Generic Closed Control Loop of a High Efficiency Low Volume Bioethanol Distillery

A thesis presented in partial fulfilment of the
requirements of the degree of

Masters of Engineering
in
Mechatronics

At
Massey University
Auckland, New Zealand

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2012

Foreword

To my adoring mother who always believed that I could obtain anything that I wanted, and who supported me throughout my University Carreer and to Johan, thank you for teaching me over the last 8 years, you have been a great role model for me and many other students.

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1.0 Abstract

Bioethanol is a type of biofuel that is created by fermenting organic materials into a solution called mash. This mash contains water, dead yeast cells, feed stock solids, and 10% - 15% bioethanol (alcohol). The bioethanol is extracted by heating the mash above the boiling point of ethanol to create a vapour which is then condensed in to a liquid that is greater than 93% bioethanol in a process called distillation.

bioethanol is a viable replacement for petrol, however comparisons between the two fuel types show that with the current processes used petrol has a higher net energy yield. Bioethanol contains 30% less energy than petrol, so to compete with petrol bioethanol must be created in a way that greatly reduces its total energy cost. The most energy intensive process in the production of bioethanol is distillation, an Advanced Process Control algorithm (APC) must be implemented to make this process more efficient.

My project is based on the implementation of an APC to increase the efficiency of a bioethanol still. By using a Siemens PLC (Programmable Logic Controller), combined with their PID (Proportional, Integral, and Differential) control algorithms I intend to monitor and control the distillation of a mash containing 14% bioethanol.

With this approach I have been able to manufacture a low volume still that can produce high quality bioethanol consistently. This approach increased the total bioethanol yield by 10%, also producing a solution that is consistently above 93% ethanol which can be fed straight into a molecular sieve for dehydration, producing 100% bioethanol that can be used as a biofuel.

2.0 Introduction

With the increase in fuel prices and the imminent end of the worlds oil reserves, alternative technologies are being considered to fuel our transportation needs. Technology for both fast charging electric cars and hydrogen fuel cells are becoming more socially acceptable and financially viable. A transition phase from combustion engines to electric motors will be necessary and with it the possibility that oil may become a financially un-viable energy source before this transition is complete.

Ethanol is the most logical bridge for this transition phase as most states in America already use petrol containing 10% bioethanol (Hulsey & Coleman, 2006), with both financial and environmental benefits. It is cheaper than petrol and reduces emissions from standard petrol power plants by up to 16%(Hulsey, Coleman, 2006). Auto mobile companies are already manufacturing production models that can run on 100% ethanol, a mix of between 85% to 15% ethanol, and even regular petrol if biofuel is not available (Flexifuel Vehicles).

2.1 Background

Early combustion engines and cars were originally configured to run on alcohol, however auto mobile companies opted to manufacture cars configured for the cheaper alternative, which in the 1900s was petrol. Combustion engines are designed to burn nearly any liquid fuel and ethanol was originally chosen, not only for its renew-ability but because it was a visibly cleaner burning fuel compared to petrol. In **1917** Alexander Graham Bell said *"Alcohol makes a beautiful, clean and efficient fuel… Alcohol can be manufactured from corn stalks, and in fact from almost any vegetable matter capable of fermentation… We need never fear the exhaustion of our present fuel supplies so long as we can produce*

an annual crop of alcohol to any extent desired." ("Timeline of alcohol fuel", 2012).

The production of bioethanol is achieved through a biological process called fermentation. Yeast cells are introduced in to a sugar-rich environment, in which the yeast converts the sugar into ethanol and carbon dioxide. This process creates a mixture of ethanol, water, and feed stock solids (un-fermentable organic components and dead yeast cells) called mash.

The ethanol is then extracted from the mash by a process called distillation. Distillation is a process in which the mash is boiled creating a vapour that is then condensed into a liquid of greater purity than the mash. The boiling point changes as the percentage alcohol in the mash decreases, control of this boiling point is necessary to ensure the vapour, and distillate stream are greater than 93% ethanol.

The ethanol can not be distilled above a purity of 95% as at this purity the vapour creates an azeotrope (a mixture of 2 components has a lower boiling point than either component). This azeotrope of 95% ethanol and 5% water has a lower boiling point (approximately 78.5°C) than that of 100% ethanol (approximately 80°C) so it can not be distilled further. For use as a fuel or fuel additive the bioethanol must be passed through a molecular sieve which allows the ethanol molecules to pass through, while stopping the larger water molecules to produce a solution that is 100% ethanol.

bioethanol is a more efficient fuel than petrol as it is a more complete burning fuel that has more favourable combustion characteristics. These characteristics allow more bioethanol to be combusted than petrol in a fixed volume. Since more bioethanol can be combusted, more energy can

be released allowing a engine running on bioethanol to produce more power than petrol from a combustion engine of the same size.

For example; a family sedan with a 2L petrol engine has a power output that is restricted by many factors. These factors will include noise, fuel efficiency, and durability, all of which are dependent on the fuel type the engine is optimised for. The efficiency at which bioethanol burns results in bioethanol engines being able to produce more power from a 2L engine than petrol without seriously effecting durability or the drive-ability of the vehicle.

This increased fuel combustion will result in poor fuel efficiency. A smaller engine that took full advantage of bioethanols favourable combustion characteristics could be used. These characteristics will allow the engine to be optimised in such away that the smaller engine could produce the same power as a 2L petrol engine with a comparable fuel efficiency.

2.2 Problem

Crude oil refining has evolved other the past 100 years with research focusing on higher yields and lowering costs per litre. Although ethanol distillation is not a new process, its production has evolved for human consumption, with research focused towards high quality alcohol and post distillation treatment for flavour enhancement. Production of ethanol for use as fuel has been steadily increasing, followed by a increase in research focused on producing more alcohol per litre of mash and also reducing the cost per litre.

The main problem with bioethanol production is that energy balance equations used to calculate a fuels perceived inputs and outputs show

bioethanol costs energy rather than creates energy. As bioethanol is constantly competing with petrol for world wide adoption, bioethanol needs to be created in a way that is more energy efficient. By being more energy efficient biofuel production will be kinder to the environment and change the energy balance equation to prove that bioethanol is a viable petrol alternative.

There are two distinct areas of research for the production of bioethanol, 1) fermentation of alcohol and 2) the distillation of ethanol. Fermentation research uses both chemical and genetic engineering to increase the yield from the fermentation process. Distillation research uses mechatronics engineering to increase the yield from the distillation process while reducing the energy needed for this process. The area in which I will be studying is the distillation process, mainly around the reduction of energy consumption through the use of closed loop control.

2.3 Solution

Bioethanol distillation uses large amounts of energy to separate the bioethanol from the mash. Optimisation of this process is required to increase the total energy yield from the bioethanol. Reducing the amount of energy needed to extract the bioethanol will not only increase the energy yield from the production process, but also reduce the carbon footprint, making bioethanol a much cleaner fuel supply.

Control of the distillation process will require the implementation of a APC algorithm. A PID algorithm has been chosen as this type of algorithm is implemented on top of a closed loop control system. PID algorithms are generic closed loop control algorithms used to monitor and control the amount of energy that is introduced in to the still.

A similar project at Badger State Ethanol (BSE) used a APC algorithm to increase production of corn based bioethanol. BSE used a non-linear predictive model to increase overall production by 10.24%, and reduced steam consumption by 9.9%(Rueda & Duke, 2008). This algorithm used a mathematical model of the entire plant and process to calculate the amount of input needed to get a desired change in output.

PID control loops gave a similar improvement without the expense of modelling the plant and process. PID control of a bioethanol plant was not only a more financially viable choice, it also allowed for greater scalability compared to fixed model solution. A generic control algorithm can be used on many differed plants, the model produced for BSE is only applicable to their plant, or very similar plants which could use a modified model.

To control the system I am using a Siemens S7-200 PLC to automate the distillation process, which will allow me to control, monitor, and easily reprogram the system throughout the design process. The Siemens PLC programming IDE (Integrated Development Environment) has tools for tuning the PID control loops, greatly reducing the development time. The IDE will also allow me to monitor crucial information about the distillation process during both automated and manual distilling, which will give me access to data needed for analytical comparison of the two distillation processes.

In my project I will be using a “Home Brew” distillation unit and spirit distilling tools with the goal of creating an aqueous solution that I can distill both manually and automatically. Using “Home Brewing” equipment will allow me to create a mash that will consistently yield 14% alcohol. This will allow me to use these results for scientific analysis to determine both the efficiency and effectiveness of the still.

2.4 Aim

The aim of this thesis is to produce evidence that closed loop control can both reduce the amount of energy needed to produce bioethanol, and that this type of control will remove more bioethanol per litre of mash. When ethanol is removed from a mash manually, the quality of ethanol produced reduces as time increases. The solution obtained at the end of this process will be of a low quality requiring further processing and energy to produce a solution that is 100% bioethanol.

Objectives:

- To create a control system that will automate the distillation process that is more cost effective than other distillation methods.
- Create a control algorithm that will produce ethanol that is of greater purity than manual stilling by keeping tighter controls on the system, ensuring that only ethanol of 93% and above is being produced by the still.

2.5 Summary

The research that follows is based on the manufacturing of a low volume, high efficiency bioethanol still, and the comparison of this still against manual distillation. The still I am using for this project is a 60L still producing ethanol at a rate of 1L/hr, and at a proposed quality of greater than 93%. This can only be achieved with exceptional control of both the distillation tank and the column and closed loop control.

I will be using a Siemens PLC to implement a PID control loop to monitor and adjust the inputs to the distillation process. With this control system I hope to increase the amount of total ethanol extracted while decreasing the energy used. This is with the aim of producing bioethanol in a more efficient way that is financially and environmentally friendly.

3.0 Literature Review:

The literature review contains two types of information:
1) Information directly related to this thesis,
2) Information from other studies carried out on biofuel.

Information directly related to this thesis is information needed to understand the thesis, including information about how ethanol is created, the process of distillation, the control system and its implementation. Other studies in the biofuel area are included to show the current state of technology and other research being carried out around the production of bioethanol, most applicable being that in the area of optimisation of road car engines to run on neat alcohol.

The information directly related to my research is separated into 3 sections:

- Fermentation (bioethanol and its creation)
- Distillation (separating bioethanol from the mash)
- The algorithm and control systems implemented to control the distillation process.

3.1 Fermentation

In this section I will discuss ethanol, how it is created (a brief description of the chemical reaction that takes place), and how it fits in to the transportation industry. Knowledge of both the product and process are necessary as fermentation is a key part of my project and it must be carried in accordance with scientific method in order to produce standardised results. This is to ensure results found reflect the distillation process and not the fermentation process. Although fermentation is one of the oldest biological processes known to man,

precautions must be taken to ensure each fermentation is carried out in such a fashion so as not to artificially reduce or increase the amount of ethanol produced between production runs.

3.1.1 Ethanol

Ethanol is a clear, colourless liquid that has many different industrial uses most notably as a psychoactive drug found in alcoholic beverages. The same alcohol can be used as a solvent, temperature sensor in thermometers, fuel additive for petrol auto mobiles, and as a fuel for specially modified vehicles. The molecular formula for Ethanol is C_2H_5OH, which is a straight chain alcohol that burns with a smokeless blue flame (Figure 3.0).

Figure 3.0 The blue smokeless flame of ethanol combusting

Ethanol burns cleanly because it has a high oxygen content, thus requires less added oxygen to be fully combusted. When added to normal petrol it can increase the octane rating and reduce harmful emissions from a standard petrol engine. The added ethanol reduces harmful emissions by burning the fuel more completely, this is due to the extra oxygen supplied by the ethanol.

Ethanol is already used around the world as a fuel source, most notably in Brazil and more recently in America. The automotive industry already produces standard productions models with Flexifuel power plants that enable the driver to select between petrol and E85 (85% bioethanol and 15% petrol) fuel. Flexifuel cars do not take advantage of ethanols favourable combustion properties, which allow racing cars to produce performance figures an equivalent petrol engine could not produce.

As a result from 2007 – 2008 ethanol in global gasoline type fuel increased from 3.7% to 5.7%, with Brazil and America accounting for 88% of global ethanol production ("Ethanol fuel in Brazil", 2012). Currently Flexifuel vehicles make up 22% of all light vehicles registered in Brazil and 4.0% in America ("Ethanol fuel in Brazil", 2012) removing approx 30 million petrol dependent vehicles from the roads. The biggest barrier for use of E85 fuel has been determined as education- 68% of American Flexifuel vehicle owners did not know they owned Flexifuel cars that could run on E85 ("Ethanol fuel in Brazil", 2012).

Brazil is the world second largest producer of bioethanol fuel and is considered the worlds first sustainable biofuel economy and industry leader. Since 1976 the government made it mandatory to blend ethanol with gasoline ("Ethanol fuel in Brazil", 2012). At present the lowest blend allowed to be sold is E18 although E100 is available at all petrol stations. Today there are no light vehicles that run on pure petrol and all vehicles

in Brazil can run on a mixture of up to 25% ethanol. This requires slight modifications to standard petrol engines, but all vehicles manufactured or sold within Brazil are modified to use such fuel blends (“Ethanol fuel in Brazil”, 2012).

When combusted, bioethanol produces less energy than petrol, however bioethanol is burned more completely due to its higher oxygen content, reducing pollution. When combusted, bioethanol produces 22.3 MJ of energy per litre, while petrol produces 32 MJ of energy per litre , which is 30% less energy. Petrol has more energy per litre, however bioethanol has more oxygen per litre so requires less added oxygen to combust, and also a lower latent heat, and better ignition authority than petrol (Alcohol fuel, 2012).

The fuel contains the energy and the combustion chamber releases and converts this energy into rotation. The more fuel a combustion chamber can burn, the higher the energy output. An engine cylinder has a fixed volume, which limits the amount of fuel that can be burnt in the combustion chamber by limiting the amount of oxygen it can hold. Bioethanol can combust with less oxygen than petrol, meaning more ethanol can be combusted in the same sized combustion chamber, conceivably doubling the power output without increasing the engine size and with no effects on durability.

The fuel to air ratio is important when discussing internal combustion engines, as an incorrect ratio can lead to problems with the engine. Too much fuel in the combustion chamber means the engine will not perform properly, slow throttle response, and lower power as not all the fuel is burnt. Too little fuel and the engine will detonate before the piston is at the top of its stroke and cause damage to the engine. The power output of a combustion engine can only be increased by increasing the amount

of fuel it can burn, this is achieved by increasing the amount of oxygen the combustion chamber can consume (“Internal combustion engine”, 2012).

Petrol engines are further limited by the physical properties of petrol as it releases large quantities of excess heat. When increasing the performance of a combustion engine there will be a performance ceiling, at which point the engine will be unable to run as the heat produced will either weld the pistons to the cylinder, or poor spark authority will detonate and destroy the engine block. To get further performance increases, one must increase the volume of the engine. Bioethanol is limited, but the heat threshold is far higher than petrol, allowing for great performance figures from an engine smaller than its petrol performance equivalent.

Figure 3.1 Biofuel powered super car the Koenigsegg

Swedish super car manufacturer Koenigsegg have developed a mid-engine super car that is optimised to run on E100 and E85 (Figure 3.1). This car is able to produce more power using bioethanol than if it ran on petrol, due to bioethanols cooling properties and better spark authority,

allowing them to use large amounts of supercharger boost. This configuration enables the 4.7L V8 engine to produce 1,064 hp. In comparison the Bugatti Veyron uses a 8.0L W16, quad turbo engine optimised to run on petrol produces 1,001hp which is nearly double the size of the bioethanol optimised engine with similar performance.

Top fuel drag cars are able to produce thousands of horsepower by using Nitrogen-Methane, an alcohol that is 90% Nitro-glycerine and 10% Methanol. Similar to ethanol, this fuel has less energy per litre than petrol but higher oxygen content per litre meaning 8.7 times the amount of nitrogen methane can be burnt in the combustion chamber. This means it can produce four times as much power as the petrol engine, which is limited by the volume of air it can fit in the cylinder, and the physical properties of petrol. Top fuel drag cars do not need a radiator as alcohol is burnt so efficiently that minimal heat energy is released. This further reduces the weight of an alcohol powered vehicle, again adding to its efficiency (“Top Fuel”, 2012).

Flexifuel cars can run on both petrol or bioethanol depending on its availability, as bioethanol is not yet available at every petrol station across America. At this point in time most vehicles that run on biofuel are Flexifuel cars, these use modified petrol engines. A Flexi fuel vehicle can run on both petrol and bioethanol by adding more bioethanol via a modified ECU map (Engine Control Unit) (“Flexible-fuel vehicle”, 2012).

These engines are not able to take full advantage of the favourable combustion characteristics of bioethanol as they must still be able to operate with petrol as well. This reduces the efficiency of the bioethanol fuel, resulting in poor performance compared to petrol. A similar example would be running petrol in a diesel engine; it is possible but the result will be poor compared to diesel fuel (“E85”, 2012).

The lower energy content of ethanol is cited as one of the main reasons it is an unsuitable replacement for petrol. Application of the above properties and further research into neat alcohol engines could lead to a change in the engine configurations of biofuel models that car manufacturers release. Research shows that engines configured to run on pure bioethanol can achieve greater than 40% brake thermal efficiency resulting in engine configurations that can a achieve better economy than a similar sized diesel engine (Brusstar & Bakenhus, 2002).

3.1.2 Fermentation

There are two methods which can be used to obtain ethanol - Synthesis, which requires petroleum substrates so will not be considered, or fermentation, which is a biological process where yeast saccharomyces consume sugars (fructose, sucrose and glucose) excreting CO_2 and ethanol. In my project an understanding of this type of ethanol production is necessary as the organic materials needed to feed this reaction are considered a renewable energy source. Bioethanol is a renewable energy source meaning that we are able to reproduce the materials that are needed for its creation.

Yeast cells are Chemo-organotrophs, meaning they use organic material as a source of energy for reproduction and respiration and do not require sunlight to grow. The life-cycle of a yeast cell begins with reproduction, consuming excess oxygen and sugar to bud (reproduce) then in a low oxygen phase the cells ferment the available sugar into ethanol and CO_2 until it dies from excessive reproduction scars. This attribute allows the single celled fungi to ferment plant material into ethanol.

Figure 3.2 shows a yeast cell budding to create a daughter cell, also

behind this is a cell with multiple budding scars. Once a cell has reproduced to a point where its cell wall is fully covered in scars it can no longer reproduce. A colony that is badly scarred is unable to reproduce and can no longer metabolise sugar or reproduce and should be discarded.

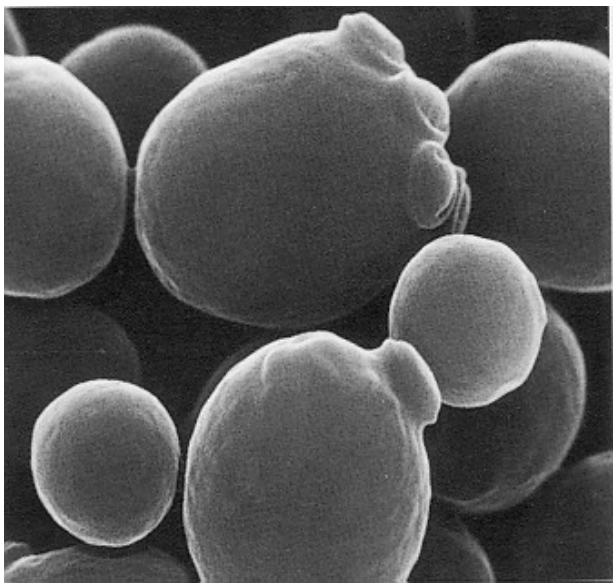


Figure 3.2 Yeast cells budding

When introduced to a environment that is optimal for fermentation, yeast cells begin by reproducing (budding) to create a high concentration of yeast cells. These yeast cells use excess oxygen in an aerobic phase to asexually reproduce, then in a low oxygen anaerobic phase the yeast cells will only ferment the remaining sugar. In this phase the yeast consumes sugar and excrete ethanol and CO_2, if oxygen is present throughout the fermentation the yeast will ferment the sugar right down to CO_2 and water.

Oxygen is introduced early in the mash creation process by agitating the mash, this is then sealed usually with some form of airlock allowing the CO_2 to escape. The air lock not only stops unwanted oxygen and micro-

organisms entering the fermentation but allows the brewer to visually monitor the CO_2 production. CO_2 is the best indicator for the health of a fermentation; if CO_2 is not being produced the yeast have stopped fermenting.

The feedstock used to fuel a fermentation comes in the form of sugar (sucrose, fructose, glucose, and maltose). Yeast use the energy stored in the sugar for reproduction and respiration. The sugar can come from sugar crops such as cane sugar, sugar beats or other plants with a high sugar content. A cheaper source of sugar that can be used is starchy food such as grain, corn, and potato, which require pre-processing to release the sugar from the starch enzymes.

Starch based plants can also be grown in more tepid climates making them more abundant and a better feedstock for biofuel. America has built a healthy biofuel industry around starch based feedstock, most notably corn. Starch based feedstock is cheaper to purchase than sugar as they are more abundant and need pre-processing to release the available sugars.

In Brazil, sugar cane and its associated by products are used in conjunction with other sugar crops and by-products as feedstock for a healthy and mature biofuel industry. Sugar crops specifically grown for the transport industry are supplemented with products form other farming sectors which may not be fit for human consumption. These feedstocks are readily available in Brazil due to its climate and geological location, Brazil has the most sustainable biofuel industry and economy in the world (“Ethanol fuel in Brazil”, 2012).

