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by David Thomas

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1 - Executive Summary

This project aimed to prove the established theory of process control employed for various control systems. Initial research was undertaken to investigate control systems, in particular the three main systems incorporated in industrial plants, namely flow, level and temperature, and process control methods utilised, including PID controllers. Using the knowledge gained, factors affecting process control, including optimal tuning of PID algorithm parameters, to improve process response and reduce error, could be used to inform the project.

A classroom-based setting was used to undertake the project, each process station incorporating components such as transmitters, a controller, valve or pump as required for the control system. Reaction curves were produced for each system and the gradient used to calculate the required transfer functions. Using Simulink, initial calculated values were used to simulate the response of each process station. Control loops were designed to operate individually for tuning and alterations, or combined in a cascading manner. Once primary process station response curves had been established, tuning of each of the PID algorithm parameters, K_p , K_i and K_d as appropriate was undertaken to allow re-simulation of each process station. Following this, a comparison of the process response curve, degree of error and any overshoot or lag could be made to confirm whether optimal response and therefore successful tuning had been achieved, and a comparison to the literature made.

2 – Research & System Investigation

2.1 - Research

Process control is essential to industrial processes to ensure end products, or applications are obtained/met in a safe, profitable manner and are of the quality desired. Such control can be costly and requires precision, time and expertise to be successful. Understanding the impact small changes can have on a process, and how parameters such as temperature, level, and flow can be carefully and reliably controlled, is vital. (PAContol, 2006) Correctly cited

2.1.1 - Control Systems

No need to tell your reader how important something is, sound like you are instructing them

Firstly, the principle of control systems must be understood. Control systems use the mathematical concept of control theory, how behavior of dynamic systems incorporating inputs, are modified by feedback (Anome_et_al, 2018) Input and output are mathematically linked; one system controls/influences the behavior of another system, or apparatus, to obtain a set result (Electrical4u, 2020). This relationship may be proportional (linear) or as with most real-control systems, associated by non-linear differential equations (non-linear) (Anome_et_al, 2018).

Repetition

In industry, where processes are designed to ensure a process variable (PV) is maintained at a chosen set point (SP), control systems achieve this by means of a control loop. Control systems are formed of discrete elements, combining to perform basic functions: measurement, comparison, computation, and correction (Anome_et_al, 2018).

Element	Comment
Sensor (primary element)	First element of any control system e.g. Capacitance cell, thermocouple. Changes in process conditions lead to a change in the sensor property.
Transducer / Converter	Transducer: Converts mechanical into electrical signal Converter: Coverts one signal type into another
Transmitter	Converts sensor/transducer readings into a signal to be transmitted to a controller e.g. pressure, flow, level transmitter
Signal	Transmit PV measurement to controller e.g. pneumatic (rare), analog (4-20mA), digital
Indicator	Displays process information. Allows engineers to check measurements during operation e.g. temperature gauge
Recorder	Records measurement output. Allows for process history, trend analysis by engineers.
Controller	Receives PV data from measuring instrument, compares to SP and signals to final control element if required to make a change. May be pneumatic, electronic or programmable. May perform complex or simple calculations.

Final Control Element	Aims to cause physical change in the variable. Most commonly device is a valve, or pump commonly acting to increase/decrease fluid flow
Actuator	Causes a physical change in final control device e.g. valve actuator to open/close the valve.

Table 1 - Elements of a Control System

(PAControl, 2006)

Function	Element
Measurement	Sensor, transducer & transmitter
Comparison & Computation	Controller e.g. Proportion, Proportional-Integral, Proportion-Integral-Derivative controllers, Programmable Logic Controller
Correction	End Control Element e.g. valve that alters the input/output of the control system to affect a process variable.

Table 2 - Functions of a Control System

(Anome_et_al, 2018)

Control System Feature	Comment
Accuracy	Under normal operating conditions, accuracy defines the error limits. The inclusion of error detection and feedback improves the level of accuracy of the system
Sensitivity	Environmental surroundings are constantly changing and can impact the control system parameters. Control systems should ideally be insensitive to these parameter changes and respond solely to input signals.
Minimize noise	Undesired/unintended input signal impacts performance of the control system e.g. sensor readings. The system should have the ability to reduce any effects of noise
Stable	Bounded input and output signal; input = 0, output = 0
Large Bandwidth	For the frequency response, the bandwidth should be as wide as possible.
Speed i.e. response time	The control system should be able to achieve a stable output in minimum time
Oscillation trend	Small numbers, or consistent oscillations in general represent a stable system

Table 3 - Features of a Good Control System

(Electrical4u, 2020)

Control systems can be defined firstly by method of control: manual-control (rare in industry); requires human operators to make adjustments, or conversely automatic-control; requires no human intervention (PAControl, 2006).

A second categorization is open or closed-loop control. In open-loop, no feedback from system output occurs; control actions are not in response to feedback from PV condition (Electrical4u, 2020) e.g. a pre-set timer system to open a cool

water valve reducing temperature irrespective of that measured (PAContol, 2006). All manual control systems fall into this category.

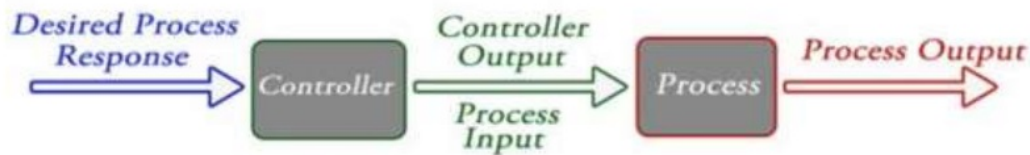


Figure 1 - Block Diagram of an Open-Control System

(Electrical4u, 2020)

In contrast, closed-loop systems compare measured PV to SP, taking action to rectify any deviation (PAContol, 2006). i.e. there is a feedback loop, output affects quantity of the input (Electrical4u, 2020). This involves generation of an error signal resulting from the comparison, which is applied to the controller for correction of the output (Electrical4u, 2020). Feedback signals can be positive or negative, these systems offering several advantages including a reduction in system input-output error, and system gain (factor $1/1 \pm GH$), along with an improvement in insensitivity and stability (Electrical4u, 2020).

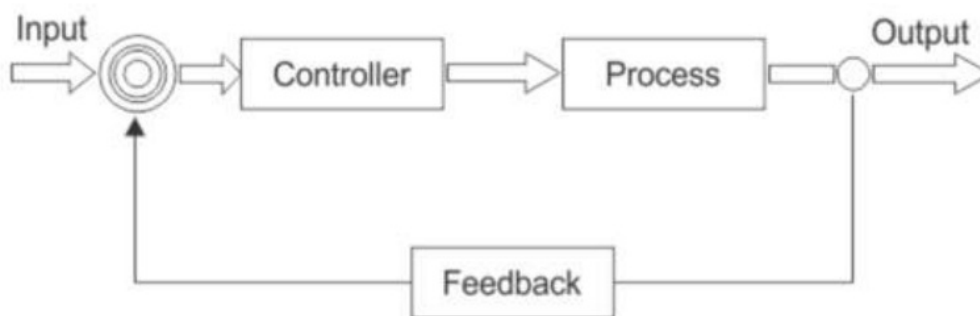


Figure 2 - Basic closed-loop system

(Electrical4u, 2020)

Open-Loop Control System	Closed-Loop Control System
No feedback	Feedback
No error detection (i.e. deviation of PV from SP)	Error detection (e.g. PID)
Generally stable system	Can become unstable – care in design required. Can make sensitivity small to improve
Simple construction	Complex construction
Economical	Costly
Minimal maintenance	High level of maintenance
Invariably inaccurate	Accurate (even if system demonstrates non-linearity – see below)
Unreliable	Reliable
Inaccurate	Accurate – errors corrected by means of feedback signal. Less affected by noise.
Small bandwidth	Large bandwidth

Table 4 - Comparison of Open & Closed Control Loop Systems

(Electrical4u, 2020)

2.1.2 - Process Control

Process control describes methods used to control PV(s) within a control system with the aim of reducing variability, increasing efficiency and ensuring safety (PAContol, 2006). It relies on knowledge of the following terms within the system:

Term	Description	Comment
Error	Difference (positive/ negative) between PV and SP. Aim is to minimise/eliminate error	3 elements: Magnitude: deviation between SP & PV. Duration: length of time error has been in existence Rate of change: determined from slope of error graph
Offset	Sustained deviation of PV from SP	E.g. consistent temperature of 0.5 above the SP is an offset of 0.5
Control Algorithm	Control function defined mathematically	Often used to calculate complex control loop requirements. Consider factors such as: Amount of valve opening required in response to deviation from SP Length of time of opening

Table 5 - Process Control Terminology

(PAContol, 2006)

To achieve the desired level of control, controller type must be carefully considered. Three main types exist: Discrete, Multistep & Continuous (PAContol, 2006).

Controller Type	Description
Discrete Controllers	Two action modes only, ON/OFF. These are rarely used in control systems as they do not maintain the SP, rather a proximity around it, the dead zone
Multistep Controllers	>2 action modes that perform an intermediate step as the SP is approached. Results in a lower oscillation around the SP compared to discrete controllers.
Continuous Controllers	Compare PV to SP and determine any error and if needed adjust the output in accordance with set parameters. These are the most common types of controller used in industry, known as P, PI or PID controllers.

Table 6 - Process Controller Types

(PAContol, 2006)

2.1.3 - PID Controllers & Tuning

A control system performance can be described by means of the transient (step) response to a particular magnitude/unit of step input (Electrical4u, 2020). PID controllers aim to improve response by achieving rapid SP steady-state, and preventing routine overshoots and lags associated with discrete controllers, assessing the following parameters to provide control (PAContol, 2006).

PID Parameter	Comment
Proportional Mode (P): (variation between PV & SP)	Determines how much, or the magnitude, of correction required
Integral Mode (I): (considers previous variance from SP)	Determines how long, or the duration, of the controller output adjustment
Derivative Mode (D): (predicts future variance based on previous & current variances)	Determine how fast, or the speed, at which the adjustment is made.

Table 7 - PID Parameters

(PAContol, 2006)(WestCS, 2018)

To effectively manage process disturbances, PID controllers must be tuned to meet system requirements which, if done correctly, will compensate for any disturbance, prevent overshoot and protect processes and equipment (WestCS, 2018). PID controllers act to automatically calculate PID and variances over time (self-tune), however PID variables can also be calculated manually by an engineer, both determining action required to maintain a process' SP (WestCS, 2018).

Correctly cited

Tuning of PID controllers involves optimally setting the three PID algorithm parameters, considering responsiveness to error, degree of overshoot and amount of oscillation. Tuning therefore may be specific to the process being controlled e.g. whether degree of overshoot for safety concerns, or energy expenditure in achieving SP is of concern. In general, most processes require a stable response and minimal oscillation across a variety of conditions or SPs (Poe.W, 2017).

