

CO2 Dosing system

by Feran Kanda

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CO₂ dosing system to regulate the acidity of water leaving the plant

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Abstract

The aim of this report was to design a CO₂ dosing system that can regulate the acidity of water leaving a plant. The system was to be fitted just before the treated water leaves the plant to control its acidity. The role of a control system in the CO₂ dosing system was to reduce the pH value of the water that was measured around 8.5 – 13 and reduce it between pH 6.5 – 7.5. Thus, Minimising and reducing the risk to human health and also save the environment.

The pH sensor was a major component of the control system because the measurements provide from the sensor was feedback into the system, so the control system can take the appropriate actions. In this paper a method was proposed into to complete the main objective and the entire control system was designed and implemented using MATLAB. The stability of the system was also analysed from a series of output response time diagrams to determine if it was stable or unstable.

Introduction

Control systems are important part of our modern society. Control systems is a vital concept that is include in numerous of applications surrounding our everyday life. The operation that are associated with control have always existed in nature. There are some control systems even within a human body, such as the pancreas, which regulates the blood sugar. Another example, is the adrenaline rush that occurs in time of fight or flight. The adrenaline increases along with the heart rate causing more oxygen to flow through the cell. The human eyes can track or follow a moving object to keep it in view. In addition, the hands can grab or pick up an object and place it precisely at a predetermined location. [1]

A control system, is a system of integrated elements and processes (or plants) assembled for the aim to obtain a desired output within a desired range of values, given a specified input. An example of a control system is an elevator in a building. When the fourth-floor button is pressed on the first floor, the elevator rises to the fourth floor with a speed and floor-levelling accuracy designed for passenger comfort. [1]

The two terms which help define a control system are input and output. A control system's input is the stimulus applied to a control system from an external source to produce a specified response from the control system. In the elevator example the push button of the fourth floor is an input that represents the desired output. Control system output is the actual response obtained from a control system. In the elevator example, the elevator rising to the top floor is the actual response. [1]

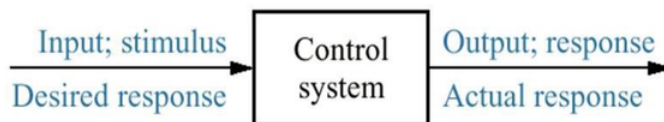


Figure 1- A simple description of a control system, Source [1]

Advantages of Control System

Control systems allows us to move large equipment's with precision that would otherwise be impossible to move. Control system are designed for four primary reasons:

1. Power amplification
2. Remote control
3. Convenience of input form
4. Compensation for disturbances

An example of power amplification would be a radar antenna that is positioned by the low-power rotation of a knob at the input. This system requires a large amount of power for its output rotation and yet with a control system this rotation can be achieved with a turn of a knob at the input. Control systems can also be useful in remote or dangerous location, such as radioactive environments. A robotic arm can be used to pick up materials or even move items, without placing any human life in danger. [1]

Control systems can also be used to provide convenience by changing the form of the input. An example of this is, in a temperature control system. The input is a position on a thermostat and the output is the heat. Another advantage of a control system is the ability to compensate for disturbances, especially when dealing with variables such as temperature in a thermal system. [1]

Fundamentally, there are two types of approaches to a control loop and these are, an open-loop and closed-loop systems.[2]

Open-Loop control system

In an open-loop system, the product variable is not compared to or with any references/ desired value. One of the advantages of an open-loop system is that the system is simple to construct, and it is also easy to maintain and generally have no stability problems. As a result, most of the open-loop systems has limited use. The block diagrammatic representation of a typical open-loop system is shown in figure 2. [2]

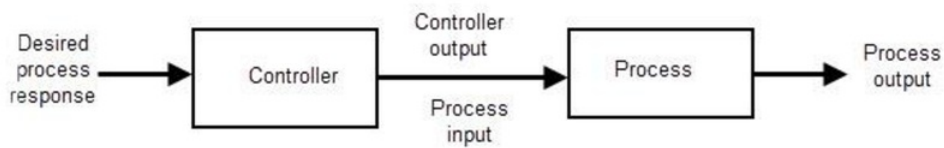


Figure 2 - Open-loop, Source [3]

