EFFECTIVE CONTROL OF A LOW-COST TWIN-SCREW FOOD EXTRUDER

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ABSTRACT

Title:	Effective control of a low-cost twin-screw food extruder
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Africa has one of the largest rates of poverty and famine. The hunger crisis in Africa is due to poverty as well as the little availability of nutritional food. Many locally grown crops are available in Africa but are not used to their fullest potential.

There is a huge demand for proper food production methods. The food crops in Africa are still cooked in traditional methods by using wood and coal. This method of cooking produces food of very low quality and nutritional value. The reason for this is the over-cooking of food, breaking down proteins and other nutritional components.

Extrusion is the process whereby high quality food is manufactured by using simple raw materials. Food extrusion is a process in which a food material is forced to flow, under one or more conditions of simultaneous mixing, heating and shearing, through a die, which is designed to form and/or puff-dry the ingredients.

The main disadvantage of extruders available on the market today is the cost per unit. Extruders are currently manufactured in the USA, Europe and the Far East. These machines are very expensive and unaffordable for the African market. The first barrier to overcome is to find a high quality extruder that is affordable for the African economy.

This dissertation will provide an introduction to extrusion technology and the application of an effective control system. Chapter 2 contains a literature study of the types of extruders available and discusses the different components of the extrusion process of the co-rotating twin-screw food extruder. The different needs and barriers for developing extrusion technology in developing countries will also be discussed. In Chapter 3 we will discuss the different components that form a control system and the various control modes that can be implemented to improve the control system, reduce offset and enhance stability.

Chapter 4 discusses the purpose of each component of the extrusion process, PLC implementation and control-philosophy of each component.

Chapter 5 involves a short case study of a corn grit extrusion process. In this chapter we will discuss three basic stages in the extrusion process and the corresponding input parameters for each stage. The relation between extruder screw speed, feeder screw and percentage of water injected into the extruder process, will be investigated.

Recommendations and conclusions of this study will be summarised in Chapter 6.

OPSOMMING

Titel : Die Effektiewe beheer van 'n lae koste dubbelskroef-voedselekstrueerder.
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Afrika is een van die lande met die hoogste armoede en hongersnoodsyfers. Die hongersnoodkrisis in Afrika is as gevolg van armoede en die tekort aan voedsel met hoë voedingswaarde. Daar is 'n groot hoeveelheid plaaslik-verboude landbouprodukte in Afrika maar dit word totaal en al onderbenut.

Daar is tans 'n baie groot aanvraag na aanvaarbare voedselproduksiemetodes in Afrika. Die maaltye wat in Afrika voorberei word, word nog op die tradisionele metode voorberei deur die gebruik van hout en steenkool. Hierdie metode veroorsaak dat die eindproduk van lae gehalte en voedingswaarde is. Die rede hiervoor is dat die doodkook van voedsel die noodsaaklike proteïne en vitamiene vernietig.

Ekstrusie is die proses waarmee hoë kwaliteit voedsel geproduseer word vanaf eenvoudige roumateriale. Dit is 'n proses waarin voedselmateriaal forseer word om te vloei onder een of meer toestande van vermenging,

verhitting en vervorming deur ‘n matrys wat ontwerp is om die produk te vorm en/of op te pof.

Die grootste nadeel van ekstrueerders wat vandag op die mark beskikbaar is, is die hoë koste per eenheid. Ekstrueerders word tans net vervaardig in die VSA, Europa en die Verre Ooste. Dit veroorsaak dat die masjiene baie duur en onbekostigbaar vir die Afrika mark is. Die eerste hindernis om te oorkom, is om ‘n hoë-kwaliteit bekostigbare ekstueerder vir die Afrikamark te vind. Hierdie studie sal ‘n inleidende beskrywing bied van ekstrusietegnologie en die toepassing van ‘n effektiewe beheersisteem. In Hoofstuk 2 sal daar ‘n literatuurstudie gedoen word oor die tipes ekstrueerders beskikbaar en die verskillende komponente van die ekstrusieproses van ‘n ko-roterende dubbelskroef-ekstrueerder sal bespreek word. Die verskillende behoeftes en hindernisse word ook in hierdie hoofstuk behandel.

In Hoofstuk 3 sal ons die verskillende komponente wat deel uitmaak van ‘n beheersisteem bespreek, asook die beheermetodes wat geïmplimenteer kan word om die beheersisteem te verbeter.

Hoofstuk 4 bespreek die doel van die ekstrusiekomponente, die PLC-implementering en beheerfilosofie van elke komponent.

Hoofstuk 5 bevat ‘n gevallestudie waar ontkiemde mielies geëkstrueer word. Die drie basiese fases in die ekstrusieproses en die ooreenstemmende insetparameters van elke fase sal bespreek word. Die verhouding tussen die ekstrueerder-skroefspoed, voerskroef en persentasie watertoediening in die proses sal nagevors word. Aanbevelings en gevolgtrekkings van hierdie studie sal opgesom word in Hoofstuk 6.

Aims of this study

The following are aims of this study

1. Develop an affordable and reliable control system for a twin - screw food extruder.
2. Investigate the types of extruders on the market today and discuss the different components and their functions in the extrusion process of a co-rotating twin-screw food extruder.
3. Investigate the different variables that are involved in the extrusion process and the importance of control to aid the operator.
4. Define the needs and barriers for effective control.
5. Define the components of the control system and the various control modes that can be implemented to improve the control system.
6. Investigate the implementation of an effective PLC control system and define the control-philosophy for each component of the extrusion system.
7. Investigate the application of the PLC control system to extrude corn grits.
8. Investigate the relation between extruder screw speed, feeder screw speed and the percentage of water injected into the extrusion system.
9. Calculate the mass and energy balance of the extrusion process in conjunction with the control system to achieve steady state conditions.
10. Determine the necessary amount of mechanical and heat energy to extrude corn grits in relation to effectively control the extrusion process.

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1 Chapter 1: Introduction

1.1 Introduction

Africa has one of the largest rates of poverty and famine. The hunger crisis in Africa is due to poverty, as well as the little availability of nutritional food. Many locally grown crops are available in Africa but are not utilised to their fullest potential.

Inappropriate social and economic policies, natural disasters and civil strife have all contributed to the deteriorating conditions in Sub-Saharan Africa today. A struggling one-third of the population is malnourished. Childhood mortality rates are among the highest in the developing world. Eighty percent of all Africans live on a daily income of less than US$2; nearly half struggle to survive on US$1 a day or less (Hazell and Johnson, 2002).

Despite the projected increase in mortality, resulting from infectious diseases, African population growth rates remain among the highest in the world. Hunger and poverty interact to fuel a vicious downward spiral that limits people's ability to grow or purchase food. Africa is the only continent where hunger and poverty are projected to worsen in the next decade.

There is a huge demand for proper food production methods. Traditional food preparation methods are still being applied by using wood and coal to cook maize. This cooking method produces food with very low quality and nutritional value.

Improving the poor performance of Africa's stagnating agricultural sector, in recent decades one of the worst in the world, is part of the key to solve some of the problems of hunger and poverty.

Where African governments have actively supported new investments in agriculture and rural development, these worrisome trends have started to turn around. In Uganda, for example, when political leaders embraced new agricultural programs in the 1990s, they were able to reduce rural poverty from 50 to 35 percent. In the past, development practitioners erroneously believed that small farmers were unwilling to change their traditional farming practices, but many studies now prove that small farmers respond to meaningful incentives (Hazell and Johnson, 2002).

Simple inexpensive extruders were developed in the United States in the 1960s for on-the-farm cooking of soybeans and cereal feeds (Riaz, 2000). The low-cost extruder designs were quickly adapted in the mid 1970s for use in nutrition intervention projects in many less-developed countries (Crowley, 1979).

Extrusion processing of foods and feeds has become a very popular production process (Dziezak, 1989). The subject of extrusion cooking is now of major importance in the food and feed processing industry. Extrusion is a highly versatile unit operation that can be applied to a variety of food processes (Riaz, 2000).

Extrusion is a process that combines several unit operations including mixing, cooking, kneading, shearing, compressing and forming. In essence, an extruder consists of a screw pump in which food is compressed and formed into a semi-solid mass. This is forced through a restricted opening (the die) at the discharge end of the screw (Lee, *et al.*, 2002).

Extruders can be used to cook, form, mix, texturize and shape food products under conditions that favour quality retention, high productivity and low cost. The use of cooker extruders has been expanding rapidly in food and feed industries over the past few years (Riaz, 2000).

Because extruders are being applied in so many diverse operations, effective control in the food extrusion process has become of major importance. Advantages of automating cooking extruders include the achievement of constant product quality, automatic start-up and shutdown, process optimisation and more effective information management (Moreira, 2001). Extrusion processes and extruders have been developed simultaneously in various industries during the past two centuries (Janssen, 1978; Harper, 1981). Numerous mechanical problems were experienced with early low-cost extruders (LCEs), but later models are more reliable and are widely used for processing different foods and crudely texturized foods in LDCs. Twin-screw cooking extruders have been manufactured in Europe for over 35 years but did not attract significant interest in the United States until the early 1980s (Riaz, 2000).

The introduction of a LCE makes it possible to produce low-cost nutritional food in many less-developed countries (LDCs) (Crowley, 1979).
Production of food does not only aid those areas but also enhances job creation and independence.

Before Africa can utilise the potential of extrusion technology, a way has to be found to manufacture cheaper extruders, tailor-made for the conditions in Africa. Africa has large amounts of available food crops for the manufacturing of nutritious food.

In order to counter the deterioration of African countries, it is inevitable that inexpensive nutritional food has to be produced. Extrusion technology has to be applied to aid in the fight against hunger and poverty. The answer to address some of Africa's problems lies in an inexpensive, reliable and versatile "African twin-screw food extruder", designed to meet the needs of Africa.

1.2 Objectives of this study

The main disadvantage of extruders available on the market today is the cost per unit. Extruders are currently manufactured in the USA, Europe and the Far East. Due to the exchange rate, these machines are very expensive and unaffordable to the consumer in the African market. The first barrier to overcome is thus to design and manufacture a high quality extruder, affordable for the African economy and equip it with an effective control system.

Extrusion technology has to be researched extensively to ensure that the development of the extruder and control system will be in line with technology currently available on the international market. It will also set out certain criteria for the minimum requirements needed for an extruder to be acceptable in the food industry.

The successful implementation of a suitable and effective control system for a twin-screw food extruder must ensure that the extruder is:

- affordable for developing countries;
- suitable for African conditions;
- versatile to apply to different processes;
- in line with international food processing standards;
- easy to operate; and
- reliable.

The possibility to automate the extruder with predefined programs to produce different kinds of products has to be investigated.

1.3 Scope of the study

- Investigate the types of extruders on the market today, and discuss the different components and their function in the extrusion process of a co-rotating twin-screw food extruder.
- Investigate the different variables that are involved in the extrusion process and the importance of control to aid the operator.
- Define the needs and barriers for effective control.
- Define the components of the control system and the various control modes that can be implemented to improve the control system.

- Investigate the implementation of an effective PLC control system and define the control-philosophy for each component of the extrusion system.
- Investigate the application of the PLC control system to extrude corn grits.
- Investigate the relation between extruder screw speed, feeder screw speed and the percentage of water injected into the extrusion system.
- Calculation of the mass and energy balance of the extrusion process in conjunction with the control system to achieve steady state conditions.
- Determine the necessary amount of mechanical and heat energy to extrude corn grits in relation to effectively control the extrusion process.

1.4 Summary

This chapter gives a brief introduction of what motivated this study. It also describes the process that was followed during the study. This study contributes to social as well as economical progress in developing countries.

The importance of extrusion and the application of extrusion technology are briefly discussed to produce nutritious food for Africa.

The successful implementation criteria of a suitable and effective control system are defined for a twin-screw food extruder.

The possibility to automate the extruder with predefined programs to produce different kinds of products will be investigated and a recommendation will be made at the end of this study as to how this can be implemented.

2 Chapter 2: Literature study

2.1 Introduction

The process of extrusion has been practised for well over a century. It involves forcing an extrudate through an opening to produce a predefined shape. A helical screw is used to force this medium through a restriction or die. Material is fed continuously into an extruder inlet port/hopper while the material is transported forward by the rotation of the screw. As it reaches the die, the pressure increases to the level required to propel the extrudate through the die orifice. The rotating screws convey the material from the inlet to the discharge side of the barrel by slipping the material on the screw surface (Huber, 2000).

In the food and feed industries, bread, cereals, pasta, snacks, meat and starches are dependent on extrusion. Extrusion is also used in the pharmaceutical and nutraceutical industries (Huber, 2000).

Extrusion cooking can be defined as "the process by which moistened, expansile, starchy, and/or proteinaceous materials are plasticized and cooked in a tube by a combination of moisture, pressure, temperature, and mechanical shear" (Smith, 1976).

The objectives of this chapter are to review the principles of extrusion and highlight the advantages and disadvantages of the extrusion process. The chapter will also introduce the terminology used in twin-screw extrusion technology.

The needs and barriers of effective control of an extrusion process will also be discussed.

2.2 Definition of extrusion

Extrusion processing in foods and feeds has become very popular. The subject of extrusion cooking is now of major importance in food and feed processing. Because extruders are being applied in so many diverse operations, they are regarded as versatile processes. Most new industries in first-world countries are installing extruders rather than the traditional processing systems.

Extrusion is simply the operation of shaping a plastic or dough-like material by forcing it through a restriction or die (Riaz, 2000). Rossen and Miller (1973) have offered the practical definition: "Food extrusion is a process in which a food material is forced to flow, under one or more conditions of mixing, heating and shear, through a die which is designed to form and/or puff-dry the ingredients." A food extruder is a device that shapes and restructures pre-cooked food ingredients. Extruders are very versatile and can be used to cook, form, mix, texturize and shape food products under conditions that favour quality retention, high productivity and low cost (Riaz, 2000).

2.3 Functions of an extruder

Extruders have a wide range of operating conditions that applies to the food and feed applications. The following are some of these functions based on Riaz, 2000:

Agglomeration: Ingredients can be compacted and agglomerated into discrete pieces.

Degassing: Ingredients that contain gas pockets can be degassed.

Dehydration: During normal extrusion processing, a moisture loss of 4-5% can occur.

Expansion: Due to the high pressure and temperature possible inside the extruder, products can be expanded to create puffed shapes e.g. cheese curls.

Gelatinisation: Extrusion cooking improves starch gelatinisation.

Grinding: Ingredients can be ground in the extruder barrel during processing.

Homogenisation: An extruder can homogenise by restructuring unattractive ingredients into more acceptable forms.

Mixing: A variety of screw configurations are available which can cause the desired amount of mixing action in the extruder barrel.

Pasteurisation and sterilization: Ingredients can be pasteurised and/or sterilized using extrusion technology for different applications.

Protein denaturisation: extrusion cooking can denature animal and plant protein.

Shaping: An extruder can make any desired shape of product by changing a die at the end of the extruder barrel.

Shearing: A special configuration within the extruder barrel can create the desired shearing action for a particular product.

Texture alteration: The physical textures can be altered in the extrusion system.

Thermal cooking: The desired cooking effect can be achieved in the extruder.

Unitising: Different ingredient lines can be combined into one product to produce special characteristics by using an extruder.

2.4 Advantages of extrusion

The principle advantages of extrusion technology compared to traditional methods according to Smith (1969) and Smith (1971) (with some modifications) are the following:

Adaptability: By changing the operation conditions and minor ingredients, a wide range of different products can be produced from the same basic raw materials.

Product characteristics: The extrusion process can produce a wide range of shapes, colours, textures and appearances that is not possible with traditional systems.

Energy efficiency: Extruders operate with relative low moisture and therefore less drying is needed after production.

Low cost: Extrusion has a lower processing cost than other cooking and forming processes. Savings of raw material (19%), labour (14%) and capital investment (44%) when using the extrusion process have been reported by Darrington (1987). Less space per unit of operation is also required.

High productivity and automated control: The continuous high-throughput of an extruder can be fully automated.

New foods: The extrusion process can modify animal and vegetable proteins, starches and other food materials to produce a variety of new and unique food products.

High product quality: Since extrusion is a high temperature short-time heating process, it minimises degradation of food nutrients while it improves digestibility of proteins and starches. It also destroys anti-nutritional compounds, i.e. trypsin inhibitors and undesirable enzymes such as lipases, lipoxidases and microorganisms.

No effluent: Extrusion produces little or no waste streams.

Process scale-up: Data obtained from a pilot plant can be used to scale up the extrusion system for production.

Use as a continuous reactor: Extruders are being used as continuous reactors for deactivation of aflatoxin in peanut meals and destruction of allergens and toxic compounds in castor seed meal and other oilseed crops.

2.5 Types of extruders

Screw extruders are usually classified according to the amount of mechanical energy they can generate. A low shear extruder is designed to minimise mechanical energy to prevent cooking of the dough e.g. the extrusion of pasta. A high shear extruder is designed to generate a high level of mechanical energy that is converted to heat to cook the dough. Alternative energy sources can be installed to produce even higher heat levels to cook the extruded material (Frame, 1994). These alternative energy sources may include heated oil located inside a jacket, surrounding the extruder barrel or cartridge elements located externally on the barrel of the extruder.

2.5.1 Single –screw extruders

Single screw extruders rely on drag flow to move material down the barrel and develop pressure at the die. When the material is pushed forward it should not rotate with the turning of the screw. The drag or the friction on the barrel wall assists the forward motion of the material by restricting the material to turn with the screw. Single screw extruders are mainly used for the production of snack foods and breakfast cereals (Frame, 1994).

2.5.2 Counter-rotating twin-screw extruders

Fully intermeshing counter-rotating twin-screw extruders prevent the cylindering effect in the barrel and have a positive displacement effect on the material. Extremely high die pressures can be achieved with counter-rotating screws but these extruders exhibit poor mixing abilities. Application of these extruders in food manufacturing tends to be limited to low viscosity systems e.g. liquorice (Frame, 1994).

2.5.3 Co-rotating twin-screw extruders

Co-rotating, self-wiping twin-screw extruders have become popular in the food processing industry because of their high capacity and enhanced mixing capability. Self-wiping screws prevent build-up of ingredients on the barrel surface that can cause surging which may interrupt the conveying action through the barrel. Co-rotating extruders can be operated at higher screw speeds than counter-rotating screws because radial forces are more uniformly distributed. In general, co-rotating twin-screw extruders offer the most flexibility for producing a wide variety of food products (Frame, 1994).

The remainder of this study involve using the co-rotating twin-screw extruder.

2.6 Differences between single-screw and twin-screw extruders

A single-screw extruder is literally an extruder with a single rotating screw. A single-screw extruder (SSE) relies on drag flow to move material down the barrel and develop pressure at the die. To be conveyed forward, the dough should not rotate with the turning screw. This can be compared to a bolt being turned while the nut turns with it; it will not be tightened. When the nut is held fast, it moves forward when the bolt is rotated (Frame, 1994).

The drag and friction between the material and the barrel ensures that the material is forced forward. The barrel has grooves cut into the inside in order to promote adhesion to the barrel wall.

SSEs induce their own heat due to the high friction. Some have heating jackets but most commonly induces their own heat. This means that for each product, feed rate, screw speed and water feed the extruder has a certain working point. This point is where the temperature is at its maximum due to the release of mechanical energy.

A SSE is commonly used for simple pet foods, expanded snacks and breakfast cereals. The production rate and product quality varies appreciably during the extrusion process due to the inconsistent pressure distribution along the barrel. The temperature is also difficult to control. Product quality obtained by using a SSE is very low and inconsistent. There is very little to no mixing in a SSE. This means that only simple ingredients can be produced with a single screw.

The above-mentioned and other shortcomings not mentioned here, led to the development of twin-screw extruders.

The most commonly-used and most preferred twin-screw extruder (TSE) consists of two co-rotating screws running intermeshing alongside each other. Like the SSE the co-rotating twin-screw extruder is a drag-flow device. However, the potential for the material to rotate with the screw is impeded by the flight of the second screw.

TSEs offer better conveying and narrower residence-time distribution than SSEs. The conveyance capability of TSEs allows them to handle sticky and other difficult-to-convey food ingredients. In general, co-rotating TSEs offer the most flexibility for producing a wide variety of food products.

In co-rotating extruders, the material is transferred from one screw to the other. The flow mechanism is a combination of drag-flow and positive displacement flow.

TSE is thus the answer to all the needs identified in SSE, and more. TSE provides the operator with full control over temperature, pressure and quality of the product. As mentioned earlier, by only changing one of the parameters a completely different product can be produced. The total control over the parameters in a TSE, makes it the most versatile food processing equipment in the world.

The advantages of TSEs are the following:

- they handle viscous, oily, sticky, or very wet materials and some other products, which will slip in a SSE;
- they have positive pumping action and reduced pulsation at the die;
- there is less wear in smaller parts of the machine than in a SSE;
- they feature a non-pulsating feed;
- a wide range of particle size (from fine powder to grains) may be used whereas a SSE is limited to a specific range of particle size;
- cleanup is very easy because of the self-wiping characteristic;
- the barrelhead can be divided into two different streams;
- they provide for easier process scale-up from pilot plant to large-scale production; and
- the operation process is more forgiving to inexperienced operators.

The above-mentioned advantages make the co-rotating twin-screw extruder the obvious choice for the design of a local extruder. High-temperature/short-time cooking extruders are versatile processing machines. They can use a wide variety of raw materials and formulations to produce new and existing products. A few examples are: breakfast cereals, expanded snack food, liquorice, pre-cooked pasta, "Purity" baby food, advanced pet foods, aqua feeds, third generation snacks and texturized vegetable proteins used as meat analogues, to name only but a few.

2.7 Extrusion process description of the co-rotating twin-screw extruder

High-temperature/short-time cooking extruders are versatile processing machines that can produce a wide range of products. The extruder can be operated by controlling specific process variables in order to produce a wide range of engineered foods. The process conditions and recipes can be altered to change the final product (Huber, 2000).

The extrusion cooker is made up of several sub-components common to all extrusion processes. The main processing components of the co-rotating extruder consist of the following:

- Hopper/Holding bin;
- Pre-conditioner;
- Extruder assembly;
- Die;
- Cutter; and
- Dosing pump

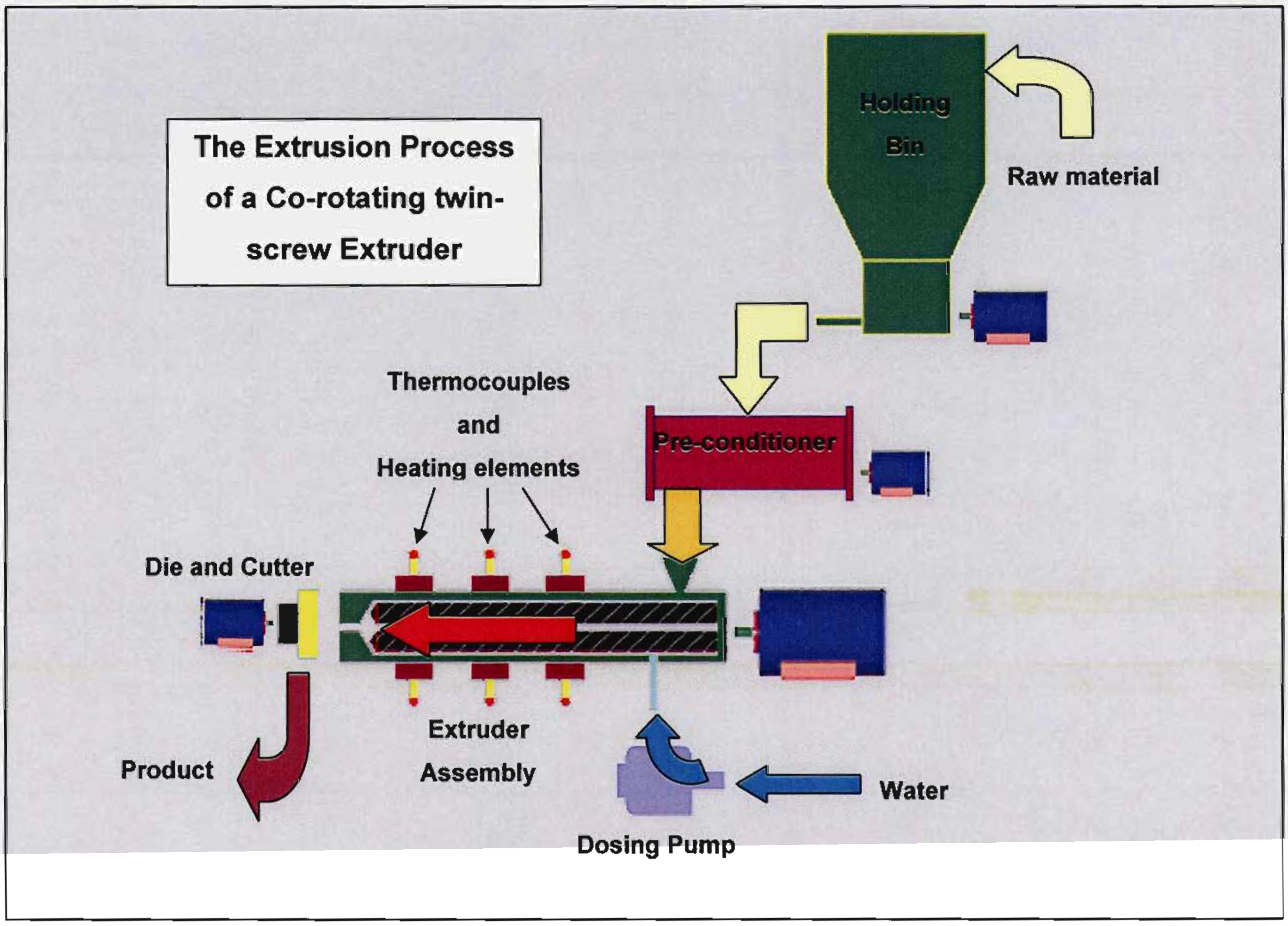


Figure 2.1: Extrusion process of a co-rotating twin-screw extruder and the main processing components.

Raw material is fed into the holding bin / hopper by the use of an Auger or conveying device. The holding bin provides a buffer of raw material so that the extruder can operate continuously without interruption.

The raw material is uniformly discharged from the holding bin by the use of a variable-speed feeding screw into a pre-conditioner. The feeder-screw can also feed directly into the extruder inlet port / hopper.

The pre-conditioner is an ancillary process-component that is designed to improve product quality and/or increase outputs (Frame, 1994).

After the material is fed into the extruder, the motion of the co-rotating screws conveys the material forward. Water is injected into the barrel to add additional energy for the cooking process. The heating elements add additional heat to the extrusion process to cook the material. The dough-like material is then forced through a restriction or die to shape the final product. A cutting device is used to cut the extruded profile to the desired length.

2.8 Description of individual components of the co-rotating twin-screw extruder

2.8.1 Holding bin

A holding bin provides a buffer of raw material at the inlet of the extruder so that the extruder can operate continuously as mentioned before. The holding bin acts as a short-term storage device of raw material (Huber, 2000).

The holding bin design and type of raw material can have a great influence on the consistency of flow. Blocking or bridging of the raw material inside the bin is a common problem that interrupts the flow of raw material through the orifice of the bin (Rhodes, 1998). To prevent this problem, the bin has to be equipped with a device to ensure even flow. This will be discussed in Chapter 4.

Two basic types of dry-feeders are used to feed extruders:

a) Volumetric
b) Gravity

In volumetric feeders, fine particulate materials are prone to aerate or hold air pockets in the feed hopper that may frequently be responsible for inconsistent flow. Vertical sided conical hoppers can be used in feeding the raw material into the process. A variable-speed feeding screw is used to uniformly discharge material from the bin (Frame, 1994).

2.8.2 Pre-conditioner

Pre-conditioning may be defined as a prerequisite processing step of putting the raw material in the proper or desired condition (Riaz, 2000).

Pre-conditioning is an important part of the extrusion process. This ancillary process is designed to improve product quality and increase outputs (Frame, 1994). Steam and water is injected into the pre-conditioner cylinder to combine with the dry recipe. The dry recipe combined with the steam and water is retained long enough for each particle to achieve temperature and moisture equilibration. The single most important aspect of pre-conditioning is that the system prolongs mixing and retention time.

There are basically two types of continuous pre-conditioners available:

- Pressurised pre-conditioners
- Atmospheric pre-conditioners

2.8.2.1 Pressurised pre-conditioners

Pressurised conditioning chambers provide approximately 1 to 3 minutes residence time at temperatures up to 115°C.

Pressurised conditioning has a negative effect on nutritional quality of food products according to research. Their operation and design are also more complex (Frame, 1994).

2.8.2.2 Atmospheric pre-conditioners

Atmospheric conditioning chambers provide from 20 to 240 seconds retention time during which the raw material is preheated and moisture is allowed to penetrate the particles of the material. Pre-conditioning enhances flavour and aids the final product texture (Huber, 2000).

2.8.2.3 Pre-conditioner operations

There are a number of operational variables over which the operator has control when operating a pre-conditioner. The on-line changes include steam addition rate, water injection rate and the dry recipe rate. Above mentioned operational variables assist in longer retention and mixing time (Strahm, 2000).

Atmospheric pre-conditioners are limited to a maximum of approximately 95°C discharge temperature. Because of the high specific heat, the amount of water added has a large influence on the amount of steam that can be added. The water creates a greater heat sink to absorb more energy from the steam, and therefore a greater quantity of steam can be added (Strahm, 2000). The water steam ratio can be seen in the figure below.

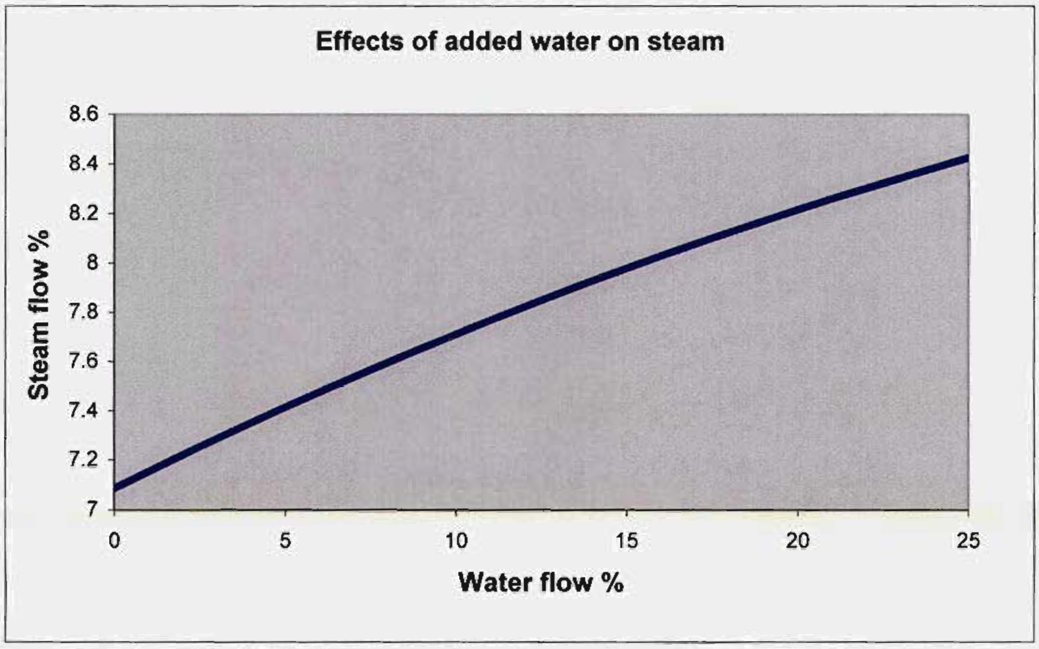


Figure 2.2: Effects of added water on steam to reach maximum temperature.

2.8.3 Extruder assembly

The extruder assembly is composed of rotating screws and barrel. The co-rotating twin-screw food extruder must exert several actions in a short time from the point where the raw material or pre-conditioned material is fed into the extruder until it is discharged from the extruder. These controlled, continuous, steady state operation conditions include: heating, cooling, conveying, feeding, reacting, compressing, mixing, melting, cooking, texturizing and shaping (Huber, 2000).

The layout of the extruder assembly components can be seen in figure 2.3.

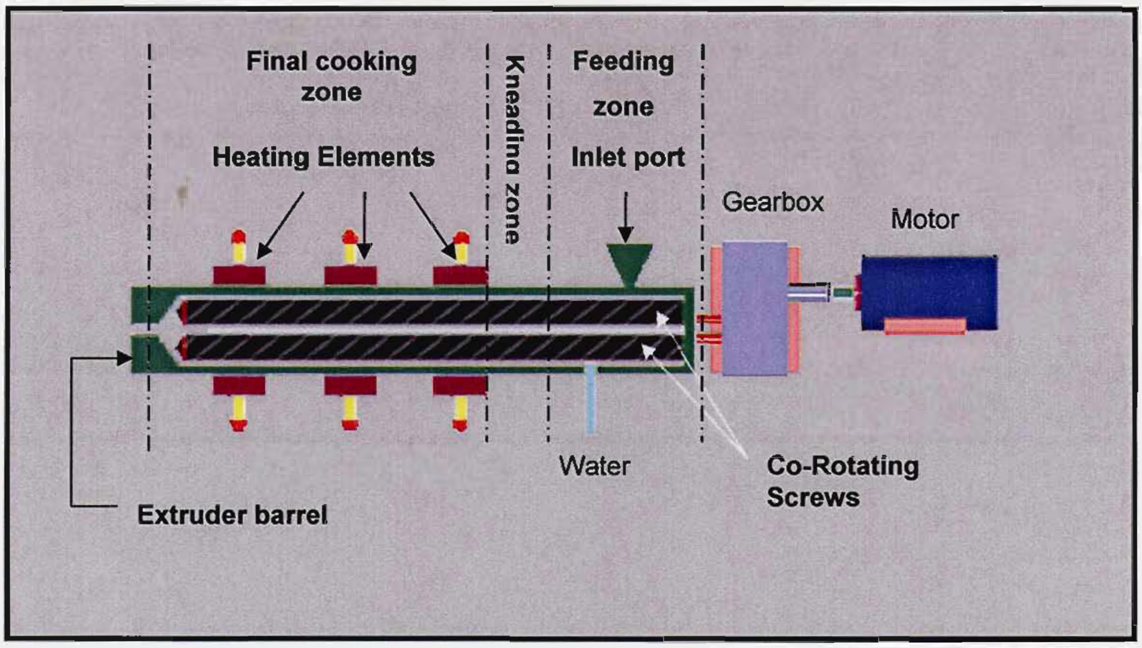


Figure 2.3: Extruder assembly of the co-rotating twin-screw extruder.

2.8.3.1 Rotating screws

A multitude of screw configurations are available, but the normal practice is to configure the screws as a series of conveying and mixing elements (Frame, 1994). Conveying screws generate pressure for the material to flow forward.

The sequences and actions inside the barrel can be subdivided in different processing zones. These zones include the feeding zone, kneading zone and final cooking zone depending on the screw configuration.

The feeding zone is the area where low density, discrete particles of raw material is introduced into the barrel inlet. Thus often, preconditioned material is then conveyed forward into the interior of the chamber. The density is low because of air that is entrapped within the material. The material is compressed as it moves forward and the entrapped air is expelled through the die. Water is usually injected into the feeding zone of the barrel to enhance conductive heat transfer and to alter textural and viscosity development (Huber, 2000).

As the material is conveyed into the kneading zone, the material is further compressed and the flow channel of the extruder achieves a higher degree of fill. The extrudate density begins to increase as it loses its granular definition. The pressure increase in the barrel as the extrudate flows through the kneading zone. As extrudate moves forward, it becomes a flowing dough mass and reaches its maximum compaction (Huber, 2000).

In the final cooking zone the temperature and pressure increases most rapidly. This is where the texturizing occurs and where the shear rates of the screw configuration and compression of the extrudate is the highest.

From the cooking zone, the extrudate will discharge from the barrel through the die to yield the desired final product texture, density, colour and functional properties.

2.8.3.2 Barrel

The barrel usually consists of segments that are bolted together to form a channel wherein the screws can rotate and convey the material. The barrel can be fitted with an additional jacket to circulate water or oil around the barrel to cool the extrudate off or for additional heating. The cooling or heating medium is never in direct contact with the extrudate. Heating elements can also be applied to heat the barrel.

2.8.4 Die and cutter

The barrel is capped with a die through which the extrudate must flow. The die contains one or more openings that form the shape of the final product and provides resistance against the pumping motion of the screws.

Dies are designed to be highly restrictive in order to increase barrel fill, residence time and energy input (Huber, 2000).

The die consists of transition and die-plate sections as seen in the figure below.

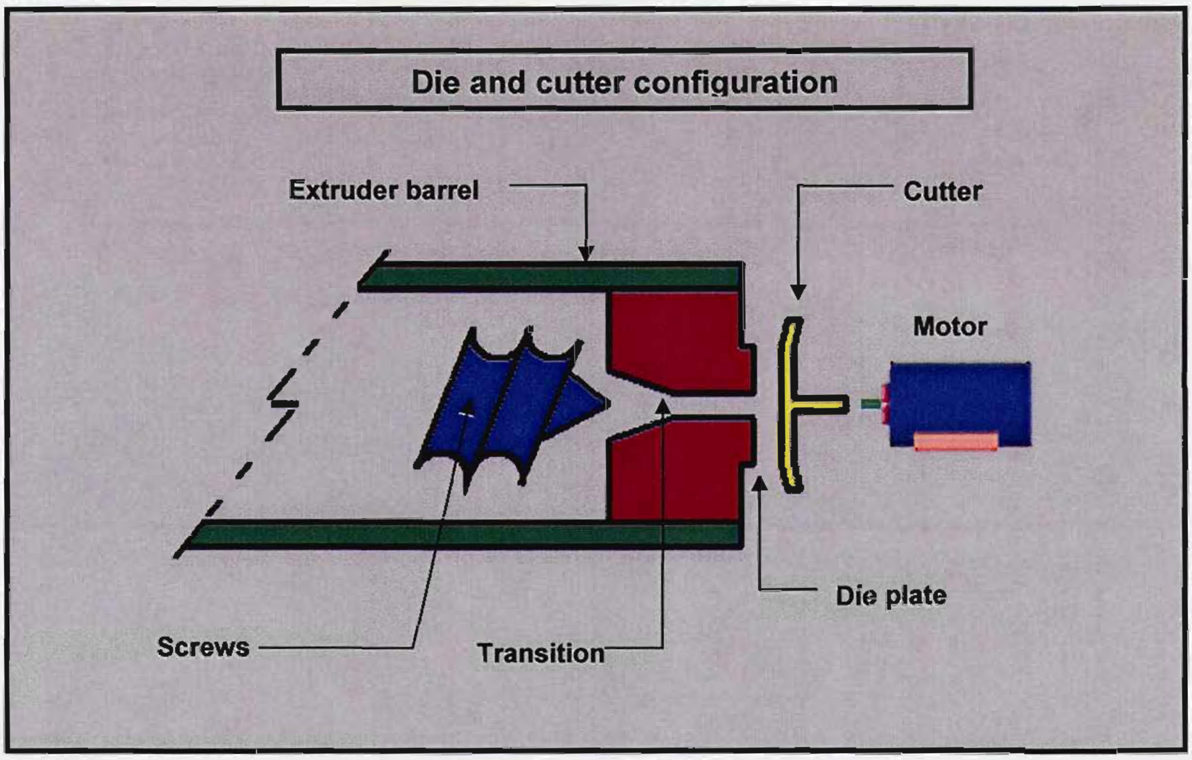


Figure 2.4: Die and cutter configuration.