Tuning often focuses on adjustment of gain; change in output divided by change in input, ensuring changes in controller input changes controller output. Valve position(s) should change enough to remove error but not cause instability or oscillation (PAContol, 2006). Three tuning methods are described below:

Method	Comment	Example of process
Trial & Error Method/Manual Tuning	Simplest tuning method	I & D set to zero; increase P gain until oscillation of output is steady to allow system response to be faster but remain stable. I then set to reduce oscillations and change value until reduction of steady-state error. Note: Overshoot can increase Increase D gain until response to SP is quick. This will also decrease overshoot.
Zeigler-Nichols Method	2 methods based on transient response characteristics of the system	Method 1: requires S shaped curve for step input. Obtain step response experimentally; obtain delay & time constants; set Kp, Ti & Td values. Method 2: similar to trial & error above. I & D set to zero; increase P gain to achieve constant oscillations of output (critical gain); set values of Ti & Td.
Software		Commonly utilizes MATLAB or Simulink

Table 8 - Tuning Methods

(Electronicshub, 2015)

Method	Advantages	Disadvantages
Trial & Error Method/Manual Tuning	Doesn't require any mathematical calculations. Useful where tuning needs to be undertaken while the system is still in use	Knowledge & experience of tuning required. Can be time consuming.
Zeigler-Nichols Method	Well known & understood method	Can disturb the process. Can be aggressive
Software	Consistent Can simulate & test a number of sensor/valve inputs before applying	Software costs Training & knowledge of the system

Table 9 - Tuning Method Comparisons

(Costa, 2011)

2.1.4 – Temperature-Control Systems

Many industrial processes require temperature control with the aim of maintaining temperature, PV, at a stable given value, SP, irrespective of environmental changes (Danaher, 2021). With manual control, used in less critical applications, process temperature is read periodically by an operator, who makes temperature adjustments by increasing or decreasing the amount of cooling input. In practice however, this is impractical due to the resource required, and can only be used where process upsets are scarce, and time taken to correct does not risk exceeding the SP (Garrett-Doyle, 2014). Automatic control is more common.

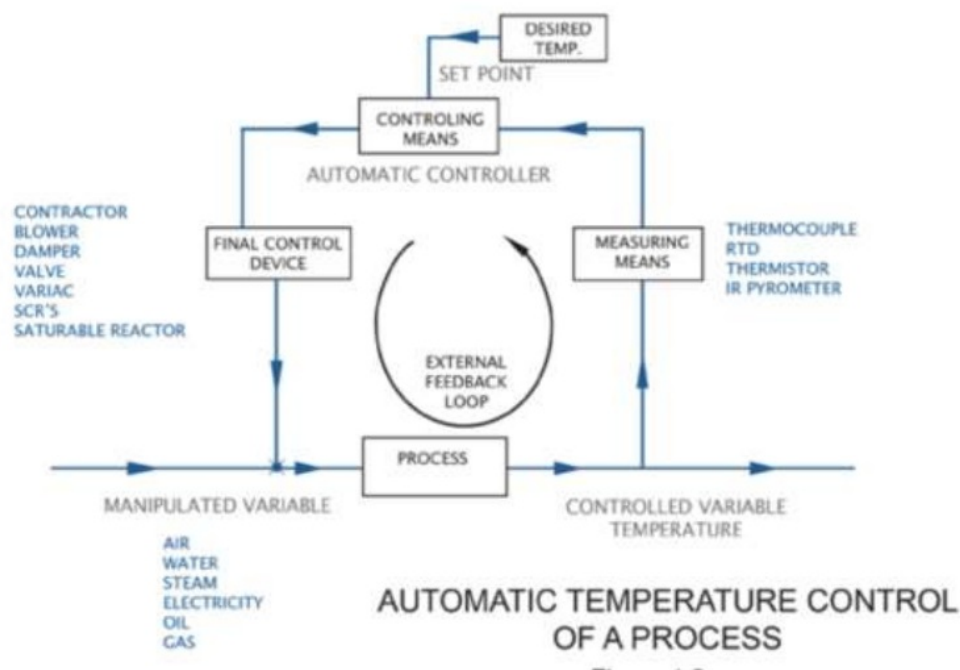


Figure 3 - Example of Temperature Control

(Garrett-Doyle, 2014)

Temperature-control systems can range from basic open-loop, application of heating or cooling regardless of the actual temperature (output), or more sophisticated closed-loop (Garrett-Doyle, 2014). Given the degree of accuracy control required for industrial processes, closed-loop systems, involving constant measurement of temperature, to adjust and maintain the SP are favored.

In such systems temperature is measured by a sensor such as a Resistive Thermal Device (RTD), thermocouple or infra-red pyrometer, converted to a signal by the transformer/transmitter, and read by the controller (Garrett-Doyle, 2014). SP comparison enables manipulation of the required variable such as air, steam, electricity, or water by the final control element to bring the temperature back to the SP. These are most commonly pneumatic operated dampers/valves, blowers, or phase-fired SCRs. In the majority, temperature-control systems are first-order i.e. a first-order equation describes the transfer function (input/output relationship), the 1st derivative with respect to time describing the system. The speed of response (duration to reach steady-state) can be defined (Electrical4u, 2021).

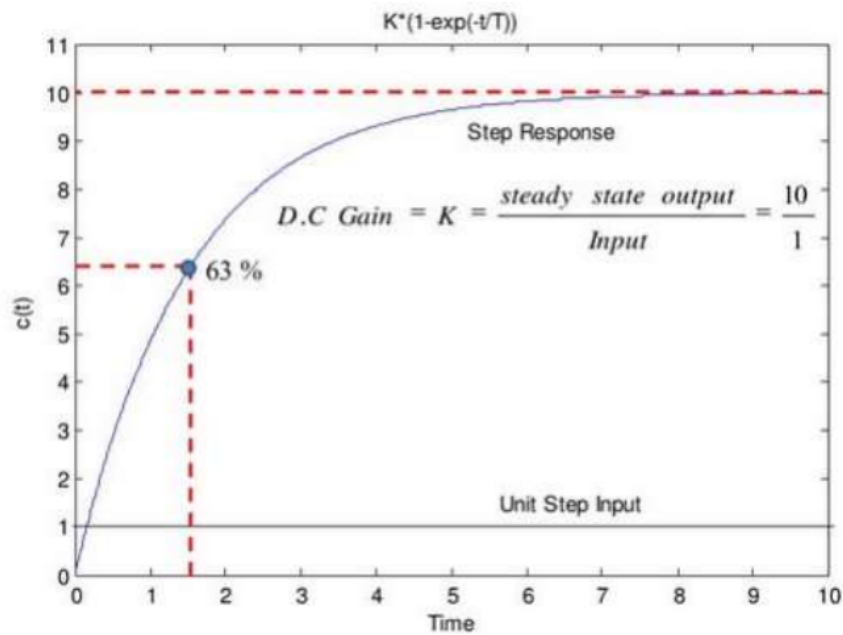
$$\frac{C(s)}{R(s)} = K \frac{1}{Ts + 1}$$

$C(s)$ = Output; $R(s)$ = Input; K = Gain; T = time response i.e. time taken to respond to a magnitude/unit step input

Equation 1 - First Order Equation

(Electrical4u, 2021)

Rise time, in the case of 1st-order usually time to progress from 10-90% of SP, can be calculated, along with settling time; time for response to attain and remain at $\pm 2\%$ SP (CMTS, 2021). An initial lag/delay may be seen (Engineering.ju, 2021).



Equation 2 - First order rise time

(Engineering.ju, 2021)

Successful control relies on knowledge of the process, level of acceptable deviation from the SP and use of an optimal, appropriately tuned controller (Garrett-Doyle, 2014).

Temperature-control systems consist of a number of common parts:

Temperature System Parameters	
Controller: Input (Sensor & signal)	Type depends on controlled process: RTD (e.g. 1000hm platinum sensor), thermocouple (e.g. J, K, S type) Can be set to accept voltage/current input signals from pressure, level or flow sensors. Often incorporate features to detect faulty sensors (sensor break detect) to prevent damage to the equipment if in fault by controller halting the process immediately.
Controller: Outputs	Can perform several functions e.g. actuate a heating/cooling source, initiate an alarm, transit PV value to controller or recorder. Commonly include relay output (e.g. single-pole double-throw relay plus DC voltage coil), Solid State Relay driver (logic output turning on/off a relay), linear analog (signal changes are a percentage of the output)
Setpoint	Operator set target value.
Alarm Value	Indicates given condition reached. High: prevent damage from heat source e.g. de-energizing of source of temperature > SP Low: dropped below SP Deviation: process varied by pre-programmed value from SP
PID parameters (if used for control)	Proportional, Integral, Derivative values

Table 10 - Temperature System Parameters

(Danaher, 2021)

2.1.5 – Level-Control Systems

Level-control systems are designed solely for the purpose of controlling fluid level within a tank (ElectronicsCoach, 2021). The aim is to achieve and maintain a desired level by controlling the rate at which a pump delivers fluid (ElectronicsCoach, 2021).

They are commonly closed-loop, formed of the following components:

Component	Descriptor
Fluid Tank	Storage vessel of sufficient size to contain the required fluid amount
Sensor	System of measurement to sense/detect the current fluid level (PV)
Controller	Maintains desired level through feedback loops to start and stop the pump
Pump (actuator)	Supplies water to the tank when signalled/triggered by the controller

Table 11 - Level Control Components

(ElectronicsCoach, 2021)

Tank size and shape, along with input and output pipe flow-rate, can largely affect the speed of change in a level control system (PAContol, 2006). A variety of sensors types can be used to provide feedback on the level within the tank (Hawker_Electronics, 2020).

Sensor type	Function
Conductivity Systems	The contact or departing of a conductive liquid from an electrode at the point of switching results in an electrical circuit (between it and earth), causing operation of a control unit switch. Simple, accurate and economical
Capacitive System	Non-conductive material requires change in capacitance as liquid contacts or departs the electrode to control the unit switch.
Hydrostatic System	Use a pressure transducer/transmitter to measure pressure. Changes are representative of depth and therefore level
Float system	Rise and fall of a magnetic float actuate control unit switches to provide information on fluid level.

Table 12 - Examples of Level Control System Sensors

(Hawker_Electronics, 2020)

Most commonly the final control element is a valve located on the inflow or outflow connection of the vessel, however it may also be control of a pump. Rate of supply can vary due to resistance, capacitance and inertia e.g. resistance to flow as fluid leaves the tank, and laminar/turbulent flow within the pipes (ElectronicsCoach, 2021).

Due to risks associated with overflow, level systems will often contain an addition, redundant, control system as a safety measure (PAContol, 2006).

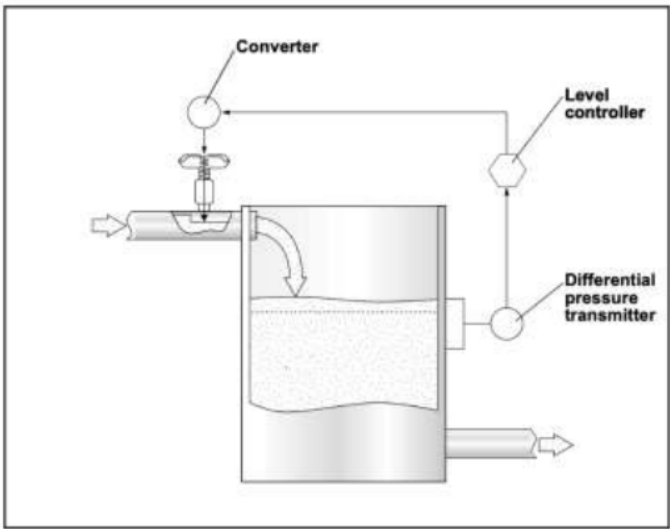


Figure 4 - Example of a Temperature Loop

(Hawker_Electronics, 2020)

An example of a level-control system operation using feedback control	
•	Level of liquid (i.e. tank height) is measured by a sensor (level transmitter) and a signal transmitted relating to the level to the controller.
•	Level reading compared to the pre-programmed SP.
•	Controller (e.g. PID) sends signal to the valve/pump at the top or bottom of the tank changing the flow rate through the valve dependent on whether fill or loss is required to maintain the level.
•	If the controller is tuned correctly, the valve change should be sufficient to change the flow rate in order to bring the height (level) in line with or close to the SP.
•	Where water in = water out it demonstrates first-order
•	Loop repeated.

