Non-Classical Level Control of the UTC Distillation Column

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Abstract

This paper researches the enhancement of accuracy for level control for an operational distillation column. This was achieved through an analysis of both controller and sensor components. The UTC distillation column reboiler level control, like any control system, has multiple sources of error resulting in increased imprecision and inaccuracy. Several fundamental inaccuracies in processing of data were identified and then minimized by the introduction of a non-linear mathematical model prior to any actual controller development. This provides more accurate level measurement and a base for developing accurate controllers.

In exploring the effectiveness of alternative controllers, two non-classical controllers are considered in this project for the case of continuous operation. These two new, more effective controllers have been designed, implemented and evaluated through comparison to their classical counterparts. One controller uses a very simple binary proximity sensor as its basis leading to an almost simplistic concept that proves to be surprisingly effective in controlling the complex system. Fuzzy-logic is used in another controller configuration to minimize the complexity of mathematical calculations in decision-making by modeling a controller on abstract ‘human’ logic. Remote operation is achieved for this proximity controller to enable users to operate the distillation column via the internet.

The performance of the proximity controller is found to be excellent. On the other hand, the fuzzy controller has not been completely debugged. The effort needed to develop the fuzzy controller was great and I recommend using this type of controller for more complex systems where the investment in time and effort is better justified. The binary proximity sensor based controller was especially effective considering its simple concept and even simpler development. Additional possibilities exist for enhancing the gathering and processing of level data using data fusion, alternate sensors such as a thermistor-based sensor, and alternate means of tuning the problematic fuzzy controller such as neural networking. Research into the development of parallel controllers based on different theory and sensors has been shown to be a way to improve and optimize the level control system.

1. DEFINITION AND SCOPE

1.1 Definition of the Problem

The process under consideration is distillation - the concept of separation of mixed liquids using the principle that each liquid substance has a different characteristic boiling point. The UTC Distillation column has many control systems to regulate and control various processes in the column, and yet one process that has not received an adequate solution is the level control of the reboiler. Accurate regulation of the level of the liquid in the reboiler is necessary so as to avoid damage to the heating elements (when the level is too low) and also to avoid flooding the lower trays in the case of too much liquid. Therefore, a control system to accurately monitor and control such an apparatus is necessary. Boiling liquid can be problematic due to the motion of the liquid on the surface making measurement inaccurate. The current level sensor, a differential pressure sensor, has proven unreliable in accomplishing this task consistently. Additionally, this system is problematic due to the complexity of the interactions within the system - the functions of temperatures, pressures, pump feed rates, mixture proportions and other factors are all interrelated.

1.2 The Goals of the Project

The goals of the project are four in number:

- Design and implement a non-classical proximity-sensor-based expert controller
- Design and implement a non-classical controller using Fuzzy Logic
- Design and implement remote operation for both controllers
- Compare the effectiveness of the controllers

In this project, I will extend the work initiated by Rebecca Williams (Williams) by designing a proximity-sensor-based controller and a fuzzy-logic reboiler level controller. The combination of control systems for the distillation system will be made accessible via the internet enabling remote operation.

I will not direct my attention to the other control systems in the UTC distillation column, but rather will model the level control of the reboiler as an independent system.

The first controller uses a completely new sensor that has not been used for level control in this distillation column. This controller is non-classical because the sensor signal is used in a scheme that uses expert information to control the equipment. The development of the second non-classical controller investigates the possibility of overcoming the imprecise nature of the present controller with fuzzy logic decision-making.

While the efforts of this project are directed towards solving the irregularities of a specific distillation column, there is no reason why the designs for the proximity-based controller or the concepts of fuzzy logic control cannot be applied to other level control procedures, or other control systems in general. Remote operation is reasonably within the scope of most control systems, as it is realistic and removes the restriction of location that has been placed on the machine operator.

2. NOMENCLATURE

Classical Control – is the mainstream control theory using a continuous time signals for the domain of its input and a continuous range for its output. It is used for linear control systems on a single input single output (SISO) basis.

Control system – is a device used widely in engineering to control a process by measuring an input and making an automated decision. A control system can be summarized through its three fundamental functions – measure, decide, act.

Controlled Variable – is the variable whose control is desired.

Expert system – is a classification of a control system. It is defined as an automated controller that replaces a skilled human operator (or 'expert') in an operation.

Fuzzy Logic – is logical theory that is moving away from the traditional Aristotelian logic whereby everything is crisp and definite. Fuzzy logic has a mathematical base in abstract algebra, but unlike traditional mathematics, it claims that answers occur in degrees. Fuzzy theory allows modeling of complex systems more easily through fuzzy logic control systems where crisp definite equations are too complex to determine.

Manipulated Variable – is the variable that the operator manipulates in order to make the system create an output as desired.

Thermistor – is a resistor whose resistance is noticeably dependent on temperature. The word is a combination of ‘thermal’ and ‘resistor.’

Virtual Instrument – is a software program that performs the tasks of a conventional measuring instrument. Data manipulation in the form of noise reduction, necessary arithmetic, statistic and calculus operations can be performed as desired.

3. BACKGROUND

3.1 The UTC Distillation Column

The UTC distillation column has the following general characteristics – a vertical shell, twelve column intervals (trays), a condenser at the top, a reflux control valve for the distillate, a reboiler with heating rods, and pumps controlling the inlet feed rate, distillate feed rate and reboiler outlet flow rate (Williams, 2). See Figure 3.1.1 overleaf for the diagram of the distillation column.

The process of distillation is the separation of liquid-phase substances in a mixture using the property of varying boiling points. When boiled into a mixture in a gaseous state, the different substances will have varying volatilities, causing them to separate with the less dense gases rising higher up the vertical shell. A condenser located at the top can then change the state back to liquid and the distillate can be collected.

While distillation is used in many chemical processes with varying mixtures, the UTC distillation column uses a methanol-water mixture.

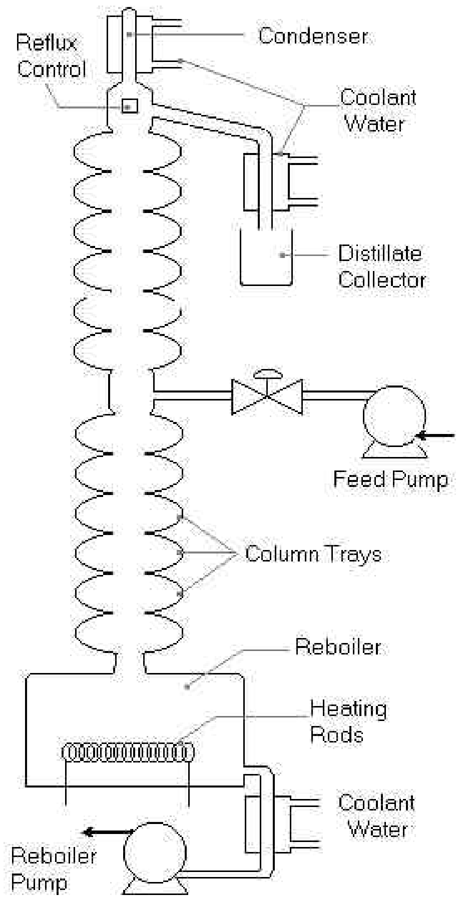

FIGURE 3.1.1 – Grote Distillation Column

<u>3.2 Reboiler Level System</u>

The level of the reboiler should be maintained between 8.5 liters and 16.5 liters. If the level decreases beyond this minimum prescribed limit, the electrical resistance heating rods will be exposed, causing them to overheat and degrade rapidly. If the level is too high, the liquid mixture will enter the lowermost trays degrading the distillation process. The figure overleaf (3.2.1) shows the physical layout of the reboiler.

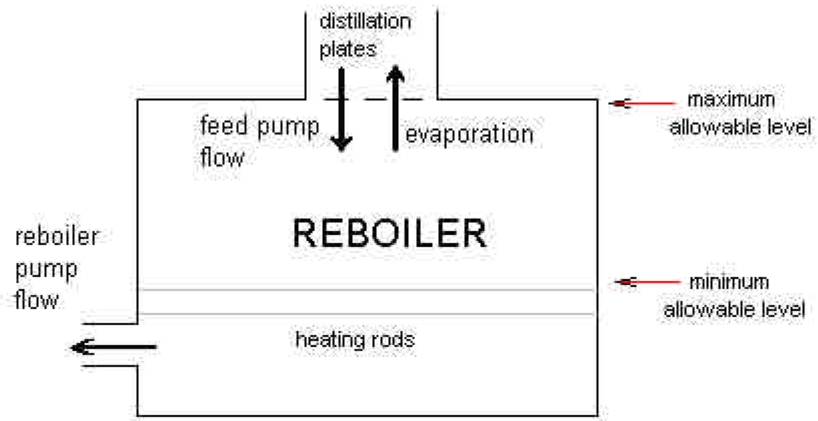

FIGURE 3.2.1 – Reboiler schematic with liquid flow

The system itself can be summarized through the block diagram shown below in Figure 3.2.2. It can be observed that the reboiler pump is manipulated (hence its termed the manipulated variable M) to create the desired level output in the reboiler (controller variable C). The other factors that affect the system include feed pump rate, the loss of liquid through evaporation, which in turn is a factor of the rate of heating and the ratio of methanol in the solution. Thus the other factors that can be altered for different runs are many - creating a complex system to control.

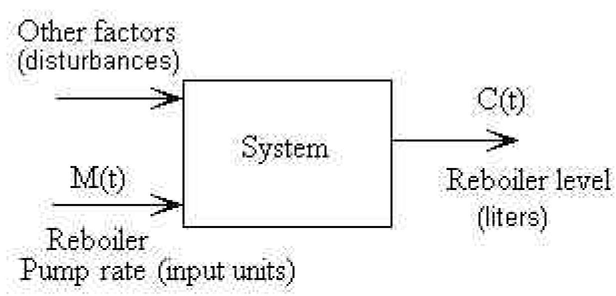

FIGURE 3.2.2 – Reboiler system block diagram

3.3 Current Level Sensor

The current level sensor used for the maintenance of the level of the reboiler at the desired level is a differential pressure sensor. This type of sensor makes two pressure measurements – the gas pressure in the reboiler, and the pressure at the bottom of the liquid. The difference between these two readings is proportional to the height of the liquid in the reboiler, and thus a reading for the volume of liquid can be obtained.

The specifications of the differential pressure sensor are given in Appendix 1. The equation governing the readings of this pressure sensor, derived from Bernoulli's equation for hydrostatic pressure is:

$$\Delta P = rg\Delta h$$

Thus it can be seen that the change in pressure is proportional to the change in liquid level. The calculation of the constants can be done easily through calibration to two data points (known level readings). The output is linear due to the proportionality of the equation above (we consider the fluid density and the gravitational acceleration to be constant).

One primary problem that has been experienced with the pressure sensor is the brief erratic fluctuation of the level reading under particular unknown operating conditions. The erroneous reading is usually brief and thus the reading returns to the original level reading soon afterwards. However, such an error is potentially hazardous to the reboiler level since there is a likelihood that the current crisp control system may react to these surges with action that is unwarranted.

Expert operator Dr. Jim Henry believes that the sudden surges may be due to condensation of gas, which may then flow along the tube to the gas-pressure sensor end. Obviously, even minute amounts of liquid stagnation at the gas-pressure end will cause deviations in readings affecting the overall level output from the sensor.

3.4 Use of LabVIEW software

LabVIEW is a software application by ‘National Instruments’ that allows for digital data acquisition and manipulation. It allows users to construct ‘Virtual Instruments’ – programs that perform the tasks of a conventional measuring instrument. This includes data acquisition and manipulation (such as noise reduction, calculations, calculus operations, sample means) – which is then displayed as per the user’s needs. The low-level programming that LabVIEW executes is a language named “G”. One of the greatest advantages with this program is the visual icon-based programming which is much easier than traditional text-based programming.

LabVIEW has a Fuzzy Logic Toolkit that enables users to integrate fuzzy logic control into virtual instruments. This toolkit will be utilized in for the first controller implementation. While it is possible for fuzzy logic virtual instruments to be designed directly from low-level languages, the programming capabilities and expertise are beyond the scope of this thesis. Thus, a ready-made (user-friendly) toolkit must be utilized to implement this controller.

The second proximity-based controller does not require this fuzzy toolkit. It requires ordinary manipulation that is implemented as normal through the LabVIEW diagram.

The easiest approach to building these VIs may be to develop sub VIs for each of these controllers and integrate them with the already-existing hierarchy of VIs that currently in place controlling all the systems in the distillation column. In other words, we do not need to build everything from scratch, but merely develop an additive sub-VI to replace particular functions for level control.

4. PROXIMITY CONTROLLER DEVELOPMENT

4.1 CONTROLLER DEVELOPMENT

4.1.1 Proximity Sensor Theory

Introduction

The proximity sensor is a capacitive sensor that senses the presence (or absence) of an object through the detection of induced electric fields. The type used in this controller is a simple binary (on-off) capacitive sensor that exhibits a non-zero voltage (in this case 6V) when an object is placed up to 20cm directly in front of the sensor. Otherwise the sensor exhibits 0V. The orientation of the sensor can be seen in Figure 4.1.1. Note that the presence of the air between the sensor and the reboiler glass wall itself that are both undetected by the sensor. However, the sensor accurately detects the presence of the (transparent) liquid.

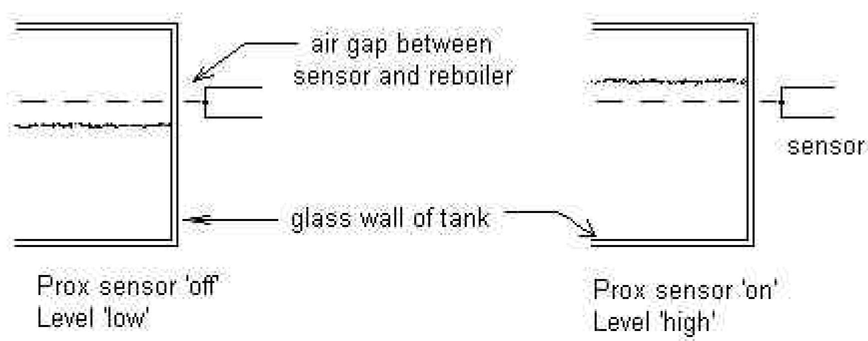

FIGURE 4.1.1 – Proximity Sensor Orientation

An obvious advantage that this proximity sensor has is the lack of contact with the liquid, thereby reducing deterioration of the sensor and other potential complications. The external mounting of the sensor also introduces various advantages for the new control system. It is a lot more convenient to replace, check and handle the sensor since it is externally mounted. There is also no interruption to any experiments that are being conducted.

Testing of Apparatus

The initial testing was carried out with the idea of testing both the reliability of the sensor with regards to several potential hindrances. These questions of reliability can be summarized as:

- Will the sensor erroneously detect the glass wall of the reboiler as a presence of liquid?
- Does the sensor have hysteresis? Will the change in reading of liquid presence/absence be different for when the liquid level is increasing as opposed to when the liquid is decreasing?
- Do the changes in conditions in the reboiler due to liquid boiling affect the performance?

The testing confirmed that:

- The glass wall is not detected if the sensor is placed adjacent to the wall.
- This is true even when boiling conditions coat the reboiler wall with droplets.
- The sensor reading does not depend on whether the level is increasing or decreasing - thus it has no hysteresis.

Application of the proximity sensor

For a continuously operating distillation process, the use of the proximity sensor can help in the control of the reboiler level. The proximity sensor can be placed at the desired height along the wall of the reboiler, reflecting the set point at which the height of the liquid level needs to be maintained. The continuous influx of feed (via feed pump) will enter the reboiler. If the proximity sensor is ‘off,’ the controller can assume that the liquid level is below the set point and thus will take no action in terms of reducing the liquid. Since the feed pump will be adding liquid feed, this case will not exist for a long time. If the proximity sensor is ‘on,’ the controller may assume that the liquid level is too high and will activate the reboiler pump to lower the level of the reboiler liquid.

4.1.2 Controller Tuning

Unlike the fuzzy controller, there are no theoretical guidelines as to the proper procedure for tuning such a controller. Typically binary sensors (or on-off) lead to on-off controllers. If this were applied here, the pump would be turned on full speed when the level was high and turned off when the level was low. This would, however, be a violent control scheme that would not utilize the full operating range of the pump. Instead of the controller turning on the pump at full speed when the level was high, we would have the pump speed increased by some fraction (less than 1).

Due to the fact that the proximity sensor will only give a binary output (on or off) the issue of tuning is relatively much simpler. See Table 4.1.2 below for the simple decision process.

TABLE 4.1.2 – Controller decision based on proximity sensor voltage output

Voltage Signal	Proximity Sensor	Controller conclusion	Action
0 – 4 V	Off	Level too low	Shut off reboiler pump
4 – 6 V	On	Level too high	Increase reboiler pump

The tuning parameter identified for this controller is the *rate of increase of the reboiler pump*. This value is important so that the level does not exceed the set point for a long period nor fall below for a long period. Ideally, it can be said that choosing a gain that produces a proximity sensor output of alternating on-off signals for different feed rates is optimal.