For my experiment I will be using Chelsea grade 1A sugar as the feed stock, which is sucrose (table sugar, formula is $C_{12}H_{22}O_{11}$). Yeast can only

ferment glucose, so the sucrose must first be broken down in to glucose. When added to water the sucrose is broken down into two parts glucose by a process called hydrolysis, catalysed by the enzyme invertase.

$$C_{12}H_{22}O_{11} + H_2O + \text{invertase} \rightarrow 2\ C_6H_{12}O_6$$

After the sucrose is broken down into glucose the yeast use an enzyme, zymase, to catalyse the chemical reaction that converts the glucose into ethanol. One mole of glucose is converted into two parts ethanol and two parts carbon dioxide.

$$C_6H_{12}O_6 + \text{Zymase} \rightarrow 2C_2H_5OH + 2CO_2$$

The conversion of sucrose to ethanol is dependent on the temperature of the fermenting environment, and the presence of trace nutritional elements such as nitrogen needed for yeast to reproduce and ferment. Organic material (corn, fruit or organic waste) contain these required nutrients, sucrose fermentation requires the addition of these special nutrients.

3.2 Distillation

Distillation is a physical process in which an aqueous solution made up of multiple liquid components is separated into its individual components. This process works on the basis that different solutions have differing boiling points because of the different atomic structures of the individual solutions. By boiling the solution, the component with the lower boiling point will turn into steam first, the steam is then captured and condensed into a liquid.

One of the most common types of industrial distillation is fractional distillation, which enables the column to extract different compounds at

different temperatures up the still column. A fractional still (figure 3.3) is made up of a vertical column with a heated mixture at the bottom and a cool reservoir at the top of the column. The column is subject to a temperature gradient along its length, and as the heat transfers up the column, this temperature gradient allows for extraction of substances with specific boiling points at specific points up the column.

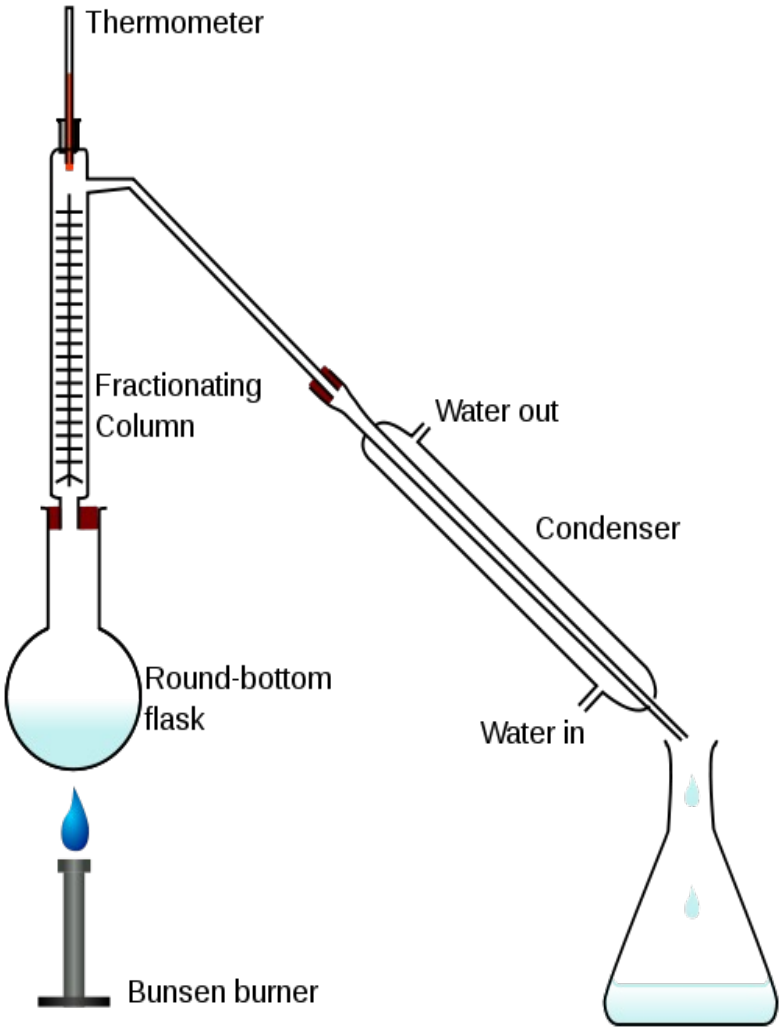


Figure 3.3 Basic distillation apparatus

Along the column are plates or reservoirs that allow the vapor to condense and then evaporate at an increased purity compared to the plates below. This process uses the heat energy from the rising steam to

phase change from liquid to vaporous. This cycle repeats up the column on each plate, re-distilling the vapour multiple times producing a highly concentrated vapour at the top of the still column to be extracted as a high purity liquid (greater than 90%).

Figure 3.4 is a diagram of a how the fractional still works as vapour rises up the column collecting on plates for further distillation. Vapour is passed through the caps and is cooled by the collected liquid on the tray, this transfers energy into the liquid allowing the more volatile component to phase change into vapour and continue up the still. As this happens the less volatile liquid is allowed to collect in the tray until it overflows back down to the tray below until eventually all the volatile liquid has passed up the column and the less volatile liquid is left in the still tank.

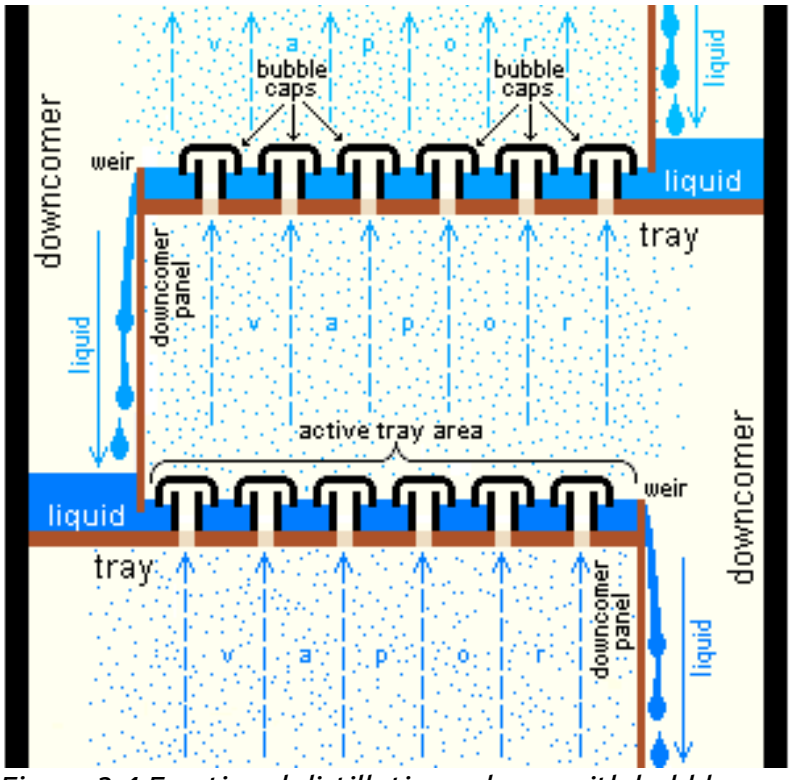


Figure 3.4 Fractional distillation column with bubble caps

The phase diagram in figure 3.5 is an example of a binary distillation of hexane and pentane carried out on a fractional column with 3 plates. This example is used as it has similar physical characteristics to water/ethanol distillation. The vapor point (The point at which a solution turns into vapor) of a one to one mix of pentane and hexane is at point L1, this vapor condensates at point V1 at a quality of less than 20% hexane. The solution vaporises at point L2 condensing at point V2, and finally condensing at point L3 which is pure pentane. This distillation is using idealised liquids so we would not be able to obtain complete separation in three phase changes.

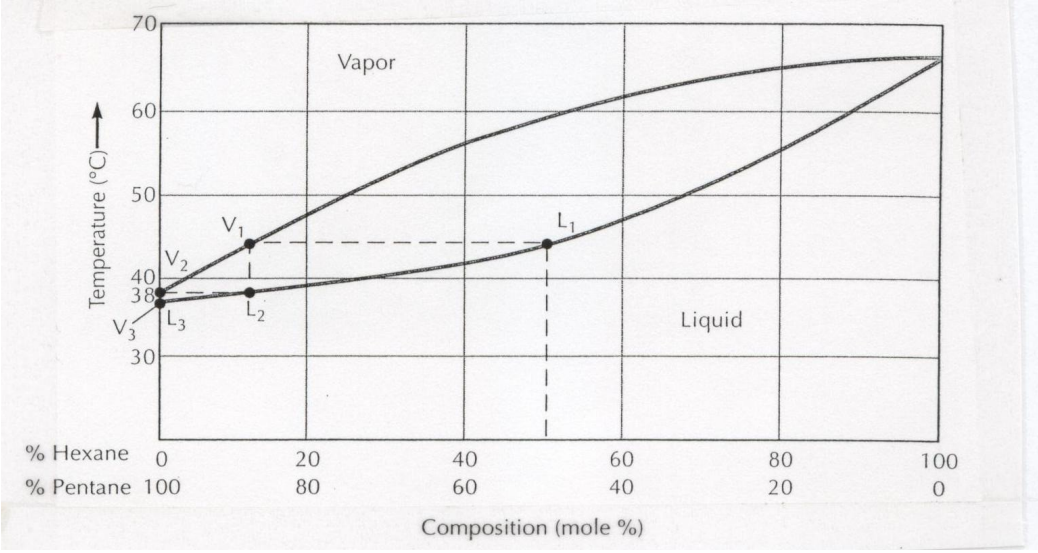


Figure 3.5 Phase change diagram of Hexane and Pentane

Figure 3.5 is the basis for a fractional distillation, each plate allows the vapor to condensate then evaporate at a different purity. This process will be repeated many times up the column allowing a highly purified liquid to be collected in a real world situation. The purity and volume of distillate to be processed determines the number of plates and length of the column (Halvorsen & Skogestad, 1999).

A fractional still not only increases the purity at which a component can

be distilled but also allows for the separation of a multi-component mixture into its individual components. The temperature at a specific point up the column can be used to collect a component from the solution with a similar boiling point. This component will not be able to travel further up the column so will collect at this point while a component with a lower boiling point will continue up the still to a point where it can be collected.

As I am only separating ethanol from water (binary distillation) and collecting it from the column, I do not need the added functionality of a fractional still. A packed column is similar in principle to a fractional still but uses a packing medium (Figure 3.6) instead of column trays. The packing medium functions as a fractional column allowing the vapor mixture to condense and evaporate on the packing medium also ensuring a constant temperature gradient along the column.

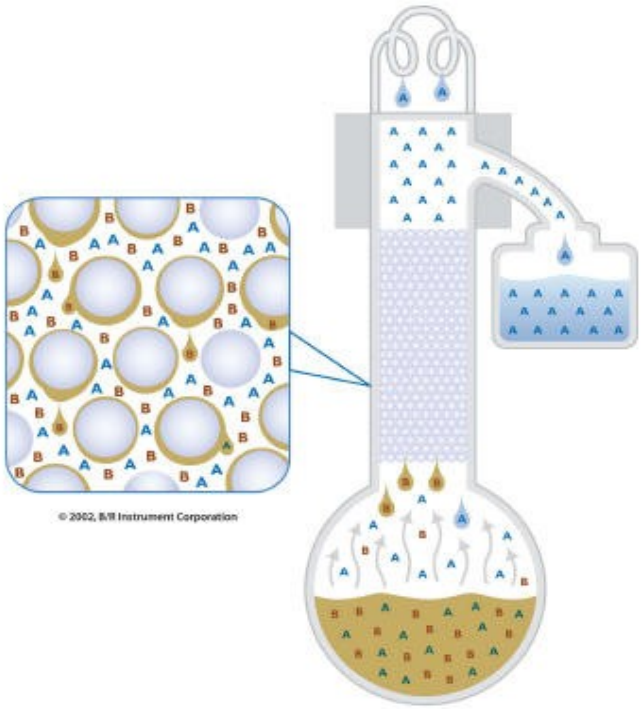


Figure 3.6 Fractional still using a packing medium

A binary distillation is made up of components A and B, A representing alcohol and B representing water. As the mash is heated up the molecules begin to separate off and travel up the column as a vapor mixture of A and B with a higher concentration of A than in the mash. As this mixture condenses on the packing medium some of the B molecules will fall back down the column while the A molecules are left to evaporate. This evaporation will be at and even higher purity than the first vapor to collect on the packing medium and this process will continues up the entire column.

Producing high quality ethanol (>90%) from the still requires the temperature control of two separate areas of the still that must be maintained at a steady temperature. Maintaining these temperatures requires closed loop control to ensure only the required amount of energy is entered into the system. By monitoring these temperatures and applying only energy needed to maintain these temperatures, my still will be able to increase the purity the alcohol extracted, thus increasing the the total yield while reducing the amount of energy needed to distill alcohol.

3.3 Control System

While theory of both fermentation and distillation are important to understand my studies and required to execute the experiments effectively, the control system is where most of the research and resources were used. The main resource was the PLC used to create a control system that would run the still consistently without failure and control the plant in such a way as to produce high quality ethanol. Background research was used to generate initial solutions to the problem but these were refined throughout the experimentation process to create the system used to obtain data displayed in this thesis.

3.3.1 Programmable Logic Controller

A computer program is a list of instructions a computer carries out in a specified sequence. This sequence can be changed in response to inputs, which will lead to manipulation of the computer program and changes to the outputs augmenting the system. Programable Logic Controllers (PLCs) are a special type of computer called a hard real-time systems allowing the programmer/engineer to control a system in which specific inputs generate known outputs.

A hard real-time system is a system that reacts to a change in the system within strict time constraints. If this deadline is missed the whole system has failed. This type of system is used in situations where a failure to react to a signal will lead to physical damage of the system, its surroundings or humans (directly or indirectly). An example is a nuclear reactor, failure to respond to a signal within a set time constraint can lead to destabilising of the reaction resulting in a reactor meltdown.

PLCs were invented in 1968 at the request of the American automotive industry for use in industrial control to reduce production line down time (Mastilovich, 2010). Large costs were incurred when production lines were being changed from one job to the next requiring large, highly skilled teams to rewire large relay boards and reset hundreds of machines and cams. These cost were to be reduced by replacing these production line changes with software revisions instead.

A PLC is more suited to controlling industrial plant operations than micro controllers or PC based control systems. These controllers are built specifically to meet many industry standards and are made by leading electrical manufacturers, therefore are easily interfaced with electrical devices and sensors. PLCs are also designed to operate in harsh industrial environments (excessive electric noise, vibration, and dusty

environments) making them ideal for my project.

The modular design of a PLC means everything is built into the system so that it can operate when power is applied. The internal design of a PLC is shown in figure 3.7, the CPU, memory and communications are all built in to the module. These features of the PLC must be considered when selecting a PLC for your specific application as they will determine how large your computer program can be (memory constraints), and also the complexity of your computer program (processing constraints).

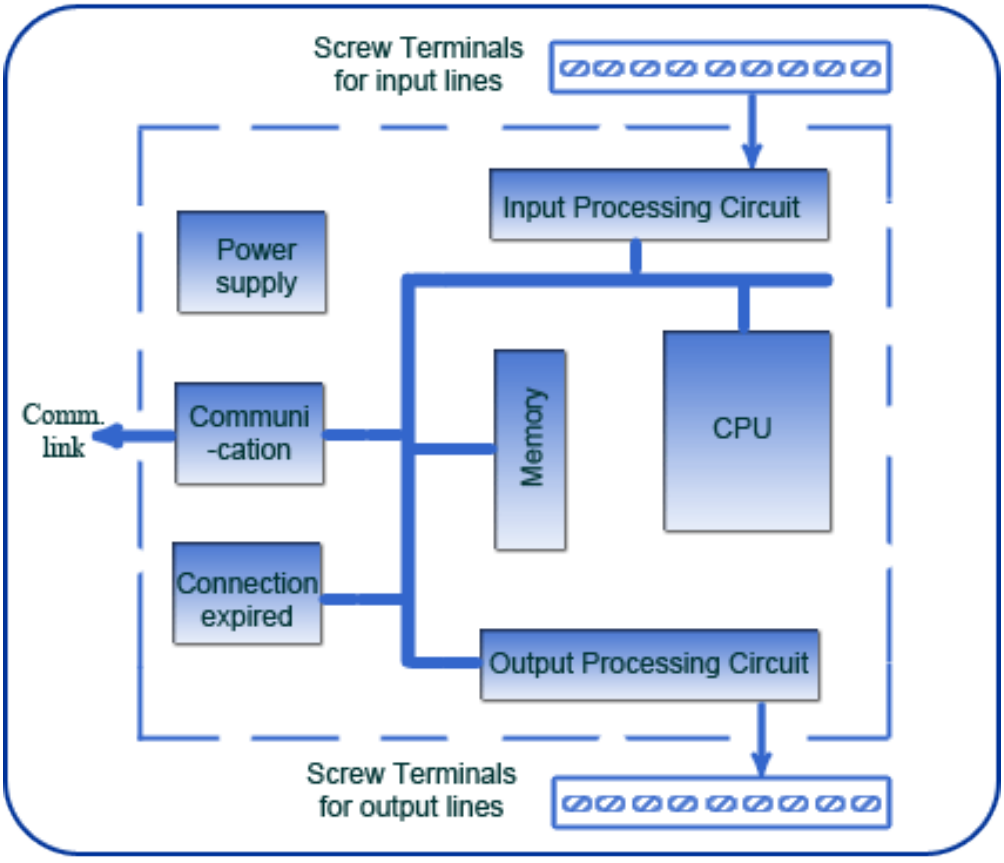
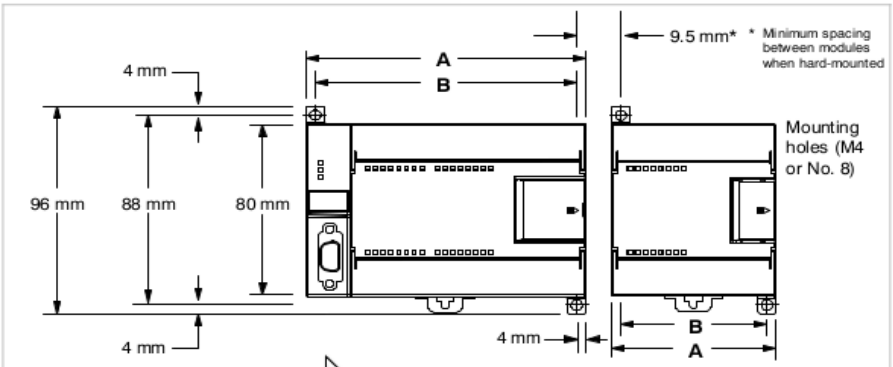


Figure 3.7 PLC hardware architecture

Figure 3.7 shows how the PLC communicates with the inputs and outputs of the system through its digital inputs and outputs that are buffered from the CPU by processing circuitry. This buffer allows the programmer

to specify situations or events that allow the inputs and outputs to use CPU hardware efficiently. An example is a hardware interrupt that can be triggered by a user defined input, a emergency stop button. This must interrupt the current state of the system and stop the process immediately or the system could physically damage its environment.

The modular design specific to the Siemens S7-200 series PLC is an exceptional feature of the Siemens range of PLCs (*Figure 3.8*). The design allows an engineer to easily expand the PLC with off the shelf products. These modules can be used to increase the number of inputs, outputs, type of inputs and outputs, and also the CPUs capability. An advanced control system such as the distillation apparatus needs to constantly monitor the temperature of the system.



S7-200 Module		Width A	Width B
CPU 221 and CPU 222		90 mm	82 mm
CPU 224		120.5 mm	112.5 mm
CPU 224XP, CPU 224XPsi		140 mm	132 mm
CPU 226		196 mm	188 mm
Expansion modules:	4- and 8-point DC and Relay I/O (8I, 4Q, 8Q, 4I/4Q) and Analog Out (2 AQ)	46 mm	38 mm
Expansion modules: Modem	16-point digital I/O (16I, 8I/8Q), Analog I/O (4AI, 8AI, 4AQ, 4AI/1AQ), RTD, Thermocouple, PROFIBUS, Ethernet, Internet, AS-Interface, 8-point AC (8I and 8Q), Position, and	71.2 mm	63.2 mm
Expansion modules:	32-point digital I/O (16I/16Q)	137.3 mm	129.3 mm
Expansion modules:	64-point digital I/O (32I/32Q)	196 mm	188 mm

Figure 3.8 S7-200 Mounting instructions

The S7-200 CPU222 Unit is supplied with 8 digital inputs and 6 digital outputs. To read the temperature of the still column and condenser tube

I have used K type thermocouples to monitor these temperature from the still apparatus. This type of electronic temperature measurement outputs an analog signal that needs to be conditioned before it can be used by the PLC CPU. I have used a EM231 (Analogue input Expansion Module) and configured it to work with K type thermocouples.