Table 13 - Example of Level Control with feedback control

(ElectronicsCoach, 2021)

2.1.6 – Flow-Control Systems

Flow-control systems involve fast control loops, demonstrating rapid response to changes, and are second-order; the 2nd derivative with respect to time defining the system (Electrical4u, 2021).

$$\frac{C(s)}{R(s)} = K \frac{1}{Ts^2 + 1}$$

$C(s)$ = Output; $R(s)$ = Input; K = Gain; T = time response i.e. time taken to respond to a magnitude/unit step input

Equation 3 – Second Order Equation

(Electrical4u, 2021)

Consequently, equipment used must offer quick sampling and response times, and fluctuations and noise can be seen in the control signal, in addition to oscillations resulting from inertia. Many transmitters must therefore include a dampening function, such as a filter to reduce oscillation frequency and improve system response (PAControl, 2006). Assessing whether the system (response curve) is under-damped or over-damped will enable optimal tuning of PID parameters to achieve a critically-damped system (Electrical4u, 2021).

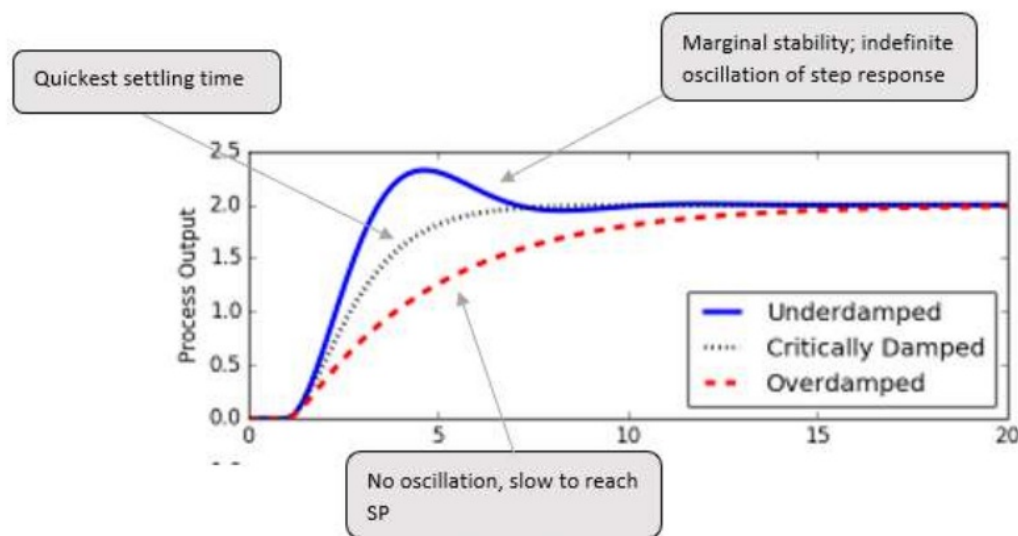


Figure 5 - Process curve illustration

(Apmonitor, 2021)

Most systems incorporate a flow sensor, transmitter, controller and valve/pump; however, some also include a sensor for temperature measurement due its effects on density, allowing it to be accounted for in control calculations (PAContol, 2006). Flow control systems are often found in plants housing a number of control loops involving process variables such as temperature, level and flow. The control process is such that valves open/close to achieve a desired maximum level (Corrosionpedia, 2014).

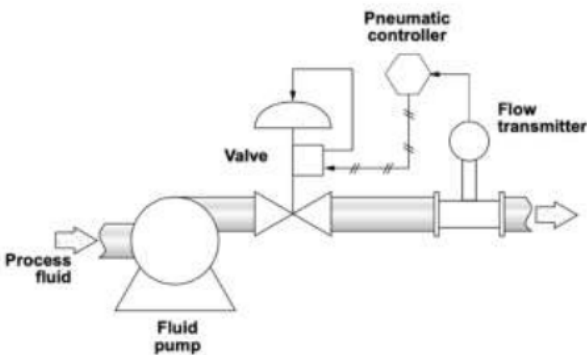


Figure 6 - Example of a Flow Loop
(Anome_et_al, 2018)

Most commonly automatic control valves are located in hydraulic actuators which respond to changes in pressure and flow.

An example of a flow-control system
• Increase in flow closes the valve; decrease opens the valve (feedback system)
• Valves can be opened/closed using air/fluid pressure therefore no external power is needed.
• Flow is usually measured upstream as not to affect the flowmeter calibration.
• Measurement position relative to adjustment not usually critical as flow should be equal on either side of the valve.

Table 14 - Flow-control system example

(Corrosionpedia, 2014) Correctly cited

In all three systems, process control is typically achieved using a closed-loop feedback system incorporating a PID controller, however not all necessarily require all three algorithms to provide control: simple proportional control often sufficient if the process is not affected by a minor offset; PI where noise and prolonged ‘dead time’ is acceptable; PID in systems where there can be no offset, no noise and limited dead-time (PAContol, 2006). Correctly cited

Variable	Proportional Control	Proportional-Integral Control	Proportional-Integral-Derivative Control
Temperature	Yes	Yes	Yes
Level	Yes	Yes	Yes but infrequently used
Flow	Yes	Yes	Yes but rarely used

Table 15 - Example of uses of P, PI, PID control suitability in Temperature, Level and Flow Control Systems

(PAContol, 2006)

In order to provide process control, engineers must have a good level of knowledge and understanding over the system being controlled, sensor and measurement positioning, and the error that can be, or is produced, especially where tuning of PID controller variables is required. Understanding of the relationship between control signal and output is essential to enable tuning of the variables to meet a system's design specification (Christiansen D, 2005). inclusion of indicators and recorders provides engineers with the ability to monitor control systems during operation and review data for trend analysis, such that comparison of the process overtime can be made to establish where changes/controller tuning may be required for improvement (PAContol, 2006).

Correctly cited

2.2 - System Investigation

The CIM system P&ID diagram (appendix 9.5) shows the entire CIM system. Flow, level, and temperature control loops investigated, shown in appendix 9.5, form part of the overall process system. The flow control loop is a closed-loop second-order system, consisting of FT535-flow transmitter, FC535-flow controller and LY541-pump/amplifier. Level control is a first-order open-loop system, consisting of LT541-Level Transmitter, LC541-Level Controller, LY541-Pump/Amplifier and V500-Drain solenoid valve. The temperature control loop is a first-order closed-loop system, consisting of LS542 and TC511 Temperature controllers, TT511-Temperature Transmitter, V515 and V516 solenoid valves, LY541-Pump/Amplifier, SSR and heating element.

Control loops were designed to operate individually for tuning and alterations, or combined in a cascading manner. A level transmitter reads the level in process tank B1. When the SP is set or reached, the transmitter sends a signal to the level controller that controls the pump/amplifier and drain valve. Using the CV from the level loop, the flow transmitter transmits an inline flow measurement back to the flow controller to control pump/amplifier speed, altering flow rate to process tank B1. From feedback of the temperature transmitter to temperature controller, the controller automatically makes adjustments depending on the temperature in process tank B1, activating the heating element and cooling fans automatically, to maintain the set temperature.

3 - Flow Control System

From the plant data (appendix 9.5), the flow process reaction curve was obtained (appendix 9.2). Below, a simulated open-loop process reaction curve was obtained, displaying a final value of 96.47. From equations in appendix 9.2, t_y , t_x , τ_1 , and τ_2 values were calculated, from which the transfer function was then derived. Using extracted plant data in combination with the Caldwell method, based on a 2nd-order system being the product of two 1st-order systems in series with their respective time constants, a model was created for data comparison.

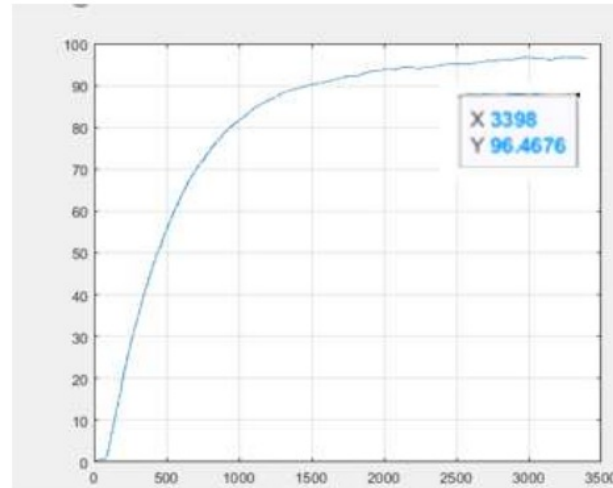


Figure 7 - Process Reaction Curve

$$G(S) = \frac{23.42}{s^2 + 12.60s + 23.42}$$

Equation 4 - Flow Control Transfer Function

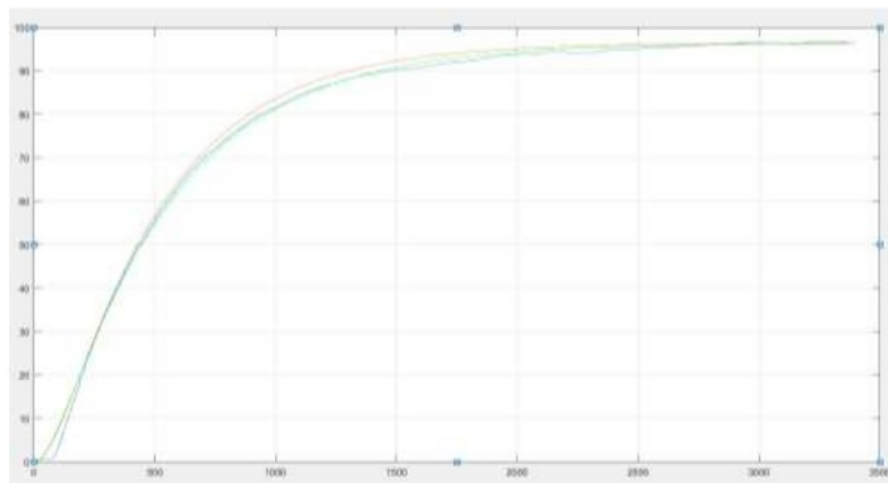


Figure 8 - Transfer Function Response

Above, the blue line demonstrates the process reaction curve, the red showing calculated transfer function response. As there is some deviation on the process and calculated responses reaction curve, alterations were made to calculated transfer function values to achieve a better match for the response. Altered transfer function values, indicated by the green line, are a better match for the process reaction curve produced by the plant (see appendix 9.2 for Matlab images).

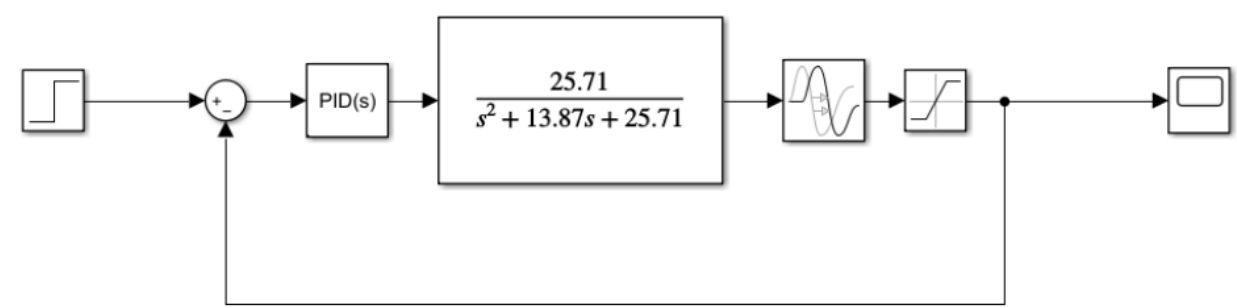


Figure 9 - Flow Simulink Model

Above, the Simulink model was created for flow control, with adjusted values inputted to the transfer function for simulation. Shown below, autotune was used to find the most appropriate response. The block response demonstrates the reaction curve of calculated Kp, Ki and Kd, while the solid line represents tuned response i.e. altered values of Kp, Ki and Kd. Although unable to confirm without the calculation of gain, there are indications of an under-damped system in the step plot, when compared to figure 5 in section 2.1.6, especially in the block response curve.