The rate of increase was initially chosen to be a constant value (K), where every successive reading of ‘on’ by the proximity sensor would increase the reboiler pump by +K. This value was initially tuned to be 0.1 per minute, so that the reboiler pump would be increased by 0.1 for every 1 minute it stayed in the condition ‘on’, regardless of the sampling time. However, at greater feed rates this was found to be lacking in effectiveness since the pump didn’t speed up fast enough to match the high feed rate.

The gain was then adjusted so that the increase would be proportional to the input feed rate. Therefore, with a feed rate of F, the increase in the reboiler pump would be +F for every 1 minute it stayed in the condition ‘on’ (if a reading of ‘off’ was received from the sensor, the reboiler pump would be shut off). The main reason for having the pump shut off completely (instead of incrementally) is that the greatest danger to equipment is when the level is lower than intended. This would ensure that as the feed rate was increased (or changed to any value), the controller would compensate and increase (in the same proportion) the reboiler pump rate.

4.1.3 Controller Code

The LabVIEW coding overleaf shows the diagram of the controller (Figure 4.1.3). Features that can be seen are the set-point reading and the signal from the proximity sensor at the top left.

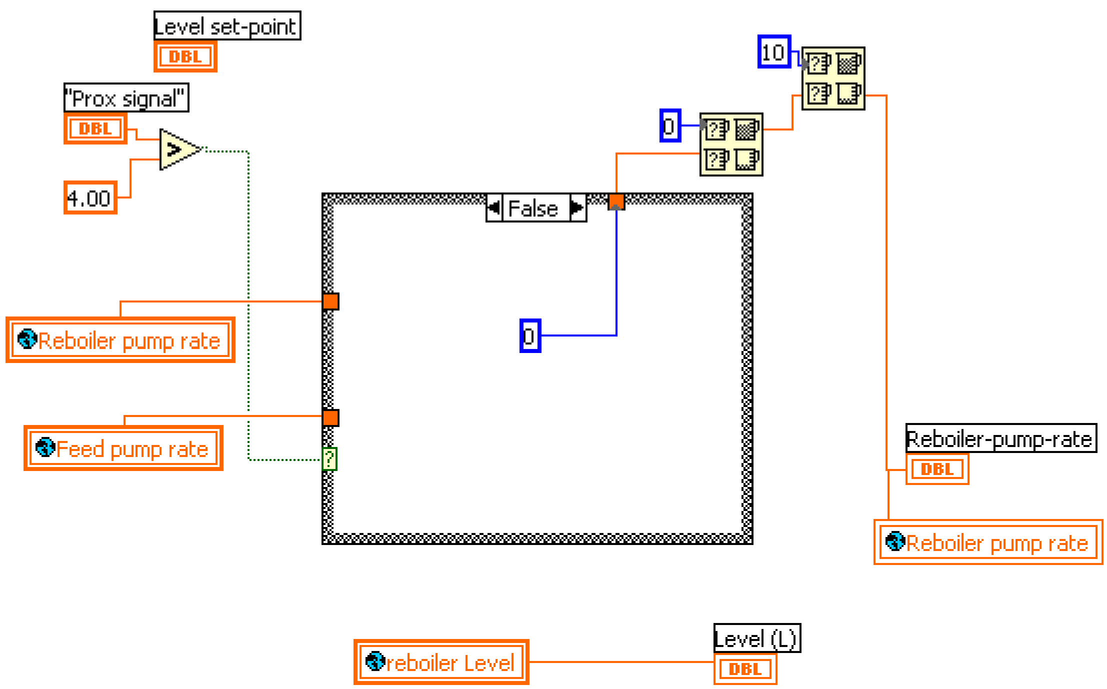

FIGURE 4.1.3 – Proximity Sensor Controller Diagram Window when sensor is OFF

If the proximity signal is greater than 4 (the level is 'high') and the results can be seen in Figure 4.1.4. The reboiler rate is increased by a constant that is proportional to the feed rate and the time scale factor. The time scale factor is the time interval between readings obtained from the sensor. This factor can be chosen by the operator of the VI. The final result is coerced between 0 and 10 (since the reboiler pump has these hardware limits) and finally, the result is written as an output that is then executed. If the Prox signal is less than 4 (level is “low”) then the reboiler pump rate is replaced by 0 – which keeps the reboiler pump shut down.

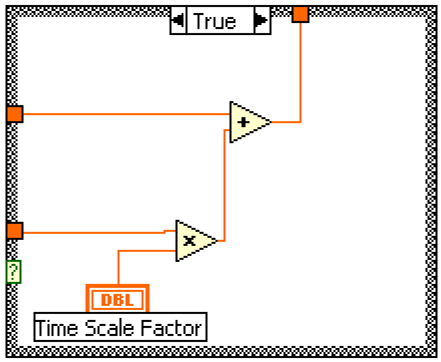

FIGURE 4.1.4 – Proximity Sensor Controller Diagram Window when sensor is ON

4.2 CONTROLLER TESTING

The controller testing was divided into two separate types of tests according to the operating conditions inside the reboiler. Non-boiling tests were conducted first to determine whether the controller tuning is roughly accurate. The boiling tests were done to see whether the controller could adequately cope with the inaccuracies introduced by liquid in motion inside the reboiler.

4.2.1 Non-Boiling tests

The controller was set at a fixed set point (11.0 liters) and the feed rate was changed to see the controller effectiveness (The appendix contains the data gathered). See figures 4.2.1-4 for the variation in level and reboiler pump rate with the proximity signal during the tests. The feed pump rates chosen were 1, 6, 8, 10 to measure the responses of the larger feed pump rates, and compare this to the smallest value of 1.

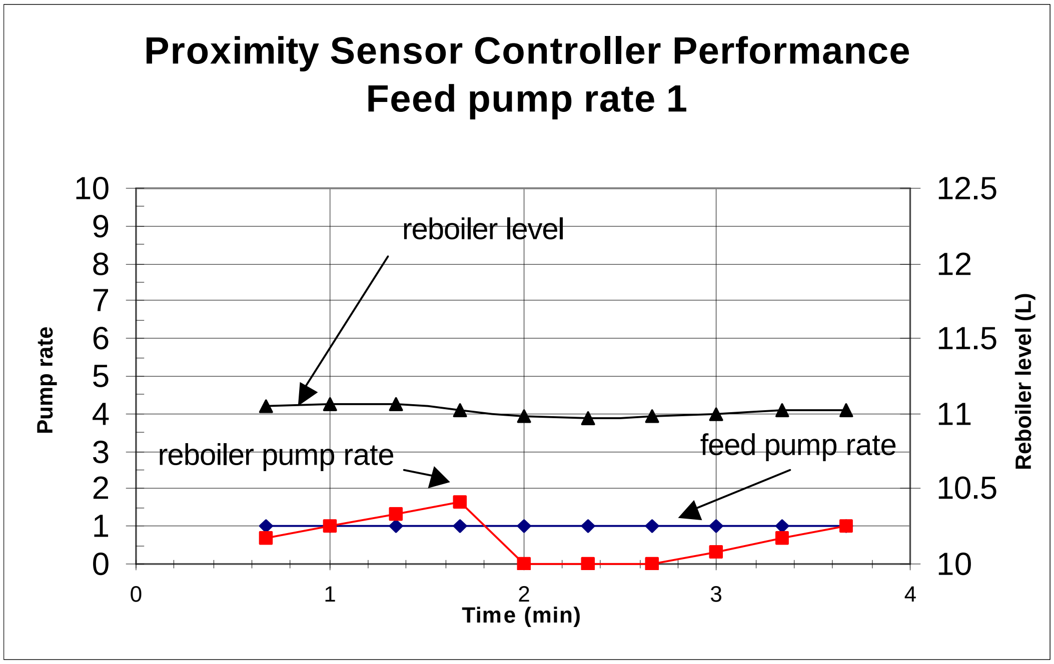

FIGURE 4.2.1 – Proximity Sensor Controller performance at a feed rate of 1.

At a feed pump rate of 1 (Figure 4.2.1), the non-boiling operational condition showed that the controller increased the reboiler pump rate for 1 minute and then shut it down for one minute (reboiler pump rate of zero). Also, it can be observed that the level increased to a maximum value of 11.1 liters, which indicates an overshoot of 0.1 liters.

At a feed pump rate of 6 (Figure 4.2.2), the proximity sensor was on for almost 7 minutes (increasing reboiler pump rate) and then off for a fraction of a minute (reboiler pump rate touches zero). The maximum level observed was 11.8 liters - an overshoot of 0.8 liters.

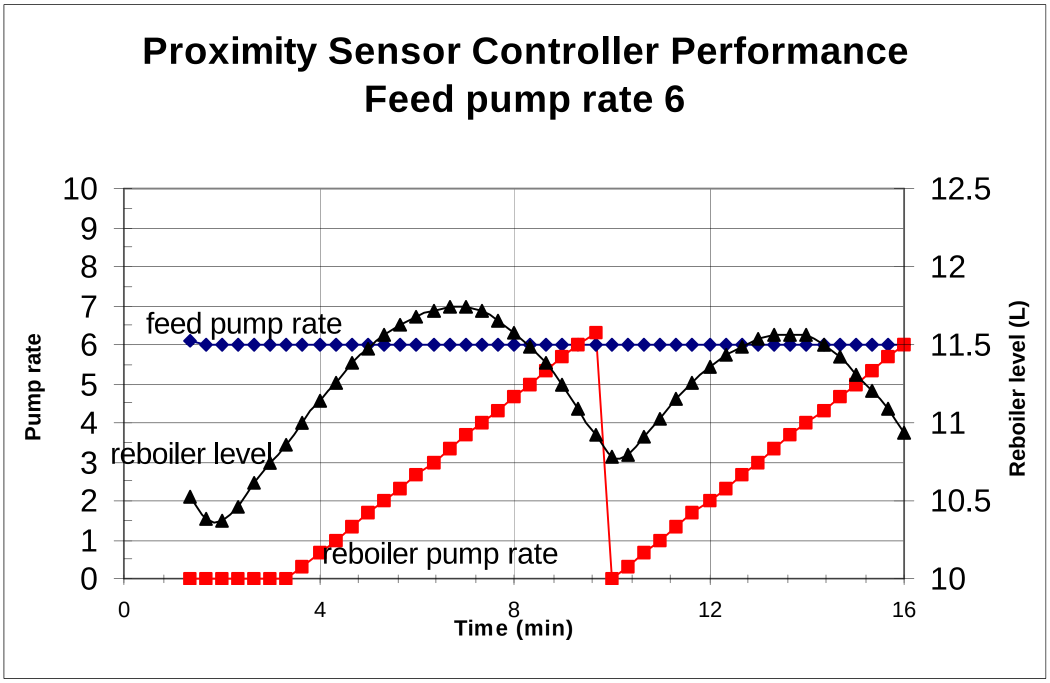

FIGURE 4.2.2 – Proximity Sensor Controller performance at a feed rate of 6.

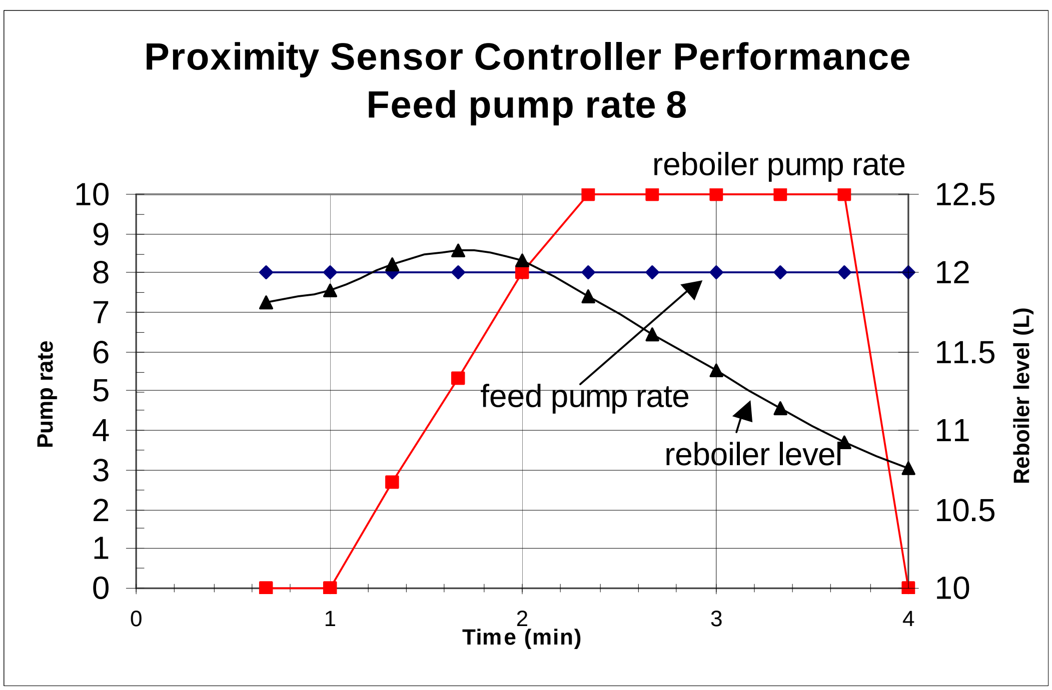

FIGURE 4.2.3 – Proximity Sensor Controller performance at a feed rate of 8.

At a feed pump rate of 8 (Figure 4.2.3), the proximity sensor was on for 3 minutes (non-zero reboiler pump rate). Several new features may be noted – the rate of increase has now been multiplied by the feed rate, therefore the slope of increase of the reboiler pump rate is not 1 as before, but in this case is 8. Also, the reboiler pump rate reaches its hardware maximum at 10 units and the corresponding linear decrease of level can be observed. The maximum level observed was 12.1 liters - an overshoot of 1.1 liters.

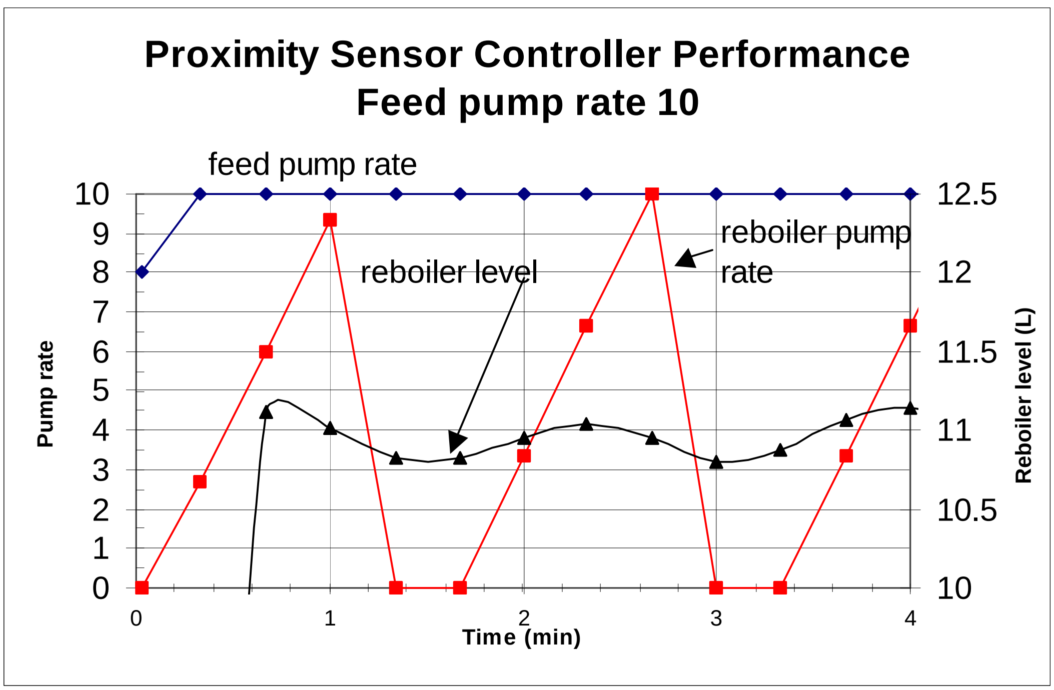

FIGURE 4.2.4 – Proximity Sensor Controller performance at a feed rate of 10.

At the maximum possible feed pump rate of 10 (Figure 4.2.4), the new and improved controller can be observed to effectively deal with increasing level. Since the slope is proportional to the feed pump rate, the controller effectively increases the feed pump rate quickly enough to curtail the level increase. Maximum overshoot is 0.2 liters (11.2 liters recorded).

4.2.2 Boiling tests

Since the non-boiling tests were satisfactory in keeping level at set point, actual distillation operating conditions were simulated with boiling liquid. The boiling tests were carried out by heating the reboiler until the liquid started to boil and then turn on the controller at the feed pump rates of 1, 3 and 6. Note that no tests at feed rates higher than 6 were done since maintaining boiling conditions within the reboiler is not possible with such a high rate of feed coming in at room temperature. The set point was 0.5 liters.

At a feed rate of 1 (Figure 4.2.5), no overshoot was visible. The decreasing liquid level continued to decrease with the boiling and the level dropped below 10.0 liters indicating an error of –0.5 liters. Thus for the boiling case, it can be seen that the error can be negative unlike the non-boiling case.