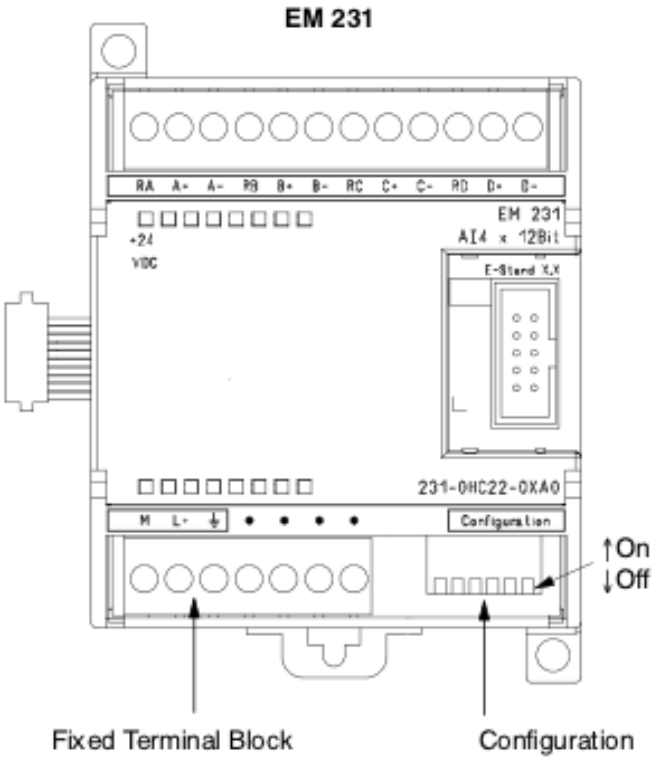


Figure 3.9 S7-200 PLC Layout

Figure 3.9 is a diagram of the EM231 which uses the configuration switches in the bottom right corner of the module to determine the operation parameters. These switches are configured to each application and allow the engineer to determine their own preferences for thermocouples, temperature, accuracy, and error signals.

- Switches 1-3 are used to determine which type of thermocouple the module is reading form, for a K-type thermocouple the configuration is 001.

- Switch 4 must always be off as stated in the data sheet.
- Switch 5 is used to determine whether the open wire detection is for positive or negative temperatures it is 0 for my configuration which configures it for positive numbers,
- Switch 6 is used to enable open wire detection which sends an error message if the thermocouples break or come loose, this is enabled and set to 0 for the still.
- Switch 7 is used to select between Celsius (0) and Fahrenheit (1). This is set to 0 for my still as I am measuring in °C.
- Switch 8 is used to disable cold junction compensation for using RTD (Resistive Temperature Device), this must be enabled for thermocouples so is set to 0.

For my specific application I have configured the DIP switches to 00100000. This tells the module to measure and condition the output for degrees Centigrade from a K-type thermocouple with open wire detection enabled for positive readings.

The critical nature of industrial control and the integration of machines into the human workspace increases the impact a system failure has on its environment. The hard real-time system model is used by most PLC manufacturers to allow their hardware to integrate safely in to the human-machine workspace. This ensures a PLC scan cycle is executed within a defined time (usually in mSec), a feature that must be taken into consideration when writing a PLC program.

A PLC does not read or write to individual inputs and outputs, instead the PLC reads in all inputs and writes to all outputs every scan cycle. This scan cycle determines how quickly the system reacts to a signal and can be impacted by some complex algorithms. Figure 3.10 illustrates this concept .

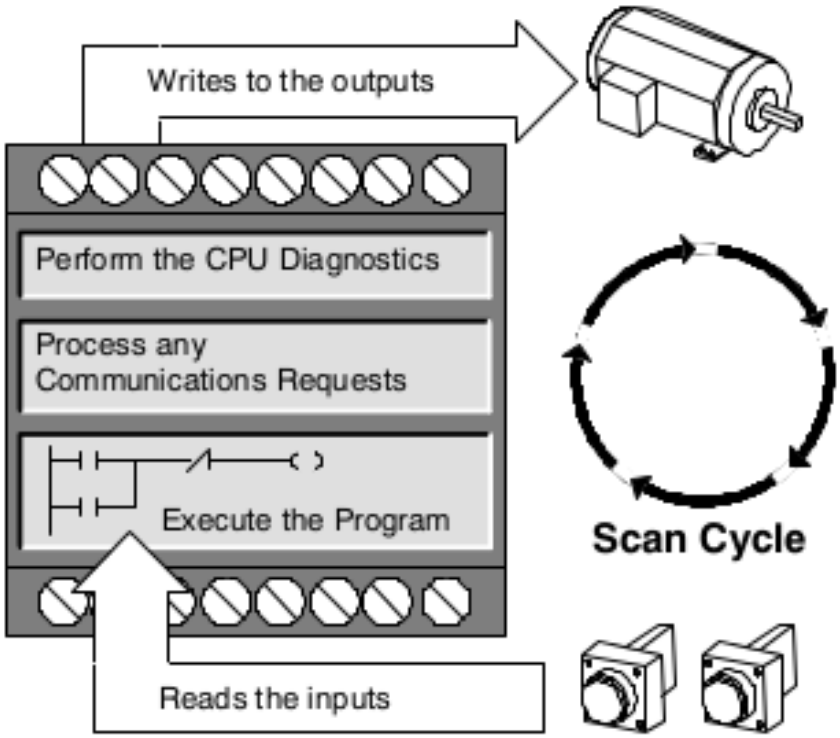


Figure 3.10 PLC scan cycle

A PLC runs on a four step cycle as shown in figure 3.10:

1) Scan Input Circuit

- If a input has been given a special function (Interrupt), jump to specified code
- Inputs are updated in the input register for use by the PLC program.

2) Execute program cycle

- Use Input register to change state of the program and evaluate any algorithms.

3) CPU requests and house keeping

- Any specialized CPU requests are processed such as communication (Internet monitoring and/or SCADA).
- CPU clean up of temporary variables.

4) Scan Output Cycle

- Output register is updated by the PLC changing the plants state.

3.3.2 PID Control Algorithm

A control algorithm is a series of tasks carried out in sequence to control a system. Different algorithms have different tasks ordered in different sequences. A control algorithms main task is to control a systems output in such a way that minimizes the error (the difference between the set-point, and the process variable). A PID loop is an example of a control algorithm Figure 3.11 shows the control loop for a PID algorithm this is a closed loop control algorithm because it requires the monitoring of the output, which is then fed back into the system and multiplied by 3 different constants which are then summed to determine the output.

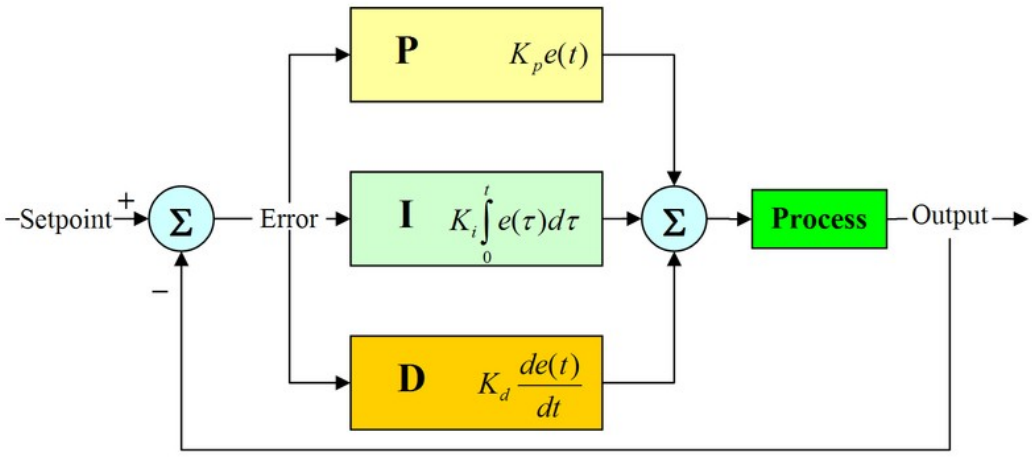


Figure 3.11 PID loop algorithms

The PID algorithm is expressed in figure 3.11 and shows the output subtracted from the set-point to calculate the systems error. The error is a measure of how far away the system is from the setpoint. The error is then fed into the PID algorithm which calculates how the systems output should respond. A larger error requires a larger response with the goal of finding a steady state for the system with minimal oscillation (+/- 0.1% of the setpoint, pending tolerances) (“PID controller”, 2012).

The PID control algorithm is a generic closed loop control algorithm used extensively throughout industrial control systems. One of the main advantages PID algorithms have over other control algorithms is the fact that an in depth knowledge of the system is not needed, (you do not need to model the system). Extremely complicated or financially unviable system models need not be created to gain outstanding control of a system quickly and efficiently.

These systems are very dynamic and can make adjustments to compensate for loss of control medium. The PID algorithm subtracts the error from the set point and calculates an output for the system. The algorithms tries to reduce the error through each iteration to get to a steady state that oscillates around the set-point by +/- 0.001, or a value that is negligible to the system.

Adjustments to the algorithm is made by adjusting the gain (P), the integral term (I) and the differential term (D). Each variable adjusts the systems response characteristics and determines how aggressively the system responds to a change in the output. An engineer must adjust each variable to suit their specific system with a desirable system response.

Figures 3.11.0 – 3.11.2 show how each variable effects the output response of the system independently. The gain P (Figure 3.11.0) adjusts the sensitivity of the system to the output. The I (Figure 3.11.1) variable adjusts the size of the error or the amount of fluctuation the system experiences in early stages of initialization. And the D (Figure 3.11.2) variable adjusts the length of the error or how long the system will take to settle to a steady state.

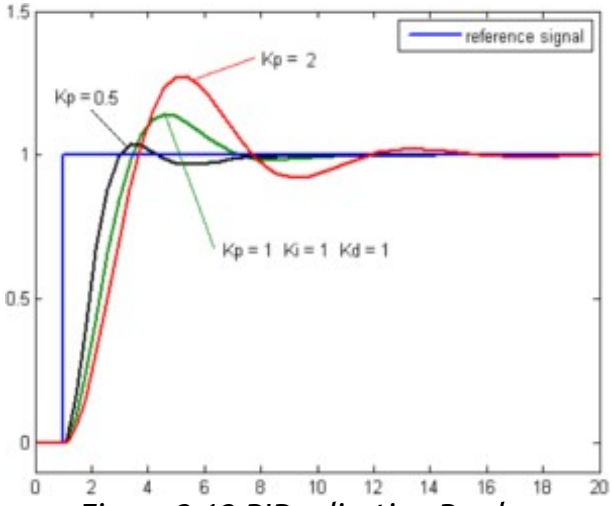


Figure 3.12 PID adjusting P value

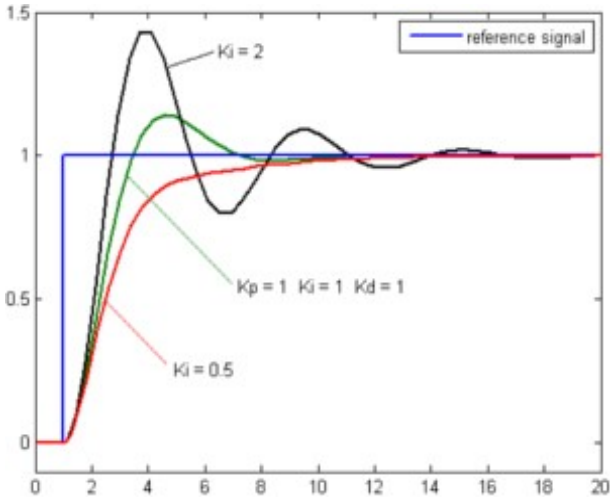


Figure 3.13 PID adjusting I value

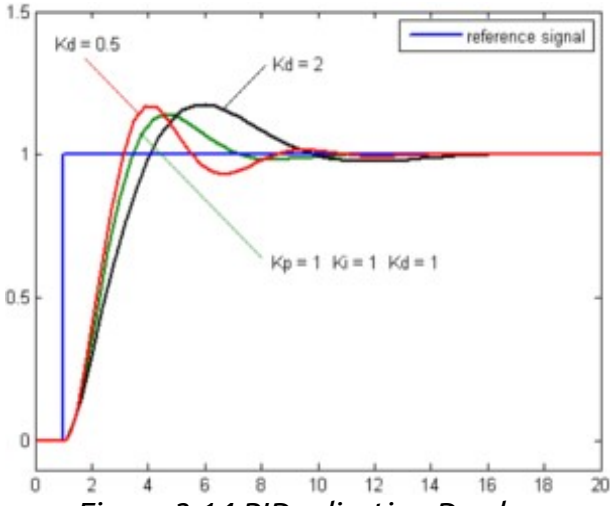


Figure 3.14 PID adjusting D value

Figure 3.11 shows the PID loop algorithm, to use this on a PLC it needs to be reduced down to a mathematical formula that can be turned into a computer program. Figure 3.15 is a mathematical representation of Figure 3.11 and expresses the output M(t) as the function of a proportional term, an integral term and a differential term.

$M(t)$	=	$K_C * e$	+	$K_C \int_0^t e\,dt + M_{initial}$	+	$K_C * de/dt$
output	=	proportional term	+	integral term	+	differential term

Figure 3.15 PID calculations separated in to individual terms

M(t) Loop output as a function of time

Kc The Loop gain

e The Loop error

M_{intial} The initial value of the loop output.

In order to calculate M(t) the continuous functions must be quantized (sample the continuous function so that is becomes a discreet data set) into periodic samples. Figure 3.15 can be further simplified for use by the S7-200 CPU to figure 3.16.

M_n	=	MP_n	+	MI_n	+	MD_n
output	=	proportional term	+	integral term	+	differential term

Figure 3.16 Quantized PID algorithm

Mn The calculated value of the loop output at time n

MPn The proportional term of the of the loop at time n

MIn The Integral term of the loop at time n

MDn The Differential term of the loop at time n.

The proportional term is the product of the gain (Kc) and the error:

$$MPn = Kc \times (SPn - PVn) \quad (1)$$

MPn is the value of the proportional term of the loop output at sample time n

Kc is the loop gain

SPn is the value of the setpoint at sample time n

PVn is the value of the process variable at sample time n.

The integral term MIn is proportional to the sum of the error over time:

$$MIn = \frac{Kc \times Ts}{Ti \times (SPn - PVn) + MX} \quad (2)$$

MIn is the value of the integral term of the loop output at sample time n

Kc is the loop gain

Ts is the loop sample time

Ti is the integral time (also called the integral time or reset)

SPn is the value of the setpoint at sample time n

PVn is the value of the process variable at sample time n

MX is the value of the integral term at sample time n-1 (integral sum or the bias).

MX is updated after each loop calculation with the initial value set to Intimal just prior to the first loop output.

The differential term MD is proportional to the change in the error:

$$MDn = \frac{Kc \times TD}{TS \times (PVn-1 - PVn)} \quad (3)$$

MDn is the value of the differential term of the loop output at sample time n

Kc is the loop gain Ts is the loop sample time

TD is the differentiation period of the loop (also called the derivative time or rate)

SPn is the value of the set-point at sample time n

SPn-1 is the value of the set-point at sample time n – 1

PVn is the value of the process variable at sample time n – 1

PVn-1 is the value of the process variable at sample time n – 1

3.3.3 PID Tuning

Tuning a PID control loop requires adjustment of the control parameters to obtain optimum values that give an acceptable system response to variable inputs. As PID is a generic control algorithm, and “acceptable response” will mean different things to different systems. An over-damped system figure 3.12.1, Ki = 0.5 (one in which the process variable does not go over the set-point) may be perfect for an oven where a substance cannot be exposed to heat above the desired set-point, however the response time maybe unacceptable for another application.

A PID loop can be used on many different systems without and in depth knowledge of the system. Values of the P, I and D variables must be determined for each implementation, with no two implementations having correlated P,I and D variables. To obtain these values the system must be on-line and operating for an engineer to obtain and tunes these

variables, even if the engineer is using one of the mathematical tuning algorithms. There are 3 main tuning algorithms: manual tuning, Ziegler-Nicholas method, and Auto-tune. All 3 have differing advantages but both Ziegler-Nicolas and Auto-tune require some degree of manual fine tuning.

Manual tuning requires the engineer to have past experience with similar systems so that they maybe able to approximate variables to allow the system to start operating. One documented technique for manual tuning is to set the I and D variables to zero, then increase the gain (P) to a point where the output expresses a sinusoidal oscillation. At this point the gain should be decreased by approximately half, to a value that drives the output oscillation with a quarter amplitude decay. The second peak where the PV crosses over the SP is ¼ the amplitude of the first peak (Figure 3.17) .

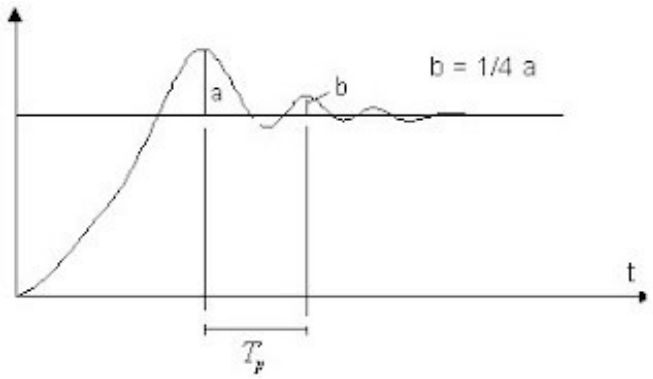


Figure 3.17 PV ¼ amplitude decay

Once the system is oscillating with a decay the I variable should be incrementally increased, decreasing the time the system needs to settle on the set-point. The D variable should only be used to decrease the response time of the system if it is unsatisfactory, as too much D or I can lead to a unstable system. Manual tuning is greatly aided by the use of

the table in figure 3.18 as this helps beginners and experts to see how the response of a system will be affected by increasing the corresponding variables.

Effects of *increasing* a parameter independently

Parameter	Rise time	Overshoot	Settling time	Steady-state error	Stability[3]
K_p	Decrease	Increase	Small change	Decrease	Degrade
K_i	Decrease[4]	Increase	Increase	Decrease significantly	Degrade
K_d	Minor decrease	Minor decrease	Minor decrease	No effect in theory	Improve if K_d small

Figure 3.18 PID manual tuning table

Ziegler Nichols method is similar to manual tuning and requires the system to be on-line and operational. Initially the gain is increased until it oscillates around the set-point, this gain value is determined as Ku, and the oscillation period P_U is determined as the time between one complete cycle. These are substituted into the table Figure 3.19 to determine the corresponding P, I, and D variables. After this tuning takes place some minor tweaking is required, using the table in figure 3.18 to obtain an acceptable control of the system, with acceptable response time and error.

Ziegler–Nichols method

Control Type	K_p	K_i	K_d
P	$0.50K_u$	-	-
PI	$0.45K_u$	$1.2K_p / P_u$	-
PID	$0.60K_u$	$2K_p / P_u$	$K_pP_u / 8$

Figure 3.19 Ziegler-Nicholas tunning table

The auto tuning algorithm used in the S7-200 is based upon a technique called relay feedback in which a small oscillation is produced and sustained in the process. By setting numerical bounds for the process variable (PV) that are within an acceptable range for the desired system the auto tune algorithm can drive the system to the upper limit of the PV and then back to the lower bound. After each iteration (driving the PV from the upper limit to the lower limit) the algorithm determines new values which are then used to evaluate the next iteration. This process is carried out until the PV oscillates around the set point with the desired amount of amplitude determined by the type of response needed for the system Figure 3.20.

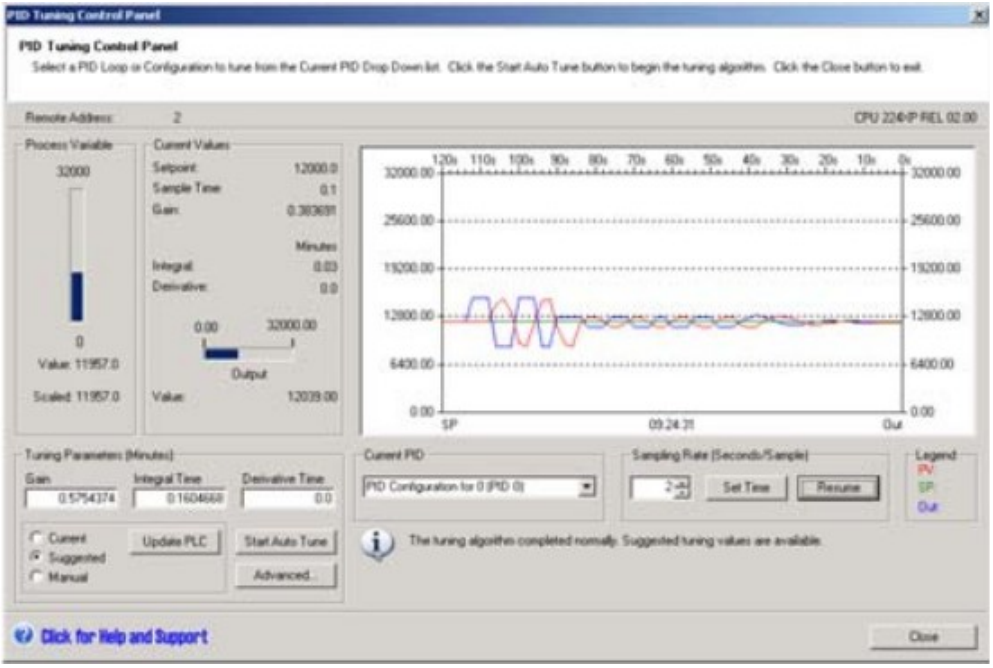


Figure 3.20 Siemens PLC IDE auto-tuning screen

3.3 Research Related Literature Review

The literature review is a overview of the work that has been undertaken in the field that best relates the specific thesis. Simai Haji Mati has

gracefully summed up the purpose of a literature in a quote that states *"a literature review should be referred to as reviewing and analyzing the work of literature in relation to the specified topic in research".*

The aim of my literature review is to summarise material from two different subcategories of bioethanol research: optimization and control of bioethanol distillation, and the use of bioethanol in the transport sector. Most studies carried out on biofuel focus on biofuel and its proposed cost benefit ratio, however this is not reviewed on its own as this takes into account growing costs, transportation, and other inputs which I have not used or controlled in my research. The energy cost was a topic of research for my project but only on the distillation side as this is the most energy intensive process in the production of bioethanol consuming up to 50% of the overall energy cost, proposed by C. Black (cited in Collura & Luyben, 1988).

