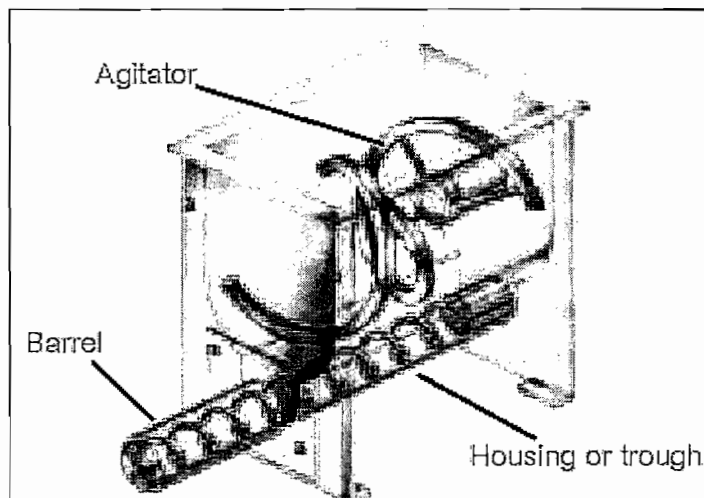


Figure 10: Volumetric Feeder
(Couch *et al*, 2003)

2.8.2 Gravimetric feeders

In most large-scale operations, repeatability³ of the process is of essence. When a gravimetric feeder is employed this becomes crucial. The two most popular gravimetric feeders are the weigh-belt-feeder and the loss-in-weight feeder. Each measures the mass rate and adjusts operations automatically to maintain this

feed rate, despite changes in the feed material and its flow characteristics (Mercier *et al*, 1998). In *Figure 11* a loss-in-weight volumetric feeder can be seen.

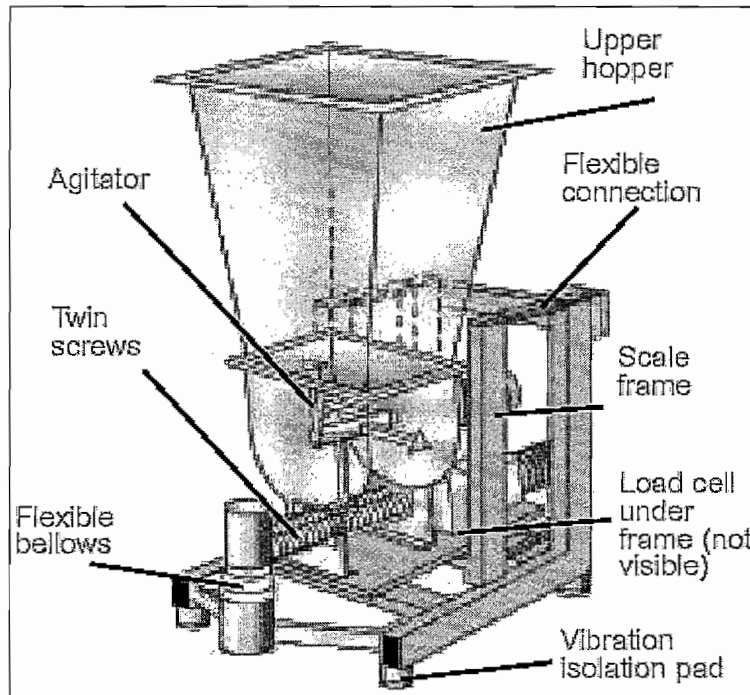


Figure 11: Loss-in-weight-feeder
(Couch *et al*, 2003)

2.9 Extruder scale up

The definition of extruder scale up according to Mercier *et al* (1998) is: "... the task of producing an identical, if possible, process result at a larger production rate than previously accomplished".

Extruder scale up is basically a process of building a lab extruder or pilot plant and testing it with various screw configurations and parameters. When satisfactory results have been achieved, the extruder will then be rebuilt to a full size production machine.

Parameters that increase during the scale up process are as follows (Frame, 1995):

- Barrel diameter
- Available barrel volume per unit length
- Barrel inner surface area per unit length
- Screw tip speed (for similar revolutions per minute)
- Power to drive unit
- Barrel heating and cooling capacity
- Barrel cross-sectional area (available for die placement)

According to Frame (1995), the following equations can be developed for the scaling of an extruder:

On the majority of commercially available twin-screw extruders the geometric profile is constant across the size ranges. From this, the following relationships can be developed. The available cross sectional area of the extruder is a constant function of the squared diameter and the barrel length is a constant multiple of the diameter. Therefore, the available volume of the extruder is a function of the cubed barrel diameter:

$$\text{Available area for die placement} = f(D^2) = K_1\pi(D^2 / 4)$$

$$\text{Available volume} = f(D^3) = K_1\pi(D^2 / 4)L$$

The geometry of the TSE also dictates that the inside circumference of the barrel is a constant function of the barrel diameter. Therefore the inside surface area of the barrel is a function of the square of the barrel diameter:

$$\text{Available inside surface area} = f(D^2) = K_2\pi DL$$

The screw tip speed is dependent on the screw diameter and the shaft speed (in rpm).

Assuming similar speed across the size ranges then the screw tip speed is a function of barrel diameter:

$$\text{Screw tip speed} = f(D) = \pi DN, \text{ where } N = \text{RPM}$$

The main extruder drive size and heating and cooling capacity are not determined by the barrel geometry but by the designer. There is a large amount of flexibility allowed in the design because it is mechanically dependent upon the extruder geometry of shaft size and strength or the area available for heater and cooling channel placement. The available area for die placement is dependent on the cross sectional area of the barrel to some extent and therefore is a function of the square of the barrel diameter:

$$\text{Available area for die placement} = f(D^2) = K_1 \pi (D^2 / 4)$$

These relationships can be used to evaluate the process and determine the scale-up requirements.

There are two types of extrusion processes; one is an adiabatic process where all the heat is basically generated by the drive motor and the other is a heat transfer process during which the extruder acts as a heat exchanger.

In an adiabatic process, the process is limited by the amount of shear or viscous dissipation energy that can be generated in the product. This is determined by the amount of power (in kW) available from the main drive motor, the screw tip speed and the product residence time. The product residence time is determined by the feed rate, which in turn is determined by the amount of free volume available in the barrel. From the previous functions, the feed rate can be increased by a ratio equal to the increase in volume. Therefore, the available power may increase by the same diameter cubed ratio than that of the feed rate.

In a TSE the screw speed is a direct function of the shear rate. Therefore, the screw tip speed should be kept as constant as possible across extruder sizes. This is not practical, since the available power is a function of shaft torque and speed. In practice the screw speed (in rpm) is kept constant for most sizes and the tip speed increases for larger extruders. This increases the shear rate in the larger extruders and in some cases increases the efficiency of the extruder. There are limitations since at excessively high tip speeds, feeding operations and the mechanical wear can cause problems. With this being said, most manufacturers decrease the speed in rpm to a point where the shafts can still handle the torque (Frame, 1995).

The formula below is the formula used to calculate the torque of an electric motor. Considering this, as the speed in rpm increase, the torque will decrease and vice versa.

$$\text{Torque (N.m)} = \frac{kW \times 9550}{rpm}$$

Based on these considerations, the scale-up rate in an adiabatic operation can be increased by the cubed increase in barrel diameter:

$$Rate_2 = (D_2 / D_1)^3 Rate_1$$

In a heat transfer operation the scale up is similar to that in a heat exchanger. The energy input is a function of the heat transfer coefficient of the material, the temperature gradient and the surface area available for heat transfer. There are many processes that are combinations of adiabatic and heat transfer operations. In these cases it must be established what portion of the total energy input is provided by each (Mercier *et al.*, 1998).

The scale-up equation could be expressed as:

$$Rate_2 = (D_2 / D_1)^c Rate_1$$

Where c is the scale-up factor.

2.10 Chemical composition changes in extrusion products

The chemical changes that extrusion products undergo during extrusion will be explained in two categories namely:

- Polymers
- Food products

2.10.1 Polymers

Polymers can be divided into three main groups: thermoplastics, thermo-sets and elastomers. Thermoplastic materials soften when they are heated and solidify when they are cooled. If the extrudate does not meet the specifications, the material can generally be reground and recycled. Thus, the basic chemical composition of a thermoplastic does not change significantly as a result of the extrusion process.

Thermo-sets undergo a cross-linking reaction when the temperature is raised above a certain temperature. This cross-linking binds the polymer molecules together to form a three-dimensional network. This network stays intact when the temperature is reduced again. Cross-linking causes an irreversible chemical link in the material. Therefore, thermosetting materials cannot be recycled as thermoplastic materials.

Elastomers or rubbers are materials capable of very large deformations with the material behaving in a largely elastic manner. This means that when the deforming force is removed, the material completely, or almost completely, recovers (Rauwendaal, 2001).

Techniques like vibrational spectroscopy and ultrasound measurements can be used to monitor and inspect polymer molecular structure alterations during and after extrusion.

2.10.2 Food Products

Within the extruder barrel, unique chemical transformations occur during extrusion. Although process of food extrusion is very similar to the extrusion of synthetic polymers, plastics are much more homogenous and do not present the difficulties encountered with food. Thus, modelling food extrusion must take into consideration the natural variations in moisture, starch, and protein content, as well as any experimental changes (Riaz, 2000).

Five general chemical or physicochemical changes can occur during food extrusion:

1. Binding
2. Cleavage
3. Loss of native conformation
4. Recombination of fragments
5. Thermal degradation

Table 2 contains some primary and secondary factors influencing chemical changes during extrusion:

Primary	Secondary
Barrel temperature	Mass (product) temperature
Die geometry	Pressure
Extruder model	Specific mechanical energy
Feed composition	
Feed moisture	
Feed particle size	
Feed rate	
Screw configuration	
Screw speed	

*Table 2: Factors influencing chemical changes in products during extrusion
(Riaz, 2000)*

The primary factors listed are essential during the extrusion process in order for the required product quality and specification to be acquired.

2.11 Summary

The literature surveyed in this chapter addresses all the various components that need to be considered, designed and manufactured during the process described in this project. The following main components will be at the core of this study:

- Die and cutter
- Extruder barrel
- Screws and shafts
- Frame
- Feeder

The chapter also provides a brief introduction into the various types of available extruders and their sub-components. The basic operation of an extruder is explained with reference to the operation of the extruder screw and other components for instance the thermocouples. Another important design parameter that is explained in this chapter is the process of extruder scale-up.

A brief introduction is also provided on the chemical composition alterations during the extrusion of products.

As was seen in the survey, a number of design options exist for the various components. The variety of options will have to be weighed against each other to execute the choice with optimal advantages.

All the various components, methods and operating conditions explained are relevant for this study to assist in making the correct decisions when deciding upon various components. Each of the components and processes can be a study by itself, but only the most relevant information was selected for input in this study.

Chapter 3: Generic design approach

3.1 Introduction

A generic design tree can be developed for the design of an extruder. By doing this, relevant questions can be asked to speed up the process of the design of an extruder. The tree should also enable less experienced designers to be able to perform the groundwork.

Work done previously will firstly be discussed whereafter the generic design tree will be discussed. Reasons and explanations for various choices will also be provided in this chapter.

3.2 Work previously done

A twin-screw food extruder has been developed over recent years. The extruder is currently operating in a production environment and is delivering satisfactory results. However, there are a few problems with the extruder:

- The barrel was designed for either heating or cooling. This causes a problem when switching between products with different heating or cooling requirements
- Another problem is that when a specific zone generates enough internal heat it becomes difficult to control the process parameters. These problems can be overcome if the barrel has both heating and cooling abilities
- The design of the temperature-monitoring equipment was not adequate to comply with normal production environment conditions. The thermocouples were broken off after just a couple of weeks of operation. This caused many problems because of the limited ability of the extruder to provide either heating or cooling

- After extended operating hours the barrel tends to crack. This can be attributed to either the high pressures of extruder operation or the mechanical damage from opening and closing the barrel. This makes the material selection extremely important. The type of barrel (clamshell or solid) also plays a role

This extruder was used as a starting point for the design of the next extruder. The generic design approach was developed after studying the previously designed extruder as well as other industrial machines

3.3 Discussion of the generic design tree

Following from the experience gained during the design of the first extruder and various case studies, the design tree in *Figure 13* was formulated. It covers the basic considerations during the design process of an extruder.

A *Type of product and throughput rate*

The type of product and the throughput rate are the first considerations to be taken into account when designing an extruder. For example, if the extruder needs thorough cleaning before product switchover, a clamshell barrel will typically be used. This is because a clamshell barrel flips open (See *Figure 6, p13*), exposing the screws and bores with the product “contaminating” them. This enables the operator to clean every component thoroughly. A solid barrel will be the choice if the extruder operates under high pressures. It is typically used in polymer extrusion.

B *L/D ratio⁴, centre distance of shafts, bore diameter*

The L/D ratio, centre distance of shafts and bore diameter are directly related to the throughput rate. If all these parameters are bigger, it will result in bigger screws which in turn will result in a higher throughput rate.

The L/D ratio defines many of the operating characteristics of the extruder. The optimal L/D ratio is essential to optimise the effectiveness of the extruder and of the types of materials that it can process. The limitation of high L/D ratios is the torque available from the motor (longer screws leads to higher friction), and the capacity of the thrust bearings of the extruder gearbox.