Close-Loop control system

A close-loop system is similar to an open-loop system, but it includes a feedback path. This feedback path is through which the measured controlled variable is transmitted to a comparator for comparison, and the error so generated is used for operating a controller whose output actuates an actuator/control valve for proper functioning of the process. The block diagrammatic representation of a typical close-loop system is shown in figure 3. [2]

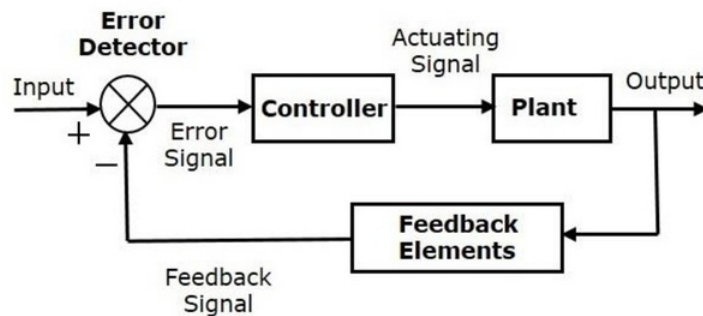


Figure 3- Close-loop, Source [4]

In figure 3, the system's output is improved with the feedback path because the output is monitored and compared with the desired output value, and if the difference between the two (the error) is used as a signal to develop corrective action to reduce the error. Examples of close-loop systems are found in many industrial processes where position or velocity at some point must be altered in a certain way. [3]

Control Modes

There are two basic modes of process control which are ON/OFF action and continuous control action. The purpose of the control is to hold the measured variable output from a process within set limits by varying the controlled input variable to the process. [4]

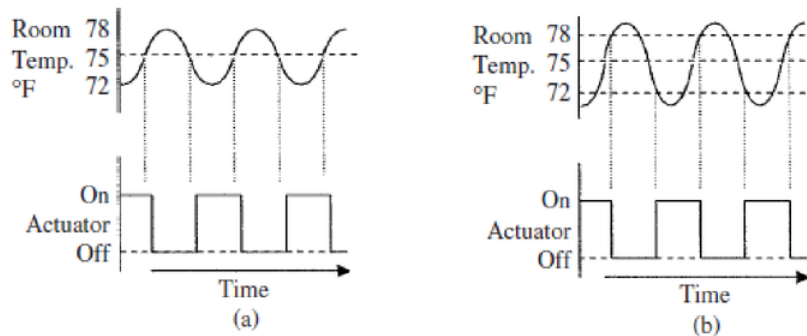


Figure 4 - (a) A simple ON/OFF action of a room heating system, (b) differential ON/OFF action, Source [4].

Figure 4, shows an example of a simple room heating system. In figure 4 (a) the top graph shows the room temperature (measured variable) and the bottom graph shows the actuator signal. The set point in this example for the room temperature is set at 75 degrees. However, when the air is being heated, the temperatures in the middle of the room would reach 77 degrees before the temperature at the sensor reaches the reference temperature of 75 degrees. Similarly, as the room cools down, the temperature in the room will drop to 73 degrees before the temperature at the sensor reaches 75 degrees. The room temperature will go from about 72 – 78 degrees due to the inertia in the system. [4]

Differential action

As it can be seen in the top graph in figure 4 (b), the thermostat which acts as the sensor in the system is supposed to switch on and off at the set reference of 75 degree but the switching point are delayed by +/- 3 degrees. This system has a built-in hysteresis or a dead-band operation. As a result, the thermostat turns OFF the actuator when the room temperature reaches 78 degrees and doesn't switch back ON until the room temperature falls to 72 degrees, giving a built-in hysteresis of 6 degrees. [4]

Proportional Control (P)

Proportional control is the most common of all continuous industrial process control action. The control initiates a corrective action to a value that is in some proportion to the change in error or deviation of the process variable from set point. The input signal is compared to a set point and any difference in amplitude between the two (error signal) is amplified and fed to a control valve (actuator) as a correction signal. The control valve controls one of the inputs to the process and by changing the input to the control, will result in a change in the output amplitude until it equals the set point or the error signal is zero. [4]