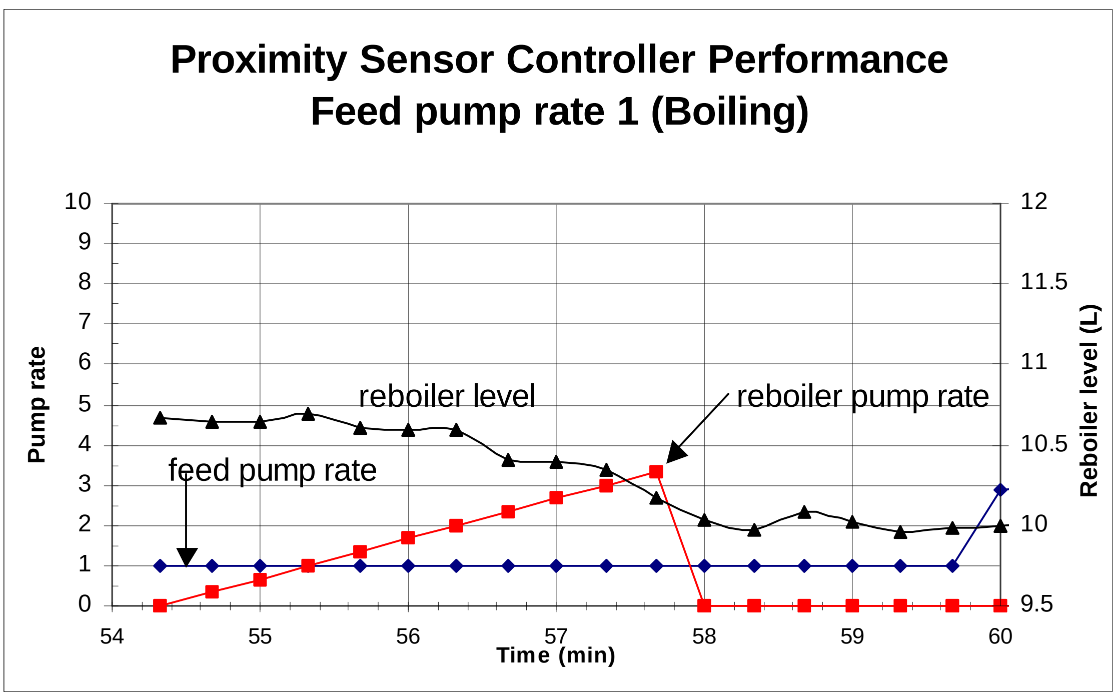

FIGURE 4.2.5 – Proximity Sensor Controller performance at a feed rate of 10.

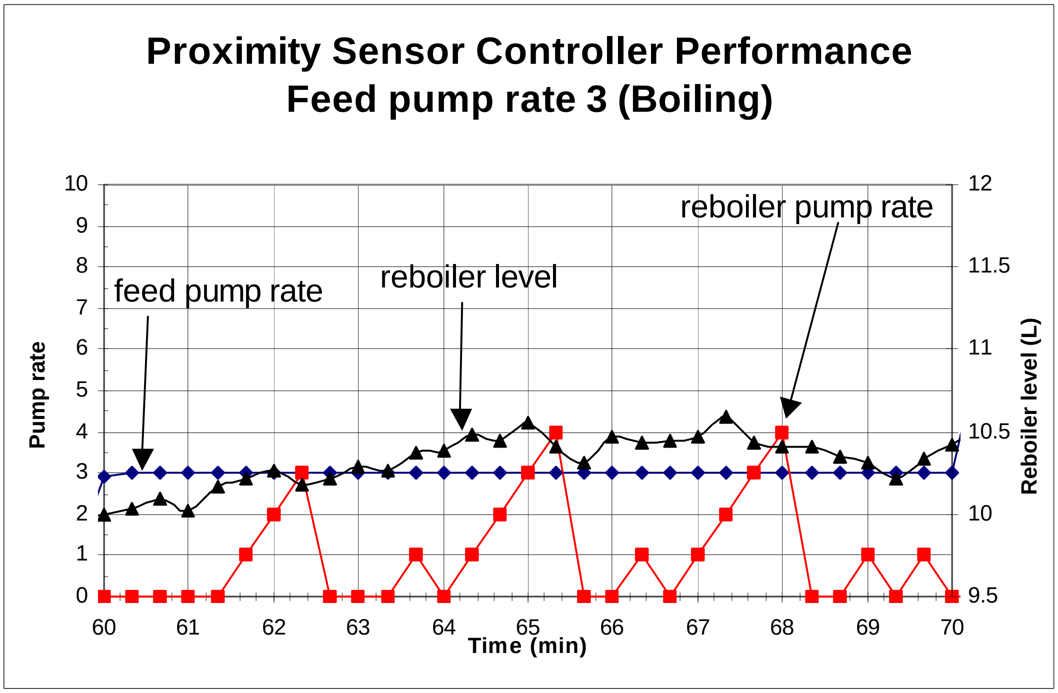

FIGURE 4.2.6 – Proximity Sensor Controller performance at a feed rate of 10.

At a feed pump rate of 3 (Figure 4.2.6), the overshoot was 0.1 liters but the maximum error was –0.5 liters.

When the feed pump rate was increased to 6 (Figure 4.2.7), again the overshoot was within 0.1liters while the maximum error value was also repeated at –0.5 liters. While the boiling conditions caused the pump to be off-for too long in the 73rd minute, the controller was successful in operating under these specified conditions.

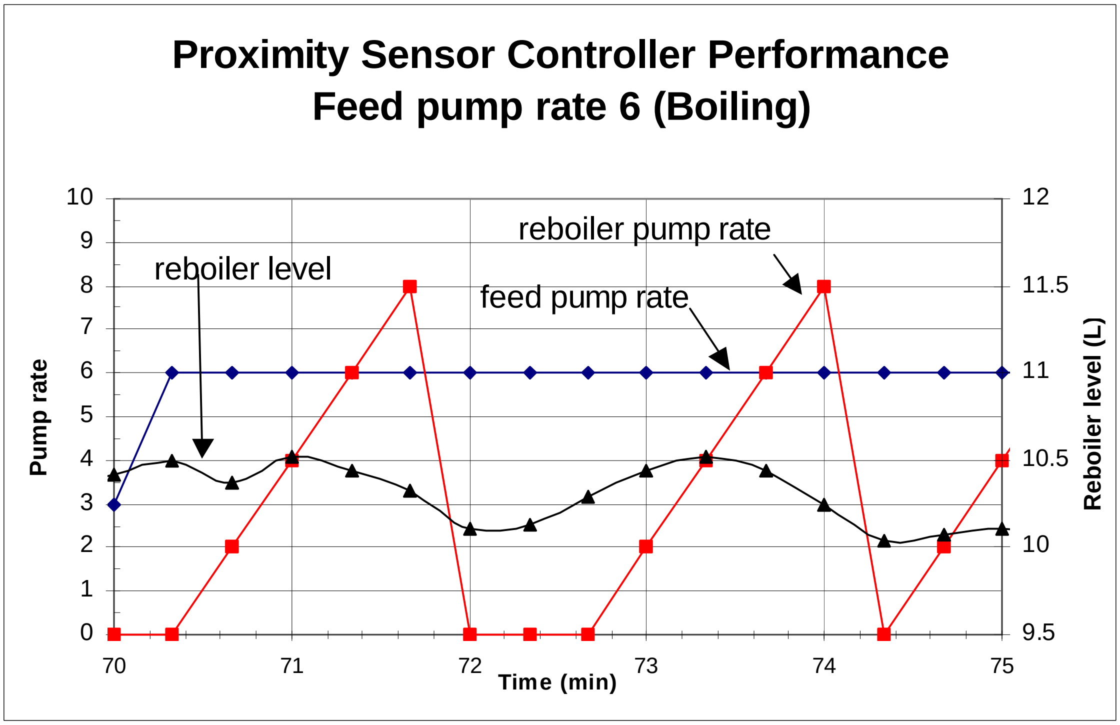

FIGURE 4.2.7 – Proximity Sensor Controller performance at a feed rate of 10.

4.2.3 Recommended Refinements

For the boiling case tests conducted and explained in the previous section, it was seen that the sensor seemed to respond in manner where the mean steady state level reading was about 0.3 liters less than that of non-boiling tests. We will assume then that under boiling conditions, the same sensor positioning corresponds to an 'effective' set point of 0.3 liters less than when the same sensor is placed under non-boiling conditions. In this view, Figures 4.2.5, 4.2.6 and 4.2.7 have an effective set point of 10.2 not 10.5L (since they are boiling tests).

There is also a possibility of oscillatory behavior seen in several figures (especially Figure 4.2.7 on previous page). Figure 4.2.5 (feed pump rate of 1) had no oscillation. Figure 4.2.6 (feed pump rate of 3) had small oscillation that may be dismissed as noise. Figure 4.2.7 (feed pump rate of 6) had observable ‘growing’ oscillation. Comparing these figures, it can be seen that the oscillatory motion seems to increase with higher feed pump rate. A cause for concern is the possibility that at a higher feed pump rate (such as at 6) and boiling conditions, the proximity controller may have entered an unstable region of operation. It is highly recommended that this phenomenon be further investigated.

If oscillatory motion is verified through experimentation, refinements to the VI will be necessary to stabilize the responses. It can be further observed from Figure 4.2.7 that the peaks correspond to the peaks of the reboiler pump rate (which is M(t)) and the troughs correspond to reboiler pump rates of zero. One suggestion is that if these steep ramp functions can be replaced by a ramp function of lesser peaks and higher troughs, the response of reboiler level (C(t)) may have negligible oscillation. From the pattern seen in Figure 4.2.7, it can be seen that the peaks and troughs corresponded to the reboiler pump rate being at its largest value in this experiment (in this case 8) before being turned off. See next page for a sample pseudocode for implementing this procedure.

An algorithm for the suggested refinement to the controller is given below:

Pseudocode 1:

(1) Establish the maximum value and the minimum value of the range

(2) Initiate loop

(3) Subtract one from the maximum and add one to the minimum to reduce range

(4) Continue with loop until the prox sensor reads ‘on’ repeatedly or ‘off’ repeatedly OR until the (minimum – maximum) < 3

(5) If response is ‘on’ repeatedly, subtract 1 from minimum and maximum (back to loop)

(6) If response is ‘off’ repeatedly, add 1 to minimum and maximum (back to loop)

This code make the range of reboiler pump rate small (within 3) which would minimize oscillatory behavior. Also due to the fact that if the proximity sensor is on or off repeatedly, the range will be adjusted so that the sensor will alternate with on/off readings.

Since one can observe that the average reboiler pump rate is half of the maximum peak rate. A second alternative is that perhaps the pump rate can be maintained at this value (which would be half of the value of the reboiler pump rate in the reading prior to it being shut down) to minimize oscillation. This can be a second stage of controller, after the initial stage of incremental pump rate that has been implemented already. If there is a change in feed rate or set point, then once again, the controller should go back to the first stage of ramp functions until a steady value is found.

4.3 REMOTE OPERATION

Remote operation was carried out using LabVIEW version 6.1. The VI front panel can be accessed via the internet. The front panel layout is seen below in Figure 4.3.1. Note that this is exactly the same front panel as that which can be seen when running the VI at the local Grote Hall workstation.

4.3.1 Implementation Procedure

The procedure for enabling remote operation is much simpler using LabVIEW version 6.1. This newer version was thus installed prior to remote implementation. The stepwise procedure is described below:

- In the controls toolbar, go to "Tools"
- Select "Web Publishing Tool"
- Start "Web saver"
- Save to disk
- Done

This procedure creates a web page in html format. The front panel of the VI appears as shown in Figure 4.3.1 overleaf. Along with other edited text in the html file that can be manipulated as necessary. Since it is an html file, graphics and text can be added easily (other than on the VI front panel itself which must be changed through LabVIEW).

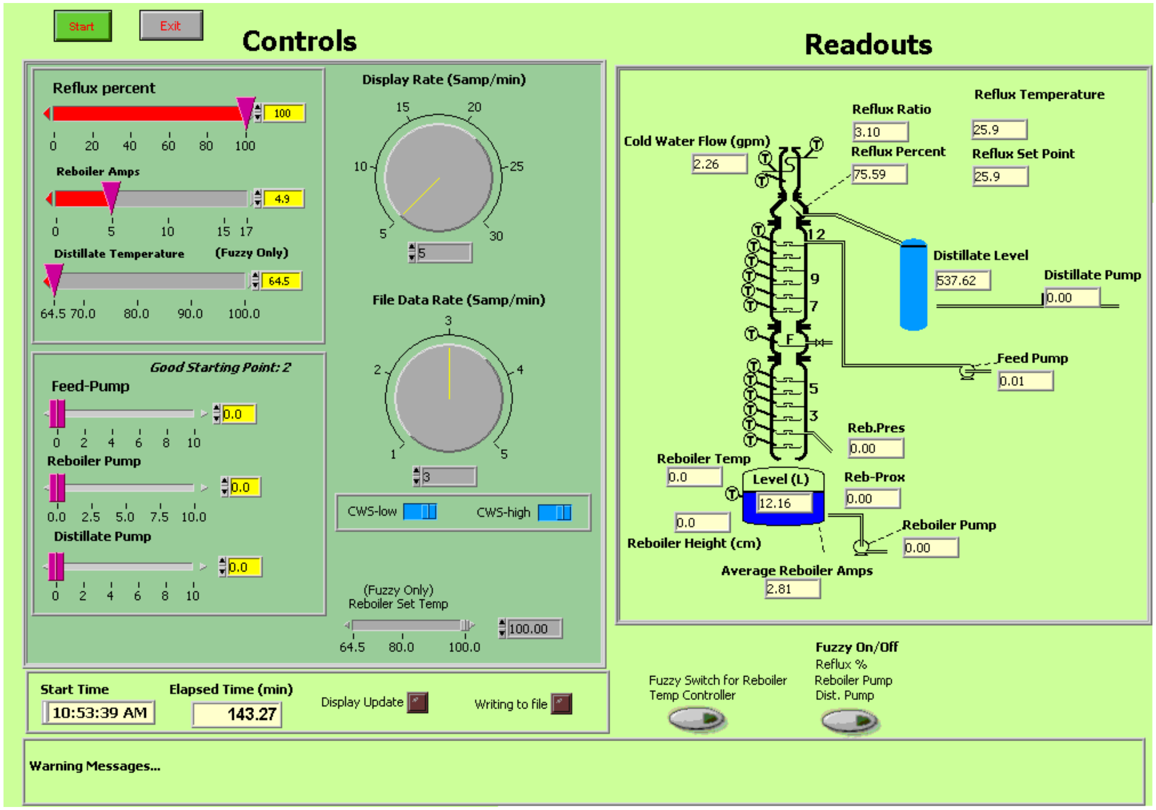

FIGURE 4.3.1 – Front Panel of the remote VI

4.3.2 Operation

The web address at which this VI is located is:

http://distillation.engr.utc.edu/Mevan-2002-remote1.htm

In order to control the VI remotely (via the internet) follow this procedure:

1. Open a web browser and type in the web address given above.
2. Right click the mouse on the VI front panel and select “Request Control”.

If the VI is currently in use, control will be denied since only one user can have control at any given time. Otherwise control should be granted – a message will appear on the screen to notify you on your position.

3. Click “start” on the VI front panel once control is granted.

Also note that the set point is currently fixed at 11.0L – this cannot be changed remotely.

4. Vary feed pump rate and observe the variations in level and the proximity sensor output in the diagram on the right side of the front panel.

4.4 PROXIMITY CONTROLLER EVALUATION

4.4.1 Observations on controller performance:

- The level error is negative under two operational conditions – when the sensor imprecisely identifies liquid when there is none, and due to dead time between sampling periods when the reboiler pump stays on. Under boiling conditions the first error occurs and seems to be unavoidable. The second error is minimized by using smaller feed rates. Such results may be further minimized by increasing the sampling frequency to reduce the dead time.
- Under boiling conditions inside the reboiler, the level can fall as much as 0.5L below the set point. Operators should compensate for this likelihood.
- The overshoot is larger for larger feed pump rates, but is reduced under boiling conditions. It is assumed that this is because the evaporation accounts for a larger reduction rate of level and the proximity sensor reads a value higher than actual level due to the surface activity of the liquid while boiling. As a guideline for operators the overshoot is less than 0.3L.

4.4.2 Effectiveness:

- The proximity sensor controller effectively deals with the problem of controlling the level for a continuous distillation process. While the data from the sensor indicates slight error (both negative and positive), visual observation confirmed that the controller effectively kept the level at the set point.

- This controller is most effective in its ease of implementation by a control engineer when compared to its capability to keep the level from dropping *below* the set point.
- The set point must be changed by manually moving the proximity sensor, and is therefore a drawback.
- Successful remote operation enables more users to experiment with this controller. However, the set point is determined manually, and thus cannot be changed by remote means.