The extrudate is forced through the transition phase where it is then forced through the die opening. The cutter, situated in front of the die opening, cuts the shaped extrudate into desired lengths. A variable speed drive regulates the cutting speed of the cutter blades. When the speed is increased, the extrudate is cut into shorter lengths and the opposite occurs when the cutting speed is reduced.

The die can be regarded as a fixed control variable for a specific application.

2.9 Extrusion processing variables

Control of the extrusion processing variables is vital to ensure production of a successful product. It is important to understand what processing variables can be controlled directly and which variables is a result of what is controlled in the system. The extrusion processing variables may be subdivided into two categories:

- independent variables; and
- dependant variables.

The interaction of the extrusion processing variables is of great importance to the operator of the extruder. Changing the independent variables can result in altering the final product characteristics.

2.9.1 Independent variables

The independent variables are the process parameters that the extruder operator can control directly from the control panel. The variables of the system will vary from operating system to operating system. The independent variables include:

- dry recipe and dry recipe feed rate;
- water and or steam injected into the pre-conditioner;
- water and or steam injected into the extruder;
- extruder configuration;
- extruder screw speed;
- extruder barrel heating or thermal fluid temperature; and
- die configuration.

2.9.2 Dependent variables

The dependant variables are process parameters that change as a result of changing one or more of the independent variables. The dependant variables include:

- retention time, moisture and temperature in the pre-conditioner;
- retention time in the extruder;
- moisture in the extruder;
- temperature in the extruder;
- pressure in the extruder; and
- mechanical energy input into the extruder.

2.10 Influence of the dependent variables

Optimisation of machine process variables and feed ingredients are preconditions for the stability of the extrusion system, output and product quality. The main independent process operating variables, which include feed-rate, in-barrel moisture content, screw speed and barrel temperature profile, are directly controlled by the extruder operator.

The following discussion is primarily intended to give an overview of the system variables for food extrusion process control.

2.10.1 Feeding

Co-rotating extruders are in general starve-fed, i.e. the conveying capacity of the extruder exceeds the rate at which the material is fed into it (Frame, 1994).

The first important factor in the extruder operation is the stable, consistent flow of raw material into the extrusion process. Inconsistent flow-rates of feeds more than often produce inconsistent flow of product (Frame, 1994). The product will, for example, have a large size distribution, poor shape and varied textures.

2.10.2 In-barrel moisture content

Moisture is a critical catalyst in extrusion cooking processes. Moisture in the form of steam or water, injected into the extruder barrel, adds additional energy for the cooking process. This increases capacity and reduces the requirement for large drive motors. As moisture increases, the mechanical energy required decreases. The moisture acts like a lubricant and frictional heat is significantly reduced.

2.10.3 Screw speed

Screw speed directly affects the degree of barrel fill, and hence the residence time, distribution and the shear stress on the material being extruded. The screw speed is a factor in determining the maximum volumetric output of the extruder and therefore extruder manufacturers design the machines to run at maximum speeds between 400 and 500 rpm (Frame, 1994).

The disadvantage of running the extruder at high rates is the increased wear of the screws and barrel. Most ingredients used in food extrusion are thixotropic or pseudoplastic and therefore there is a linear relationship between speed and torque/pressure. The torque and die pressures change with screw speed (Frame, 1994).

Barrel-fill is a factor that affects the product stability. The barrel-fill length decreases with an increase of screw speed and die area but increases with feed-rate. To maintain extruder stability a balance must be made between feed-rate, die area and screw speed (Frame, 1994).

Screw speed, feed-rate and die geometry require optimising for each product formulation. In the following graphical representation, the relationship between feed-rate, screw speed and die area can be seen.

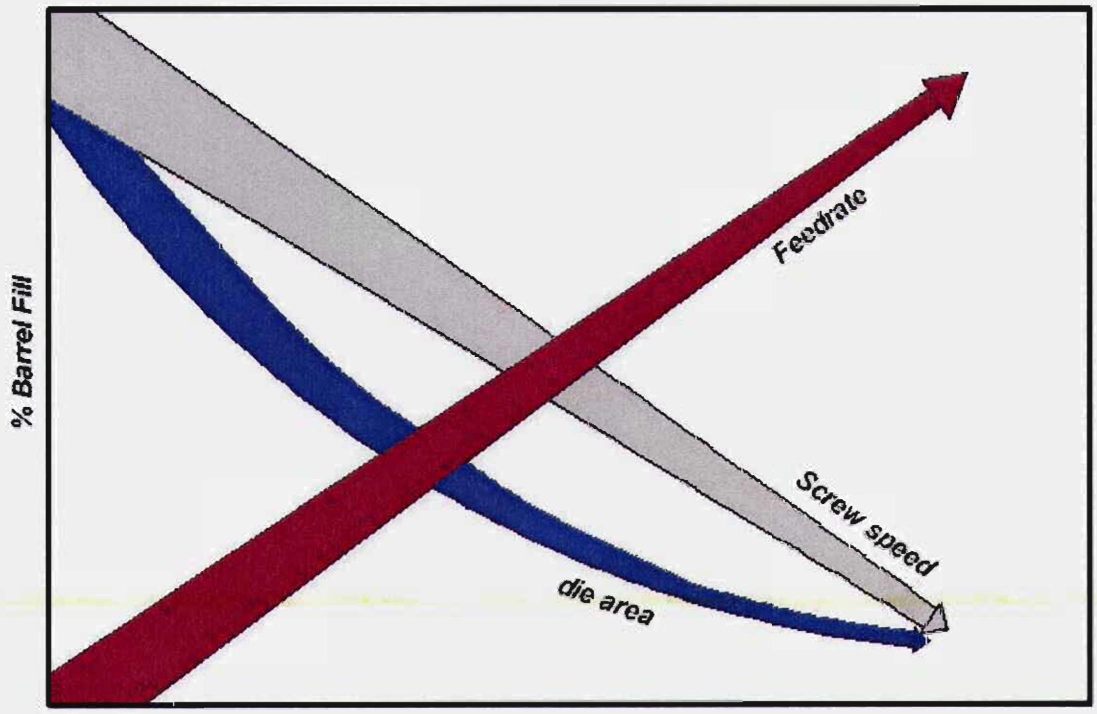


Figure 2.5: Relationship between feed-rate, screw speed and die area.

A normal minimum screw speed range is 70-100 rpm. Below this range, the volumetric capacity will be limited and make the extruded product costly to manufacture. The normal reason for operating at low speed is to achieve maximum residence time. Cheaper methods of extending residence time are available by pre-treatment of materials before extrusion e.g. pre-conditioning (Frame, 1994).

2.10.4 Barrel temperature and heat transfer

Extruders can be classified thermodynamically, by pressure development or by shear intensity (Huber, 2000). Thermodynamically, extruders exhibit the following properties:

a) Autogenous (nearly adiabatic) extruders generate their own heat by mechanical conversion. There is no indirect heating or cooling of the barrel involved.

b) Isothermal extruders operate with either cooling to remove heat from the barrel generated by mechanical energy or heating to maintain the temperature of the product within the barrel (Rossen and Miller, 1973).

Most extruders operate with temperature control and the degree of indirect heating or cooling depends on the product that is extruded. The rate of heat transfer is a function of surface area, temperature differential between the material boundary layer and metal barrel, and the heat transfer coefficients of the different materials (Frame, 1994).

2.11 Final product characteristics

The result of the changes made to the independent variables that influences the dependent variables are embedded in the final product of the extrudate. The final product characteristics are thus measures of the final product quality. Altering certain variables can control the final product characteristics. A few of these characteristics include:

- moisture – stability;
- expansion - bulk density, size and shape;
- solubility – stickiness;
- absorption - water, fat, milk;
- texture - cell structure;
- colour - light, dark; and
- flavour - strong, mild, sweet.

2.12 Critical parameters

All of the above mentioned product characteristics are directly influenced by four critical processing parameters. The influence of the critical parameters and their effects on the raw material determines the characteristics of the final product. Altering the independent variables directly changes the interaction of these critical parameters. The four critical parameters are as follows:

Critical Parameter	Description
Moisture	Actual moisture in the process
Mechanical energy GME = Gross Mechanical energy [kWh / kg] SME = Specific Mechanical energy. [kWh / kg]	$\text{GME} = \frac{\text{Power}}{\text{Mass flow rate}}$ $\text{SME} = \frac{(\text{Power}_{\text{loaded}} - \text{Power}_{\text{empty}})}{\text{Mass flow rate}}$
Thermal energy input	For heating the extruder barrel • Thermal fluids • Electrical heat
Retention time t' = Average retention time m = Amount of extrudate in the process m' = Mass flow rate	Total time in each of the process $t' = \frac{m}{m'}$

Table 2.1: The critical parameters that influence the final product characteristics.

To maintain consistent duplication of a final product, all of the critical parameters must be controlled and kept constant (Huber, 2000).

Moisture is a critical catalyst in the extrusion process as mentioned previously.

Mechanical energy is a function of the measured screw torque and mass flow rate and is an indication of how much energy is used to extrude the raw material.

Thermal energy input is an indicator of how much energy is added to the system in the form of heat to cook the raw material. Thermal energy can be added in the form of thermal fluids or heating elements.
Retention time is a direct measure of how long the material resides in the barrel until discharged through the die (Huber, 2000).

2.13 Need for effective control

Maintaining consistent product output and final product characteristics is of great importance in the extrusion industry. Often quality measurements cannot be made on-line. To ensure such a quality, a certain degree of automation and control has to be implemented to control the critical parameters.

Applying modern control methods to food extrusion is a useful way of improving production (Eerikäinen and Linko, 1998). The production of low cost, high quality products is essential in the extruder industry and is only possible by implementing an affordable control system.

The effective automation and control of the extrusion system eliminates the potential for human error and can improve process optimisation (Frame, 1994). The optimisation of the extrusion process involves the constant feedback of the operating parameters and the fine-tuning of the parameters to produce high quality products.

Automatic start-up and shutdown sequences can minimise waste of raw material and blockage.

A control system aids the operator and makes it easier for someone that is inexperienced in extrusion processes to operate the system.

2.14 Barriers for effective control

The automation and control of an extrusion process largely depends on the cost aspect of the implementation of such a control system. Thus the first barrier to overcome is the large cost involved in implementing a control system. There are many different methods of control that can be implemented, but with the complexity of the system and reliability, the cost also increases. Therefore the application and costs involved for implementation must be established before implementing a control system.

During processing many problems can occur in an extrusion system, some of which are directly coupled to the control of the system and the experience of the operator. These problems include surging, wedging, distortion of the product, variation in product density, colour variation and lower feed-rates. All of the above-mentioned can be corrected by changing some of the processing variables. Surging occurs when the extruder is not running at full capacity. In this case, the problem can be corrected by slowing the extruder screw speed down, and increasing the feed-rate, or to plug some of the die open area.

When wedging occurs, the product flows unevenly from the die and the cutter cuts the extrudate thicker on the one side. The cause of this problem may be that there are too many knives cutting the extrudate. To correct this problem, the number of knives must be reduced and the speed of the cutter must be increased.

A product can get distorted if it is too soft, or is undercooked. The solution to the problem can be to decrease the moisture in the barrel.

Density is a function of expansion, size and shape. The variation in product density can be corrected by changing worn dies, increase feed-rate, cooling the barrel or increasing the starch content in the recipe.

Colour is usually a function of the cooking process, particle size of the ingredients and added colour. Changing the feed of the dry material and the addition of moisture can control colour variation.

Lower feed-rates are the result of worn screw segments and causes back-flow of the material. This situation can be corrected temporarily by increasing the screw speed, but new screw segments will have to be installed. Another possible cause for a lower feed-rate may be the increased viscosity of the extrudate. Reducing oil or water addition in the recipe can solve this problem.

2.15 Conclusion

In conclusion to this chapter the different types of extruders were discussed, and also the components of the extrusion process of a co-rotating twin-screw food extruder.

The different variables that are involved in the process were discussed and the important role that process control exhibits in the extrusion process.

After taking the needs and barriers for effective control into consideration, it is inevitable that an affordable control system will complement the extrusion process and aid the operator.

3 Chapter 3: Automation and Control

3.1 Introduction

A control system is an interconnection of components that form a system configuration that will provide a desired system response or output (Dorf and Bishop, 1998).

Automatic process control involves the control and regulation of the operating parameters to operate at pre-set values. These operating parameters can only be controlled if there is a consistent feedback to the operator of the system. Such a system is called a closed-loop feedback control system. A closed-loop control system utilises a measurement of the output and compares it with the desired output response. A simple closed-loop feedback control system is shown in fig 3.1.

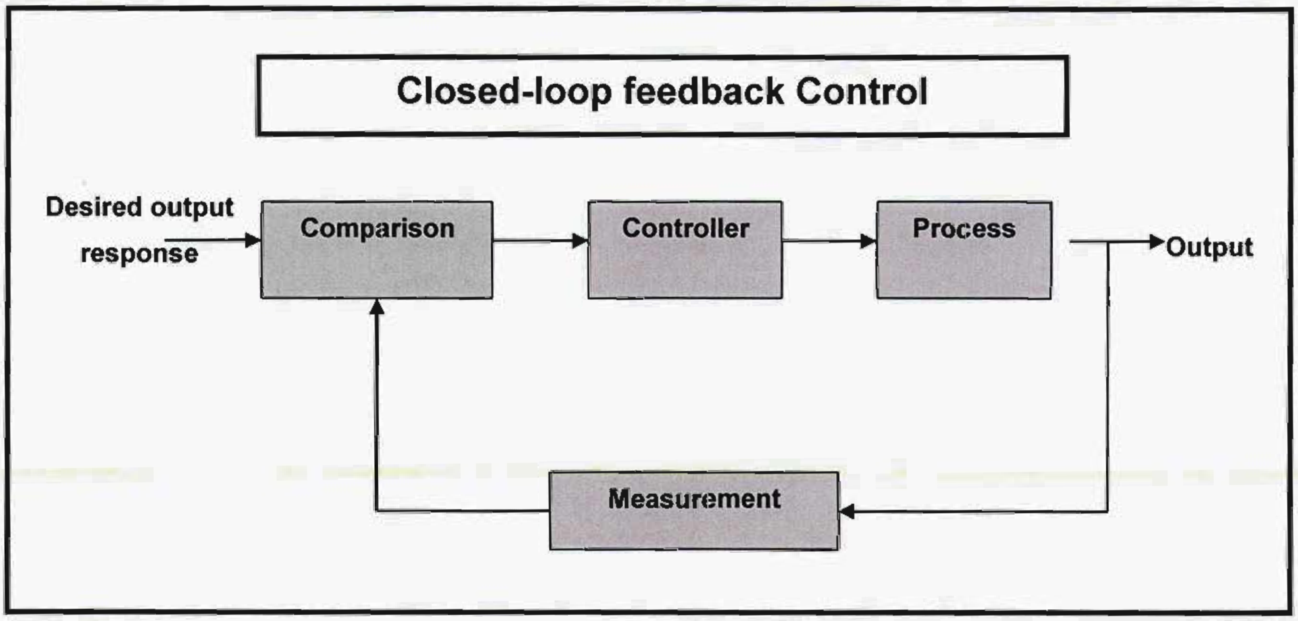


Figure 3.1: Closed-loop feedback control system.

An example of a closed-loop temperature control system is illustrated in the following figure. The desired output response is the set point that the operator inputs into the control system. When the heating elements are switched on, the extruder barrel is heated. The thermocouple acts as the measuring component of the system, and measures the actual temperature of the barrel.

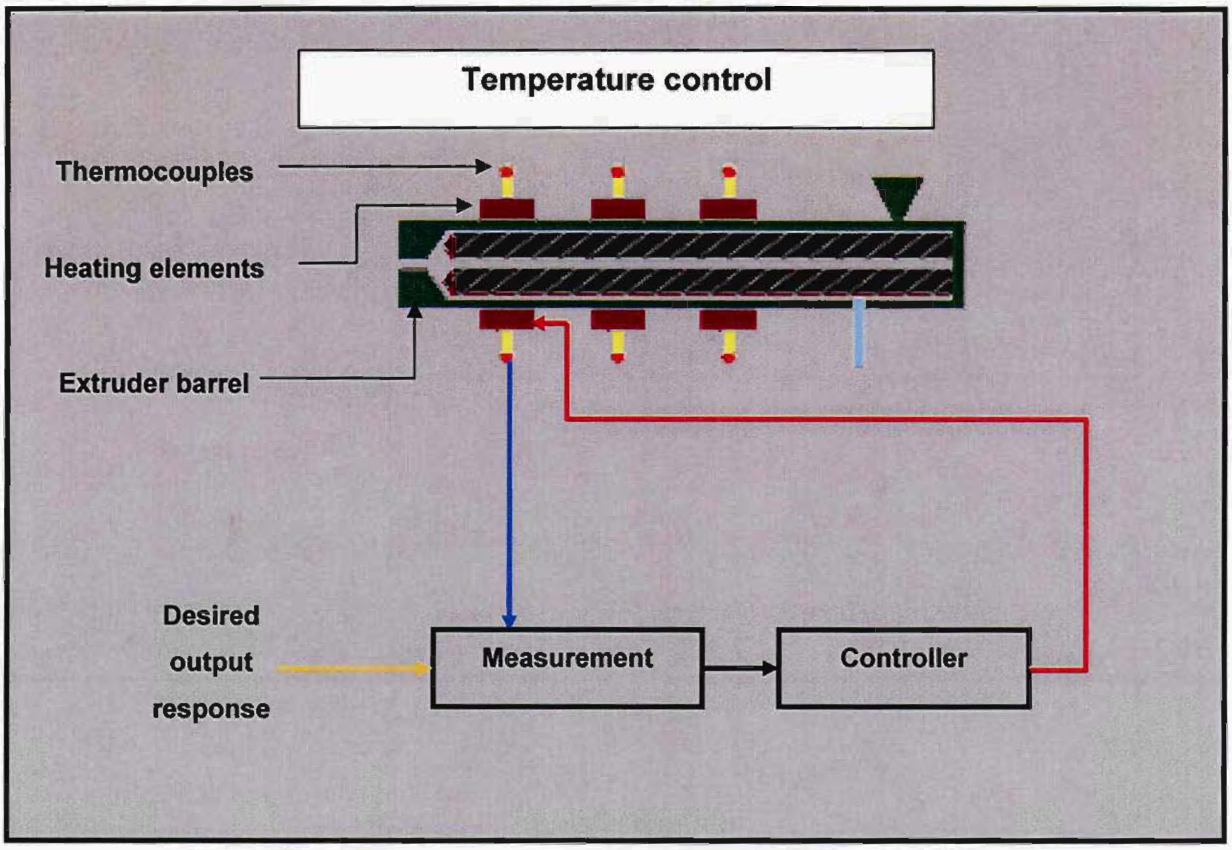


Figure 3.2: Closed-loop temperature control system.

The temperature measurement is the feedback to the controller. The controller compares the input value from the operator and the feedback signal from the thermocouple. If there is a deviation between the desired output and actual output, the controller rectifies the deviation by sending a corrective response to the heating elements.

Another form of control system is an open-loop control system. The open-loop control system is a system without feedback. Such a system can be termed as a compensated control system (Dorf and Bishop, 1998).
A common example of an open-loop system is an electric toaster, used in the kitchen.

3.2 Definitions

The following terms are provided by British Standard 1523:Part1: 1967, which describes the terms below.

Controlled variable: The quantity or physical property measured and controlled, e.g. the extruder barrel temperature.

Desired variable: The desired value of the controlled variable at which the control system must be maintained.

Set point: The value of the controlled variable set on the controller interface to control, e.g. 120°C set as the set point on the controller interface.

Control point: The value of the controlled variable that the controller is trying to maintain. This is a function of the mode of control, e.g. with proportional control and a set point of 120°C±5°C, the control point will be 125°C at full heating load, 120°C at 50 % load and 115°C at zero load.

Deviation: The difference between the set point and the measured value of the controlled variable at any instant, e.g. for a set point of 120°C and an instantaneous measured value of 125°C the deviation is +5°C.

Offset: A sustained deviation caused by an inherent characteristic of the control system, e.g. with a set point of 120°C±5°C the offset is +5°C at a full heating load, 125°C being maintained.

Primary element (also termed as a sensor): The part of a controller, which responds to the value of the controlled variable in order to give a measurement, e.g. a thermocouple measuring temperature.

Final control element: The mechanism altering the plant capacity in response to a signal initiated at the primary element, e.g. control valves or variable speed drive.

Automatic controller: A device which compares a signal from the primary element with the set point and initiates corrective action to counter the deviation, e.g. electronic analogue temperature controller.

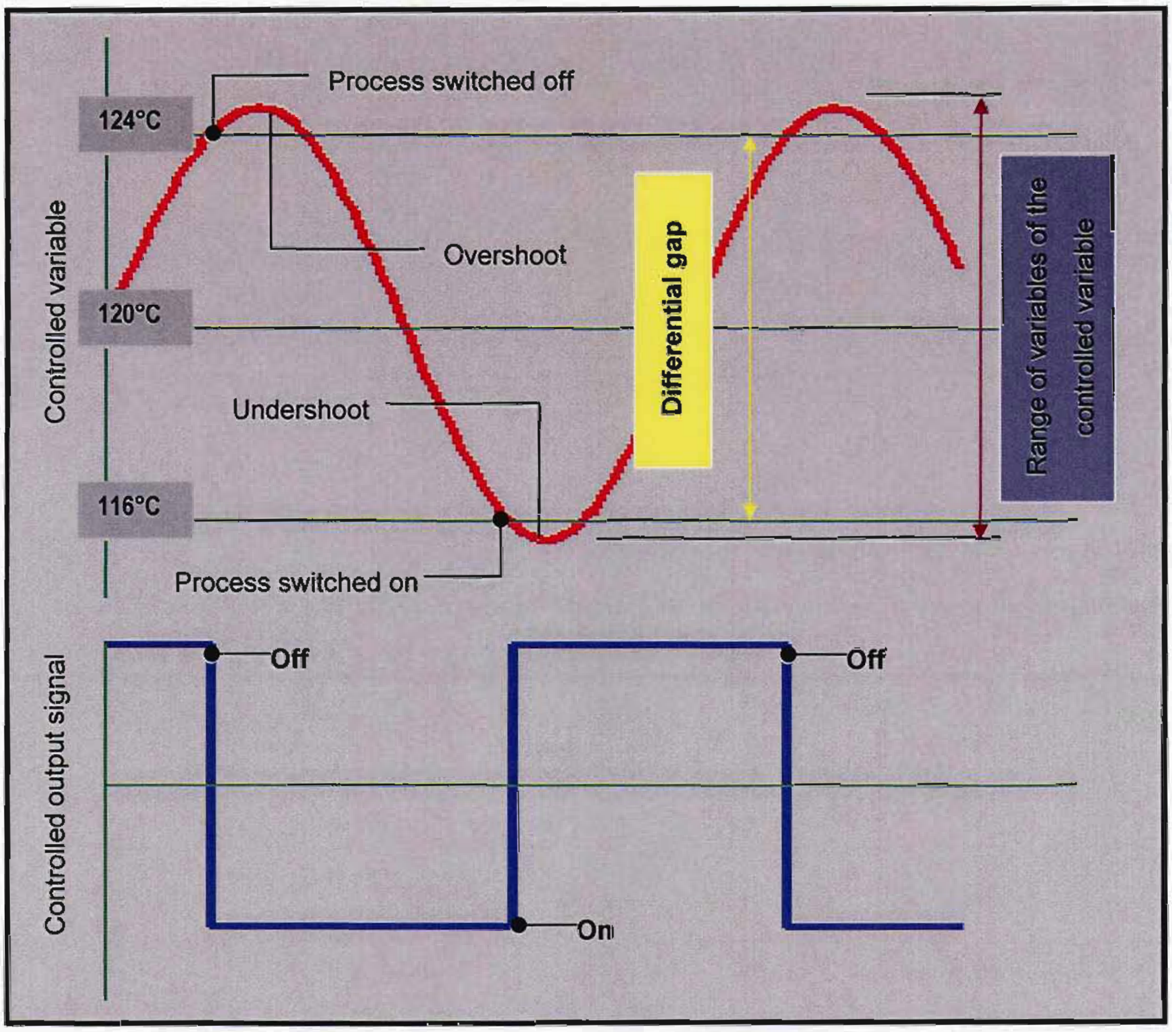


Figure 3.3: Two-position control indicating the differential gap.

Differential gap: This refers to two-position control and is the smallest range of values through which the controlled variables must pass for the final control element to move between its two possible extreme positions, e.g. if a two position controller has a set point of 120°C±5°C the differential gap is 10°C. See figure 3.3.

Proportional band: This refers to proportional control and the range of values of the controlled variable corresponding to the movement of the final control element between its extreme positions, e.g. a proportional controller with a set point of 120°C±5°C has a proportional band of 10°C. See figure 3.4.

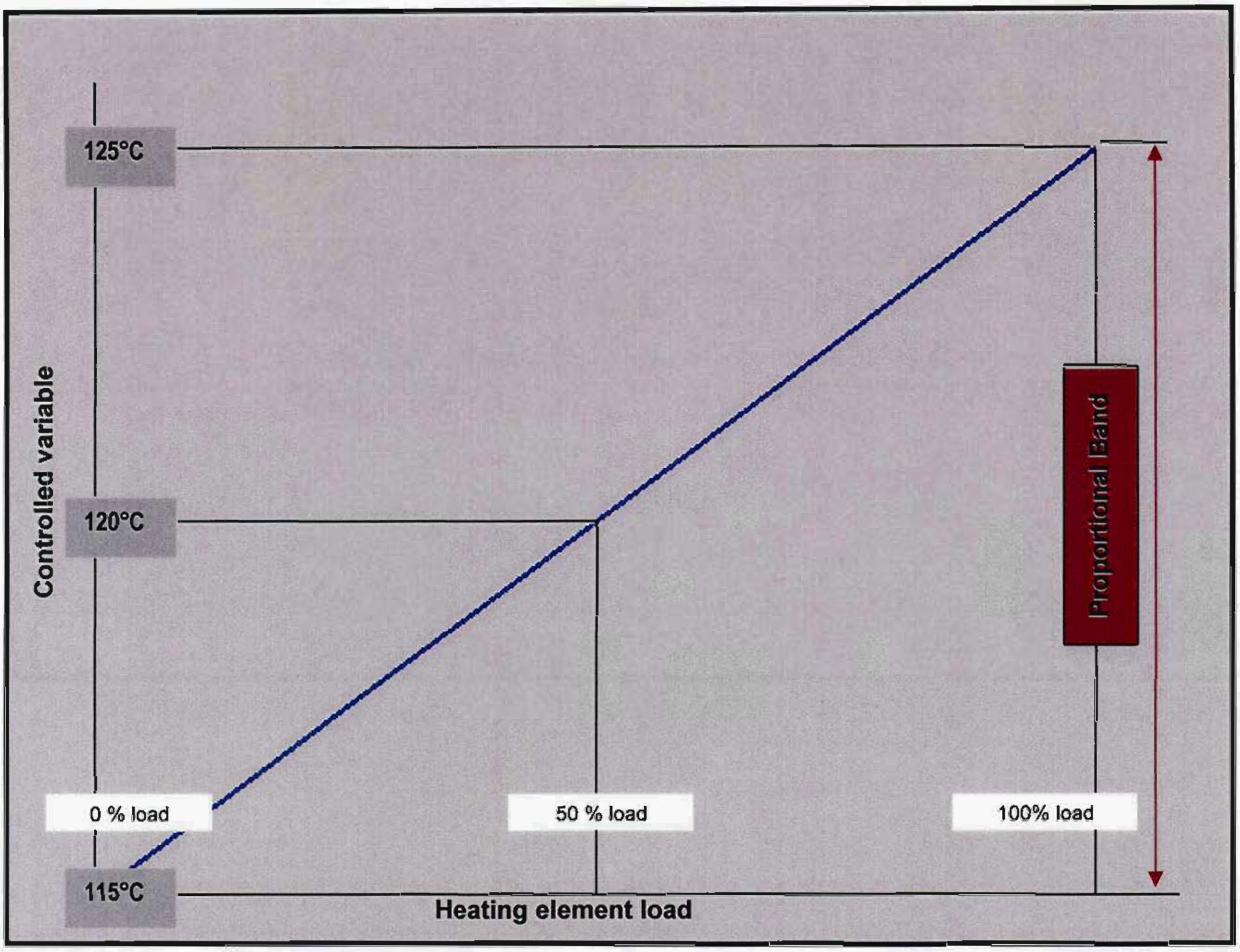


Figure 3.4: Proportional control.

Cycling: Also known as hunting, this is a persistent, self-induced, periodic change in the value of the controlled variable.

Open-loop system: A control system without feedback.

Closed-loop system: Control systems with feedback so that the deviation is used to control the action of the final control, and reduce the deviation.

Dead time: The time between a signal change and the initiation of perceptible response to the change.

3.3 Control system components

In order to understand a control system, the individual components that make up the system must be analysed. A control system consists of the following components:

- primary elements;
- controllers;
- final control elements; and
- process.

(Svrcek, Mahoney and Young, 2000).

It can clearly be seen in figure 3.1 in which the closed-loop feedback control loop is shown. The primary elements consists of the thermocouple or sensor, a controller that calculates the difference between the actual output (the reading from the sensor) and the desired output (set point) and then adjusts the final control element (heating element) to correct the output.

The primary elements have a very important function in the control system and therefore have to be reliable, consistent and effective.

3.3.1 Primary elements

The primary elements are the instruments used to measure the controlled variables in a process such as temperature, pressure, revolutions of an electric motor, etc. and give feedback to the controller. The primary elements have a very important function in the control system and therefore have to be reliable, consistent and effective. The primary elements include:

- temperature measurement;
- pressure measurement;
- flow rate measurement; and
- quality analysis instrumentation.

The following discussion is intended to give a brief overview of temperature measurement.

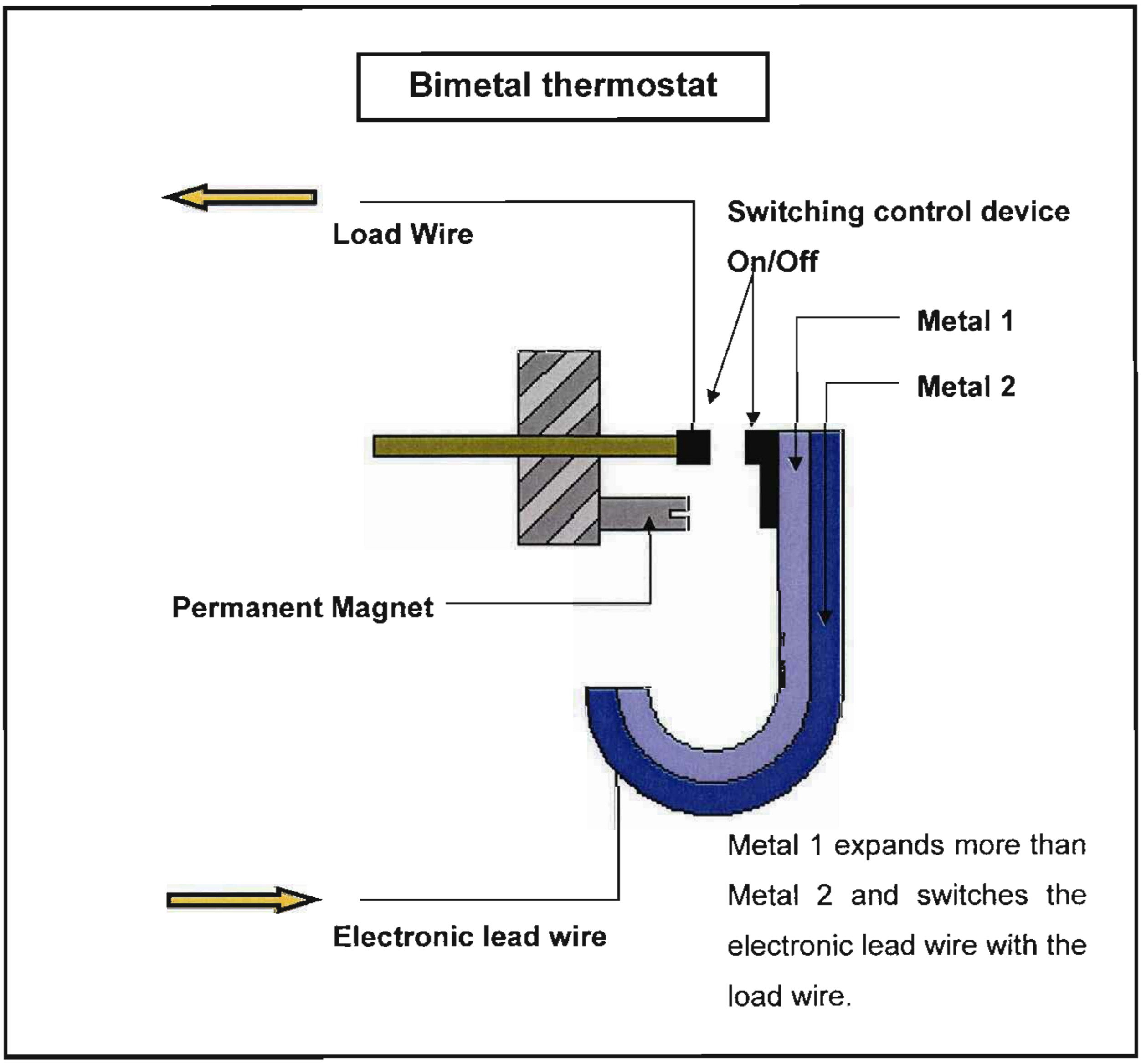
3.3.1.1 Temperature measurement

The most common elements in use are as follows:

a) Bimetal thermostats

A pair of dissimilar metals having different coefficients of linear thermal expansion is joined together. When subjected to the same temperature rise, differential expansion takes place, causing the composite bar to bend. The bimetal bar in turn switches a control device on or off, depending on the temperature.

The temperature range for bimetal thermostats is between 0°C and 400°C with an accuracy of ± 5%. An example of a bimetal thermostat can be seen in the figure below.



Metal 1 expands more than Metal 2 and switches the electronic lead wire with the load wire.

Figure 3.5: Bimetal thermostat.

b) Thermocouples

When two dissimilar metal wires or alloy wires are joined together to form a complete circuit, the junction temperature difference from that of the ends induces an electromotive force (emf). The magnitude of the emf generated is dependent on the types of materials used and the temperature difference between the metal wires and the junction.

If the reference or cold junction is maintained at a constant or known value and the thermocouple characteristics are known, the magnitude of the emf generated will be a measure of the temperature of the junction. The relationship between the generated emf and temperature of the two dissimilar metals can be expressed in the following equation:

$$e = a \times (T_1 - T_2) + b \times (T^2{}_1 - T^2{}_2)$$

It must be noted that the emf generated is non-linear, except over limited ranges as indicated in figure 3.6. Thus, on the steep part of the curve, the relationship can be indicated as per the equation above. T_1 and T_2 are the hot and cold junction temperatures in Kelvin, and (a) and (b) are constants for the given dissimilar materials. The relationship between the temperature and the generated emf for a Cu/Fe thermocouple system is given in figure 3.6 below.

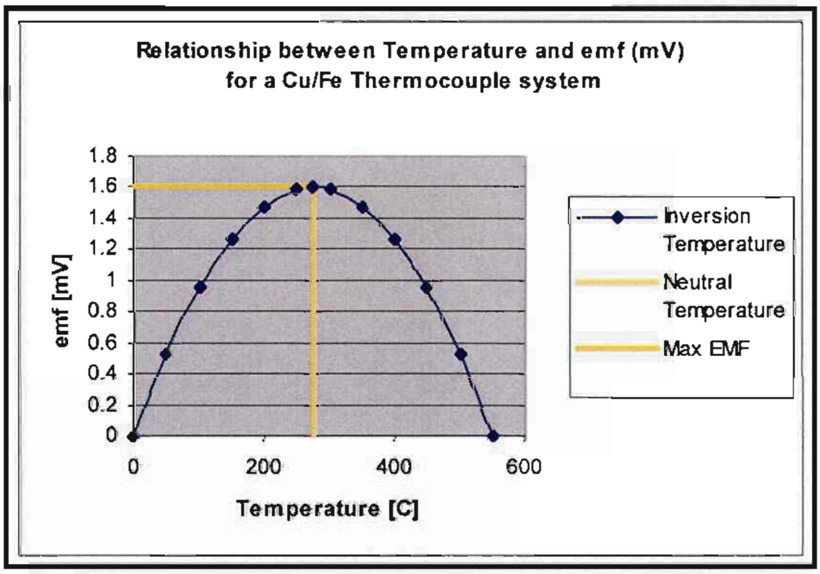


Figure 3.6: Relationship between temperature and emf (V) for a Cu/Fe thermocouple system.

There is a wide range of thermocouples for every application and these can be sub-divided into two categories:

i. **Base metal thermocouples types**

   Type T – Constantan/Copper (range 0 to 400°C)
   Type E – Constantan/Chromel (range 0 to 700°C)
   Type J – Constantan/Iron (range 0 to 850°C)
   Type K – Alumel/Chromel (range 0 to 1100°C)

ii. **Noble metal thermocouples types**

   Type R – Platinum/ Platinum 13% Rhodium (range 0 to 1400°C)
   Platinum 5% Rhodium/Platinum 20% Rhodium (range 0 to 1500°C)
   Tungsten 20% Rhemum/Tungsten (range 0 to 1500°C)

c) Resistance thermometer detectors (RTDs)

RTDs are made of either metal or semi-conductor materials. According to Considine (1993), these resistive materials or elements may be classed as follows:

i. Wire wound. Range –240°C to 260°C, with an accuracy of 0.75%.
ii. Photo etched. Range –200°C to 300°C, with an accuracy of 0.5%.
iii. Thermistor beads. Range 0°C to 400°C, with an accuracy of 0.5%.

RTD temperature sensors have a stable and highly linear resistance versus temperature relationship. RTDs have much higher accuracy, better linearity and stability when compared to thermocouples. However, they have a lower maximum temperature limit and have a slower response time without a thermal well.