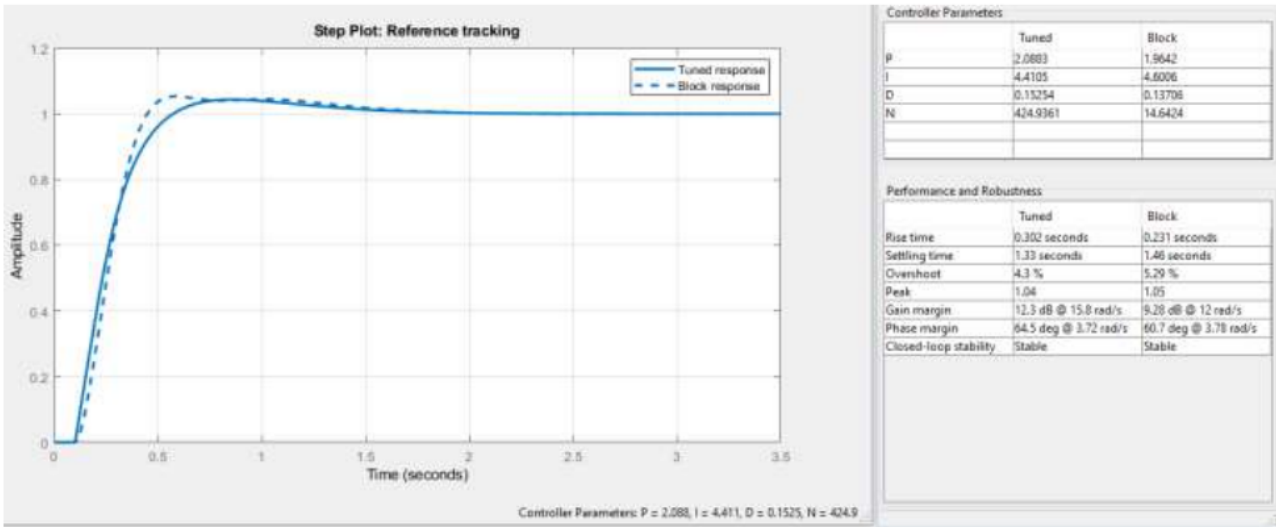


Figure 10 - Flow Simulink Autotune

Flow Tuning				
	Block Values	Tuned Values	Alterations	Inputted Values
Kp	1.9642	2.088	None	2.0883
Ki	4.6006	4.4105	Divide by 1000	0.000441
Kd	0.1371	0.1525	Multiply by 1000	152.5

Table 16 - Flow Block & Tuned Kp, Ki, Kd Values

Above are block and tuned values obtained from Simulink autotune. To demonstrate process station response, tuned Kp, Ki and Kd values were inputted, however the response was still not satisfactory; a large error evident (see appendix 9.2) This could be a result of the process station pump not being linear, however, Kp, Ki and Kd values were altered further to try and minimize the error and improve response.

Adjusted Flow Tuning				
	Tuned Values	Altered Values	Alterations	Inputted Values
Kp	2.088	0.900	None	0.900
Ki	4.4105	1	Divide by 1000	0.001
Kd	0.1525	137	Multiply by 1000	137,000

Table 17 - Flow Tuned & Altered Kp, Kd Values

Adjusted values of Kp, Ki and Kd were inputted into the process station and tested on the process rig until an appropriate response and minimum error value were obtained (appendix 9.2 for images). The response demonstrated below, shows a reduction in error between the SP (blue) and PV (red) to 0.07, a more acceptable response, resulting in a more accurate and efficient process station.

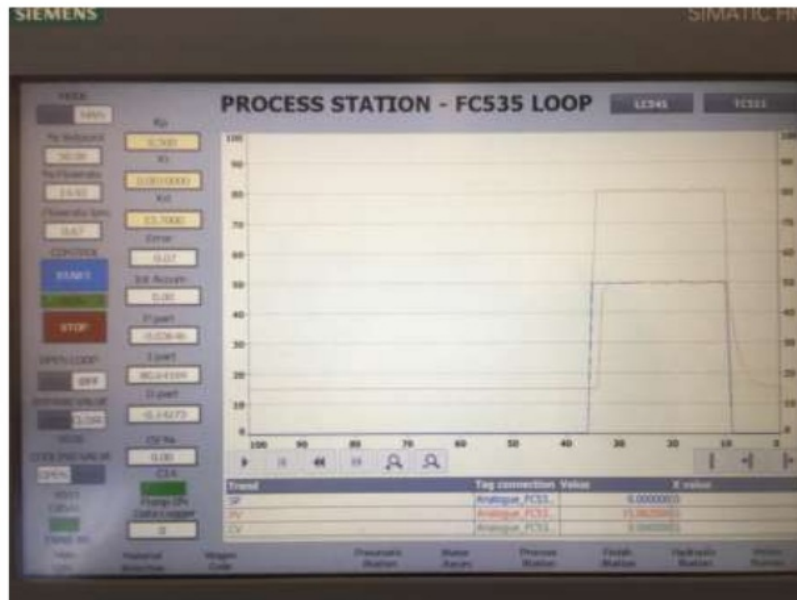


Figure 11 - Altered Kp, Ki & Kd Value Response

4 - Level Control System

From the process station, a level control reaction curve was produced. From the values obtained a gradient was calculated (appendix 9.3), and an open-loop transfer function developed. Illustrated below, the transfer function block was added to the developed Simulink model with an additional PD control.

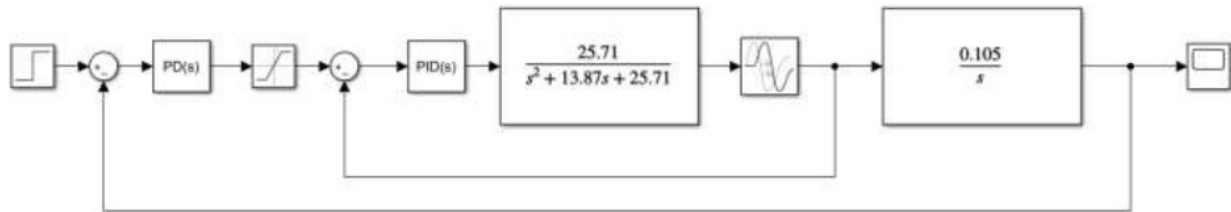


Figure 12 - Level Simulink Model

Autotune was used to find the most appropriate reaction curve for the model. The block response demonstrates the reaction curve of calculated Kp, Ki and Kd, while the solid line represents tuned response i.e. altered values of Kp, Ki and Kd

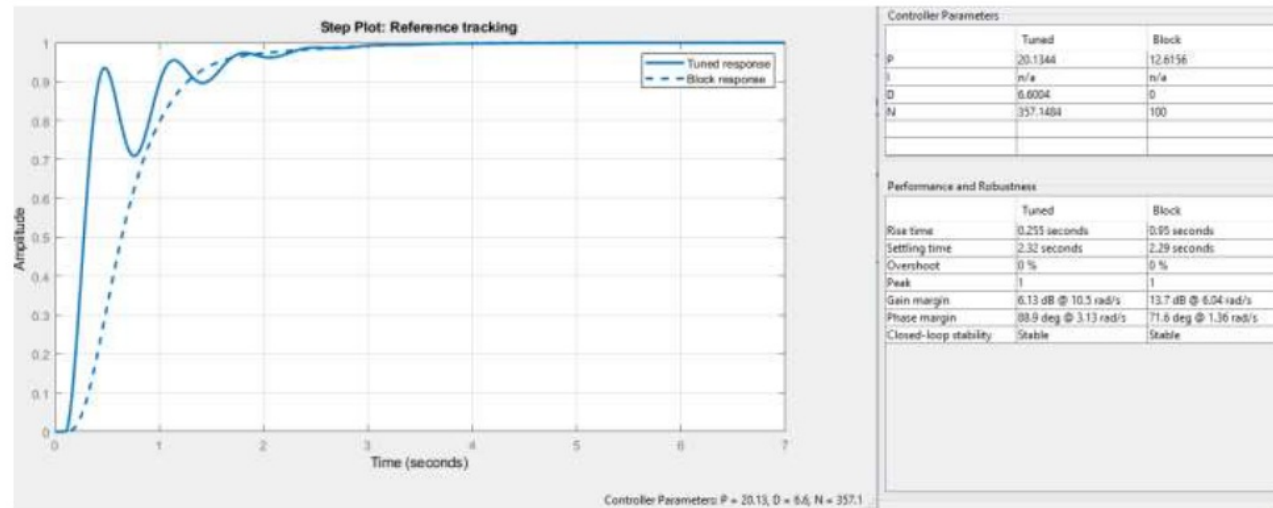


Figure 13 - Level Simulink Autotune

Level Tuning				
	Block Values	Tuned Values	Alterations	Inputted Values
Kp	12.6156	20.1344	None	12.62
Ki	N/A	N/A	N/A	0
Kd	0	0.066	Multiply by 1000	6.6

Table 18 - Level Block & Tuned Kp, Kd Values

Above are the block and tuned values. With tuned Kp and Kd values inputted, the process station response was not satisfactory; a large error seen (see appendix 9.3). Kp and Kd were altered further to try and minimize the error and improve response.

Adjusted Level Tuning				
	Auto Tuned Values	Altered Values	Alterations	Inputted Values
Kp	20.1344	100	None	100
Ki	N/A	N/A	N/A	0
Kd	6.6004	0.01	Multiply by 1000	10

Table 19 - Level Tuned & Altered Kp, Kd Values

Various Kp and Kd adjusted values were inputted into the process station and tested on the process rig until an appropriate response and minimum error value were obtained (appendix 9.3 for images). The response, demonstrated below, shows a more accurate and efficient process station with final inputted values, the error between the SP (blue) and PV (red) greatly reduced to 0.14.