The drive for an alternate transport fuel has two main factors:

1) the need to replace oil with a renewable alternative as oil reserves are running lower each day.
2) the gases released from burning oil based products are filled with chemicals that pollute the air, harming all living organisms.

Oil based fuels (diesel and petroleum) are becoming more and more expensive as the demand for oil increases while the supply (oil, at present can not be produced synthetically) is decreasing. With as little as 50 years of oil left in reserve, the supply versus demand is driving the price of a barrel of oil to record highs. Bioethanol is both a renewable energy source and a cleaner burning energy source reducing, emissions from both neat alcohol power plants and blended fuel power plants.

3.3.0 Distillation Research

Distillation was discovered around the 8th century with water distillation being used in the 1st century Alexandria, and the principle has not changed much since then (“Distillation”, 2012). Distillation requires the use of an energy source to change a liquid into steam then a cooling source to convert the steam back to a liquid.

Although process equipment has become bigger and more efficient in separating the base elements, the general method has not changed. Most of the advancements in modern alcohol distillation processes have been in the pre and post distillation phases. These advances are mainly based around the fermentation (the creation of ethanol), aging and flavor enhancements in post production for alcoholic beverages.

Studies into the distillation process for chemical engineering are aimed at reducing the amount of energy a distillation run consumes, while increasing the amount of distillate collected. A paper by Lina Rueda and Jacob Duke (2008) states “Distillation is the top energy consuming process in the chemical engineering industry. Increasing it production while reducing energy usage requires continuous optimization to drive the equipment to peak performance”. This paper stated the use of a advanced process control (APC) with the use of a non-linear model predictive control algorithm (MPC) which used the model as a reference to adjust plant outputs for known inputs.

In a paper by Michael A Collura and Wiliam Luyben written in 1988 based on energy saving distillation designs in alcohol production it was concluded “To produce a distillate concentration above 95% the column must be operated at sub atmospheric pressure”(Collura, Luyben, 1988). In theory, reducing the pressure in the distillation tank reduces the boiling point of ethanol, allowing for a reduction of input energy. The

consequence is that the energy required to place a large volume under a sub-atmospheric pressure is unrealistic.

The same quality of bioethanol can be achieved by double distilling the ethanol collected. This is not ideal as the energy input to distill the fermented alcohol is doubled. A hybrid solution in which two distillation columns are used will produce similar results. The mash is preheated or roughly distilled at a high temperature in the first column producing a low purity ethanol steam (approximately 60%). This is then fed into the distillation column, which acts like another distillation process using only energy from the first column to excite the ethanol molecules with and output stream over 93% ethanol.

MPC at Badger State Ethanol (BSE) used a mathematical model to describe the plant, from beer column through to the 100% bioethanol produced out of the molecular sieve (Rueda, Duke 2008). The MPC algorithm is based on a dynamic model produced by Pavilion Technologies for this specific plant with the critical component in the algorithm being this model (Rueda, Duke 2008). Emperical methods and first order principles were used to model the plant “Empirical modeling alone is often used in MPC because solving a set of complex differential equations of first order principles models for the calculation of the optimal sequences at each control interval may not be feasible”(Rueda, Duke 2008).

Figure 3.21 is a diagram of the Badger State Ethanol distillation plant. The 95% (190 proof) ethanol is feeds in to a series of molecular sieves which use recycled product and energy to regenerate spent sieves. BSE sends mash in to a beer column which only partly distills the mash into a solution of approximately 60%. The low purity steam is then fed in to the rectifier column which further separates the the water from the solution

to send 95% ethanol vapour to the molecular sieves.

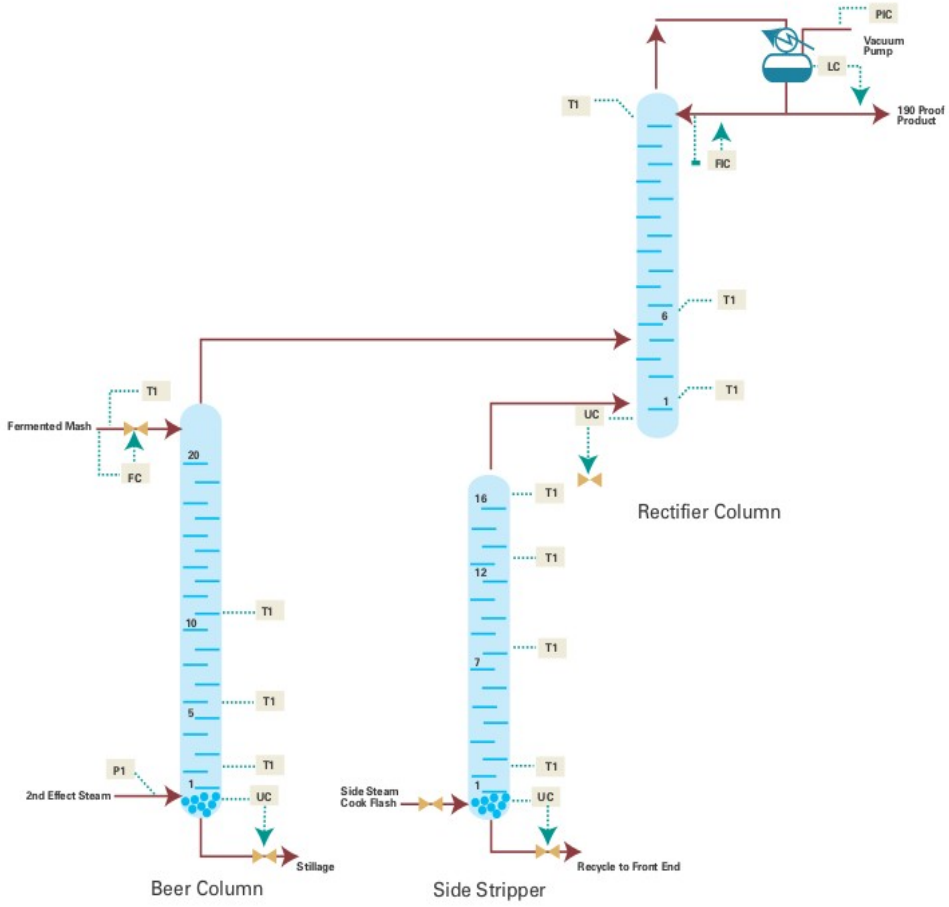


Figure 3.21 BSE

Once the steam is passed into the rectifier column, the high purity ethanol travels up and out of this column. Low quality ethanol and water will fall to the bottom of the rectifier column. This liquid is collected in the side stripper which allows high purity ethanol to escape, while feeding water and low quality ethanol back into the beer column to ensure no fermented ethanol is lost during the distillation process.

Badger State Ethanol contracted Pavilion Technologies to implement an APC system on this established bioethanol plant to increase the output

of bioethanol collected while reducing the the total energy consumed (Rueda, Duke 2008). Badger State Ethanol uses a multi-column still to produce 95% ethanol, which is fed through a molecular sieve that removes the last 5% water to produce 100% ethanol. The MPC algorithm that Pavilion technologies implemented reduced the amount of steam usage for the plant by 9.95% while increasing the plants bioethanol production by 10.24% (Rueda, Duke 2008).

3.3.1 Ethanol Fuel Research

With the increased production capacity of bioethanol and the reduction in cost per litre research into the best way to use this new fuel source is steadily maturing. A future in which cars run on neat bioethanol (100% ethanol as their primary source of energy) is the goal which will totally remove the need to consume oil. However the oil industry has spent hundreds of billions of dollars on infrastructure and supply chains to ensure a constant supply of oil based products in every country.

The adoption of bioethanol has already begun with America running most petrol powered vehicles on E10 (10% bioethanol and 90% petrol) with the next logical step being E30, followed by E50, eventually running all spark injection power plants on E100. This staged approach to biofuel adoption is not only the most logical approach to the oil crisis it is also an environmentally sensitive choice. Bioethanols higher oxygen content make it a great fuel additive as it aids fuel combustion by supplying extra oxygen. Significant pollution reduction can be achieved from blended fuel types, reducing overall pollution by up to 16%, even in blends as low as E10(Hulsey, Coleman, 2006).

Some research into the use of bioethanol in auto mobiles concludes that it causes an increase in ozone potential chemicals (Hulsey, Coleman,

2006). These studies are however based on computer models that do not relate to analytical results. Analytical experiments carried out in Wisconsin, California, and New York show a consistent reduction in air pollution that corresponds to the adoption of E10 fuel in the associated cities. *Clearing the Air with Ethanol* by Brett Hulsey and Brooke Coleman (2006), reviewed data about air pollution and the associated emissions benefit from the use of E10. This paper concluded that "Ethanol reduces carbon monoxide (CO) and soot particulate matter (PM) emissions by at least one-third" and can increase overall air quality up to 16%(Hulsey, Coleman, 2006).

A study in South Eastern Wisconsin (SEW) compared the areas ozone excedence days before and after adopting the use of E10 for all petrol vehicles. This study showed a dramatic reduction in ozone excedance days after 1994, the year that Wisconsin introduced E10. *"Before 1994 the average was 630, after 1994 the average was 539 a reduction of 16% in ozone excedance days"*(Hulsey, Coleman, 2006).

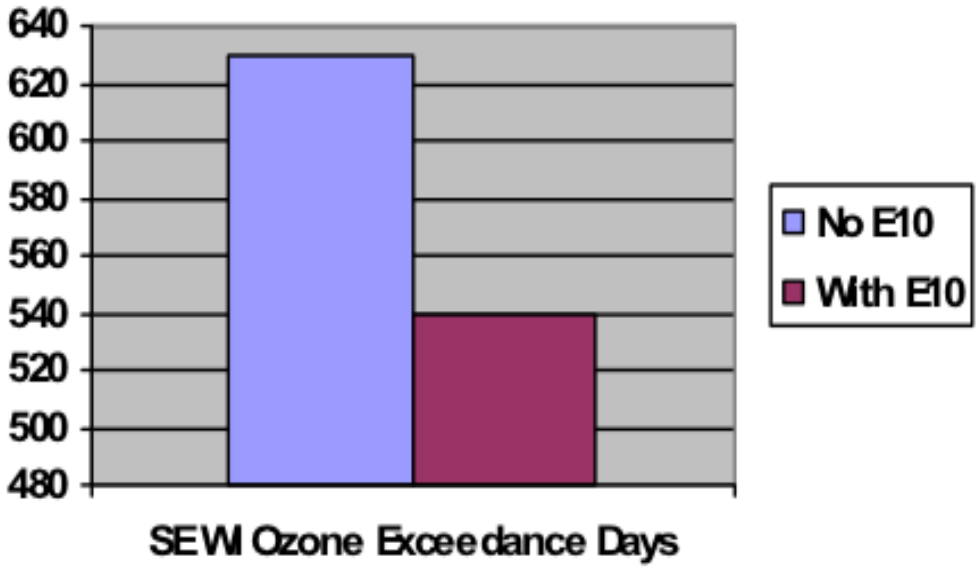


Figure 3.22 Graph of SEW Ozone exceedance days

While it is proven E100 would greatly reduce both on-road and off-road carbon monoxide emissions, the infrastructure needed to supply this fuel is cost prohibitive and irresponsible with the current global economic state. Lower blend fuels (E10 and E30) not only reduce emissions from standard petrol engines but they are also a catalyst for bio-industrial growth and fuel diversification. This will allow the biofuel industry to grow using private money. With 80% of the American emission inventory for carbon monoxide being accounted for by on- and non-road vehicles, a reduction of 20% emissions will have a great impact. A 36% decrease in soot particles is predicted to dramatically reduce health side effects associated to petrol powered vehicles and their emissions(Hulsey, Coleman, 2006).

Comparisons of petrol engines to petrol engines running on E85 are not a good representation of the potential biofuel has as a fuel source for the future. Flexifuel vehicles can run on E85 but they are not optimized to, and the need to run on petrol restricts the extent to which these combustion engines can be reconfigured. The comparison is similar to a diesel engine running on petrol, it is theoretically possible but the engine will perform poorly compared to its diesel equivalent.

Flexifuel vehicles which can run using either petrol or blended fuels are petrol power plants that have been modified to enable their petrol engine to run on neat bioethanol. When using neat bioethanol these engines produce less power and consume more fuel than running on petrol. When running on alcohol the engine does not change but the ECU (Electronic Control Unit) uses a different fuel map, increasing the amount of fuel supplied, which negatively impacts the fuel consumption.

The combustion characteristic are very different for petrol and bioethanol, which is due to their chemical structure (similar to petrol and

diesel). While bioethanol can be combusted in a environment optimised for petrol combustion, petrol can not be used to fuel a power plant optimised for bioethanol. Flexifuel vehicles do not utilise the advantageous characteristics of bioethanol, most notably the reduced amount of oxygen it needs to combust, resulting in smaller engines that can produce similar power figures to a much larger petrol engine.

"The benefits and challenges of neat alcohol fuels in PFI (Port Fuel Injection) applications have been demonstrated in numerous earlier works. Benefits such as higher efficiency and specific power and lower emissions may be realized with alcohols: their high octane number gives the ability to operate at higher compression ratio without preignition [5]; their greater latent heat of vaporization gives a higher charge density [1-3, 6]; and their higher laminar flame speed allows them to be run with leaner, or more dilute, air/fuel mixtures [7]. In addition, alcohols generally give lower fuel heat release rates, resulting in lower NOx emissions and reduced combustion noise [2]. The engine described in the present work uses these inherent advantages of alcohol fuels as the basis for its design and control, thereby enabling attainment of efficiency levels exceeding that of the diesel, with low emissions." (Brusstar, Stuhldreher, swain, and Pidgeon, 2002).

The paragraph above was from a research paper *High Efficiency and Low Emissions from a Port-Injected Engine with Neat Alcohol Fuels* by the U. S. Environmental Protection Agency, in which they state *"Alternative fuels, especially alcohol fuels, offer potential to mitigate national security and economic concerns over fuel supplies as well as environmental concerns over tailpipe emissions and resource sustainability" (*Brusstar, Stuhldreher, swain, and Pidgeon, 2002). In this paper a heavily modified VW Turbo charged diesel engine is used as a test bed for neat alcohol combustion. A diesel engine was used as the compression ratio at factory is quite high

so only slight modification were made to the compression ratio. Spark ignition was fitted with direct port inject to increase spark authority and increase efficiency, Figure 3.23 shows the test engines specifications.

Engine Type	4 cyl., 4-stroke
Combustion Type	PFI, SI
Displacement	1.9L
Valves per cylinder	2
Bore	79.5 mm
Stroke	95.6 mm
Compression Ratio	19.5:1
IVO	-344° ATDC*
IVC	-155° ATDC*
EVO	152° ATDC*
EVC	341° ATDC*
Bowl Volume	18 cc
Clearance volume	26.4cc
Swirl Ratio	2.0
Injectors	Holley, 36 lb/hr, 12-hole nozzle
Rail Pressure	4 bar
Spark Plugs	Champion recessed gap, dual electrode
Turbocharger type	Variable geometry
Exhaust Aftertreatment	Ford FFV 2-stage, three-way catalyst

Figure 3.23 Bio-fuel engine specifications

This study concluded that engines optimized to run on bioethanol can produce better than 40% brake thermal efficiency, better than a comparable diesel plant and with extremely lower emissions(Brusstar, Stuhldreher, swain, and Pidgeon, 2002). This configuration has one last barrier which is cold start emissions but further research will reduce these, *"The present engine, optimized for alcohol fuels, exceeds the performance of current conventional- fueled engines, and has potential as a lower-cost alternative to the diesel"*.(Brusstar, Stuhldreher, swain, and

Pidgeon, 2002)

*“An important step toward increasing alcohol fuel demand, then, may lie in providing economical engine technology options that utilize such fuels more efficiently, to compensate for the lower fuel energy density. The FFVs produced today, however, use fairly typical gasoline engines, which, because they must retain dual-fuel capability, are not able to take full advantage of the favorable combustion characteristics of alcohols” (*Brusstar, Stuhldreher, swain, and Pidgeon, 2002*)*

4.0 Process

The chapter below describes the processes used to create the mash, assemble the distillation apparatus, and how the results were measured. This is with the aim of displaying my understanding of how ethanol is created and the control algorithms and hardware that are used to control this process. I intend to convey this understanding though thorough explanations of the mash creation process and how I used the Siemens hardware and IDE to control and measure the distillation process.

This chapter will also be useful reference material for students wishing to further the study of energy efficient bioethanol distillation. Supplying information which will enable a person to create and distill bioethanol quickly, allowing them to focus their resources on their desired subtopic. Both of these goals will be achieved by describing the procedures used step by step with in-depth explanations accompanied by photos from the actual process used in my experiments, supplemented with research media.

4.1 Brewing Ethanol

In section 3.1.2 (Fermentation) it is explained that yeast can ferment nearly any sugar source to create bioethanol. When using raw organic material (fruits, vegetables, and organic waste material) the sugar content is different between each type and batch of feedstock used. For a viable fermentation (greater than 10% bioethanol is present in the mash) to occur the sugar content will need to be measured and the amount of feedstock adjusted to create a viable mash.

The feedstock used will determine the amount and type of nutrients

supplied to the mash, and may also have an impact on the pH level. Even when using the same feedstock between batches these values may fluctuate due to differing agricultural environments. Nutrient corrections need to be carried out to ensure the mash is an optimum fermentation environment, ensuring complete fermentation of the available sugar. For this type of fermentation these inputs cannot be fixed and the results may not relate to the distillation process alone.

Table sugar (Sucrose) was chosen as the feedstock for my experiments as it can be assumed that the quantity of glucose is the same between batches. This means the amount of feedstock required for each fermentation is fixed, resulting in a known quantity of bioethanol from each batch. As the amount of feedstock is fixed between batches the nutrient and pH adjustments can also be fixed. Fixing these inputs is important as the aim on my thesis is to maximise the bioethanol yield from the distillation process, not the yield from the entire process.

When using sucrose as a feedstock more nutrient corrections are needed than a organic material feedstock. This is because the sugar does not contain the trace mineral elements needed for fermentation. Organic materials contain these trace elements, most notably nitrogen. These minerals and a pH of 4.5 are necessary for the reproduction of yeast cells and the fermentation of sucrose to bioethanol and carbon dioxide.

In the introduction I explained that I will be using “off the shelf” brewing equipment and products to not only ferment the alcohol but also to separate the alcohol from the mash. Off the shelf or hobbyist brewing materials simplify the process of brewing ethanol and are available in convenient quantities. These products are also designed with manual distillation in mind, allowing me to use one distillation apparatus for both manual and automatic distillations.

These products are designed for hobbyist brewers, removing the need for a laboratory to culture yeast and measure the nutrient corrections needed for the mash. The simplicity of these products reduces the possibility of human error by providing pre-packaged quantities of yeast, nutrients and pH correction that are guaranteed to ferment. This allows me to create a test scenario in which all inputs are fixed between experiments ensuring standardised results.

Turbo yeast fermentation packs (Figure 4.0), which can be brought off the shelf, are designed to yield 14% ethanol consistently in home brewing situations. These packs contain the correct amount of yeast, nutrients and pH corrections for a 25 litre mash with 6 kilograms of sugar. These packs are stacked (2 packs used in the same fermentation) in my experiments with 12 kilograms of sugar to produce a 50 litre mash at 14% alcohol content, approximately 7 litres of bioethanol.

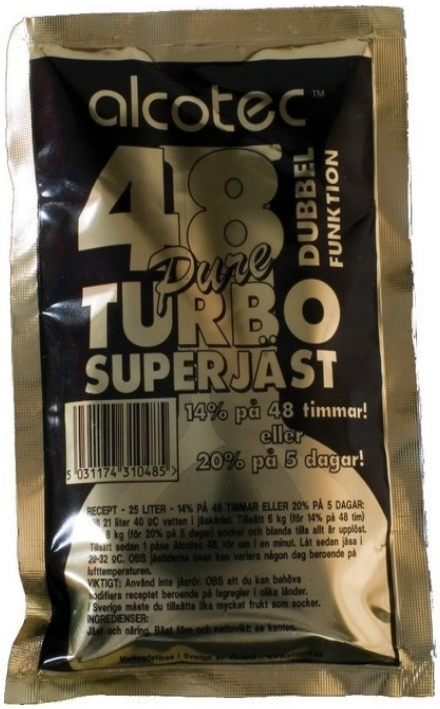


Figure 4.0 Turbo yeast packet

These packets come with a specific procedure for the creation of the mash. This procedure is to ensure the right temperature for fermentation is achieved and that there is full fermentation of the available sugar. Sanitation is extremely important to ensure that no unwanted organisms can grow in the mash. This can cause the fermentation to stall as the organisms consume all the sugar before the yeast can ferment it.