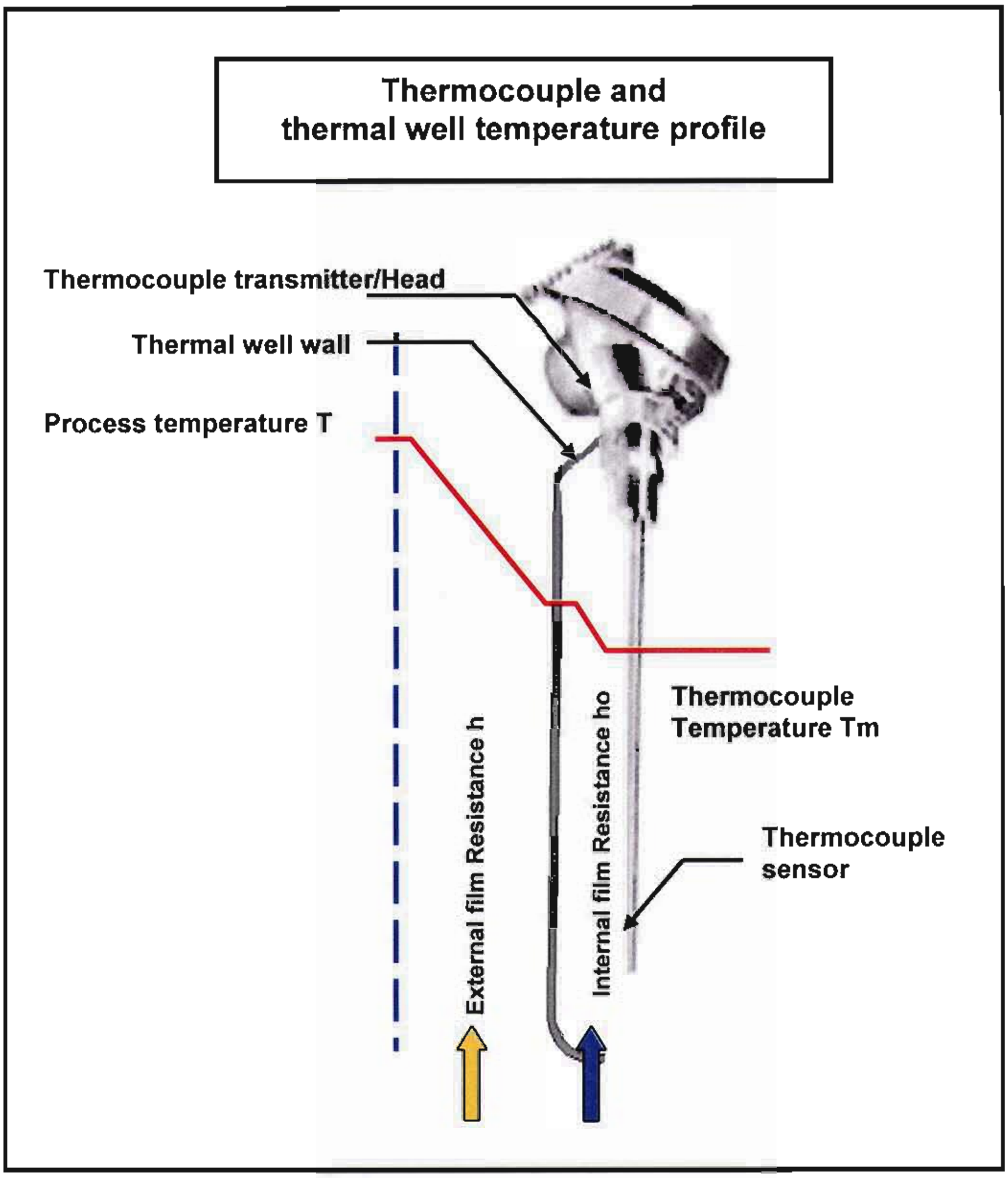


Figure 3.7: Thermocouple and thermal well temperature profile.

As illustrated in figure 3.7, the thermocouple sensor is placed in a protective thermal well. The thermal well is typically made of metal or ceramic, depending on the application and is filled with a conductive material. The thermocouple reading can be illustrated by the following second order system:

$$\tau^2 \cdot \left[\frac{\left(d^2 \cdot Tm\right)}{dt^2} \right] + 2 \cdot \zeta \cdot \tau \cdot \left(\frac{d \cdot Tm}{dt} \right) + Tm = T$$

Where τ is the time constant and can be defined in electrical terms as the product of the resistance and the capacitance

$$\tau = RC$$

ζ is a parameter that is dependent on the construction and material characteristics of the thermocouple.

T is the process temperature and Tm is the temperature that the thermocouple sensor will read.

Every component in the measuring system as shown in figure 3.7 has an associated time constant τ. So each component in the measuring system will increase the measurement lag depending on the size of its time constant. Good practice dictates that all the time constants:

Thermal well wall $\tau_{wall}= R_{wall}C_{wall,}$, thermal well fluid $\tau_{ho} = R_{ho}C_{ho}$ and thermocouple sensor $\tau_{senor} = R_{sensor}C_{sensor}$ should be minimized to achieve a more accurate reading of the actual process temperature.

3.3.2 Controllers

The purpose of the controller in regulatory control is to maintain the controlled variable at a pre-determined set point. The operator determines the set point and inputs the value into the controller. The controller controls the set point by interpreting the feedback from the primary elements and then outputs a corrective action to the final control elements to sustain the set point.

There are various methods of control or algorithms used in controllers in feedback control loops. These control modes include:

- two position control or on/off control;
- proportional control – (P-only);
- integral control – (I-only);
- proportional plus integral control – (PI);
- derivative action – (D);
- proportional plus derivative control –(PD); and
- proportional integral derivate control – (PID).

These control methods are all aimed at improving the control system whereby the offset is reduced or stability enhanced. The form of control chosen must suit the application and must be as simple as possible to achieve the desired results consistently.

The following discussion is intended to give a brief overview of two-position control, proportional control and proportional plus integral control.

3.3.2.1 Two-position control

The most rudimentary form of regulatory control is on/off control. This type of control is primarily intended for use with final control elements that are either switched on or off, i.e. a light switch or basic form of temperature control. An example of a two-position temperature control system can be seen in figure 3.8 below.

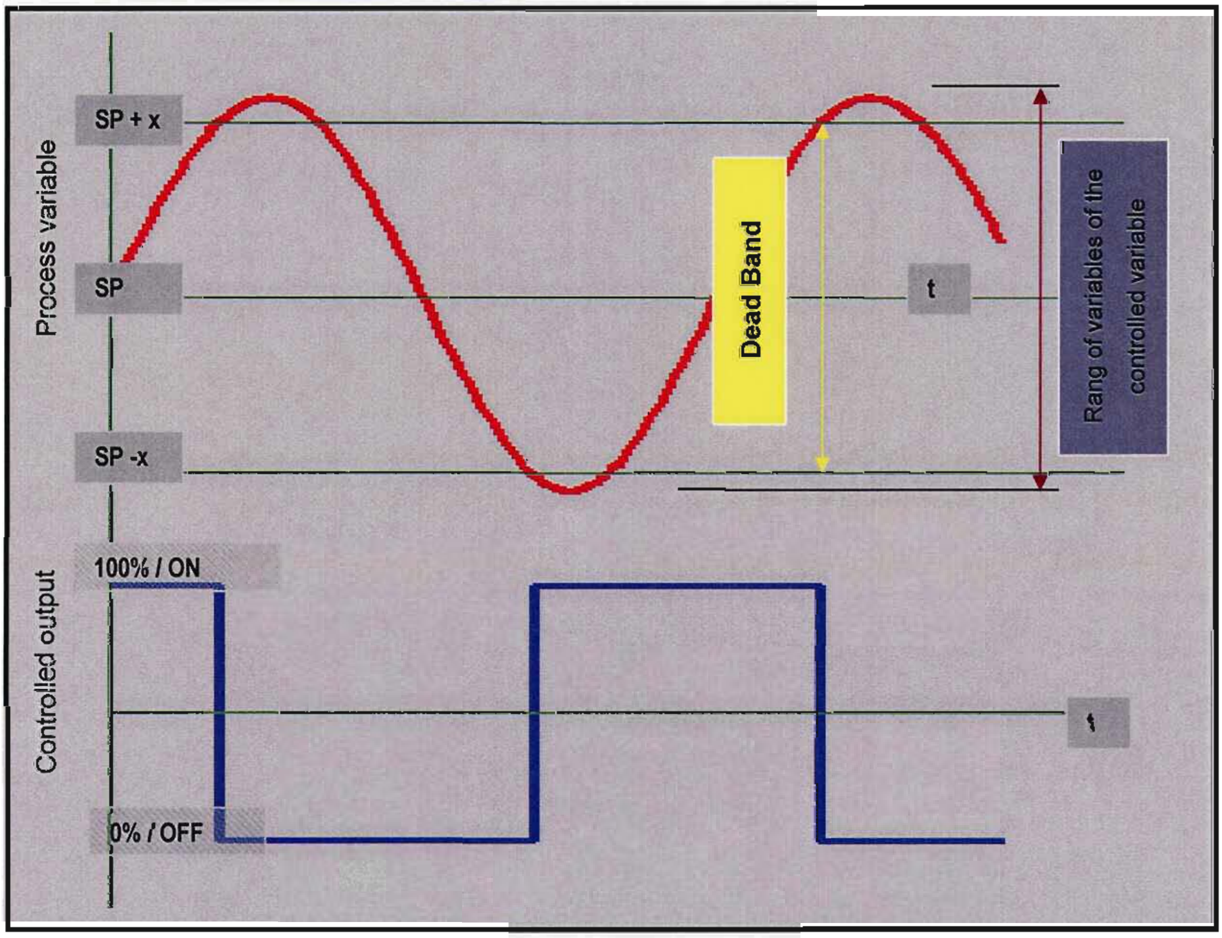


Figure 3.8 Two-position controller response.

Whenever the temperature or process variable (PV) exceeds the dead band or differential gap top limit (SP+x), the controller switches the heating elements off (0%). When the measured temperature or PV reaches the bottom limit of the dead band (SP-x), the heating element switches on (100%). This behaviour is represented by the equation below.

$$\text{Controlled output} = 0\% \text{ for } SP+x < PV$$

and

$$\text{Controlled output} = 100\% \text{ for } SP-x > PV$$

This method of control is a simple and cheap form of control if used in an appropriate application.

3.3.2.2 Proportional control – (P-only)

Proportional control is a continuous control mode that can damp out oscillations in the feedback control loop (Svrcek, Mahoney and Young, 2000). This control mode minimizes the process variable (PV) from hunting around the set point (SP). As an example, consider a liquid level control situation as illustrated in figure 3.9. The liquid level in the container must be maintained at a constant level. This is shown by the equation below.

$$\mathbf{F_{in} = F_{out}}$$

The inflow $\mathbf{F_{in}}$ is equal to the outflow $\mathbf{F_{out}}$ to maintain a constant level. Furthermore

If $\mathbf{F_{out}} > \mathbf{F_{in}}$ then the level will decrease

To rectify the decrease in fluid level, the inflow valve has to be adjusted until $\mathbf{F_{in}}$ is equal to $\mathbf{F_{out}}$ and the level stops dropping. The new steady state level that has been reached in the container is now lower than the initial level. The difference between the initial level and the new steady state level is dependent on how wide the inflow valve was opened to reach the equilibrium state. A similar situation would occur if $\mathbf{F_{out}} < \mathbf{F_{in}}$ but then the level will increase.

The above-mentioned scenario describes what a proportional controller would do if it were connected to the container. The output of a proportional controller will be proportional to the error. The error can be defined as the deviation of measurement between the Controlled Variable (CV) and the Set Point (SP). The Liquid Level Controller (LLC) receives a signal from the level transmitter (LT) and compares it with the set point. It then outputs a manipulated variable (mv) to the final control element, the control valve, to either close the valve or open the valve, depending on the corrective action.

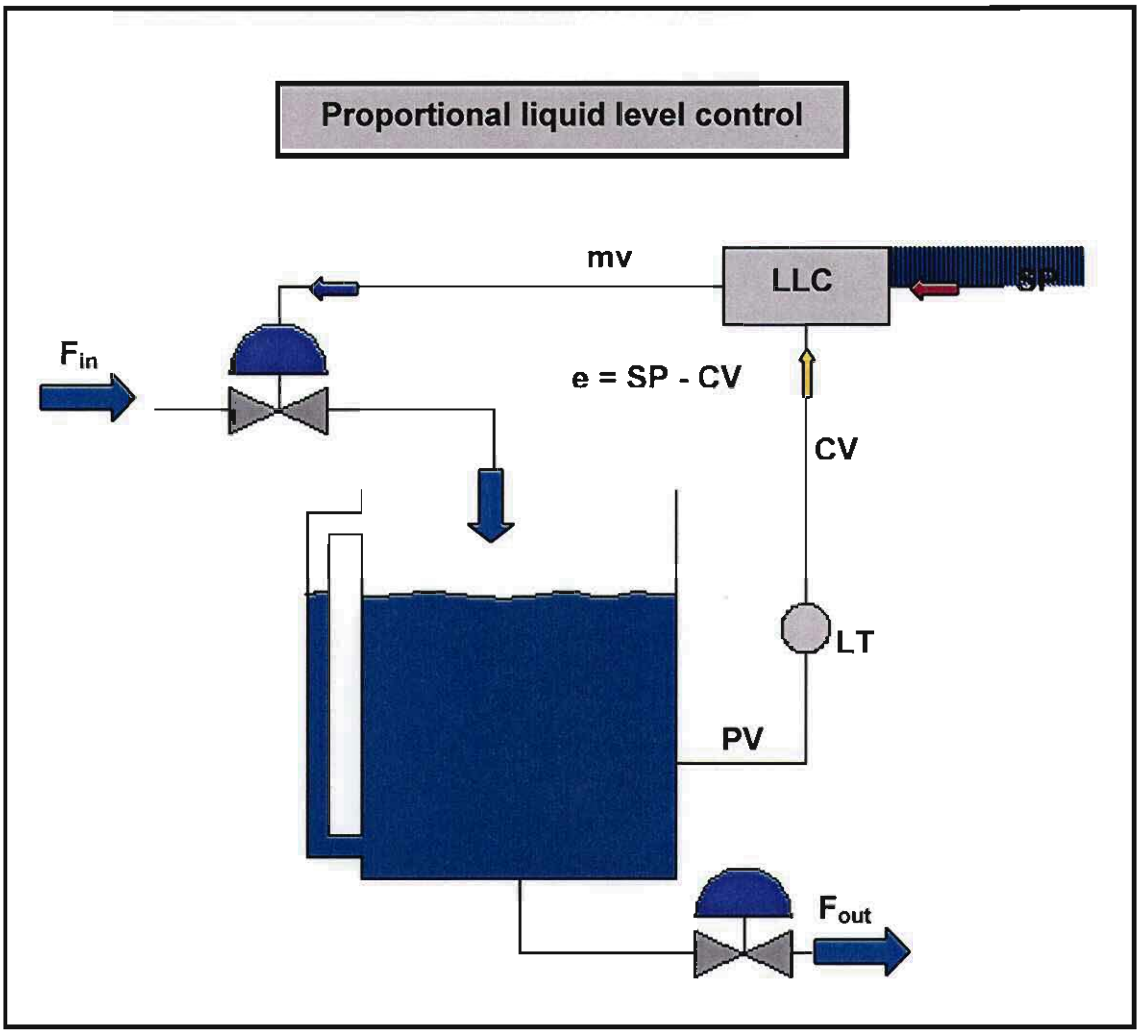


Figure 3.9: Proportional liquid level control.

The manipulated variable (**mv**) signal that is sent to the control valve can be expressed by the following equation.

$$\mathbf{mv} = K_c\, e$$

Where K_c is the controller gain and e is the error. The error can be expressed as:

$$\mathbf{E = SP - CV}$$

$$\mathbf{e = CV - SP}$$

To allegorise proportional control we will use the liquid level loop indicated in Figure 3.9. Let us assume the proportional controller is placed in manual mode and the level in the container is manually adjusted to equal the set point. With

$$\mathbf{F_{in} = F_{out} = 50\%}$$
$$\mathbf{CV = SP = 50\%}$$

and

$$\mathbf{K_c = 2}$$

When the controller is placed on auto mode the error will be zero because

$$\mathbf{e = SP - CV}$$
$$= (50\text{-}50)$$

and **mv** will therefore also be zero. The control valve will receive a zero signal and will not start opening or closing to regulate the level. The level in the container will begin to drop because $\mathbf{F_{in} < F_{out}}$. To stop this movement $\mathbf{F_{in}}$ and $\mathbf{F_{out}}$ must equal 50% again. If a linear relationship is assumed between $\mathbf{F_{in}}$ and controller output **mv**, then $\mathbf{F_{in}}$ = 50% and **mv**= 50%.

If **mv** = 50% and controller gain $\mathbf{K_c}$=2 then **e** =25% and **CV** = 25%

Thus the controller output becomes 50% when the measurement form the level transmitter, **CV**, drops by 25%, creating a 25% error. The proportional controller created a large enough error so that the controller could make

$\mathbf{F_{in} = F_{out}}$ It must be noted that the new steady state level does not return to the initial set point. This sustained error is called the offset and by combining proportional control with one of the other control modes, this offset can be eliminated. Such a combination is termed “compound control action”.

3.3.2.3 Proportional plus integral control – (PI control)

A proportional plus integral controller will give a response period longer than a P-only controller but a much faster response than an I-only controller (Svrcek, Mahoney and Young, 2000).

The equation for a PI controller is as follows.

$$mv = K_c \cdot e + \frac{K_c}{T_i} \int e \, dt$$

The PI controller gain has an effect on the error as seen previously, but also on the integral action.
This is illustrated in the equation below with

$$mv = \underbrace{K_c \cdot e}_{\textbf{Proportional action}} + \underbrace{\frac{K_c}{T_i} \int e \, dt}_{\textbf{Integral action}}$$

Integral action provides a bias that is automatically adjusted to eliminate any error. The bias is simply defined as the output of the controller when the error is zero. If we revisit the liquid level control example, we remember that when the level in the container was manually adjusted to equal the set point. With

$$\mathbf{F_{in} = F_{out} = 50\%}$$
$$\mathbf{CV = SP = 50\%}$$

and

$$\mathbf{K_c = 2}$$

the controller was then placed on auto mode and the error was zero because

$$\mathbf{e = SP - CV}$$
$$= (50-50)$$

and the output **mv** was also zero to the control valve. The control valve received a zero signal and did not start opening or closing to regulate the level and then the level dropped in the container because $\mathbf{F_{In} < F_{out}}$. The bias portion of the PI controller action equation assures that the control valve will never receive a zero signal even if the error is zero. This results in the liquid level being maintained on the original set point level in the container.

Luyben (1990) stated two fundamental laws for process control

- The simplest control system will work best.
- The process must be understood before it can be controlled.

It was previously mentioned that these control methods are all aimed at improvement of the control system, whereby the offset is reduced or stability enhanced. The form of control chosen must suit the application and must be as simple as possible to achieve the desired results consistently.

The following figure is intended to give a brief overview and a comparison of the different control modes that can be applied to achieve the desired output.

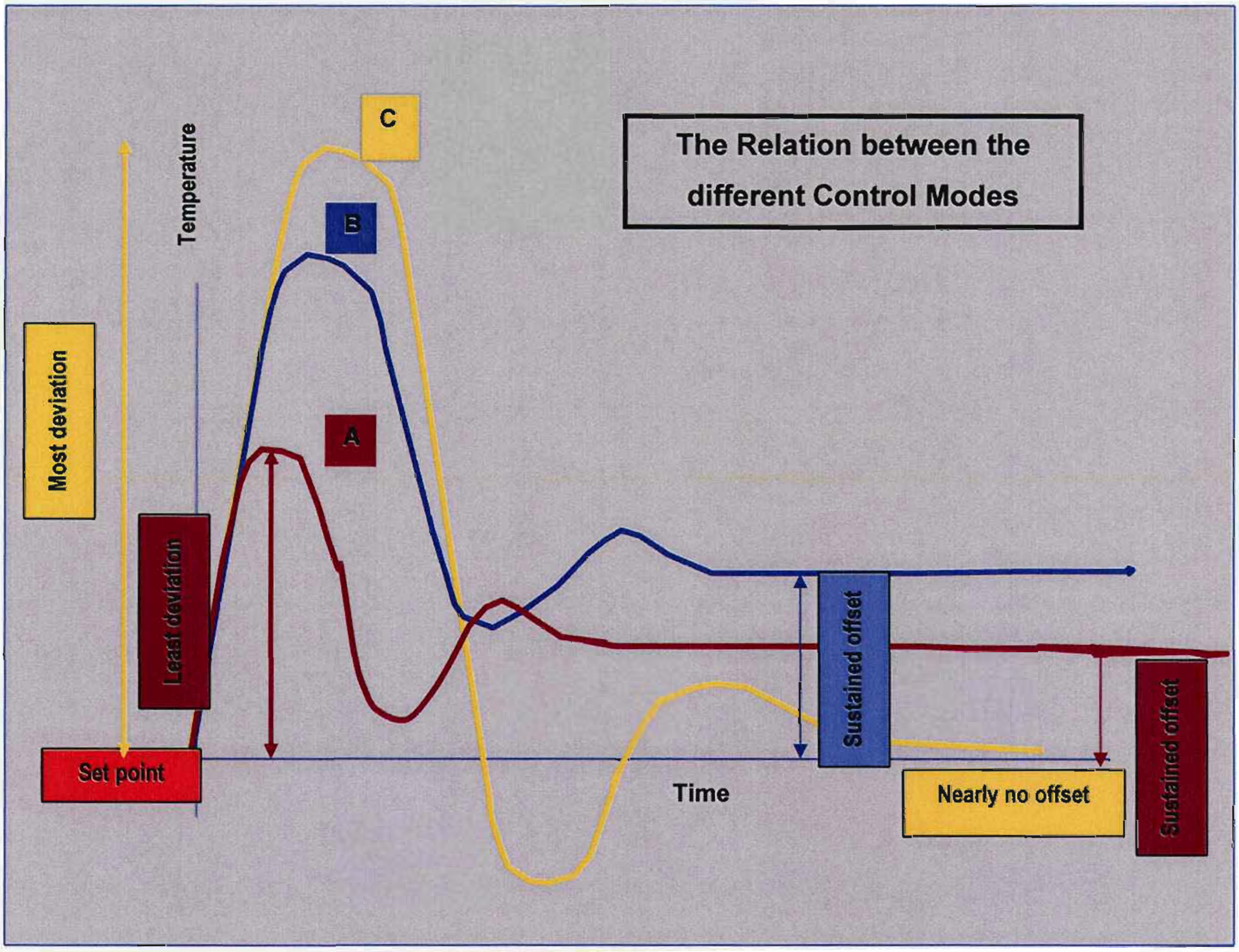


Figure 3.10: The performance of different control modes with respect to time.

Curve A is an example of proportional plus derivative action. The curve reaches a steady state quite rapidly but a sustained deviation is evident.

Curve B shows the case of proportional control. The curve has a larger initial deviation and the final offset is greater than curve A.

Curve C shows the case of proportional control with integral action. The maximum initial deviation is much greater than for Curves A and B, but the value of the Controlled Variable (CV) oscillates for some time before it settles to a steady state value close to the set point and in some cases no offset.

Proportional plus derivative plus integral action was not discussed in previous sections, but the behaviour of PID control will be very similar to Curve A and C except for the CV settling down quicker than for curves A and C. There will also be no offset from the set point after the steady state condition is reached.

3.3.3 Final control elements

A final control element can be termed as a device that receives instructions from a controller and changes the state of the control system to achieve or sustain the desired set point.

In the extrusion process there are many final control elements that can be incorporated to control the system. These final control elements may include:

- variable speed drive coupled to a motor;
- metering pumps; and
- heating elements.

A Variable Speed Drive (VSDs) can be defined as an electronic device used to control a motor to give variable rotational speed control. Standard motors are essentially constant speed devices when operated from the mains power supply (220V AC, 380V AC, 525V AC). A VSD has multiple parameters that are pre-set to manipulate and limit the control of the connected motor. Some of these parameter settings include:

- Ramp-up and ramp-down functions. This parameter regulates the amount of time that it takes for the motor to operate form the minimum allowable rotational speed to the desired rotational speed.
- Maximum allowable motor current that the motor may draw during operation.

- Maximum and minimum rotational speed.

An electronic variable speed drive provides a variable voltage and frequency supply that enables the motor speed and current to be precisely controlled. VSDs may also be termed as adjustable speed drives, Inverters or Frequency Converters.

Metering pumps are positive displacement pumps and are generally used to dose or meter precise quantities of fluid into a system. They are widely used in the extrusion industry for dosing water, colourants, etc.
The implementation, function and control of the final control elements implemented in the project will be discussed in the following chapter.

3.4 Controller hardware

The controller element of the control system can be divided into three main categories.

- Single functional stand-alone controller. This controller for example only controls the temperature of a system and works independently from the system.
- Multi-functional central controller with input and output (I/O) modules.
- Multi-functional central controller with a network of sub-controllers complete with I/O modules.

The following illustration is an example of a multi-functional central controller with remote I/O modules.

The operator inputs the set point from an input device, for example a touch panel or keyboard. The information is then transferred to the central processing unit. Information from the input modules, gathered from the primary elements in the process is also transferred to the central processing unit. The information is then processed and outputted to the output modules.
The I/O modules can be sub-divided in to two categories.

- Analogue I/O modules.
- Digital I/O modules.

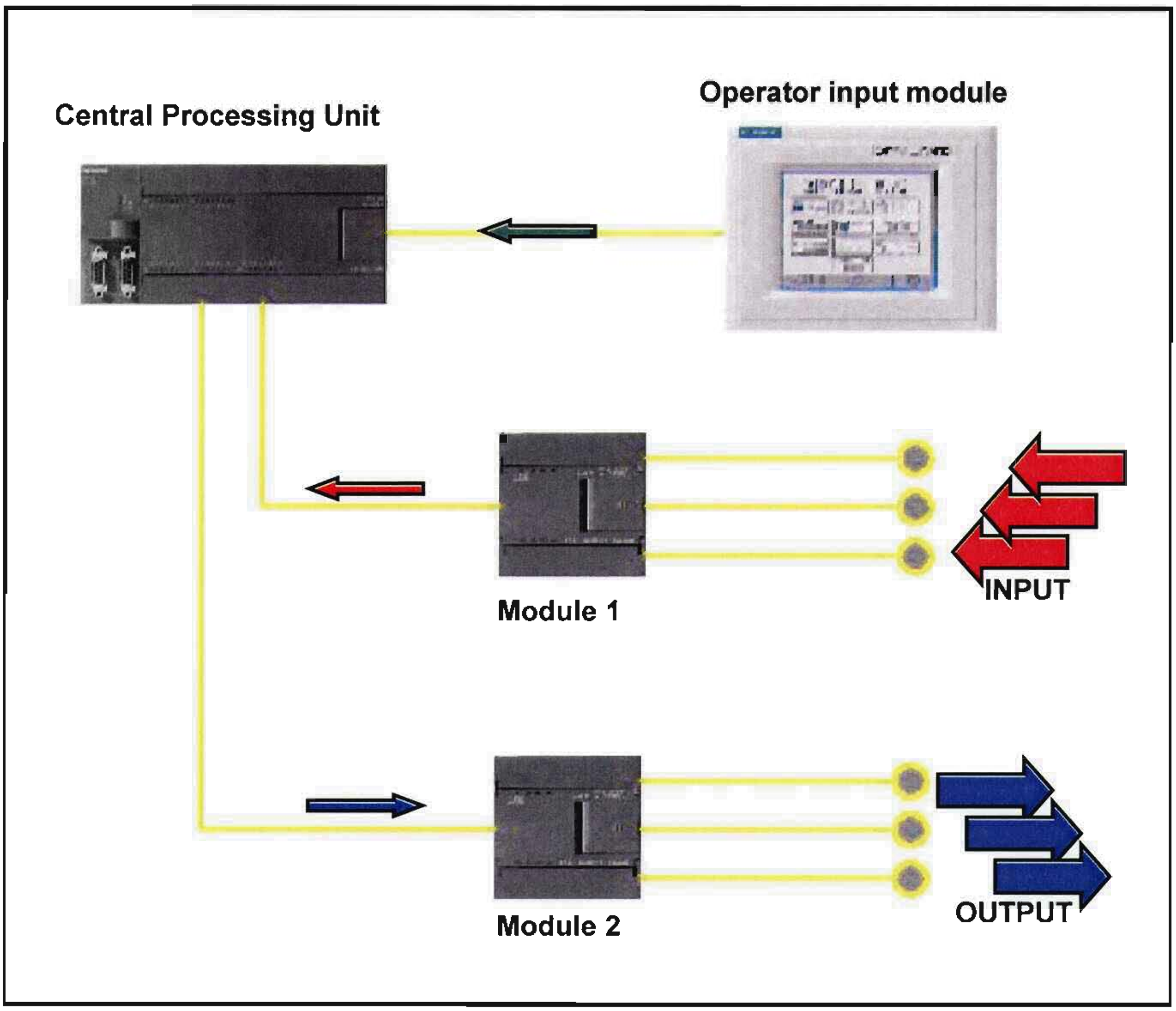


Figure 3.11: Diagrammatic representation of the arrangement for a multi-functional central controller with I/O modules.

Analogue I/O modules can send or receive analogue signals. These signals are usually based on a 0 to 10V signal or 4 to 20mA signal, depending on the application.

A digital I/O module sends or receives digital signals. These signals can only be a 0 or a 1, or rather on and off signals.

The output module receives information from the central processing unit, converts the signal into digital or analogue signals, and then outputs the converted signal to the final control elements. The input will receive analogue or digital information from the primary element, converts the signal, and then outputs the converted signal to the central processing unit.

3.5 Programmable Logic Controller (PLC)

The Programmable Logic Controller is a multi-functional controller complete with processing unit and add-on (I/O) modules. The PLC processing unit is fully programmable to operate an entire system or process. The operating program is written in a special PLC language using a graphical user interface designed especially for PLC programming. The program is then uploaded to the PLC, were the controller interprets the code and responds accordingly via the I/O modules.

In the present research a Programmable Logic Controller with I/O modules was used for the effective control of the extruder. The PLC implementation, control system layout and programming used in the project will be discussed in the following chapter.

3.6 Conclusions

- A control system consists of interconnecting components that can be divided into measurement elements, controllers and final control elements.
- There are various control modes that can be implemented to improve the control system, reduce offset and enhance stability.
- The method of control must suit the application and must be as simple as possible to achieve the desired results consistently.
- The process must be understood before it can be controlled.
- The control system must be reliable and effective.

4 Chapter 4: Implementation of an effective PLC Control System for a twin-screw food extruder

4.1 Introduction

In the preceding chapters the types of extruders on the market today were discussed and the different components of the extrusion process of a co-rotating twin-screw food extruder. Furthermore, the different variables involved in the process were discussed and the important role of control in the process. Chapter 3 addressed the elements of a control system and the control hardware. The implementation of an effective PLC control system of the twin-screw food extruder that was designed and constructed during this project will be addressed in the remainder of this chapter.

The complete extruder arrangement of the actual extruder that was designed and constructed by engineers of North-West University can be seen in figure 4.1.

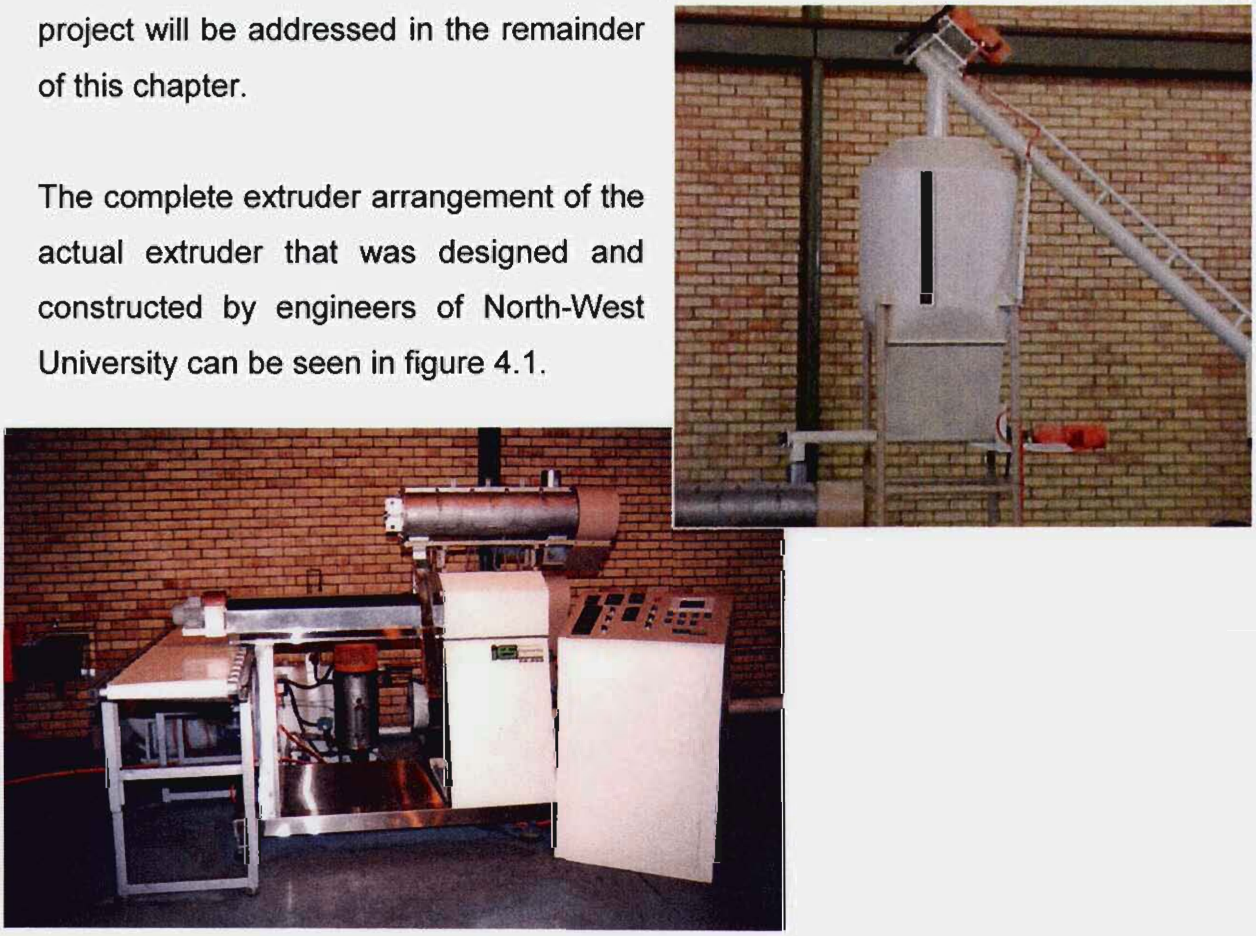


Figure 4.1: Complete extruder arrangement.

Each component of the extrusion process will be discussed in terms of its function, design and implementation into the control system. These components include:

- Hopper, complete with variable feeding screw, air valve and screw conveyor (Auger);
- Pre-conditioner; and
- Extruder assembly, complete with co-rotating screws, gearbox, die and cutter assembly, thermocouples, heating elements and dosing pump.

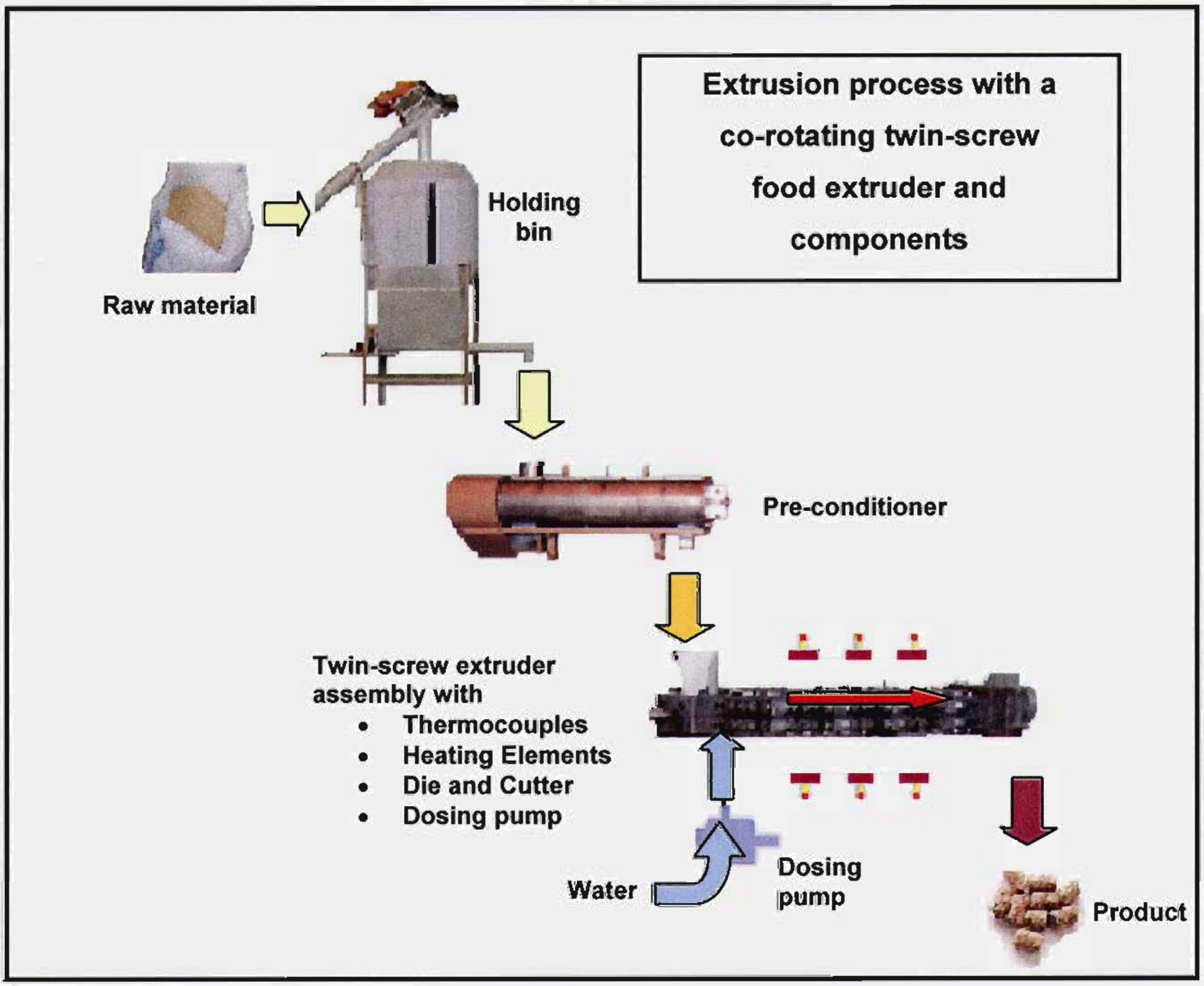


Figure 4.2: Extrusion process and equipment.