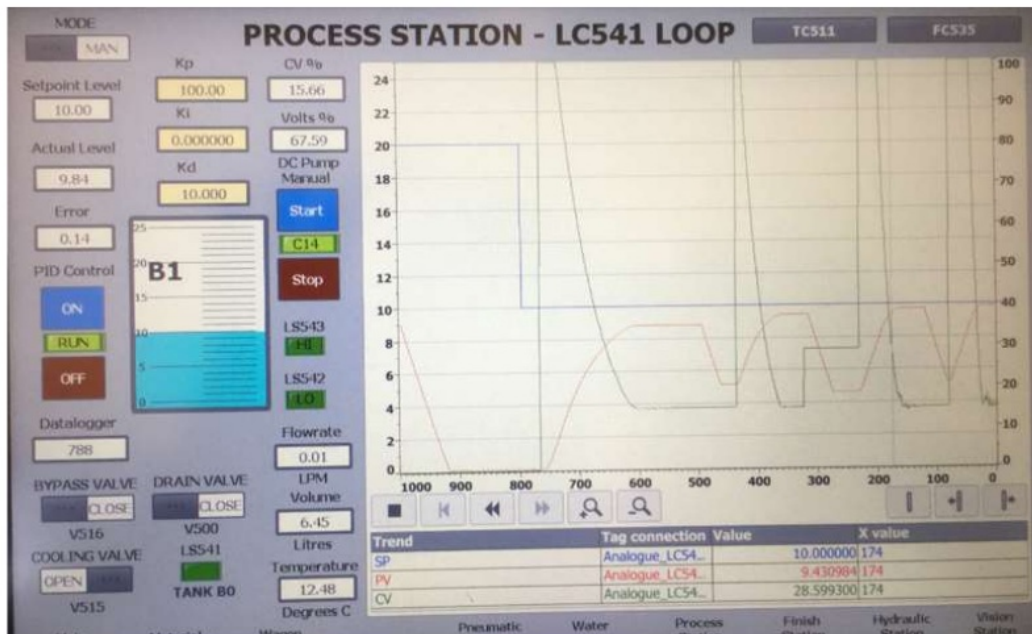


Figure 14 - Level Altered Kp & Kd Value Response

5 - Temperature Control System

For temperature control, the process tank was filled with water to 10cm, a SP of 50°C selected, and heating element turned on to full power. A process reaction curve was produced and a gradient calculated using the values obtained (see appendix 9.4). Illustrated below, a Simulink model was created.

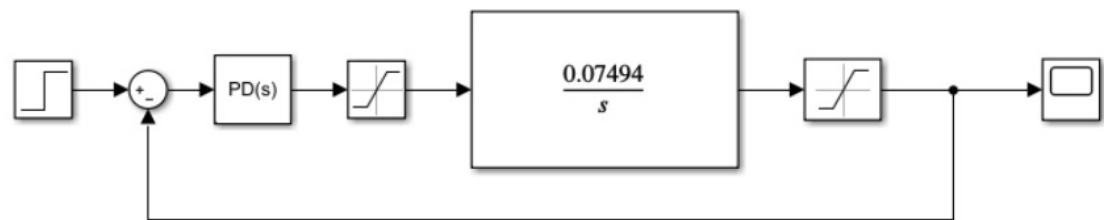


Figure 15 - Temperature Simulink Model

Autotune was used to find the most appropriate reaction curve for the model. The block response (dashed line) demonstrates the reaction curve of calculated values of Kp and Kd, whilst the solid line demonstrates tuned response with altered values of Kp.

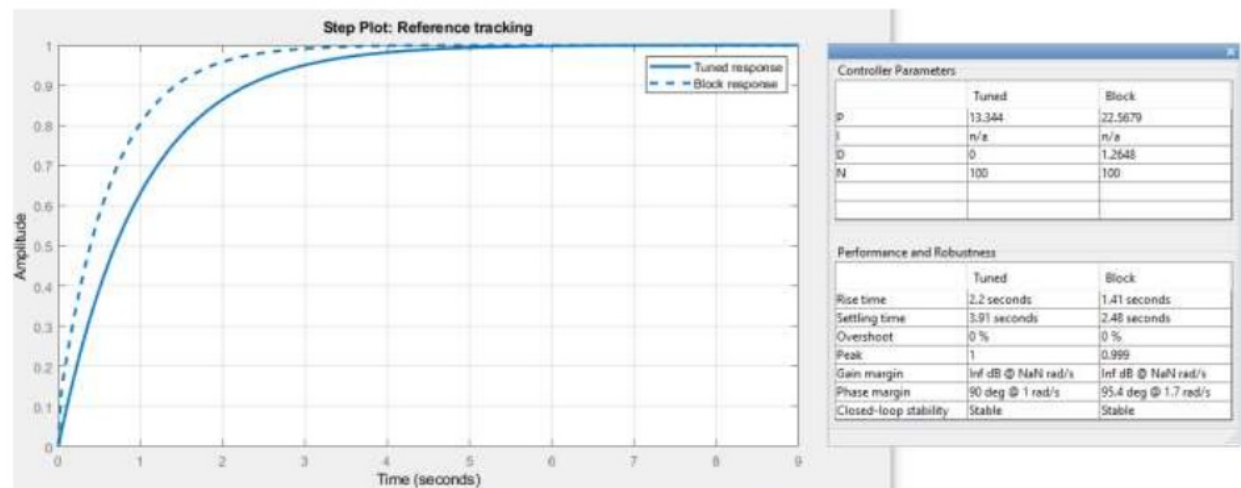


Figure 16 - Temperature Simulink Autotune

Temperature Tuning				
	Block Values	Tuned Values	Alterations	Inputted Values
Kp	22.5679	13.344	None	13.344
Ki	N/A	N/A	N/A	0
Kd	1.2648	N/A	N/A	0

Table 20 - Temperature Block & Tuned Kp, Kd Values

Above are the block and tuned values obtained from Simulink autotune. To demonstrate process station response, the tuned value of Kp was inputted, however the response was not satisfactory; a large error seen. Kp was further amended to 50, however although the error was acceptable, a degree of overshoot was present (see appendix 9.4).

Adjusted Temperature Tuning				
	Auto Tuned Values	Altered Values	Alterations	Inputted Values
Kp	13.344	35	None	35
Ki	N/A	N/A	N/A	0
Kd	0	N/A	N/A	0

Table 21 - Temperature Tuned & Altered Kp, Kd Values

A final applied value of Kp, shown in the table above, was inputted to the process station. Illustrated below, a slight, much reduced, degree of overshoot was seen with a satisfactory error value between SP and measured temperature maintained. The low CV percentage value once the SP, or steady-state, has been achieved demonstrates minimal output of heating element was required to maintain the temperature of the process station.

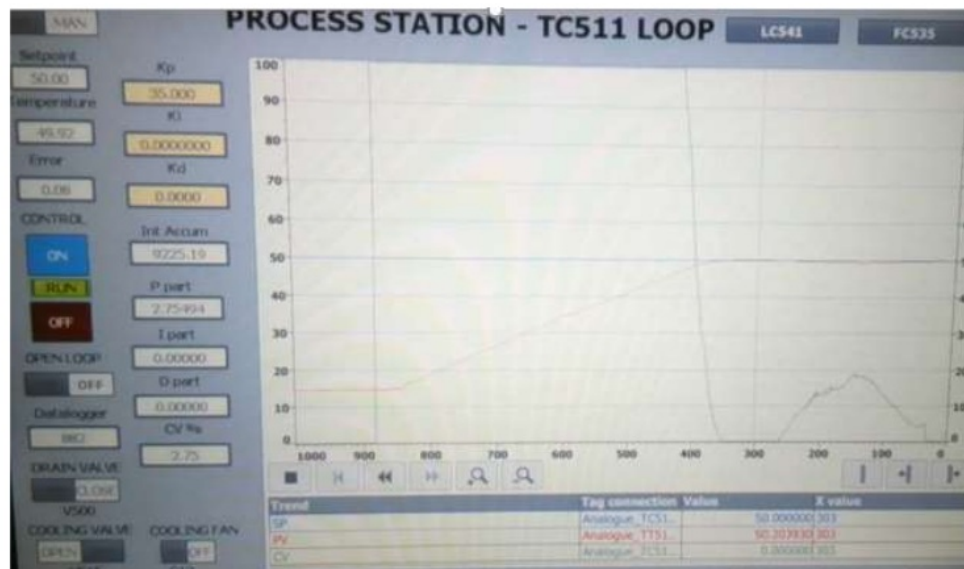


Figure 17 - Temperature Altered Kp Value Response

6 - Conclusions and Recommendations

Control systems used in industry require control to produce a safe, efficient and quality process or product. Many plants utilise flow, level and temperature control systems which may operate independently or in a cascade, typically exhibiting 2nd-order (flow) or 1st-order (level, temperature) control. The inclusion of an effective controller, often in the form of a PID controller, is key to achieving process control, however unless these are appropriately tuned to the individual system, effective control with regard to minimising gain, reducing error and producing optimal response cannot be met.

This established theory was supported by the findings obtained during the project, Simulink used to successfully simulate each control system using calculated values, these initial values demonstrating significant error and poor response curves. Tuning of the PID parameters, K_p, K_i and K_d as appropriate however, demonstrated a significant improvement in response, with a reduction in error and in the case of temperature, overshoot of the SP.

That said, the final process station response for each of the control systems was not optimal, time spent further tuning the values of K_p, K_i and K_d would have offered significant benefit, and with further calculations assessed whether critical damping was achieved in the flow control system. In addition, in order to generate an optimal flow control system, incorporation of a linear pump to reduce error and product the expected 2nd-order kinetics throughout the response curve.

Good point made about the pump. Tuning is not just about damping as the addition of PID control increases the order from 2 to three and adds zeros also giving a better response than critical damping

7 - Team Working

For the practical applications, team working was required, however, given the current global situation, safety measures had to be taken. Appropriate PPE was worn as well as social distancing maintained in line with current government guidelines.

As group working was limited, we would often find ourselves concentrating on specific tasks, each then repeated by different group members. The gathered information was shared and discussed on a dedicated social network group, allowing for safe and effective ways to maintain contact in the current climate.