C Energy considerations

The first major energy consideration is the motor size. The motor size is mainly controlled by the amount of torque the shafts need to transfer. The specific mechanical energy (SME) can be defined as the specific work input from the motor to the material being extruded and is provided by the following equation :

$$SME [kWh/t] = \frac{2 \cdot \pi \cdot \text{screwspeed [rpm]} \cdot \text{torque [kNm]}}{60 \cdot \text{throughput [t/h]}}$$

The specific thermal energy (STE) can be defined as the sum of the energy contributions of all the raw materials:

$$STE = (E_w + E_s + E_d + E_x + E_{\dots}) / \dot{m}$$

where E_w = Energy contribution from water

E_s = Energy contribution from steam

E_d = Energy contribution from dry mix

E_x = Energy contribution from other sources

Q_t = Output

\dot{m} = Mass flow rate

$$STE = \frac{\sum (m \cdot \Delta t \cdot c)}{\dot{m}} = \frac{\text{sum}(\text{massflow [kg/hr]} \cdot \text{heat.capacity [kJ/kg}^\circ\text{C]})}{\text{massflow [kg/hr]}}$$

The ratio of mechanical energy to thermal energy is an important parameter for many products and is expressed as:

$$\frac{SME}{STE} = \frac{\text{specific mechanical energy}}{\text{specific thermal energy}} \quad (\text{Rubin, 2006})$$

D Shaft material and shape

There are a number of different shaft types that are currently used commercially. In Figure 12 a few examples of the most common types are provided:

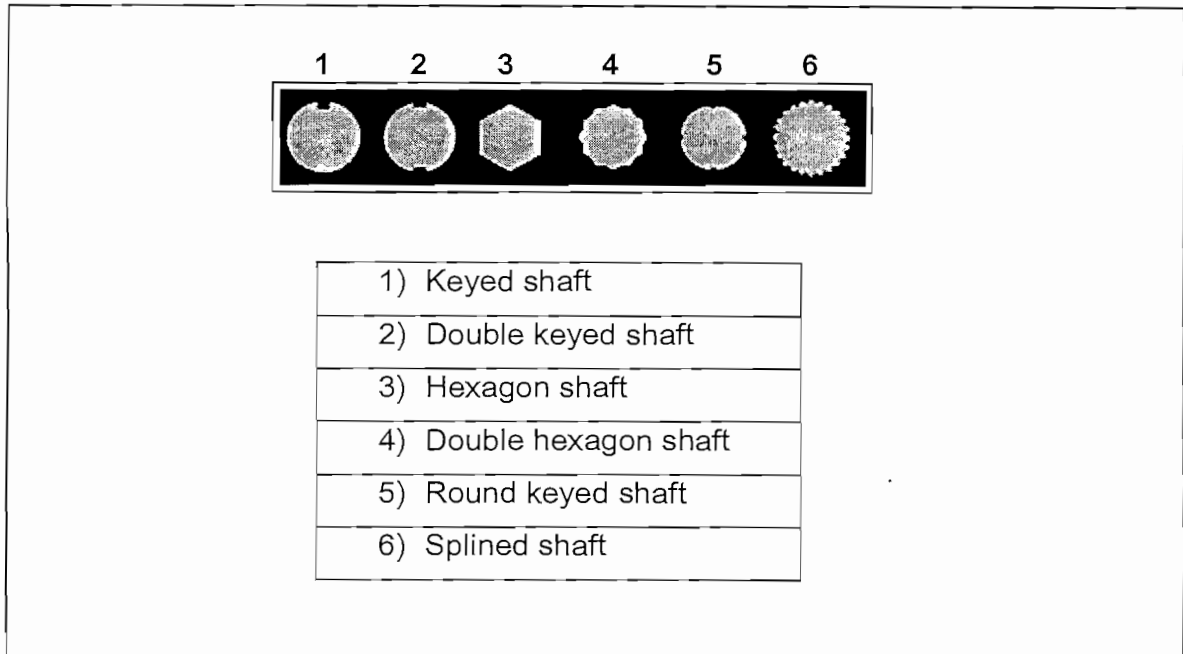


Figure 12: Common shaft shapes
(Xtrutech, 2005)

The splined shaft is the best choice when it comes to shaft selection.

Listed below are the major advantages of using a splined shaft:

- *It can deliver a very high torque,*
- *Allows the biggest free volume area for conveying the extruded material*
- *Screw removal is easy*

A disadvantage of this shaft type is that complex machinery is required to manufacture this type of shaft. This results in a considerable increase in cost of for this particular shaft type. The best choice for the South African market will be a hexagon shaped shaft.

The major advantages of this shaft type are:

- *Hex bar is available “of the shelf” without any machining needed*
- *Reduces costs*
- *Screws can easily be slid on or off the shaft*

This shaft type reduces downtime considerably because of its availability. The design for such a shaft enables a supplier to supply such a shaft in a short period of time at a considerable lower cost than a splined shaft. The only disadvantage of a hexagon shaft is that it doesn't allow as much “free volume” as a splined shaft would.

E *Screw configuration*

The screw is the heart of the extruder. The specific configuration will depend on the desired product. When a completely new product is developed, a pilot plant will be used in the development of the product. The screw configuration will then be chosen through a combination of experience as well as a method of trial and error. The configuration will then be applied to the commercial production machine by scaling it to the desired size. There are models currently being developed to have a more scientific approach to selecting a specific screw configuration, but the correct configuration is ultimately chosen through trial and error.

F *Type of barrel*

There are two types of barrels, namely solid barrels and clamshell barrels. The major design considerations are:

- *Accessibility to the screws for configuration changes and cleaning*
- *Pressure under which the extruder operates*

From *Figure 6* it can be seen that the clamshell barrel physically flips open to allow access to the screws. The solid barrel needs to be slid off the screws. This can either be done manually or by the use of hydraulic systems.

G *Clamshell barrel*

A clamshell barrel is normally used, as mentioned earlier, in applications where accessibility to the alteration of screw configuration and cleaning is often necessary. Access to the clamshell barrel is considerably easier, thus cleaning is easier and configuration changeover can be done much quicker. These types of barrels are used in almost all the extrusion applications.

H *Solid barrel*

Solid barrel extruders are typically used for polymer extrusion in which much higher pressures are required. A disadvantage of this barrel type is that it's more difficult to clean than a clamshell barrel.

I *Die*

As indicated in the previous chapter, there exists a number of dies for the different products. The shape, state, type, etc. of the product determines the type of die. The type of extrusion process also determines the complexity of the die. Profile extrusion dies are much more complex than general dies used for food and polymer applications.

J *Cutter*

A cutter normally consists out of rotating blades that passes over the die insert openings at a pre-determined speed cutting the product to the desired length. The cutters' shape and size depends on the type of product that needs to be cut (See Chapter 2 Par 2.7).

K *Frame*

The frame of the extruder should be modular so that the L/D ratio can be easily varied if necessary. This can be done in various ways, amongst others by using hydraulic or hand-operated systems to extend the frame. In other cases, the frame has a mounting which supports the barrel at a strategic point to allow the barrel to be extended.

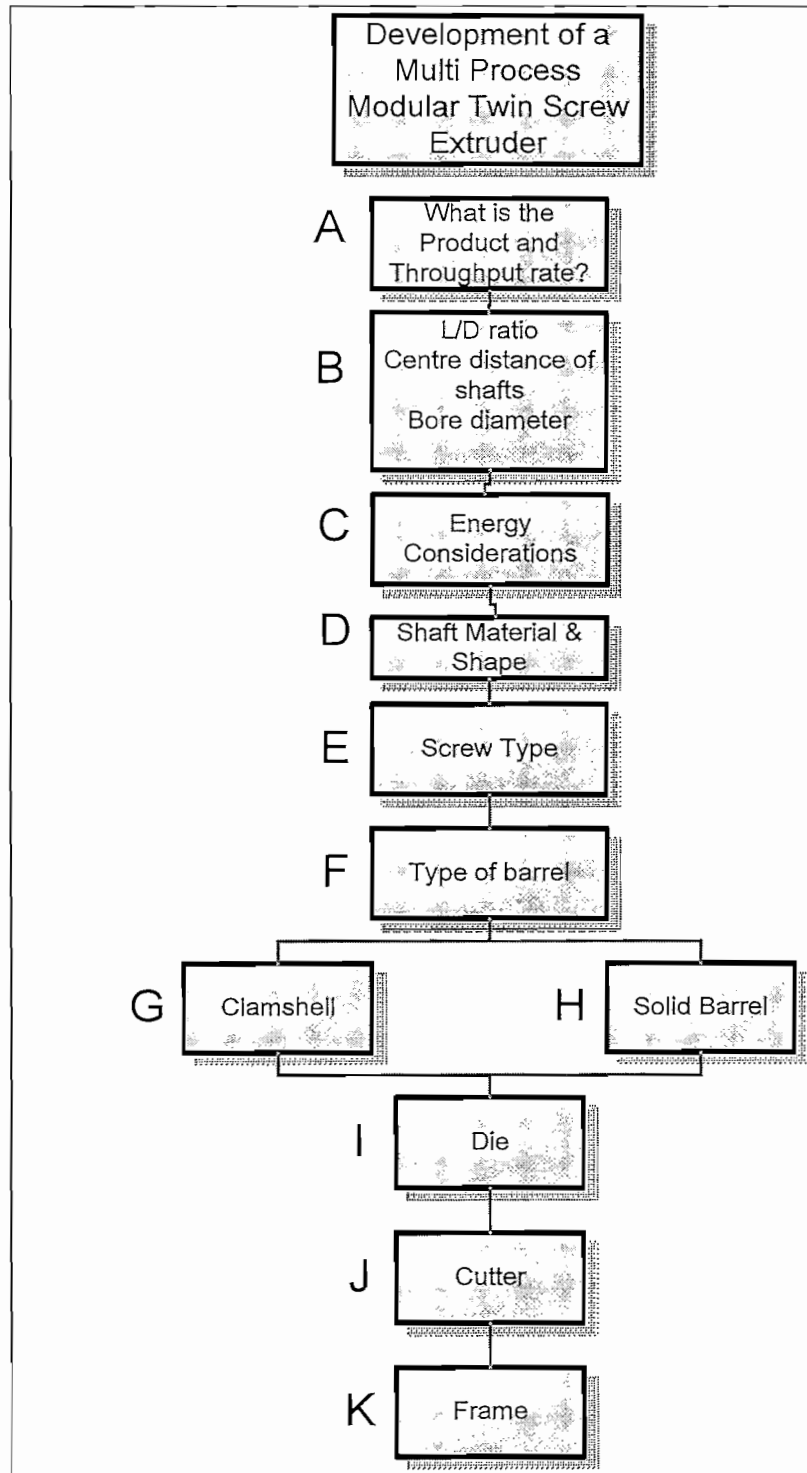


Figure 13: Generic design tree for a co-rotating twin-screw extruder

The following are separate design trees for the two types of barrels:

3.3.1 Generic design tree for clamshell barrels

It was necessary to discuss the design considerations of the types of barrels separately. In *Figure 17* the generic design tree for the clamshell barrel can be found.

3.3.2 Discussion of the design tree for a clamshell barrel

G1 *Liners*

The two most popular ways of designing liners are the separate liner method and the insert liner method (See *Figure 13*). In *Figure 14*, it can be seen that in the insert method, the liners are physically entered into a “slot” in the cooling jacket. This “slot” is generally created by using machined square bars and fastening them on the sides of the cooling jacket.

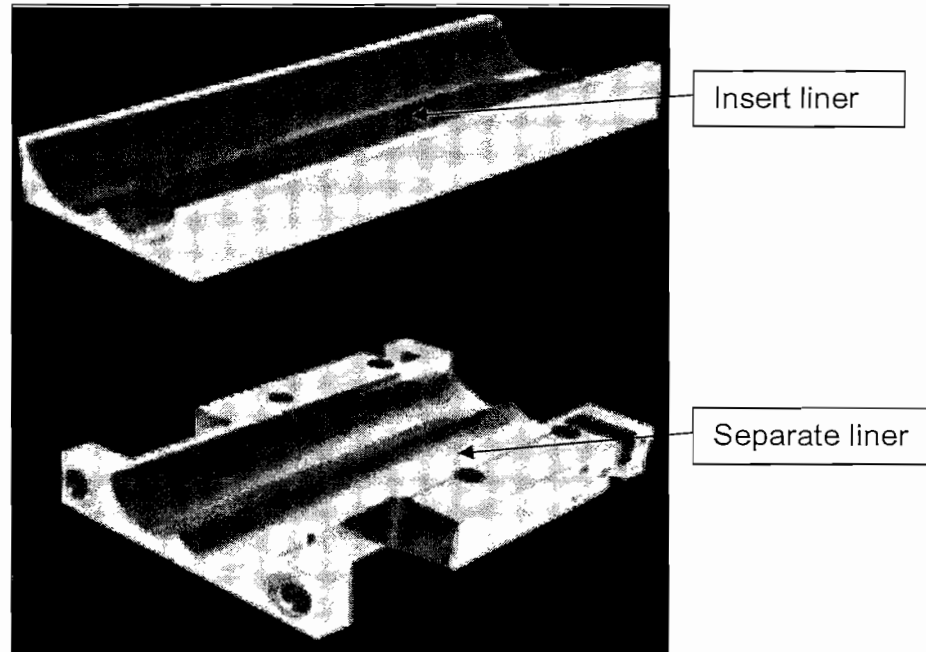
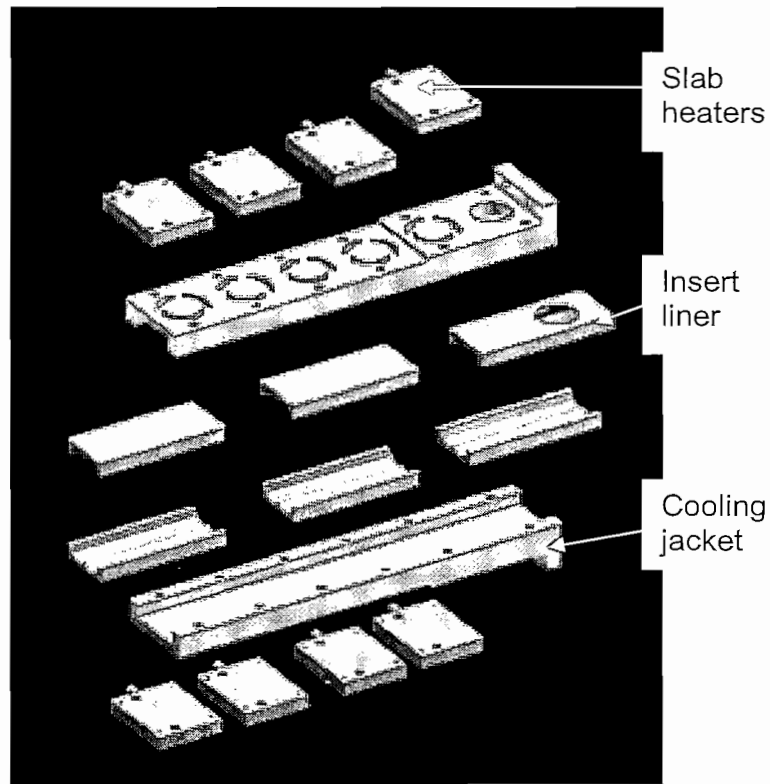


Figure 14: Separate liners
(Xtrutech, 2005)



*Figure 15: Insert liner method
(Xtrutech, 2005)*

This slot method is cheaper in the long run due to the fact that the liners are normally the first components to wear down in the barrel. In comparison, the insert liners are much smaller than the separate liners, cutting the cost on material and manufacturing.

In the separate liner method, the liners just lie on top of the cooling jackets. They are then fastened by using a number of screws and bolts. This is shown in *Figure 16*.