Raw pre-mixed material is pumped via a screw conveyor (Auger) into a hopper or holding bin. During the extrusion process the raw material is pumped out of the holding bin via a variable speed screw feeder. The material passes through the pre-conditioner into the twin-screw food extruder, where the material is kneaded, cooked and extruded through the die. The product is then cut into desired lengths.

4.2 Components of the extrusion process

4.2.1 The Holding bin

Co-rotating extruders are normally starve-fed, meaning that the conveying capacity of the extruder exceeds the rate at which the material is fed into it. The first important factor in the extrusion operation is the stable, consistent introduction of raw material into the extruder (Frame, 1994).

A holding bin provides a buffer of raw material at the inlet so that the extruder can operate continuously. The bin must be able to handle a sufficient amount of raw material and also be designed to discharge raw material at a consistent flow rate.

The layout of the holding bin can be seen in the figure below. The raw material is fed into the holding bin via a screw conveyor or Auger. The Auger is designed in such a manner that the bin can rapidly be filled to ensure a continuous buffer of raw material. The bin has a holding capacity of 350kg raw material where the extruder has a production rate of 250kg/h. This ensures that the bin only needs to be filled every hour. The bin is also designed with an inspection window so that the operator can see when the bin is starting to run empty and start the Auger when necessary.

In the bottom of the bin, a variable screw feeder is installed to ensure that the raw material is fed into the pre-conditioner at any desirable rate.

An air valve was installed inside the bin just above the screw feeder. The valve was connected to a 10 bar compressor and discharged compressed air into the bin at intermediate rates, controlled by the PLC system to prevent rat-holing and the formation of tunnels.

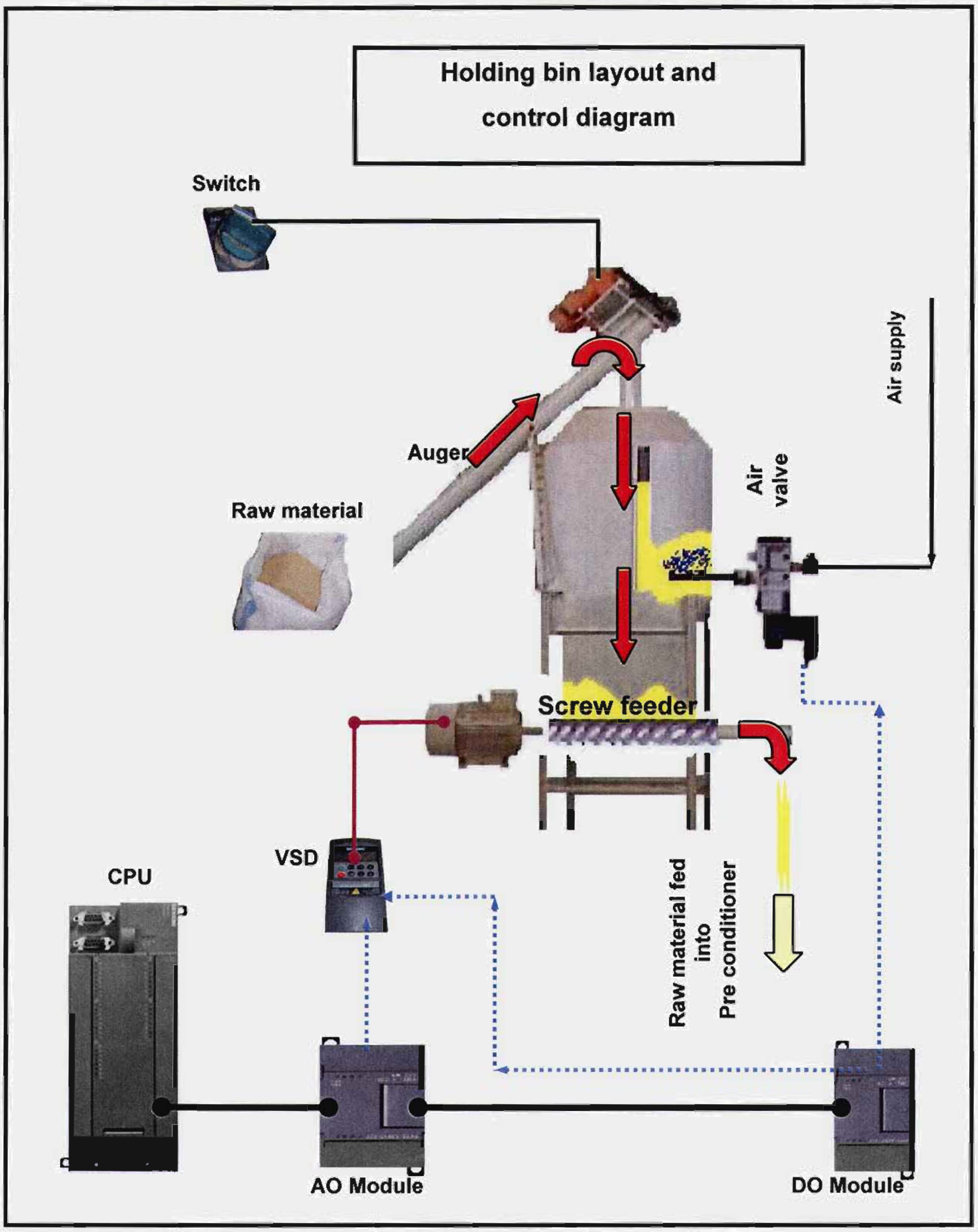


Figure 4.3: Holding-bin layout and control diagram.

4.2.1.1 Holding bin control-philosophy

The Auger is controlled with a switch situated on the control panel where the operator can manually switch the Auger on or off whenever it is necessary to feed raw material into the bin.

The screw feeder is controlled via the PLC operating system where the operator inputs the predefined set point in the control system. The set point value is sent from the touch panel to the (CPU) central processing unit. The processor instructs the analogue output module to send a signal to the variable speed drive (VSD) to increment or decrement the frequency of the motor. A 0.7 kW electrical motor drives the screw feeder.

When the frequency is incremented, raw material is fed faster into the pre-conditioner and the opposite when the frequency is decremented on the touch panel. The motor will only respond once the operator inputs a set point and switches the motor into the start or on position. This is done on the touch screen that, in turn, sends the signal to the processor and the processor sends the signal to the Digital Output (DO) module. The DO module sends an on signal to the VSD to start the motor.

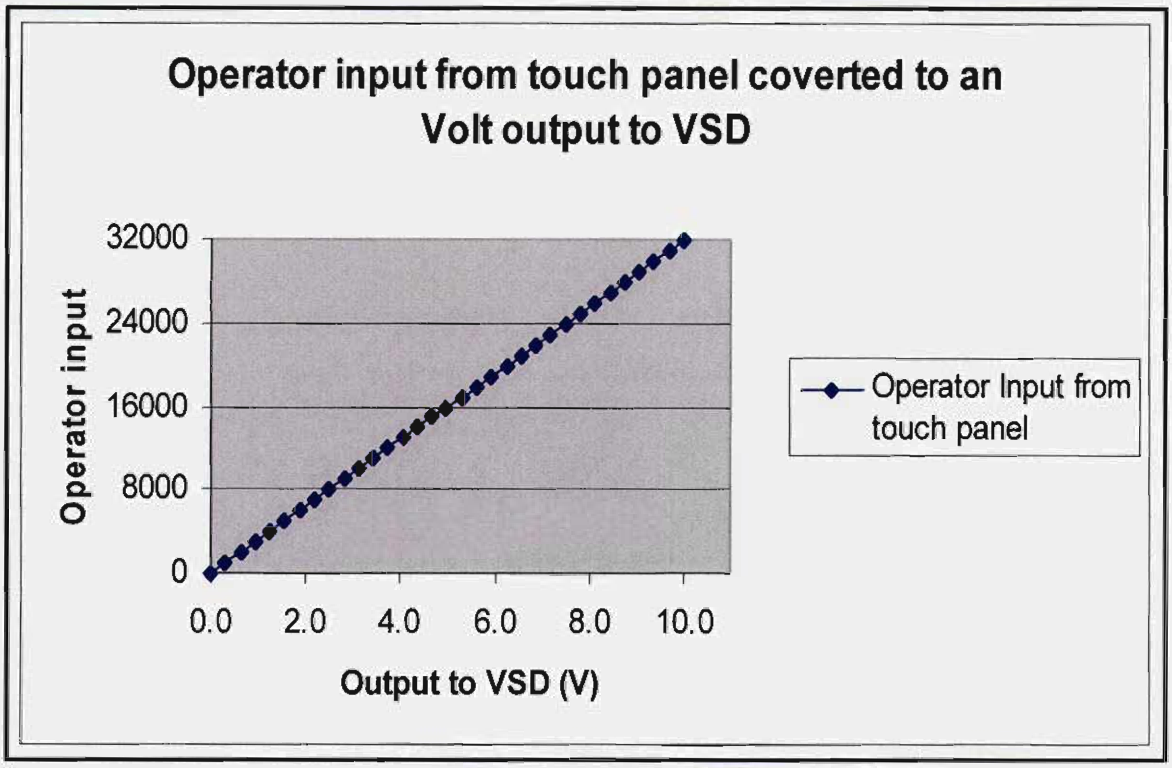


Figure 4.4: Operator input into control system and volt output to VSD.

The signal converted by the AO Module and output to the VSD is illustrated in the figure above. The operator inputs a value between 0 and 32000 from the touch panel and then the AO module receives this signal from the processing unit. The AO module then converts the signal into a volt output for the VSD to interoperate and act accordingly to the instruction.

The pneumatic valve is independently operated by the PLC. As previously discussed, the valve is connected to an air supply and opens and closes at intermediate intervals. A timer programmed into the PLC sends a signal to a digital output module to open or close the valve.

4.2.2 Pre-conditioner

Conditioning of raw materials prior to entry into the extruder is often employed to accomplish modifications to pH, hydration, colour and flavours, as well as application of heat (Frame, 1994).

The benefits of pre-conditioning have been recognised to be fourfold. Firstly, in the area of extruder life, the life of wear components in the extruder barrel will be increased several times. Secondly, the capacity will increase the throughput of the extruder. Pre-conditioning will also assist in altering product textures and functionality. Un-preconditioned raw materials are generally crystalline or glassy amorphous materials. Research has also shown that adding pre-conditioning to the extrusion process enhances product flavour (Riaz, 2000).

The pre-conditioner is mounted between the holding bin and the extruder barrel. The feeding bin provides a consistent flow of raw material into the pre-conditioner. At the discharge of the pre-conditioner, a diverting chute allows the operator either to bypass the material into a waste bin or to direct it into the extruder. This assists the operator to control the process and to ensure that a steady state process is achieved before the material is diverted into the extruder. The figure below is an illustration of the pre-conditioner and control diagram.

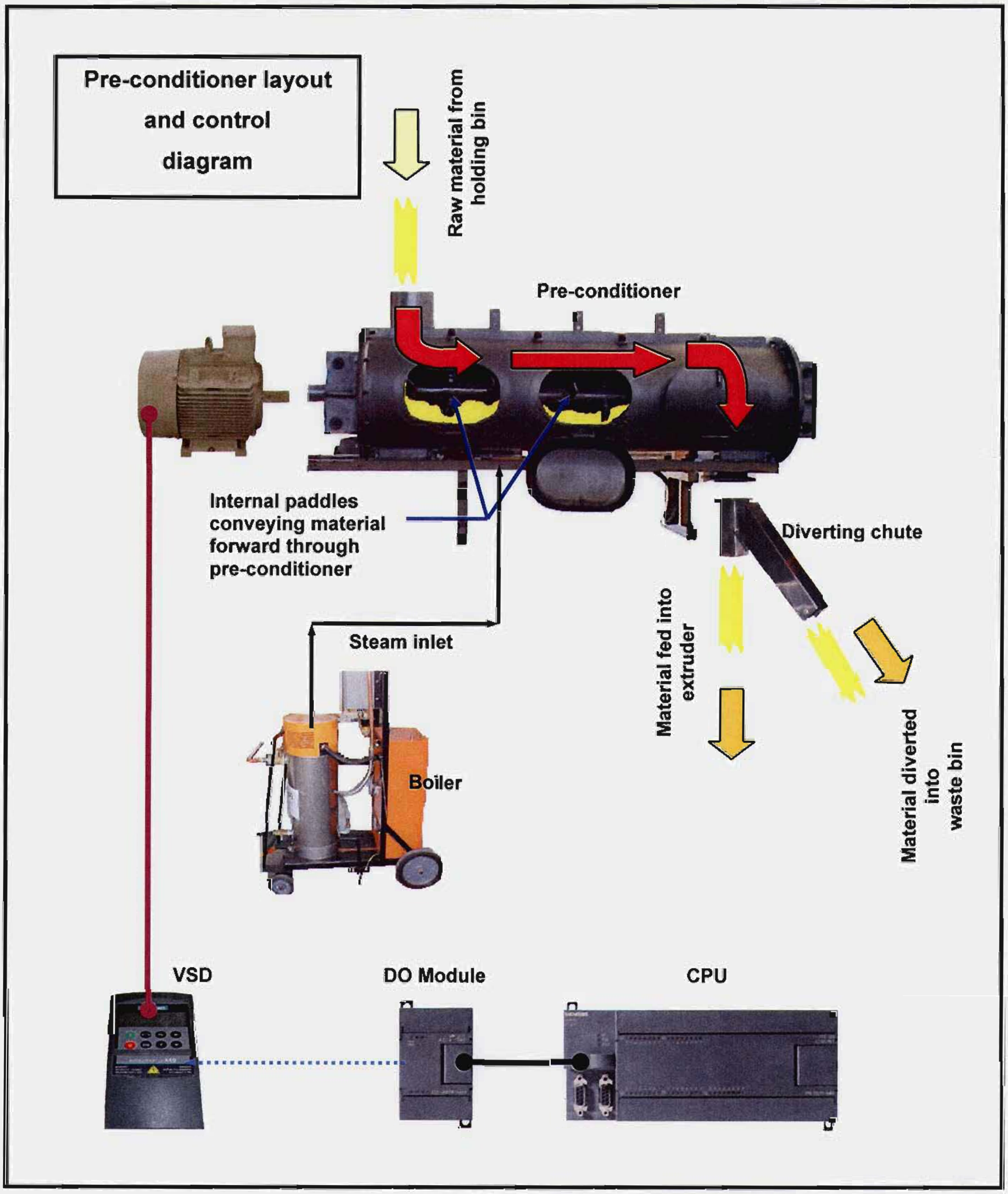


Figure 4.5: Pre-conditioner layout and control diagram.

The pre-conditioner consists of a figure-eight-like barrel with two parallel shafts. The shafts are fitted with adjustable paddles (Figure 4.6).

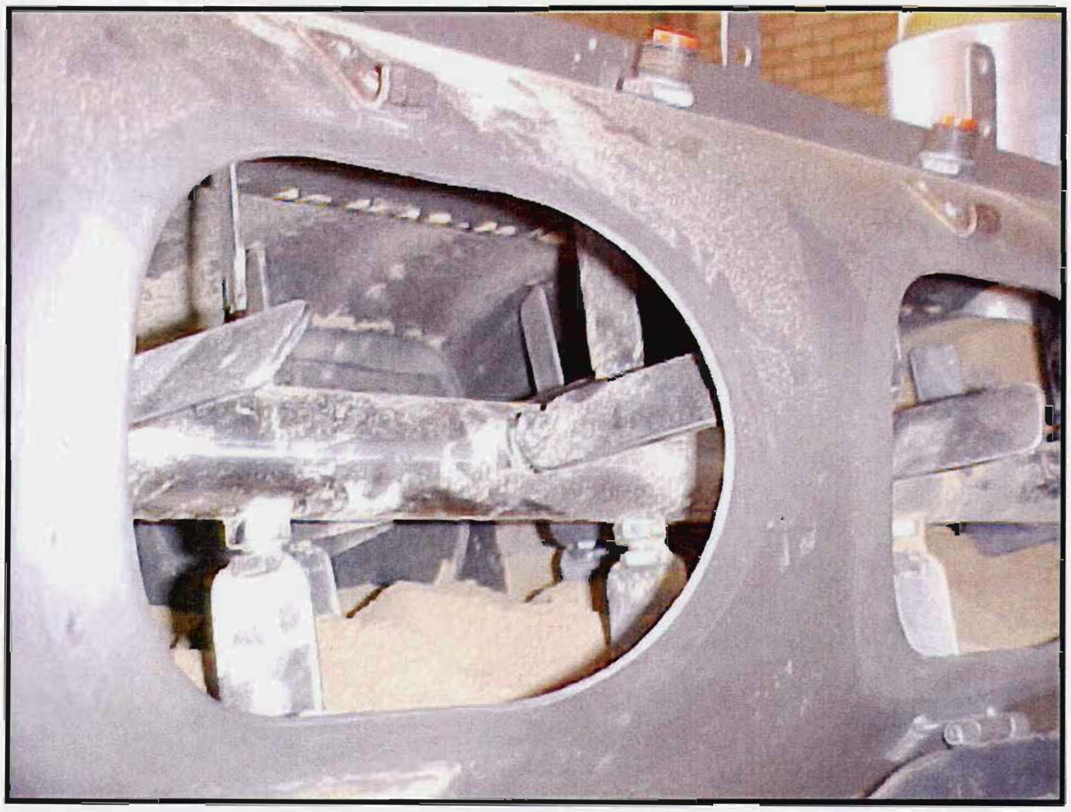


Figure 4.6: Adjustable paddles and inspection hatches on the pre-conditioner unit.

The paddles are configured to convey the material forward through the pre-conditioner. The pre-set angles of the paddles maximise the dispersion and retention time of the material in the barrel. Retention time varies from 20-240 seconds. The paddles should be adjusted to ensure proper mixing.

The raw material enters the pre-conditioner at the top and discharges into a diverting chute. Before the material is fed into the extruder, it is crucial to ensure that the consistent flow of material is reached. The operator switches the diverting chute to discharge into a waste bin. After a steady state flow is reached, the operator can divert the material into the extruder.

The pre-conditioner is also connected to a boiler, which discharges steam into the barrel. The steam is injected at the bottom of the barrel and water is added at the top. As previously discussed, the water creates a greater heat sink to absorb more energy from the steam, and therefore a greater quantity of steam can be added (Strahm, 2000). The water/steam ratio can be seen in the figure below.

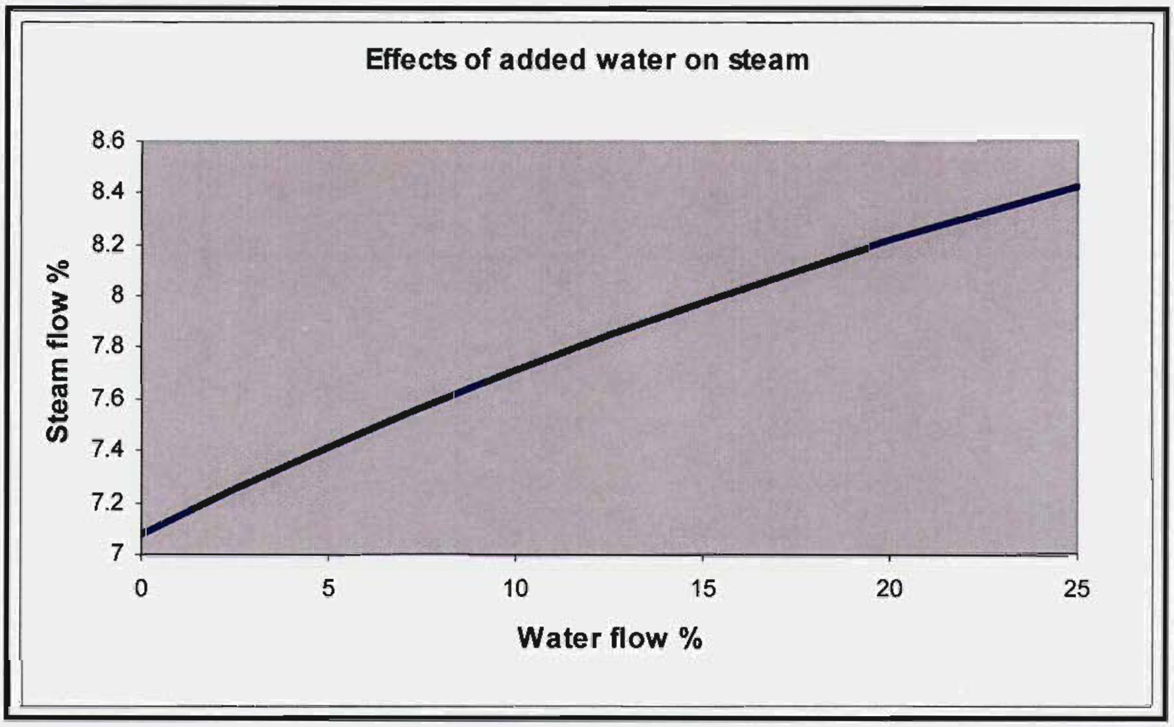


Figure 4.7: Effects of added water on steam to reach maximum temperature.

The addition of steam and water in the pre-conditioner increases the preliminary temperature of the material before the extrusion process and therefore increases the throughput through the extruder.

Figure 4.8: Example of a locally manufactured low pressure steam boiler.

For the purpose of this study the use of the boiler and the addition of water were not necessary for the specific extrusion process followed.

The pre-conditioner also has six inspection hatches to ensure easy access for cleaning purposes. The pre-conditioner requires cleaning every 5-7 days due to a thick layer of material that collects on the paddles.

4.2.2.1 Pre-conditioner control-philosophy

A 5.5kW motor drives the pre-conditioner. The motor is connected to a VSD and PLC configuration. The pre-conditioner is operated at a constant speed and therefore the operator only switches the pre-conditioner on or off from the touch panel. The DO module shown in Figure 4.5 switches the VSD in the on position and allows the motor to start. The VSD is pre-programmed to ramp the motor up to the desired rpm. Once the pre-conditioner is running, the raw material is fed from the holding bin into the pre-conditioner. It must be noted that when the raw material is fed into the pre-conditioner, it takes a while for the raw material to flow at a steady rate. The operator must ensure that the flow rate is steady and consistent before the material is fed into the extruder.

The boiler and water feed is manually operated and tested during a test run.

4.2.3 Extruder assembly

The extruder assembly consists of different components, which include:

- gearbox;
- dosing pump;
- barrel and screws;
- heating elements;
- J type thermocouples; and
- die and cutter.

The extruder assembly components and control diagram is illustrated in the following figure.

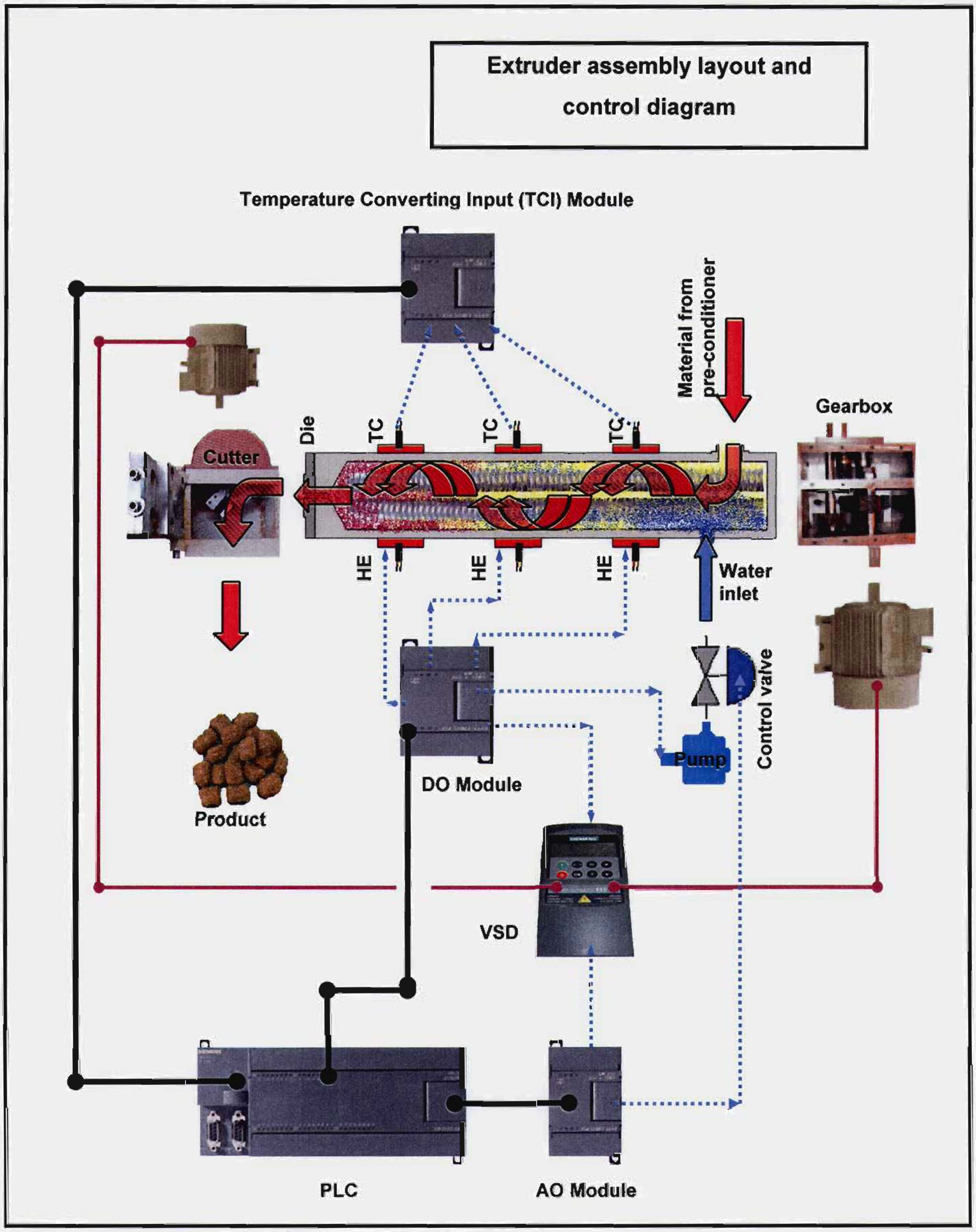


Figure 4.9: Extruder assembly and control diagram.

The material from the pre-conditioner enters the extruder barrel at the feeding port and is conveyed forward by two co-rotating screws driven by a reduction gearbox. During the conveying process, water is injected into the barrel and mixed with the material. The Heating Elements (HE) cook the conveying material while the thermocouples (TC) monitor the pre-defined set temperature for the process. Once the cooked material reaches the front of the extruder barrel, the screws force the material through a die into predefined shapes where the extruded product is then cut into desired lengths. The product can then be transferred for final processing where the product is dried, coated with colourants or packaged, depending on the process.

During the extrusion process, the operator continuously monitors the final product and alters the set parameters to achieve desired quality. These parameters include for example:

- raw material feed rate into the extruder;
- extruder screw speed;
- barrel temperature;
- water injection; and
- cutter speed.

The following section is intended to give a brief overview of the extruder assembly components concerning function and control-philosophy in the extruding process.

4.2.3.1 Gearbox

The gearbox is driven by a 32 kW AC electrical motor and consists of a drive shaft (input shaft) and two smaller co-rotating output shafts. The gearbox has a 3:1 reduction that ensures that the output shafts rotate at one third of the input shaft rpm with a maximum power output of 15kW per shaft (du Toit, 2000). The 32kW motor is governed via the connected VSD to output a maximum of 20 kW so that the gearbox can be operated continuously at 2/3 of the maximum allowable power output. The gearbox has an efficiency of 85% and a maximum operating power output per shaft of 8.5 kW.

The reduction gearbox output shafts are connected to the extruder screws located inside the extruder barrel. The following figure is an illustration of the layout of the reduction gearbox.

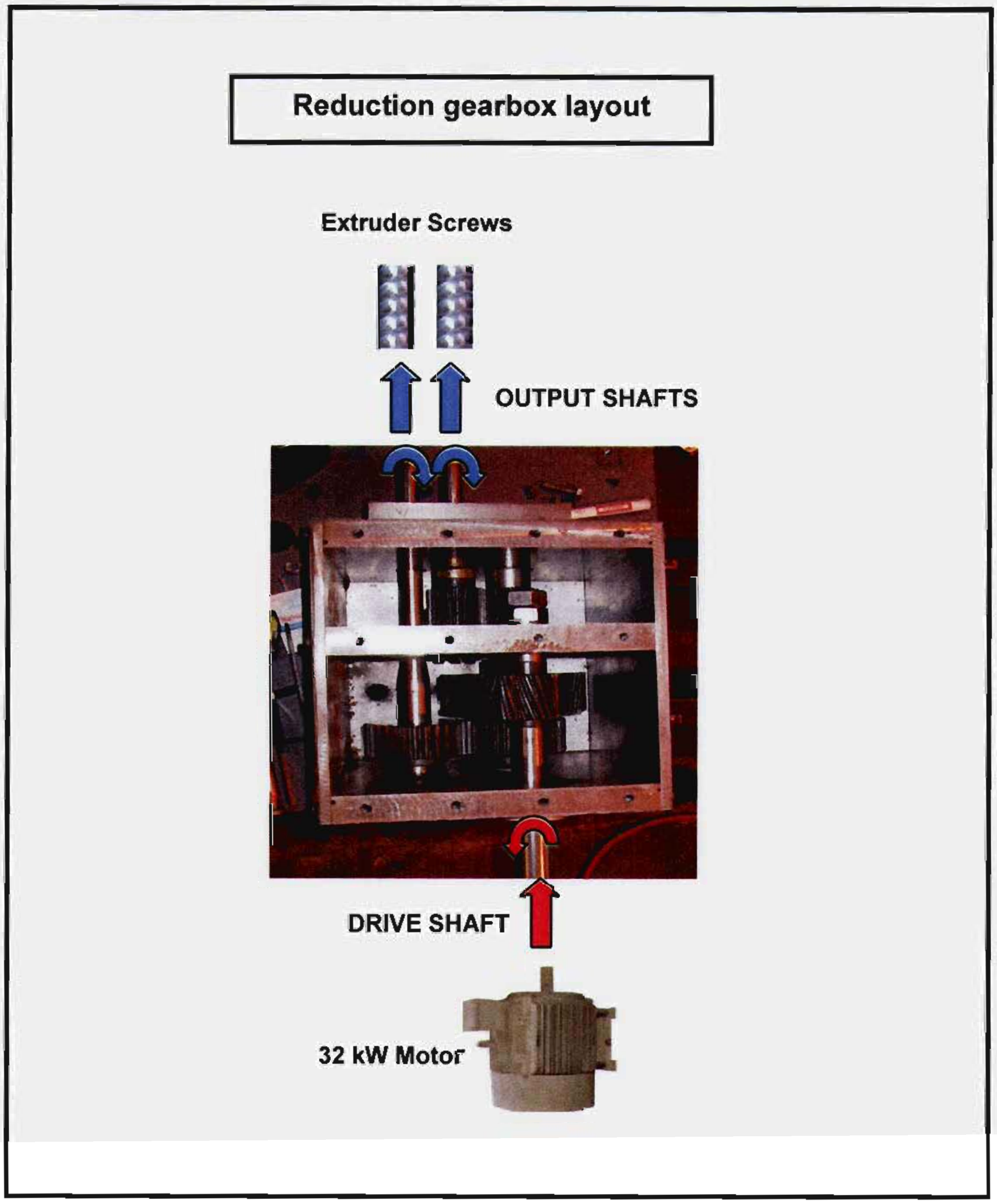


Figure 4.10: Reduction gearbox layout.

The mechanical energy input calculations from the extruder motor and gearbox can be seen in ***Appendix D.***

4.2.3.2 Barrel and screws

The barrel of an extruder is the pipe-like retainer in which the screws run. As material is fed into the extruder through the feed port, the two intermeshing screws convey the material forward through the barrel.

The barrel consists of segments that are bolted together to form this pipe-like retainer as seen in the following figure.

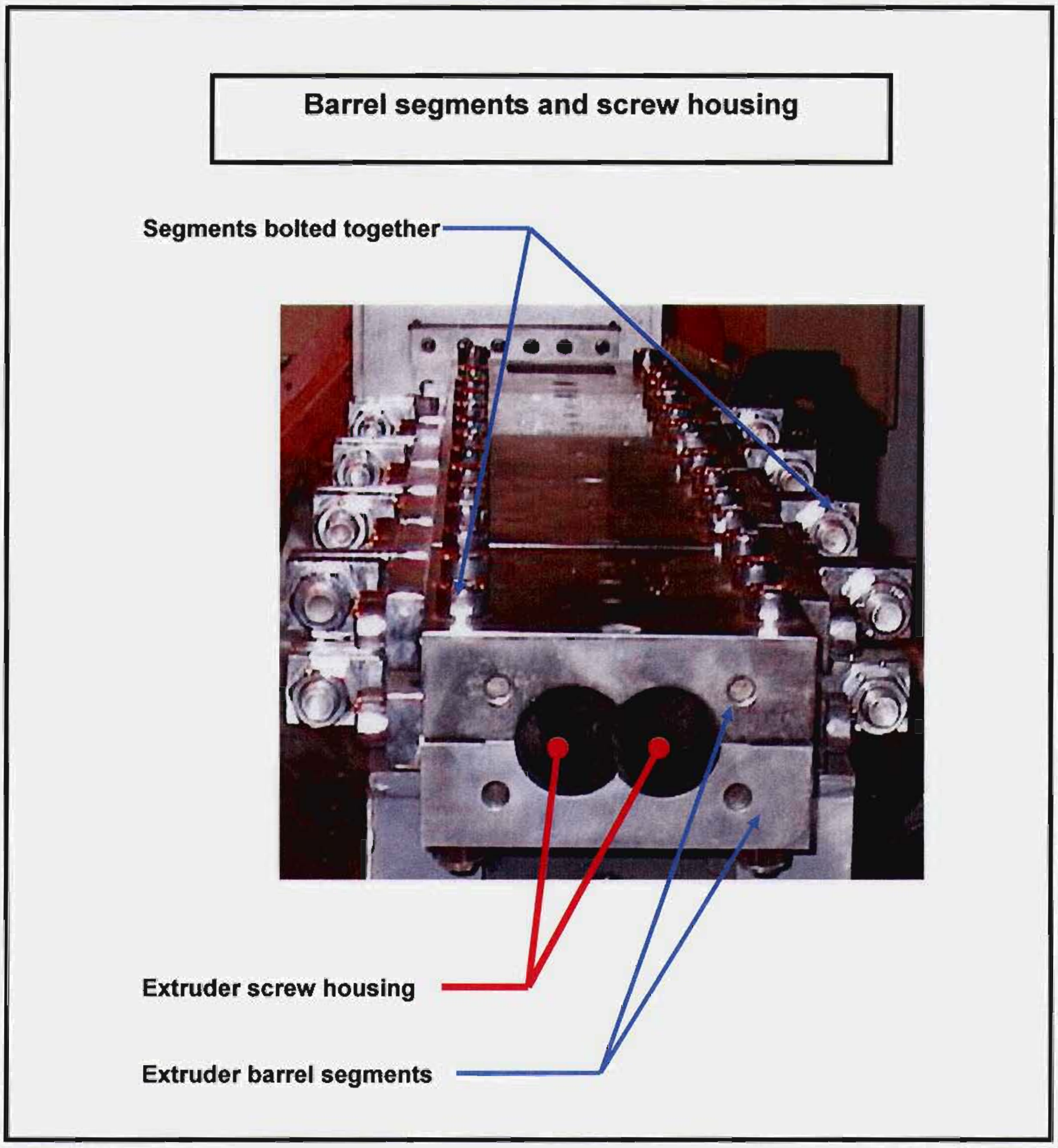


Figure 4.11: Extruder barrel and screw housing.

The screws are located inside the extruder screw housing, which forms part of the barrel. The extruder screws consist out of numerous pitch lengths that are combined to form the screw segments.
The pitch of the screws is 54 mm, making each segment 108 mm long with a diameter of 50mm. The segments slide over the shaft and are held in position by a key and keyway. At the end of each shaft, a bolt is used to lock the segments together (van der Merwe, 2000).

A multitude of screw configurations are available to the operator, but normal practice is to configure the screw as a series of repeated conveying and mixing elements. The conveying screws generate the pressure necessary for the material to flow through the mixing restrictions, which create the biochemical conversions. The degree of barrel fill cannot be seen visually, but information such as torque and pressure differentials provide the symptoms for diagnostic purposes. Measurements of the number of screws filled and how full they are, give an indication of the viscoelastic nature of the material being extruded (Frame, 1994).

The choice of screw design and its positioning in the barrel were decided by taking the following considerations into account:

- volumetric flow requirements;
- the match of pumping efficiency with the rheology of the material being extruded;
- strength and wear characteristics;
- surface area for heat transfer and narrow resistance time distribution;
- pressure and flow distribution at the entrance of the die;
- the degree of shear or intensive mixing required;
- degree of barrel fill; and
- the motor size.

(Frame, 1994).

The following figure illustrates the extruder screw layout within the barrel and the control diagram for the co-rotating screws that were applied in this project.