8 - Reference List

Correct method of
finding

Wide Range of
Control

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9 - Appendix

9.1 - CIM System

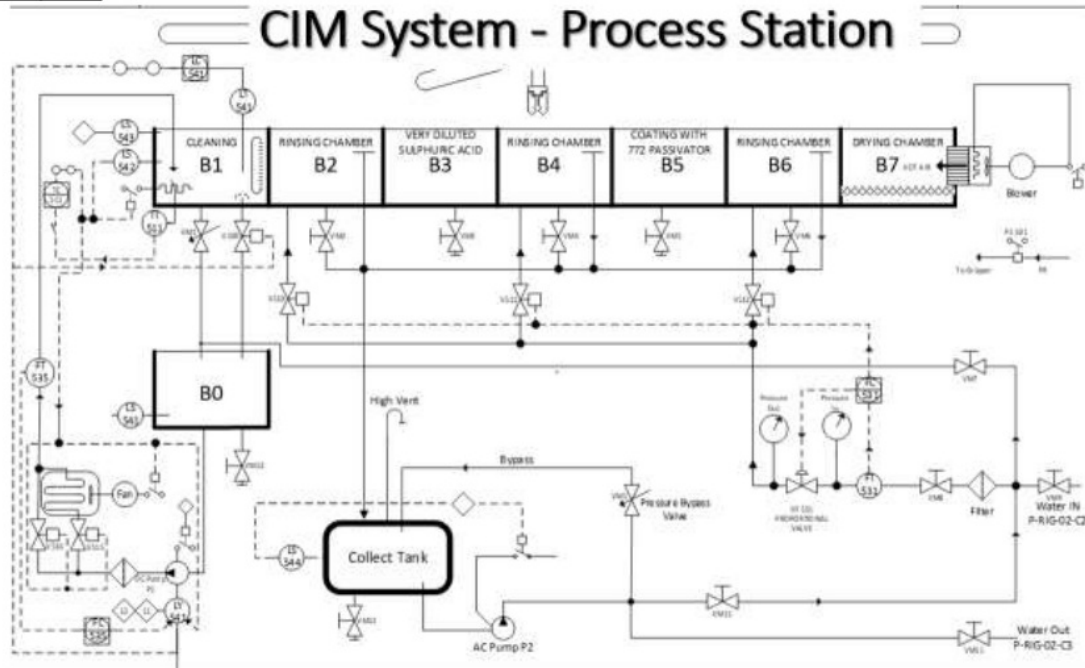


Figure 18 - CIM System P&ID Diagram

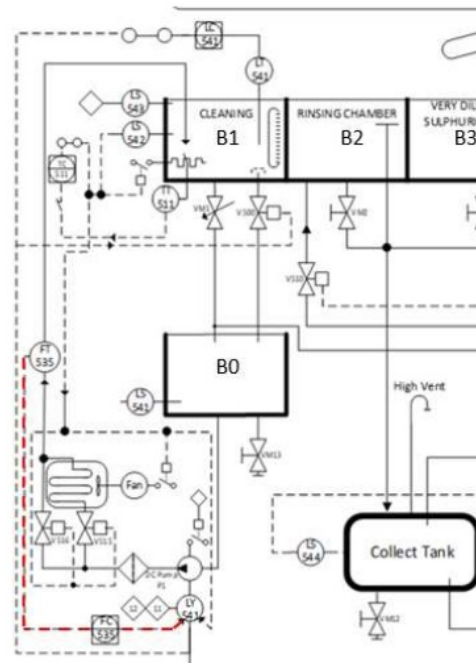


Figure 19 - Flow Control Loop

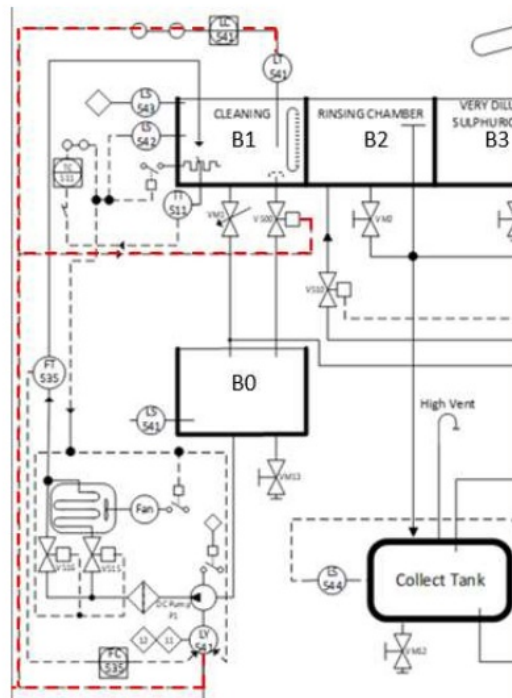


Figure 20 - Level Control Loop

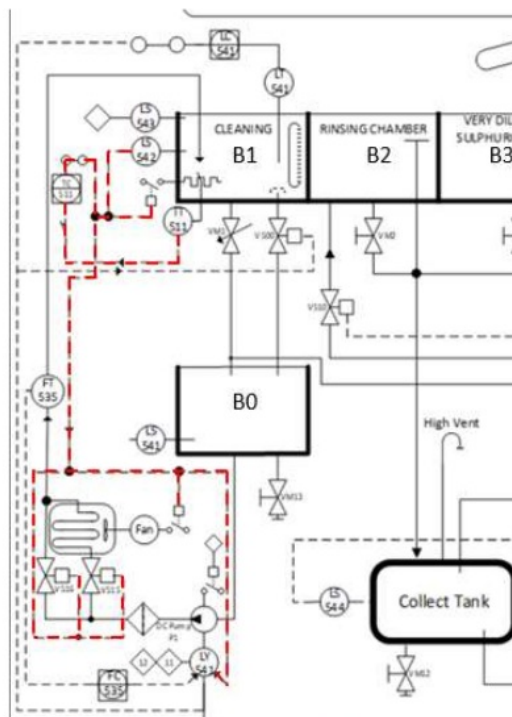


Figure 21 - Temperature Control Loop

9.2 - Flow Control System

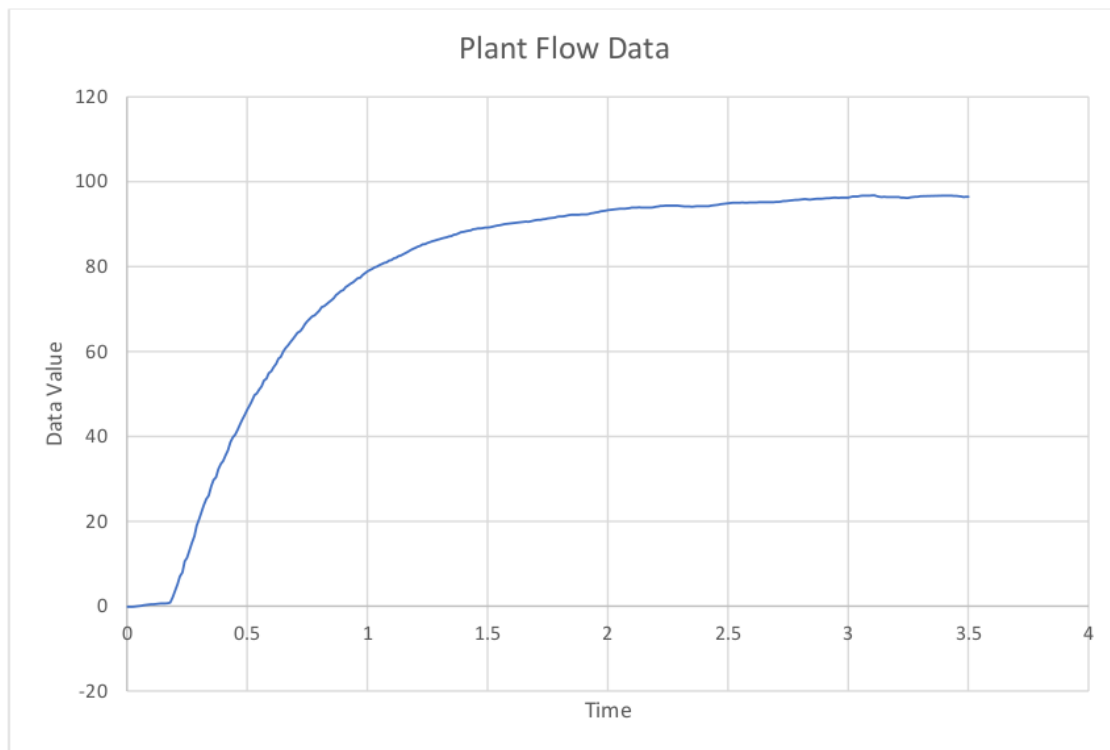


Figure 22 - Extracted Process Reaction Curve

$$ty = \left(\frac{96.46}{100}\right) \times 73 = 70.416 \text{ or } ty = 0.710 \text{ seconds}$$

Equation 5 - ty Value Calculation

$$r1 + r2 = \frac{ty}{1.32} = \frac{0.710}{1.32} = 0.5378$$

Equation 6 - r1+r2 Value Calculation

$$tx = \frac{r1 + r2}{2} = \frac{0.5378}{2} = 0.2689$$

Equation 7 - tx Value Calculation

$$x = \frac{30.377}{96.46} = 0.3149$$

Equation 8 - x Value Calculation

(30.377 value is taken from the Matlab)

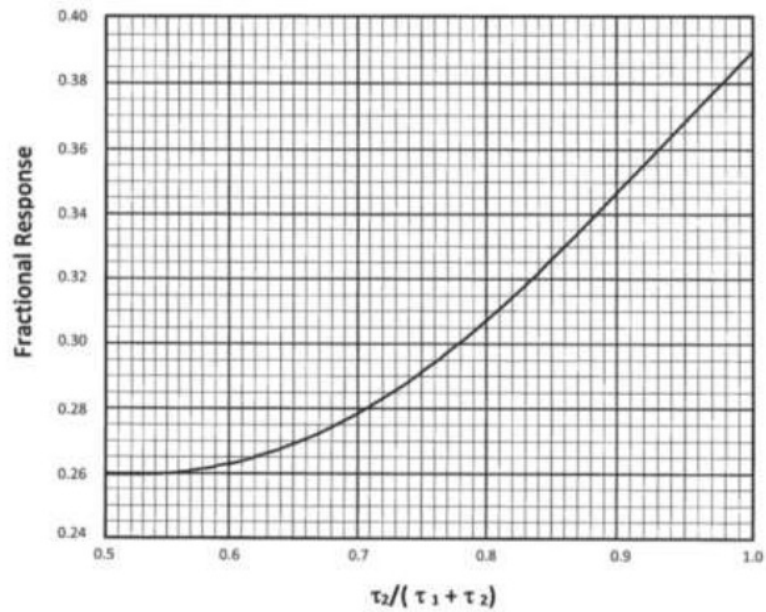


Figure 23 - Caldwell Graph

From the Caldwell graph at the value of 0.32. (x Value)

$$\frac{\tau_2}{\tau_1 + \tau_2} = 0.82$$

Equation 9 - Value from Caldwell graph

$$\tau_2 = 0.82 \times (\tau_1 + \tau_2) = 0.82 \times 0.5378 = 0.441$$

Equation 10 - τ_2 Value Calculation

$$\tau_1 = (\tau_1 + \tau_2) - \tau_2 = 0.5378 - 0.441 = 0.0968$$

Equation 11 - τ_1 Value Calculation

$$G(s) = \frac{\frac{1}{\tau_1 \tau_2}}{s^2 + \left(\frac{\tau_1 + \tau_2}{\tau_1 \tau_2}\right)s + \frac{1}{\tau_1 \tau_2}}$$

Equation 12 - Level Control Transfer Function

$$\frac{1}{\tau_1 \tau_2} = \frac{1}{0.0968 \times 0.441} = 23.42$$

Equation 13 - $1/(\tau_1 \tau_2)$ Value

$$\left(\frac{\tau_1 + \tau_2}{\tau_1 \tau_2}\right) = 0.5378 \times 23.42 = 12.60$$

Equation 14 - $(\tau_1 + \tau_2)/(\tau_1 \tau_2)$ Value

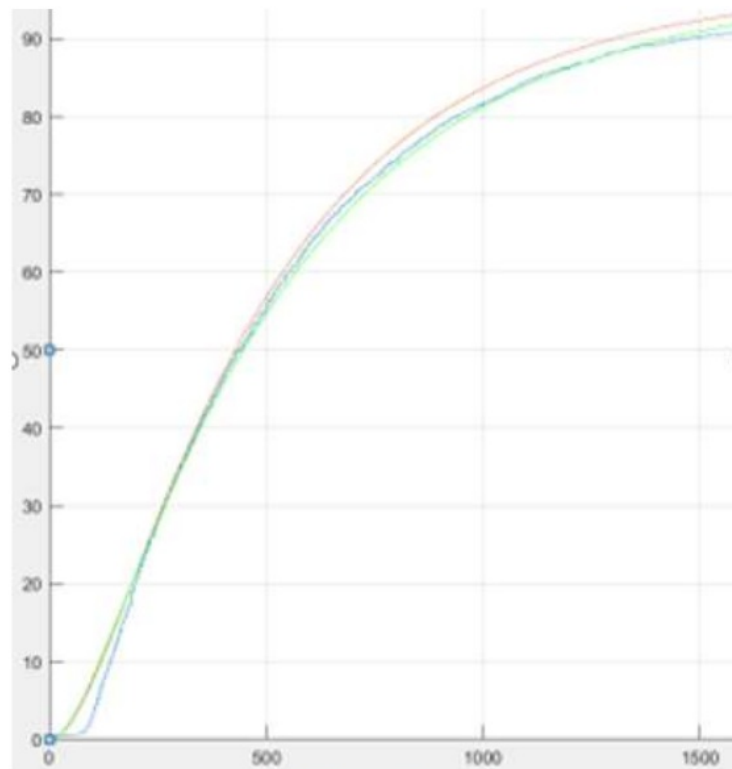


Figure 24 - Process Reaction Curve

```

LAB R2020b - academic use
PLOTS APPS EDITOR PUBLISH VIEW
Open Save Compare Go To Comment Insert Breakpoints Run Run and Advance
Print Find Indent EDIT BREAKPOINTS
C:\Users\iam_ Downloads
Editor - C:\Users\iam_ Downloads\Flow_Matlab_Model.m
Flow_Matlab_Model.m
1 - clf
2 - % Blue Line Shows Plant Process Reaction Curve
3 - load Flow_Process_Reaction_Curve_a.csv;
4 - sample_time = Flow_Process_Reaction_Curve_a(:,1); %column 1
5 - flow_rate = Flow_Process_Reaction_Curve_a(:,2); %column 2
6 - plot(flow_rate);
7 - hold on;
8 - grid on;
9 - t=(0:0.001:3.399);
10 - % Red Line shows Calculated Data
11 - num1=[23.42];
12 - den1=[1 12.60 23.42];
13 - model_1 = step(96.46*num1,den1,t);
14 - plot(model_1);
15 - % Green Line shows Adjusted data for closer reaction curve
16 - num2=[25.8];
17 - den2=[1 14.8 25.8];
18 - model_2 = step(96.46*num2,den2,t); %Green line
19 - plot(model_2);