1. The fermentation tank and all brewing equipment are washed using bottle wash to ensure no micro-organisms are present
2. 12Kg of sugar is added to a 60L fermentation tank
3. Boiling water (approximately 15L) is added to the sugar
4. The syrup is mixed until all the sugar is dissolved
5. Tepid water is added to create a solution of 50L at 30°C
6. Add 2 packets of Turbo yeast 48Hr to the solution immediately
7. Mix solution vigorously for 1 minute to introduce excess oxygen and stimulate yeast reproduction.
8. A Pre-fermentation specific gravity reading is taken and recorded.

4.1.1 Brewing Temperature

Once the yeast has been pitched (added and mixed to the sugar syrup) and the fermentation begins, the temperature of the mash must be closely monitored. Yeast can only ferment in a small temperature window between 20°C and 40°C. Below 20°C the yeast begin to hibernate and cannot ferment, conversely, over 40°C the yeast will die. Outside of these conditions the number of yeast cells available to convert sugar into ethanol is reduced, resulting in slower fermentations and reduced ethanol productions through inefficient sugar conversion.

Temperature control of the fermentation tank was not used in my

experiment as it was unnecessary for the size of the tank. Precautions were taken to ensure that the environment in which the mash was fermented did not fall below 20°C as it can be assumed ambient temperatures in New Zealand do not go over 40°C. The best time for fermentation was summer as the overnight temperatures indoors did not fall below 20°C.

I tried to avoid fermentation during winter but it was necessary and the mash was fermented next to a heater. This was to avoid the tank temperature falling below 20°C, and the mash was monitored every 6 hours to ensure it was fermenting. This worked well for a fermentation tank of 50 litres, however anything larger and this solution would not work as there is not enough surface area to keep the mash warm.

4.1.2 Air Lock

Yeast cells are living organisms and the biological process where yeast cells convert sugars into ethanol and carbon dioxide (fermentation) goes through two phases. In the first phase, reproduction, the yeast consumes the excess oxygen in the fermentation tank and uses it with the glucose as an energy source for reproduction budding. In the second phase, respiration, the yeast consume the glucose without oxygen and excrete ethanol and carbon dioxide.

The use of an air lock (Figure 4.1) in the production process is necessary even if it is only applied after the first 24 hours. This will allow the rapid production of carbon dioxide to take place while supplying oxygen to the yeast to ensure good reproduction is achieved. After the colony of yeast has fully reproduced (approximately 24 hours) the air lock should be applied to ensure no oxygen is present for fermentation, while allowing the carbon dioxide produced to escape ensuring a good conversion of

glucose to ethanol.

Figure 4.1
Fermentation air lock

Both oxygen and sugar are introduced into the mash in the early stage of mash creation. First the sugar is mixed with water vigorously, serving two purposes: it aerates the mash introducing excess molecular oxygen for yeast reproduction, and it mixes all the sugar into the solution ensuring full fermentation of all available sugar. Both sugar and oxygen are vital but without the proper nutrients available and a slightly acidic mash, proper fermentation will not occur. Slow/low yielding fermentation may occur but there are no guarantees.

4.1.3 Measuring Fermentation

A fermentation is complete when all the sugar in the mash has been consumed by the yeast, which is indicated by the specific gravity of the

mash. The difference between the pre-fermentation specific gravity and the current specific gravity reading of the mash can be used to determine how much ethanol has been produced. For a sucrose feedstock fermentation the final specific gravity reading should be below 0.992, from an original gravity of 1.100 this would indicate a mash of 14% Alcohol, approximately 3.5 litres from 25 litres of mash. Equation (1) is used to determine expected yield, equation (2) is readings from my experiments.

$$((1.05 \times (OG - FG)) / FG) / 0.79 \times 100 \quad (1)$$

$$((1.05 \times (1.100 - 0.992)) / 0.992) / 0.79 \times 100 = 14.47 \quad (2)$$

Specific gravity is the ratio of the density of the liquid measured to the density of water. To measure the specific gravity of a liquid, an instrument called a hydrometer is used. A hydrometer is usually made from glass with a cylindrical stem and a bulb weighted at the bottom to make it float vertically. The hydrometer is placed into the liquid allowing it to float freely, the point at which the surface of the liquid touches the stem of the hydrometer is noted.

Figure 4.2 Hydrometer

Hydrometers usually contain a scale inside the stem so that the specific gravity can be read directly, a variety of scales exist and are used differently depending on the context. The hydrometer I used was designed to determine the specific gravity of a fermenting mash (*Figure 4.2*). The readings from the hydrometer scale and equation (1) are used to determine alcohol potential. When sugar is mixed into the mash it increases the density of the mash, as the yeast consumes the sugar and excretes alcohol the density of the mash decreases.

By taking readings on a regular basis and recording them the brewer can then use this information to determine how much fermentation has occurred and calculate the rate of fermentation. The rate at which the fermentation is occurring can be used to determine the the health of the fermentation batch, and may signal to a problem before it occurs. A stalled fermentation is one in which the decrease in specific gravity stops before it has used all of the available feedstock, resulting in wasted feedstock.

4.2 Distillation

Once fermentation has been completed, the mash must be moved into the still tank (Figure 4.3 (1)). Once in the tank the still head (column) is fitted to the top of the tank (Figure 4.3 (2)) by slotting the rubber seal on to the tank flange. After fitting the column the water lines are connected to the water mains and the drain is routed outside into the fermentation tank. Thermocouples 0 and 1 are connected to the head and the condenser respectively (Figure 4.3 (3)) , and the program started.

The still used in my experiments is a 60 litre Euro still with a 1.5 kilowatt main coil and a 2 kilowatt booster coil. The distillation head is packed with steel wool and has six cold water injection points, the longest being

down the condenser shaft. The column and the condenser are two areas that must be controlled independently to obtain high quality bioethanol.

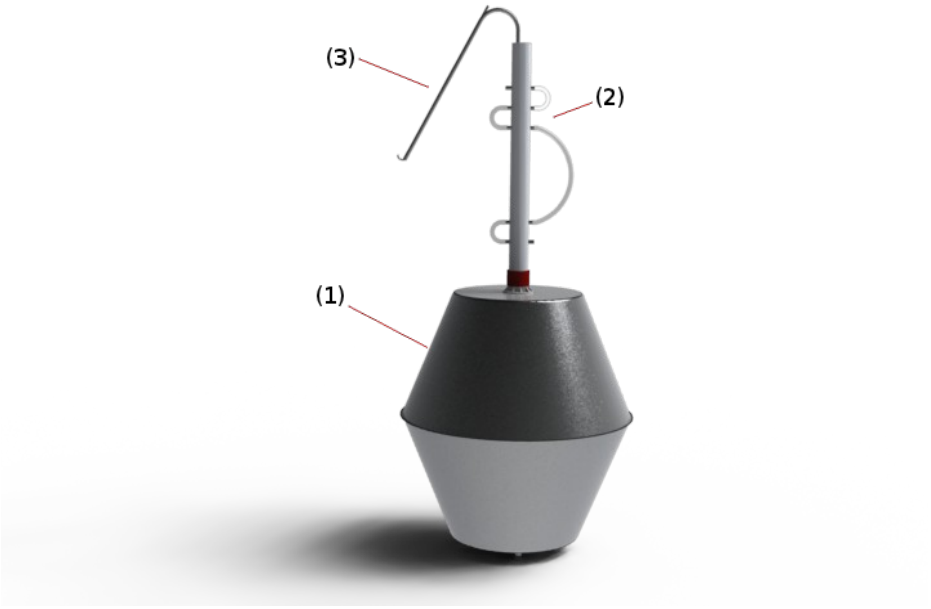


Figure 4.3 50 Litre Euro-still

The still separates the solution by introducing heat energy to change the ethanol from a liquid phase into a gaseous phase. This gas then rises up the distilling head, condensing and evaporating over the entire length of the column until the vapour enters the condenser. The column has cold water introduced at five locations to remove some of the heat energy from the vapour before it enters the condensing chamber to be cooled below 70°C. Vapour entering the condenser is flowing in the opposite direction from the column to ensure the ethanol vapour is pure.

Temperature control of the mash is important as this will determine both the purity and the efficiency of the distillation. Oscillation around the boiling point is not ideal as this will both increase the amount of water in the receiver tank lowering the quality of the biofuel, and increase the time of the distillation. A longer distillation increases the total energy

cost of the batch, decreasing the efficiency of the still . Low quality bioethanol also increases the total energy cost, as further processing is needed if the total batch quality is below 93%.

To manually conduct a distillation the tank must be heated to approximately 80°C, at which point the booster coil is turned off. Once steam rises up the head to the condenser, water must be passed through the cooling circuit and adjusted to keep a steady stream of ethanol flowing out of the condenser. This process must be watched closely because as the temperature increases in the column, the amount of water must to be increased accordingly. For manual distillation there is limited control over the heat energy entering the tank so the percentage bioethanol steadily decreases as the distillation progresses.

The key to a good distillation is determining how much energy is needed to convert the ethanol in the solution to a vapour. This is the Set Point (SP) of the distillation and the control system must maintain the Process Variable (PV) as close as possible to the SP. Controlling the amount of energy used to separate the bioethanol from the mash is important, as this will control the purity of the distillate collected and also the efficiency at which it is collected.

The amount of energy needed to distill 95% ethanol must be determined as to remove the bioethanol and no water. Water has a boiling point of 100°C and ethanol 80°C. An aqueous solution of these two chemicals has a boiling point in relation to the molar volumes of each chemical in the solution. Figure 4.4 is the equation that is used to determine the vapour pressure ($Y_{ethanol}$) at which the ethanol will vaporise off the solution made up of $Po_{Ethanol}$ and Po_{Water} where Po is molar percentage.

$$Y_{ethanol} = \frac{P^{o}_{ethanol} X_{ethanol}}{X_{ethanol} (P^{o}_{ethanol} - P^{o}_{water}) + P^{o}_{water}} \quad (5)$$

Figure 4.4 Ethanol vapour pressure calculations

Using figure 4.4 to calculate the SP of the distillation tank shows that as the ethanol evaporates the boiling point increases. This was confirmed through experimentation, as the SP of PID loop 0 had to be increased every hour or so to generate a bioethanol stream out of the still. This was solved by moving the thermocouple to the top of the column and changing the SP to 78.5 °C (temperature of the azeotrope of 95% ethanol and 5% water) which produced an constant stream of bioethanol at over 93% purity.

To control the still autonomously I programmed the Siemens S7-200 with two PID control loops to control two areas of the still and maintain constant temperatures of these areas independently. These control loops were set up from the MicroWin PLC programming IDE (Figure 4.4) with the PID tuning tools supplied in the IDE. The MicroWin IDE was used to program the PLC, tune the PID loops and used to debug and monitor the distillation process. Figure 4.5 is the IDE being used to monitor and debug the PLC, blue networks are active and grey networks are inactive.

The PID tuning wizard *(Figure 4.6)* enables the programmer to directly input variables for their PID loop. This can also be used to monitor the PID loop in real time. The blue line is the output, red line is the input and the green is the set-point. This screen allows you to view the PID loop in real time and adjust the variables so that you can see how this effects the PID algorithm immediately.

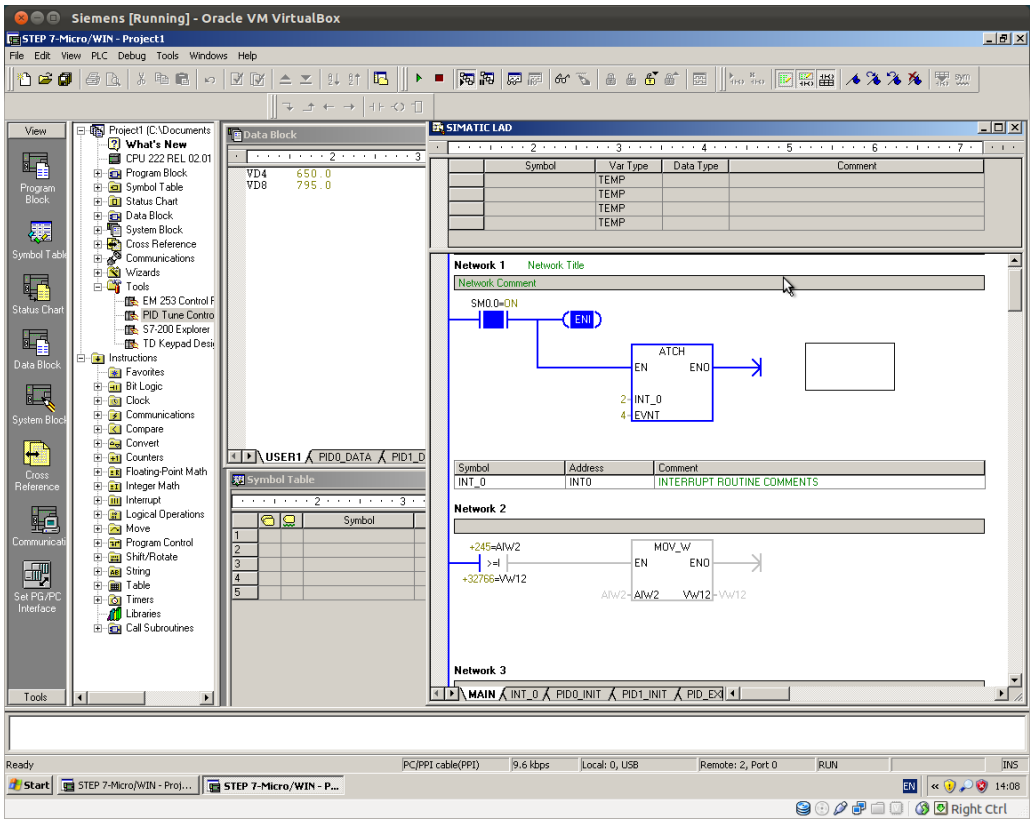


Figure 4.5 Siemens PLC IDE programmer

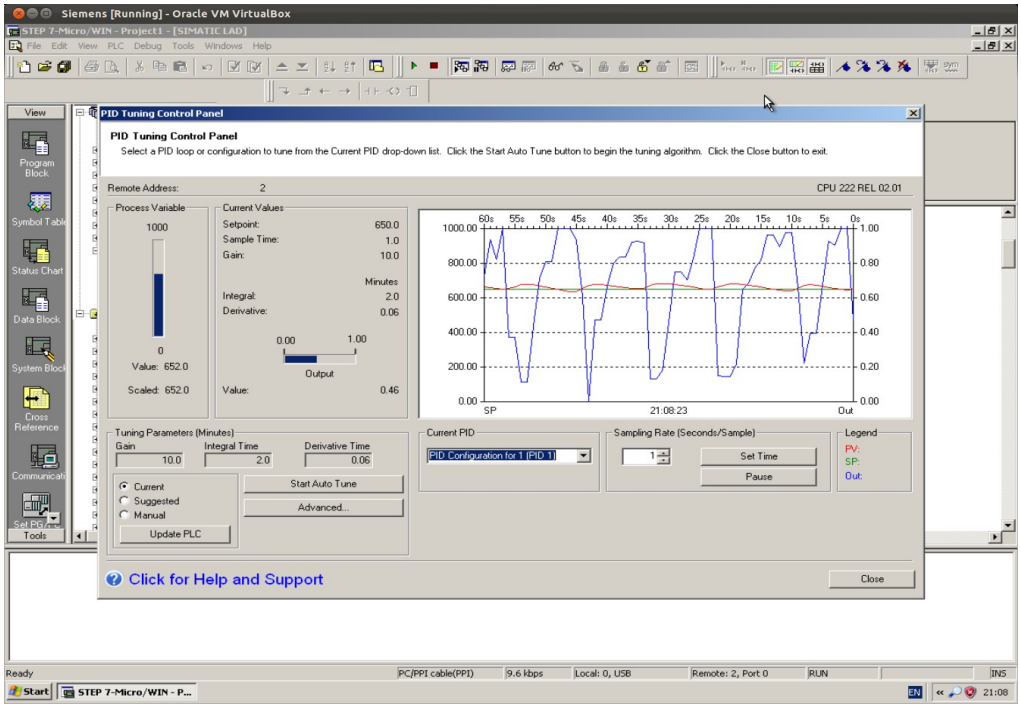


Figure 4.6 Siemens PLC IDE PID wizzard

4.3 Program design:

The S7-200 PLC continuously loops through the program logic until it is either manually stopped or a user defined state is reached stopping the process. The PLC cycle begins by reading the status of the inputs, which are then read by the control logic (computer program) and used to evaluate the current state of the system. Once the program has cycled through, the PLC writes the new control logic data to the outputs. Figure 4.7 shows a basic PLC application where a Stop/Start switch is used to turn on or off a motor, when the Start_PB is pressed the logic evaluates the current state and turns M_Starter on starting the motor.

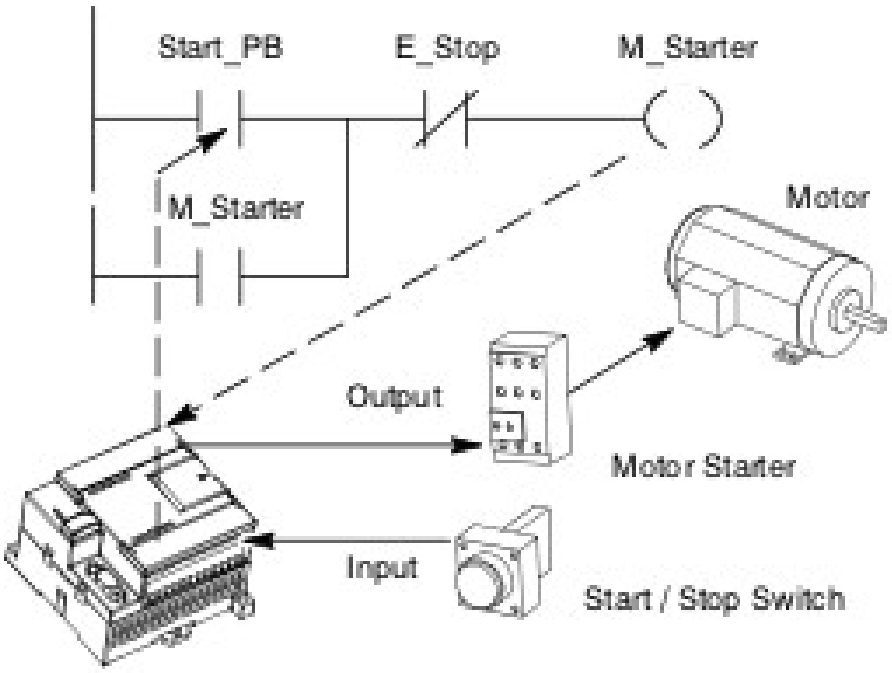


Figure 4.7 Basic PLC program

In figure 4.7 the first two logic operations start and run the motor, Start_PB is activated which activates M_Starter, this memory location then keep the network live until E_Stop is activated. The first two logic operations are normally open, meaning they must be activated to close

the circuit, E_Stop is normally closed which will break the circuit if the E_Stop button is depressed. These logic operations are the computer program, and are scanned every cycle of the PLC ensuring the control system is always monitoring the state of the physical system.

Figure 4.8 shows the MicroWin IDE used to program the PLC. There are three main areas of the IDE: the navigation bar, the instruction tree and the program editor. The navigation bar allows the IDE to quickly swap between screens containing vital information about the PLC, the instruction tree displays all the available instructions the PLC can use, and the Program editor is used to write and debug PLC programs.

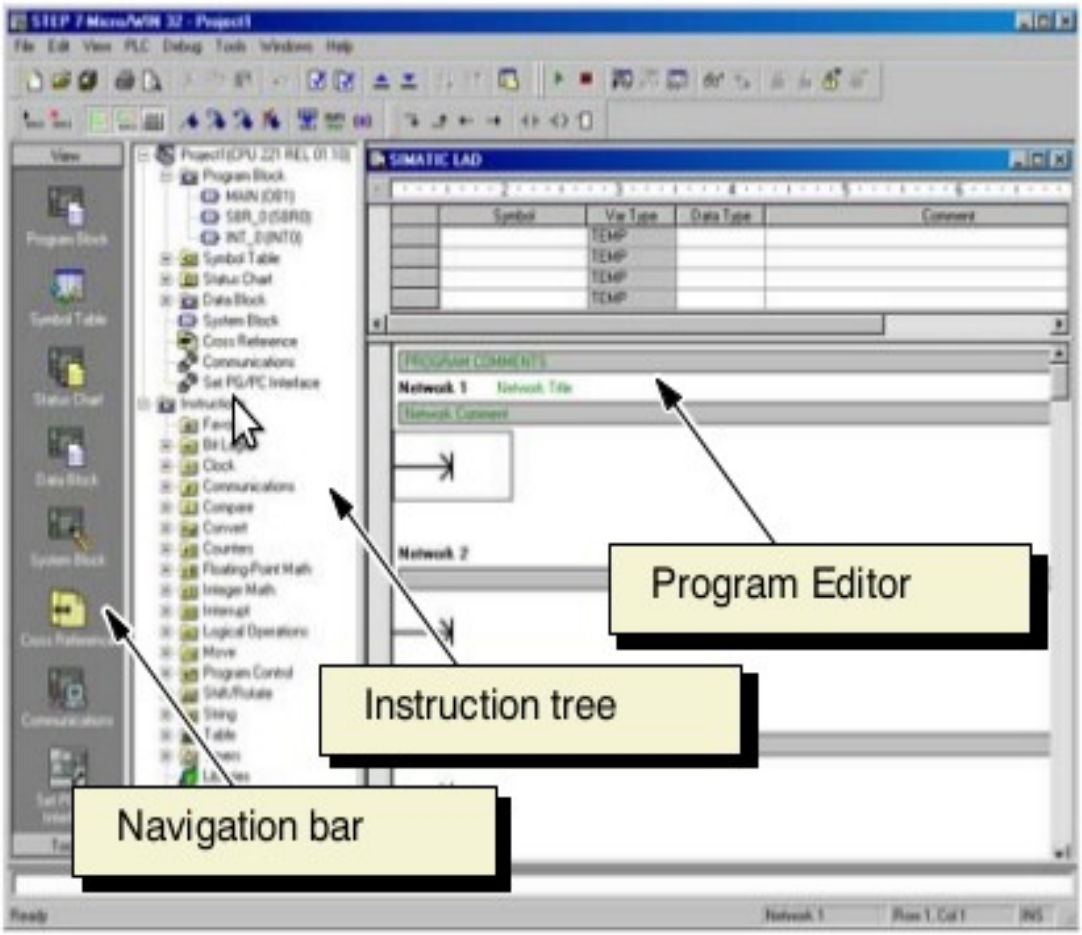


Figure 4.8 Siemens PLC IDE

To control the still in a efficient and safe manner the program was separated in to 4 areas that are independent from each other. The interrupt routine, recording the highest temperature, and the two PID loops are all independent and are controlled as such. Each of these sections was evaluated to ensure that a failure of a component or the PLC did not cause the plant to become unsafe. An example is the emergency stop button - a failure in the wiring or the button would not be apparent until it was needed. Holding the input high ensures an emergency stop would occur and the plant would not work if a failure occurred in the circuit.