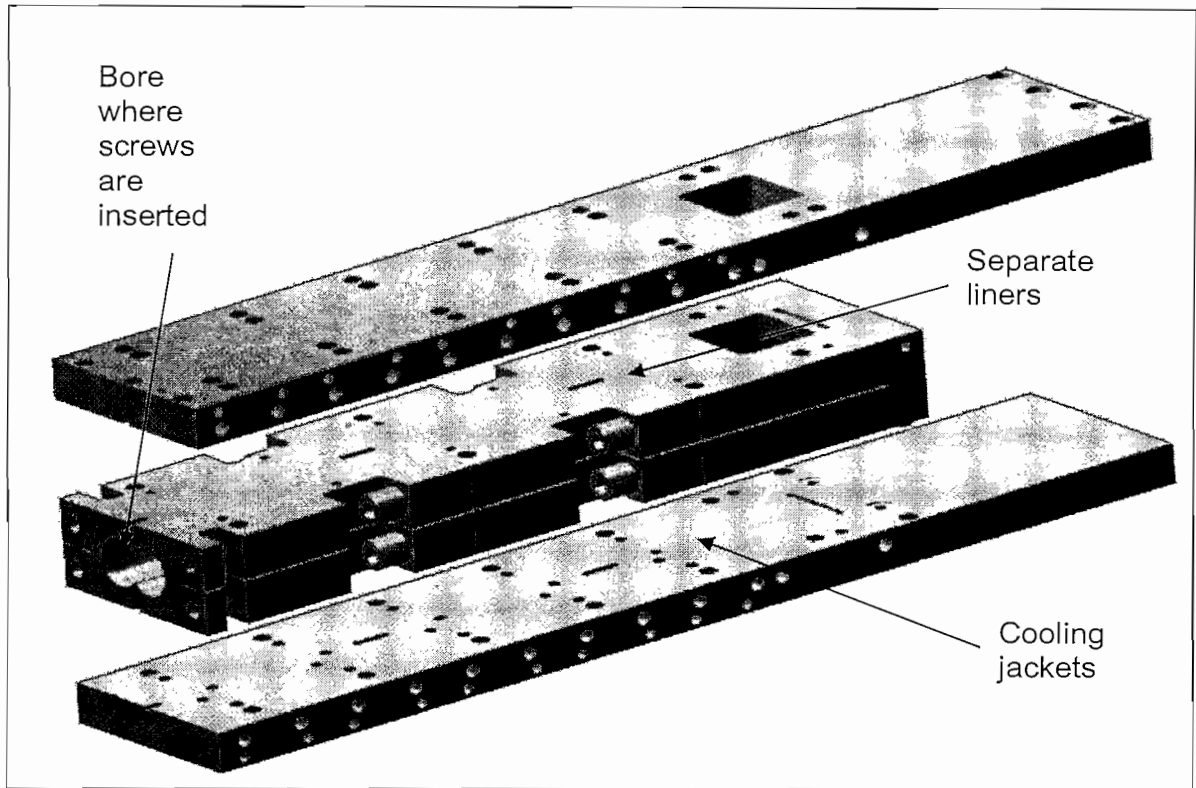


Figure 16: Separate liners

G2 Cooling

Cooling of a clamshell barrel is normally obtained by means of a cooling jacket. Water passes through holes in the jacket in order to acquire the required cooling effect. The maximum amount of cooling has to be achieved, as it is then easier to change the cooling manifold than it is to change the cooling jacket. This allows more flexibility for the operator to tweak the extrusion process until it is operating at maximum capacity. The faster the system runs, the more heat is generated, therefore the cooling ports should be as big as possible and the flow as turbulent as possible.

G3 Heating

There are two types of heating elements commonly used namely:

- Slab heaters
- Cartridge elements

The cartridge element has the disadvantage that it could develop a hot spot and fuse in the hole from which it can only be removed by drilling. This is a tedious process that is very time-consuming. Slab heaters, on the other hand, are more user-friendly, although they are not widely used yet. Slab heaters only recently started to gain popularity. The slab heaters are merely placed on top of the cooling jacket and fastened by means of bolts.

G4 *Opening mechanism*

The current extruder used as a pilot study machine has suffered extensive damage to the barrel due to mistreatment during the opening and closing of the barrel. For this reason, the opening mechanism is a critical factor in the design of an extruder barrel. Opening is normally done by hand or by means of hydraulics. By using hydraulics, the opening and closing action can be better controlled, thus protecting the barrel against possible damage. The disadvantage of adding a hydraulic system is that it raises the cost of the extruder.

G5 *Joining of the liners*

The joining of the liners is only an issue with the separate liner method. It can be done in a number of ways that mainly depends on the amount of available space in and around the bore and the extruder. Brackets or slots are normally used to join them. Both these methods will be further discussed in the case studies.

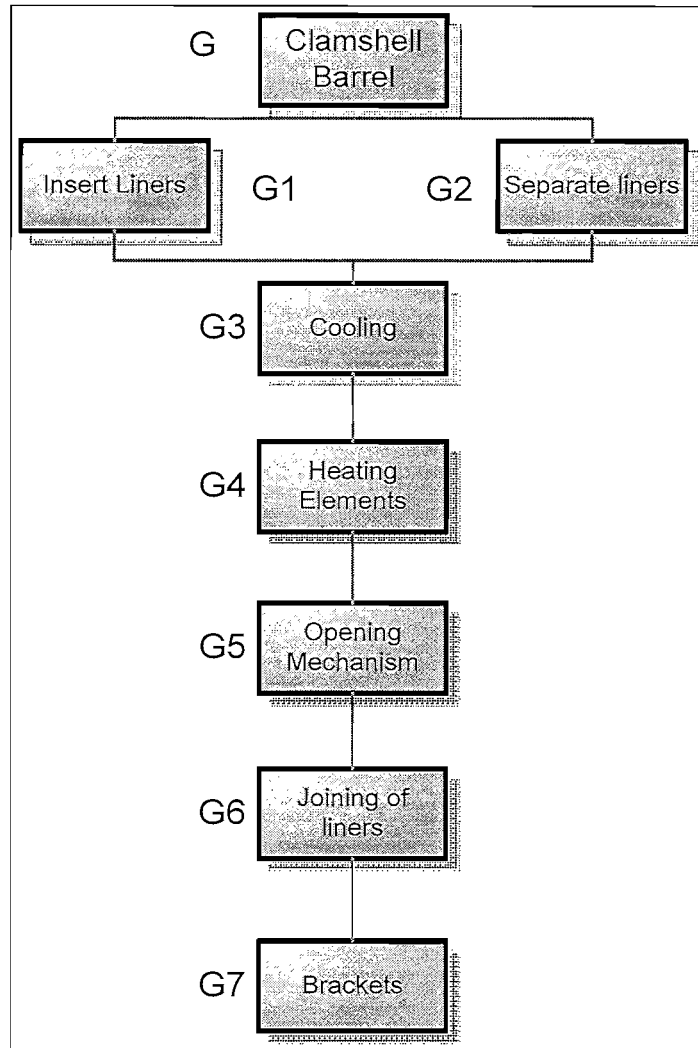


Figure 17: Generic design tree for a clamshell barrel

3.3.3 Generic design tree for a solid barrel

The following is the discussion for the design tree used during the design of a solid barrel.

3.3.4 Discussion of the design tree for a solid barrel

H1 *Shape of the barrel*

A solid barrel normally has one of two shapes, either square or round. The design determines the shape of the barrel. In *Figure 7* a square barrel segment is shown.

H2 *Bi – Metallic*

A solid barrel is usually made in one of two ways, bi-metallic or through a surface hardening process. In the bi-metallic method, two different metals, normally a tool steel and a type of high or low carbon steel will be mixed to produce the barrel. The tool steel liner will be hardened by using a heat treatment process to acquire the necessary wear and abrasion resistance. When the inner liner becomes worn, it can be pressed out and replaced with a new one instead of replacing the entire segment. This method has proved to be more cost effective.

H3 *Surface Hardening*

The other method used is normally a type of surface hardening process. It depends on the manufacturer of the barrel what process will be used. This method is considered to be older technology, as explained **H2** above.

H4 *Heating*

Heating is similar to the heating process used for the clamshell barrel, although ceramic band heaters are used in applications where the solid barrel has a round shape. For a square shaped barrel, slab heaters or cartridge elements can be used.

H5 Cooling

Cooling of the barrel segments is also done by pumping chilled water through cooling ports in the barrel segment. The same fundamentals apply to the solid barrel as to the clamshell barrel.

H6 Joining of the segments

The segments can be joined in a number of ways by using clamps, flanges, etc. This, once again, depends on the design. The various ways will be further discussed in the case studies.

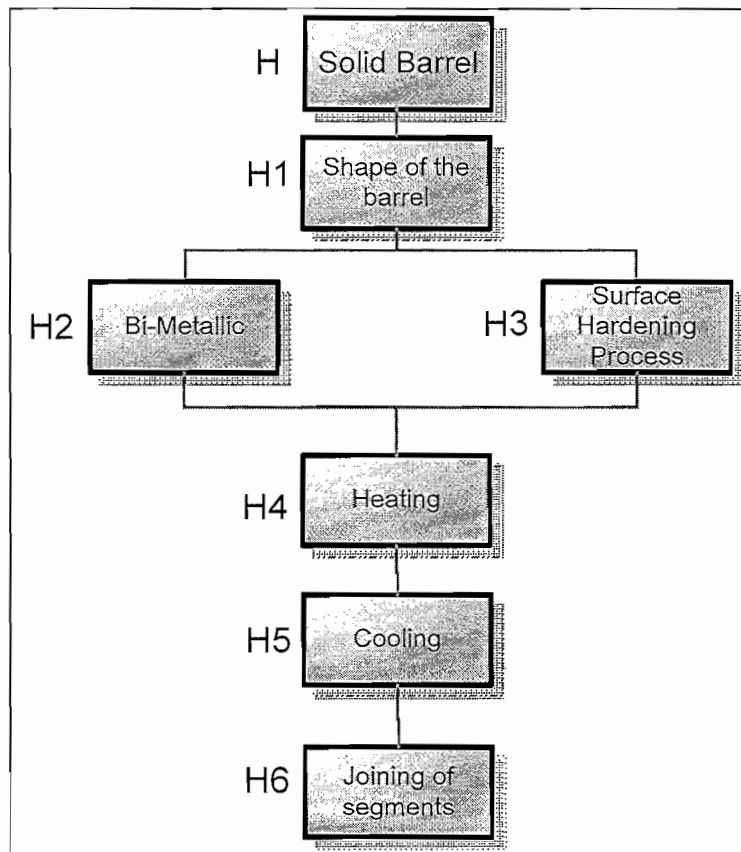


Figure 18: Generic design tree for a solid barrel

3.4 Summary

In this chapter generic design trees were formulated for the design of the various components of the extruder. It addresses the most important aspects that need to be focused on during the design process:

- Type of product and throughput rate
- L/D ratio, centre distance of shafts, bore diameter
- Energy considerations
- Shaft material and shape
- Screw type
- Type of barrel
- Clamshell barrel
- Solid barrel
- Die
- Cutter
- Frame

It also guides the designer to follow a specific thinking pattern that can avoid problems later on in the design process. The aspects listed above are also explained with illustrations where necessary.

The two types of extruder barrels are also discussed with separate design trees. The barrel type has a lot more sub-components to consider than the rest of the components and for this reason they have their own separate design trees.

Through the use of the design trees formulated, the extruder and its various sub-components will be designed. The design trees were also tested in two case studies of two barrels, a clamshell barrel and a solid barrel.

Chapter 4: Basic screw design for a twin-screw extruder

4.1 Introduction

In this chapter the basic design and manufacturing of the various types of screw segments will be discussed. The most important factor in designing twin-screw segments is that the elements must mesh without touching, although they should still provide the tightest possible seal between themselves (Zimmerman, 2004). Factors like shaft centre distances, outside diameter, root diameter, etc. are some of the parameters involved in producing optimum meshing. From *Figure 19*, various basic equations can be formulated.

The basic equation for the shaft centre distance AD (See *Figure 19*) is:

$$AD = RA + RK = 0.5 \times (DA + DK)$$

Free volume for conveying the product is determined by two parameters.

The first is the root diameter HF:

$$HF = 0.5 \times (DA - DK) = DA - AD$$

The second parameter is the screw land, KA, but this is much more difficult to compute because of geometry changes, pitch changes, etc. (Zimmerman, 2004).

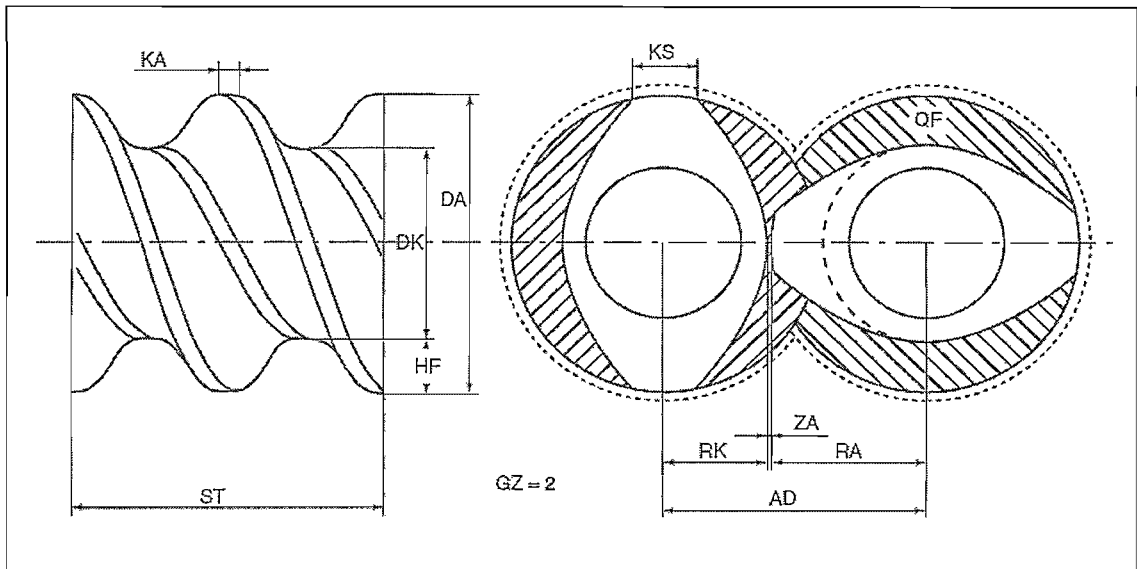


Figure 17: Parameters for the design of twin-screw elements
(Plastics Additives & Compounding March/April 2004)

Every parameter needs a certain amount of thermal and mechanical energy to achieve the required output. Various screw elements have different functions in the extrusion process. Conveying, melting, shearing and mixing are the main functions of the various types of screw elements.

The choice of the overall assembly of the screw depends on the following considerations (Frame, 1995):

- Volumetric flow requirement
- The match of pumping efficiency with the rheology of the material being extruded
- Strength and wear characteristics
- Surface area for heat transfer and narrow residence time distribution
- Pressure and flow distribution at the entrance to the die
- The degree of shear or mixing required
- The degree of barrel fill
- The motor size

4.2 Screw element definitions

The following nomenclature for the basic screw element can be found in

Figure 20:

- **Flight:** The conveying surface or thread.
- **Pitch:** The pitch of the screw is measured by the distance between two matching points on the same screw. The pitch can vary for different screws.
- **Screw clearance:** Clearance between the screw and the barrel. This clearance depends on the OEM.
- **Axial flight width or land:** The edge of the screw that is in close proximity to the barrel. Depending on the face profile of the screw, this land width can vary.
- **Root:** The flight of the screw is wound around the root. This root diameter can vary. A smaller root diameter means a bigger free volume for conveying the product.
- **Channel:** This is the space between the flights in which the material moves down the barrel.