Proportional plus derivative (PD)

In order to reduce the correction time that would have occurred using proportional action, proportional plus derivative was created to achieve this. This control action senses the rate of change of the measured variable and applies a correction signal that is proportional to the rate of change. [4]

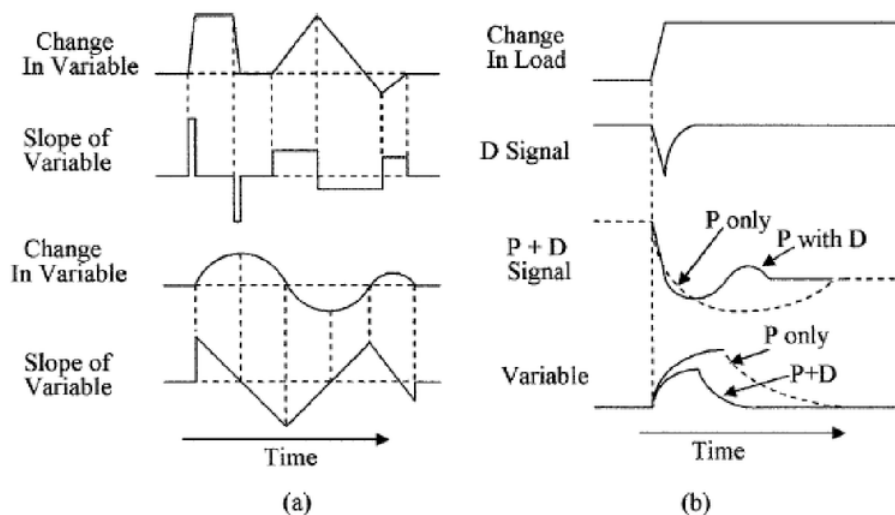


Figure 5 - (a) and (b) shows the examples of both the derivative action and the effect of PD action on the correction time, Source [4].

In figure 5 (a), a derivative output is obtained only when the load is changing. However, figure (b) shows the effect of PD action on the correction time, when a change in loading is sensed both the proportional and derivative signals are generated and added together. Once these signals are combined it produces a signal that speeds up the actuator's control signal. The faster reaction time of the control signal reduces the time to implement corrective action. [4]

Proportional plus Integral (PI)

Proportional plus Integral action is known as the reset action which was developed to correct for long term loads and applies a correction proportional to the area under the change in the variable curve. Figure 6, shows that the Integral action gives a slower response to changes in the measured variable to avoid overshoot. However, it normally has a high gain so that with long term load changes it takes over control of the manipulated variable and it applies the correction signal to actuator. [4]

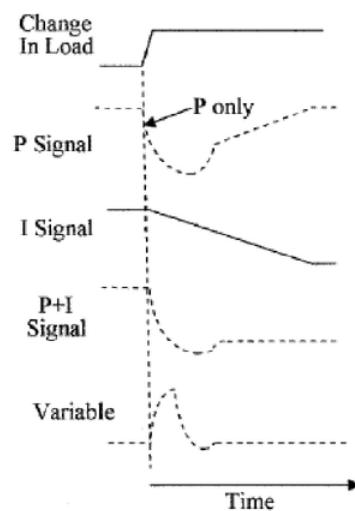


Figure 6 - Effect of proportional and integral action on a variable, Source [4]

Proportional plus Integral and derivative (PID)

All three actions described above can be combined to form a PID action. Figure 7, below shows the waveforms of PID action which is the most often used corrective action for process control. [4]