Interrupt routine: The interrupt routine is used to stop the system if the Emergency stop button is activated. By using the input hardware buffer the PLC can allocate one of its inputs to interrupt the CPU at any stage of the scan cycle and execute a user defined routine. This routine turns all the outputs off and holds the system until the Emergency stop button is activated, as the interrupt routine is activated by the falling edge of the Emergency stop input.

Recording temperatures: The PID loop used to control the temperature of the column and condenser can become unstable if the P, I and D variables are not correct. This instability can be hard to detect as it may only occur after long operation runs. By recording the highest temperature read by the thermocouples one can identify this problem and make adjustments to increase the systems stability.

PID loop 0 and 1: The column and the condenser are two areas which are controlled independently. This is so different PID loops can be used to control the different systems. Although these areas are attached to the same system they need independent control as they have differing operational characteristics.

The above sections were translated to the actual program below on pages 71, 72, and 73 that was used to run a distillation autonomously, achieving over 93% ethanol throughout the entire distillation. Each network (line of code) is explained in-depth in the following pages.

Network 1: SM0.0 (this bit is a Special Memory bit that is always on) to enable interrupts and assign this interrupt to an input. INT_0 assigns the interrupt subroutine activation to be attached to I0.3, which is my emergency stop button. Attaching I0.3 to the interrupt switches the hardware buffer to activate a CPU interrupt if I0.3 is triggered. EVNT = 4 assigns this hardware interrupt to activate subroutine INT_0 on the falling edge of I0.3. This is a safety feature as the emergency button is always on so when it is pressed the input I0.3 will fall, triggering the interrupt routine which resets all outputs and shuts down all the coils immediately. This case is also true if there is a failure with the emergency stop circuit, as a failure of this circuitry would cause I0.3 to fall stopping the system.

Network 2: recording the maximum temperature at the condenser throughout operation, to indicate if the PID algorithm is functioning and is not becoming unstable during operation. This is useful for problem solving, if the feed purity suddenly drops or the overall production is of poor quality one can quickly determine weather it is a still problem or a fermentation problem. The CondTemp is read from AIW0 and compared to VW12 which is a memory location storing a word at position 12 in Variable memory which is the previous Maximum temperature. Each cycle the comparison determines whether the current value is greater than the previous maximum temperature, if it is the reading is moved into the CondMax variables (VW12), if not the program moves on and compares values next cycle.

Network 3: record the maximum temperature at the tower (distillation column) throughout operation, to indicate if the PID algorithm is functioning properly. The TowrTemp is read from AIW2 and compared to VW10 which is a memory location storing a word at position 10 of variable memory which is the previous Maximum temperature. Each cycle the comparison determines whether the current value is greater than the previous maximum temperature, if it is the reading is moved into the TowrMax variables (VW10), if not the program moves on and compares values next cycle.

Network 4: PID_0 loop is used to control the 1.5 kilowatt coil, this block requires SM0.0 to keep it running at all times and drives bit V8.0 which is a variable I have assigned TowrDrv. The PID loop compares the TowrTemp to VD8 which is a Double variable at variable memory position 8 this contains the set-point of the tower. This network then drives network 7 and 8, network 7 turns on the coils when V8.0 is on and network 8 turns the coil off when V8.0 is off.

Network 5: This network is used to control the larger 2 kilowatt coil as this coil is only used to quickly bring the mash up to temperature. The 2 kilowatt is turned off once the tower is over 70°C Network 5 compare AIW2 to a fixed value of 700 this equates to 70.0°C. If the comparison is true (the tower is over 70°C) the Network resets the Q0.1 output turning the 2 kilowatt coil off.

Network 6: During the early phases of distillation a booster coil is used to increase the temperature of the mash quickly. Network 5 turns the coil off, Network 6 is used to turn the coil on by comparing the AIW2 to a fixed value of 700 if its lower than 700 the coil is switched on.

Network 7/8: Network 7 and 8 are used to drive the 1.5 kilowatt coil

controlled by the PID loop. In the Siemens IDE the PID loop can not directly drive the outputs of the PLC so Networks 7 and 8 switch the 1.5 kilowatt coil on or off controlled by the PID loop.

Network 9: PID_1 loop is used to control the water valve, this block requires SM0.0 to keep it running at all times and drives bit V8.1 which is a variable I have assigned CondDrv. The PID loop compares the CondTemp to VD4 which is a Double variable at variable memory position 4 this contains the set-point of the condenser. This network then drives Network 10 and 11, network 10 turns on the coils when V8.1 is on and network 11 turns the coil off when V8.1 is off.

Network 10/11: Network 10 and 11 are used to drive the coil controlling the water valve which introduces the water needed to cool the condenser. These networks are the same as Network 7 and 8, interfacing between the PID loop and the physical coils it is driving.

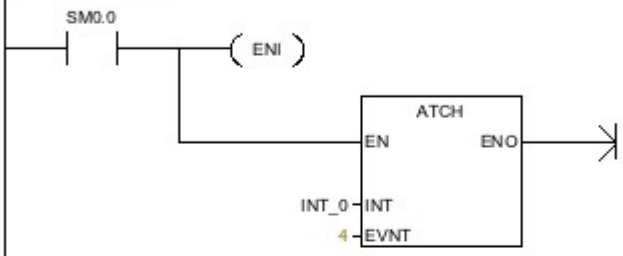
Block: MAIN
Author:
Created: 07/08/2009 03:29:51 pm
Last Modified: 03/21/2012 05:52:34 pm

Symbol	Var Type	Data Type	Comment
	TEMP		
	TEMP		
	TEMP		
	TEMP		

PROGRAM COMMENTS

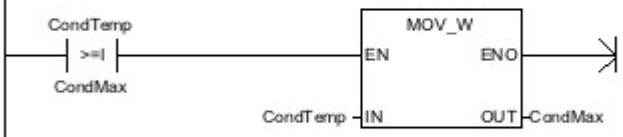
Network 1 Network Title

Network Comment



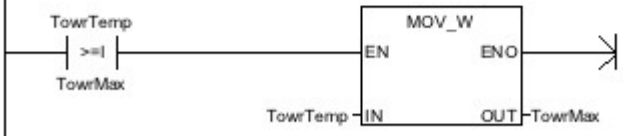
Symbol	Address	Comment
INT_0	INT0	INTERRUPT ROUTINE COMMENTS

Network 2



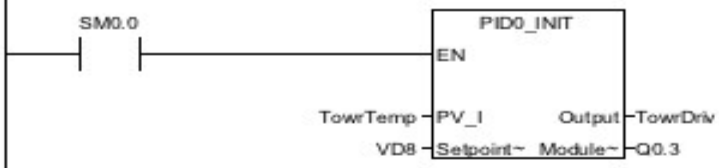
Symbol	Address	Comment
CondMax	VW12	
CondTemp	AIW0	

Network 3



Symbol	Address	Comment
TowrMax	VW10	
TowrTemp	AIW2	

Network 4



Symbol	Address	Comment
TowrDriv	V8.0	
TowrTemp	AIW2	

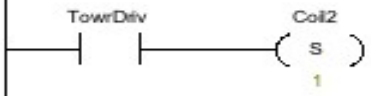
Network 5

Symbol	Address	Comment
Coil1	Q0.1	
TowrTemp	AIW2	

Network 6

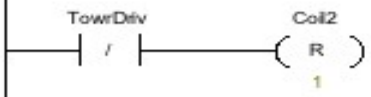
Symbol	Address	Comment
Coil1	Q0.1	
TowrTemp	AIW2	

Network 7



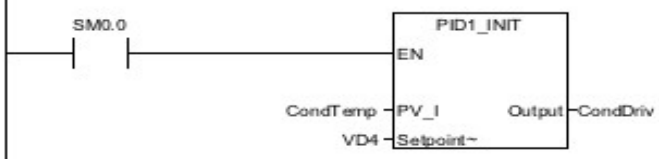
Symbol	Address	Comment
Coil2	Q0.2	
TowrDriv	V8.0	

Network 8



Symbol	Address	Comment
Coil2	Q0.2	
TowrDriv	V8.0	

Network 9



Symbol	Address	Comment
CondDriv	V8.1	
CondTemp	AIW0	

Network 10

Symbol	Address	Comment
CondDriv	V8.1	
Water	Q0.0	

Network 11

Symbol	Address	Comment
CondDriv	V8.1	
Water	Q0.0	

4.4 Electrical design:

The electrical part of the system was separated into two areas: the control system and the plant (distillery). The control system utilises industrial control hardware to operate the still to enable the systems to be scaled up for further research. Industrial distillation apparatus were not used due to the associated operational costs. The second part of the electrical system containing the still elements and water valve were not industrial quality but did not fail during operation. The water control valve was from an automated garden watering system, and the hot water elements are no different to those found in most household kettles.

The scalability of the PLC had was a major factor when choosing a control system but also the hard, real-time nature of a PLC was far more desirable than cost benefits for a micro controller. When operating a still, dangers are present in the form of high temperature liquids, high pressure steam, and toxic gas (95% ethanol vapour is harmful to humans). The loss of control of such a system can cause serious damage to the systems environment and its human operators. For a small scale system like my still a micro controller would be sufficient but constant monitoring is needed to ensure the system does not get out of control. With the PLC after the first few operations it was observed that with the system stability one could safely operate the system remotely.

4.4.1 PLC Commissioning

Siemens offer a large number of PLC configurations to enable control of a wide variety of industrial systems. When selecting a PLC one must allow for scaling to occur as the machine may grow in capabilities, the S7 PLC series allows the engineer to use the same PLC for many machine iterations by increasing the functionality of the PLC with expansion modules. Figure 4.9 is the S7-200 used in my project. It has eight digital inputs and six digital outputs, with a processor capable of evaluating

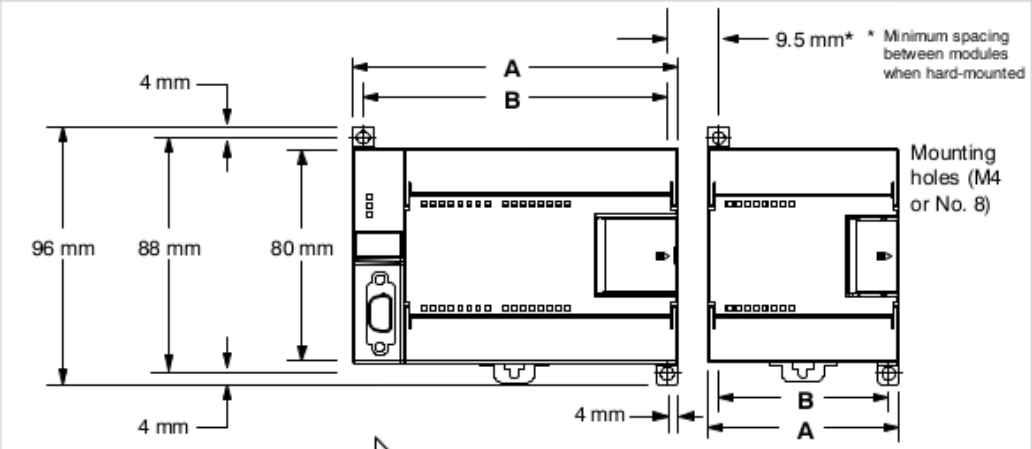
Boolean instructions in 0.22 milliseconds.

Figure 4.9 S7-200 PLC

To ensure that no live inputs or outputs become loose and short during plant operation, the PLC must be rigidly fixed to some form of common mounting board to which all electrical devices are attached. In industrial situations an enclosure should be used to ensure minimal dust, water or other foreign objects do not interfere with normal operation. Enclosures also ensure humans do not inadvertently come in contact with high voltage terminals or allow them to interrupt or override normal scan cycles, causing damage to machines.

When mounting the PLC, cable guides need to be used to ensure initial commissioning and set-up are able to be commenced as quickly as possible. This also means that time spent fault finding is dramatically reduced. These guides should run in a square enclosing the mounting surface with horizontal rungs placed like a ladder from the top to the bottom of the surface, allowing ample space for din rail and hardware attached to the din rail. As the PLC could be running non stop processing

complex algorithms, a 20mm gap above a below the PLC must be allowed for to ensure ample convective cooling can take place.



S7-200 Module		Width A	Width B
CPU 221 and CPU 222		90 mm	82 mm
CPU 224		120.5 mm	112.5 mm
CPU 224XP, CPU 224XPsi		140 mm	132 mm
CPU 226		196 mm	188 mm
Expansion modules:	4- and 8-point DC and Relay I/O (8I, 4Q, 8Q, 4I/4Q) and Analog Out (2 AQ)	46 mm	38 mm
Expansion modules: Modem	16-point digital I/O (16I, 8I/8Q), Analog I/O (4AI, 8AI, 4AQ, 4AI/1AQ), RTD, Thermocouple, PROFIBUS, Ethernet, Internet, AS-Interface, 8-point AC (8I and 8Q), Position, and	71.2 mm	63.2 mm
Expansion modules:	32-point digital I/O (16I/16Q)	137.3 mm	129.3 mm
Expansion modules:	64-point digital I/O (32I/32Q)	196 mm	188 mm

Figure 4.10 S7-200 Mounting instructions

The PLC was mounted to a prototyping board along with a 240v/12v power supply used to power the PLC and other electrical devices in the system. The analogue input module was connected to the PLC via the expansion port connected through a Siemens specific bus connector. Figure 4.10 shows the mounting positions for all its S7-200 PLC series and all the applicable expansions modules. This guide was used to mount both modules ensuring good air flow for the convective cooling employed by these modules

There are three inputs: the emergency stop (Digital) and the two

thermocouples (Analogue), and three outputs: the 1.5 kilowatt and 2 kilowatt coils and a water valve, all of which are digital. The emergency stop button is connected straight to one of the S7-200s inputs while both thermocouples are attached directly to the EM231 module. All of the outputs use an optically isolated Solid State Relay to interface the PLC digital outputs and the coils in the devices they are driving. Figure 4.11 is a wiring schematic used for my project.

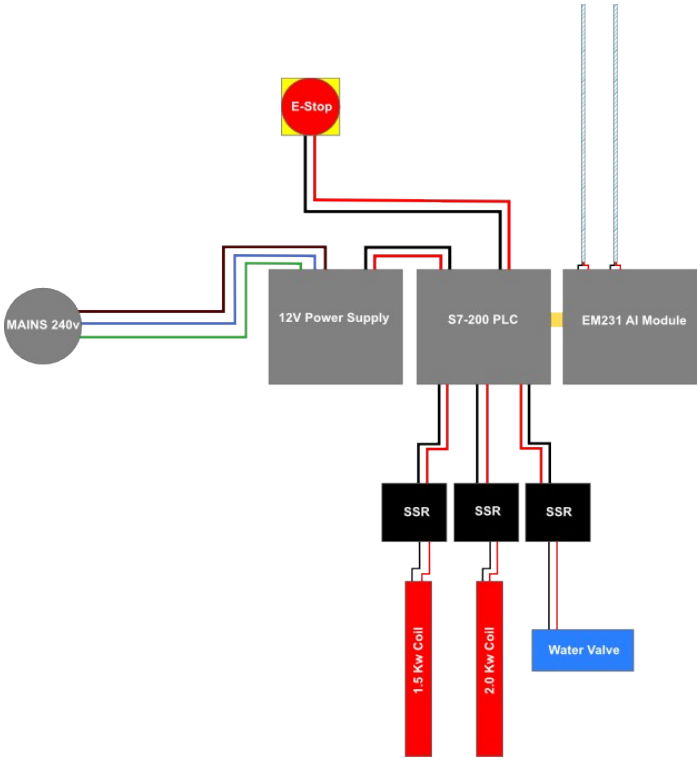


Figure 4.11 Still wiring diagram

4.4.2 Solid State Relays

Back EMF generated when power is removed from a induction coil can generally be disregarded, however the frequency at which the induction coils are driven can generate large amounts of back EMF and will cause reverse breakdown of the silicon in the PLC output circuitry. The output circuitry has adequate internal protection for most applications relays

and other coils need external protection, the S7-200 manual suggests a suppression circuit Figure 4.12. The Diode A is used to ensure current can only flow from the PLC output and not into its circuitry, negating the back EMF. Additionally, diode B should be used for high frequency applications as it reduces the time it takes to dissipate the back EMF.

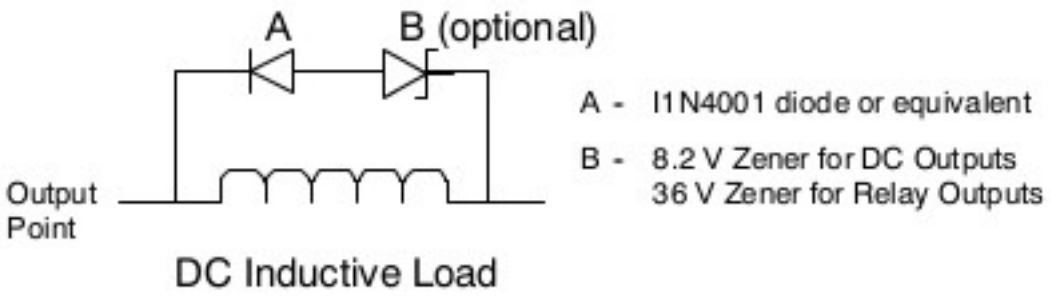


Figure 4.12 Inductive load protection circuit

A more robust solution is to use a optically isolated Solid State Relays (SSR). These relays separate the driving circuit and load circuit using a LED and LRD to activate and close the load circuit. Figure 4.13 is a diagram of the internals of the SSR used in my project. Points 3 and 4 are connected to the driving circuit (the PLC) used to activate the load circuit (the heating elements and the water valve) connected through points 1 and 2.

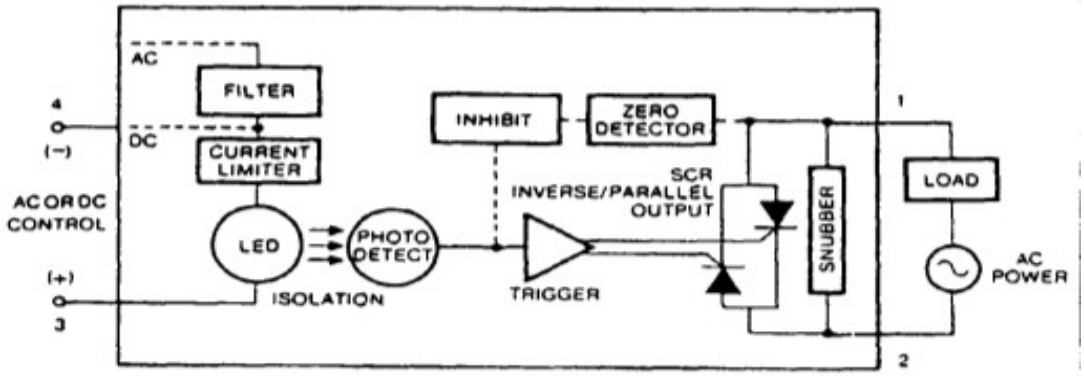


Figure 4.13 optical isolating circuit

The physical size of the relay is due its oversized driver chip used to activate the load circuit. This allows the SSR to be used in conditions where high back EMF is expected and high frequency drive occurs, ensuring the long life expectancy of such a device. This was the reason for using such a device to ensure that long run cycles (10hrs+) would not break or destroy the circuit, resulting in poor or unexplainable operation of the plant.

The solid state relays (SSR) need to be connected to a heat sink to ensure proper operation of the SSR is not impeded by heat soak at full load. The SSR is attached to the large aluminium prototyping board that holds the entire electrical system used by my still as seen in figure 4.14. This is not the heat sink specified by the manufacturing company but can be assumed to be sufficient as the SSR are mounted directly on to the aluminium, giving them good contact between the SSR and the heat sink. The effects of the heat sink is apparent from figure 4.15, reducing the SSR max load current by 60%.