4.4.3 Future recommendations:

- The possibility of oscillatory behavior under boiling conditions at feed rates at around 6 exists. An investigation through experimentation is necessary to make sure that the controller is stable in this range of operation. Several suggested pseudocode to minimize oscillation is given under the testing section.
- Currently, the set point of the proximity sensor cannot be set automatically. The only way this can be done is through manually adjusting the height of the proximity sensor. A mount for the proximity sensor with an adjustable height setting would simply the task of resetting the set point. In it even conceivable to

automate this process by introducing a small motor to elevate the sensor to the necessary set point.

- The controller may be used in other distillation columns to regulate the liquid level.
- An array of proximity sensors may be used to monitor different set points. This would allow users to select a set point from several discrete values depending on the placement of the sensors.
- A graphical representation of the data) especially the reboiler rate, feed rate, proximity signal and level) would enhance the present VI. This is especially true for remote users who do not have the option of physically seeing the reboiler level changes.
- A live video stream to show the reboiler during operation is also a possibility to give remote viewers a more comprehensive laboratory experience.

5. FUZZY LOGIC CONTROLLER

5.1 CONTROLLER DEVELOPMENT

5.1.1 Fuzzy Logic Controller Theory

The basic process for a feedback control system using fuzzy logic can be seen in Figure 5.1.1. below. The concepts relating to this diagram are described below along with possible tuning parameters. The steps in one cycle of data acquisition and processing include, fuzzification of the acquired signal (the input), subjecting it to a rule base where a decision is made which is then defuzzified in turn to produce the output. Once action is taken, the feedback will lead to another cycle of data. E(t) represents the error term that is fed into the controller and M(t) represents the manipulated variable output signal that is sent from the controller to the system.

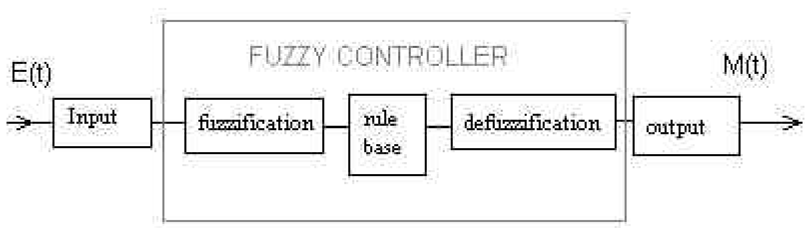

FIGURE 5.1.1 – Block diagram of Fuzzy Logic Controller Open Loop

Fuzzification

Fuzzification is the theoretical mapping of a real input to a non-digital and abstract (or 'fuzzy') function. To be fuzzified, the system must decide on the 'degree of membership' of the input to a purposefully vague concept such as 'high' or 'low' or 'medium.' This is achieved through a rulebase that makes decisions based upon the degree of membership. The membership function, usually of triangular, square or trapezoidal nature, but not limited to such, is a simple algebraic method of determining the degree of membership to the given abstract concept. This concept is based around the idea of a more 'human' controller who may make decisions based less on crisp algebraic mathematical relations but more on the experience he has gathered as an operator (Jantzen, 25).

As an illustrative example, consider a simple level control system as shown in Figure 5.1.2. Two situations that may warrant action include when the level of liquid is either too low or too high. Thus, it would make sense to fuzzify the crisp input received through the sensor into the abstract 'fuzzy' concepts of 'high' and 'low.' A comparison to a pre-tuned membership function, such as that given in Figure 5.1.3 must be carried out for this purpose. Note that the membership functions shown here are examples, not the membership functions chosen for the solution. Each of the graphs represents a 'fuzzy' concept – in this case 'high' and 'low.' The degree of membership is determined by comparison of the crisp input (lets say 7 liters of liquid to both the 'high' graph and the 'low' graph). The degree of membership is the fuzzified input and this proceeds to the rulebase. Note that M(t) is the manipulated variable which is the inlet pump rate in this case, and the controlled variable C(t) is the liquid level.

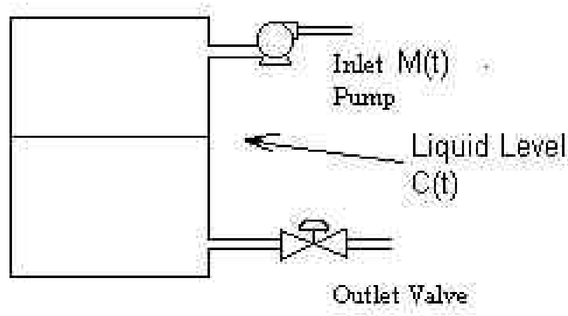

FIGURE 5.1.2 – A simple example of a liquid level control system

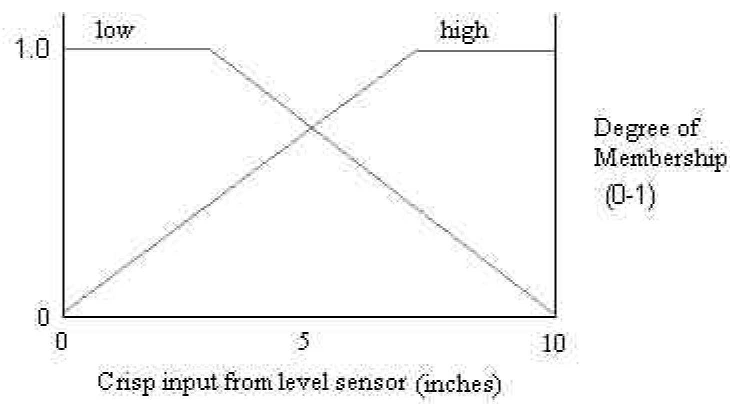

FIGURE 5.1.3 – Example of a simplified fuzzy membership function for level

For a more accurate tuning of the control system, it may be advisable to also note the rate of change of level – knowing whether the level is rising, steady or falling is helpful. Thus a second set of membership functions for the time-derivative of the level can be established for processing according to the rulebase. In fact, for the fuzzy logic equivalent of Proportional-Integral (classical) control, the derivative term is needed. The fuzzy controller developed in this project uses the derivative of the level.

Rulebase

These are the rules that make decisions based on the degree of membership that has been established in the fuzzification process. The rule base utilizes if-then condition statements to alter the controlled variable. The ‘inference engine’ is part of the rule base. Simple syllogisms are used to ‘infer’ a decision from one or several conditions. For the example for fuzzification given above, the basic pseudocode for the rules is given below in tabular form in Table 5.1.4 below. Note that this is an example rulebase, not the rulebase used in the controller developed in this project.

TABLE 5.1.4 – An example Rulebase for a fuzzy controller

RULE	*ACTION*
If level is ‘high’ & rate is ‘rising’	Then, decrease outlet pump by 20 rpm
If level is ‘high’ & rate is ‘steady’	Then, decrease outlet pump by 10 rpm
If level is ‘high’ & rate is ‘falling’	No action
If level is ‘low’ & rate is ‘rising’	No action
If level is ‘low’ & rate is ‘steady	Then, increase outlet pump by 10 rpm
If level is ‘low’ & rate is ‘falling’	Then, increase outlet pump by 20 rpm

Defuzzification

Defuzzification is the inverse process by which the decision taken on the input is transformed into a crisp output. Defuzzification can be carried out in several methods including the center of gravity method (COG), Mean of Maxima method (MOM), Last of Maxima (LOM) & the First of Maxima (FOM) methods (Jantzen, 35). The COG method will be used for this example (also known as the Center of Maximum COM).

To transform the instructions given by the rulebase into a single crisp output, assume that outlet pump rpms are positive. Here are the example membership functions for defuzzification shown below in Figure 5.1.5.

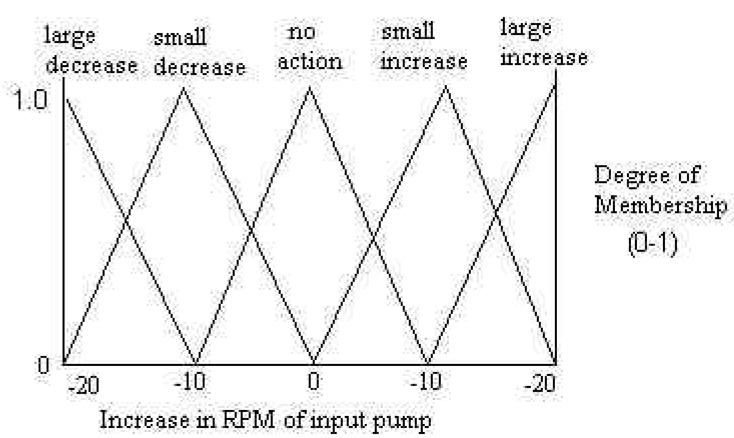

FIGURE 5.1.5 – Example of a fuzzy membership function for the change in level

An example of processing of the input according to the rulebase is shown below. The degrees of membership are from 0 to 1 (that maps to 0 to 100% in the figures 5.1.3 &

5.1.5). The 0-100% and 0-1 systems are both standard membership ranges. So, lets say for a particular reading, the degrees of membership are:

High 0.8 *Rising 0.1*

Low 0.2 *Steady 1.0*

Falling 0

From these values it can be seen (from a fuzzy 'human' perspective) that the level is 'more' high than 'low' and also its 'more' steady than rising or falling. This numerical degree of membership is useful for both fuzzification and defuzzification. Then, the calculations according to these memberships are tabulated below:

TABLE 5.1.6 – Tabulation of calculations for defuzzification by COM method

Linguistic term combination	Degree (0 to 1)	Minimum degree	Expert response	Product
High & Rising	0.8 & 0.1	0.1	-20	-2
High & Steady	0.8 & 1.0	0.8	-10	-8
High & Falling	0.8 & 0	0	0	0
Low & Rising	0.2 & 0.1	0.1	0	0
Low & Steady	0.2 & 1.0	0.2	10	2
Low & Falling	0.2 & 0	0	20	0
		Σ=1.2		Σ= -8

The defuzzified value is the quotient of Σ(Products) over the Σ(Degrees) = -8/1.2 = -6.67. This indicates a decrease in the pump by 6.67 RPMs will be carried out to the pump.

Tuning Parameters

The fuzzy logic controller can be modeled closely to the existing forms with proportional terms and integral terms. However Fuzzy PI, Fuzzy PID, Fuzzy PD or Fuzzy PI+D controllers are tuned very differently from conventional controllers (Jantzen, 46-49). Instead of require Kc and Ti for a conventional PI controller, the tuning parameters for a Fuzzy PI controller include:

- The description of abstract sets (or ‘states’ such as ‘hot’ or ‘cold’ or ‘medium’)
- The number of abstract sets
- Possible inclusion of derivative term sets (and their corresponding number of sets)
- Accurate membership function type fuzzify each abstract set (and derivative set)
- Accurate membership function range
- The values of increase/decrease chosen as decisions by the rulebase
- Method of Defuzzification

5.1.2 CONTROLLER TUNING PROBLEM

The complexity of the problem of tuning a fuzzy controller can be broken down into 3 stages - tuning associated with fuzzification, the rulebase and finally the defuzzification. Each stage has tuning parameters that must be considered and yet methods for their approximation aren't as established as would be preferred by control engineers. This is reflected by the variations found for tuning at each stage.

Fuzzification involves creation of fuzzy sets. First **linguistic variables** must be chosen such as level and the derivative of level (to name just two). The **universe** for each variable must be chosen accordingly. The **input gain** is a simple multiplication that is used to map the input to the fuzzy universe. Next, the greater the number of **linguistic terms** chosen, the greater will be the complexity in the rulebase. Large numbers of linguistic terms (up to 7) allow for more specific alterations and can model more complex systems. The **shape of each function** is a tuning parameter - factors such as tolerance, shouldering and overlap must be considered to obtain a membership function that impacts the controller in a manner that is desired.

The rulebase has a fixed number of rules depending on the number of variables (v) and terms for each variable (t). The number of rules is given by R = v.t. However, each rule can be accorded a **degree of support –** essentially specifying the weight accorded to each rule in the overall defuzzification that will proceed.

The defuzzification stage also involves tuning parameters that must be considered carefully. The **method for defuzzification** (center of maximum, center of gravity and mean of maximum are just 3 of the available methods to defuzzify) is important. Next, the **output gain** must be considered – exactly what will be changed and how much? A **universe** for this function must be realized as well as **membership functions**. Singletons are the easiest to model, but may be too simple for complex control problems. Singletons are discrete values used for defuzzification not unlike the crisp multiplication seen in Table 5.1.5 where a fuzzy input is multiplied by a strict discrete constant. More complex (non-discrete) functions may be used for modeling more complex systems. When using singletons Center of Maximum and Center of Gravity converge to become the same defuzzification method.

5.1.3 PROCESSING OF THROUGHPUT

Pre-processing

Pre-processing refers to the necessary data manipulation after leaving the sensor and prior to processing by the fuzzy controller. There are several steps that must be carried out beginning with obtaining the derivative.

The sensor will only obtain a value for the level – the derivative must be taken for obtaining the rate of change of level. This is approximated by the quotient of the level change over the time interval. Essentially, the change in level will be the current level reading minus the previous level reading, while the time interval will be the constant value of the sampling time period ‘Ts.’

Next, as a precautionary measure, limits must be set for the data gathered. Data that may be erroneous (detected because it is outside the universe of the set) can occur due to noise and momentary fluctuations that are a problem with every real sensor. For example, if the sensor only reads between 8.5 and 16.5 liters, and a surge provides a reading of 22 liters, we can reasonably assume that this is an error. In order to prevent any action being taken from data that are obviously inaccurate (beyond the endpoints of each universe), we will assume that these erroneous values will equal the endpoints. Thus the 22 liters reading will be recorded as 16.5 liters. It is important to set these limits in a realistic fashion, so that processing can occur effectively – we must be certain as possible of the end points of each universe.

The maximal and minimal values for both the level and its derivative were obtained through consultations with the experts who operate the column and through experimentation. The column was observed at its most extreme conditions, creating the most extreme readings for the sensor. A minimum value of 8.5 liters was chosen for the level, which was a decision based on the fact that lower levels may cause it to damage the heating rods. Thus, the level decreasing beyond 8.5 liters is not an option according to the fuzzy control system and action will be taken well in advance of this eventuality.

Finally, we need to match the universe values of the level and its derivative to the fuzzy controller universe. This is done using the gains GE and GCE. The gains derived from the previous section are used along with the offset value of 8.5 liters in order to 'zero' the range of level. The derivative does not need an offset constant. The figure below illustrates the data flow. The triangular elements in the diagram represent arithmetic operations carried out on the data – the type of operation carried out is displayed inside the triangle. Only subtraction and multiplication are used in preprocessing. The values of the universe for both level and its derivative are shown throughout each operation so that the transformation into the fuzzy universe can be followed easily.

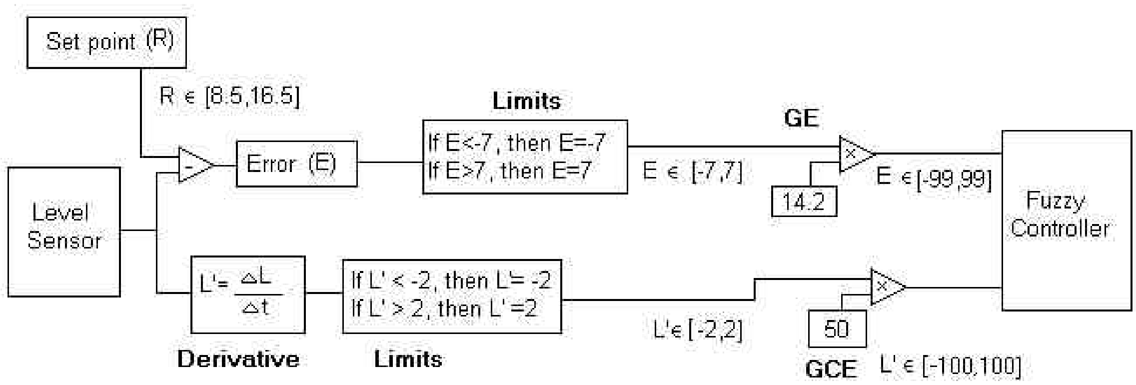

FIGURE 5.1.7 - Pre-processing schematic

Post-processing

Post-processing refers to the necessary manipulation of data between the fuzzy controller and the feed pump. The only output from the fuzzy controller is the output U [0,100]. The only manipulation needed is the multiplication of the output gain GU to translate the controller output into the feed pump rate. There are no offsets. See diagram overleaf.

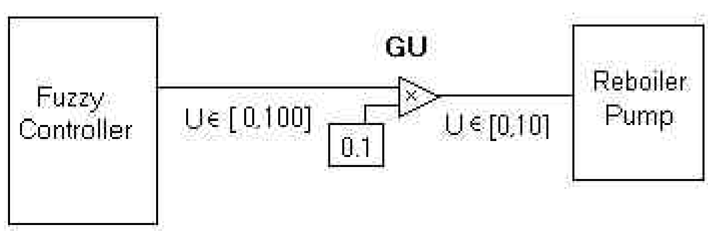

FIGURE 5.1.8 - Post processing schematic

It is important to realize that the processing of data shown above applies to the universes of level (L), rate of change of level (dL/dt) and the output feed pump setting (U). The actual LabVIEW block diagrams will have universes of voltage. Although the processing is parallel to the universes shown above, the gain and offset values may be different. Additionally, the gains due to signal conditioning are considered part of the sensor’s overall characteristics, and these data manipulations are also not illustrated in this section.