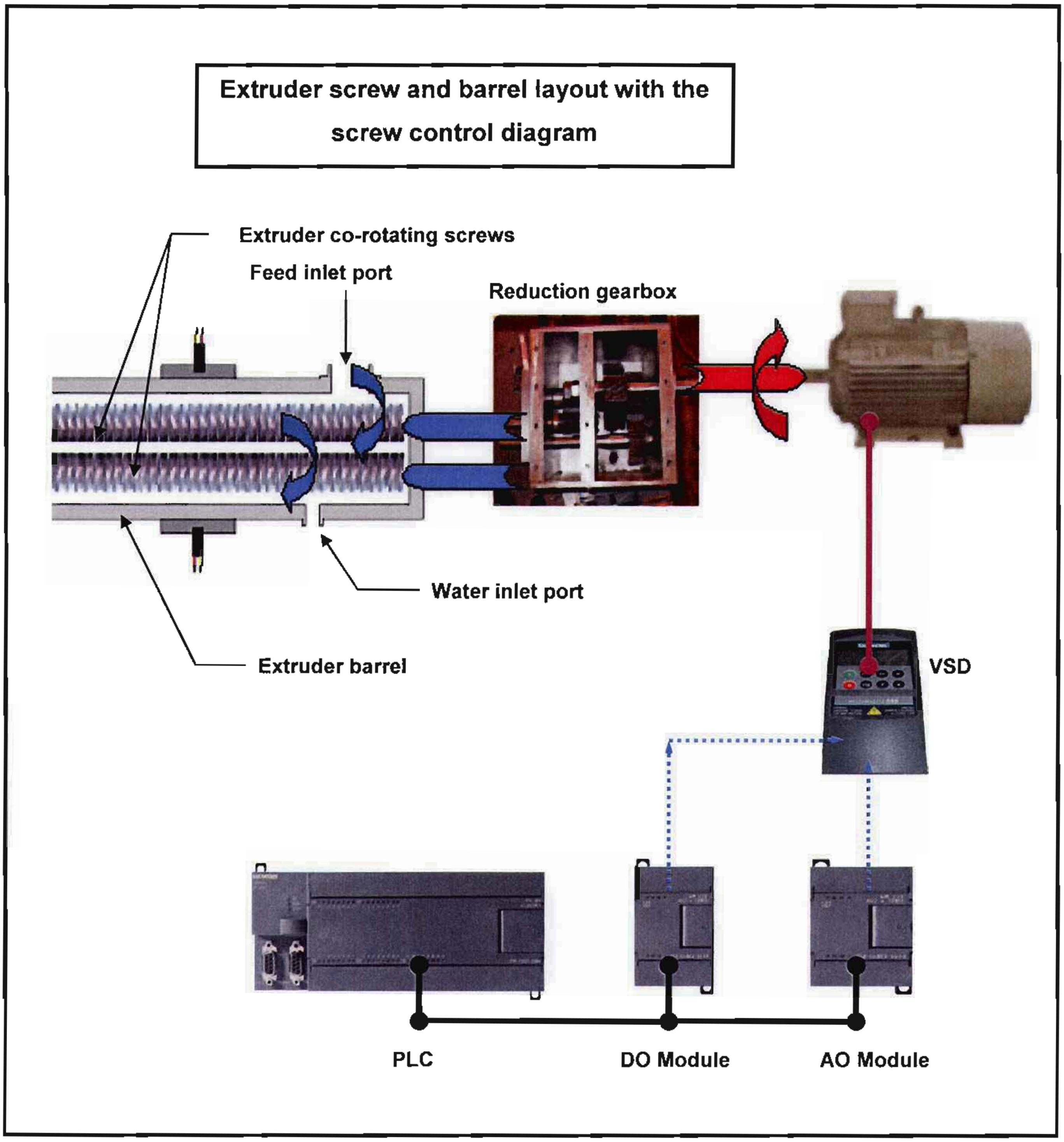


Figure 4.12: Extruder screw and barrel layout with the screw control diagram.

4.2.3.2.1 Extruder screw control-philosophy

A 32 kW motor drives the reduction gearbox that is connected to the extruder screws as seen in figure 4.12. The motor is connected to a VSD and PLC configuration.

The extruder screws are controlled via the PLC operating system where the operator inputs the predefined set point in the control system. The value is sent from the touch panel to the Central Processing Unit (CPU). The processor instructs the Analogue Output (AO) module to send a signal to the Variable Speed Drive (VSD) to increment or decrement the frequency of the motor.

When the frequency is incremented, material is fed faster through the extruder and the opposite occurs when the frequency is decremented on the touch panel. The motor will only respond once the operator inputs a set point and switches the motor into the start or on position. This is done on the touch screen that, in turn, sends the signal to the processor and the processor sends the signal to the Digital Output (DO) Module. The DO module sends an on signal to the VSD to start the motor.

The signal converted by the AO Module and output to the VSD, as previously discussed, is illustrated in figure 4.4 on page 54. The operator inputs a value between 0 and 32000 from the touch panel and the AO Module receives this signal from the processing unit. The AO Module then converts the signal into a volt output for the VSD to interoperate and act accordingly to the instruction.

The extruder motor current can be read from the extruder VSD to give feedback to the operator whether the screw speed must be increased or decreased. The relations of the motor current drawn, raw material feed rate and water injection will be discussed in the following chapter.

4.2.3.3 Heating elements and temperature sensors

Many extruders operate with temperature control and the degree of indirect heating or cooling depends on how the extruder is operated. The pressure differentials and shear forces influence reaction rates and generate friction heat. Barrel heating also generates conductive and convective heat in filled and partially filled zones and the proportion of each heat source depends on the physical and rheological properties of the feed and the barrel temperature profile (Frame, 1994).

Electrical heating elements are used as a heat source in this case. Three pairs of heating cartridges are bolted to the barrel. The cartridges consist of four electrical heating elements, generating approximately 3kW of heat per cartridge. Pockets are machined into the barrel housing at the centre of each heating cartridge and are fitted with J type thermocouples to measure barrel temperature. The electrical elements have a combined heat output of approximately 18kW. The layout of the heating cartridge, heating elements located in each cartridge and J type thermocouples can be seen in the following figure.

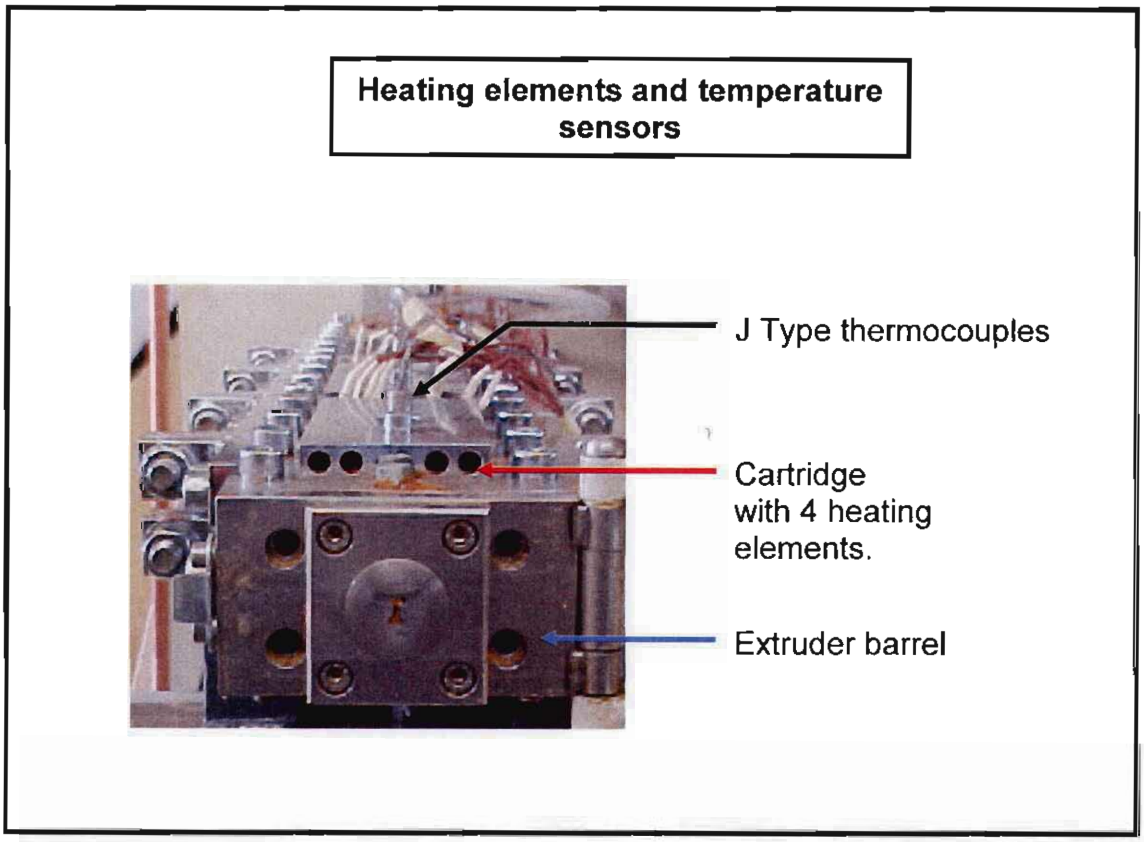


Figure 4.13: Heating cartridge elements complete with J type thermocouples.

As discussed in the previous chapter, there is a wide range of thermocouples for every application. J type thermocouples form part of the base metal thermocouple types and can measure temperatures ranging from 0°C to 850°C.

Type J thermocouples are made up of a positive iron wire and a negative constantan wire as seen in the figure below.

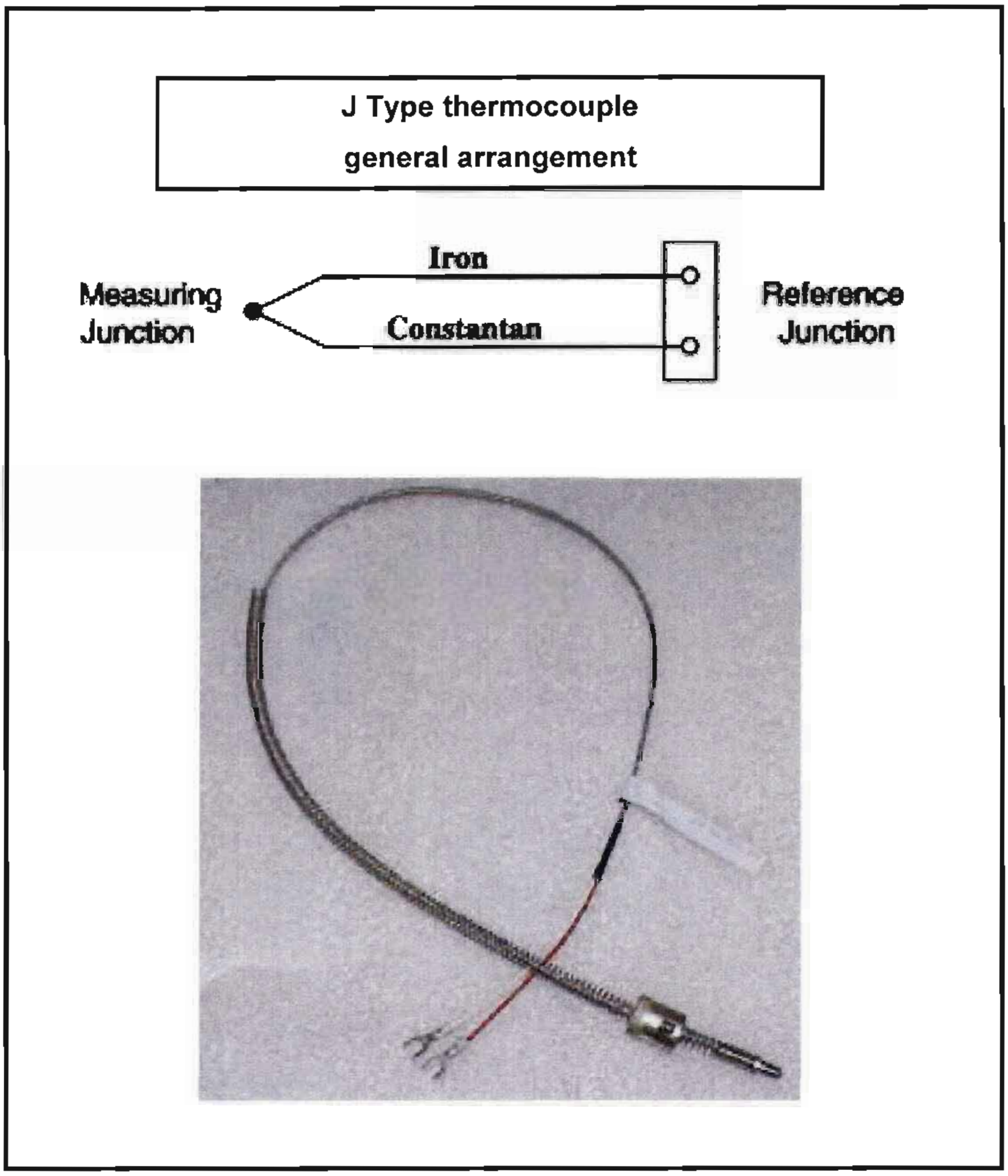


Figure 4.14: J Type thermocouple general arrangement.

The two dissimilar metal wires are joined at the measuring end forming the "measuring junction" also known as the “hot junction". A small voltage, known as the “Seeback” voltage, is created at a junction of the dissimilar alloys. This voltage changes as a function of temperature. The TCI Module measures this small voltage and converts it to a temperature signal for the PLC controller to interpret.

The heating element layout and temperature control diagram can be seen in figure 4.15.

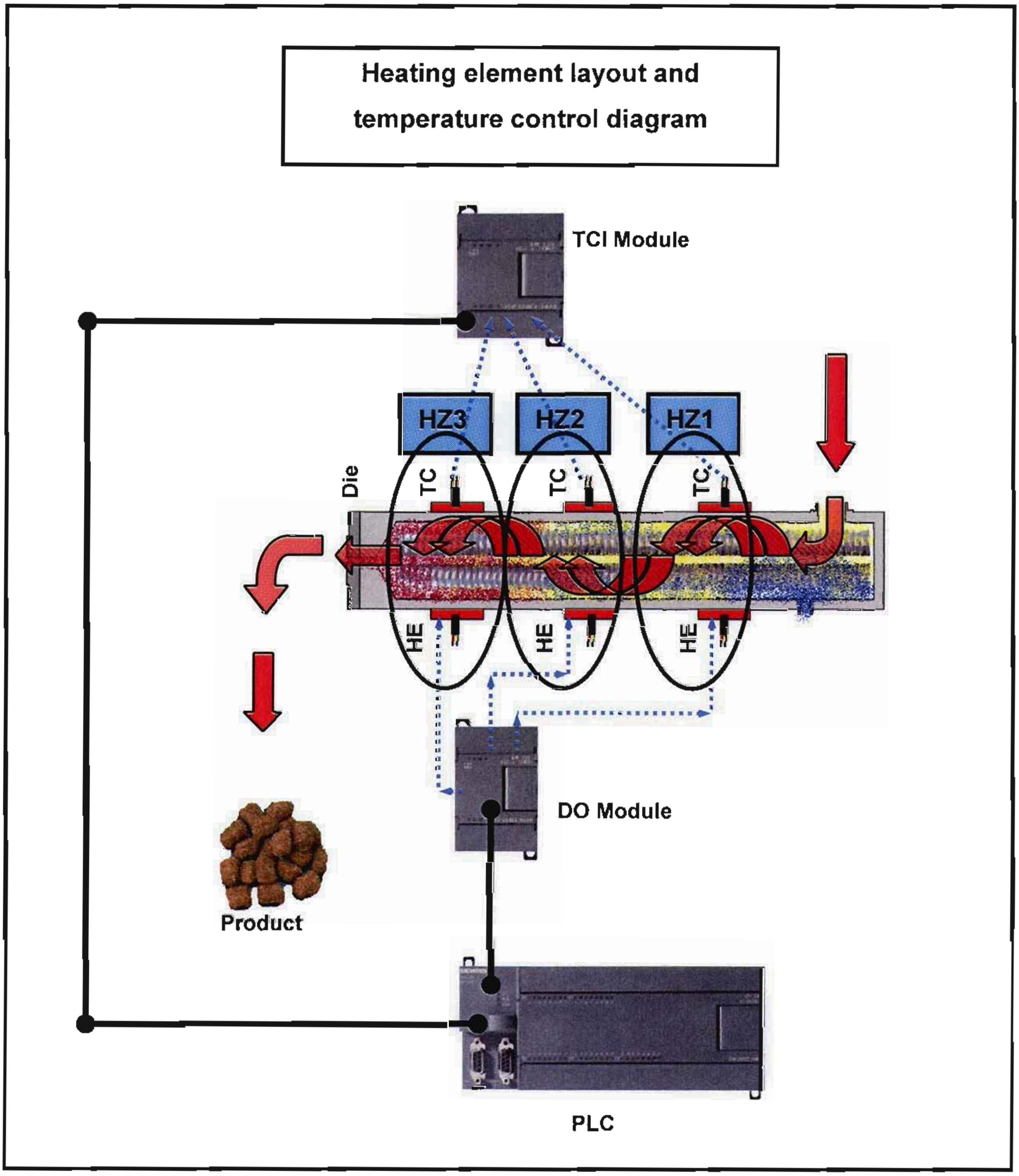


Figure 4.15: Heating element layout and temperature control diagram.

Various models describing heat transfer has been cited in literature, e.g. Yacu (1983) and Van Zuilichem (1992). However, to make the models suit a variety of products, requires a detailed energy evaluation of the extruder.

4.2.3.3.1 Temperature control-philosophy

The extruder heating system can be categorized into three (3) distinct heating zones (HZ) namely:

- Heating Zone 1 - (HZ1);
- Heating Zone 2 - (HZ2); and
- Heating Zone 3 - (HZ3).

Each heating zone comprises of one set of heating cartridges complete with heating elements and two J type thermocouples situated on the top and bottom of the extruder barrel respectively as indicated in figure 4.15. The heating zone temperature control system is designed to work independently to ensure that the correct amount of heat is transferred through the different stages of the extrusion process.

The operator has the option to set each pair of elements at a different temperature, depending on the process heating requirements. For example, some products need to cool down a few degrees before it enters the die. The third set of elements (HZ3) can then be set at a lower temperature as the first two heating zones. In other cases some products also need higher temperatures before it enters the die and the elements can be set accordingly. The heating elements have a controllable temperature range of approximately 50°C – 250°C and are controlled by the PLC control system.

The extruder temperature control is based on a closed loop two-position (on/off) control system where the heating element acts as the final control elements and the thermocouples as the temperature feedback to the PLC control system.

The operator inputs the desired temperature set point for each heating zone into the PLC control system and switches the heating elements on via the touch panel. The PLC receives the heating zone set points and the on signal from the touch panel and instructs the DO Module to switch the respective heating element elements on or off. When the heating elements are switched on, the extruder barrel is heated. The J type thermocouples continuously measure the actual barrel temperature and a small voltage is created at a junction of the dissimilar metals of the thermocouple. This voltage changes as a function of temperature and can be seen in figure 4.16.

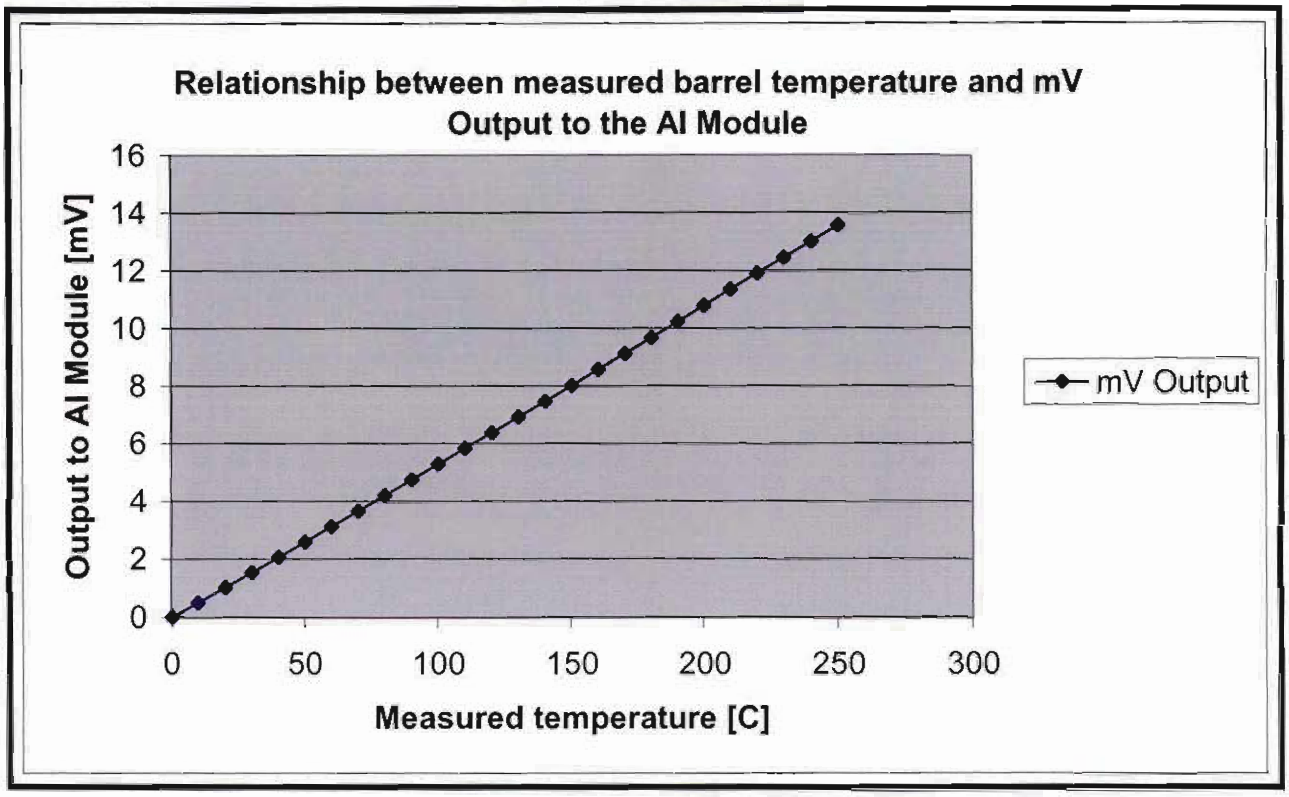


Figure 4.16: Relationship between measured barrel temperature and mV output.

The Temperature Converting Input (TCI) Module receives this signal and transmits it to the PLC where the controller compares the input value from the operator and the feedback signal from the thermocouple. If the temperature measurement is above the desired set point of the respective heating zone, the controller switches an internal counter on and switches off the heating zone via the DO module after the counter has stopped. The same applies to the opposite actions. The PLC internal counter acts as the differential gap for the two-position control to ensure that the heating zone element is not switched on and off within milli-seconds (ms). The differential gap is a preventative action to ensure a longer live cycle of the relays within the PLC control system modules. Refer to the explanation of the two-position control system in the previous chapter.

4.2.3.4 Die and cutter

The die of an extruder is situated on the end of the barrel. The main purpose of a die is to form the cooked material into the desired shapes. The die design, for example, the amount of holes and shapes, influences the pressure in the extruder barrel.

The size of the openings may vary from large holes 50 mm in diameter to small holes, the size of a pin's head. The die size is very important and is directly in relation to the die pressure. When, for example, producing expanded snacks, the die opening must not be too big. If it is too big, the die pressure will not be high enough to induce a pressure drop between the extruder internal barrel pressure and atmospheric pressure to ensure the product to expand if normalised. If the die opening is too small, products like bran can clog the opening and stall the extruder screws.

There exist basic formulae of fluid dynamics that can be used to model the flow through the die. However, the entrance and exit effects, the product rheology and the phase changes that occur at the die have a significant effect on the flow pattern and force the models to become approximations that must be tested empirically.

Currently there are no generalised solutions available for non-Newtonian fluids moving through multi-holed dies with irregular shapes. Flow through circular pipe capillaries has been extensively studied in the field of rheology and sound methods exist to adequately predict the pressure drops versus outputs (Frame, 1994).

The die design used in this study combined fluid calculations and experimental trials to get the desired design. For the purpose of this study, the detail calculation and die design is not discussed.

The cutter is located on the die product discharge side. The purpose of the cutter is to cut the extruded material into the desired lengths as it exits the die opening. By varying the cutter speed, the product can be cut into various lengths. The cutter consists of one or more blades rotating over the exit holes of the die. The blades run as close as possible to the die face to ensure that the product is cut off cleanly.

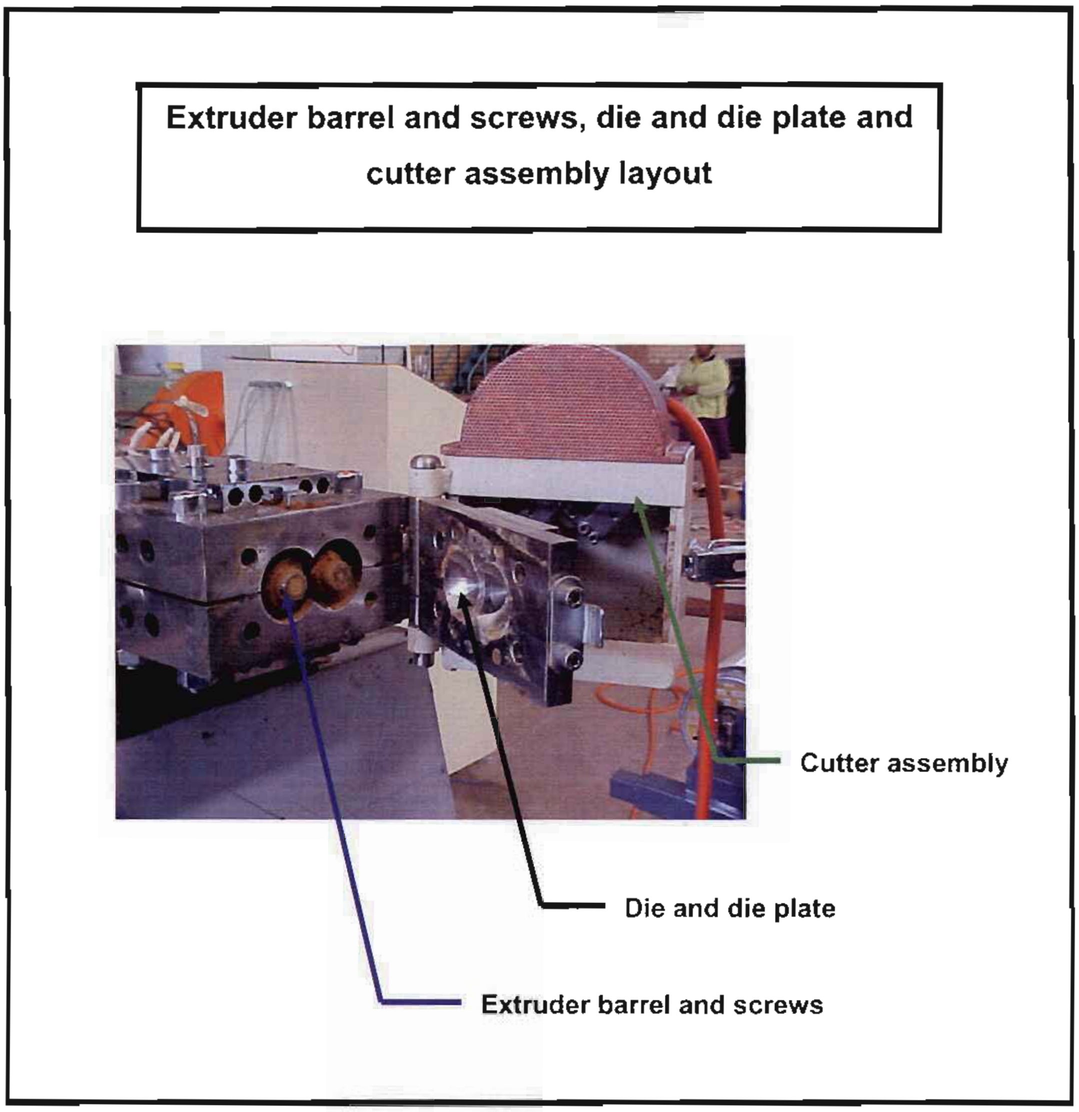


Figure 4.17: Extruder barrel and screws. Die and die plate and cutter assembly layout.

The die plate and die is connected to a hinge as shown in figure 4.17. The die plate is bolted onto the front of the extruder barrel. When the extruder starts running, the die plate is swivelled away from the barrel. The operator can now set the parameters of the machine until the desired flow rate and water/raw material mixture is achieved. The die plate is then swivelled closed and bolted to the barrel. This gives the opportunity to the operator to make sure that the material can flow easily through the die opening. If this method is not used during start-up, the die could get clogged and the machine must then be stopped and cleaned.

The die assembly is designed to ensure that it is possible to use different die shapes on the same assembly.

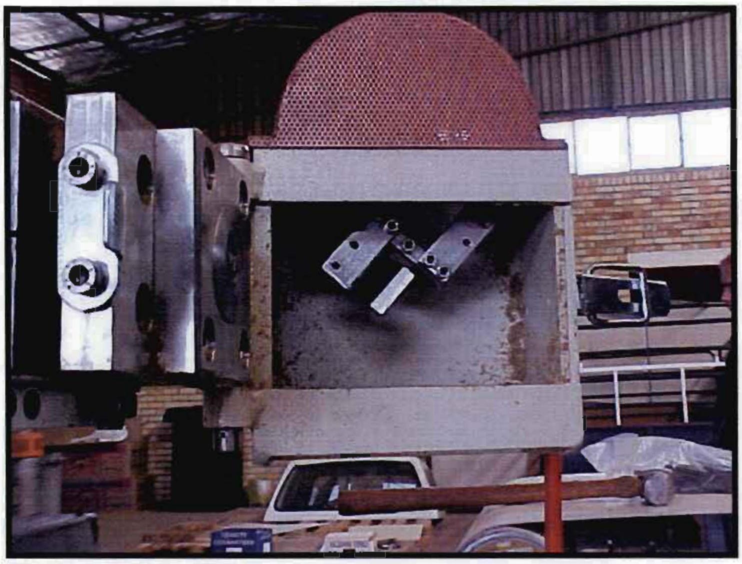


Figure 4.18: Cutter assembly with housing and two rotating blades.

The cutter is designed with two adjustable blades. The cutter assembly can be swivelled over the die assembly as soon as the extruded material has reached the desired texture and shape. The blades are designed to be easily interchangeable and can easily be removed for sharpening. A 0.55 kW electrical motor drives the blades.

The die assembly and cutter assembly has been designed to be as versatile as possible and is manufactured at a very low cost due to the simple design.

The assembly of the different components is based on basic principles to ensure easy operation.

The die and cutter layout and cutter control diagram is illustrated in figure 4.19 below.

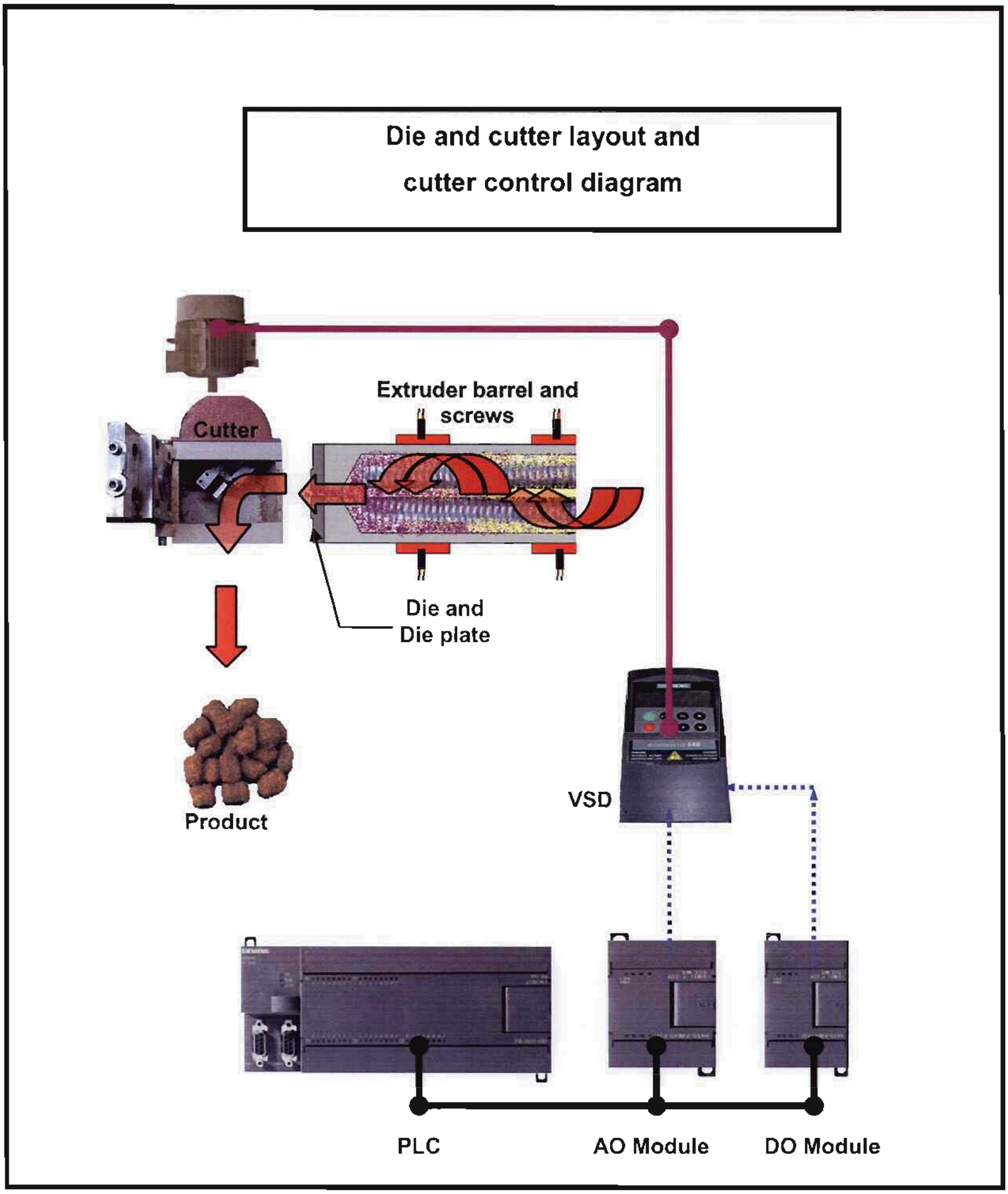


Figure 4.19: Die and cutter layout and cutter control diagram.

4.2.3.4.1 Cutter control-philosophy

A 0.55 kW motor drives the cutter that is located on the die product discharge side of the extruder in front of the die. The motor is connected to a VSD and PLC configuration.

The cutter speed is controlled via the PLC operating system where the operator inputs the predefined set point in the control system. The value is sent from the touch panel to the Central Processing Unit (CPU). The processor instructs the Analogue Output (AO) Module to send a signal to the Variable Speed Drive (VSD) to increment or decrement the frequency of the motor.

When the frequency is incremented, the cutter speed increases and the extruded product is cut into shorter lengths. When the frequency is decremented on the touch panel, the cutter speed decreases and the cutter cuts the extruded product into longer lengths.

The motor will only respond once the operator inputs a set point and switches the motor into the start, or on, position. This is done on the touch screen that in turn, sends the signal to the processor and the processor sends the signal to the Digital Output (DO) Module. The DO module sends an on signal to the VSD to start the motor.

The signal converted by the AO Module and output to the VSD has been previously discussed and illustrated in figure 4.4. The operator inputs a value between 0 and 32000 from the touch panel and the AO Module receives this signal from the processing unit. The AO Module then converts the signal into a volt output for the VSD to interpret and act accordingly.

4.2.3.5 Dosing pump

The dosing facility is achieved by using a positive displacement pump with stroke adjustment. The pump has a rated flow rate of approximately $0.7m^3/h$ and is capable of a discharge pressure of 10 bar.

The dosing pump injects water at the back of the extruder barrel closest to the material feed port as illustrated in the figure below. This ensures that the water and fed material are adequately mixed during the extrusion process. A control valve is implemented to control the flow rate of the water before it is injected into the system. Both the pump and control valve is controlled by the PLC system as illustrated in the dosing pump, control valve layout and control diagram.

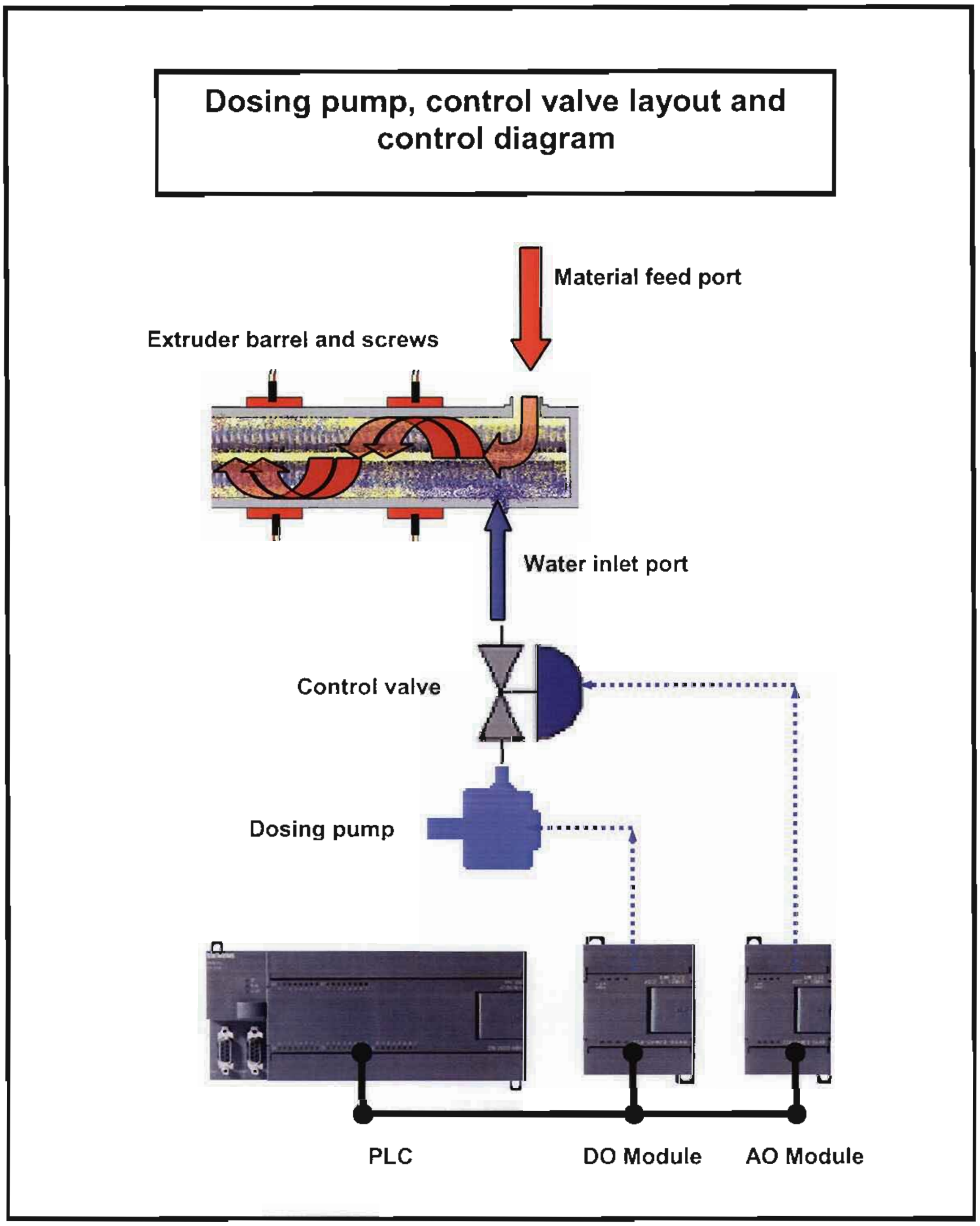


Figure 4.20: Dosing pump, control valve layout and control diagram.