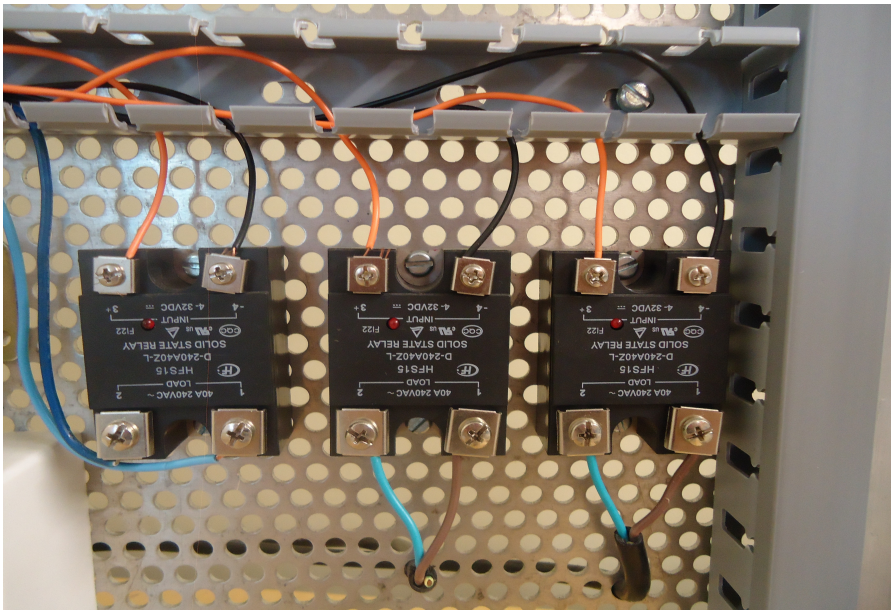


Figure 4.14 Optical isolators

Figure 4.15 shows a graph of the maximum load current that can be used on the SSR versus ambient temperature, and clearly shows the importance of a heat sink for this device. From the graph it can be seen that a load current on the SSR should not exceed 4 amps (RMS), when using a heat sink a load of 10 amps(RMS) can be used. It can also be seen that active cooling needs to be implemented in applications in which this device will be operated in temperatures over 40°C . As it can be assumed at this point in time these ambient temperatures are unlikely in New Zealand, only passive cooling was used with these SSRs.

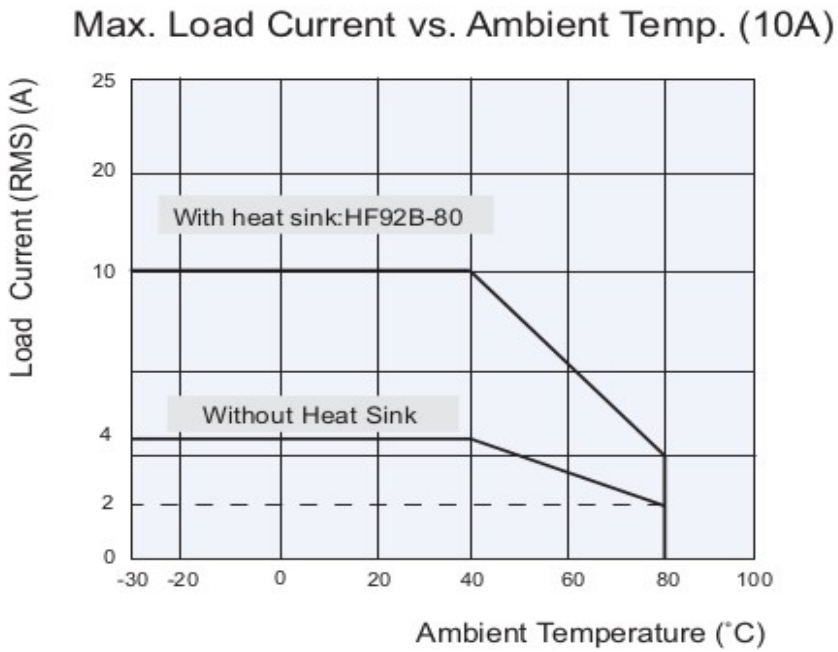


Figure 4.15 Load vs Ambient Temperature for Optical Isolators

4.4.3 Analogue Input Module

The EM 231 is a low cost analogue input module with a high speed 12 bit analogue to digital converter, allowing it to convert an analogue signal to a corresponding digital value in 149 milliseconds. The analogue conversion executes each time the program accesses the memory

location corresponding to the analogue input. This time is added to the basic execution time of the instruction and should be considered if execution time restraints are important to your system. The EM 231 module sends the PLC an unprocessed digital representation of the supplied analogue voltage, that can follow rapid changes in signal including noise. For a slow changing process value (PV) like the still the inputs need to averaged to minimise reading to reading variations.

The analogue input module supplied by Siemens for use with the S7 series PLC can be configured for all types of thermocouples or resistive temperature detectors (RTD) out of the box. This allowed me to attach two K-type thermocouples directly to the AI module with out any calibration. After attaching the module to the PLC and the two thermocouples the system could read temperatures in degrees celcius within +/-0.1°C allowing for precise measurements without the need to calibrate the system.

The EM 231 and all devices that use thermocouples to measure temperature are actually reading the voltage created by the thermocouple. This analogue voltage is then converted into a digital word that represents a number, figure 4.16 shows how the EM 231 system actually works and how the information is transferred to the PLC. The PLC program calls either A,B,C, or D which latches the current reading into the analogue to digital converter circuitry, this value is then stored in the appropriate memory location and used accordingly.

When a reading is called from the PLC the appropriate circuit is energised and the voltage across the cold junction is measured and fed into the Op-amp which magnifies the signal from a few millivolts to a voltage comparable to the reference voltage (12V). The output from the Op-amp is passed through a gain filter to allow for calibration if

excessive noise is present in the circuit, this is fed into a buffer to allow the A/D (analogue/digital) converter to take synchronised readings without data colliding on the actual A/D converter.

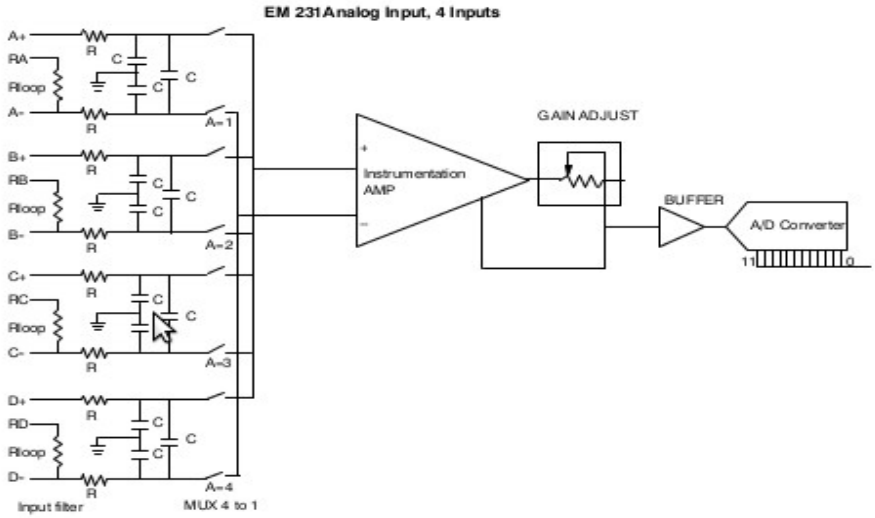


Figure 4.16 S7-200 Analog to Digital converter

4.4.4 Thermocouple

A thermocouple is a device that uses this principle of voltage creation in relation to temperature difference, and are a widely used temperature sensor in industrial processes. Any junction of two dissimilar metals will produce a small electrical voltage that is related to the temperature difference experienced by this junction. Different alloys are used for different temperature ranges, all of which produce predictable and repeatable relationships. Figure 4.17 shows how a thermocouple is used in most applications, with two dissimilar metals attached at the “Hot junction”, and the “Cold junction” used to measure the voltage produced by the temperature difference between these two junctions.

The K type thermocouple was chosen after reference to figure 4.18, as it has a continuous working range of 0 – 1100 (the junction will not fail in

these ranges), is cheap, widely available and was concluded to be the best thermocouple for this application. Another thermocouple that could replace the K-type if unavailable is the T-type, which has a much smaller range than the K-type, resulting in better accuracy across this range.

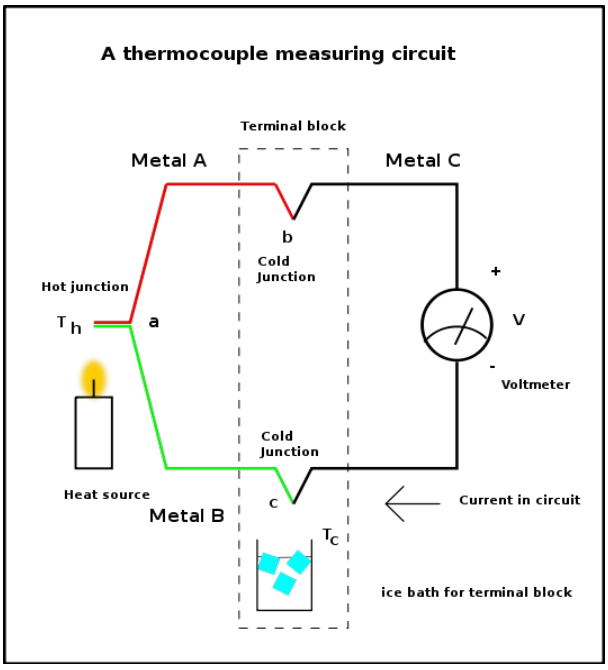


Figure 4.17 Thermocouple circuit

Type	Temperature range °C (continuous)	Temperature range °C (short term)	Tolerance class one (°C)	Tolerance class two (°C)	IEC Color code	BS Color code	ANSI Color code
K	0 to +1100	−180 to +1300	±1.5 between −40 °C and 375 °C ±0.004×T between 375 °C and 1000 °C	±2.5 between −40 °C and 333 °C ±0.0075×T between 333 °C and 1200 °C			
J	0 to +750	−180 to +800	±1.5 between −40 °C and 375 °C ±0.004×T between 375 °C and 750 °C	±2.5 between −40 °C and 333 °C ±0.0075×T between 333 °C and 750 °C			
N	0 to +1100	−270 to +1300	±1.5 between −40 °C and 375 °C ±0.004×T between 375 °C and 1000 °C	±2.5 between −40 °C and 333 °C ±0.0075×T between 333 °C and 1200 °C			
R	0 to +1600	−50 to +1700	±1.0 between 0 °C and 1100 °C ±[1 + 0.003×(T − 1100)] between 1100 °C and 1600 °C	±1.5 between 0 °C and 600 °C ±0.0025×T between 600 °C and 1600 °C			Not defined.
S	0 to 1600	−50 to +1750	±1.0 between 0 °C and 1100 °C ±[1 + 0.003×(T − 1100)] between 1100 °C and 1600 °C	±1.5 between 0 °C and 600 °C ±0.0025×T between 600 °C and 1600 °C			Not defined.
B	+200 to +1700	0 to +1820	Not Available	±0.0025×T between 600 °C and 1700 °C	No standard use copper wire	No standard use copper wire	Not defined.
T	−185 to +300	−250 to +400	±0.5 between −40 °C and 125 °C ±0.004×T between 125 °C and 350 °C	±1.0 between −40 °C and 133 °C ±0.0075×T between 133 °C and 350 °C			
E	0 to +800	−40 to +900	±1.5 between −40 °C and 375 °C ±0.004×T between 375 °C and 800 °C	±2.5 between −40 °C and 333 °C ±0.0075×T between 333 °C and 900 °C			
Chromel/AuFe	−272 to +300	n/a	Reproducibility 0.2% of the voltage; each sensor needs individual calibration.				

Figure 4.18 Thermocouple colour guide

5.0 Discussion & Results

In this chapter the results are compared from both manual and automated distillation, and statistical analysis is used to provide evidence in favour of PID control system implementation on distillation apparatus. These result show both the direct benefits to the distillation process and the benefit this control system has on the process of bioethanol production. The results provide evidence that shows a 28% increase in total energy gained from the PID controlled still, which positively impacts the energy balance equation for bioethanol.

The design process of the still from early concept to functioning plant and potential improvements to the still are documented. The still that was used to generate data for this thesis was designed through experimentation, only finalising the still once satisfactory results were obtained. Further improvements could not be made due to resource restraints but these improvements are documented as I believe these modifications could be used to further increase the amount of energy gained from the still.

5.1 Design

Although the still was an “off the shelf” unit, modifications were required to allow the still to interface with the control system (Figure 5.0). Additional modifications were made to the still hardware to achieve a greater quality of ethanol. These modifications were identified throughout the experimentation process and were implemented to reduce the stress on the control system and the still.

The final iteration of the bioethanol still was created with features selected both from basic assumptions about distilling alcohol and

research into energy efficient distillation apparatus. These features were tested during early experimentation with the final design being used to run six distillations (three manual and three automated) which were recorded for use in this thesis. Features that impacted positively on the distillation process, both for manual and automated distillation were adopted to ensure the experimentations were fair and did not skew the results to either distillation process.

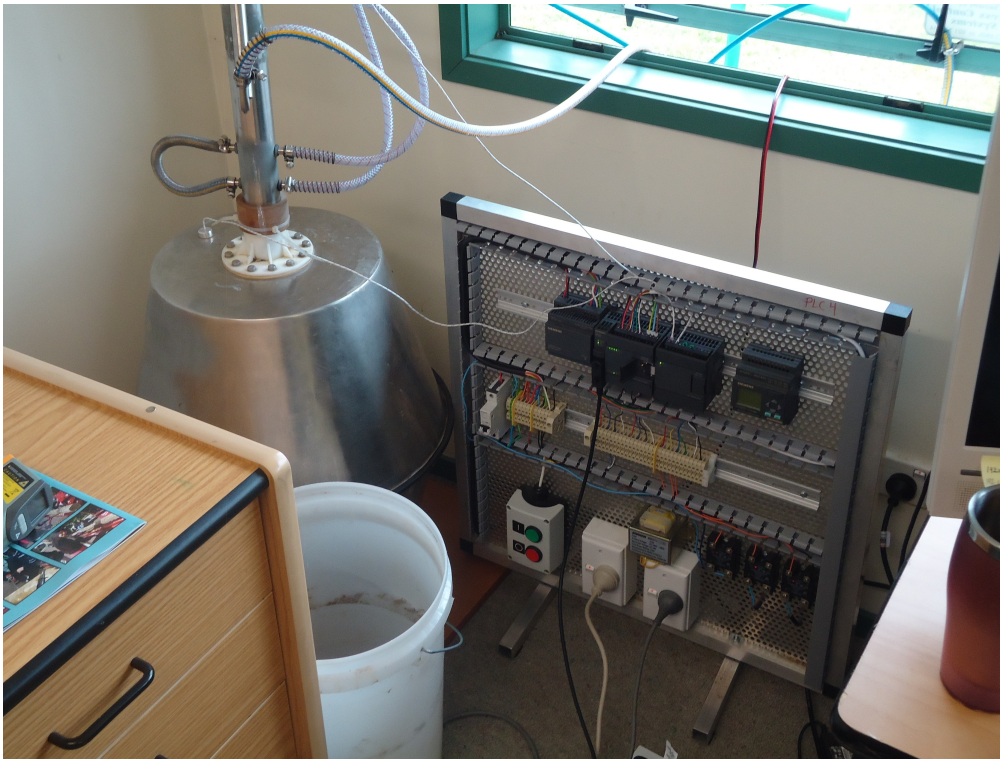


Figure 5.0 Distillation test rig

5.1.1 Still Interface

Initially it was assumed that the mash could be brought up to 80°C and the ethanol would separate out from the mash. It was quickly discovered that this was not the case, and in fact the lower the percentage ethanol present in the mash the higher the boiling point of the mash. The mash needed to be heated above the boiling point to excite the ethanol

molecules enough to be released as steam, this steam would then pass up the column for collection out of the condenser.

On the first iteration of my still, the first thermocouple was located at the top of the boiler tank (Figure 5.1). This was used as the process variable for PID loop 0 to control the temperature in the distillation tank. The original mounting position at the top of the tank was not actually in contact with the mash, it read the temperature of the steam above the mash and had little correlation to the actual purity of the steam being collected at the top of the column.

Figure 5.1 Mash temperature sensor location

This was a problem because the set-point of 80°C would not produce ethanol as there was not enough energy to move the steam up the column. The set-point of the tank had to be calculated to produce a steam temperature of 78.5°C at the top of the column. The temperature of the tank and the rate at which this temperature would need to increase as the percentage ethanol in the mash deceased throughout the distillation process had to be calculated.

It was later discovered that better control of the distillation tank could be gained by moving this thermocouple to the top of the distillation column (Figure 5.2). Measuring this temperature directly correlated to the temperature of the steam that had passed up the column to be condensed to a liquid. This gave better control over the quality of bioethanol extracted from the mash because at 78.5°C the steam would form an azeotrope consisting of 95% alcohol and only 5% water.

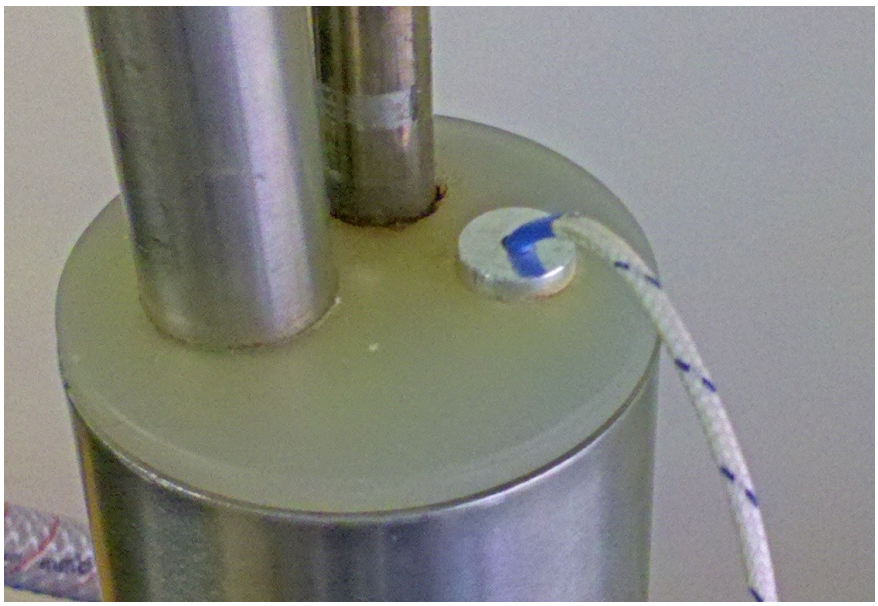


Figure 5.2 Column Temperature sensor location

Controlling the temperature of the steam at the top of the column reduced the complexity of the control system. This required the top of the column to be kept constant at a temperature of 78.5°C. Controlling the temperature of boiler tank required the set-point temperature to increase as the percentage bioethanol in the mash decreased during the distillation process.

Calculating the increasing set-point would require the the system to measure the amount of Bio-ethnaol left in the mash. Measuring how much bioethanol was left in the mash would increase the complexity of

the physical system as well as the algorithm used to run the still. Conversely a control system that incremented the temperature every hour would not adhere to the Advanced Process Control algorithm and could cause unforeseen problems.

5.1.2 Temperature Measurements

Temperature control of the column was done using a PID control loop to maintain a constant rate of separation of bioethanol from the mash. While the thermocouple was moved to the top of the column the PID loop remained relatively the same. The response time of the loop needed to be increased, as the steam temperature in the column changes much faster than the mash temperature.

The PID loop was adjusted to respond quicker to these changes in temperature. By increasing the Integral (I) variable and the Derivative (D) variable the system was able to respond in an acceptable manner to temperature changes, maintaining the top of the column at 78.5°C. The I variable was used to decrease the response time of the control system, with the D variable used to bring stability back in to the output.

The adjustments were made to the system through the WinCC IDE during a distillation run, meaning the system was on-line. While monitoring the Process Variable (PV), the set-point, and the output through the IDE I was able to incrementally increase the variables and in real time view how the changes had effected the systems response. Figure 5.3 shows the PID wizard which is used to tune the PID loop for my individual application, with the P,I, and D variable inside the red box. Auto-tuning was available but I felt that the adjustments made produced an adequate system response.