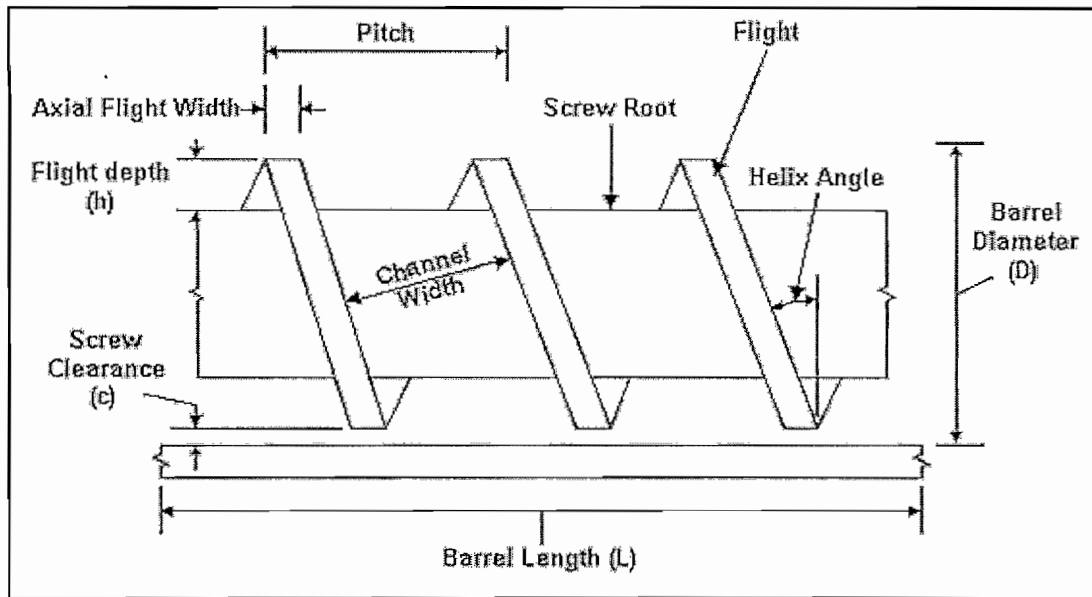


Figure 18: Basic screw geometry

4.3 Segment types

In almost every screw configuration three different types of screw elements are present:

- Feed screws
- Kneading blocks
- Compression elements

These elements are available in different shapes and sizes. Variations exist to change their processing abilities to suit various needs an end-user may have. The arrow in *Figure 21* indicates the conveying direction if the screw rotates in a counter clockwise direction.

From *Figure 21* the following prevails:

- A large pitch screw is mainly used for feeding/venting (1,2)
- The medium pitch screw is mainly used for conveying the product (3)
- Narrow/fine pitch: Pressure generation, heat transfer, high screw fill (4)
- Forward/reverse conveying elements (5,6):
 - High shear forces to melt powders
 - Reverse elements to seal vent ports
 - Generation of back pressure
- Transition elements are used to create a smoother transition from single flight elements to twin flight elements. They help reduce dead spots in the conveyed product mass.

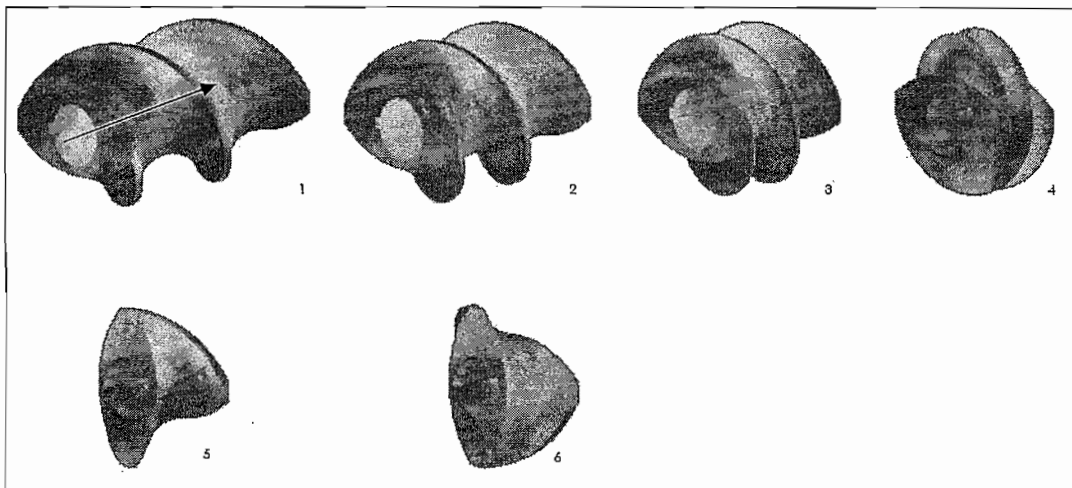


Figure 19: Various twin-screw elements

4.4 Paddle elements

The main purposes of the paddle elements are mixing, kneading and shearing. The arrow in *Figure 22* indicates the conveying direction if the paddles rotates in a counter clockwise direction.

- **Small disks:** Mixing of liquids and powders, some pressurisation
- **Medium disks:** Less mixing, more shearing effect
- **Large disks:** Only shearing

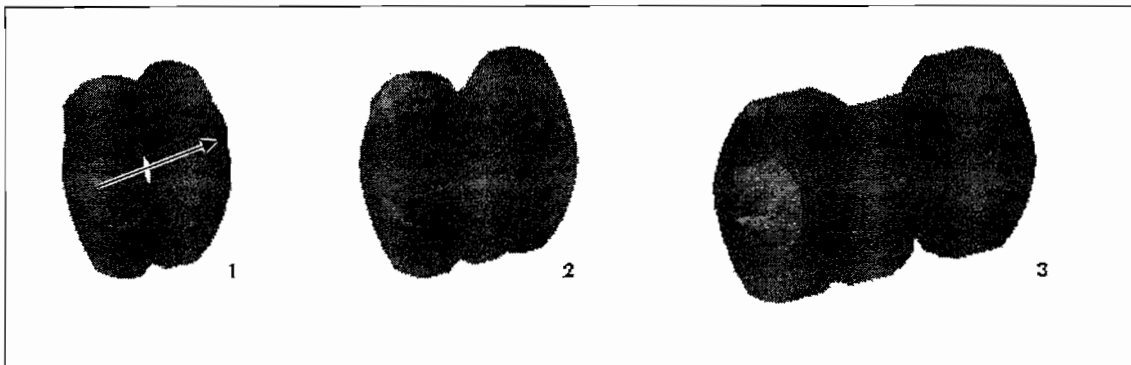


Figure 20: Various right hand kneading elements (Paddle blocks)

Right hand blocks have a forward conveying action but they generate backflow. Conveying efficiency of kneading block elements is reduced (interrupted melt flow).

The arrow in *Figure 23* indicates the conveying direction if the paddles rotates in a clockwise direction.

- **Small disks:** Mixing of liquids and powders
- **Medium disks:** Less mixing, more shearing effect
- **Large disks:** Biggest shearing and kneading effect

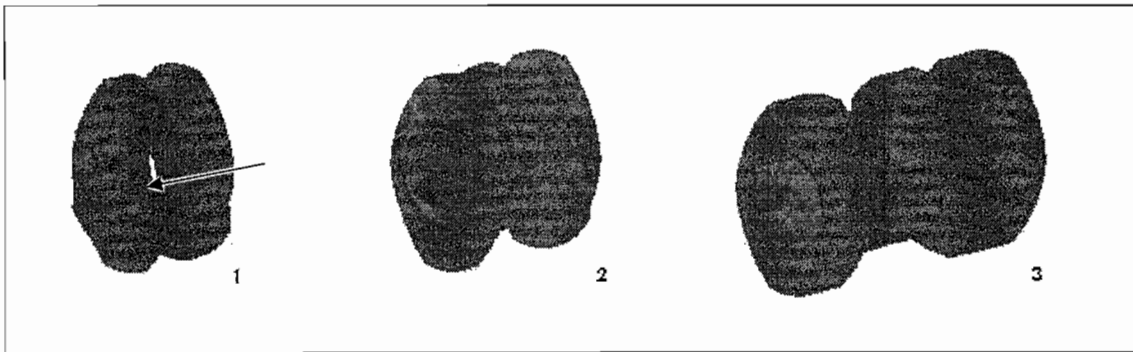


Figure 21: Various left hand kneading elements (Paddle blocks)

Left hand paddle blocks have reverse conveying action and restrict total flow. They are mostly used to apply back pressure with an increased kneading effect.

4.5 Constructing the geometry of a self-wiping co-rotating screw

The construction of the profile for a self-wiping co-rotating TSE is a very logical and simple exercise (See *Figure 24*). The construction of the screw geometry for co-rotating extruders, as described in detail by Rauwendaal (2001), are the following:

- Draw line AB in such a way that AB equals the centreline distance, this defines the intermesh angle $2\alpha_1$
- Locate point D in such a way that angle COD equals π/n , where n is the number of flights
- Point P is located on the circle midway between points B and D
- Make PD equal to QD, this defines one screw tip; the other tip is Q'P'
- The centre M_p of the flank curve through P lies on circle at distance L_c from P
- Construct the flank curve PR, add other flank curves thereafter
- One screw cross section is now completely defined

The similarities between the two profiles can be seen in *Figure 25*, depicting the radius of the Tip, Flank and Root as the same.

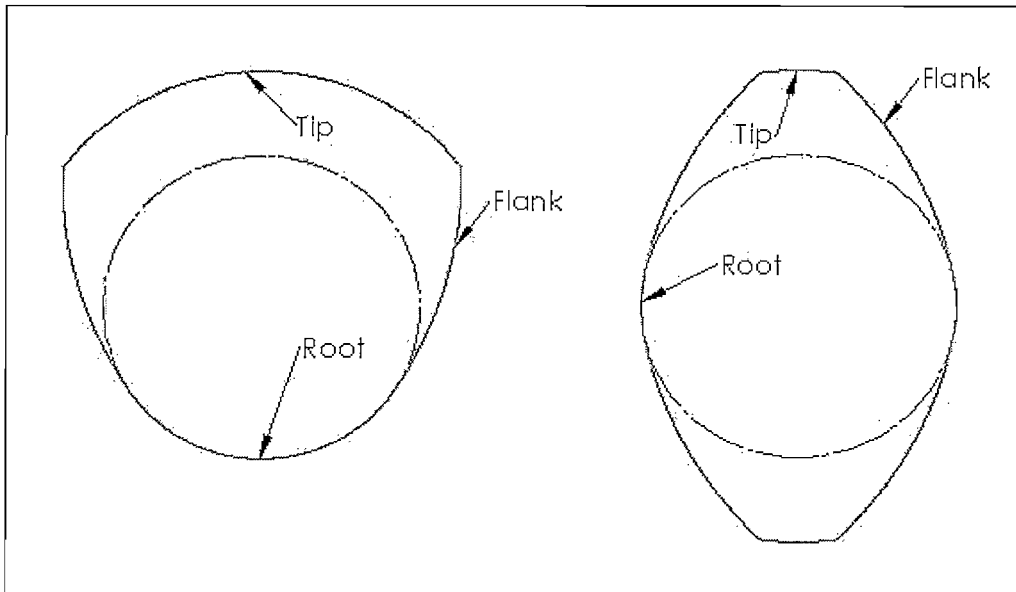


Figure 23: Similarities between a twin flight and single flight profile

4.5 Manufacturing process

The material commonly used for the manufacturing of the screw segments is a hardened tool steel. The process of heat treating the elements increases their strength and abrasion resistance which produces a higher quality segment.

4 Axis CNC machines are used to manufacture the various segments. The g-code⁵ for a typical feed screw is quite complex. The most complex segment of all to manufacture, is a transition element. A transition element is a segment that has a single flight profile on the one side, and a twin flight profile on the other. The two sides are basically “morphed” into each other (See *Figure 26*).

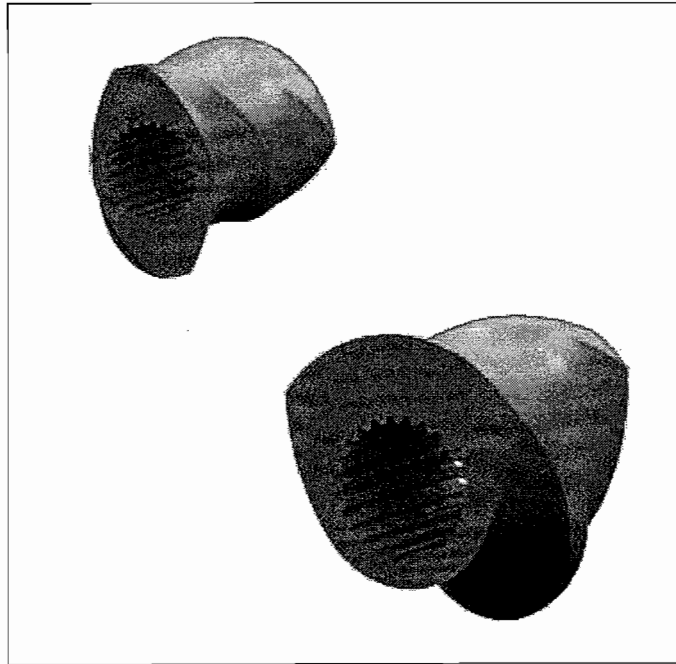


Figure 24: A transition element

4.6 Summary

This chapter gives an introductory background on the basic operation of various screw segments. It also explains how the geometry of the segments are constructed and provides the basic nomenclature of a screw element. The type of screw segments are also listed, including:

- Feed screws
- Kneading blocks
- Compression elements

The various shapes and sizes of the elements and their basic function are also discussed in a summarized paragraph form. The method of manufacturing was only briefly mentioned because this depends on the OEM how the manufacturing process will be undertaken.

All the screw segments, used in this study, were designed by using the methods explained. All the segments gave a close intermeshing profile and was implemented successfully in a production environment. (See *Figure 2*, Chapter 2)

Chapter 5: Case study: Barrels

5.1 *Introduction*

The following case studies of the two different types of barrels will be reviewed in this chapter:

- Case 1: 100 mm clamshell barrel
- Case 2: 50 mm solid barrel

The barrels of the above-mentioned extruders had to be redesigned in order for the generic design trees for the two types of barrels to be implemented. The aim of the case study was to test the generic approach to barrel design.

5.2 *Case 1: 100 mm clamshell barrel*

5.2.1 Background

The primary function of this machine is to extrude the product used for powder coating. The specifications for the extruder are the following:

- An L/D ratio of 10
- A throughput of ± 1500 to 3000 kg/h.
- Three temperature controlled zones

The barrel had to be redesigned and still maintain the same level of performance. This means that the throughput, product quality, etc. should remain constant. Another aim was to reduce maintenance cost.