```

Figure 25 - Matlab Script for Process Reaction Curve

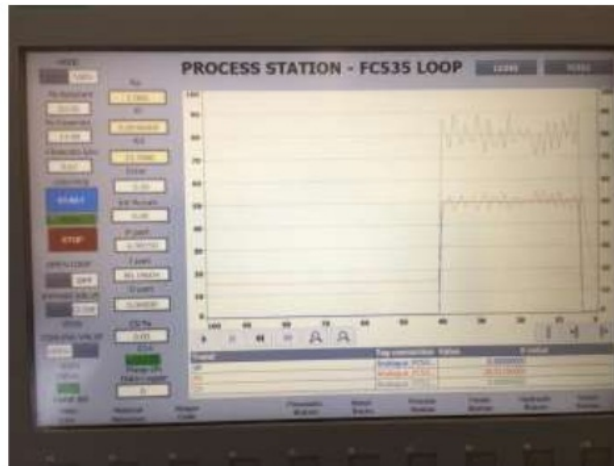


Figure 26 - Process Station Using Flow Block Values



Figure 27 - Process Station Using Flow Tuned Values

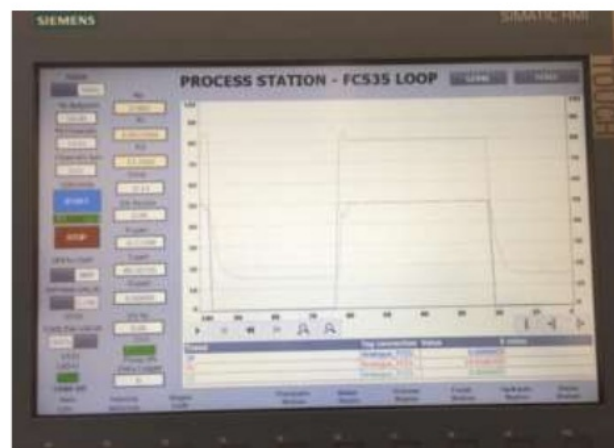


Figure 28 - Process Station Using Altered Flow Tuned Values

9.3 - Level Control System

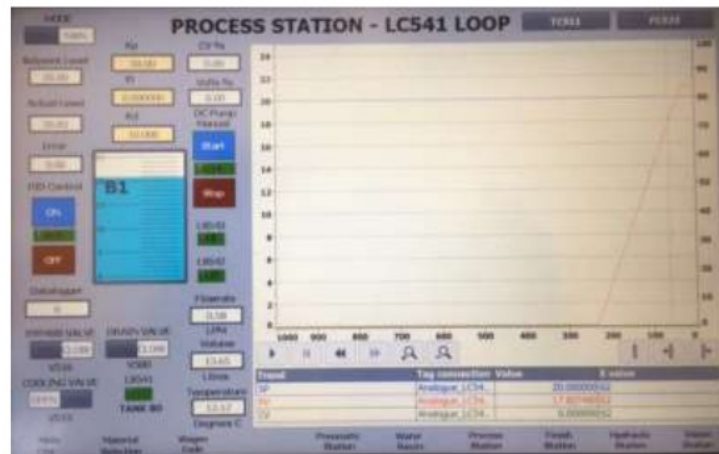


Figure 29 - Process Station Level Reaction Curve

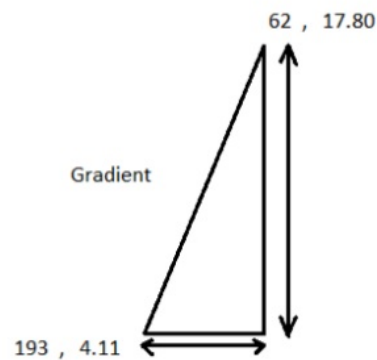


Figure 30 - Gradient from Process Station

$$17.8 - 4.11 = 13.69$$

$$193 - 62 = 131$$

Equation 15 - Level Gradient

$$\text{Gradient} = \frac{13.69}{131} = 0.105$$

Equation 16 - Level Gradient Value

$$tf = \frac{\text{gradient}}{s} = \frac{0.105}{s}$$

Equation 17 - Level Transfer Function

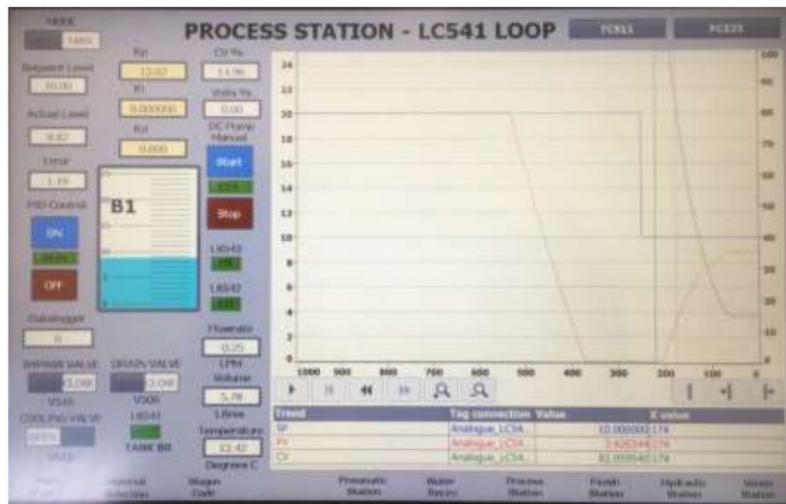


Figure 31 - Process Station Using Level Block Values

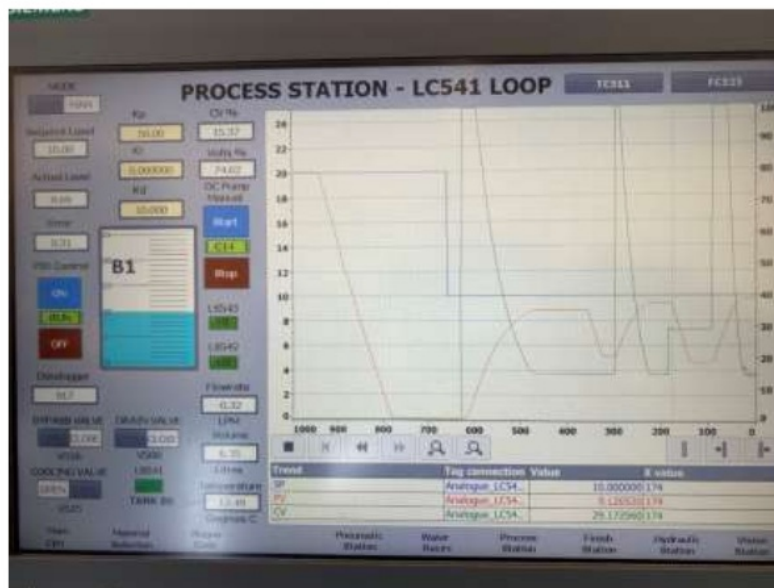


Figure 32 - Process Station Using Level Tuned Values

9.4 - Temperature Control System

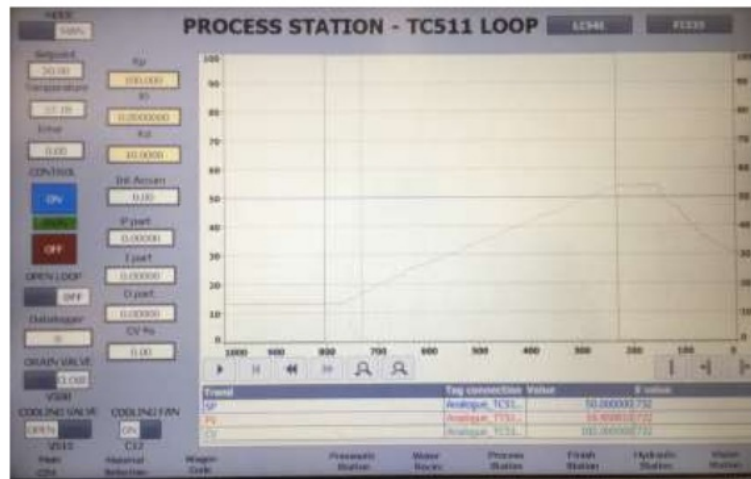


Figure 33 - Process Station Temperature Reaction Curve

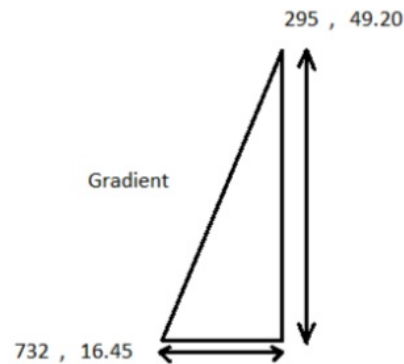


Figure 34 - Gradient from Process Station

$$49.20 - 16.45 = 32.75$$

$$732 - 295 = 437$$

Equation 18 - Temperature Gradient

$$\text{Gradient} = \frac{32.75}{437} = 0.07494$$

Equation 19 - Temperature Gradient Value

$$tf = \frac{\text{gradient}}{s} = \frac{0.07494}{s}$$

Equation 20 - Temperature Transfer Function

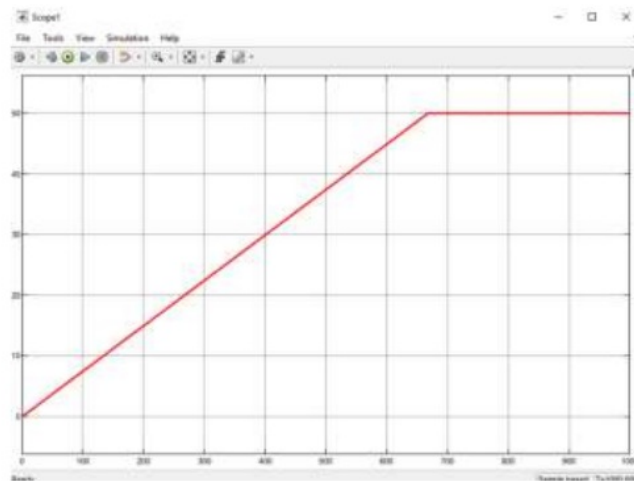


Figure 35 - Temperature Gradient from Simulink Model

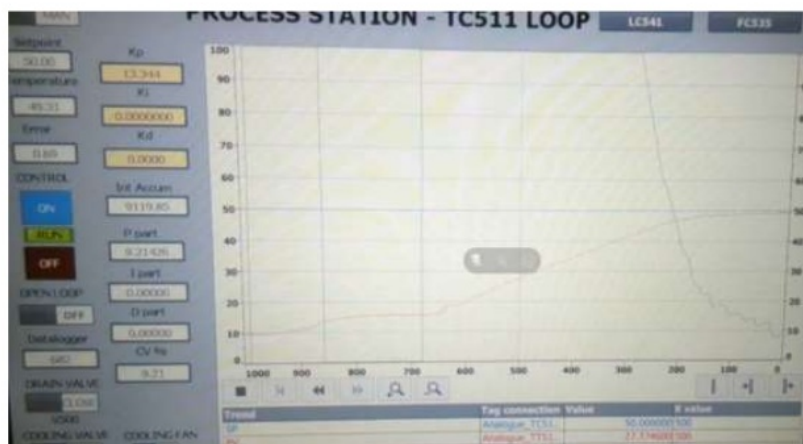


Figure 36 - Process Station Using Temperature Tuned Kp Value



Figure 37 - Process Station Using Temperature Altered Kp Value

9.5 - Extracted Plant Data

Plant Data																	
Time	Value	Time	Value	Time	Value	Time	Value	Time	Value	Time	Value	Time	Value	Time	Value	Time	Value
0	-0.1499996	0.4	34.225	0.8	69.58039	1.2	84.43333	1.6	90.2299	2	93.29362	2.4	94.26176	2.8	95.79362	3.2	96.39412
0.01	-0.1499996	0.41	35.51176	0.81	70.45049	1.21	84.69068	1.61	90.27892	2.01	93.37941	2.41	94.24951	2.81	95.8549	3.21	96.36961
0.02	-0.1499996	0.42	36.77402	0.82	70.68333	1.22	84.89902	1.62	90.36471	2.02	93.47745	2.42	94.27402	2.82	95.91618	3.22	96.28382
0.03	-0.1132355	0.43	38.56323	0.83	71.13676	1.23	85.24216	1.63	90.45049	2.03	93.52647	2.43	94.3598	2.83	95.86716	3.23	96.2348
0.04	-0.01519585	0.44	39.81323	0.84	71.59019	1.24	85.35245	1.64	90.49951	2.04	93.57549	2.44	94.48235	2.84	95.79362	3.24	96.18578
0.05	0.0215683	0.45	40.40147	0.85	72.08039	1.25	85.57304	1.65	90.53627	2.05	93.62451	2.45	94.54362	2.85	95.87941	3.25	96.18578
0.06	0.1073532	0.46	41.61471	0.86	72.58284	1.26	85.78137	1.66	90.59755	2.06	93.66127	2.46	94.59264	2.86	95.90392	3.26	96.32059
0.07	0.2176476	0.47	42.79118	0.87	73.28137	1.27	85.97745	1.67	90.58529	2.07	93.64902	2.47	94.69068	2.87	95.96519	3.27	96.40637
0.08	0.3034325	0.48	43.95539	0.88	73.7348	1.28	86.14902	1.68	90.68333	2.08	93.68578	2.48	94.81323	2.88	95.98971	3.28	96.44314
0.09	0.3401966	0.49	45.0951	0.89	74.23725	1.29	86.30833	1.69	90.8549	2.09	93.78382	2.49	94.88676	2.89	96.01421	3.29	96.49216
0.1	0.4014702	0.5	46.2348	0.9	74.50686	1.3	86.49216	1.7	90.95294	2.1	93.88186	2.5	94.91127	2.9	96.06323	3.3	96.57794
0.11	0.450491	0.51	47.33775	0.91	75.19314	1.31	86.66373	1.71	91.01421	2.11	93.91862	2.51	94.97255	2.91	96.11225	3.4	96.725
0.12	0.5240192	0.52	48.37941	0.92	75.59755	1.32	86.79853	1.72	91.03873	2.12	93.94314	2.52	95.03382	2.92	96.16127	3.41	96.73725
0.13	0.57304	0.53	49.71519	0.93	75.95294	1.33	86.90882	1.73	91.17353	2.13	93.9799	2.53	95.04607	2.93	96.22255	3.42	96.74951
0.14	0.6098042	0.54	50.13186	0.94	76.34509	1.34	87.11716	1.74	91.24706	2.14	93.94314	2.54	95.05833	2.94	96.28382	3.43	96.725
0.15	0.6343136	0.55	50.98971	0.95	76.79853	1.35	87.22745	1.75	91.34509	2.15	93.90637	2.55	95.08284	2.95	96.27157	3.44	96.67598
0.16	0.6343136	0.56	51.83529	0.96	77.22745	1.36	87.50932	1.76	91.43088	2.16	93.88186	2.56	95.10735	2.96	96.22255	3.45	96.67598
0.17	0.6955891	0.57	53.17107	0.97	77.42353	1.37	87.58284	1.77	91.4799	2.17	93.88186	2.57	95.04607	2.97	96.24706	3.46	96.62696
0.18	0.8303928	0.58	53.58775	0.98	77.98725	1.38	87.88921	1.78	91.59019	2.18	93.94314	2.58	95.04607	2.98	96.25932	3.47	96.56568
0.19	2.092648	0.59	54.91127	0.99	78.44068	1.39	88.1098	1.79	91.74951	2.19	93.99216	2.59	95.11961	2.99	96.24706	3.48	96.40637
0.2	3.563236	0.6	55.38921	1	78.84509	1.4	88.19559	1.8	91.83529	2.2	94.10245	2.6	95.14412	3	96.28382	3.49	96.45539
0.21	5.205393	0.61	56.28382	1.01	79.17598	1.41	88.33039	1.81	91.83529	2.21	94.21275	2.61	95.13186	3.01	96.36961	3.5	96.46764
0.22	6.994608	0.62	57.14166	1.02	79.48235	1.42	88.45294	1.82	91.89657	2.22	94.31078	2.62	95.15637	3.02	96.50441		
0.23	7.938236	0.63	58.33039	1.03	79.83775	1.43	88.55098	1.83	92.05588	2.23	94.34755	2.63	95.21764	3.03	96.50441		
0.24	10.57304	0.64	58.74706	1.04	79.99706	1.44	88.78382	1.84	92.17843	2.24	94.37206	2.64	95.20539	3.04	96.55343		