5.1.4 CONTROLLER TUNING SOLUTION

What type of fuzzy controller should be used? A fuzzy P controller is too simplistic and only takes into account 1 input variable (level). A controller that would be fuzzy PI is of suitable complexity, capable of solving the level problem, and can be tuned in the time constraint for the project.

<u>Primary tuning parameters for a fuzzy PI controller</u>

When the number and type of linguistic variable is concerned, the following recommendations were considered. The minimum number necessary will be implemented since the complexity of the problem grows with a greater tuning task.

- "Linguistic terms usually have an odd number of terms… and include a middle term between extremes…As a starting point, set up the input variables with at least 3 or 5 terms, and the output variables with 5 or 7 terms." (Fuzzy Logic Toolkit, 4-3)

- "Begin with terms equally spaced within the [universe], with each term entirely overlapping its neighboring terms." (Fuzzy Logic Toolkit, 4-5)

- The standard universe on the LabVIEW Fuzzy Logic Toolkit is [-1,1]. This is modified for our purpose to fit a [-100,100] universe for the level as well as the change in level (derivative). This is to keep the fuzzy logic aspect of the controller independent from the output/input gains, so that tuning the fuzzy logic of the controller is made easier for the designer.

- Deciding for a method of defuzzification is arrived at from the Fuzzy Logic Toolkit table given below (Fuzzy Logic Toolkit, 4-8). Using this table, Center of Maximum was chosen due to its relative simplicity of calculation and intuitive sense, continuity and the fact that closed-loop control is preferable.

TABLE 5.1.9 –Advantages and Disadvantages of different defuzzification techniques

Assessment Criteria	**Center of Area Center of Gravity**	**Center of Maximum**	**Mean of Maximum**
Linguistic characteristic	Best compromise	Best compromise	Most plausible result
Fit with intuition	Implausible with varying membership function shapes and strong overlapping membership functions	Good	Good
Continuity	Yes	Yes	No
Computational effort	Very High	Low	Very Low
Application Field	Closed-loop control Decision support Data analysis	Closed-loop control Decision support Data analysis	Pattern recognition Decision support Data analysis

TABLE 5.1.10 – Choices for non-numerical tuning parameters

Parameter	**Choice**	**Tuning**
Linguistic Variables –number & type	*Error* and *Derivative Error* for input and *Pump rate* for output	Choice determined by controller choice – fuzzy PI
Linguistic Variable - universe	[-100,100] *Level Error* [-100,100] *(d/dt) Level* [0,100] for *Pump* (output)	Each input universe is different to avoid interchanging & confusion.
Linguistic Terms – Number & name	*Level Error* – Negative None Positive *(d/dt) Level* – Falling Steady Rising *Pump* – No action Reduce slightly Reduce much Reduce a lot Reduce greatly	3 terms per input variable were chosen so as to minimize rules. The nomenclature is fuzzy as recommended. 5 terms for the output variable were chosen
Input Membership functions – Shape	Standard triangular shapes, with equal overlap on both sides.	Overlap is necessary to create fuzziness. Triangular is the most basic input form
Input Membership functions – Centers	*Level Error* = -100,0,100 *(d/dt) Error* = -100,0,100	Extremes and mean of universe
Output Membership Functions – Shape	Standard triangular shapes, with equal overlap on both sides.	Overlap is necessary to create fuzziness. Triangular is the most basic input form
Output Functions - Centers	*Pump* = 0, 25, 50, 75,100	Equi-spaced in universe
Method of defuzzification	Center of Maximum	Continuity, close-loop, intuitive, low computations

Numerical Tuning Parameters for the PI controller

From an analysis of the system, the following basic information can be obtained for the system, regardless of the controller employed to stabilize level. However, the values of Kcu can itself change due to the non-linear nature of the system.

TABLE 5.1.11 –Numerical constants obtained from the system

Symbol	**System Constant**
Kcu	Critical Controller Gain
Tc	Critical time constant
ε	Allowable error

There are several numerical tuning parameters for the fuzzy PI controller that are identified in the table below:

TABLE 5.1.12 –Numerical tuning parameters

Symbol	**Tuning Parameter**
GE	Error gain (level gain)
GCE	Derivative error gain (der. level gain)
GU	Output gain (pump gain)
Ts	Sampling time interval

<u>How do I go about tuning the controller?</u>

I will assume the following about the data conveyed from the sensor. First, the maximum level reading is 16.5 liters, while the minimum is 8.5 liters, I will also assume that the maximum derivative is 2 liters/min while the minimum is –2 liters/min. Also change error (E) is equal to the set point (R) minus the Level (L), given below:

$$E(t) = R(t) – L(t)$$

TABLE 5.1.13 –Approximate values for Numerical tuning parameters

Variable	Symbol	Min value	Max value	Range	Proposed universe	Appx. Gain
Level	L	8	15	7	-	-
Set Point	R	8	15	7	-	-
Level Error	E	-7	7	14	-100,100	14.2
Derivative of Error	CE	-2	2	4	-100,100	50
Pump output	U	0	10	10	0,100	0.1

The gains are derived using the additional rules of thumb for tuning and performance that are given below. These rules form the guideline for tuning, since they are intended to increase the effectiveness of the controller by ensuring that the range produced after the gain is multiplied is as close as possible to the range of the fuzzy controller universe (Jantzen, 87).

E_{max}*GE = Universe$_{max}$E (1)

7*14.2 = 99.4 (close enough to 100)

CE_{max}*GCE = Universe$_{max}$CE (2)

2*50 = 100 (exactly the full range)

Likewise, the minimum values are obtained as follows:

E_{min}*GE = Universe$_{min}$E (1)

-7*14.2 = -99.4 (close to -100)

CE_{min}*GCE = Universe$_{min}$CE (2)

-2*50 = -100 (exactly the lowest value of -100)

These rules will ensure that the full range of the universe is utilized for both inputs.

The sampling interval (Ts) is recommended in terms of the critical time constant Tc (Jantzen, 86-7)

$0.10\ Tc < Ts < 0.20\ Tc$

The final recommendation for Ts is chosen according to this recommendation. An initial choice therefore is:

$$Ts = 0.20\ Tc \qquad (3)$$

An experiment conducted to find the critical time constant Tc, produced a result of Tc= 5 min (approximately). Therefore:

$$Ts = 0.20\ (5\ \text{min}) = 1\ \text{min}$$

Preliminary Results of Tuning gains:

TABLE 5.1.14 –Final values for Numerical tuning parameters

Gains	**Preliminary Value**
GE	14.2
GCE	50
GU	0.1
Ts	1 min

To solve for approximate values for these tuning parameters, I aim to begin with the recommendation for GE in terms of the allowable error (Jantzen, 87):

$GE < 0.5/\varepsilon$ (4)

$\varepsilon < 0.5/14$

$\varepsilon < 0.04$ liters

This essentially translates to the fact that in order to implement a fuzzy controller that is accurate to 2 significant figures (+/- 1 of the controller universe of 100), a sensor with an allowable error of 0.04 liters (40mL) is necessary. Likewise, if the controller decisions are to be accurate within 1 significant figure (+/- 10), then a sensor that is accurate to 0.4 liters (400mL) is necessary.

Tuning the Rulebase

TABLE 5.1.15 – Rule Base for the Fuzzy controller

RULE	*ACTION*
If level error is ‘positive’ & rate is ‘rising’	No action
If level error is ‘positive’ & rate is ‘steady’	No action
If level error is ‘positive’ & rate is ‘falling’	No action
If level error is ‘zero’ & rate is ‘rising’	Reduce slightly
If level error is ‘zero’ & rate is ‘steady	No action
If level error is ‘zero’ & rate is ‘falling’	No action
If level error is ‘negative’ & rate is ‘rising’	Reduce greatly
If level error is ‘negative’ & rate is ‘steady	Reduce much
If level error is ‘negative’ & rate is ‘falling’	Reduce a lot

Remembering that the level error above is defined as set point minus actual level, we see that when the level error is positive, the actual level is below the set point mark. Thus, regardless of the rate of increase the fuzzy controller will read the ‘No action’ membership function for a numerical decision. Increase in the reboiler pump rate (and thus reduction in the level) needs to be achieved when the controller reads that the level error is negative. Thus in the last three rows we see that the significant action is taken to reduce the level (translating to an increase in reboiler pump rate).

5.1.5 CONTROLLER CODE

The controller code used to implement the tuning is shown below in Figure 5.1.16. This LabVIEW diagram shows the calling of the global variables of reboiler level and previous level (on the bottom left) and the calculation of the derivative by obtaining the difference between these two and dividing by the time scale factor. The error (set point minus the actual level) is calculated on the top left. The preprocessing gains are introduced and the result is provided as an input to the fuzzy controller (the membership functions and universes and other information is stored in this sub-VI). The output is multiplied by the post-processing gain and finally this increment for the reboiler pump rate is added to the existing reboiler pump rate and executed. The minimum and maximum rates for the pump rate after modification are set at 0 and 10 respectively as can be seen on the right.

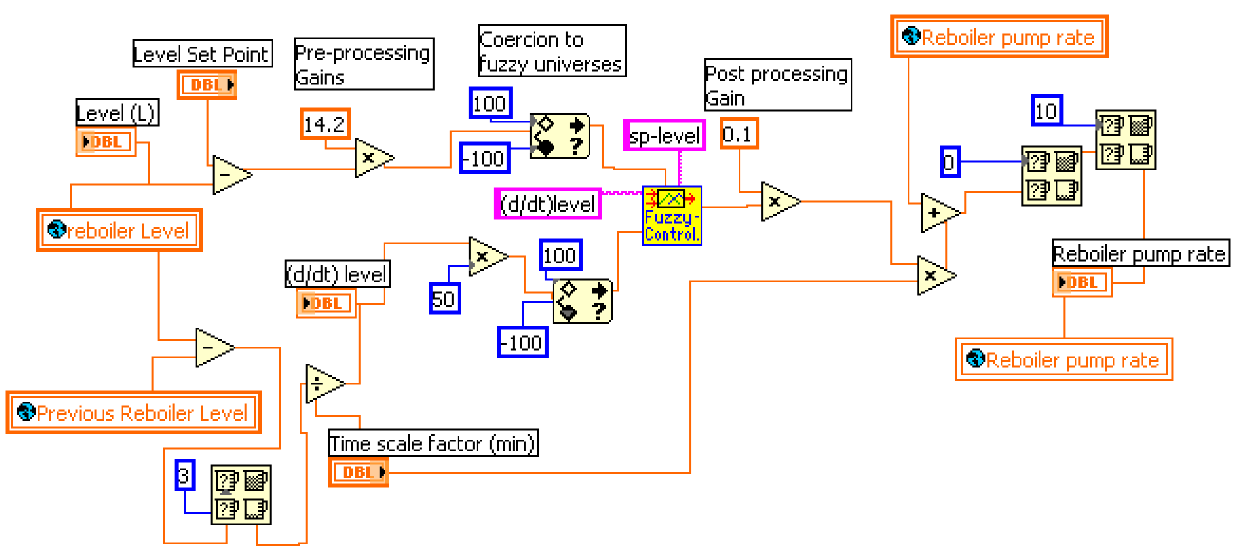

FIGURE 5.1.16 –Controller Code for the fuzzy controller

5.2 SENSORS AND EQUIPMENT DEVELOPMENT

5.2.1 Investigation

Column operators had reported precision errors with the level controller (indicating suspected problems with the current differential pressure level-sensor). I decided to investigate the reboiler level for bias errors. Dr Henry informed me that the calibration of the level was done several semesters ago and had not been verified since. The investigation was carried out in the following manner:

- Empty the reboiler of all liquid using the reboiler pump
- Divert the feed pump tube from the reservoir to pre-filled measuring beakers, in order to measure the quantity of liquid entering the reboiler
- Record various levels relating to the known volume of liquid from the beakers
- Compare with existing level output from the current virtual instrument

5.2.2 Results

The actual volumes of liquid are shown below in this side-view of the reboiler in Figure 5.2.1. Also shown are the corresponding VI values using the existing model (see section 5.2.3 for the description of the existing linear model).

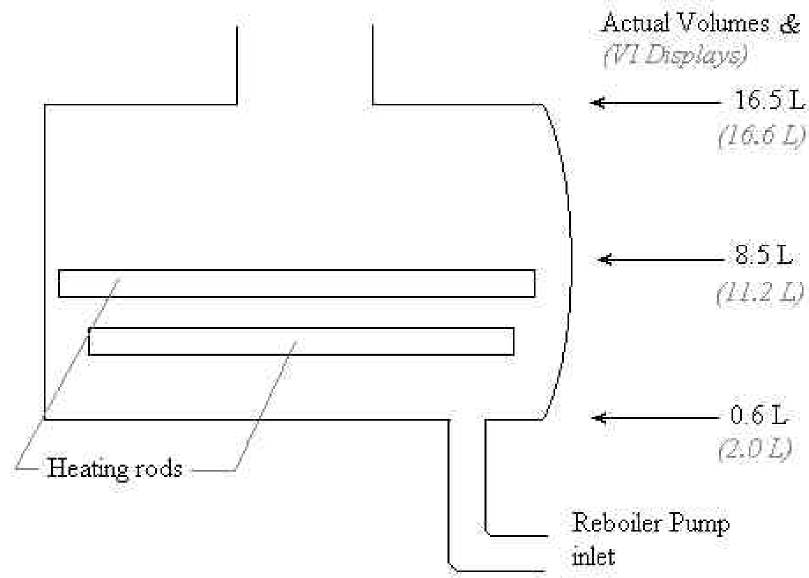

FIGURE 5.2.1 – Selected Level values for the reboiler

In the comparison of results, the VI's output displays were inaccurate at lower liquid volumes. Dr Henry suggested that in addition to other inaccuracies that could be related with the sensor itself, there may be a source of error in the equations used to process the output voltage from the sensor. Upon investigation it was found that the mathematical processing was based on a linear fit that would yields inaccurate results. A non-linear fit is necessary for more accurate level data.

5.2.3 Modification to existing level processing

The standard process of conversion of an output signal to the controlled variable is through a linear equation. While most signal conditioning modules and sensors use linearization as a simplification tool, there are instances in which this will yield an inaccurate reading. Linearization, in its basic form, involves 'fitting' the output data onto a linear input/output relationship. This formulated equation consists of a gain (k_1) and an offset value (k_2) of the form shown below where Y is the output reading and V_0 is the voltage output from the sensor.

$$Y = k_1(V_0) + k_2$$

The problem is that while sub-surface pressure varies linearly with height, the assumption is that the volume of liquid varies linearly with the height. This is the 'fit' that was used for the cylindrically shaped reboiler. See Figure 5.2.2 below. A brief inspection of the circular cross section reveals that that the volume of liquid (shaded area) needed for each unit increment of height (dh) is not constant across height values – thus it is clearly non-linear. This calibration error may be rectified using a non-linear equation to relate height with volume.

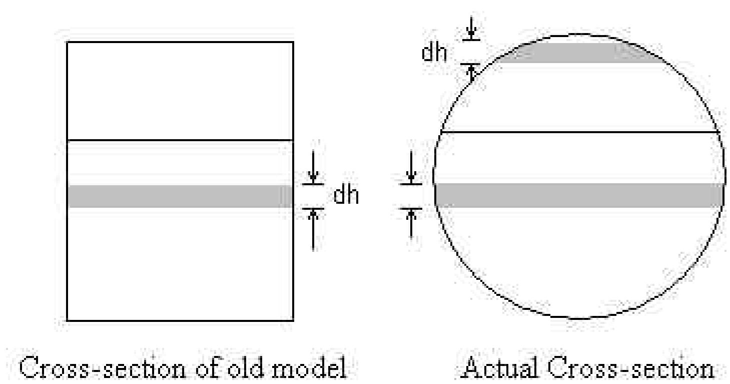

FIGURE 5.2.2 – Mathematical model versus actual cross section

5.2.4 Developing a non-linear model

The non-linear model developed uses the following assumptions:

- The cross-section of the reboiler tank remains constant across its length
- The heating rods and other sensory tubes occupy negligible space in the tank
- The circular faces at the front and at the back of the cylinder are flat (in reality, there is a mild spherical protrusion on the front face)
- Since the level sensor is necessary during operation and at such times should never fall below heating rod level (8.5 liters), the level will only be considered from this point (halfway) upto its maximum capacity (16.5 liters).

The volume of the tank (*V*) is dependent on the cross-sectional area (*A*) and the length (*L*). Length is assumed to be constant.

$$V = A\,L$$

A function of the increase in the area of the cross section with increase in height is what is desired. The developed equation is of the form:

$$A = \arcsin.h + h\sqrt{1-h^2}$$

The derivation of the equation was carried out using trigonometry and confirmed using an alternate calculus method. Please see Appendix 2, for steps followed. Using this equation, the volume can be related to the height ratio (*h*) as:

$$V = k_1(A) + k_2$$

OR

$$V = k_1(\arcsin .h + h\sqrt{1-h^2}) + k_2$$

The gain and the offset (*k1*, *k2* above) will be determined as appropriate. The height ratio (*h*) is defined as follows:

$h = r$ / R

where: *r* is the height of liquid above the center of the cross section and R is the radius of the cross section. This ensures that h is always a ratio between 0 and 1, since *r* cannot exceed the radius of the tank and it is assumed that while the reboiler is in operation, *r* will not fall below the halfway point of the tank. See figure overleaf (5.2.3).