Certain constraints required had to be identified to govern and guide the design process. The position of the thermocouples and the cartridge elements were already pre-determined by the OEM. They determine the zone positions in the barrel so that their position is fixed. With these constraints identified the design process could continue.

1) Liners

For this particular case study, reduction of maintenance cost is one of the primary goals. The components in an extruder exposed to the highest amount of wear are the liners and the screws.

With this in mind, the liner had to be redesigned to be more cost efficient than the current system. The original liner was a continuous lining without any splits. The redesigned liner was split at the strategic points in which the highest wear will occur during the extrusion process. This reduces maintenance costs because of the interchange ability achieved.

2) Cooling

The original barrel had 8 cooling ports but after prolonged use the cooling efficiency decreased. It decreased to such an extent that the extrusion process became difficult to control. After the amount of cooling needed was researched the aim was to provide the maximum amount of cooling ports possible to obtain optimal cooling.

This gives maximum flexibility to the machine with regards to cooling, and prolongs its cooling ability. As the machine gets older, the problem of overheating can be overcome if maximum flexibility is provided.

3) Heating Elements

The OEM designed the barrel with cartridge elements, therefore due to standardization requirements it was decided to keep them the same.

4) Opening mechanism

The opening mechanism was also designed by the OEM. It works on a counterweight method *Figure 27* illustrates how this method is employed.

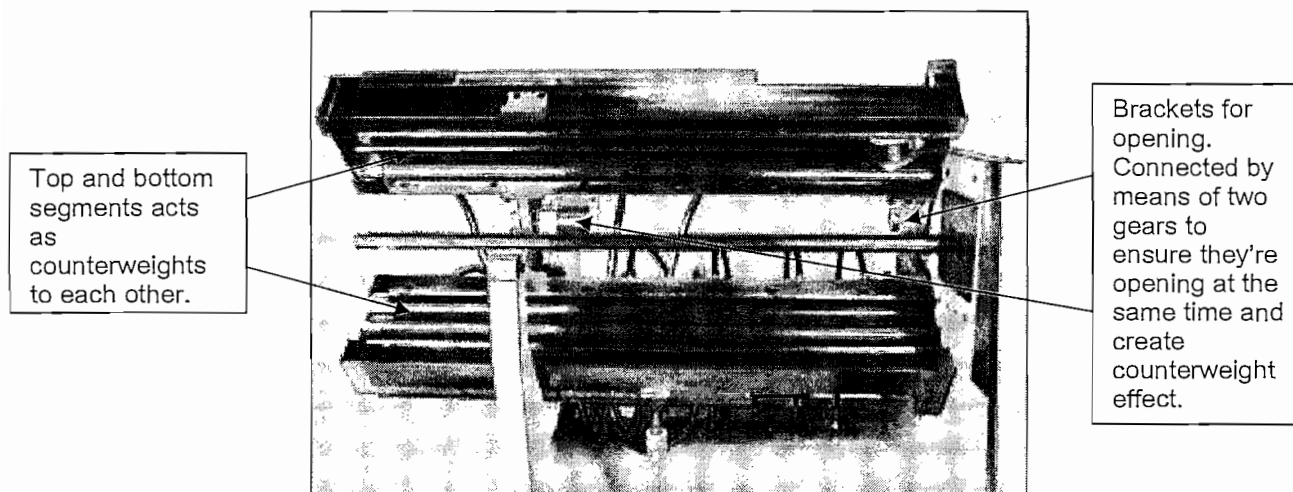


Figure 25: Illustration of the counterweight method brackets

5) Joining of the liners

After the splitting positions had been identified, the joining mechanism had to be decided upon. Three options were identified, namely:

- Option 1: Cutting slots in the side of the liner to act as brackets.
- Option 2: Cut serrations into the side of the liners onto which the brackets can be fastened.
- Option 3: Cut keyway slots into the sides of the liners to which brackets can be fastened.

It was decided that, due to space restrictions, to use Option 2.

In *Figure 28* the assembly of the 100 mm clamshell extruder barrel can be seen, with the main points of interest pointed out. A discussion of the various components will subsequently be done in the following paragraphs.

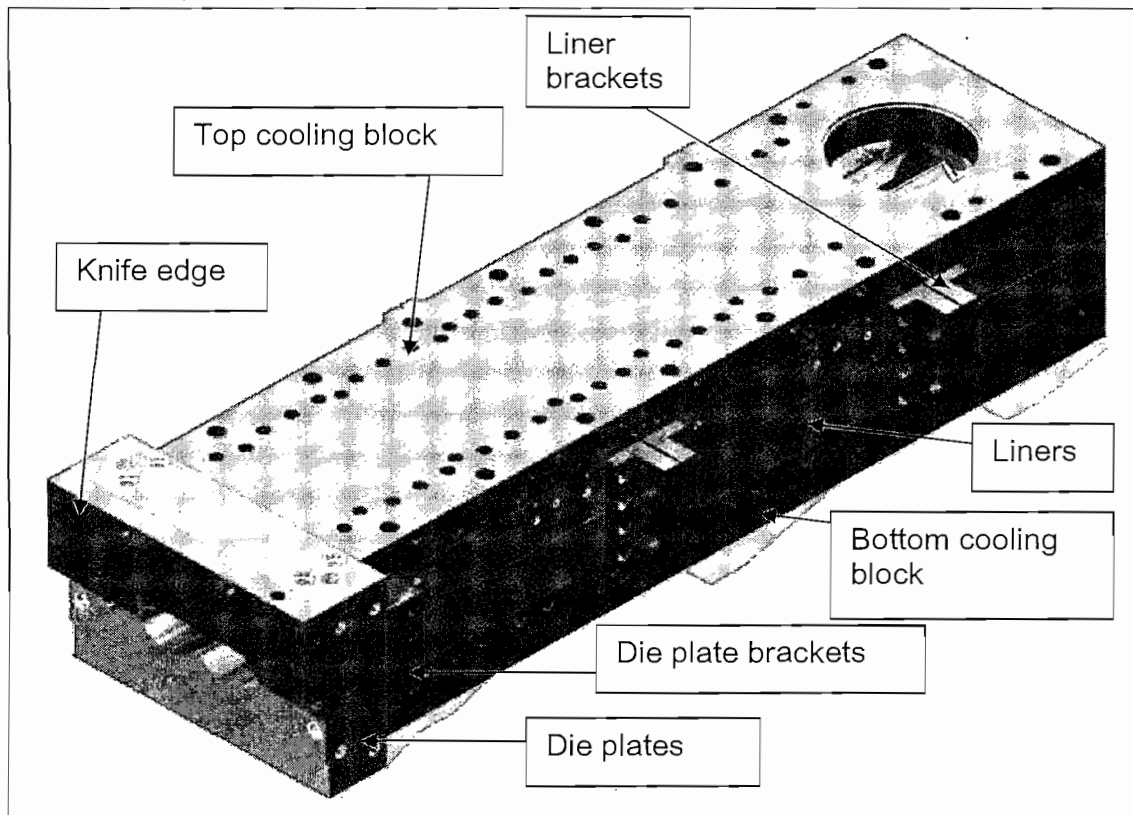


Figure 26: 100 mm Twin-screw extruder clamshell barrel

5.2.2 Cooling Blocks

Both the top and the bottom cooling blocks were made from a medium carbon steel alloy. Stainless steel was considered for the design, but due to the difficulty of machining stainless steel, the decision had been made not to use stainless steel. *Figure 29* shows the various “subcomponents” of the cooling block.

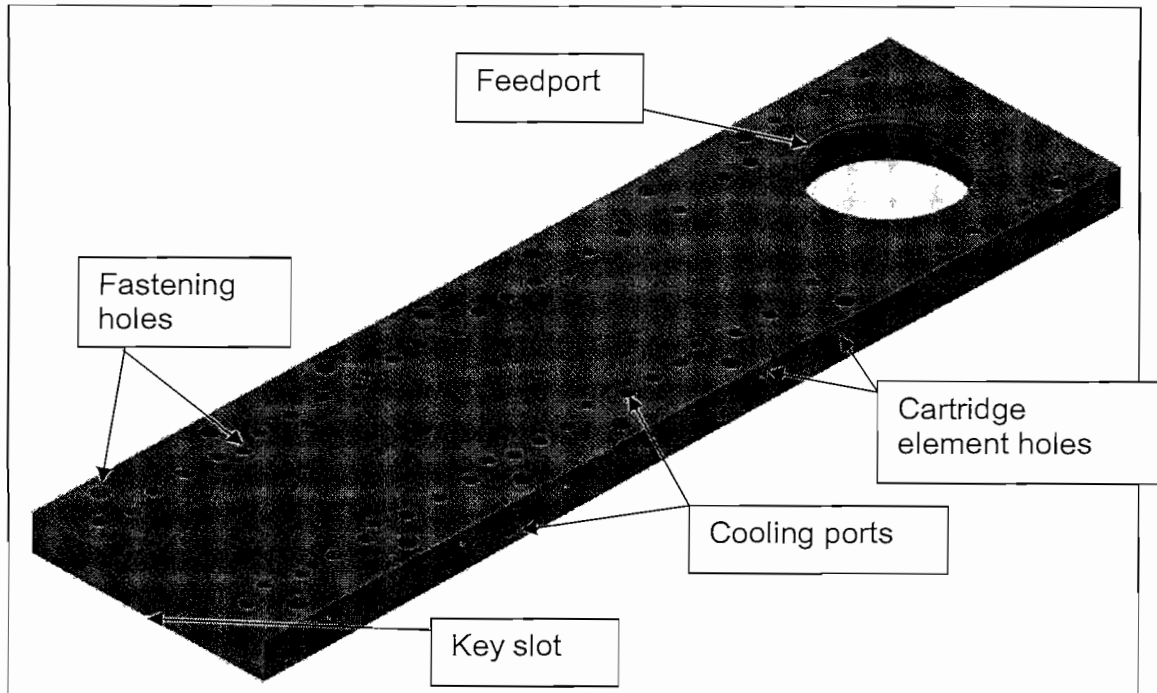


Figure 27: Upper cooling block

The extruder had sixteen holes through which 18mm stainless steel bolts fit, delivering the required clamping force to seal the barrel. It had another sixteen holes through which smaller bolts fit to fasten the liners to the cooling block.

The cooling block had seventeen 15.25mm cooling ports that can be bridged over the side or the top ports. As stated earlier, this large number of cooling ports delivered the end user with optimal cooling for the maximum period of time. It also provides maximum flexibility when unforeseen space restrictions occur.

Twelve cartridge element holes were placed at strategic places to provide sufficient heating (four elements/zone). These positions were pre-determined by the design.

Seven key slots were inserted to align the liners with the cooling block when placed upon it.

The feed port is only present in the upper cooling block because this particular extruder is fed only from above. No side-feed port is necessary.

The bottom cooling is exactly symmetrical to the top cooling, except for the thermocouple holes indicated in *Figure 30*. The reason for this is to have interchange ability between the liners.

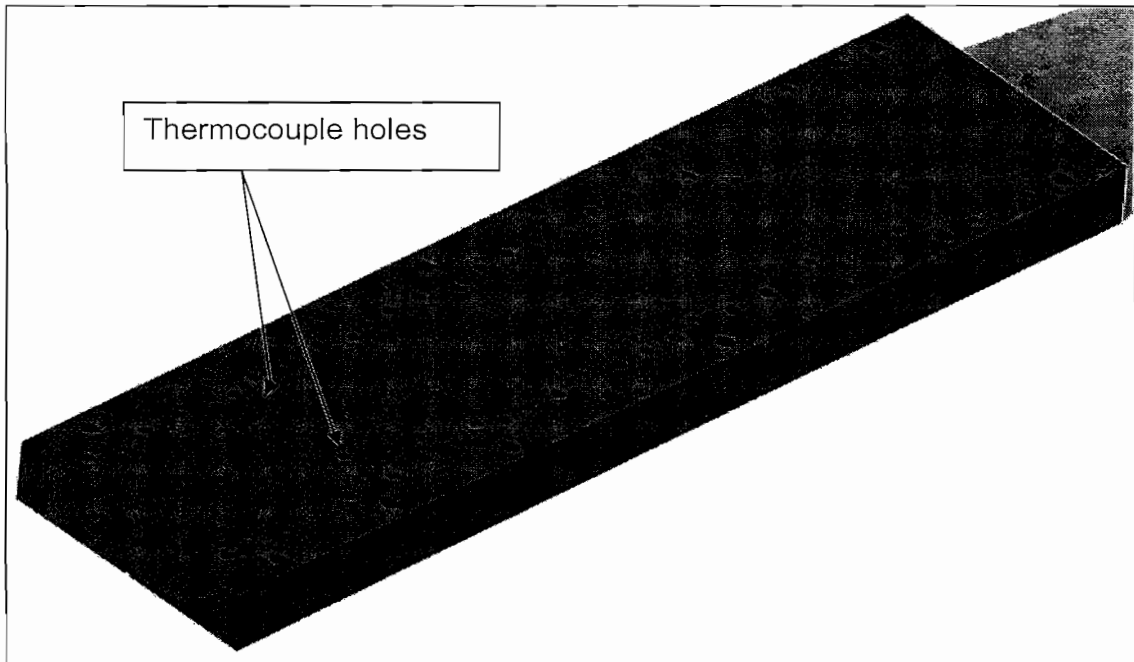


Figure 28: Lower cooling block

Six thermocouple holes were fitted in the lower cooling block, two holes/zone. These are used to measure the temperature in the different zones of the extruder. In this case, Resistance Temperature Detector thermocouples were used. The type of thermocouple was pre-determined by the OEM and had been fitted previously.

5.2.3 Liners

The upper and lower liners in this design were exactly symmetrical (See *Figure 31*). The reason for this is that when the part starts to wear, only the worn segments need replacing. This reduces maintenance costs.