4.2.3.5.1 Dosing pump control-philosophy

The extruder-dosing pump is connected to a water-filled sump where the water is stored. The dosing pump pumps the fluid from the water sump into the extruder barrel while a control valve controls the flow rate. The dosing pump and control valve are both connected to the PLC control system.

The dosing pump is a positive displacement pump with stroke adjustment. The stroke length can be manually adjusted to increase or decrease the flow rate, but a control valve is used to complete this action. The stroke length is set to a predetermined stroke length and controlled via the DO Module which is connected to the PLC. This enables the operator to start the dosing pump from the PLC touch panel and control the control valve, which is connected to the AO Module. The pump will only respond once the operator switches the motor into the start, or on, position. This is done on the touch screen that in turn, sends the signal to the processor and the processor sends the signal to the Digital Output (DO) module. The DO module sends an on signal to the dosing pump and the pump starts pumping water out of the water sump.

The control valve consists of a valve and actuator configuration. The actuator receives the 0V to 10V signal from the AO Module and opens or closes the valve upon instruction from the operator. The signal converted by the AO Module and output to the actuator, as previously discussed, is illustrated in figure 4.4 on page 54. The operator inputs a value between 0 and 32000 from the touch panel and then the AO Module receives this signal from the processing unit. The AO Module converts the signal into a volt output for the actuator to interoperate and act according to the instruction. When the operator increments the set point of the control valve, the valve opens and the water injection flow rate increases. When the operator decreases the set point the valve closes and the injection rate decreases.

The valve is configured in the PLC program to open when the dosing pump is started. This is a precautionary measure to ensure that the dosing pump does not pump while the control valve is closed.

During the extrusion process, the operator continuously monitors the extruded product moisture and increase or decrease the water flow rate as desired.

4.2.4 Control station.

The control station is the primary interface medium between the operator and the extrusion system. It comprises of the PLC control system complete with the PLC touch panel, VSD's, switchgear and power distribution board as illustrated in the figure below.

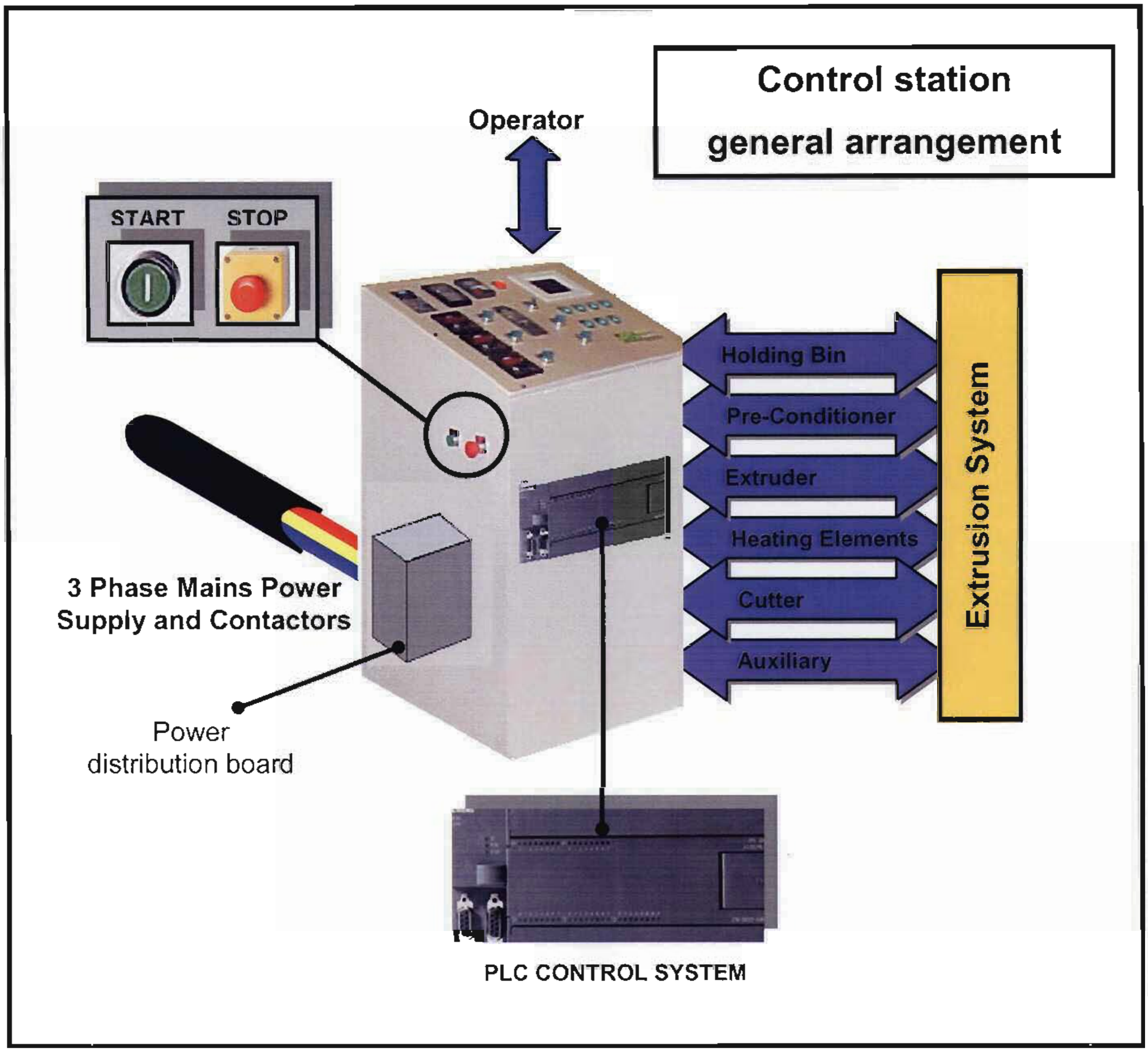


Figure 4.21: Control station general arrangement.

The control station is supplied with a 3 phase power supply where the power is distributed to all the extrusion components via the power distribution board located inside the control station.

All the extrusion equipment is plugged in at the back of the control station as seen in the figure below.

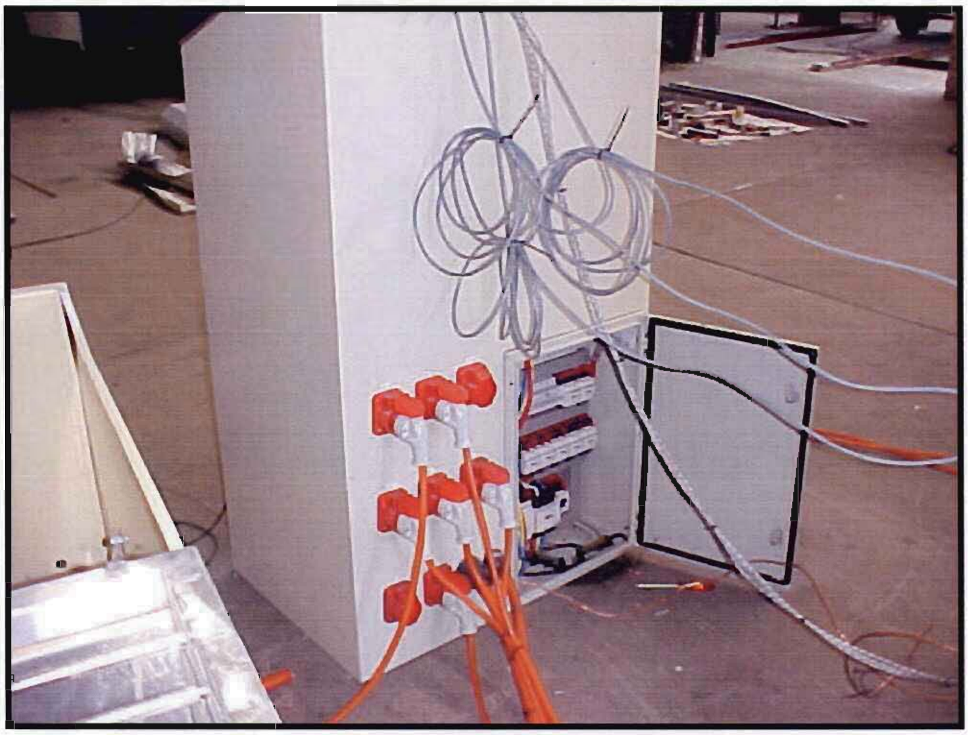


Figure 4.22: Extrusion equipment plugged into the control station.

A start button and emergency stop button is located on the side of the control station. The start button powers up all of the extrusion equipment as well as the control panel. The function of the emergency stop button is to halt the entire system whenever the extrusion process becomes unstable and acts as a safety feature of the control system.

The control station can be sub-divided into two main categories namely:

- The control panel; and
- The PLC control system.

4.2.4.1 Control panel

The entire extrusion process, including auxiliary equipment, for example the Auger, is controlled from the extruder control panel. The control panel layout can be divided in to two sections namely:

- PLC control section; and

- manual control section.

The layout of the control panel is illustrated in the figure below.

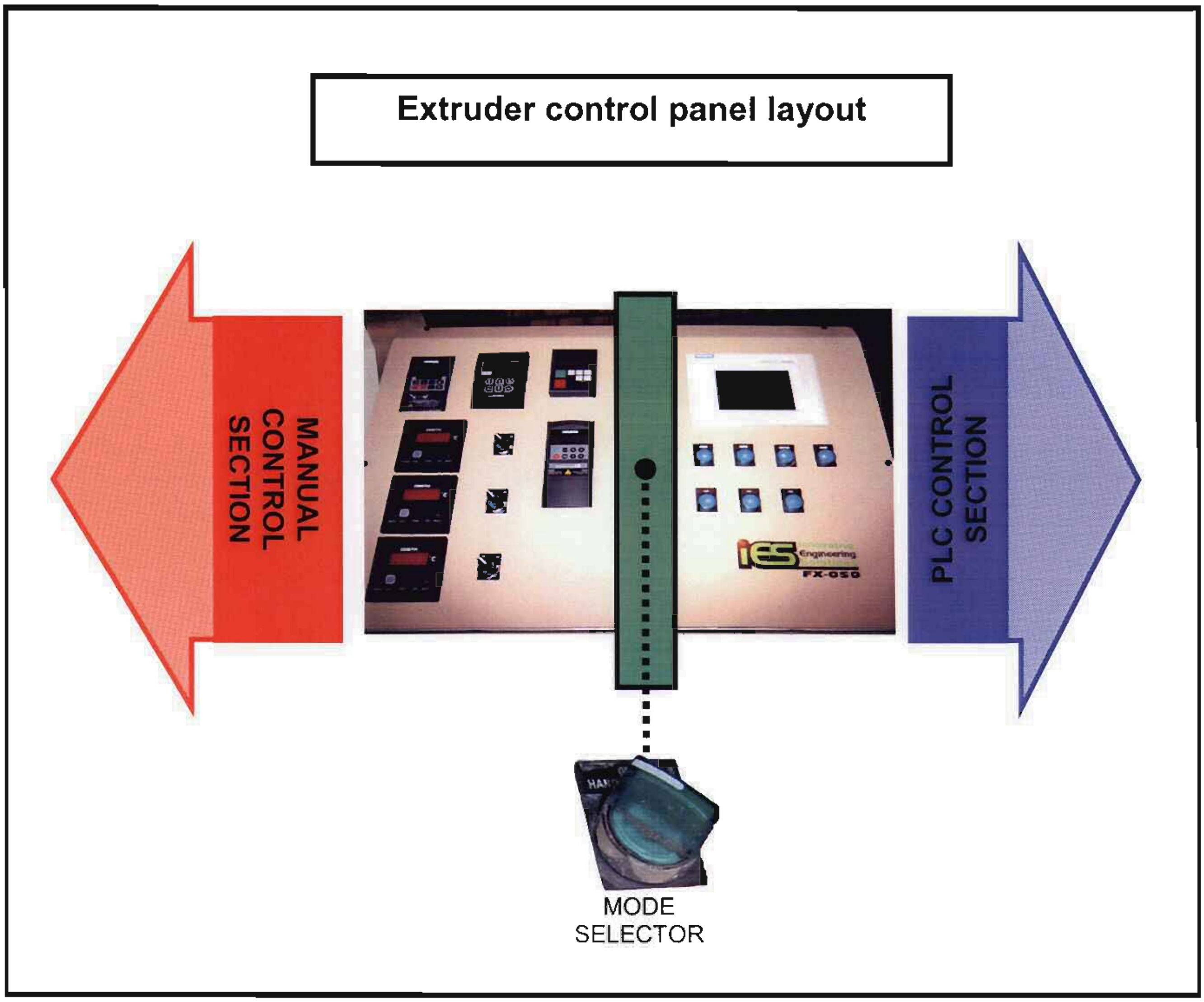


Figure 4.23: Extruder control panel mode selection indicating the manual and auto section.

The PLC control section comprises of the control-philosophy previously discussed in this chapter and utilises the PLC Touch screen as the main operator control medium.

The manual control section consists of most of the secondary modules used by the PLC operating system, for example the VSDs, but overrides the PLC control and is operated manually by the operator. The total extrusion operation is managed by the operator, inputting control variables into the secondary modules. These secondary modules include the VSDs and the temperature controllers.

The selector switch, located at the centre of the control panel, switches the extruder operation into the abovementioned modes. All the auxiliary equipment, for example the auger and conveyor, can be operated in both operating modes.

The control panel layout can be seen in figure 4.24. When the extrusion components are started from the touch panel, the respective indicators for the equipment light up to give an indication to the operator that the equipment is enabled or running.

The main extrusion component indicators located on the control panel is the:

- feeder (holding bin feeder);
- pre-conditioner;
- extruder screws;
- cutter;
- heating element Zone 1;
- heating element Zone 2; and
- heating element Zone 3.

The power indicator light indicates that there is power connected to the control station. When the start button on the side of the control station is pushed and the mode selector switch is set to the PLC control side, the PLC control system is enabled and all the extrusion components and secondary components (VSDs) are powered up.

The hopper and aux switches are used to control the auxiliary equipment. The “Hopper switch” switches the auger on and off and the “Aux switch” switches the conveyor belt, located below the cutter, on and off.

The PLC touch panel is the main operator control medium of the extrusion process. The touch panel is linked via a PC/PPI cable to the PLC central processing unit. The operator inputs all the desired set points via the touch panel into the PLC control system and monitors process variables from the system on the touch panel, for example barrel temperature.

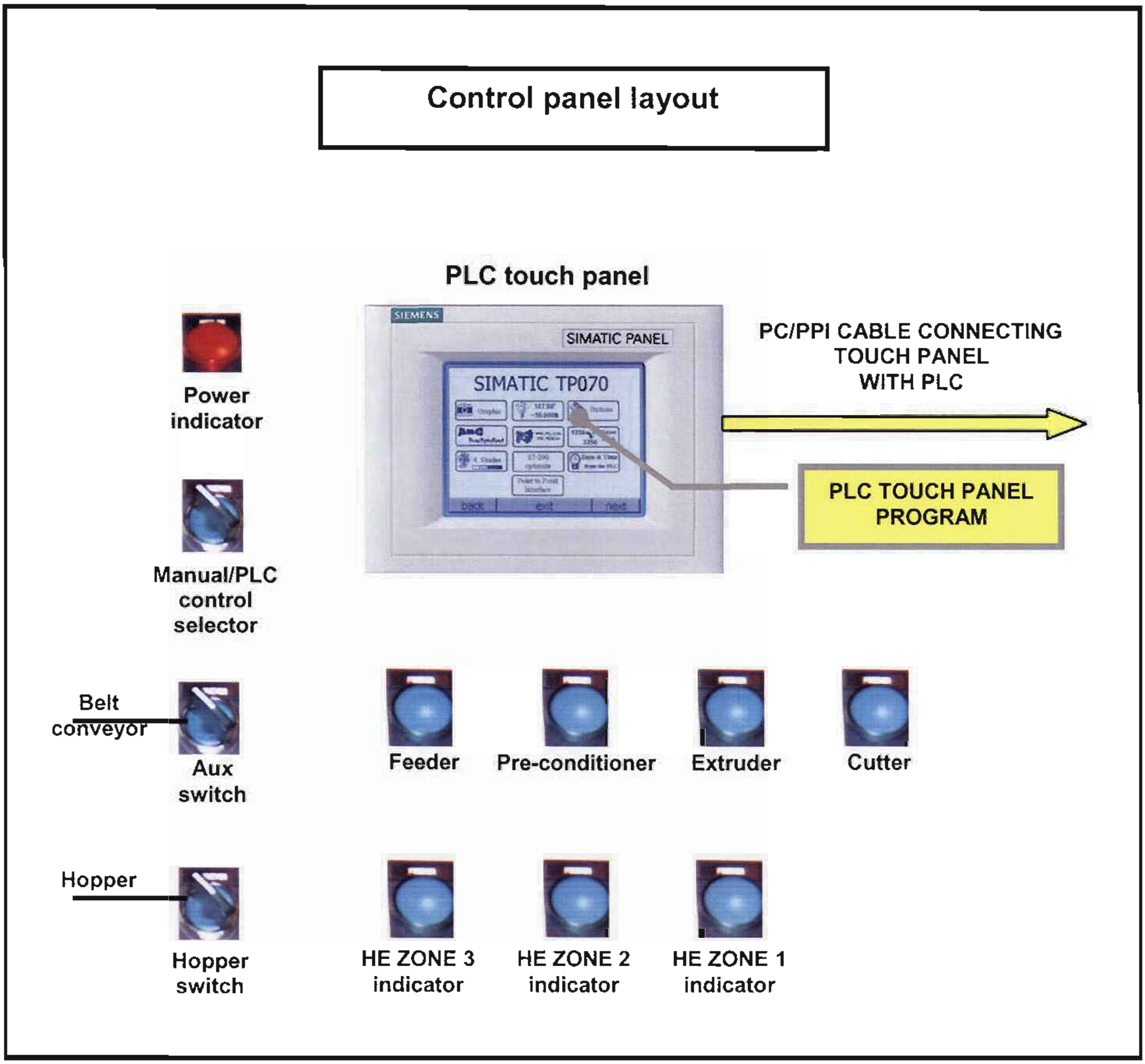


Figure 4.24: Extruder control panel layout.

The touch panel user interface is programmed on a PC and uploaded to the touch panel. The touch panel user interface that was designed for this study can be seen ***Appendix B***. The main menu of the touch panel consists of different extrusion processes. When one of the extrusion process tabs is pressed, the system menu appears on the touch panel. On the System menu there are five tabs that can be accessed. These tabs include the:

- drive tab;
- temperature tab;
- control valve tab; and
- Start and stop tabs for the heating elements.

The drives tab accesses the drive menu where all the extrusion components that are controlled via a VSD or actuator can be incremented or decremented and switched on or off, these components includes the:

- Screw Feeder of the holding bin. The operator increments or decrements the feed speed on this menu and start or stops the feeder.
- Pre-conditioner. The operator switches the pre-conditioner on or off on this menu.
- Extruder screws. The operator increments or decrements the extruder screw speed on this menu and start or stops the screws.
- Cutter. The operator increments or decrements the cutters speed on this menu and start or stops the cutter.
- Control valve. The operator opens or closes the control valve from this menu.

When the back button is pressed, the drive menu is closed and the System Menu reappears.

The temperature tab accesses the temperature menu and consists of three heating zone set point fields and three feedback fields. The feedback fields indicate the temperature reading from the J type thermocouples that forms part of the extruder barrel. The operator inputs the set point temperature of the respective heating zones in this menu and can also monitor the actual barrel temperature of the extruder. Once the set points are loaded, the back button can be pressed and the system menu reappears. The elements will only function once the start button on this menu is pressed. When the start button is pressed, the heating elements engage and heat the extruder barrel. The PLC regulates the temperature around the operator set point for each heating zone.

The control valve tab accesses the control valve menu. The control valve actuator position is illustrated on this menu and acts as feedback to the operator. When the back button is pressed the control valve menu is closed and the System Menu reappears.

The programmed touch panel Main Menu also has a system mode tab. When the system mode tab is accessed the system mode appears on the touch panel. This menu has no influence on the actual control of the extrusion system but assists the operator to conduct certain touch screen functions. These functions include:

- Transfer mode. When a program is uploaded into the touch panel, the panel must be set in the offline and transfer mode.
- Calibration of the touch panel. When this tab is accessed the operator is asked to press a marker indicated on the screen. The touch screen verifies the position where the operator sees the marker.
- Setting the touch panel in online or offline mode. When a program is uploaded, the touch screen must be placed in the offline mode. Once the transfer is executed, the touch screen can be placed back in the online mode.
- Cleaning the touch panel screen. During the extrusion process a lot of dust accumulates on the touch screen. When the operator wants to clean the screen without interrupting the process control, the screen has to be placed in the clean screen state. The screen will disable the touch panel and the operator is free to clean the screen. This state is only held for a certain number of seconds and then switched back to the operational mode.

It is advisable that the system mode is rather accessed during non-extrusion activities.

4.2.4.2 PLC control system

The operator inputs the control variables from the control panel and the Programmable Logic Controller (PLC) located inside the control station processes the information. The way the PLC processes the information is pre-determined by a program uploaded into the central processing unit (CPU) of the PLC. After the loaded information is processed, the PLC outputs the necessary instructions to the PLC control modules.

The layout of the PLC control system and the control diagram of each of the extrusion processing components have been discussed in previous sections of this chapter and can be seen in ***Appendix A*** .The uploaded PLC program that was written for this study can be seen in ***Appendix C***.

4.3 Conclusion

In the preceding sections of this chapter, the implementation of an effective PLC Control System for a Twin Screw Food Extruder was discussed. The layout of each extrusion component and the control-philosophy using a PLC control based system was addressed.

The advantages of using a PLC control based control system are numerous for example:

- The start-up and shutdown sequences for the extrusion process can be preset and activated each time the extruder is started or shut down. This saves production time and minimizes human error.
- More than one recipe can also be preset in the memory of the PLC unit. If the producer needs to change to a different product the parameter values can be loaded and the extruder can be started by the push of a button on the touch screen. This ensures that the food products produced on the extruder have a more consistent quality, texture and shape.
- By using an automated PLC control system the operator is not required to extensive knowledge of extrusion processing to produce extruded products.

There are various ways to implement a control system into any process but the aim of this study was to keep it simple, effective and reliable for the operator running the extrusion process.

The value of a PLC based control system is evident from the above discussion.

5 Chapter 5: Case Study – Extrusion of Corn Grits

5.1 Introduction

In this chapter the PLC controlled extrusion process will be applied to produce an expanded snack from corn grits. The experimental procedure followed and the results obtained will be discussed in this chapter.

5.2 Process description

The extrusion process of the corn grits can be divided into three stages. These stages include:

- The start-up stage that involves preparing the extrusion equipment for the expanded snack extrusion process;
- the run stage where the corn grits are extruded and an expanded snack is produced; and
- the shutdown stage that includes stopping the extrusion equipment step by step and cleaning the barrel.

Degermed maize (corn) grits were extruded to produce cheese curls as the final product for this study.

Degermed corn grits can be classified as kernels of maize (corn), cleaned from impurities and ground to a particle sizes of approximately 2 mm. The grinding process removes the germ, situated inside the kernel. The standard specification for the raw degermed corn grits can be seen in the table below.

Description	Typical Corn Grit Analyses
% Moisture	11%
Bulk density	690 kg/m^3
Grit size	2mm
% Protein	8.0%

% Fat	0.8%
% Fiber	0.4%
% Ash	0.3%

Table 5.1: Degermed corn grit specification.

The extrusion process involves conveying the raw material into the holding bin and feeding the material into the pre-conditioner. No pre-conditioning was necessary for this specific extrusion process and the corn grits were only conveyed through the pre-conditioner and fed into the extruder. After the corn grits entered the extruder, the co-rotation screws conveyed the raw material forward through the extruder. Water was injected into the system and the heating elements were used to cook the raw material before it was extruded through a 4mm diameter die opening.

When extruding expanded snacks, for example cheese curls, the following critical parameters have a great influence on the final product.

- The correct amount of pressure must be generated inside the extruder barrel to expand the product when exiting the extruder through the die.
- The die opening has to be the correct size to induce a large enough pressure drop between the extruder internal barrel pressure and atmospheric pressure.
- Adequate moisture and heat to cook the material.
- Holding bin feed rate.

The above-mentioned stages to extrude the cheese curls will now be briefly discussed in the following sections.

5.2.1 Start-up stage

- The control panel is switched on and all of the extrusion components are test run to ensure that they are working properly. This is done from the control panel.
- The raw material or corn grits are conveyed into the extruder holding via the auger. When the Holding bin is adequately filled with the raw corn grits, the auger is stopped.

- The three heating element zones are set from the touch panel to heat the extruder barrel before the corn grits are extruded. It takes approximately 15 minutes for the extruder barrel to reach the set temperature.
- The diverting chute located between the pre-conditioner and extruder feed port is directed into a waste bin and the pre-conditioner is started.
- The holding bin screw feeder is started and the corn grits are fed into the pre-conditioner.
- After a steady state flow rate through the pre-conditioner into the waste bin is reached, the extruder is started and set at a low screw speed.
- The diverting chute can now be set to divert the raw material into the extruder.
- Start the dosing pump and adjust the flow rate to 50% of rated capacity.
- The raw material will now mix with water injected into the extruder barrel and form a fluidised corn grit composition.
- After a steady state flow is reached through the extruder barrel, the operator closes the extruder barrel with the hinged die plate configuration located at the front end of the extruder. The die plate is securely fastened onto the extruder barrel and the corn grit-water mixture is diverted through the die opening. The extruder is now ready for the extrusion operation.

The set point parameters for the start-up stage loaded by the operator into the PLC control system can be summarized in the table below.

No.	**Parameter**	**Operator Input Variables**	**Description**
1.	Raw material feed-rate into pre-conditioner	4000 **Start**	Actual feeder screw speed = 37 rpm. Approximately 115kg/h

2.	Dosing pump flow rate (Control valve)	16000 Start	Control valve =50% Open. Approximately 12 Litres / min
3.	Extruder screw speed	6000 **Start**	Actual extruder screw speed = 90 rpm.
4	Extruder barrel temperature	HE Zone 1 = 120°C HE Zone 2 = 150°C HE Zone 3 = 180°C **Start**	Specific Heating Element Zone set temperatures.
5.	Pre-conditioner	**Start**	The pre-conditioner operating at a constant speed.

Table 5.2: Start-up set point parameters.

5.2.2 Run stage

- The Holding bin feed rate and extruder screw speed can now be slowly incremented on the touch panel. Care must be taken when the feed rate and extruder speed is incremented. When the feed rate is incremented too fast and the extruder screw speed is kept constant, the screws may not be able to convey the raw material forward and the barrel may be flooded. Extruder screw speed and feed rate must be incremented intermittently until desired set point is reached.
- The water injection flow rate can now be slowly decreased by closing the control valve until the desired product / moisture ratio is achieved.
- The Heating Element Zone temperatures can be increased if the extruded product is not fully cooked, or decreased when the product is over-cooked.
- The cutter set point can now be set and started from the touch panel. The cutter assembly is positioned in front of the die–opening and locked. The operator may increment the cutter speed to decrease the extruded product length or decrease the speed to cut the product into longer lengths.

The set point parameters for the run stage loaded by the operator into the PLC control system can be summarized in the table below.

No.	Parameter	Operator Input Variables	Description
1.	Raw material feed-rate into pre-conditioner	Incremented 4000 - 8000	Actual feeder screw speed incremented from 37 rpm – 73 rpm Approximately Increased from115kg/h to 230 kg/h
2.	Extruder screw speed	Incremented 6000-14000	Actual extruder screw speed incremented from 90 rpm – 200 rpm.
3.	Dosing pump flow rate (Control valve)	Decremented16000-5000	Control valve is slowly closed to 16 % Open. Approximately 2 Litres / min
4	Extruder barrel temperature	HE Zone 1 = 100°C HE Zone 2 = 120°C HE Zone 3 = 160°C	Re-set Specific Heating Element Zone set temperatures.
5.	Extruder cutter	10000 Start	Cutter Speed can be adjusted to cut extruded product into desired lengths.
6.	Pre-conditioner	**Running** The Pre-conditioner operating at a constant speed.	

Table 5.3: Run set point parameters.

5.2.3 Shutdown stage

The shutdown stage involves shutting down the extrusion equipment step by step.

- Shut off the holding bin feed screw from the touch panel.
- Shut off the pre-conditioner.

- Shut off elements.
- Shut off extruder screws
- Shut off cutter and remove from die-face.
- Shut off dosing pump.
- Open die plate.
- Start the extruder screws at a low screw speed and empty the excess un-extruded product in the extruder barrel.
- Remove the diverting chute located between the Pre-conditioner and feed port.
- Add raw soybeans into the extruder feed port to remove excess product around the extruder screws and inside the barrel. Repeat this procedure until the barrel and screws are adequately cleaned.
- Shut off extruder screws.

No.	Parameter	Operator Input Variables
1.	Holding bin screw feeder	STOP
2.	Pre-conditioner	STOP
3	Extruder barrel temperature	STOP HE Zone 1,HE Zone 2, HE Zone 3
4.	Extruder screw speed	STOP
5.	Extruder cutter	STOP
6.	Dosing pump flow rate (Control valve)	STOP

Table 5.4: Shutdown set point parameters.

5.3 Experimental procedures

Architectural Energy Corporation's MicroDataLogger® portable data acquisition system was used to collect the extrusion process data. The data acquisition system consists of a four-channel data logger and sensors that records time-series data. The Data logger can be seen in the following figure.

Figure 5.1: Micro Data Logger

The data that was measured by the Micro Data Logger and includes current (amps) readings from the extruder motor, temperature readings from each of the Heating element zones (HE Zones) of the extruder barrel and the current (amp) readings from the HE Zone Indicators located on the Control panel. The sampling rate interval for the measured data is illustrated in the table below.

Measurement	Unit	Sampling Rate
Extruder motor Amps	A	3-second intervals
Temperature	°C	1-second intervals
Heating Element Zone Indicators	A	3-second intervals

Table 5.5: Sampling rate interval for the measured data.

The operator input values were documented at 60-second intervals and combined with the recorded data. The experimental results will be discussed in the following section. Extrusion data was collected over 3 runs, each run comprising approximately 30min.

5.4 Experimental results

The experimental results that were obtained include:

- The relation between the holding bin feed rate, extruder screw speed and water injection rate into the barrel (barrel moisture content) during the extrusion process.
- Temperature measurement and Barrel Temperature Control.
- Mechanical energy input during the Start-Up, Run and Shutdown stage.

5.4.1 Relationship between Extruder screw speed, Feeder screw speed and Percentage of water injection

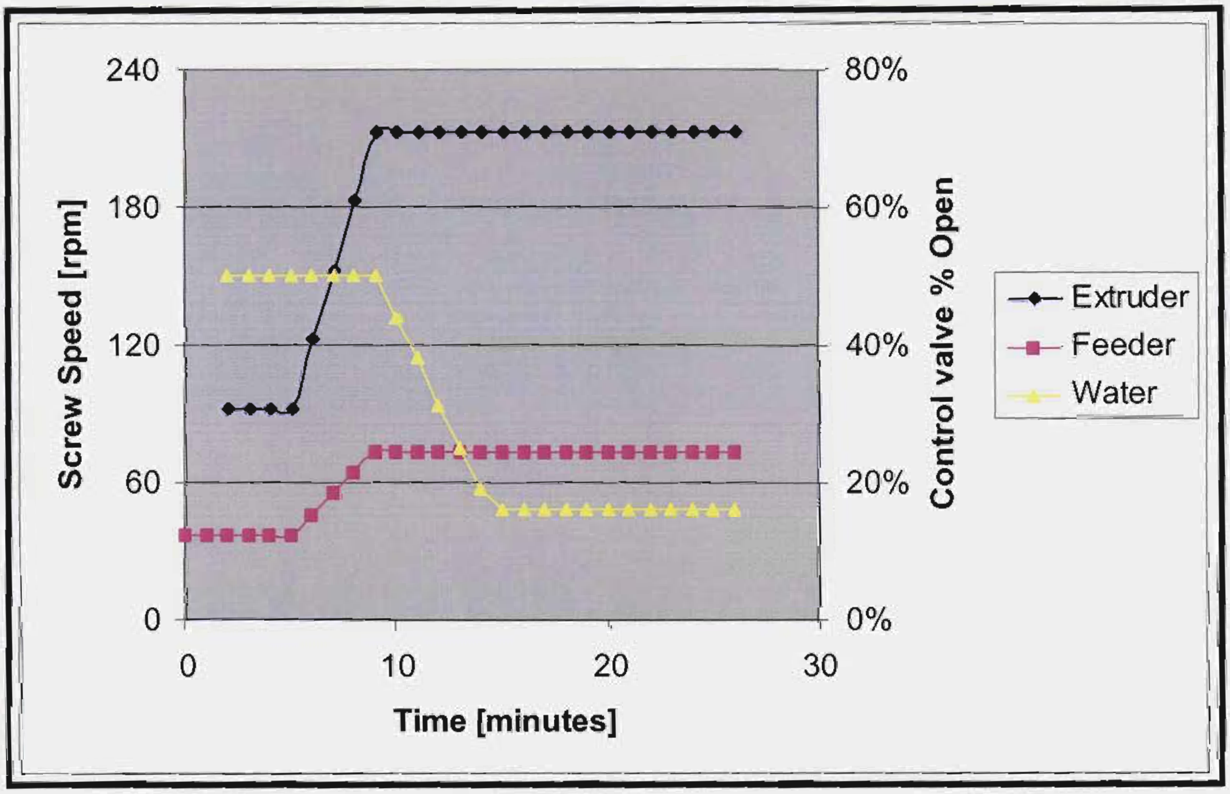


Figure 5.2: Input parameter relationship.

The relationship between Extruder Screw Speed, Feeder Screw Speed and Percentage of Water Injection can be seen in figure 5.2 above. The extruder screw speed and feed rate are incremented intermittently until the extruder screw speed is approximately 200rpm (14000 set point) and feeder screw speed 73rpm (8000 set point). The water injection flow rate is slowly decremented from 350 l /h (control valve 50% open) to 109 l/h (control valve 16% open).

The Feeder screw speed and percentage of water injection rate into the extruder at steady state conditions can also be expressed in terms of mass flow rates as illustrated in the figure below.

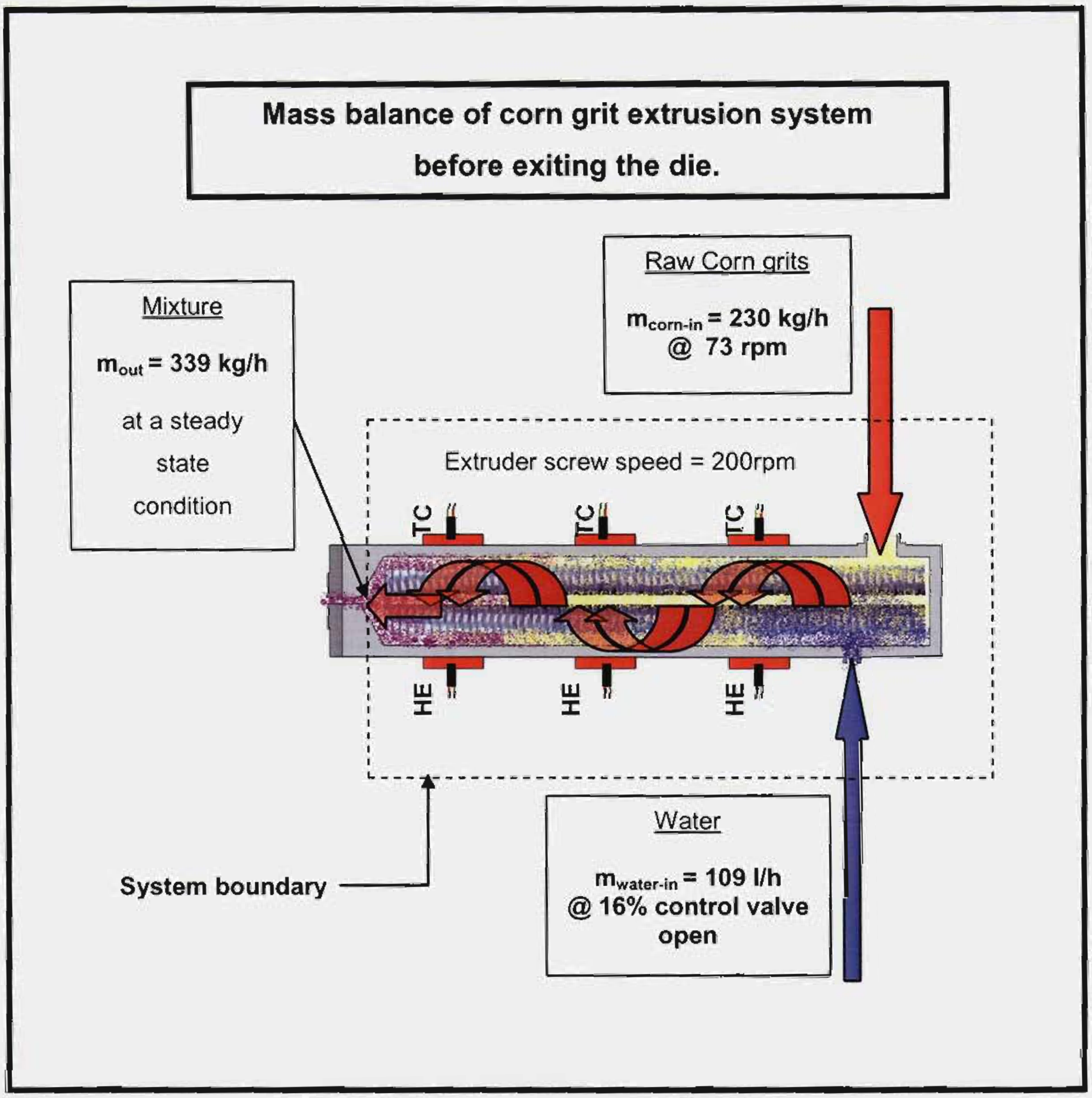


Figure 5.3: Mass balance of corn grit extrusion system before exiting the die.

Assume a system boundary as indicated in the figure above with the water injection rate at 109 l/h and the feed rate at 230 kg/h fed into the boundary system.

The extrusion mass balance can be expressed by the following equation.

$$\sum m_{in} - \sum m_{out} = \Delta m_{sys}$$

Where $\sum m_{in}$ = Sum of all input mass flows into boundary system.

$\sum m_{out}$ = Sum of all outgoing mass flows from boundary system.