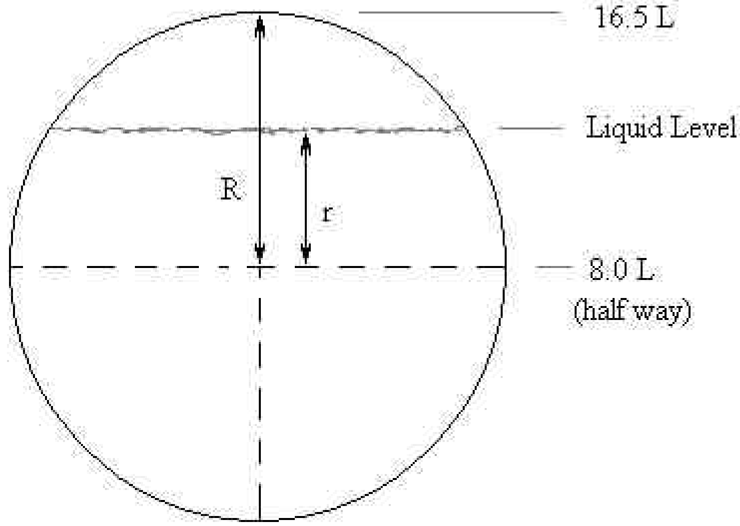

FIGURE 5.2.3 – Variables used for non-linear model derivation

5.2.5 Implementation of the new model

The implementation of the new model involves the following:

- Identify the correct stage at which to divert the flow of data from the sensor to the controller.
- Learn the LabVIEW programming skills necessary to implement the new model in LabVIEW.
- Divert the flow of data, connect the new model and bypass the existing model.
- Tune the model so that readings are accurate

The data flow was interrupted after the signal-conditioning module had conditioned the data and prior to the linear scaling that was done. This linear scaling was part of the old model for level determination. The linear fit that was used worked very well for all the other data gathered through the VI, so the data was processed in a cluster. In order to process the data differently, the one channel of data had to be separated from the main cluster, then introduced to the mathematical calculations through a formula node and finally reintroduced into the cluster so that the rest of the VIs and subVIs would not have to be altered. This was carried out as shown in the screen shot showing the selected portion of the diagram below (Figure 5.2.4). The case-wise logic shown in Figure 5.2.4 is for the condition that the voltage reading (after calculation) falls between 0 and 1. This is the “True” case. If “False,” the formula node executes the code shown in Figure 5.2.5. This is to ensure that if there are any erroneous voltage fluctuations, the level reading does not go below 8.5 liters and not above 16.5 liters.

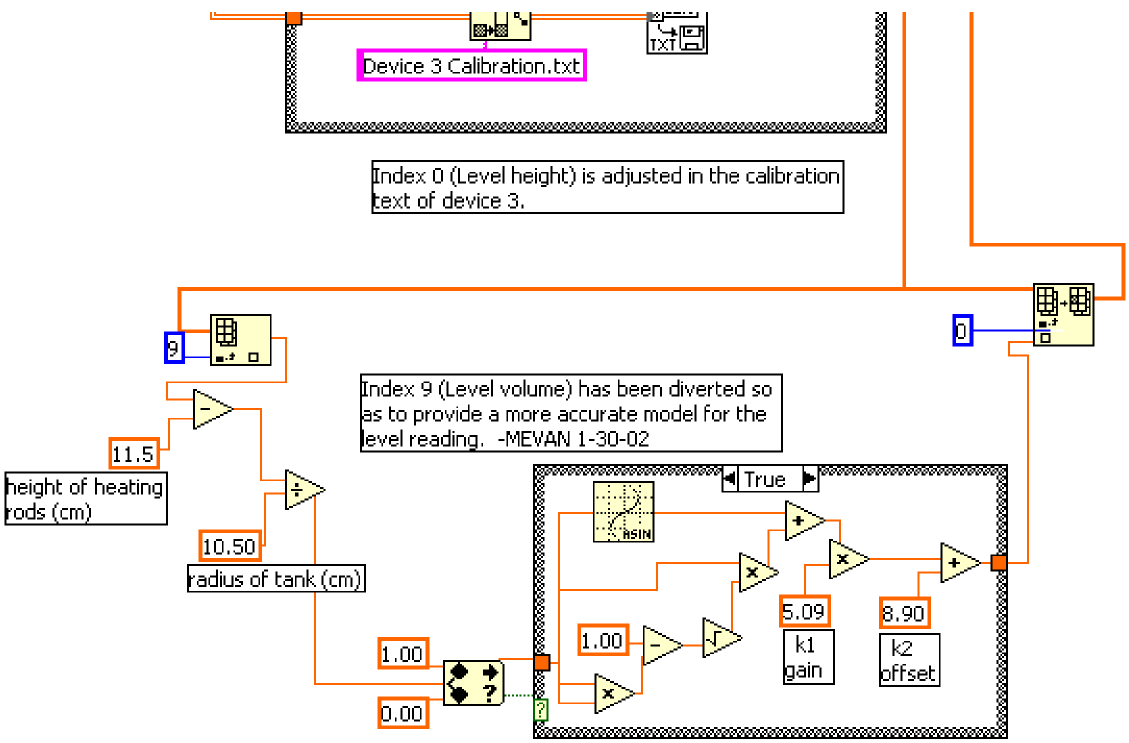

FIGURE 5.2.4 – LabVIEW programming for the non-linear model- Case 1

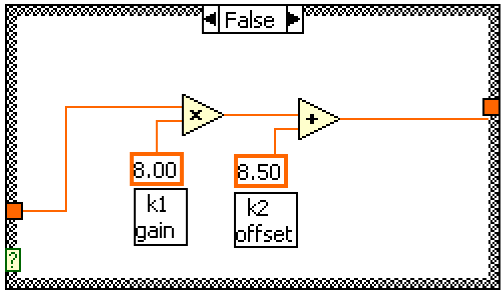

FIGURE 5.2.5 – LabVIEW programming for the non-linear model- Case 2

The complexity of bypassing the linear calibration is complex due to the fact that the processing was done as an array. All numerical data, formed into an array was processed through this device by subtracting a constant (offset) and then multiplying by a second constant (gain). The constants for the level determination were thus changed to an offset of 0 and a gain of 1, which logically means an unchanged voltage leaving the linear calibration node.

Additionally, the radius of the reboiler tank was measured and entered into the formula node shown in Figure 5.2.4. A value 1cm greater was used used for the height of the heating rods. In effect, this means that 8.0L is the level at the center of the tank (10.5cm) and 8.5 liters is the level at which the heating rods are fully immersed (11.5 cm). In tuning the model, the values of the radius of the reboiler tank and the offset were altered slightly to fit the actual readings. The values of the offset and the gain were also fine-tuned as needed.

4.2.6 Testing the new non-linear model

After completion of tuning the various numerical parameters as described in the previous section, the non-linear model was tested. The reading of level through the VI (using the non-linear model) was compared at several data points where the actual physical level was known. In a previous calibration experiment, the levels at which 8.5, 10, 12, 16.5 liters were marked on the reboiler tank outer surface using tape. The liquid level was brought up to these known levels and the VI reading was recorded. The results of the 5 tests carried out are shown below. Note that these comparison tests were done with alternating increasing/decreasing liquid level – to observe any hysteresis present in the system. This is shown in Table 5.2.6 below as tests when the reboiler was being emptied/filled.

TABLE 5.2.6 – Non-linear model accuracy testing at selected data points

	Test number					mean
	1	2	3	4	5	
Volume (L) Actual	emptying VI Reading	filling VI Reading	emptying VI Reading	filling VI Reading	emptying VI Reading	VI Reading
8.50	8.50	8.50	8.50	8.50	8.50	8.50
10.0	9.83	10.01	10.11	10.04	9.90	9.98
12.0	11.55	11.83	11.80	11.77	11.67	11.72
16.5	16.26	14.27	14.10	15.78	16.02	15.29

From the data given in Table 5.2.6, it was concluded that the level corresponded very closely to the actual level. A comparison of the mean of the new non-linear VI reading and the old linear VI reading to the actual level is shown below in Figure 5.2.7. The information is graphed in Figure 5.2.8. This figure (5.2.8) clearly shows that the accuracy of the new non-linear model is clearly much greater than the previous linear model used for the lower range (8.5 liters – 15 liters). At the higher values, the old model is more accurate. However, the mean difference between the upper range values is only 1.2 liters for the new VI. This compares favorably to the 2.7 liters error in the old VI for the lower range of readings.

TABLE 5.2.7 – Comparison of VI readings from old and new models to actual level

Data point	Volume (L) Actual	mean new VI Reading	old VI reading
1	8.50	8.50	11.2
2	10.0	9.98	13.1
3	12.0	11.72	14.5
4	16.5	15.29	16.6

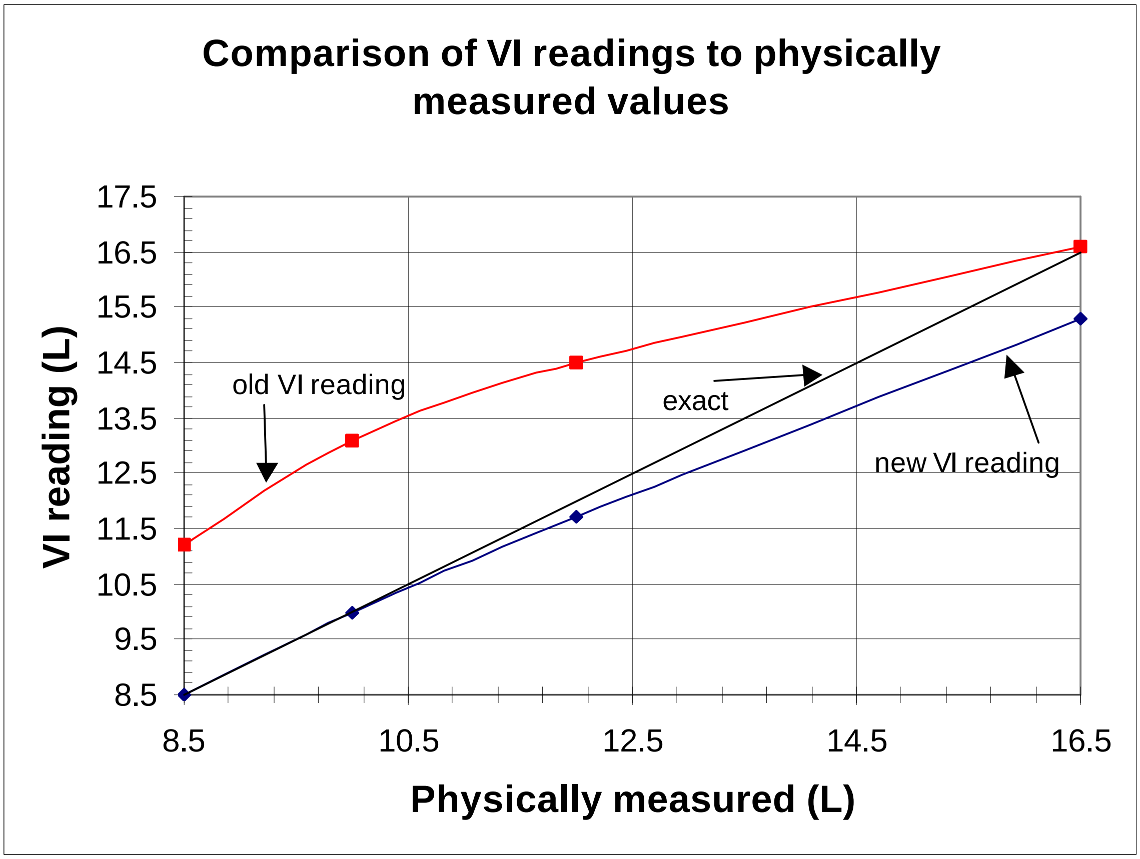

FIGURE 5.2.7 – Comparison of VI readings from old and new models to actual level

5.3 CONTROLLER TESTING

The controller testing for he fuzzy controller was an ongoing process to tune the controller into a form that would respond adequately to maintain the level at the set point. However, this was not successfully accomplished. The figure and table below illustrate an example response produced by the controller at present. The reboiler pump rate increases consistently regardless of the level error (whether it is positive or negative). Also, the derivative for level is a cause for concern because erroneous values often cause this calculation to be highly inaccurate. I have attempted to configure the fuzzy controller such that in case the derivative value is out of range, a mean value (of zero) is returned so that the emphasis is placed on the level error. However, the results produced are still not satisfactory.

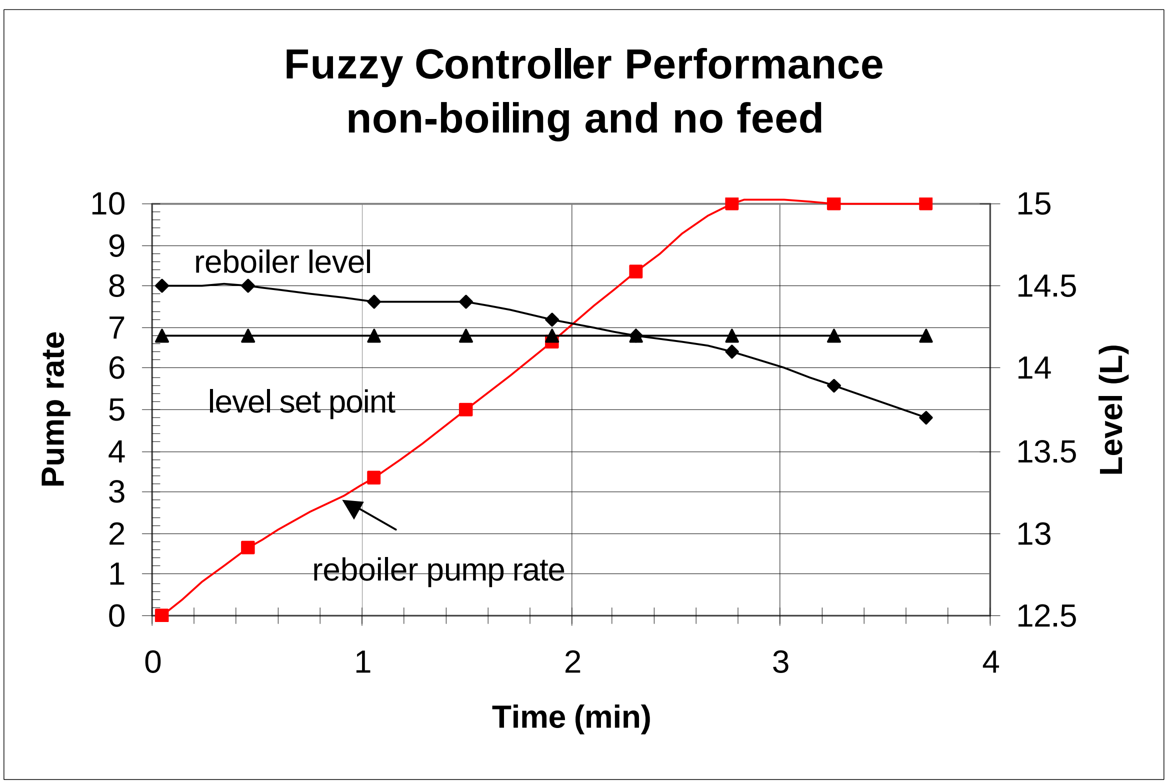

FIGURE 5.3.1 – Example Fuzzy Controller performance

5.4 Controller Debugging

A post-experimental analysis of the fuzzy controller response was done, mainly through simulated data on a spreadsheet. Since the fuzzification, rulebase and defuzzification processes can be executed through simple spreadsheet arithmetic and condition functions, this seemed the best approach to highlight the operations carried out within the fuzzy control sub-VI.

The first problem identified about the execution of the controller was created through my initial conceptual confusion in the difference between a fuzzy PD controller and a fuzzy PI controller. The latter is also named as a fuzzy Incremental controller (Jantzen, 44). The difference is that the former (PD) controller provides the output value of M(t) while the latter (PI or PInc) provides the increment value $\Delta M(t)$. The VI constructed to execute the fuzzy controller essentially functions as a PInc or PI controller, while the membership functions are geared for a PD controller. Correcting this calculation in the controller is a simple task.

The defuzzification membership function has a horizontal axis from 0-100 and output gain (GU) of 0.1. This corresponds to a range of 0-10 of M(t) that is the reboiler pump rate. However, after the VI computes a fuzzy number through the fuzzy control sub-VI in this manner, this value is not sent as the absolute value of what M(t) should be but rather the increment $\Delta M(t)$. Essentially, the membership function calculates what the reboiler pump rate should be and the VI executes this by adding this value to the previous reboiler rate. Clearly, the total reboiler rate grows to its maximum value of 10 regardless of the error or its derivative. See table and figure below.