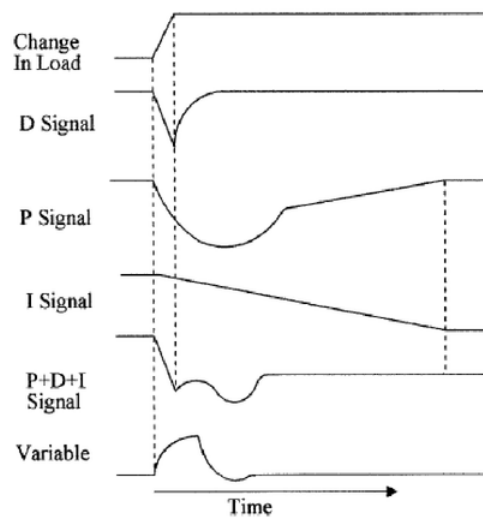


Figure 7 - Waveforms for proportional plus integral action and waveforms for proportional plus derivative and integral action, Source [4]

PID electronic controller

Figure 8, shows a block schematic of a PID electronic controller. The PID electronic uses the sensors to measure the variable and compare it with the set point in the first unity gain comparator. Its output is the error signal which is fed to the integrator with an inverting unity gain buffer and to the proportional amplifier and differentiator via a second inverting unity gain. These signals are compared to the integrator output and if there is a change in the measured variable, the error signal passes through the second comparator which is the proportional amplifier, added to the differential signal in a summing circuit and fed to the actuator to change the input variable. [4]

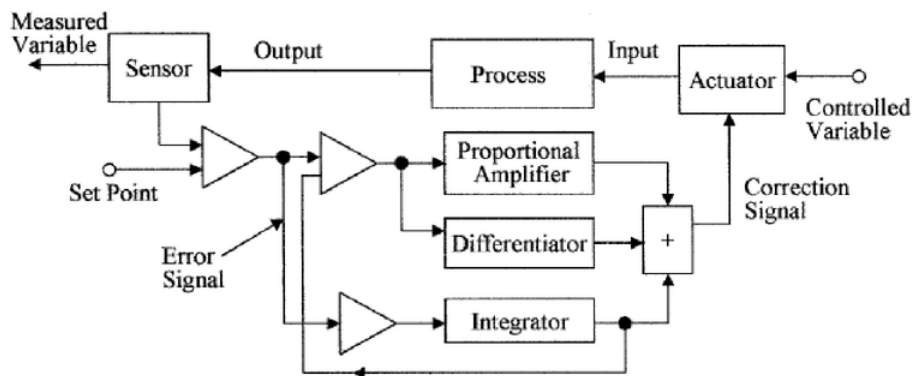


Figure 8 - Waveforms for proportional plus integral action and waveforms for proportional plus derivative and integral action, Source [4].

Method

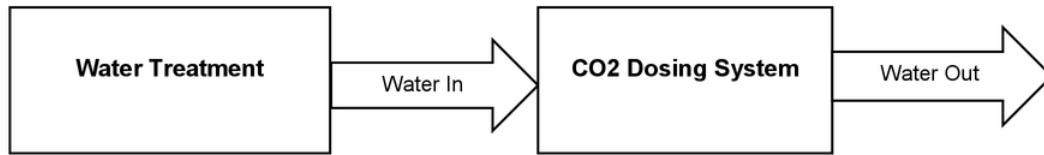


Figure 9 - Task block diagram

Figure 9 above, shows a block schematic diagram of the task that would need to be completed to treat the water with pH 8.5-13 and reduce it to a pH level between 6 -7.

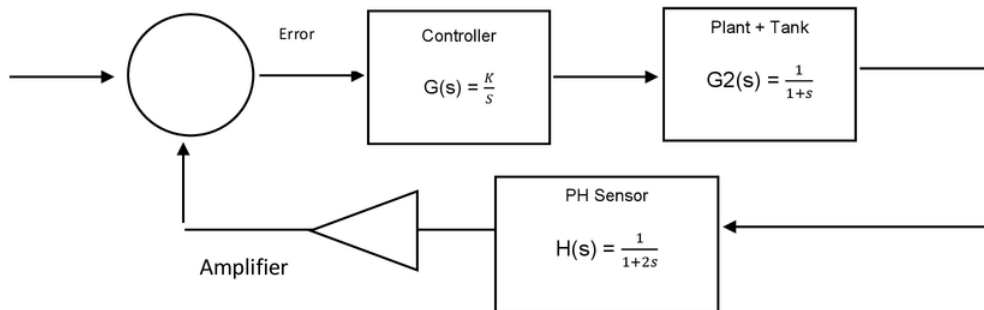


Figure 10 - Control system – closed-loop

Figure 10, shows the block diagrams with the transfer function. In this control system, there are four individual transfer functions:

- 1) Controller
- 2) CO2 Valve
- 3) Plant + Tank
- 4) pH sensor

$G = \text{controller} * \text{CO2 Valve} * \text{Diffuser} + \text{Tank}$

$H = \text{pH sensor} * (\text{Signal conditioning})$

$$\text{System} = \frac{G}{1 + GH}$$

The Concept of PH measurement and control

There are a wide range of applications from high-purity pharmaceutical processing to wastewater treatment. These applications can pose some challenges to PH measurement, including high-temperature and otherwise harsh measurement environments, stability, low conductivity and more-stringent PH control. [5]

PH is a measure of hydrogen ion concentration in an aqueous (water) solution. The PH scale range from 0 -14. A low PH value indicates acidity, a PH=7 is neutral, and a high PH value indicates alkalinity. The aim of the PH value is to tell you whether you're dealing with an acid or base, but it offers limited value indicating the true strength of the acid or base. [6]

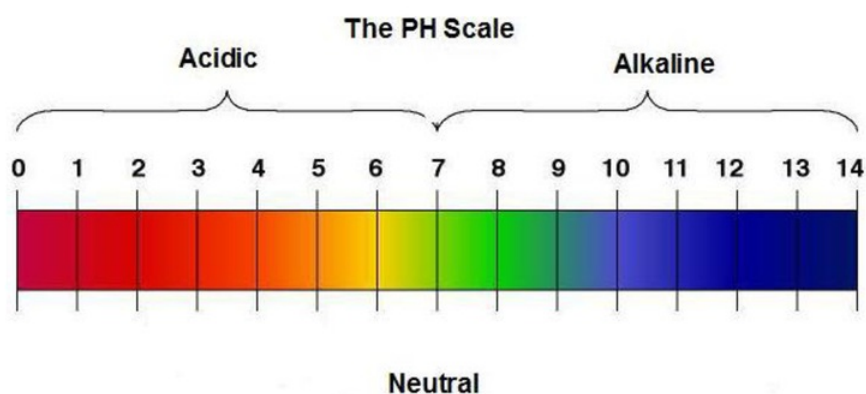


Figure 11 - PH Scale, source [11]

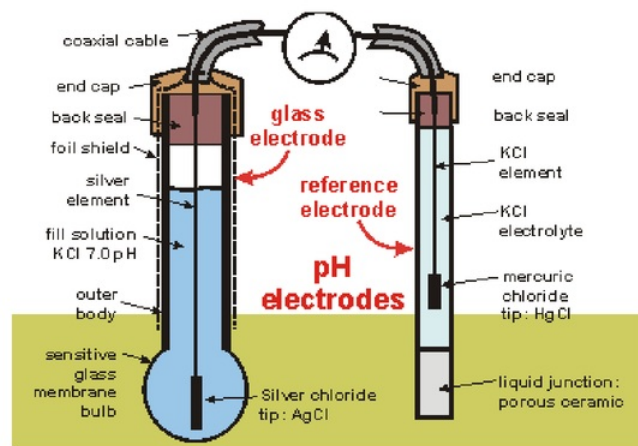


Figure 12 - PH electrode parts, source [11]

List of PH Sensors

Types	Temperature range	Accuracy	Sensitivity	Range	Response time	Linearity
Vernier pH sensor (PH-BTA)	5 to 80°C	+/- 0.2 pH units	N/A	pH 0–14	90% of final reading in 1 second	N/A
Vernier pH sensor (FPH-BTA)	0 – 100°C	+/- 0.2 pH units	N/A	pH 0–14	98% of full response in 30 s at 25°C	N/A
(CS526L)	10° to 40°C	±0.2 pH (over 10° to 40°C)	N/A	pH 2–14	N/A	N/A
(CSIM11-L)	0° to 80°C	±0.1%(over full range)	N/A	pH 0 to 14	95% of reading (in 10 s)	N/A