Δm_{sys} = Accumulation of mass in boundary system.

If a steady state extrusion process is assumed, there is no accumulation in the system.

Thus $\Delta m_{sys} = 0$

And therefore $\sum m_{in} = \sum m_{out}$

$\sum m_{in}$ = Water Injection ($m_{w\text{-}in}$) + Corn grits ($m_{corn\text{-}in}$)

Corn grits ($m_{corn\text{-}in}$) can be divided into soluble and insoluble solids

Therefore

$\sum m_{in}$ = Water Injection ($m_{w\text{-}in}$) + Corn grits $m_{corn\_soluble}$

+Corn grits $m_{corn\_insoluble}$

= 109kg/h + 6.8kg/h + 223.2kg/h with 1L water = 1kg

= 339 kg/h

The pre-extruded corn grit and water mixture will have a combined mass flow rate of 339kg/h before extrusion through the die. No external heating was assumed for the above calculation and will be discussed in the following section.

The actual mass flow rate measured at the exit of the extruder die during steady state conditions was 250kg/h. The extruded product exiting the extruder die was collected over a 10 min interval and weighed. The extruder throughput was measured at 25kg per 10 minutes and multiplied by 6 to give an average throughput of 250kg/h.

The above mass flow rate model with no heat energy input just before the die was calculated at 339kg/h and the actual extruder throughput with heat energy input was measured at 250kg/h. The difference between the two mass flow rates calculated is 89kg/h of which 84.7kg/h is moisture and 4.3kg/h is soluble. This can be attributed to evaporation losses due to the addition of heat energy to the extrusion system. Please refer to ***Appendix E*** for a detailed mass and energy balance calculation for this extrusion process.

5.4.2 Temperature measurement and barrel temperature control

The temperature measurements that were taken for the three heating zones (HZ) will be discussed in the following sections.

5.4.2.1 Temperature measurement and barrel temperature control for Heating Zone 1

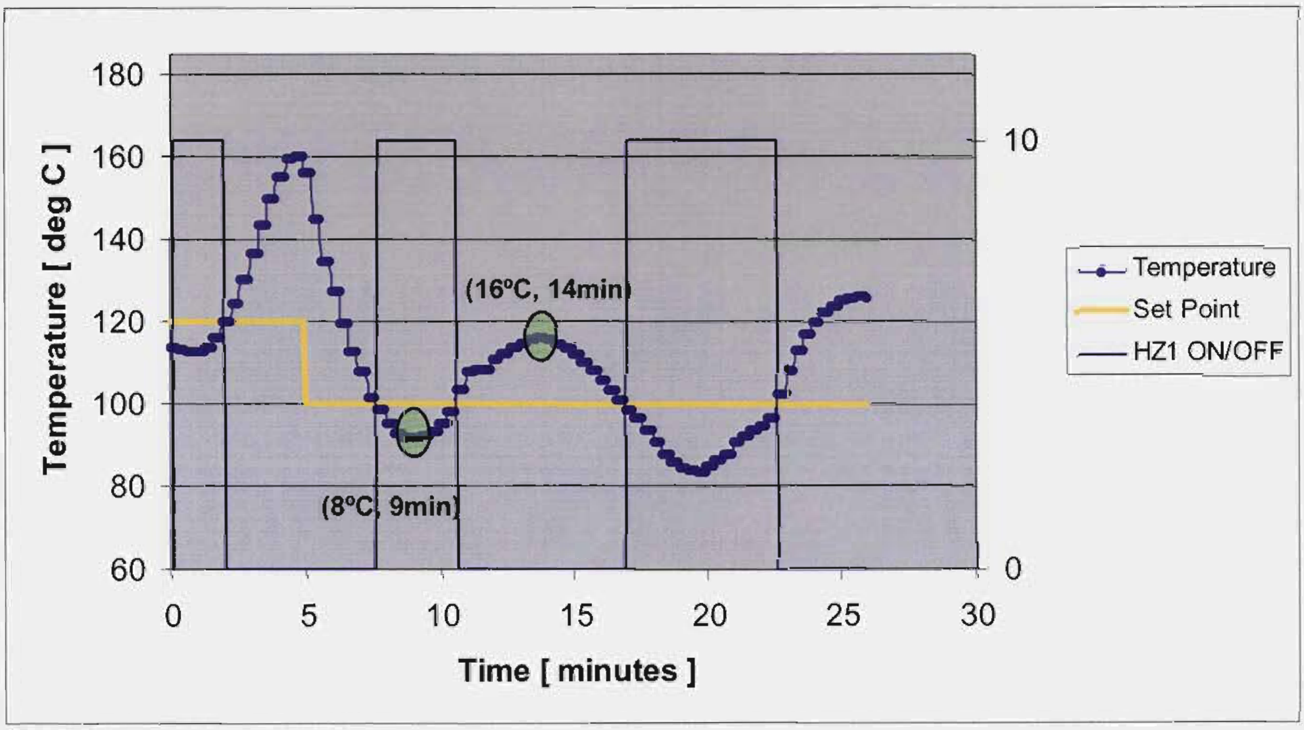


Figure 5.4: HZ1 temperature measurement and control.

The initial set point for HZ1 was set to 120°C to accelerate the barrel heating procedure and was reduced 100°C after 5 minutes. With regard to figure 5.4 it is clear that the actual barrel temperature measured in this zone after resetting the set point to 100°C, under-shoots the set point by 8°C at 9 minutes and over-shoots the set point by 16°C at 14 minutes. A possible explanation for this could be that the conduction heat transfer rate between the heating element and barrel is larger than the convection heat transfer rate between the barrel and the material in the barrel. A second explanation for this can also be that the heat transfer coefficient for the barrel material is much higher than for the material in the barrel. This implicates that better heat transfer will occur in the barrel.

It must also be noted that the first heating zone (HZ) in relation to the other two HZs is on for longer intervals than the others because the initial inlet temperatures for the two input streams (corn grits and water) is much lower than the input stream to HZ2 and HZ3 in the barrel.

5.4.2.2 Temperature measurement and barrel temperature control for Heating Zone 2

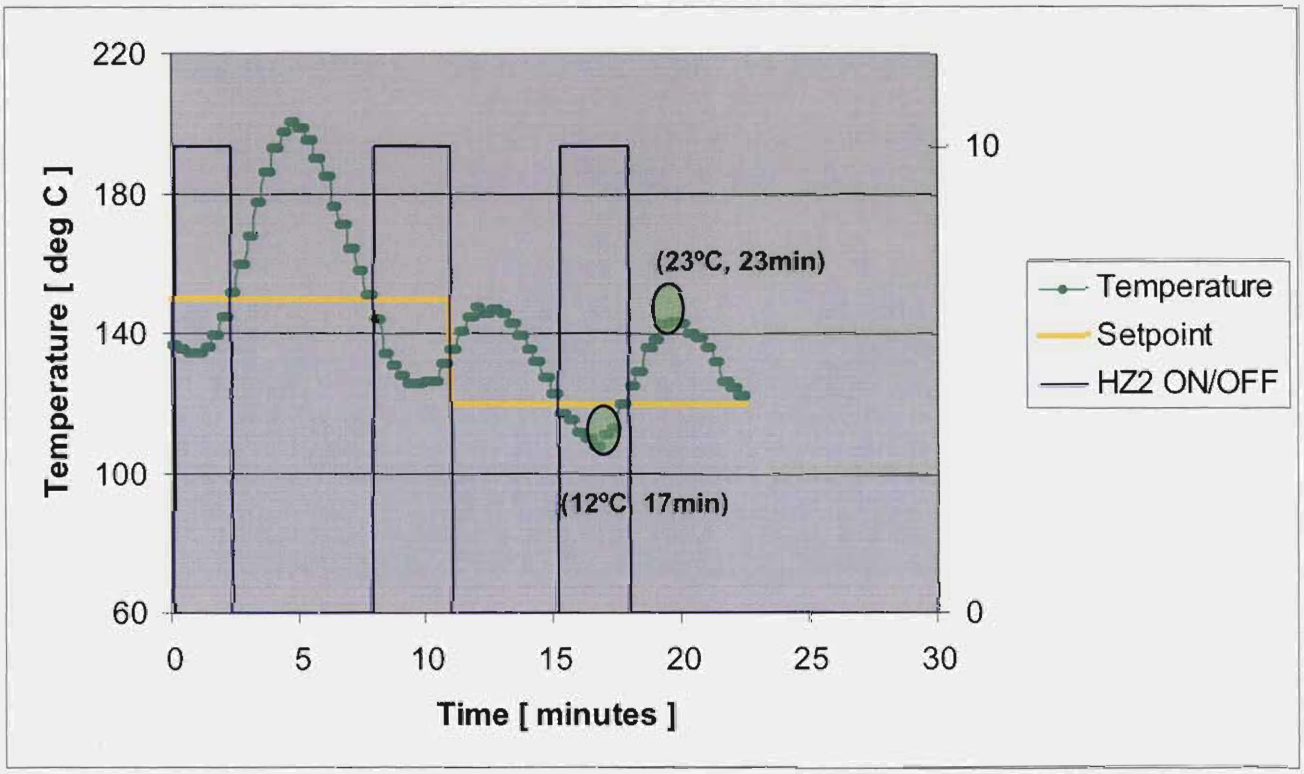


Figure 5.5: HZ2 temperature measurement and control.

The initial set point for HZ2 was set to 150°C to accelerate the barrel heating procedure and was reduced 120°C after 11 minutes. With regards to figure 5.5 it is clear that the actual barrel temperature measured in this zone after resetting the set point to 120°C, under-shoots the set point by 12°C at 17 minutes and over-shoots the set point by 23°C at 23 minutes. HZ2 is situated in the middle of the barrel between the HZ1 and HZ3. The heat generated in HZ1 and HZ3 also assists HZ2 to recover the heat transferred to the material in the barrel. HZ2 in relation to HZ1 and HZ3 is on for equally long but shorter periods.

5.4.2.3 Temperature measurement and barrel temperature control for Heating Zone 3

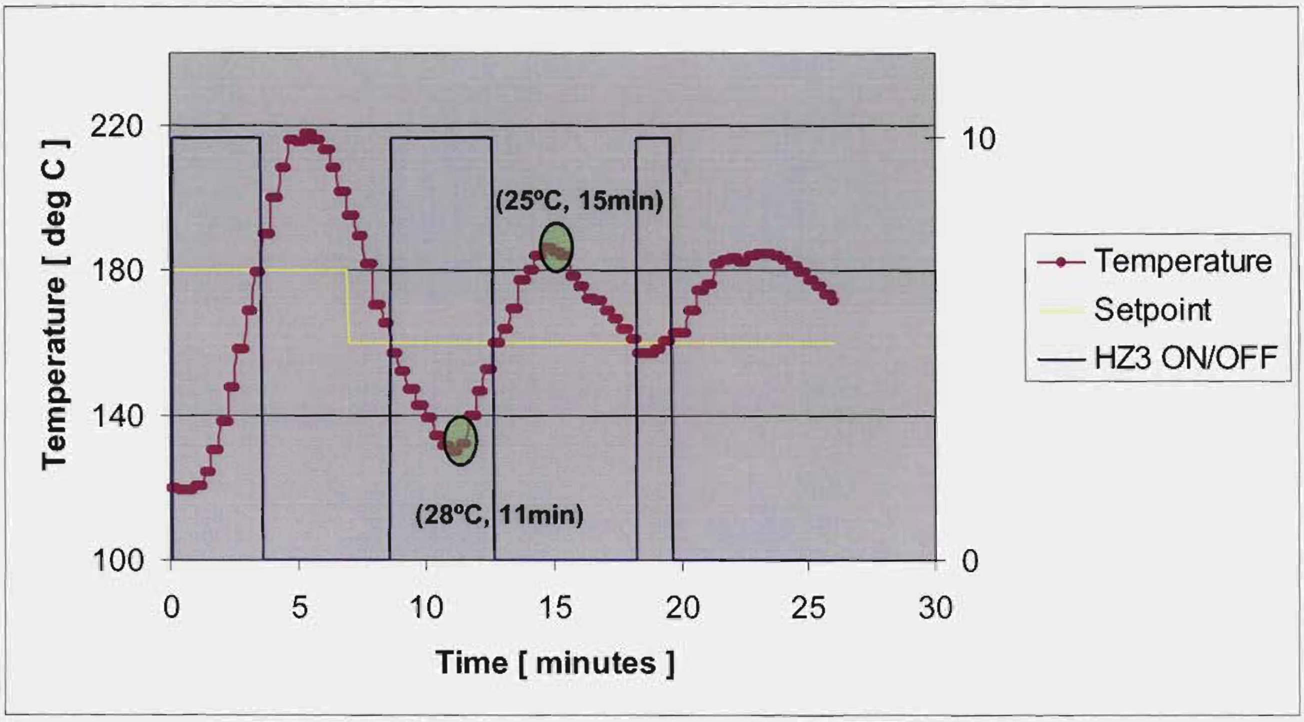


Figure 5.6: HZ3 temperature measurement and control.

The initial set point for HZ3 was set to 180°C to accelerate the barrel heating procedure and was reduced 160°C after 7 minutes. With regards to figure 5.6 it is clear that the actual barrel temperature measured in this zone after resetting the set point to 160°C, under-shoots the set point by 28°C at 11 minutes and over-shoots the set point by 25°C at 15 minutes. HZ3 is located just in behind the extruder die. This zone was set to a higher temperature set point due the specific extrusion process. The increased temperature increases the pressure behind the die and assists the extrusion process with a larger pressure drop across the die to produce the expanded snack.

5.4.3 Mechanical energy input during the Start-Up, Run and Shutdown stages

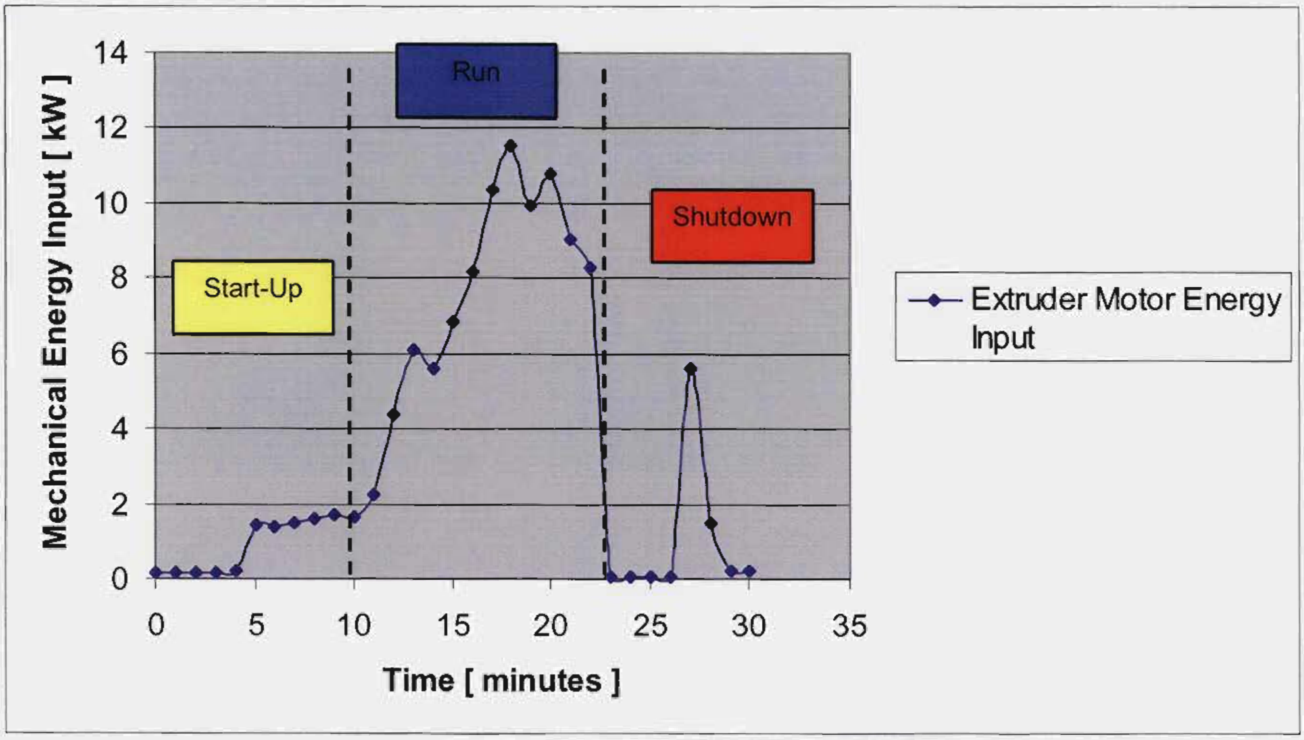


Figure 5.7: Mechanical energy input during the Start-Up, Run and Shutdown stages.

The Mechanical energy input from the extruder motor was calculated by measuring the current drawn (I) during each stage of the extrusion process as indicated in the figure above. The energy input was calculated by using the following formula.

$$Q_{me,\ extruder\ motor} = \sqrt{3} * V * I * \cos Ø / 1000$$

Where

$Q_{me,\ extruder\ motor}$ = Extruder Motor Mechanical Energy Input (kW)

V = Applied voltage

I = Current measured during the process (A)

Ø = Power Factor

The applied 3 phase voltage and power factor, as read from the motor nameplate for the mechanical input calculation was 380 Volt (V) and 0.80 respectively.

By using the maximum current drawn in the corresponding stage, the following energy input calculations were obtained:

- Start-Up stage max energy input.

  At V=380 Volt, I = 3.11 A, Ø =0.8

  $Q_{me,\ extruder\ motor,\ start\text{-}up}$ = 1.43 kW

- Run stage max energy input.

  At V=380 Volt, I = 25.15 A, Ø =0.8

  $Q_{me,\ extruder\ motor,\ run}$ = 11.53 kW

- Shutdown stage max energy input.

  At V=380 Volt, I = 12.21 A, Ø =0.8

  $Q_{me,\ extruder\ motor,\ shut\text{-}down}$ = 5.6 kW

During the Start-up stage and Shutdown stage the energy input is much smaller in comparison to the Run stage where the raw material is cooked and extruded. To calculate the net mechanical energy input to extrude the final product, the energy input with no material in the barrel must be subtracted from the energy input during the extrusion process. This can be calculated by the following formula:

$$Nett_{energy\ input} = Q_{me,\ extruder\ motor,\ run} - Q_{me,\ extruder\ motor,\ start\text{-}up}$$

$Q_{me,\ extruder\ motor,\ run}$ = 11.53 kW for the maximum energy input during the extrusion process.

$Q_{me,\ extruder\ motor,\ start\text{-}up}$ = 1.43 kW for the maximum energy with an empty barrel.

$Nett_{energy\ input} = Q_{me,\ extruder\ motor,\ run} - Q_{me,\ extruder\ motor,\ start\text{-}up}$

= 10.1 kW to convey and extruded the final product.

During the Run stage the mechanical energy input by the extruder motor increases due to the following parameters:

a) increased extruder screw speed;
b) increased feed rate from holding bin;
c) decreased water injected into the barrel;
d) temperature of the material being conveyed through the extruder barrel; and
e) die-opening.

The maximum energy input by the extruder motor during the shutdown stage was calculated as 5.6kW where 12.21A is drawn to convey the un-extruded material through the barrel during the barrel cleaning process. The main reason for the spike seen in figure 5.7 is because the extruder screws are stopped during the shutdown stage. Due to the high friction between un-extruded material and the barrel, the screws have to overcome the friction to convey the un-extruded material forward in the barrel. This is done after the die is removed to clean the extruder barrel.

5.5 Conclusion

- In the initial sections of this chapter, the application of a PLC controlled extrusion process to produce an expanded snack from corn grits was discussed.
- The three basic stages of the extrusion process were addressed and the corresponding input parameters for each stage were discussed.
- The use of the micro data logger system for the experiment was effective and sufficient data was captured to analyse the extrusion process.
- The relation between extruder screw speed, feeder screw speed and percentage of water injected into the extrusion system was investigated. It is evident that extrusion parameters must be incremented or decremented slowly in relation to each other during any extrusion process.

- The extrusion mass balance calculation proved that there are substantial moisture vaporisation losses during the extrusion process due to the addition of heat energy.
- Two-position temperature control for this specific extrusion process is effective, but must be refined for temperature-dependent extrusion processes, for example extrusion of liquorice.
- The mechanical energy input for the extruder motor was examined for each stage of the extrusion process and the net mechanical input was calculated. It must be noted that the other controllable extrusion parameter, for example the feeder, also draws energy to convey the raw material into the system.
- The PLC control system functions effectively, however the desired final product texture was not achieved during this study. The main reason for this was that the desired pressure could not be achieved due to inadequate sealing between the barrel and die plate faces.

6 Chapter 6: Conclusions and recommendations

6.1 Introduction

This chapter summarises the most important conclusions from this study and makes recommendations for future work.

6.2 Conclusions

From the results obtained during this study, the following conclusions are made regarding the effective control of a low cost food extruder:

- An effective control system is imperative for any extrusion process and definitely assists the operator to successfully extrude products.
- There are various ways to implement a control system into any process but the aim must be to keep it simple, effective and reliable for the operator operating the extrusion process.
- There are various control modes that can be implemented to improve the control system, reduce offset and enhance stability.
- The method of control must suit the application and must be as simple as possible to achieve the desired results consistently.
- The process must be understood before it can be controlled.
- The control system must be reliable and effective.
- Two-position temperature control for this specific extrusion process is effective and low in cost compared to other temperature control modes or methods. The temperature control applied for this study can still be refined and will be discussed in the following section.
- The PLC control system that was implemented is effective and reliable enough for our current needs and definitely assists the operator controlling the process. The control system is versatile and can be applied to different extrusion processes.
- The automation of an extrusion process is very complex when the influence of the extrusion processing control variables is considered.

The main conclusions that can be reached are that

- The existing PLC control system can be partially automated with some operator intervention during start-up and shutdown.

- An in-depth study on each of the controllable components of the extrusion system will have to be conducted to fully understand the interconnection of the variables influencing each other before the PLC control system can be automated fully.

6.3 Recommendations

The following recommendations are intended to enhance the operation of the extruder and PLC control system. The aim of these recommendations is to give possible guidelines in order to achieve complete automation of the Twin-Screw Food Extruder.

1. Install additional temperature sensors in the transition area located between the tip of the screws and the entrance of the die. Ensure that the probe is in direct contact with the extrudate. This will give additional feedback to the operator of the temperature before it exits the die.
2. Install a pressure transducer in the transition area of the die to give feedback of the actual pressure in that region.
3. Redesign the die and plate configuration to seat better on to the extruder barrel. During one of the corn grit extrusion runs, some of the product escaped between the barrel and die-plate. We tried to rectify the problem by installing a gasket, but due to excessive barrel pressure, the gasket did not function as expected.
4. Refine the two-position temperature control system by installing the existing temperature sensors closer to the conveying material, flush with the internal barrel wall. This will enhance the accuracy of the temperature measurement and the actual conveyed material temperature will be measured and controlled.

5. The existing water injection method by using a dosing pump and control valve is effective, but can be refined by installing a dosing pump actuator on the pump to control the stroke length of the pump. This will enhance the water injection control and accuracy.
6. With the extrusion information compiled in this study, the extruder start-up and shutdown sequence can be partially automated by programming two new procedures for start-up and shutdown into the PLC control system.

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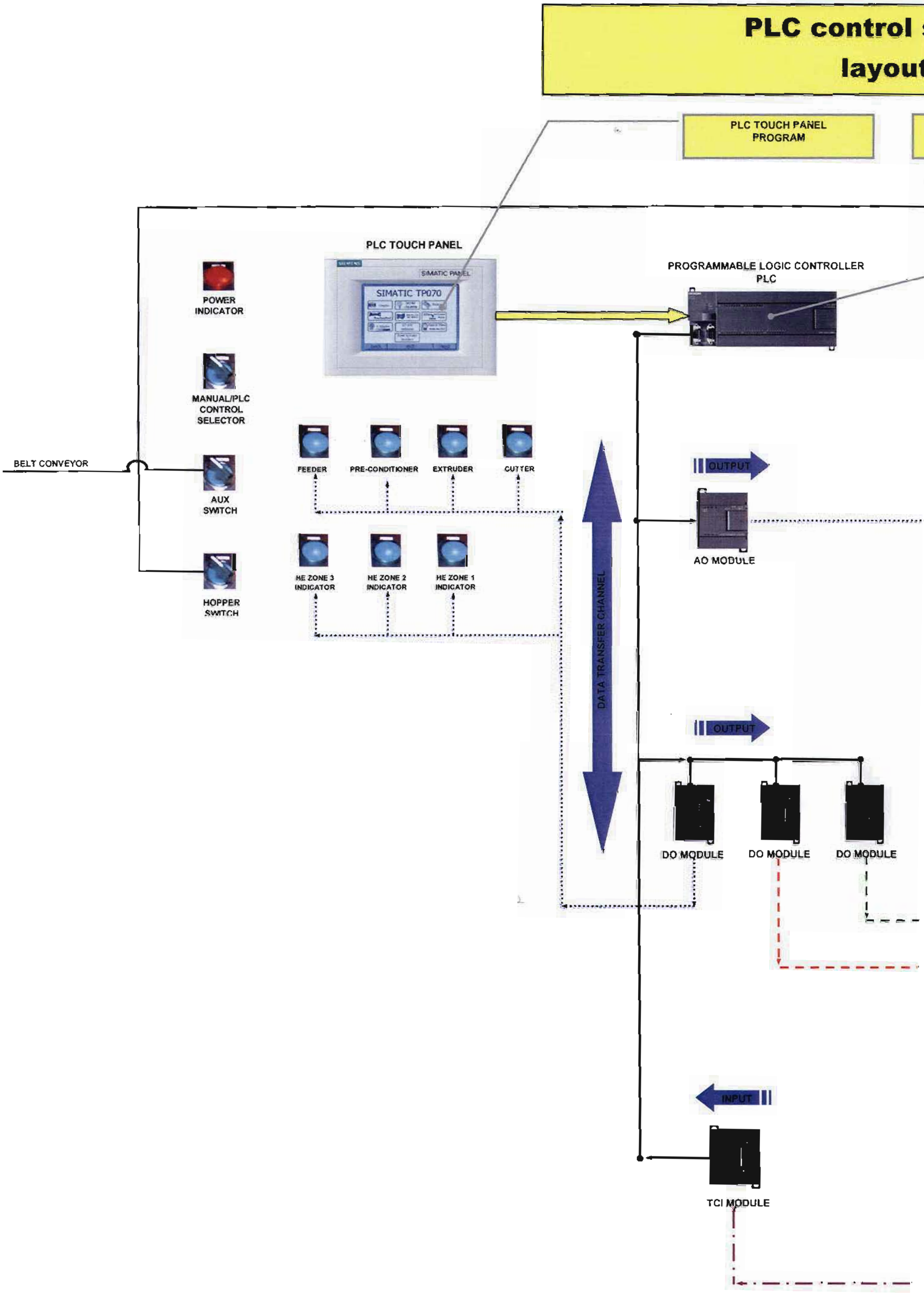
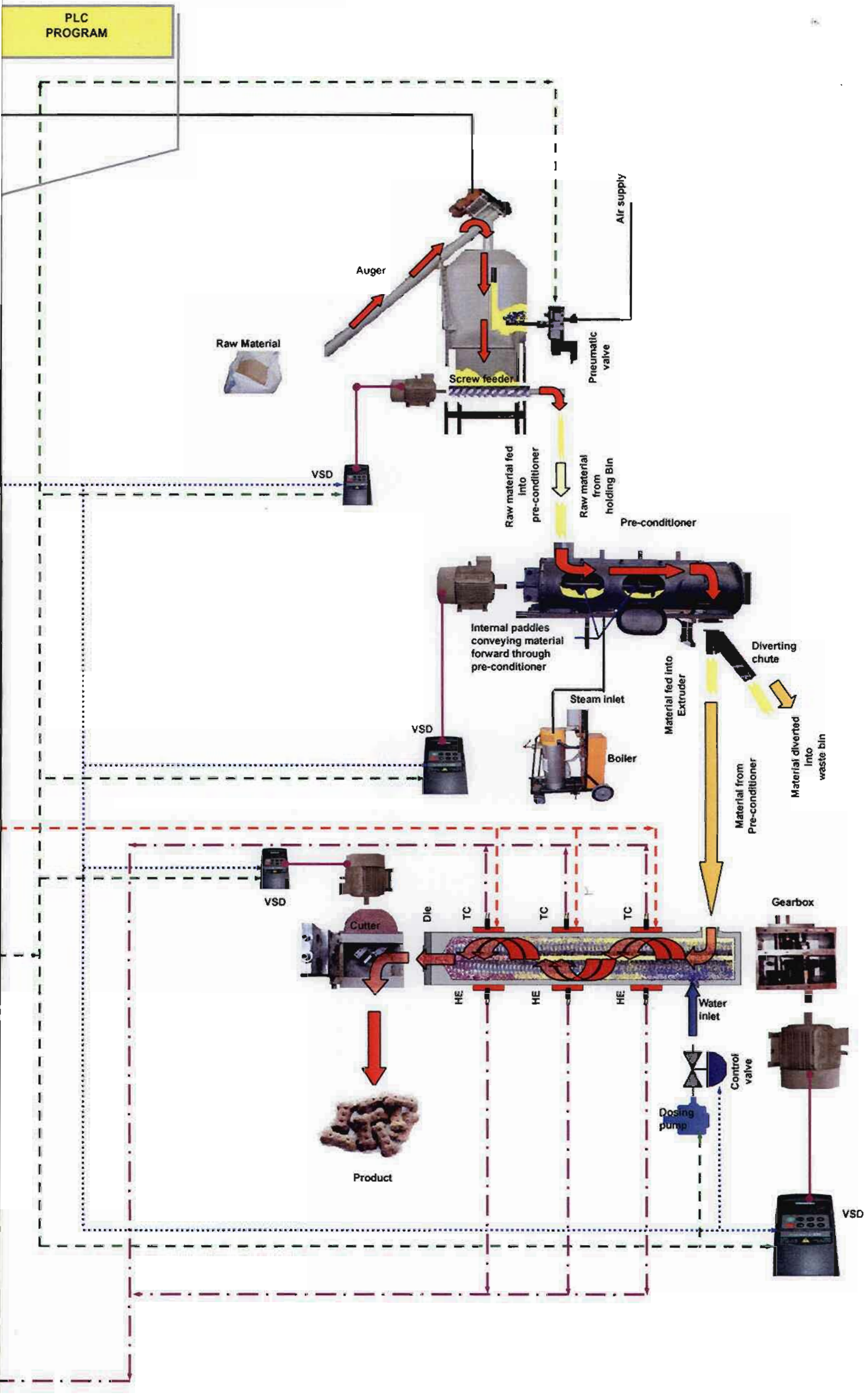
APPENDIX A

PLC CONTROL SYSTEM LAYOUT

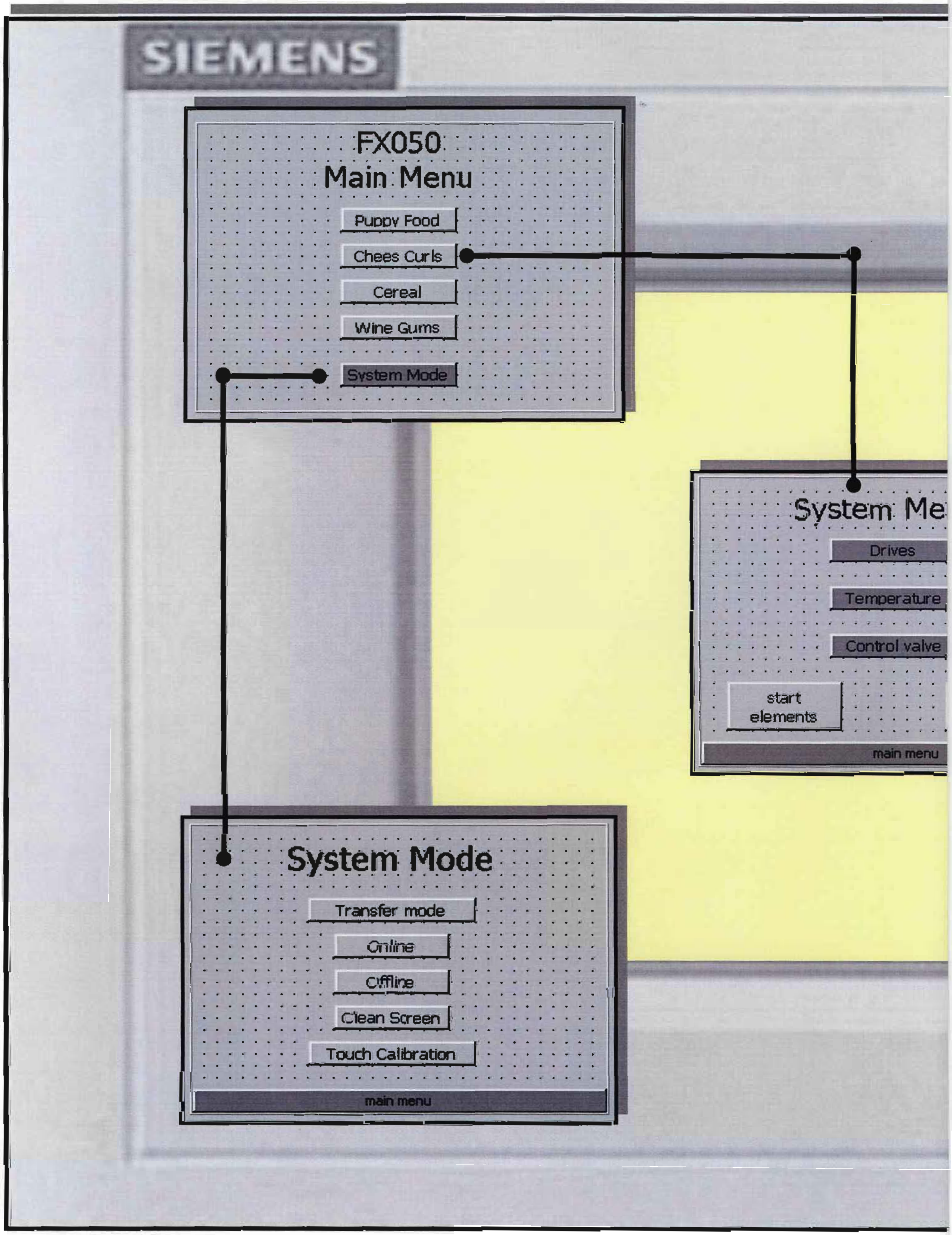

PLC control
layou
PLC TOUCH PANEL PROGRAM
PLC TOUCH PANEL
SIMATIC TP070
PROGRAMMABLE LOGIC CONTROLLER PLC
POWER INDICATOR
MANUAL/PLC CONTROL SELECTOR
BELT CONVEYOR
AUX SWITCH
HOPPER SWITCH
FEEDER
PRE-CONDITIONER
EXTRUDER
CUTTER
HE ZONE 3 INDICATOR
HE ZONE 2 INDICATOR
HE ZONE 1 INDICATOR
DATA TRANSFER CHANNEL
OUTPUT
AO MODULE
OUTPUT
DO MODULE
DO MODULE
DO MODULE
INPUT
TCI MODULE

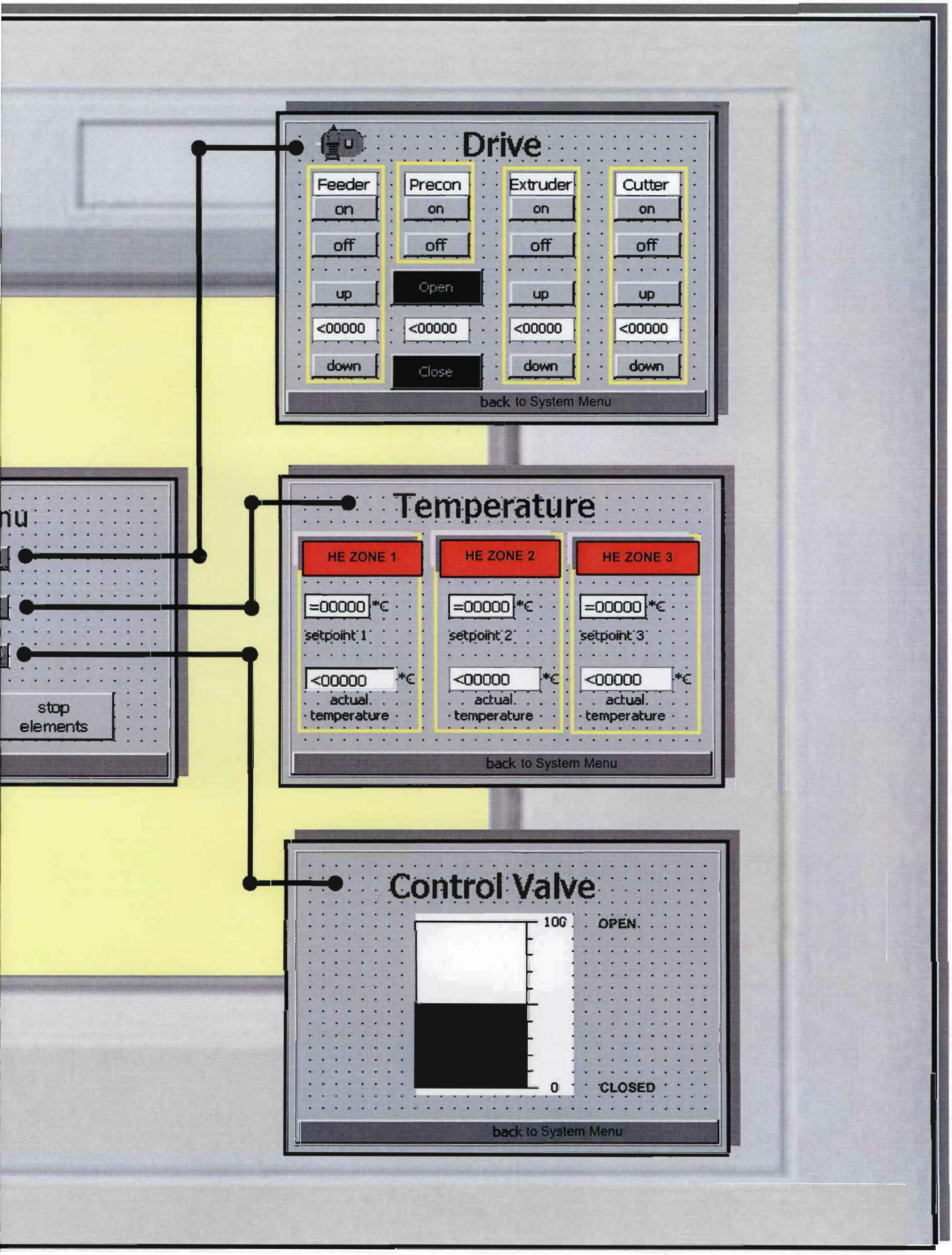
system


PLC
PROGRAM
Air supply
Auger
Raw Material
Pneumatic valve
Screw feeder
VSD
Raw material fed into pre-conditioner
Raw material from holding Bin
Pre-conditioner
Internal paddles conveying material forward through pre-conditioner
Diverting chute
Material fed into Extruder
Steam inlet
VSD
Boiler
Material diverted into waste bin
Material from Pre-conditioner
VSD
Gearbox
Cutter
Die
TC
TC
TC
HE
HE
HE
Water inlet
Control valve
Dosing pump
Product
VSD

APPENDIX B

PLC TOUCH PANEL PROGRAM


SIEMENS
FX050
Main Menu
Puppy Food
Chees Curls
Cereal
Wine Gums
System Mode
System Me
Drives
Temperature
Control valve
start elements
main menu
System Mode
Transfer mode
Online
Offline
Clean Screen
Touch Calibration
main menu


Drive
Feeder
on
off
up
<00000
down
Precon
on
off
Open
<00000
Close
Extruder
on
off
up
<00000
down
Cutter
on
off
up
<00000
down
back to System Menu
nu
stop elements
Temperature
HE ZONE 1
=00000 *C
setpoint 1
<00000 *C
actual temperature
HE ZONE 2
=00000 *C
setpoint 2
<00000 *C
actual temperature
HE ZONE 3
=00000 *C
setpoint 3
<00000 *C
actual temperature
back to System Menu
Control Valve
100
OPEN
0
CLOSED
back to System Menu

APPENDIX C

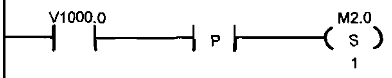
PLC PROGRAM

Block:	MAIN_MENU (OB1)
Author:	Brian Knott
Created:	04/23/02 07:16:34 PM
Last Modified:	10/12/06 08:25:04 PM

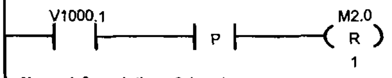
Comment:

The Main Menu is used to activate all the SUB Procedures. The SUB Procedures includes:The Temperature Control procedure for all the Heating Zones (HZ1,HZ2,HZ3).The VSD_1 (Extruder control) and VSD 2(Feeder Control) procedures.The VSD_3 (Pre-Conditioner control) and VSD 4 (Cutter Control) procedures.Control Valve and Air valve control procedure.The input parameters are inputted by the Operator from the Touch Panel. Each input parameter is assigned to a variable and is processed by the PLC program.