TABLE 5.4.1 – Description of incorrect (PD) linguistic variables and maxima

Rule	Description	Maximum
1	No action	0
2	Reduce slightly	25
3	Reduce much	50
4	Reduce large	75
5	Reduce greatly	100

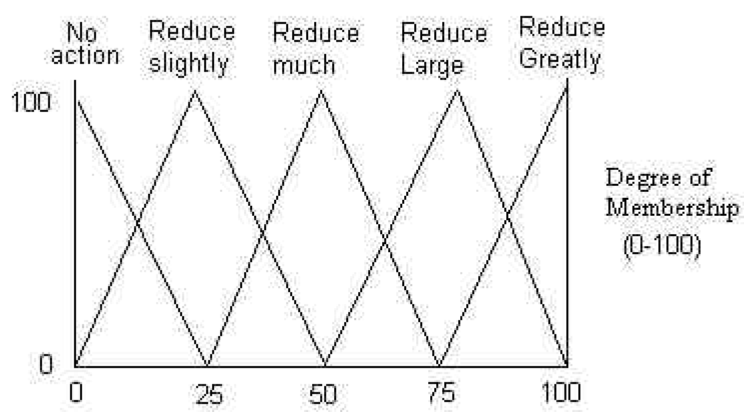

FIGURE 5.4.2 – Incorrect (PD) defuzzification functions

To rectify this problem, the output membership function should be changed. The universe of the horizontal axis should include negative values, because the increment (or $\Delta M(t)$) should extend to decreasing changes in the reboiler pump rate. The old membership functions and the new recommended functions are shown below in Table 5.4.3 and Figure 5.4.4

TABLE 5.4.3 – Description of new recommended (PI) linguistic variables and maxima

Rule	Description	Maximum
1	Reduce lot	-100
2	Reduce	-50
3	No action	0
4	Increase	50
5	Increase lot	100

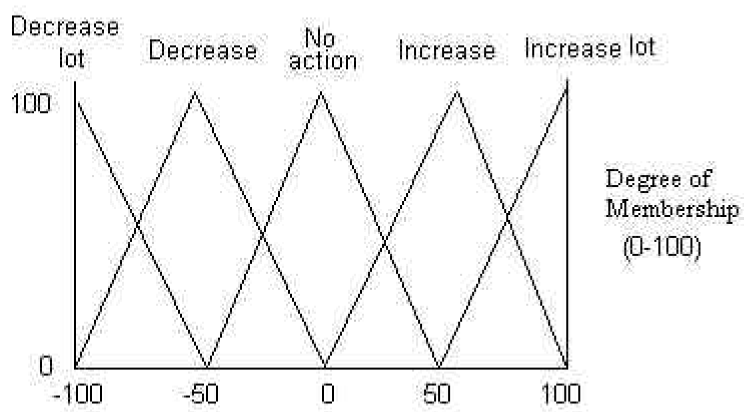

FIGURE 5.4.4 – Recommended (PI) defuzzification functions

Once this correction is made, the fuzzy tuning parameters can be fine-tuned. Implementing new defuzzification functions such as those shown above is highly recommended.

5.4 FUZZY CONTROLLER EVALUATION

5.4.1 Observations on controller performance:

- The reboiler pump rate increases until it reaches a value of 10 (the maximum) regardless of the set point.
- The derivative term for level never reaches a consistent value. More research is needed for this data. However, in case of erroneous data, the controller is assigned a mean value for the derivative. This should make the fuzzy controller compensate for the lack of accurate derivative information, by assigning an unchanged derivative. My intent was to try to make the rulebase act with more emphasis on the level error if the derivative value is out of its normal range.

5.4.2 Effectiveness:

- The controller is ineffective in sustaining the level at the set point due to inaccurate level data and other tuning bugs.
- Boiling conditions were never tested due to the lack of success in during the non-boiling condition tests.
- This controller is most ineffective in terms of the effort and time in implementation by a non-expert control engineer. The problem of tuning is great and requires an in-depth analysis.

- Remote operation was not carried out due to the shortfalls in the controller performance.

5.4.3 Future recommendations:

- First, the mistake in the defuzzification membership functions must be corrected to make the controller act effectively. Further debugging may be required.
- An automated tuning method such as neural networking can be used to minimize the time and effort needed to tune the controller.
- This type of controller coupled with this manual tuning method is not the most recommendable method for control engineers initially unfamiliar with the theory. Although the controller theoretically reduces the complexity of many complex systems by having fuzzy rules, tuning of such a controller is not an easy task.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Proximity controller implementation difficulties versus performance

1) This controller is remarkably simple in concept and in LabVIEW code.
2) The time spent on coding this controller is minimal, with relatively few errors.
3) The performance is good overall, and is excellent considering the relatively small time invested in resolving coding/programming problems.
4) One drawback is the fact that the set point cannot be altered electronically. However, for the purposes of continuous operation for the UTC distillation column, this set point is not altered often and thus is satisfactory as a viable solution.
5) The possibility of unstable behavior at certain ranges needs investigation.

6.2 Fuzzy controller implementation difficulties versus performance

1) The fuzzy controller is remarkably challenging to set up and tune. The challenge can be broken into the stages of learning the LabVIEW toolkit for fuzzy logic, identifying the extensive tuning parameters.
2) A great deal of time and effort has been wasted in tuning the fuzzy controller. Debugging the controller is not easy due to the fact that the inner calculations of the fuzzy controller cannot be highlighted – the fuzzy logic toolkit does not lend

itself to analysis through highlighting execution as does a normal VI code in LabVIEW.

3) The controller is yet not performing in a manner that can be used by an operator. Implementing a fuzzy controller seems to require more experience and time on behalf of the design control engineer.

6.3 Conclusions & Recommendations

1) The proximity sensor controller can be used to control reboiler level under boiling conditions to replace existing controllers.
2) Remote operation for the above proximity controller is a reality and is an enhancement for most control systems that is easy to implement using LabVIEW version 6.1.
3) An array of proximity controllers may enhance the control system so that the set point can be changed electronically instead of manually. This is a future possibility.
4) The exact calibration of the level sensor can be better fine-tuned through more testing. Such a calibration was carried out prior to the final tuning of the proximity sensor controller, but should be carried out after the implementation to confirm the calibration accuracy. This was not carried out in this project due to time constraints.
5) An investigation into the possibility of oscillatory behavior under boiling conditions with high feed rate needs to be investigated to insure stable operation

within the entire operating range. Modifications or refinements are suggested in the appropriate section if experimentation finds unstable behavior.

6) Several differential pressure sensors (the current type of level sensor) can be used in parallel to eliminate any singular erroneous reading. This can be done by comparing all the readings to eliminate any single deviant reading. This concept of ‘data fusion’ can be used to further minimize the original data that would be processed by any controller for the level system. This is also a future possibility.
7) Several controllers using different sensors (such as the proximity sensor and the current differential sensor) can be made available to any operator. Since improvements in any of these controllers are feasible, the optimal controller for the level system is likely to change with further research.
8) Due to the time constraint, the fuzzy controller was not made fully operational. More work needs to be done in the area of debugging the fuzzy tuning parameters to produce an effective response, starting with the defuzzification membership function.
9) Fuzzy controller tuning through other methods than direct tuning (such as neural networking) is an alternative (and perhaps more efficient) way of tuning a fuzzy controller. It is used in industry and can be researched as a possibility for obtaining a effective response from the fuzzy controller.

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PX163-120BD5V use 10Vdc
Output: 1 to 6 Vdc
Linearity: ±1.0% FS BFSL at specified voltage
Hysteresis & Repeatability: ±0.25% full scale
Zero Balance: 1 Vdc ± 0.05
(3.5± 0.05 Vdc PX163 series)
Operable Temperature Range: -40 to 185°F (-40 to 85°C)
Compensated Temperature Range:
PX161 and PX162:
0 to 145°F (-18 to 63°C)
PX163 and 164:
41 to 113°F (5 to 45°C)
Operable Overpressure: 5 psi
Media Compatibility
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P2 Gage & Vacuum: Limited only to those media which will not attack polyester, silicon, borosilicate glass, or epoxy
Response Time: 1 ms
Mating Connector: CX136-3

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PX161-027D5V	$120.00	Vacuum transducer with a range from -27.68 to 0 inches of water	0

APPENDIX 2

A2.1 Derivation for non-linear model using calculus

From circular geometry, we know:

$$x^2 + y^2 = r^2$$
$$y = \pm\sqrt{r^2 - x^2}$$
$$\int y.dx = \sqrt{r^2 - x^2}dx$$

Note that the square root function for y given above will be assumed positive and the total area will be found by doubling the area at the end of the integration to reflect the identical area of the negative half of the function.

We will assume that r =1 in order to simplify the calculation. Also we will label the specific height of liquid at a given moment as h. ($0 < h < r$, $0 < h < 1$). Thus, h will correspond to the height in absolute terms, but rather the ratio of height over radius.

The volume of the cylinder can be expressed as:

V= $A.L$

Where: A is the cross sectional area and L is the length of the tank.

$$V = A.L = L\int_0^h \sqrt{1-x^2}\,dx$$

Use the trigonometric substitution:

$x = \sin q$

$dx = \cos q \, .dq$

Therefore:

$$A = \int_{x=0}^{x=h} (\sqrt{1-\sin^2 q}\,.)\cos q\,.dq$$

$$A = \int_{x=0}^{x=h} (\sqrt{\cos^2 q}\,.)\cos q\,.dq$$

$$A = \int_{x=0}^{x=h} (\cos q\,.)\cos q\,.dq$$

$$A = \int_{x=0}^{x=h} \cos^2 q\,.dq$$

$$A = \int_{x=0}^{x=h} \frac{1+\cos 2q}{2}\,dq\,.$$

$$A = \int_{x=0}^{x=h} \frac{1}{2}\,dq\,.+\int_{x=0}^{x=h} \frac{\cos 2q}{2}\,dq\,.$$

$$A = \frac{q}{2} + \frac{\sin 2q}{4} \Big|_{x=0}^{x=h}$$

$$A = \frac{q}{2} + \frac{2\sin q\,\cos q}{4} \Big|_{x=0}^{x=h}$$

$$A = \frac{\arcsin .h}{2} + \frac{2h\sqrt{1-h^2}}{4}$$

$$A = \frac{1}{2}(\arcsin .h + h\sqrt{1-h^2})$$

Total area is now doubled to reflect the mirrored area below the x axis. Thus:

$$A = \arcsin .h + h\sqrt{1-h^2}$$

And:

$$V = AL = L(\arcsin .h + h\sqrt{1-h^2})$$

This represents the total volume of liquid above the halfway point. Since the volume of liquid is never assumed to drop below this level, the scope of interest only pertains to volumes above this level – to level at and above the level of the heating rods.

A2.2 Verification of Derivation using Trigonometry

The total volume of liquid above the center-line is proportional to the cross-sectional area shown by regions 1 through 4 overleaf. Note that the areas of regions 1 and 4 are identical as are the areas of regions 2 and 3.

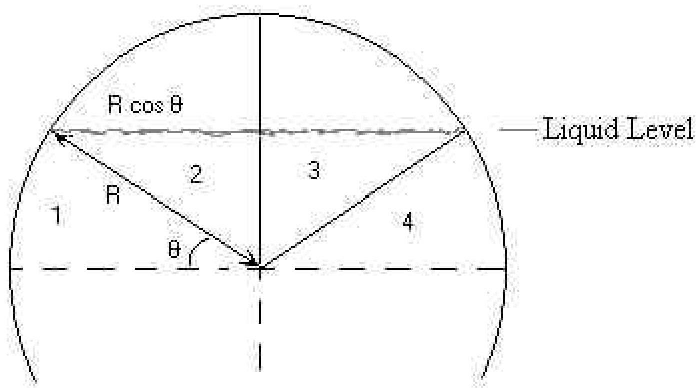

FIGURE A1 – Identification of areas for trigonometric derivation

Again, we will consider h as the ratio of height over radius, and we will consider an example cylinder with unit radius.

Ie: $r = 1$ & $0 < h < 1$

Region 1: (Sector of a circle)

$$A_1 = \frac{\theta}{2\pi}(\pi r^2) = \frac{1}{2}\theta r^2$$

Region 2: is the same as Region 1

Region 3: (Triangle)

$$A_3 = \frac{1}{2}(r.\cos\theta)(r.\sin\theta) = \frac{1}{2}r^2.\cos\theta\,\sin\theta$$

Region 4: is the same as Region 3

Total area can be expressed as:

$$A = 2A_1 + 2A_3 = (2)\frac{1}{2}qr^2 + (2)\frac{1}{2}r^2.\cos q \sin q = qr^2 + r^2.\cos q \sin q$$

From the triangle we can substitute r =1 and that h = sin q. Therefore:

$$A = qr^2 + r^2.\cos q \sin q = q + .\cos q \sin q = \arcsin h + h\sqrt{1 - h^2}$$

And:

$$V = AL = L(\arcsin .h + h\sqrt{1 - h^2})$$

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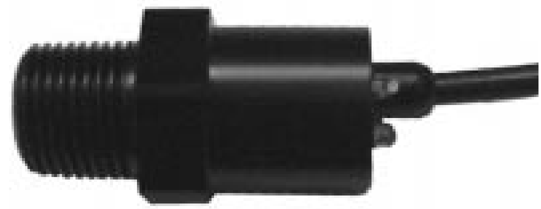

			DC Sensor
Mechanical Specifications			
Enclosure Ratings			IP67, NEMA 1,3,4,6,13
Operating Temperature Range			-25 to 70 C
LED Signal Indicator			Yes, Red or Yellow
Power On LED Indicator			Yes, Green
Potentiometer			Yes
Sensor Type			L-Type
Barrel Material			Delren
Shock			30g, 11ms
Vibration			55Hz, 1mm amplitude in all planes
Electrical Specifications			
Supply Voltage			10-48 VDC
Continuous Switching Current			300 mA
Voltage Drop			≤2 VDC
Current Consumption			≤10 mA
Switching Frequency			100 Hz
Transient Protection			2kV, 1ms, 1 kOhm
Overload Protection			Yes
Short Circuit			Yes
Reverse Polarity Protection			Yes
Part Numbers			
PNP	N.O.	Cable	C2ALLAP1-P
		Connector	C2ALLAP2-P
	N.C.	Cable	C2ALLBP1-P
		Connector	C2ALLBP2-P
NPN	N.O.	Cable	C2ALLAN1-P
		Connector	C2ALLAN2-P
	N.C.	Cable	C2ALLBN1-P
		Connector	C2ALLBPN-P

			AC Sensor
Mechanical Specifications			
Enclosure Ratings			IP67, NEMA 1,3,4,6,13
Operating Temperature Range			-25 to 70 C
LED Signal Indicator			Yes, Red or Yellow
Power On LED Indicator			Yes, Green
Potentiometer			Yes
Sensor Type			L-Type
Barrel Material			Delren
Shock			30g, 11ms
Vibration			55Hz, 1mm amplitude in all planes
Electrical Specifications			
Supply Voltage			24-240 VAC
Continuous Switching Current			300 mA
Voltage Drop			≤7.5 VAC
Leakage Current			≤1.5 mA
Current Consumption			-
Switching Frequency			25 Hz
Transient Protection			2kV, 1ms, 1 kOhm
Part Numbers			
	N.O.	Cable	C2ALLAF1-P
		Connector	C2ALLAF2-P
	N.C.	Cable	C2ALLBF1-P
		Connector	C2ALLBF2-P

APPENDIX 4

THERMISTOR-BASED SENSOR THEORY

A4.1 – Common properties used as indicators in level sensors

"The three most popular level sensors are the differential pressure, float and air-bubbler sensors" (Smith & Corripio, 733). Some of the other sensors available are also listed below along with the properties that create a measurable difference – the indicator. The 'Comments' column provides reasons why each sensor type is unsuitable for use in the Grote distillation column reboiler level control system.

TABLE A2 – Different types of level sensors and indicators

Sensor	*Indicator*	*Comments*
Differential pressure	Hydrostatic head	Current sensor
Float sensor	Buoyant force	Feasible
Air-Bubbler	Pressure needed for constant bubble flow	Boiling vapor present
Capacitance Gauge	Electrical field	Expensive
Ultrasonic sensors	Time elapsed for receiving reflected wave	Expensive
Nuclear radiation	Radiation count	Expensive

With the disadvantages shown above it can be seen why a distillation column may require an innovative level sensor. Most distillation columns in industry utilize expensive level sensors, since distillation equipment itself is high-expense apparatus.

A4.2 – Temperature-dependent resistance as Indicator

The physical property that the sensor is based upon is the temperature dependence on resistance in a thermistor. This characteristic will thus produce variations in voltage when connected in a circuit – thus producing a measurable indicator on which to base a sensor.

The temperature variation depends on the heat transfer coefficient, which is considerably different when the surrounding fluid is liquid as opposed to gas. This difference in steady-state energy transferred will create different temperatures for sub-surface thermistors as opposed to those exposed to air.