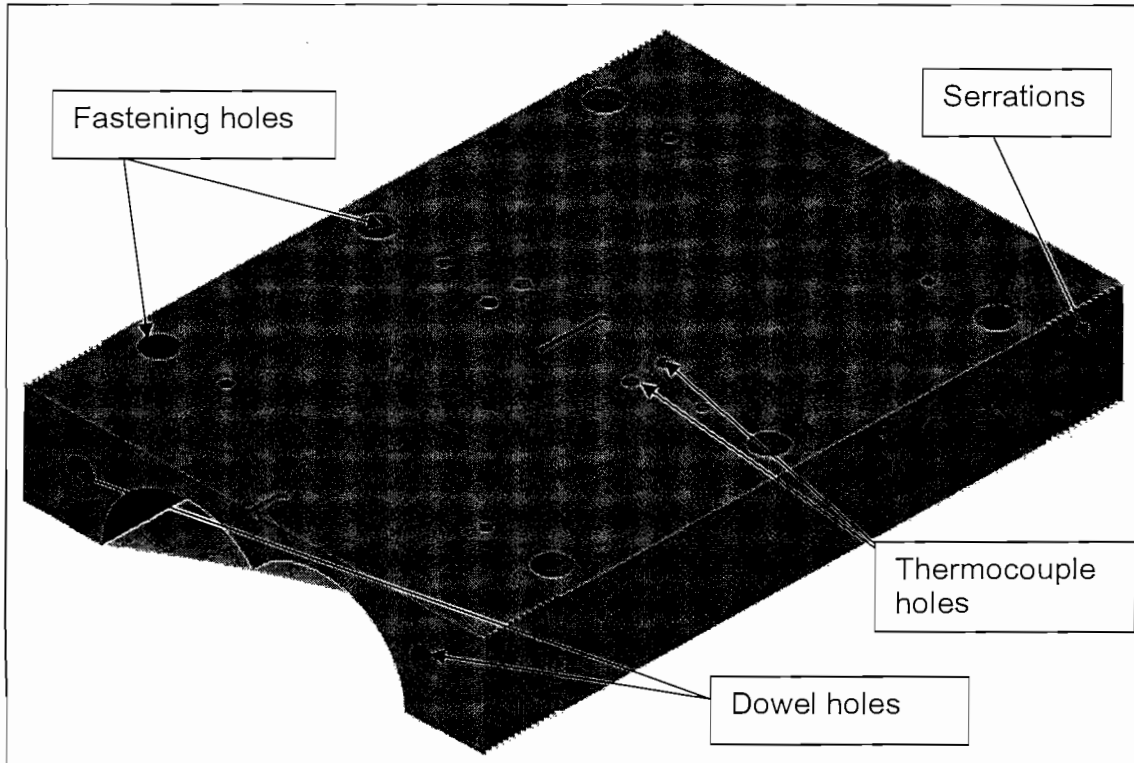


Figure 29: Front liners

The liners were lined up with each other by using dowel pins and aligned with the cooling blocks using key slots.

Serrations were used to secure the brackets onto the liners. This is the positions in which the brackets pulling the liners together are fastened.

The knife-edge and die-plates indicated in *Figure 28* act as the “die” for the extruder. They are typically used in the production of powder coating paint in order to control the flow from the end of the extruder.

5.2.4 Summary of the design

The barrel designed in this case study was a clamshell barrel. The design process was done by following the generic design approach formulated in Chapter 3. This was done to test the generic design tree to identify any shortcomings before the design process was started on the multi-process twin screw extruder.

The final decisions on the components were the following (from the generic design tree):

- Separate liner method was used for the liners due space restrictions.
- Cooling jackets were made from medium carbon steel and various cooling ports drilled through the jacket
- Cartridge elements were used for heating as this was pre-determined by the OEM
- Opening was also pre-determined by the OEM and was of the counter weight method
- Due to space restrictions, flanges, which anchored onto the liners by using serrations, were used to join the liners

The barrel produced overall satisfactory results under strenuous production conditions. This was measured by means of verbal communication with the operator and production manager. The additional cooling ports added assisted greatly in the temperature control during long periods of operation. Time of operation was extended from just one shift (08h00-16h00) to two shifts of continuous operation (8h00-00h00) before the first stoppage had to be made (for cleaning purposes).

5.4 Case 2: 50 mm Solid Barrel

5.4.1 Introduction

The solid barrel that will be discussed in this case study is used to extrude polymers. The specifications of the extruder are:

- A throughput of ± 200 kg/hr
- 6 temperature-controlled zones

Only four of the segments had to be redesigned. A general rule of thumb for solid barrel segments is that the segments are almost always $4D^6$ in length (Clextral, 2005). This particular extruder has a 50 mm bore diameter which then suggests a segment length of 200 mm. The main aim of this study was to test the bi-metallic method as the OEM used a surface hardening process in the original manufacturing of the barrel.

1) Shape of the barrel

The shape of the barrel was determined by the design and had to be round. If this had to be changed, this would have meant that new elements and thermocouples would have had to be fitted as well, which would have raised the cost of the barrel considerably.

2) Bi-metallic or surface hardening process

With cost efficiency in mind, a bi-metallic barrel segment was the obvious choice. A considerable saving can be achieved by using this method instead of surface hardening. Once worn, only the liner will need to be replaced, instead of the whole barrel segment.

3) Heating

The heating method was determined by the design. The extruder uses ceramic band heaters for heating. This was determined by the OEM.

4) Cooling

The overall design of the barrel segment had to be the same in essence than the original segments. The reason for this is that the barrel will only be partially replaced in this instance. The cooling ports in the original barrel were parallel to the bore and they were connected around the face of the segment by circular ports around the bore opening.

5) Joining of the segments

The joining of the segments was determined by the OEM. Clamps were used to pull the segments together and dowel pins were used to line them up.

5.4.2 Design of solid barrel

Figure 32 indicates what the cooling ports look like before welding takes place.

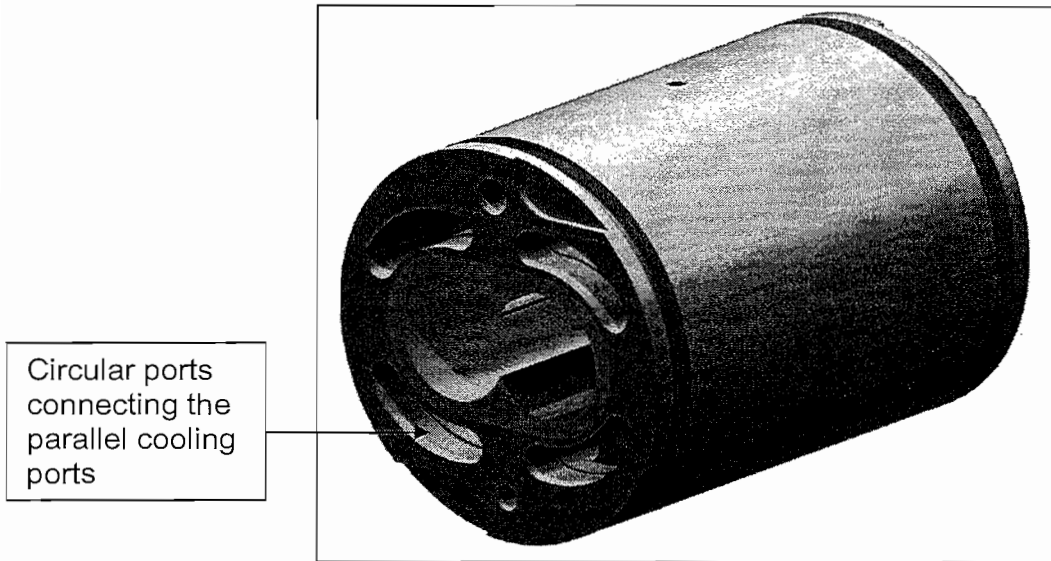


Figure 30: CAD model of a solid barrel

Plates were machined to fit exactly into the circular ports and then permanently fitted by using a normal arc welding process. A few important factors to keep in mind during this process are the following:

- The same material type as the barrel had to be used for the plates
- The welding process has to be properly specified in order to avoid leakages after welding.
- Machining over the welding had to be avoided as far as possible to avoid opening inclusions in the material. By using a purging process a full penetration weld can be achieved which has a lower risk of leaking than a normal welding process.

Listed below are the various components in this design. *Figure 33* indicates the location of the components.

- 1) Arrow 1 indicates the position where the water cooling pipes screw into the segment.
- 2) The dowel holes indicated were used to locate the liner and assure that the bores line up exactly.
- 3) The through-hardened liner is visible as indicated by arrow 3.

The material selection and the fitting between the cooling jacket and the liner were critical considerations in the design. The thermal expansion coefficients of the two materials and the fitting between the liner and cooling jacket are directly related.

- 4) The grooves into which the clamps fit. They were tapered in order to allow the clamps to pull the liners together when tightened. The faces of each liner were grounded to ensure that a proper sealing action is acquired.
- 5) Thermocouple hole. The barrel used ceramic band heaters for heating and a bayonet-type fitting to fix the thermocouples to the barrel. The thermocouple hole went through the barrel into the liner to a depth of about 3 mm from the surface of the bore.

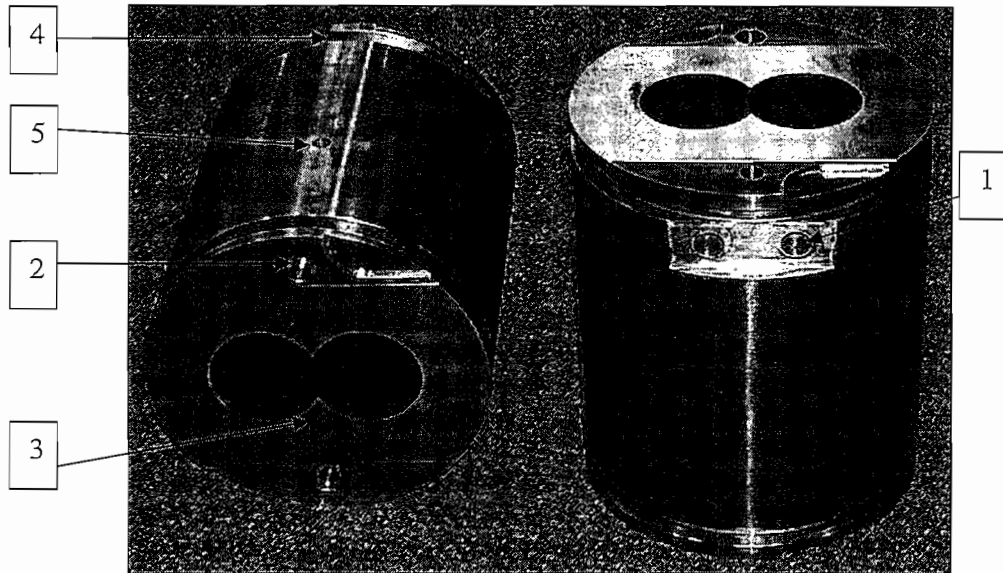


Figure 31: 50 mm solid barrel

5.4.3 Summary of barrel design

The barrel was supplied to a factory producing plastic pellets used for various applications. It was reported that the barrel produced satisfactory results and is operating perfectly under strenuous production conditions (Vorster, 2005). Important factors to keep in mind with solid barrels of this type are:

- The same material type as for the barrel had to be used for the plates that are used to seal the cooling ports
- The welding process has to be properly specified in order to avoid leakages after welding
- Machining over the weld bead has to be avoided as far as possible to avoid opening inclusions in the material. By using a purging process a proper penetrated weld can be achieved which has a lower risk of leaking than a normal welding process

- The faces of the liners has to have a ground finish to ensure that proper sealing takes place when they are pulled together by the clamps

5.5 Summary

In this chapter two case studies of the two types of extruder barrels were discussed. The design procedure was outlined by using the generic design trees formulated in Chapter 3. The various choices made were also discussed and an explanation for this specific choice was provided. Detailed illustrations of the extruder barrels were provided to ensure clarity on all the various sub components.

The sub components were also explained individually with illustrations.

After the discussion of each design, a summary for the various choices followed that highlighted the most important aspects.

In both case studies, the barrels provided satisfactory results during operation in a production environment. This was measured by verbal communication with the operator and production manager.

Through the experience gained in the two case studies, the choice for a barrel type for a multi-purpose twin-screw extruder has become a lot easier. The clamshell barrels' advantages outweigh the solid barrel during general operating conditions. Cleaning and subsequent product switchover can be done quicker and more efficiently with this type of barrel. The material choices for the two types of barrels were accurate and produced satisfactory results.

Chapter 6: Case study of an operating twin-screw food extruder

6.1 Introduction

In this chapter the generic design tree formulated earlier will be followed in the design and manufacturing of a TSE for the production of food products. The entire extruder had been manufactured locally. All components that could be manufactured on site at the University, was manufactured there. The components that were sub-contracted were the:

- Control panel including all electric motors and components
- The gears for the gearbox

More details on these components will be discussed in Chapter 7.

6.2 Background of the extruder

An extruder had to be developed to serve one of the rural countries in Africa to extrude and produce “puffs” from a grain called “mahangu”. The extruder will be used to process the mahangu in order to increase its storage life and purity.

The generic design approach had to be tested in the design of a fully functional extruder to identify any gaps or shortcomings. As this extruder was merely a prototype, some of the components were kept as basic as possible to focus more on the critical parts of the extruder. A structured discussion of the procedure followed during the design follows:

A What is the product and throughput rate?

The product has been defined as “mahangu”. Mahangu, or pearl millet, is grown in rural Namibia and is preferred to maize because of the unpredictable climate of the area.

The required throughput of the extruder is around 100 – 200 kg/hr.

B L/D ratio, centre distance of shafts, bore diameter

It is very complex to model what exactly happens in an extruder during the extrusion process, but the L/D ratio is typically determined by the process and the application that has to be satisfactory. The L/D ratio of the extruder is 15D. This was chosen from existing machines with a similar bore diameter. As mentioned earlier, the centre distance and bore diameter is in direct relation to the throughput rate. The centre distance that would give the required throughput rate is 38.5 mm. The exact bore diameter of the extruder is 49.7 mm.

C Energy considerations

The first consideration was the motor size which is mainly determined by the shaft size. With the selected profile the maximum diameter of the shaft is ± 24 mm. That is measured over the corners of the shaft, depending on the type of shaft. In this case it was measured over the corners of the hexagon.

The maximum torsional resisting moment of a 20 mm stainless steel hexagon shaft is 761.83 Nm. The selected motor for the application is a 30 kW three phase induction AC motor. The electric motor is rated at 195 Nm. The gearbox has a reduction of 3:1, thus it will deliver a torque of 585 Nm. This delivers a ± 300 Nm torque/shaft.

D Shaft material and shape

The best choice of a shaft for the extruder was a hexagon shaft (See Chapter 3, par 3.3 d). The maximum torque/shaft the extruder can deliver is ± 300 Nm. The maximum torsional resisting moment of the shaft is 761.83 Nm. That provides a safety factor of 2.53.

E Screw type

In this case, a pilot plant was not built beforehand to develop a screw configuration for the extruder. The product, mahangu, is similar (during extrusion) to normal maize. A number of extrusion experts were contacted in this regard to ensure that the correct optimal configuration would be achieved.

F Type of barrel

The extruder will be used for production as well as product development. With factors like the type providing the least effort during testing and the cost considered, a clamshell barrel was chosen.

The generic design tree for clamshell barrels was then followed during the design process.

F1 Liners

Because this extruder will mostly be used for research and development, the separate liner method was chosen for this extruder.

F2 Cooling

Existing extruders of similar size were researched concerning cooling. It was determined that they have three temperature controlled zones that delivered satisfactory results. The maximum amount of cooling ports had to be inserted. The reason for that is that if there was a changeover in product with a different extrusion requirement, it could be extruded easily with the same cooling effect.

Three temperature controlled zones with six cooling ports/zone was decided upon, with one inlet and two outlets.

F3 Heating elements

The heating elements were chosen from an existing machine with four 600 W cartridge elements per zone fitted on the machine. Four 750 W cartridge elements were supplied per zone in this machine to ensure that maximum flexibility could be achieved if there was a changeover in product with a different extrusion requirement.