0.25	11.40637	0.65	60.00932	1.05	80.32794	1.45	88.90637	1.85	92.21519	2.25	94.37206	2.65	95.16862	3.05	96.67598		
0.26	13.15882	0.66	60.83039	1.06	80.62206	1.46	88.99216	1.86	92.20294	2.26	94.3598	2.66	95.19314	3.06	96.73725		
0.27	14.83774	0.67	61.50441	1.07	80.91618	1.47	89.01666	1.87	92.22745	2.27	94.40882	2.67	95.20539	3.07	96.73725		
0.28	16.50441	0.68	62.20294	1.08	81.03873	1.48	89.09019	1.88	92.25196	2.28	94.38432	2.68	95.20539	3.08	96.71275		
0.29	18.95539	0.69	62.96275	1.09	81.45539	1.49	89.18823	1.89	92.31323	2.29	94.37206	2.69	95.20539	3.09	96.73725		
0.3	20.57304	0.7	63.71029	1.1	81.59019	1.5	89.23725	1.9	92.32549	2.3	94.31078	2.7	95.24216	3.1	96.78627		
0.31	22.2152	0.71	64.40882	1.11	81.94559	1.51	89.27402	1.91	92.32549	2.31	94.225	2.71	95.27892	3.11	96.77402		
0.32	23.77157	0.72	64.76421	1.12	82.08039	1.52	89.43333	1.92	92.35	2.32	94.21275	2.72	95.34019	3.12	96.59019		
0.33	25.25441	0.73	65.42598	1.13	82.52157	1.53	89.58039	1.93	92.55833	2.33	94.20049	2.73	95.45049	3.13	96.45539		
0.34	26.02647	0.74	66.4799	1.14	82.65637	1.54	89.71519	1.94	92.61961	2.34	94.17598	2.74	95.48725	3.14	96.41862		
0.35	28.25686	0.75	67.1049	1.15	82.95049	1.55	89.76421	1.95	92.76666	2.35	94.13921	2.75	95.51176	3.15	96.44314		
0.36	29.69069	0.76	67.71764	1.16	83.23235	1.56	89.87451	1.96	92.81568	2.36	94.20049	2.76	95.58529	3.16	96.41862		
0.37	30.37696	0.77	68.29362	1.17	83.55098	1.57	89.99706	1.97	93.01176	2.37	94.24951	2.77	95.68333	3.17	96.36961		
0.38	32.28873	0.78	68.53873	1.18	83.89412	1.58	90.05833	1.98	93.12206	2.38	94.27402	2.78	95.72009	3.18	96.36961		
0.39	33.56323	0.79	69.04118	1.19	84.18823	1.59	90.16862	1.99	93.17107	2.39	94.27402	2.79	95.75686	3.19	96.36961		

Table 22 - Extracted Plant Data

1809810

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

76/100

Instructor

PAGE 1

PAGE 2

QM

Good Structure

Report is structured exactly as stated in the assignment brief.

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

QM

Correctly cited

Citation method conforms to Harvard standard, well done.

Text Comment. No need to tell your reader how important something is, sound like you are instructing them.

QM

Repetition

Already stated elsewhere, repeating information is considered boring by your reader

PAGE 8

PAGE 9

PAGE 10



Correctly cited

Citation method conforms to Harvard standard, well done.



Correctly cited

Citation method conforms to Harvard standard, well done.



Correctly cited

Citation method conforms to Harvard standard, well done.



Correctly cited

Citation method conforms to Harvard standard, well done.

PAGE 28

PAGE 29

PAGE 30

Text Comment. Good point made about the pump. Tuning is not just about damping as the addition of PID control increases the order from 2 to three and adds zeros also giving a better response than critical damping

PAGE 31

PAGE 32

QM

Wide Range of Sources

You have shown good evidence of reading from a wide range of sources.

QM

Correct method of listing.

You have listed your sources correctly according to the Harvard method.

PAGE 33

PAGE 34

PAGE 35

PAGE 36

PAGE 37

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PAGE 39

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PAGE 42

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PAGE 44

1. ENGAGEMENT WITH LITERATURE

-  Exceptional engagement with an extensive range of relevant and credible literature. High-level referencing skills consistently applied. (17/20)

17

2. KNOWLEDGE AND UNDERSTANDING

-  Excellent, detailed knowledge and highly critical understanding of the well-established concepts and principles of the subject and the main methods of enquiry. (14/20)

14

3. COGNITIVE AND INTELLECTUAL

-  Excellent critical evaluation and analysis of concepts and principles leading to logical, evidence-based, reasoned arguments and judgements. Explicit recognition of other stances and a strong awareness of the limits of their knowledge. A capacity for independent thought and ability to 'see beyond the question', suggesting some grasp of the broader field and wider concepts. (14/20)

14

4. PRACTICAL APPLICATION



An advanced application of a range of established methods, materials, tools and/or techniques. The context of the application is well considered, and insightful. Consistent, accurate and logical application of theory to practice, making well-developed links between the two. Can identify problems and propose excellent, creative solutions outside the context in which they were first studied. (14/20)

14

5. TRANSFERABLE SKILLS



Can communicate with an exceptionally high level of professionalism, highly suitable for the audience. Work is exceptionally coherent, very fluent and is presented professionally. Can work exceptionally well within a team, showing leadership skills. Demonstrates exceptional skills for employment requiring the exercise of personal responsibility and decision-making and an appetite for further development. (17/20)

17