Consider each thermistor individually. The total energy transferred per unit time in terms of the potential drop and electrical resistance is:

$$Q = V^2 / R \qquad (4)$$

However, the energy dissipated will also equal the energy transferred (per unit time) through natural convection through the fluid, expressed in terms of the coefficient of convection (h), the surface area of the thermistor (A) and the temperatures of the fluid (Tf) and the surface of the thermistor (Ts):

$$Q = h\,A\,(T_f - T_s) \qquad (5)$$

Most importantly, it can be seen that under steady state operating conditions, 'h', 'A' 'Tf' and 'Ts' will remain the same for each thermistor in a specific fluid. An array (consisting of 10) thermistors will record similar results. All thermistors in liquid will register a particular voltage drop while all the thermistors exposed to the gas will register a different voltage drop. In order to interpret the voltage signals from the thermistors, we need to realize that a jump in the voltage will indicate that there is a change in the fluid surrounding the thermistor. The fluid level will be between the two thermistors where the jump in voltage would take place. Thus it is unnecessary to know the specific values of the constants named in equations (4) and (5). See Figure A3 overleaf:

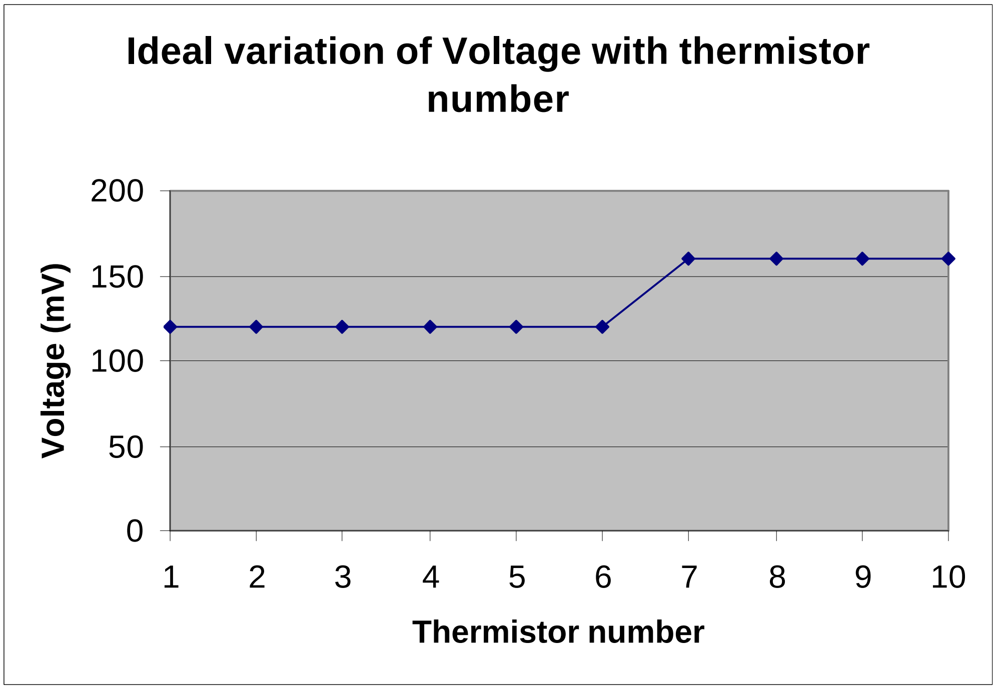

FIGURE A3 – Example of ideal voltage output from sensor

From this figure it can be seen that ideally, the voltages will be constant for thermistors below the liquid level, as will be the voltage for the thermistors above this level. The level will be located between thermistors 6 and 7, which should then translate to a prearranged value for the liquid level. Thus the goal then becomes to develop a sensor that produces a voltage response as close as possible to the ideal graph, while developing an algorithm that converts this into an output level.

A4.3 – Interpretation of Level from Voltage

While a qualitative explanation of determining the level of the voltage is apparent for an observer, a quantitative algorithm for this determination is necessary in terms of software. This algorithm is assumed to work for the ideal sensor properties described previously.

Index of terms used in pseudocode:

V1 to V10	- voltages in array corresponding to thermistors 1 to 10.
Vsum	– Sum of the voltages 1 through 10
Vn	– n'th voltage (where 1<= n <=10)
Vavg	- mean voltage from 1 to 10
Vx	- voltage at position immediately above liquid level

Steps used for interpretation:

(1) Average V1-V10: Vavg

(2) Loop until Vn > Vavg

(3) Check that [Vn, Vn+1,…V10] > Vavg

(4) Level is between Vn-1 and Vn

Pseudocode:

(1) Averaging voltages

```
Vsum=0

Vn=V1

Loop

        Vsum = Vsum+Vn

        Vn=Vn+1

        If Vn=V10

                End loop

Repeat

Vavg = Vsum/10
```

(2) Finding the first voltage greater than average (beyond the liquid level)

```
Vn=V1

Loop

        If  Vn > Vavg

                Vn = Vx

                End loop

        Else            Vn = Vn+1

Repeat
```

(3) Checking for malfunction

```
Loop

        If Vn < Vavg

                Print "error… please check thermistors"
```

End loop

Else Vn= Vn+1

If Vn=V10

(4) Printing result

Print Vx-1 < Level < Vx

End loop

Repeat

A4.4 – Preliminary Physical Design

The physical layout of the array of thermistors is shown below.

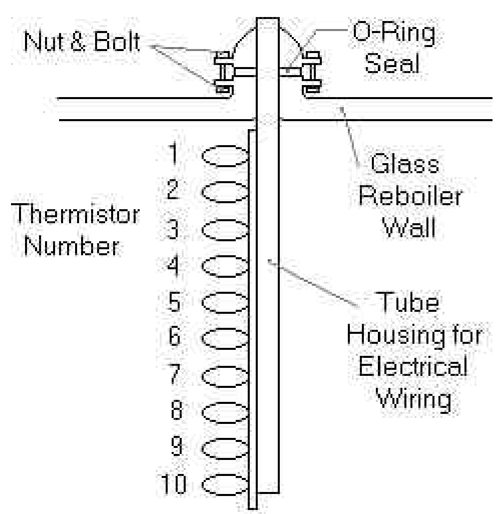

Figure A4 – physical layout

The electrical circuit that the sensor array would have to be connected to is given below.

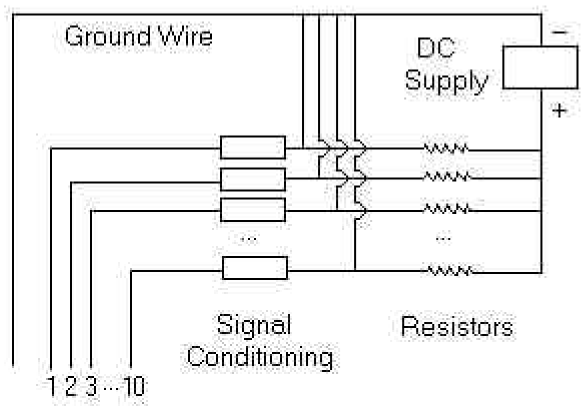

Figure A5 - circuit

All signal-conditioning modules will be type 5B30-03 with a voltage range of 0-100 mV since this is the most accessible module at my disposal for this project. All 10 modules will be connected to a standard 16-port 5B backplane, which in turn will be connected to a DAQ board on a computer. Each of the signal conditioning modules is a voltmeter capable of measuring voltage a voltage in that specific range, reducing noise and transmitting it via the DAQ board to be further processed by a virtual instrument.

A4.5 – Developing the ideal sensor

Distribution of Thermistors resistances

All data are arranged from thermistor 1 to thermistor 10. Each has been labeled in ascending order of resistance according to Test 1. The second test was done in reverse order (starting with thermistor 10 and ending with thermistor 1) in order to identify any potential error due to measuring order. According to the results in the table below, it can be seen that we can be highly certain that the variation in resistance is inherent in the thermistors.

The procedure for the testing included several precautions to ensure accuracy of results:

- No touching of the thermistor surface with fingers (source of heat)
- Equal time of measurement (closed-circuit resistance heating changes resistance)
- Forward measurement (from 1-10) followed by a repeat test in reverse order (from 10-1) done after 5 minutes (eliminates voltmeter errors due to order)

The conditions under which the test are: temperature of thermistor was $21°C$, Surrounded in ambient air.

The results of each test are given overleaf in Table A6.

TABLE A6 –Thermistor resistance tests

Test Number	*Test 1*	*Test 2*
Thermistor 1	1.59	1.58
Thermistor 2	1.59	1.59
Thermistor 3	1.61	1.59
Thermistor 4	1.62	1.60
Thermistor 5	1.63	1.62
Thermistor 6	1.64	1.63
Thermistor 7	1.65	1.68
Thermistor 8	1.66	1.66
Thermistor 9	1.66	1.68
Thermistor 10	1.71	1.70
Arithmetic Mean	1.636	1.633
Maximum Deviation from Mean	0.074	0.067
Maximum Deviation (%)	4.5%	4.1%

It can be seen from this tabulated results table that the between the liquid tests and the gas tests, the resistance varied a considerable degree. This is positive since this means a greater difference will be observed in voltage difference between thermistors in liquid as opposed to gas.

Additionally, from rearranging equation (4) and assuming that for a certain thermistor, surrounded by a particular fluid at steady state:

$$R = V^2 /Q \qquad (6)$$

Where Q is a constant independent of voltage and resistance. Thus we can see that:

$$R \alpha V^2 \qquad (7)$$

Thus from the tabulated results when R differs by 15% under identical conditions other than liquid and gas surrounding fluid, thus the voltage differs by 7.2%. See calculation below:

$$R = k V^2$$

$$1.15 = x^2$$

$$\sqrt{1.15} = x$$

$$x = 1.072$$

This 7.2% deviation is larger than the deviation from the mean for the inherent resistance variation and thus some confidence can be placed on the thermistors' ability to give us reasonable results to develop a sensor.

APPENDIX 5

VI HIERARCHY OF THE UTC DITILLATION COLUMN

This section details the virtual instrument configuration of the UTC Distillation Column at the completion of this report. Note that the VI diagram shown below does not include the complete hierarchy in use with the column, but only the VIs and sub-VIs that are directly called on or called by the proximity controller VI (Figure A7) or the fuzzy controller VI (Figure A8). They are the VIs that are necessary for the above controllers to function. Also note the lowest 4 levels of subVIs are not shown since they perform very basic functions.

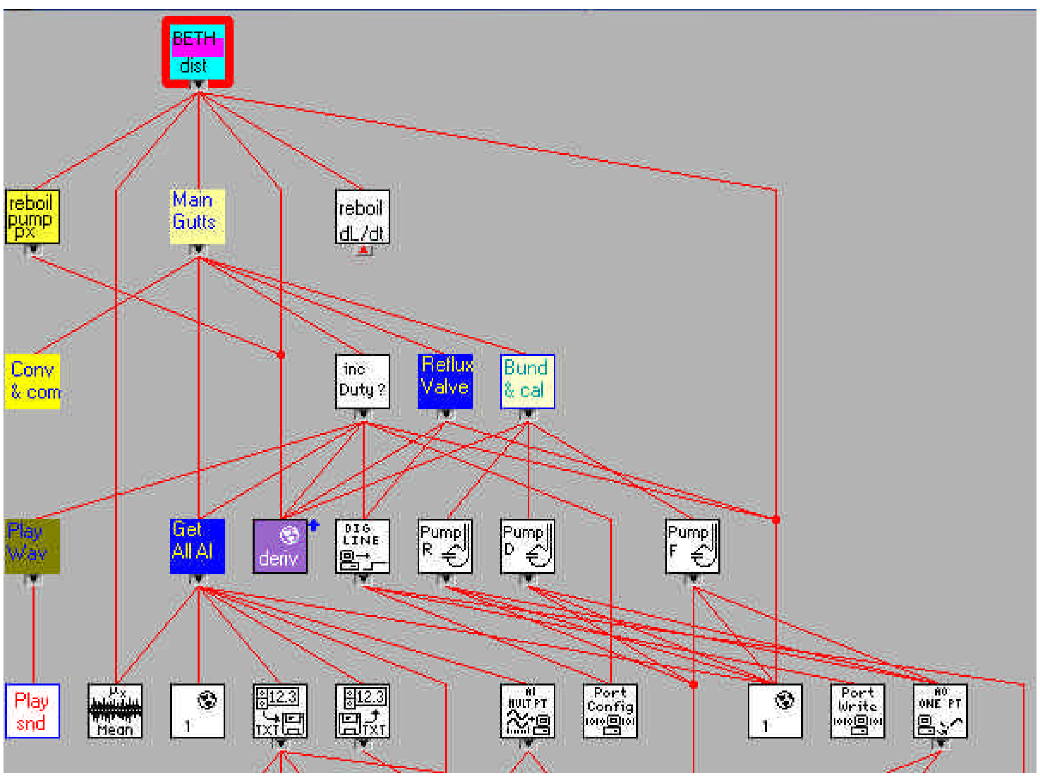

FIGURE A7 –VI hierarchy used by the proximity-sensor controller

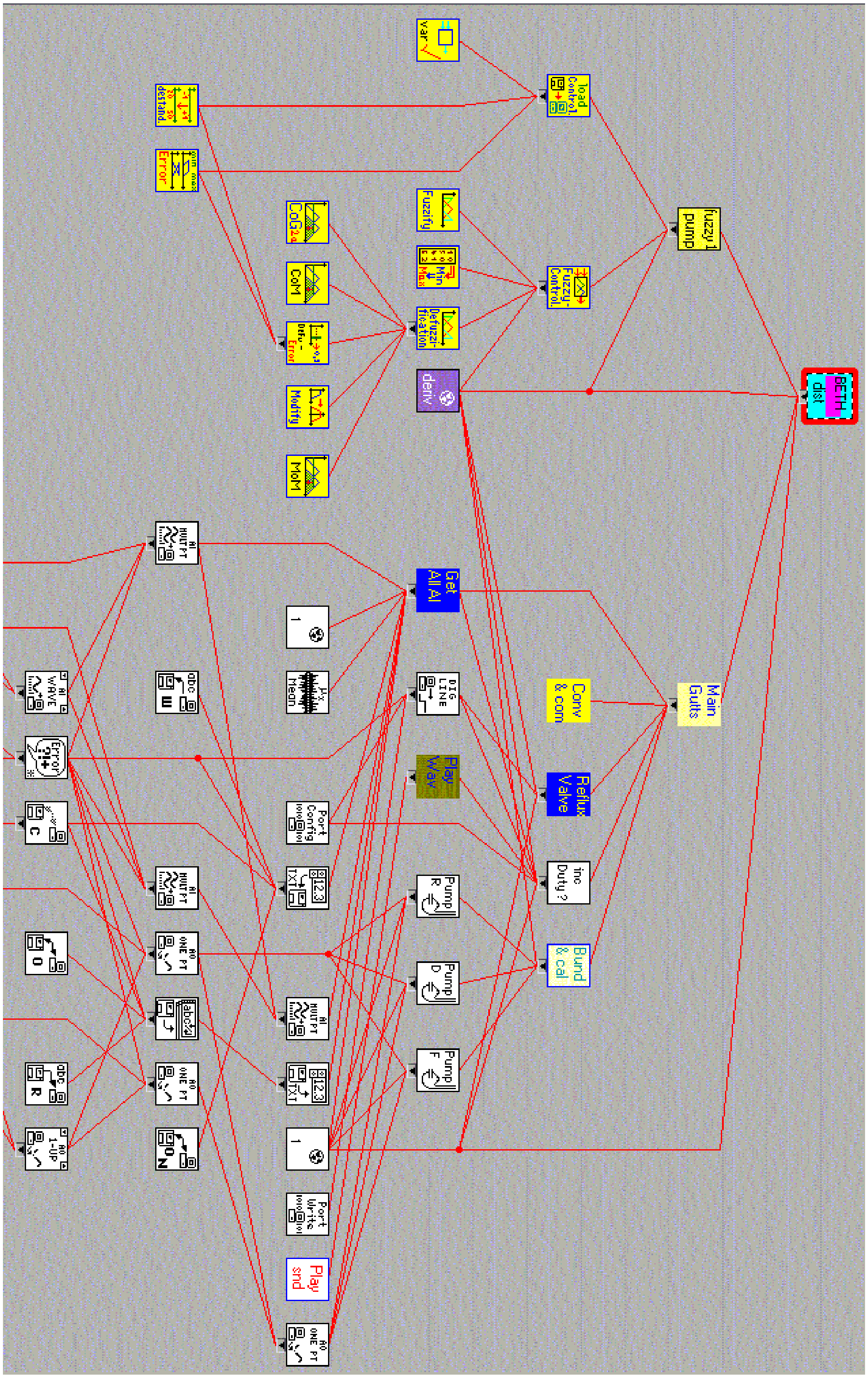

FIGURE A8 –VI hierarchy used by the fuzzy controller

APPENDIX 6

List of digital appendices in CD form:

1.) Report in individual files numbered in chronological order (21 MS Word files with appendix in htm and appendix in pdf format)
2.) The Proximity Controller library of VIs (LabVIEW 6.1)
3.) The Fuzzy Controller library of VIs (LabVIEW 6.1)
4.) The Oral examination presentation and revision (2 files in MS Powerpoint)