F4 Opening mechanism

The conventional opening method was used. This was done to reduce costs.

F5 Joining of liners

The flange method is the chosen method for joining the liners.

G Die

The die consists of a breaker plate and a die plate. The die plate has three holes into which die inserts can be placed to vary the shape and size, as needed, of the product. A bracket was fitted on the side of the die/breaker plate assembly, so the die plate can be swivelled away from the breaker plate for cleaning.

H Cutter

The cutter is a die face cutter. It has six blades which can be removed when fewer blades are needed. The cutter is driven by a 1.5 kW electric motor.

I Frame

The frame was built on a modular basis. No hydraulic or hand operated systems were fitted in order to support modularity. A support was placed 2/3rds from the back so that the extension or shortening of the barrel can be accommodated when needed.

6.3 Testing of the extruder

6.3.1 Introduction

Certain theoretical results were expected beforehand and they will be introduced first. The results from the tests will then be weighed against these results to measure the performance of the extruder as a whole. The results delivered will then be used to characterize the extruder.

Figure 34 indicates that when the screw speed increases the following happens:

- Cooking zone length reduces
 - This causes a decrease in power input and temperature
 - It also causes less puffing and more product moisture
- Increase in shear
 - This causes an increase in power input and temperature
 - It also causes increased puffing and less product moisture

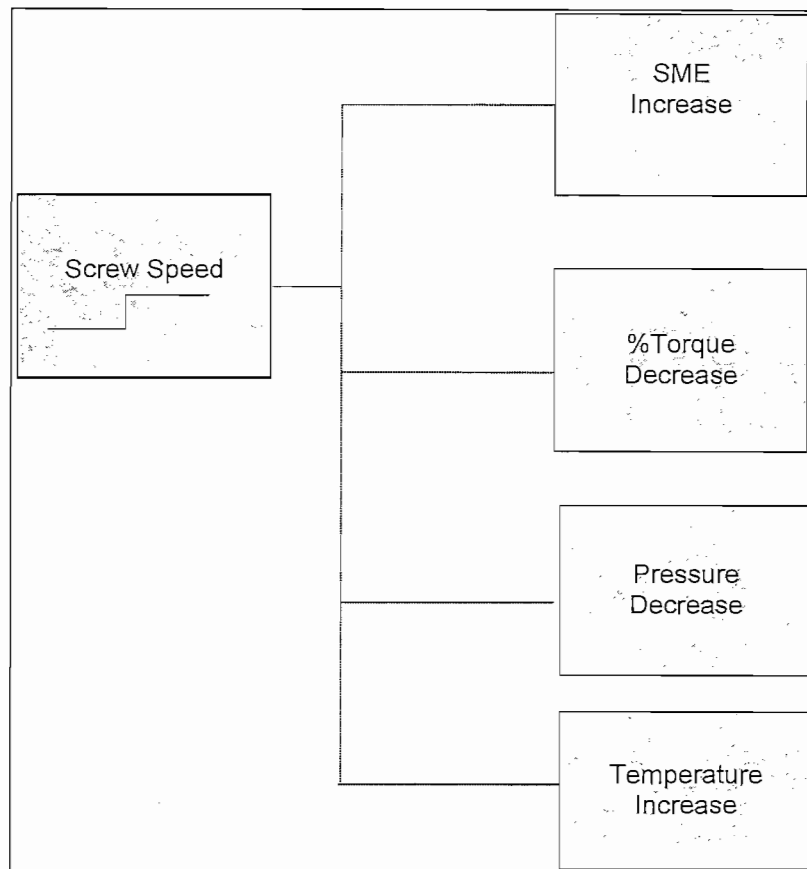


Figure 32: Response of the extrusion process to an increase in screw speed

Figure 35 indicates that when the moisture level increases the following happens:

- It decreases the viscosity of the product and the temperature
 - This cause a decrease in power consumption and pressure
 - There is also decreased puffing

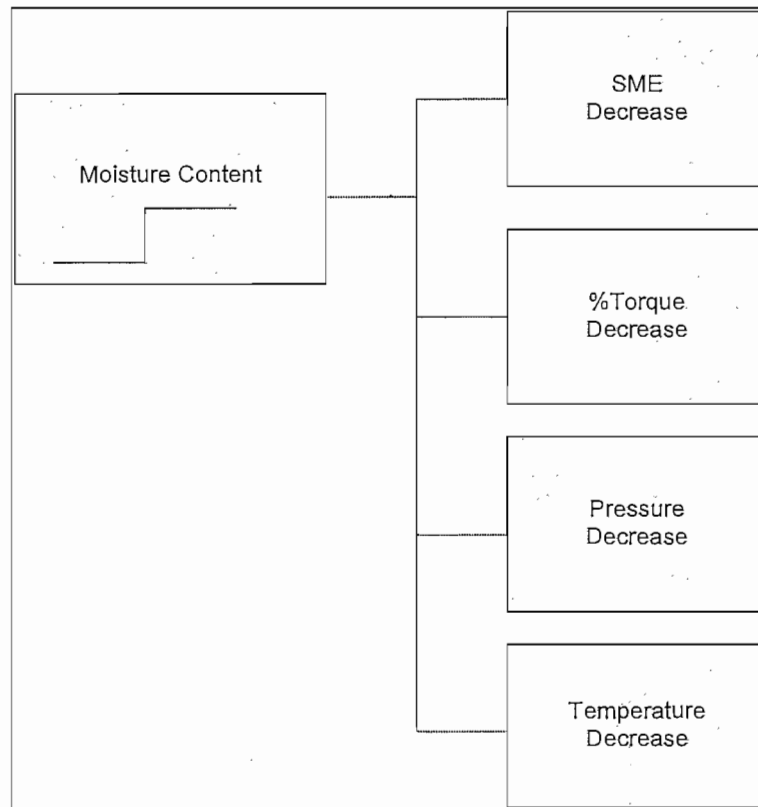


Figure 33: Response to the increase of moisture content

Figure 36 indicates the following can be seen:

- When the feed rate increases the torque increases
- The system pressure also increases
- The temperature decreases

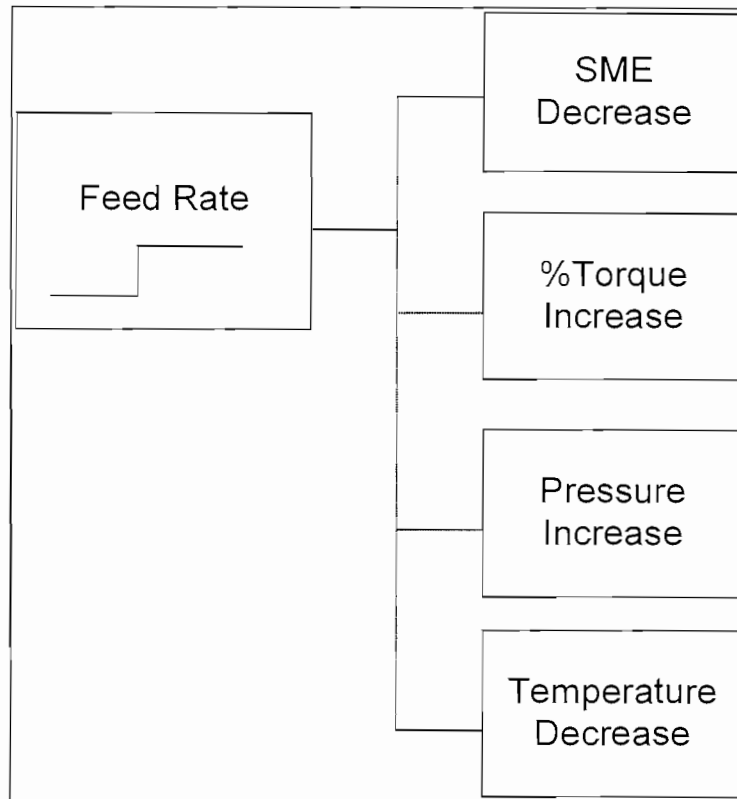


Figure 34: Response to an increase in feed rate

The parameters that were closely monitored during the extrusion process were:

- The temperature of each zone
- Feed rate/throughput rate
- Amperage of the main motor
- Dosing water flow rate

6.3.2 Testing of the extruder

A raw material had to be identified with the same composition and characteristics as mahangu. This had to be executed to ensure that the screw configuration and die geometry is correct.

The raw material identified was special maize meal.

6.3.2.1 *Settings of the extruder during testing*

A Screw configuration

The configuration was chosen from experience and advice from several extrusion experts and they suggested the following:

- Four 1D feed screw elements
- One 1D paddle block
- Two 1D feed screw elements
- One 1D paddle block
- Seven paddles staggered 30° forwarding
- One 1D feed screw element

B Die conditions

Three die inserts were cut into the die. Each one had a 2.6 mm hole in it with a 3 mm land⁷.

C Zone temperatures

The zone temperatures were set to 120 °C.

6.3.3 Summary of the test and start-up procedure followed

The product that was chosen for the first test was the special maize meal because of its similarity to mahangu (see Appendix C for the chemical composition of special maize meal).

Once it was switched on, the extruder took 8 minutes to reach the set temperatures. The screw speed was set at 200 rpm and the dosing water was opened to produce 40 l/h. The feeder was then started and kept at this rate until the product started to come out of the die inserts in a milky colour. The dosing water flow rate was steadily decreased to 10 l/h and the feeder feed rate was increased to 60 kg/h. Once slight puffing was noticed the dosing water flow rate was dropped to 5 l/h, the feed rate increased to 130 kg/h and the screw speed to 400 rpm.

Thereafter the product started puffing perfectly and the product was fully cooked. This was measured through visual inspection and tasting of the product. The extruder operated for an hour with these measurements during which the following measurements were executed.

A PT 100 thermocouple was fitted to each temperature zone to measure the different temperatures at each zone. The zones were numbered from the back (feed port side) to the front. *Figure 37* indicates that zone 3 had the highest average temperature during operation. The reasons for this are:

1. The die is next to it which has no cooling on it and a lot of heat due to friction is generated.
2. The seven paddles at the exit end generate more mechanical energy than anywhere else in the configuration to cook the product.

Zone two maintains a more or less average temperature throughout the operation. Zone one also maintains a more or less average temperature, but this average is a bit lower than the other two zones. The reason for this is:

1. The feed zone next to it has constant cooling on it
2. There is only one paddle block at the end of the zone so it does not really affect the temperature in the zone.

The temperature controls have a tolerance of $-10\text{ }^{\circ}\text{C}$ within which it must control the temperature of each zone. *Figure 37* indicates that the barrel has the correct size and amount of cooling on each zone. No leakages were detected anywhere and there were no sign of cracks in the material. The barrel and die performed well during the test.

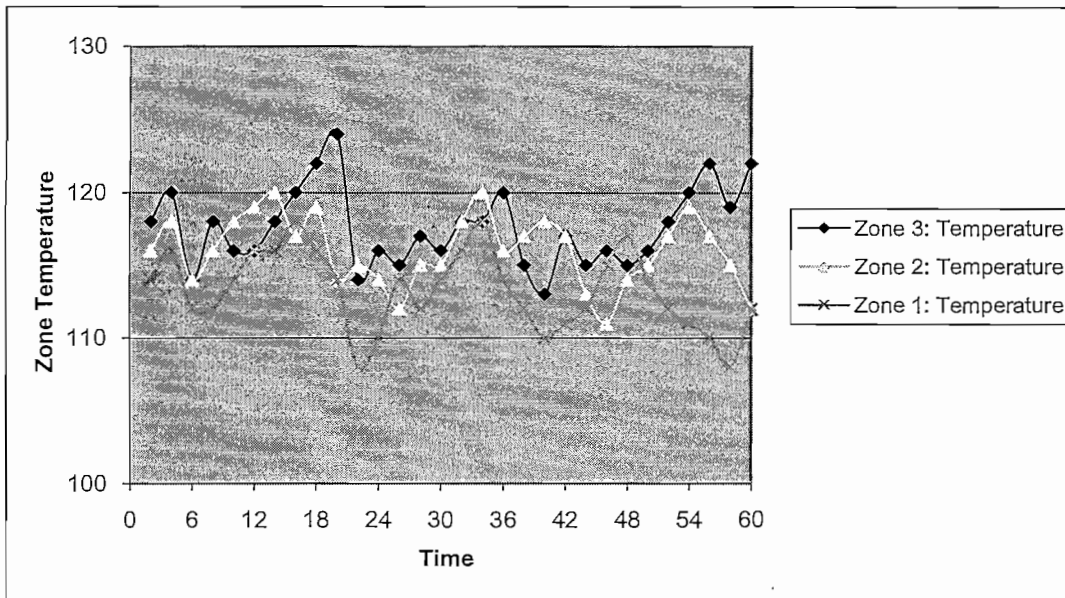


Figure 35: Zone temperature during testing of the extruder

In *Figure 38* the response of the extruder can be gathered. As the dosing-water flow rate decrease and the feed rate increase, the motor amperage also increases. This is also the point where the product starts "puffing". The maximum rated amperage of the main drive motor is 50 A. That is also the point where the motor will deliver the maximum torque of 195 Nm.

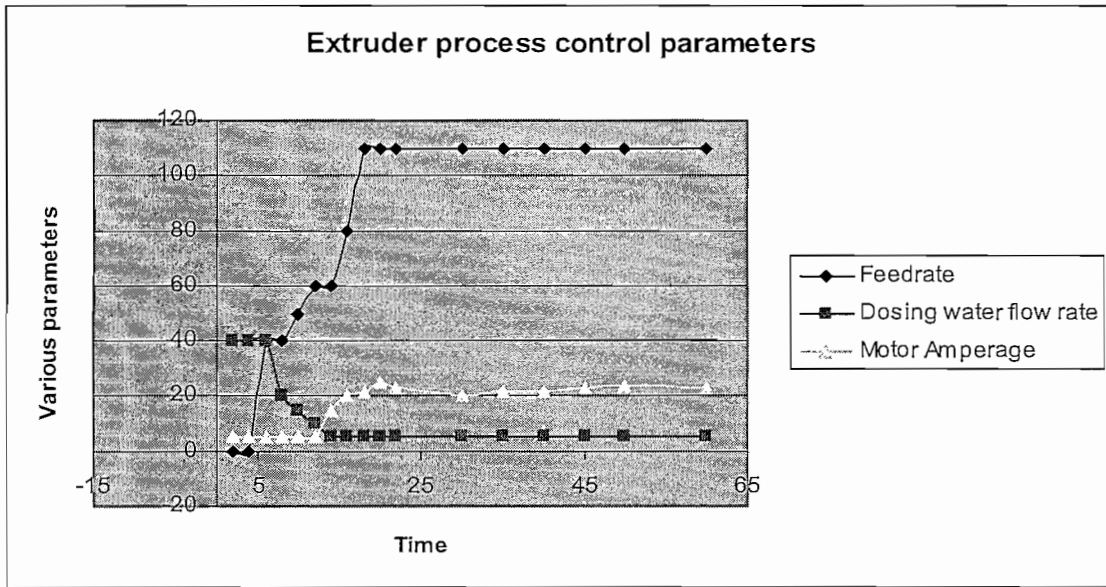


Figure 36: Extruder process control parameters response

Chapter 7: Conclusions and recommendations

7.1 Introduction

This chapter summarizes the most important conclusions from this study and makes recommendations for future research and production. Although there was a lot learnt from this study, only the most important conclusions will be highlighted and discussed.