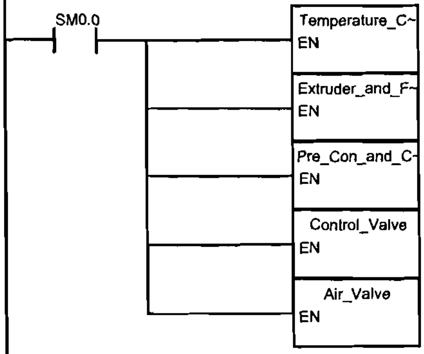
Network 1 Start and Stop Extrusion system from Touch Panel.



Network 2



Network 3 Activate Subroutines

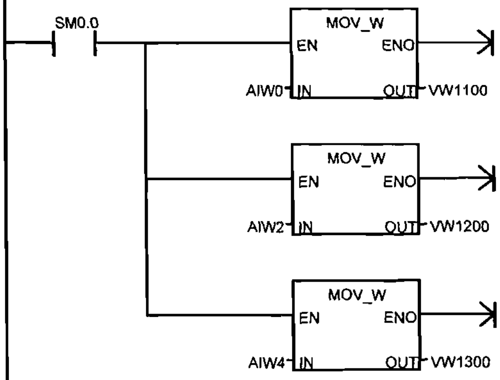


Block:	Temperature_Control (SBR0)
Author:	Brian Knott
Created:	04/23/02 07:16:34 PM
Last Modified:	07/19/06 09:11:19 PM

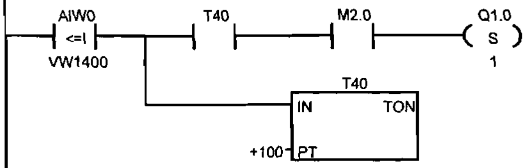
Comment:

The Temperature Control Sub Procedure consists out of the 3 Heating Element Zones(HEZ) control loops.
The temperature set points are inserted from the touch panel and assigned to a variable that is processed in each loop accordingly.
The output is sent to the respective output modules to switch the heating elements on or off.

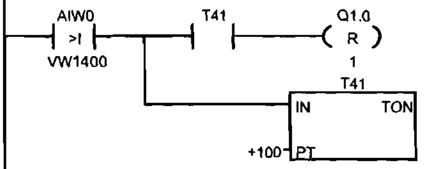
Network 1 Switch HE Zone 1 On and Off Control



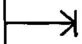
Network 2 Switch HE Zone 1 On



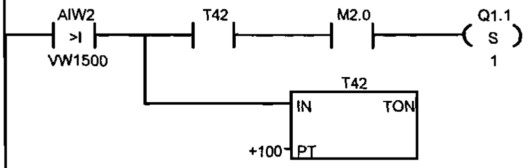
Network 3 Switch HE Zone 1 OFF



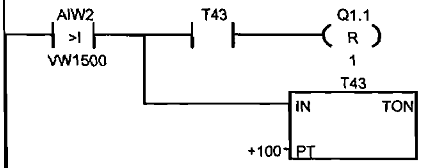
Network 4 Switch HE Zone 2 On and Off Control



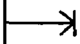
Network 5 Switch HE Zone 2 ON



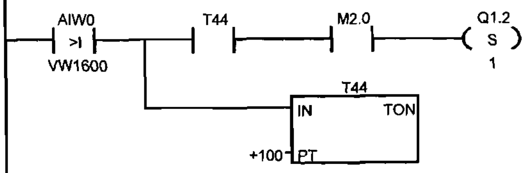
Network 6 Switch HE Zone 2 OFF



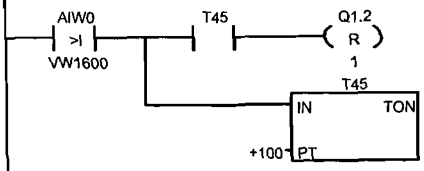
Network 7 Switch HE Zone 3 On and Off Control



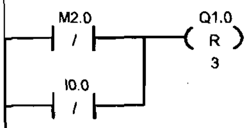
Network 8 Switch HE Zone 3 ON



Network 9 Switch HE Zone 3 OFF



Network 10 Run latch off stop all Heating Element Zones



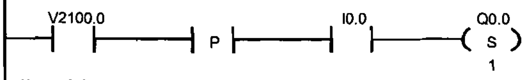
Block:	Extruder_and_Feeder_VSD (SBR1)
Author:	Brian Knott
Created:	04/23/02 07:23:36 PM
Last Modified:	07/19/06 09:11:19 PM

Comment:

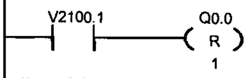
The Extruder and Feeder VSD sub procedure controls the Extruder and Feeder screw speeds.
The operator inputs the parameters from the touch panel. Each parameter is assigned to a variable and processed by the PLC program. The output from the program is sent to the respective VSD's to increment or decrement the screw speed. The Extruder and Feeder screws are also started and stopped by this sub procedure.

Network 1 Start ,Stop and Control Extruder VSD

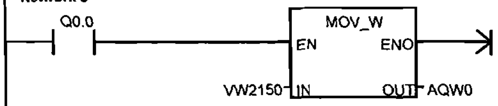
NETWORK COMMENTS



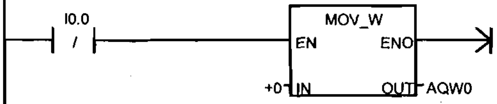
Network 2



Network 3

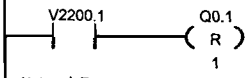


Network 4

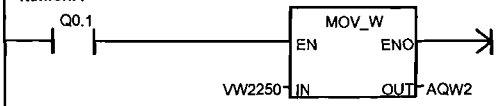


Network 5 Start ,Stop and Feeder VSD

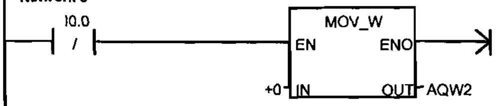
Network 6



Network 7



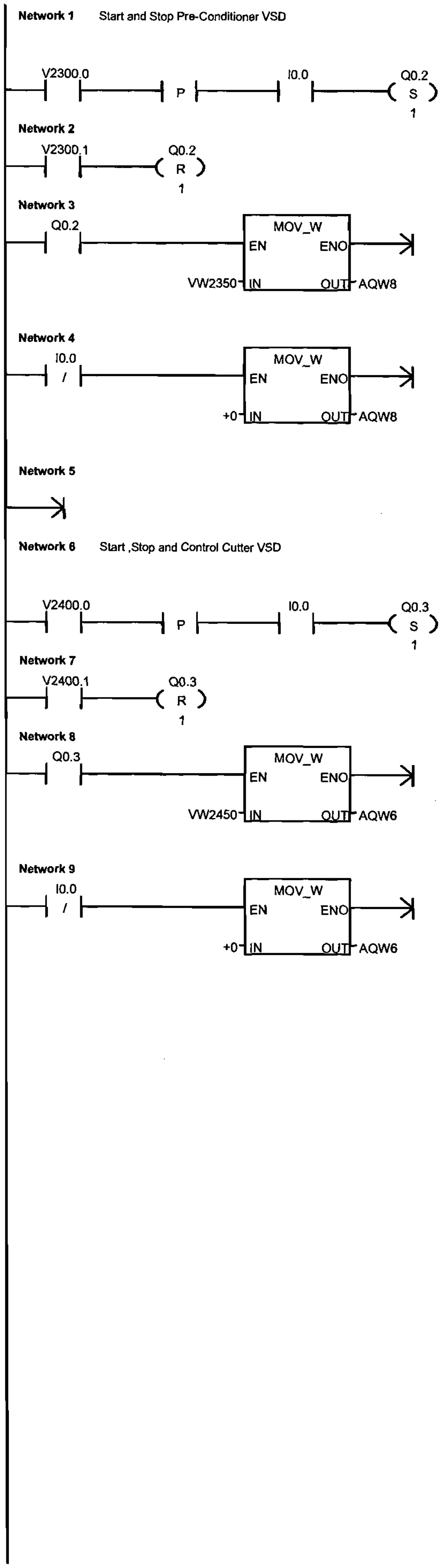
Network 8



Block:	Pre_Con_and_Cutter_VSD (SBR2)
Author:	Brian Knott
Created:	04/23/02 07:23:52 PM
Last Modified:	07/19/06 09:11:19 PM

Comment:

The Pre-conditioner and Cutter VSD sub procedure controls the Pre-conditioner and Cutter.
The operator inputs the parameters from the touch panel. Each parameter is assigned to a variable and processed by the PLC program. The output from the program is sent to the Cutter VSD to increment or decrement the cutting speed. Cutter and Pre-conditioner is started and stopped by this sub procedure.

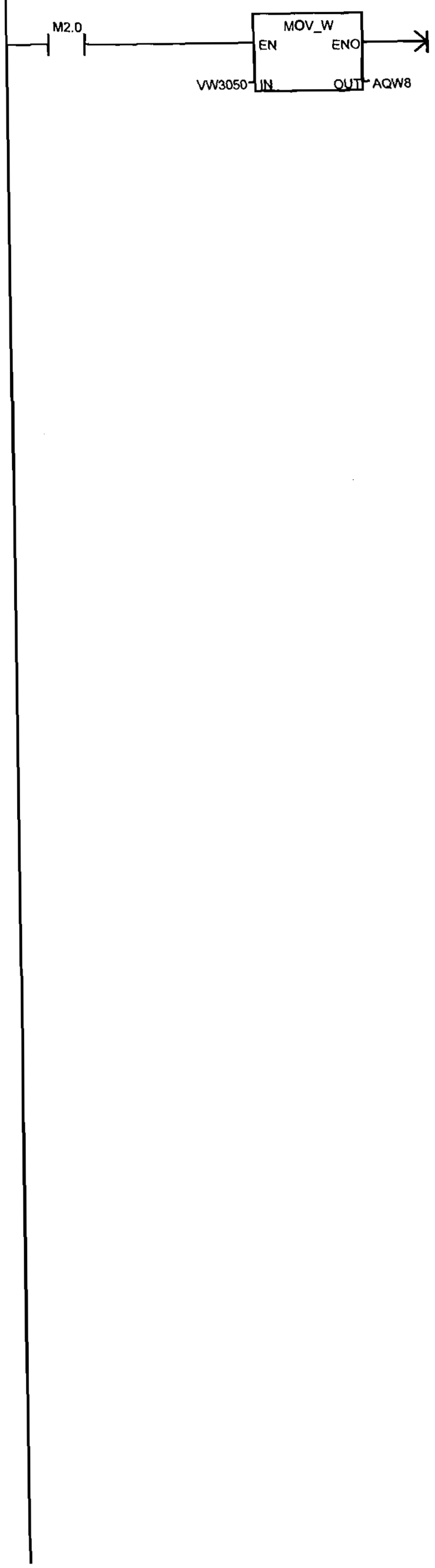

Network 1 Start and Stop Pre-Conditioner VSD
V2300.0
P
I0.0
Q0.2
S
1
Network 2
V2300.1
Q0.2
R
1
Network 3
Q0.2
MOV_W
EN
ENO
VW2350
IN
OUT
AQW8
Network 4
I0.0
/
MOV_W
EN
ENO
+0
IN
OUT
AQW8
Network 5
Network 6 Start ,Stop and Control Cutter VSD
V2400.0
P
I0.0
Q0.3
S
1
Network 7
V2400.1
Q0.3
R
1
Network 8
Q0.3
MOV_W
EN
ENO
VW2450
IN
OUT
AQW6
Network 9
I0.0
/
MOV_W
EN
ENO
+0
IN
OUT
AQW6

Block:	Control_Valve (SBR3)
Author:	Brian Knott
Created:	04/23/02 08:29:54 PM
Last Modified:	07/19/06 09:11:19 PM

Comment:

The Control valve sub procedure controls the Water Injection flow rate into the extruder.
The operator inputs the parameters from the touch panel. Each parameter is assigned to a variable and processed by the PLC program. The output from the program is sent to the control valve to open or close the valve.

Network 1 Open and Close Water Injetion Control valve

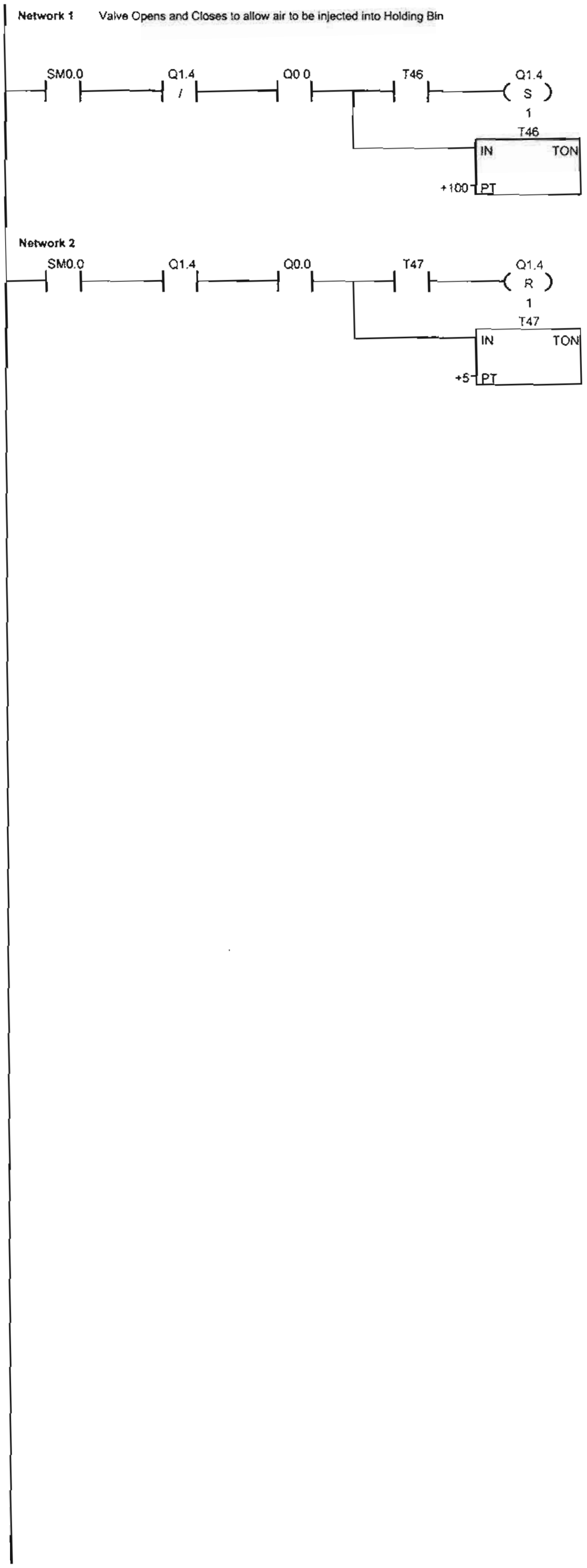


Block: Air_Valve (SBR4)
Author: Brian Knott

Created: 07/19/06 08:44:45 PM
Last Modified: 07/19/06 09:11:19 PM

Comment:

The Valve opens and closes to allow air to be injected into the Holding Bin. A built-in timer sends a signal to the output module to switch the valve every 100s.


Network 1 Valve Opens and Closes to allow air to be injected into Holding Bin
SM0.0
Q1.4
/
Q0 0
T46
Q1.4
S
1
T46
IN
TON
+100
PT
Network 2
SM0.0
Q1.4
Q0.0
T47
Q1.4
R
1
T47
IN
TON
+5
PT

APPENDIX D

MECHANICAL ENERGY INPUT FROM THE EXTRUDER MOTOR

```
V = 380
Phi = 0.80

Q_me_vol = 32
Q_me_vol = (3^(1/2))*V*I_current*cos(phi)/1000

Q_me_1 = Gearbox_operating
Q_me_1 = (3^(1/2))*V*I_current_1*cos(phi)/1000
I_current_% = I_current_1/I_current*100

Gearbox_max_kw = 30
Gearbox_operating = Gearbox_max_kw*(2/3)
Gearbox_eff = 85
Gearbox_output_kW = Gearbox_operating * Gearbox_eff / 100
Gearbox_output_per_shaft = Gearbox_output_kW / 2

I_current_startup = 3.1166
I_current_run = 25.1533
I_current_shutdown = 12.21

Q_me_start_up_max = (3^(1/2))*V*I_current_startup*cos(phi)/1000
Q_me_run_max = ((3^(1/2))*V*I_current_run*(cos(phi)))/1000
Q_me_shut_down_max = (3^(1/2))*V*I_current_shutdown*cos(phi)/1000
```

$$V = 380$$

$$\phi = 0.8$$

$$Q_{me,vol} = 32$$

$$Q_{me,vol} = 3^{[1/2]} \cdot V \cdot I_{current} \cdot \frac{\cos[\phi]}{1000}$$

$$Q_{me,1} = Gearbox_{operating}$$

$$Q_{me,1} = 3^{[1/2]} \cdot V \cdot I_{current,1} \cdot \frac{\cos[\phi]}{1000}$$

$$I_{current,\%} = \frac{I_{current,1}}{I_{current}} \cdot 100$$

$$Gearbox_{max,kw} = 30$$

$$Gearbox_{operating} = Gearbox_{max,kw} \cdot 2 / 3$$

$$Gearbox_{eff} = 85$$

$$Gearbox_{output,kW} = Gearbox_{operating} \cdot \frac{Gearbox_{eff}}{100}$$

$$Gearbox_{output,per,shaft} = \frac{Gearbox_{output,kW}}{2}$$

$$I_{current,startup} = 3.1166$$

$$I_{current,run} = 25.1533$$

$$I_{current,shutdown} = 12.21$$

$$Q_{me,start,up,max} = 3^{[1/2]} \cdot V \cdot I_{current,startup} \cdot \frac{\cos[\phi]}{1000}$$

$$Q_{me,run,max} = \frac{3^{[1/2]} \cdot V \cdot I_{current,run} \cdot \cos[\phi]}{1000}$$

$$Q_{me,shut,down,max} = 3^{[1/2]} \cdot V \cdot I_{current,shutdown} \cdot \frac{\cos[\phi]}{1000}$$

Unit Settings: [kJ]/[C]/[kPa]/[kg]/[radians]

$Gearbox_{eff}$ = 85 [%]

$Gearbox_{operating}$ = 20 [kW]

$Gearbox_{output,per,shaft}$ = 8.5 [kW]

$I_{current,\%}$ = 62.5 [%]

$I_{current,run}$ = 25.15 [Amps]

$I_{current,startup}$ = 3.117 [Amps]

$Q_{me,1}$ = 20 [kW]

$Q_{me,shut,down,max}$ = 5.599 [kW]

$Q_{me,vol}$ = 32 [kW]

$Gearbox_{max,kw}$ = 30 [kW]

$Gearbox_{output,kW}$ = 17 [kW]

$I_{current}$ = 69.78 [Amps]

$I_{current,1}$ = 43.61 [Amps]

$I_{current,shutdown}$ = 12.21 [Amps]

ϕ = 0.8 [power factor]

$Q_{me,run,max}$ = 11.53 [kW]

$Q_{me,start,up,max}$ = 1.429 [kW]

V = 380 [V]

APPENDIX E

MASS AND HEAT BALANCE OF THE EXTRUSION SYSTEM

MASS & ENERGY BALANCE FOR EXTRUSION PROCESS

$Mass_{Corn\_Grits} := 230 \frac{kg}{hr}$

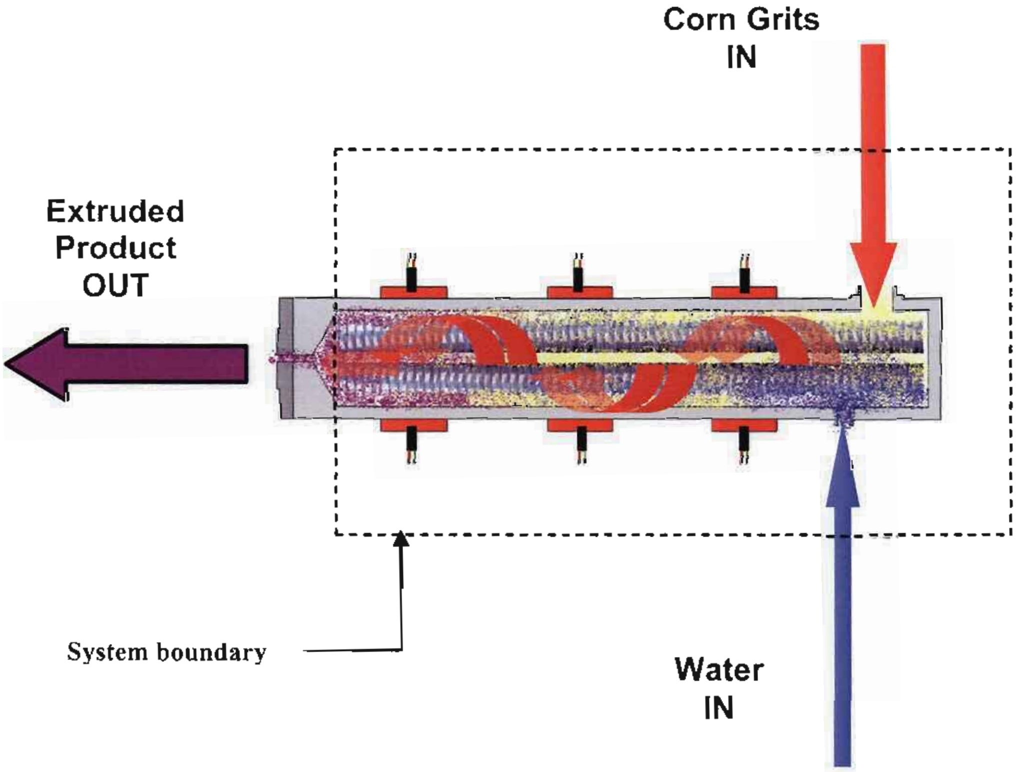
$Mass_{Frac\_moisture} := 11\%$

$Mass_{Frac\_protein} := 8\%$

$Mass_{Frac\_Fat} := 0.8\%$

$Mass_{Frac\_Carbo} := 0.4\%$

$Mass_{Frac\_Ash} := 0.3\%$



$\text{Mass}_{\text{Water}} := 109 \frac{\text{kg}}{\text{hr}}$

At steady state conditions, m.system = 0

Therefore,

$m_{\text{in}} := \text{Mass}_{\text{Com\_Grits}} + \text{Mass}_{\text{Water}}$

$m_{\text{out}} := m_{\text{in}}$

$m_{\text{system}} := m_{\text{in}} - m_{\text{out}}$

$m_{\text{in}} = 339 \frac{\text{kg}}{\text{hr}}$

$m_{\text{out\_Actual}} := 250 \frac{\text{kg}}{\text{hr}}$

The difference between the measured product rate and theoretical product rate suggests that there are system losses

$\text{Losses} := m_{\text{in}} - m_{\text{out\_Actual}}$

$\text{Losses} = 89 \frac{\text{kg}}{\text{hr}}$

We can assume that the losses in the system can be attributed to the vapourisation of water along the length of the extruder barrel. The water will include the soluble constituents of the corn grits

The solubility of corn grits in water is as follows:

$\text{Sol}_{\text{protein}} := 3.85\%$ by mass

$\text{Sol}_{\text{carb}} := 8\%$ by mass

$\text{Sol}_{\text{fat}} := 0\%$ An emulsion is formed

$\text{Sol}_{\text{Ash}} := 35\%$

Performing a Detailed Mass Balance

$Water_{in} := Mass_{Frac\_moisture} \cdot Mass_{Corn\_Grits} + Mass_{Water}$

$Water_{in} = 134.3 \frac{kg}{hr}$

$Protein_{in} := Mass_{Frac\_protein} \cdot Mass_{Corn\_Grits}$

$Protein_{in} = 18.4 \frac{kg}{hr}$

$Fat_{in} := Mass_{Frac\_Fat} \cdot Mass_{Corn\_Grits}$

$Fat_{in} = 1.84 \frac{kg}{hr}$

$Carbohydrates_{in} := Mass_{Frac\_Carbo} \cdot Mass_{Corn\_Grits}$

$Carbohydrates_{in} = 0.92 \frac{kg}{hr}$

$Ash_{in} := Mass_{Frac\_Ash} \cdot Mass_{Corn\_Grits}$

$Ash_{in} = 0.69 \frac{kg}{hr}$

Corn Grit Consituents in Water solution is as follows:

$Protein_{soln} := Sol_{protein} \cdot Water_{in}$

$Protein_{soln} = 5.171 \frac{kg}{hr}$

$Protein_{Soln} := if\left(Protein_{soln} < Protein_{in}, Protein_{soln}, Protein_{in}\right)$

$Protein_{Soln} = 5.171 \frac{kg}{hr}$

$Carb_{soln} := Sol_{carb} \cdot Water_{in}$

$Carb_{soln} = 10.744 \frac{kg}{hr}$

$Carb_{Soln} := if\left(Carb_{soln} < Carbohydrates_{in}, Carb_{soln}, Carbohydrates_{in}\right)$

$Carb_{Soln} = 0.92 \frac{kg}{hr}$

$\text{Fat}_{soln} := \text{Sol}_{fat} \cdot \text{Water}_{in}$

$\text{Fat}_{soln} = 0 \frac{kg}{hr}$

$\text{Fat}_{Soln} := \text{if}(\text{Fat}_{soln} < \text{Fat}_{in}, \text{Fat}_{soln}, \text{Fat}_{in})$

$\text{Fat}_{Soln} = 0 \frac{kg}{hr}$

$\text{Ash}_{soln} := \text{Sol}_{Ash} \cdot \text{Water}_{in}$

$\text{Ash}_{soln} = 47.005 \frac{kg}{hr}$

$\text{Ash}_{Soln} := \text{if}(\text{Ash}_{soln} < \text{Ash}_{in}, \text{Ash}_{soln}, \text{Ash}_{in})$

$\text{Ash}_{Soln} = 0.69 \frac{kg}{hr}$

Therefore, the compostion if the losses (assuming all dissolved substance have a similar volatality) will be

$$\text{Protein}_{Losses\%} := \frac{\text{Protein}_{Soln}}{\text{Protein}_{Soln} + \text{Carb}_{Soln} + \text{Fat}_{Soln} + \text{Ash}_{Soln} + \text{Water}_{in}}$$

$\text{Protein}_{Losses\%} = 0.037$

$\text{Protein}_{Losses} := \text{Protein}_{Losses\%} \cdot \text{Losses}$

$\text{Protein}_{Losses} = 3.262 \frac{kg}{hr}$

$$\text{Carb}_{Losses\%} := \frac{\text{Carb}_{Soln}}{\text{Protein}_{Soln} + \text{Carb}_{Soln} + \text{Fat}_{Soln} + \text{Ash}_{Soln} + \text{Water}_{in}}$$

$\text{Carb}_{Losses\%} = 6.521 \times 10^{-3}$

$\text{Carb}_{Losses} := \text{Carb}_{Losses\%} \cdot \text{Losses}$

$\text{Carb}_{Losses} = 0.58 \frac{kg}{hr}$

$$Fat_{Losses\%} := \frac{Fat_{Soln}}{Protein_{Soln} + Carb_{Soln} + Fat_{Soln} + Ash_{Soln} + Water_{in}}$$

$Fat_{Losses\%} = 0$

$Fat_{Losses} := Fat_{Losses\%} \cdot Losses$

$Fat_{Losses} = 0 \frac{kg}{hr}$

$$Ash_{Losses\%} := \frac{Ash_{Soln}}{Protein_{Soln} + Carb_{Soln} + Fat_{Soln} + Ash_{Soln} + Water_{in}}$$

$Ash_{Losses\%} = 4.891 \times 10^{-3}$

$Ash_{Losses} := Ash_{Losses\%} \cdot Losses$

$Ash_{Losses} = 0.435 \frac{kg}{hr}$

$$Water_{Losses\%} := \frac{Water_{in}}{Protein_{Soln} + Carb_{Soln} + Fat_{Soln} + Ash_{Soln} + Water_{in}}$$

$Water_{Losses\%} = 0.952$

$Water_{Losses} := Water_{Losses\%} \cdot Losses$

$Water_{Losses} = 84.723 \frac{kg}{hr}$

Composition of Product

$$\%Water_{Prod} := \frac{Water_{in} - Water_{Losses}}{m_{out\_Actual}}$$

$\%Water_{Prod} = 19.831\,\%$

$Water_{Prod} := m_{out\_Actual} \cdot \%Water_{Prod}$

$Water_{Prod} = 49.577 \frac{kg}{hr}$

$$\%Protein_{Prod} := \frac{Protein_{in} - Protein_{Losses}}{m_{out\_Actual}}$$

$$\%Protein_{Prod} = 6.055\,\%$$

$$Protein_{Prod} := m_{out\_Actual} \cdot \%Protein_{Prod}$$

$$Protein_{Prod} = 15.138\,\frac{kg}{hr}$$

$$\%Carb_{Prod} := \frac{Carbohydrates_{in} - Carb_{Losses}}{m_{out\_Actual}}$$

$$\%Carb_{Prod} = 0.136\,\%$$

$$Carb_{Prod} := m_{out\_Actual} \cdot \%Carb_{Prod}$$

$$Carb_{Prod} = 0.34\,\frac{kg}{hr}$$

$$\%Fat_{Prod} := \frac{Fat_{in} - Fat_{Losses}}{m_{out\_Actual}}$$

$$\%Fat_{Prod} = 0.736\,\%$$

$$Fat_{Prod} := m_{out\_Actual} \cdot \%Fat_{Prod}$$

$$Fat_{Prod} = 1.84\,\frac{kg}{hr}$$

$$\%Ash_{Prod} := \frac{Ash_{in} - Ash_{Losses}}{m_{out\_Actual}}$$

$$\%Ash_{Prod} = 0.102\,\%$$

$$Ash_{Prod} := m_{out\_Actual} \cdot \%Ash_{Prod}$$

$$Ash_{Prod} = 0.255\,\frac{kg}{hr}$$

$$\%Corn_{Product} := 1 - \%Protein_{Prod} - \%Carb_{Prod} - \%Fat_{Prod} - \%Ash_{Prod} - \%Water_{Prod}$$

$$\%Corn_{Product} = 73.14\,\%$$

$$Corn_{Product} := \%Corn_{Product} \cdot m_{out\_Actual}$$

$$Corn_{Product} = 182.85\,\frac{kg}{hr}$$

HEAT BALANCE

The temperature was measured across the length of the extruder barrel at the HE Zone 1, 2, 3.

The average temperature was used for this Heat Balance Model

$HZ_1 := 100$ °C

$HZ_2 := 120$ °C

$HZ_3 := 160$ °C

The J-Type thermocouples were inserted at a depth

$x_1 := 10\text{mm}$

below the barrel surface

Material of Barrel = Carbon Steel (EN19)

Calculation of Inside Extruder Wall Temperature - T.i

$\text{Barrel}_{\text{Thickness}} := 25\text{mm}$

$\text{Heat}_{\text{Thickness}} := \text{Barrel}_{\text{Thickness}} - x_1$

$x := \text{Heat}_{\text{Thickness}}$

$x = 15\,\text{mm}$

Total Duty of all heating elements (6) =

$Q_{\text{total}} := 18\text{kW}$

$Q_{\text{element}} := 3\text{kW}$

$k := 42 \frac{\text{W}}{\text{m}\cdot\text{K}}$

$\text{Length}_{\text{barrel}} := 1170\text{mm}$

$\text{Length}_{\text{section}} := \frac{\text{Length}_{\text{barrel}}}{3}$

$\text{Length}_{\text{section}} = 390\,\text{mm}$

$\text{Width}_{\text{barrel}} := 180\text{mm}$

$\text{Area}_{\text{section}} := \text{Length}_{\text{section}} \cdot \text{Width}_{\text{barrel}}$

$\text{Area}_{\text{section}} = 0.07\ \text{m}^2$

$$T_1 := \left(HZ_1 \cdot K + 273.15K - \frac{Q_{\text{element}}}{k \cdot \text{Area}_{\text{section}}} \cdot x \right)$$

$T_1 = 357.887\ K$

$$T_2 := \left(HZ_2 \cdot K + 273.15K - \frac{Q_{\text{element}}}{k \cdot \text{Area}_{\text{section}}} \cdot x \right)$$

$T_2 = 377.887\ K$

$$T_3 := \left(HZ_3 \cdot K + 273.15K - \frac{Q_{\text{element}}}{k \cdot \text{Area}_{\text{section}}} \cdot x \right)$$

$T_3 = 417.887\ K$

The average temperature of the inside wall of the extruder can be simplified as

$$T_{\text{ave}} := \frac{T_1 + T_2 + T_3}{3}$$

$T_{\text{ave}} = 384.554\ K$

The corn inlet temperatue to the extruder T.corn will be 25°C

$T_{\text{corn}} := 25K + 273.15K$

$T_{\text{corn}} = 298.15\ K$

$$Cp_{\text{protein}} := 1549 \frac{J}{kg \cdot K}$$

$$Cp_{\text{fat}} := 1675 \frac{J}{kg \cdot K}$$

$$Cp_{\text{ash}} := 837 \frac{J}{kg \cdot K}$$

$$Cp_{Carbo} := 1424 \frac{J}{kg \cdot K}$$

$$Cp_{water} := 4187 \frac{J}{kg \cdot K}$$

$$Cp_{corn} := \begin{pmatrix} Cp_{protein} \cdot Mass_{Frac\_protein} + Cp_{fat} \cdot Mass_{Frac\_Fat} + Cp_{ash} \cdot Mass_{Frac\_Ash} \cdots \\ + Cp_{Carbo} \cdot Mass_{Frac\_Carbo} + Cp_{water} \cdot Mass_{Frac\_moisture} \end{pmatrix}$$

$$Cp_{corn} = 606.097 \frac{J}{kg \cdot K}$$

$$L_{v\_water} := 2142000 \frac{J}{kg}$$

$$Vol_{extr} := 1170mm \cdot 50mm \cdot 92mm$$

$$Vol_{extr} = 5.382 \text{ L}$$

$$\rho_{corn} := 690 \frac{kg}{m^3}$$

$$\rho_{water} := 980 \frac{kg}{m^3}$$

$$\rho_{bulk} := \frac{\rho_{corn} \cdot Mass_{Corn\_Grits} + \rho_{water} \cdot Mass_{Water}}{Mass_{Corn\_Grits} + Mass_{Water}}$$

$$\rho_{bulk} = 783.245 \frac{kg}{m^3}$$

$$Mass_{extr} := Vol_{extr} \cdot \rho_{bulk}$$

$$Mass_{extr} = 4.215 \text{ kg}$$

$$Res_t := \frac{Mass_{extr}}{Mass_{Corn\_Grits} + Mass_{Water}}$$

$$Res_t = 44.766 \text{ s}$$

Therefore the total energy

$E := Q_{total} \cdot Res_t$

$E = 8.058 \times 10^5 \text{ J}$

$$Cp_{bulk} := \frac{Cp_{corn} \cdot Mass_{Corn\_Grits} + Cp_{water} \cdot Mass_{Water}}{Mass_{Corn\_Grits} + Mass_{Water}}$$

$$Cp_{bulk} = 1.757 \times 10^3 \frac{\text{J}}{\text{kg} \cdot \text{K}}$$

Boiling point of water is 95 °C

The system operates under sufficient pressure to suppres boiling. All energy will be consumed as sensible heat and will raise the corn / water temperature. The water will flash at the exit

$T_{boil} := 95\text{K} + 273.15\text{K}$

$T_{boil} = 368.15 \text{ K}$

$$T_{exit} := \frac{E \cdot 0.8 + Cp_{bulk} \cdot Mass_{extr} \cdot T_{corn}}{Cp_{bulk} \cdot Mass_{extr}}$$. 20% energy losses to surrounding is assumed

$T_{exit} = 385.161 \text{ K}$

The exit temperature is greater than the boiling point, therefore vapourisation will occur

$T_3 = 417.887 \text{ K}$ Extruder wall temperature at exit

$\Delta T := T_3 - T_{exit}$

$\Delta T = 32.726 \text{ K}$

Therefore it is reasonable to assume moisture losses of 89 kg/hr (water + solubles) due to vapourisation

this assumption is based on the exit temperature being greater than the boiling point as well as a 32°C delta T in approach between the corn exit temperature and extruder wall temperature at the exit at the die.