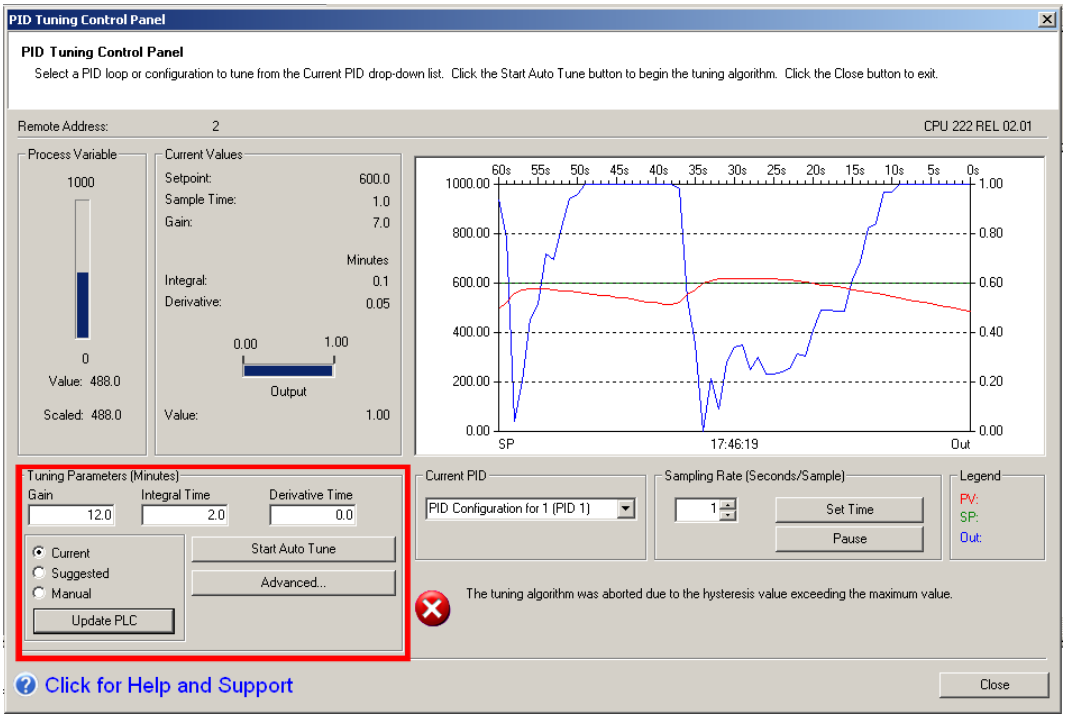


Figure 5.3 PID manual control value adjustment

5.1.3 Cooling Circuit

It was initially assumed that a PID loop used to control the rate of separation would achieve a quality of greater than 93% bioethanol. Controlling the condenser with a on/off type control loop was assumed to be sufficient as this control loop would maintain the temperature of the condenser circuit within +/- 2°C. This did not work and it was discovered that the condenser is of similar importance if not greater importance than just the rate of separation.

The condensing unit was initially thought to contain the column and the condensing shaft. This entire unit was kept below the boiling point of ethanol to allow the ethanol vapour to re-condense into a solution of 95% ethanol. After the first experiment it was discovered that this theory stopped the ethanol from travelling up the entire length of the column and down the condenser shaft.

With this column configuration the ethanol would collect at the top of the column (which was maintained at approximately 70°C) and at random ethanol would spurt out of the still at a lower percentage than required. It was concluded that this happened because the column head would flood and low quality ethanol would be pushed out the condenser shaft. At this point it was concluded that the still was made up of three sections: the tank, the column and the condenser.

After these initial experiments I moved the second thermocouple half way down the condensing shaft. This allowed the ethanol vapour to travel up the entire length of the column allowing the distillate to take full advantage of the packed column. This ensured that the vapour was of the highest quality possible also ensuring that the vapour would not collect but instead flow out of the condenser as a steady stream.

This adjustment greatly improved not only the quality of bioethanol produced, but also the production rate as the still was no longer impeded. By controlling the temperature of the column and vapour, the purity of the ethanol to be collected could be controlled by ensuring the temperature was constantly 78.5°C. Treating the condenser shaft as a separate section of the still allowed the high quality vapour to be condensed into a high quality solution.

The cooling circuit used a solenoid activated water valve attached to a mains water tap. By adjusting the length of time the valve was opened the PLC could determine how much cooling was applied. This time was determined by measuring the temperature of the condenser shaft which is then used in PID loop 1 and adjusted by the PLC using PWM (pulse width modulation) to vary the solenoids operation.

This cooling circuit configuration did enable the still to produce overall great results, allowing the still to produce a constant stream of ethanol at greater than 93% purity. The cooling system however did not produce good temperature control over the condenser column, as in Figure 5.4 it can be seen to fluctuate +/- 20°C which is not acceptable. These fluctuations are caused by the delay introduced by the physical layout of the cooling circuit.

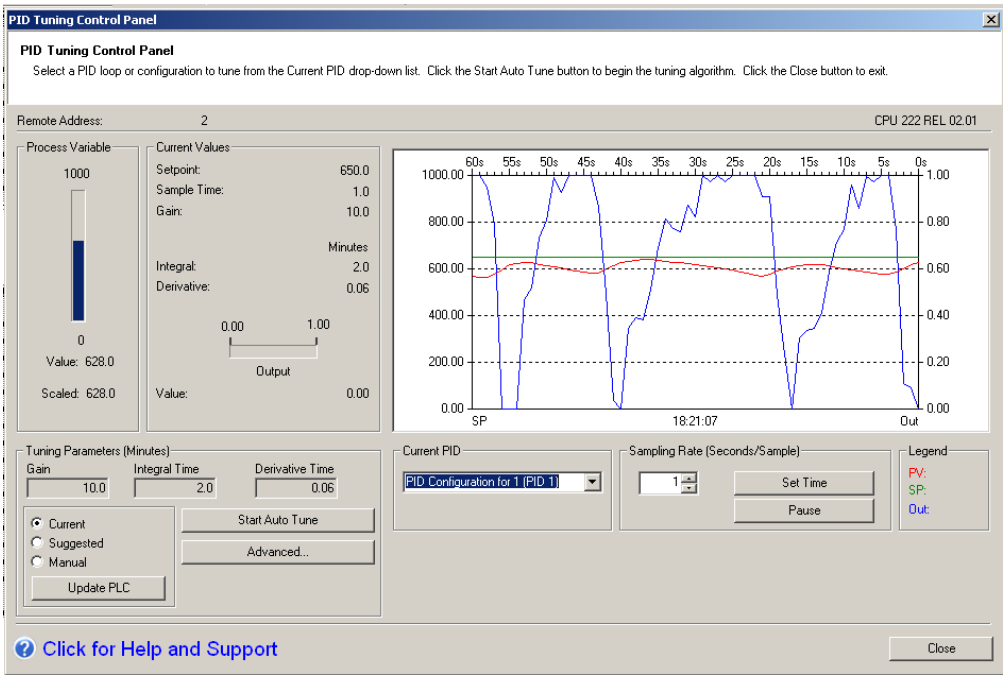


Figure 5.4 Cooling system output

The length of the cooling circuit and the pressure at the mains tap are believed to be the cause of the delay experienced by the cooling circuit. The distance between the mains tap introduces a delay between the system being activated and water passing through the system. Adjusting the pressure at the mains tap yielded little benefit as it would decrease over the distillation process.

Although the control system could be adjusted to drive the water valve

at a slower duty cycle the pressure drop cannot be solved so easily. The current duty cycle activates the solenoid but no water flows through the system. Slowing the duty cycle will allow the activation to pass water through the system. It was concluded that controlling the flow rate of the water through the system would achieve greater control over the condenser temperature.

When using the current cooling system, 50 litres of water is used to cool the column for each distillation run. This water is re-used to clean fermentation tanks and fill them with warm water for mash creation, but ultimately it is considered waste water. A better solution to the current configuration would be to use a 50 litre reservoir that feeds a sealed cooling circuit that circulated water through it utilising a radiator to dissipate heat.

This system would use a pump that feeds the cooling circuit and be controlled by the PLC with is operation speed determined by the PID loop. This would reduce the fluctuation experienced in the condenser temperature by adjusting the flow rate of the water, not just the supply of the water. This will ensure the cooling system is constantly filled with water which will terminate the delay experienced by the current solution. By giving the system continuous control over the flow, it will allow for a faster response and will also reduce the amount of waste water produced by the system.

5.2 PID Tuning

The PID control algorithm is used to gain exceptional control of two regions in my distillation apparatus. These regions need to be kept at a constant temperature to ensure energy efficient distillation of the mash, while producing high quality ethanol. These control loops are used to

monitor and control the amount of energy going into the system, ensuring the still is operated in the most energy efficient way possible.

When tuning PID variables one usually wants a system that overshoots slightly, to obtain a system with a quick response time that will also settles to a steady state quickly. When initial trials were done it became apparent that both overshoot and undershoot were not ideal for the creation of high quality bioethanol, as both states produced unacceptable output. Overshoot created bioethanol that was less than 90%, and undershoot produced no ethanol. It was concluded that an over-damped system would produce the best results.

The over-damped system ensured that energy was constantly applied to the mash at a rate that allowed the ethanol to separate without ever going over the set-point. This approach for ethanol production did not allow the system to produce low quality ethanol, while producing a constant stream of high quality bioethanol. By removing the overshoot characteristics of the PID loops I was able to eliminate the production of low quality ethanol and the undershoot.

PID loop 0, used to control the temperature of the distillation tank could not be auto tuned in the stills initial configuration, where the temperature sensor was in the distillation tank. The auto tuning algorithm needs 100 samples to compute the appropriate P, I, and D values but within a time limit of 20 seconds. The system was unable to determine 100 samples in this time because the mash temperature could not oscillate at this frequency. The time between the system overshooting the set point (heating up) and then undershooting (cooling down) was too long for the auto-tuning algorithm to compute the required values.

Since auto-tune was not working and I had not yet moved the temperature sensor to its final position, the Nicola-Kieger method was used to get rough P, I, and D variables. This brought the system into a stable state that was then manually tuned for optimal operation of ethanol productions. Manual tuning was done straight from the PID tuning screen which showed a real time graph of the input, set point, and output versus time allowing me to view how my changes affected the PID loop.

Manual optimisation tuning was done with aid from the table in Figure 3.14. Optimal control of the system was determined as production of ethanol that was greater than 93% at a constant flow of approx 1 litre per hour. After initial trials it was determined that optimal control of the still could not be obtained by controlling the tank so the thermocouple was moved to the top of the still column.

After moving the thermocouple up the still column I was able to use the IDE to adjust the rough PID variables to gain exceptional control of the still. Using an over-damped PID loop still proved to be the best way to obtain ethanol although a slightly faster response was needed as the column reacts faster to energy input. I increased the I variable to increase the response time of the system. This made the system unstable so a slight increase was made to the D variable to bring the system back in to optimal production that was extremely stable.

The cooling circuit was found to be best controlled with a PID loop, as an on/off algorithm was not cooling the condenser sufficiently. A second PID loop was implemented (PID loop1) to control the temperature of the condenser. The cooling circuit thermocouple was moved down the condenser to read the temperature of the distillate that was to be collected. The PID variables were obtained through the use of the Auto-

tuning algorithm to obtain a control system that enabled the condenser to produce bioethanol greater than 93% purity.

After the PID loop was used to control the condenser circuit it was discovered that the cooling circuit hardware was insufficient to cool the ethanol at the current rate of production. To gain exceptional temperature control of the condenser, modification to the cooling circuit need to be made.

5.3 Results

After experimenting with PID variables and control systems I was able to create a control system that fully automated the operation of the still. The control system monitored the temperatures of both the column and the condenser, then calculated the appropriate inputs needed to keep these areas at their specific set-points. This allowed the still to produce ethanol at a purity of greater that 93% without any input from the user, and by producing more ethanol with less energy I was able to increase total energy gain by 28%.

By controlling the temperature of the still and only applying the necessary energy to maintain this temperature I was able to reduce the energy needed to distill high purity alcohol. The amount of power used for each distillation was measured to compare the total energy used by the still and also to compare gross energy yielded (amount of potential energy stored in the ethanol). This was achieved using an off the shelf power meter to measure the total power used by the still over the 7 hour period, and from this the total net energy used was calculated.

To compare the manual still to the automated still 50 litres of mash at 14% alcohol was placed inside the distillation tank. A distillation was

carried out over 7 hours with an expected yield of 7 litres of alcohol, at which point the experiment was stopped. Measurements of the alcohol purity were recorded at each hour using a hydrometer taking a sample directly from the condenser stream.

The final concentration of the bioethanol collected from each distillation was measured and compared to the result from purity measurements to confirm these measurements were correct. This measurement allowed me to calculate the total ethanol collected from each distillation. With the total amount of 100% bioethanol extracted form the mash I could calculate the total potential energy extracted from the system by multiplying the total bioethanol collected by the 21.2 Mj/L.

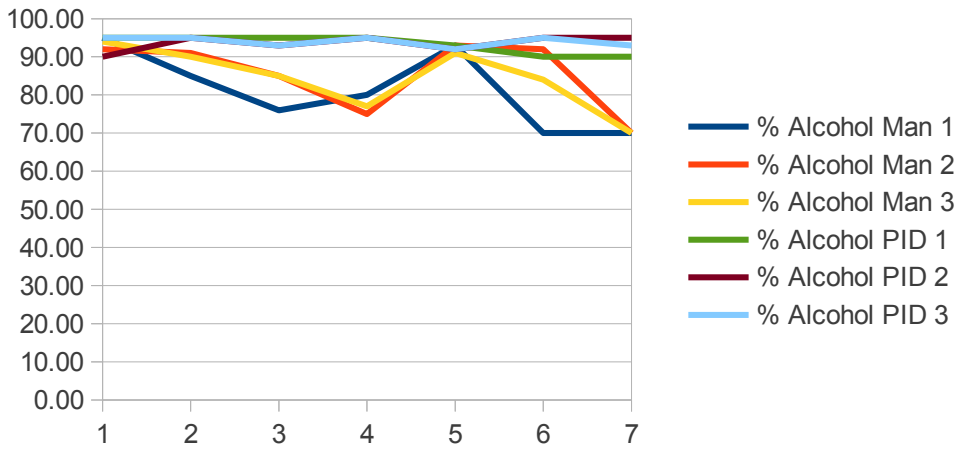


Figure 5.5 Manual vs Automated distillation Alcohol %

Figure 5.5 is a graph with both manual and automated distillations using purity against time, and shows that the automated distillations were able to produce ethanol that was consistently greater that 93% purity. The manual distillation was rather erratic and this was further qualified by the overall percentage bioethanol of the manual batches. All PID controlled batch were able to produce a batch of ethanol that was over

93% ethanol, the average quality of the manual controlled distillations was averaged out at 83%. This increase in quality enables the PID controlled still to produce on average 10% more pure bioethanol from each batch of mash processed through the same distillation apparatus.

The manual distillations all seem to follow a similar distillation cycle, in which they begin at 95% then slowly tapper down to 73%, this then rises back up to ~90%. After the distillation has risen to approximately 90% the manual distillation will taper off for the last 2 hours of operation. One could assume that this purity oscillation was due to operator error, however this cycle is repeated in each manual distillation removing this hypothesis from possible conclusions.

These results were obtained by taking samples from the still, each subsequent hour after starting the distillation. The first part of these are what would be expected of a manual distillation, starting well and slowly tapering off. No conclusion can be made as to why these distillations increase in purity near the end of their distillation run and are not what one would expect. These results were cross checked and confirmed by comparing the average purity of the measurements to the final purity of the batch.

The height, diameter ratio of the distillation column has a major effect on the quality of ethanol that the still can produce. The Euro still I was using had a short column, as a consequence the still could only achieve a quality of 93%. To obtain 95% purity requires the height of the column increase to produce a ratio of 25:1 (height:diameter) that would allow for a longer temperature variation. This increased variation allows the ethanol vapour to distill many more times increasing its final purity, also allowing the distillate to dissipate any excess heat energy reducing the stress on the condenser.

While a larger column would be beneficial, a better solution could be to use a second distillation column. This would allow the distillation run to double distill a batch of mash and could achieve 95% ethanol with little extra energy needed. This column would be of similar size to the first column but would allow the vapour to collect in the bottom as a liquid of approx 60% - 80% ethanol. This would be better, as the short column would ensure a short run time, a larger column will increase run time, also increasing energy used.

The second column would be fed steam from the first distillation column, passing through a solution of approximately 70% ethanol which would have a much lower boiling point than that of the 14% mash. This lower boiling point would allow the second distillation to use only the steam energy from the first distillation to raise the solution temperature to remove ethanol at a higher percentage, allowing the steam to go through another set of phase changes.

This type of distillation is used at BSE and most other bioethanol plants as the lower the concentration of ethanol the harder separation is, as the boiling point is closer to that of water. The first column is referred to as a beer column, in which the mash containing <10% ethanol is processed removing the ethanol as a solution of >60% ethanol. This has a much lower boiling point than the mash, this is then processed in the distillation column and removed at 95%.

5.3.1 Energy Consumption

The energy consumption of the still running manually can be calculated by multiplying 1.5 kw by 8 hours and adding 3Kwh to account for the the 2Kw coil being on for first 1.5 hours of operation. Measuring how much

energy the still consumed was done using a Kwh meter and the measurements showed a decrease in energy consumption of 10%. This was expected as during manual stilling the coil is left on until all the ethanol is removed, steadily decreasing the quality of ethanol being extracted. With automated control of the still, only the energy that is needed is introduced so not only does the quality stay high but the energy consumed reduces.

Insulation of the tank could also decrease power consumption as energy escaping through the large tank walls would be decreased. This would also heat the mash up to temperature faster decreasing the time the booster coil would need to active. This could be achieved wither through building a double walled tank or covering with a insulation layer.

The basic principle of distillation is to heat one area then remove this heat in another area. When removing heat energy from my still the heat is wasted as it is ejected through the water system. Recycling this water through a cooling circuit can introduce many areas in which this energy can be reused. Running this circuit through the fermenting mash could be used as a heat source for temperature control, this could also be used to raise the mash temperature for pitching yeast.

5.3 Further Enhancements

Efficient control of any system must implement some form of APC. Simple on/off control will not work especially when controlling large volumes of liquid as they tend to work as large thermal reservoirs, introducing a oscillation of temperature around the set-point in a sinusoidal pattern. The use of PID loops was a necessity to achieve the results I did from this distillation apparatus and its current configuration. Further improvements in distillation and energy yield could only be

achieved by modifying the still:

1) Insulation of the tank and column.
2) Adding a 2nd column to the still.

At present the still tank is exposed to its surroundings, allowing for thermal conduction between the mash and the stills environment through convection. Distillation is a process that uses energy to change the phase of a chemical with a lower boiling point than another substance, and reducing the loss of this energy will reduce the amount of energy needed. A booster coil will still be needed but the amount of time it is required will be reduced. Additionally, the coil that is used to power the distillation could be reduced, possibly even below 1 kilowatt.

The challenge with bioethanol distillation is the small quantity of ethanol present in the mash. In perfect conditions yeast can only ferment up to 20% ethanol but generally a mash will contain only 10-14% alcohol. As the bioethanol is removed from the mash the boiling point of the mash increases, getting closer to that of water. As the boiling point approaches that of water the possibility of more water particles being present in the steam increases, making the system work harder to maintain a high quality of bioethanol.

When this happens in the alcoholic beverages industry the excess water can contain impurities which are introduced in the alcohol. These impurities can lead to bad tastes or odours in the final product which is not ideal, so these impurities must be removed from the alcohol before it can be bottled. The solution used is to double distill the alcohol or even triple distill in some high end liqueurs as each distillation removes more impurities.

A second column would act much the same as double distilling the bioethanol without significantly increasing energy expenditure, as the column can be powered by steam from the tank. The column will act like a second distillation tank, allowing distillate to collect in the bottom of the column at a higher purity than the first tank (approximately greater than 80%). This distillate will then be heated up to a point where the ethanol will boil off at an even higher purity. This requires less energy, as the purity is so high and the volume is quite small in this reservoir that it could use the energy released from the first tank to operate.

6.0 Conclusion

Data retrieved from my experiments showed the PID control system produced more pure alcohol (100% bioethanol). Both distillations methods produced 7 litres of ethanol but the PID controlled system constantly produced bioethanol that was above 90%, while manual distillation would fluctuate and go as low as 70%. This consistency allowed the PID system to increase pure alcohol yield from the individual batches.

The PID controlled distillations increased pure alcohol yield from individual batches by 13%. Manual distillation produced an average of 5.671 litres of 100% bioethanol, while the PID system created 6.51 litres of bioethanol. Equation (1) and (2) represent the gross energy yield from the distillation process, (1) is for manual distillation and (2) is for the PID controlled distillation.

$$5.67\text{L} \times 21.20\text{MJ} = 120.20\text{MJ} \quad (1)$$
$$6.51\text{L} \times 21.20\text{MJ} = 138.01\text{MJ} \quad (2)$$

The increased quality of bioethanol production is attributed to the control the PID system exerts on the still. The control algorithm limits the amount of energy introduced in to the still ensuring the bioethanol produced is above 90%. This attribute decreases the amount of energy the PID system uses to produce 7 litres of bioethanol, increasing the net energy yield.

$$120.02\text{MJ} - (14.00\text{kWh} \times 3.60\text{MJ}) = 69.83\text{MJ} \quad (3)$$
$$138.01\text{MJ} - (11.20\text{kWh} \times 3.60\text{MJ}) = 97.70\text{MJ} \quad (4)$$

The net energy (gross energy yield, minus energy cost) for manual (3) compared to PID controlled (4) distillation shows a 28.5% increase in net

energy yield. Manual distillation uses 14kWh of energy while PID distillation uses only 11.2kWh of energy, a 20% decrease in energy consumption. The decrease in energy consumption coupled with the increase in material yield leads to an increase in production efficiency of 28.5%.

This consistent quality of ethanol produced not only increases the overall energy yield from the PID controlled still but allows the output to be directly fed into a molecular sieve. The only way to remove the last 5%-7% of water left after distillation is through physically removing the water molecules with a molecular sieve. This process requires an input stream of between 93% - 95% ethanol to remove the water producing 100% ethanol which can be used as a biofuel. The quality at which the PID controlled system produces allows the addition of a molecular sieve into the system.

This increase in total energy gained can be directly attributed to the use of the PID algorithm. This control algorithm and automation system ensured the production of high quality bioethanol also limiting the energy input to reduce the amount of energy that may otherwise have been wasted. These results can be further improved by making physical changes to the distillation apparatus.

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8.0 Bibliography