7.2 Conclusions

In correlation to the aims stated at the beginning of this study, the following conclusions can be made:

1. From the study of the various extruders available on the market, the following conclusions can be made:
 - The recommended liner design for a clamshell barrel is the insert liner method.
 - The recommended design for a solid barrel is the bi-metallic design so that only the liner needs to be replaced instead of the entire barrel segment.
 - The single screw volumetric feeder is the cheapest and best choice for a feeder.
 - A hexagon shaft or keyed shaft is the recommended shaft types to use for the South African market to keep the cost of shafts and extruders as low as possible.
 - Slab heaters are much more user friendly than cartridge elements.

- Cooling can easily be done by straight holes through the cooling jacket.
 - The generic design tree formulated in study still has some shortcomings and will need further refinement, although it is sufficient enough to guide an in-experienced designer through the design process of a twin-screw extruder producing an extruder that is successful. Testing the approach against various case studies proved this. Shortcomings will become more apparent once inexperienced designers uses the design trees.
2. The design and testing of a fully functional twin-screw extruder for the African market was a success and is currently operating in a production environment.
 3. Further improvements can be made on the machine, but this will be discussed in the following paragraph.

7.3 Recommendations

The following recommendations are intended to enhance the design and manufacture of a twin-screw extruder. The aim of these recommendations is to provide possible guidelines in order to achieve a near perfect design of a twin-screw extruder for the African and South African market.

1. The height at which the barrel is fixed should be so that it is accessible for an operator of medium height.
2. Calibration of the various systems, feeder system etc. should be done accurately in order to ensure the correct control parameters and specifications for the extruder.
3. A hydraulic or counterweight system should be implemented in the opening and closing system of the extruder.

4. All components on the extruder should be made user friendly so that anyone can operate the machine without any formal training.

References

APV Group, General Website, <http://www.APV.com> Date of access: 5/2/2005.

Bausano Group, <http://www.Bausano.com> Date of access: 5/2/2005.

Clextral Group, Frequently asked questions,
<http://www.clextral.com/Clextral/FAQ.html> Date of access: 4/1/2005.

Couch,W.S. Feise, H.J. ; Krieger,T.L. 2003, Screw feeders: A guide to selection and use. www.cepmagazine.org p.44-51, February 2003.

Darrington, H. 1987. "A long-running cereal." Food manufacture.3: p.47-48.

Feed Formulation. (*In* Promotion of extrusion knowledge: Introduction to extrusion technology: Papers read at the 4th annual practical short course: Aquaculture feed extrusion, nutrition, & feed formulation Held at Het Pand, University of Ghent on the 18th and 19th September 2006)

Frame, N.D., ed 1995. The Technology Of Extrusion Cooking. Wester Cleddens Road, Bishopbriggs, Glasgow: Blackie Academic & Professional p.10-15, p.33-36, p.150-155.

Huber, G.R. 1989. Extrusion of Texturised Proteins, CRC Press LLC, p.53-55

Mercier, C., Linko, P. & Harper, J.M., 1998. Extrusion Cooking.
American Association of Cereal Chemists, Inc. St. Paul, Minnesota, USA.
p.30-35, p.140-142, p.180-190.

Riaz, M.N., 2000. Extruders in food applications, CRC Press LLC, originally published by Technomic Publishing. p.92-102.

Rauwendaal, C. 1998. Understanding Extrusion. Munich: Hanser p.5-10, p.30-32.

Rauwendaal, C. 2001. Polymer Extrusion. Munich: Hanser. P.192-200.

Rubin, A. 2006. Practical Short Course: Aquaculture Feed Extrusion, Nutrition, & X-trutech Group, General Website, <http://www.xtrutech.com> Date of access: 5/2/2005

Society of Plastics Engineers, <http://4spe.org> Date of access: 5/2/2005.

Vorster, D.B, Verbal communication, 03/03/2005

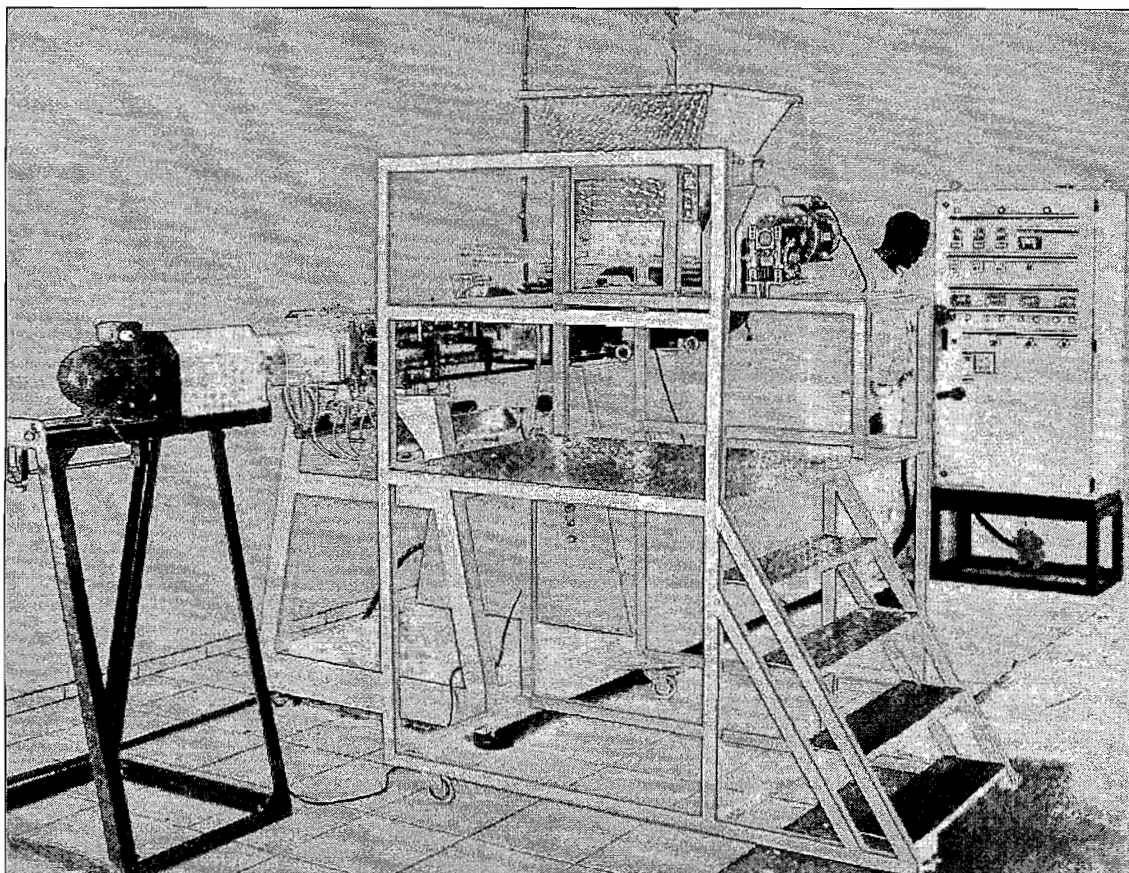
White, J.L. 1990 Twin-screw Extrusion: Technology and Principles. Cincinnati: Oxford University Press. P63-68, P134-145.

X-trutech Group, General Website, <http://www.xtrutech.com> Date of access: 5/2/2005.

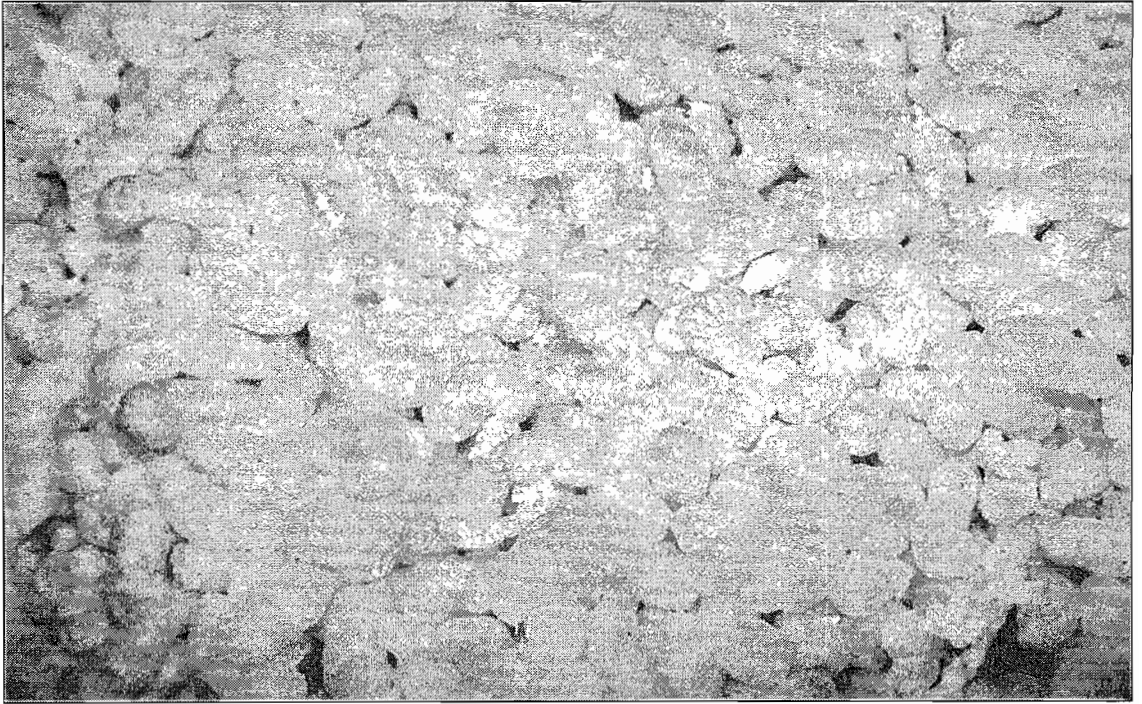
Zimmerman, D, 2004, Screw design for twin-screw co-rotating extruders, *Plastics Additives and Compounding*, 38-41, March/April

Appendix A:

Various photos of the prototype twin-screw extruder and products



A1 Extruder deployed at plant



A2 Special Maize Meal Puffs

Appendix B:

Useful formulas used during the extruder design

Shear stress in the shaft

The shear stress in a solid circular shaft in a given position can be expressed as:

$$\sigma = \frac{Tr}{I_p} \quad (1)$$

Where

σ = shear stress (MPa)

T = twisting moment (Nm)

r = distance from centre to stressed surface in the given position (mm)

I_p = "polar moment of inertia" of cross section (mm^4)

Circular shaft and maximum moment

Maximum moment in a circular shaft can be expressed as:

$$T_{\max} = \frac{\sigma_{\max} I_p}{R} \quad (2)$$

Where

T_{\max} = maximum twisting moment (Nm)

σ_{\max} = maximum shear stress (MPa)

R = radius of shaft (mm)

Combining (2) and (3) for a solid shaft

$$T_{\max} = \left(\frac{\pi}{16}\right)\sigma_{\max}D^3 \quad (2b)$$

Combining (2) and (3b) for a hollow shaft

$$T_{\max} = \left(\frac{\pi}{16}\right)\sigma_{\max} \frac{(D^4 - d^4)}{D} \quad (2c)$$

Circular shaft and polar moment of inertia

Polar moment of inertia for a circular shaft can be expressed as

$$I_p = \frac{\pi D^4}{32} \quad (3)$$

where

D = shaft outside diameter (mm)

Polar moment of inertia for a circular hollow shaft can be expressed as

$$I_p = \frac{\pi(D^4 - d^4)}{32} \quad (3b)$$

where

d = shaft inside diameter (mm)

Diameter of a solid shaft

The diameter of a solid shaft can be calculated by the formula

$$D = 1.72 \left(\frac{T_{\max}}{\sigma_{\max}}\right)^{\frac{1}{3}} \quad (4)$$

Torsional deflection of shaft

The angular deflection of a torsion solid shaft can be expressed as

$$\Theta = \frac{584LT}{(GD^4)} \quad (5)$$

where

Θ = angular shaft deflection (degrees)

L = length of shaft (mm)

G = modulus of rigidity (MPa)

The angular deflection of a torsion hollow shaft can be expressed as

$$\Theta = \frac{584LT}{(G(D^4 - d^4))} \quad (5b)$$

Torsion resisting moments of various shaft cross sections

Shaft cross section area	Maximum torsional resisting moment T_{\max} (Nm)	Nomenclature
Solid cylinder shaft	$\frac{(\frac{\pi}{16})\sigma_{\max}}{D^3}$	
Hollow cylinder shaft	$\frac{(\frac{\pi}{16})\sigma_{\max}}{\frac{(D^4 - d^4)}{D}}$	
Ellipse shaft	$\frac{(\frac{\pi}{16})\sigma_{\max} b^2}{h}$	h = "height" of shaft b = "width" of shaft h > b
Rectangle shaft	$\frac{(\frac{1}{1.09})\sigma_{\max}}{b^3}$	h > b
Square shaft	$(\frac{2}{9})\sigma_{\max} b^3$	
Triangle shaft	$(\frac{1}{20})\sigma_{\max} b^3$	b = length of triangle side
Hexagon shaft	$\frac{(\frac{1}{1.09})\sigma_{\max}}{b^3}$	b = length of hexagon side

Cooling and Heating of the extruder

The equation used to calculate the heat transfer in the extruder barrel is:

$$\frac{Q}{A} = \dot{m} c_p (T_1 - T_2)$$

where:

Q = heat to be removed

A = area of heat transfer (size and length of the cooling tube)

\dot{m} = mass flow rate

c_p = specific flow rate (Water=1)

Note: The aim with the extruder was to apply maximum flexibility in with heating and cooling abilities. The above equations is the basics applied in the design.

Appendix C:

Chemical composition of extruded products

Special maize meal chemical composition

Typical composition	Per 100g
Energy (kJ)	1490
Protein (g)	8.8
Glycemic Carbohydrate (g)	71.8
Total fat (g)	2.5
Dietary fibre (g)	3.7
Sodium (mg)	2
Vitamin A (μgRE)	188
Vitamin B ₁ (Thiamine) (mg)	0.39
Vitamin B ₂ (Riboflavin) (mg)	0.19
Vitamin B ₃ (Niacin) (mg)	3.19
Vitamin B ₆ (Pyridoxine) (mg)	0.43
Folic Acid (μg)	191
Iron (mg)	4.01
Zinc (mg)	2.25