Table 1 - List of PH sensors

List of CO2 Valves

Types	Flow rate	Proportional	Temperature	Pressure Bar
 Proportional Solenoid Model 001	0-5 SCCM to 0-10 SLPM	proportional solenoid control valves	Range: -10 to 70 °C (±14 to 158 °F)	1000 PSIG
 Flow Control Needle Valves reverse flow	20 LPM	N/A	Range: -20 to 100 °C	0 - 210
 Series 28 flow control valves	590 NI/min	N/A	Range: 0°C + 80 °C (with dry air 20°)	0+10
 DVP High Flow Proportional Control valve	70 L/min	proportional solenoid control valves	Range: 32 to 120 °F	Vac to 100psig

Table 2 - List of CO2 Valves

Transducer selection

PH sensor



Figure 13 - (PH - BTA), Source

Specifications

Type	Sealed, gel-filled, polycarbonate body, Ag/AgCl
Response time	90% of final reading in 1 second in a buffer
Temperature range	5 to 80°C (readings not compensated)
Range	pH 0–14
Accuracy	± 0.2 pH units
Isopotential pH	pH 7 (point at which temperature has no effect)
Default calibration values	slope: -3.838 intercept: 13.720
Shaft diameter	12 mm OD

Figure 14 - Specifications, Source [12]

The PH-BTA sensor would be considered for this project because the pH sensor is designed to make measurements in the pH range of 0 to 14. In addition, the pH sensor types meet the specification for the project such as response time, temperature range, range and accuracy.

Operation

This pH sensor is designed to produce a voltage of approximately 1.75 volts in a pH 7 buffer and the voltage increases by about 0.25 volts for every pH number decrease. The voltage decreases by about 0.25 volts/pH number as the pH number increases. [7]

CO2 Valve Controller

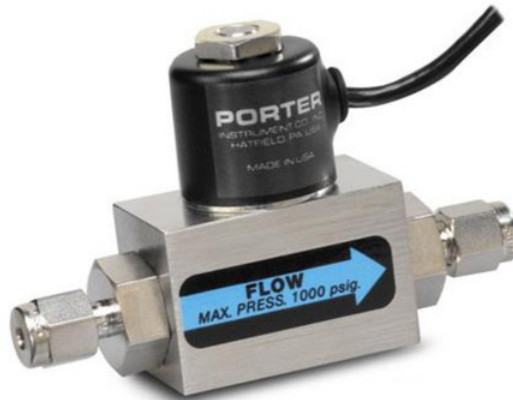


Figure 15 - Flow Control Valve, Proportional Solenoid – Model 001, Source [13]

The mass flow control valve would be considered for this project because the control valve is designed to operate in temperature range of -10 to 70°C (±14 to 158°F). Flow capacity of 0-5 SCCM to 0-10 SLPM. Operating voltage of 4-11 VDC (24Vdc maximum) and operating current nominal 150mA_{dc} (275mA_{dc}). [8]

Operation

The model 001 is a mass flow control valve which is normally closed, proportional solenoid control valve. This model consists of a valve body, valve sleeve, DC coil, which creates a magnetic field lifting the internal valve assembly from the orifice to allow the gas flow control. [8]

PH sensor Transfer function

For the pH sensor transfer function, the two-main specification type that mattered were sensitivity and response time. The sensitivity of the pH sensor was not included in the specification. However, the pH voltage increases and decreases by about 0.25 volts/pH number. Thus, this voltage was used as the sensitivity of the pH sensor.

The response time was calculated because in the pH sensor specification it stated that 90% of final reading in 1 second in a buffer. Thus, the response time was calculated using the following equations:

PH sensor transfer function

$$\frac{\text{sensitivity}}{1 + \tau s}$$

Response time

$$90\% \div 100 = 0.9$$

$$0.9 = 1 - e^{-\frac{1}{\tau}}$$

$$0.9 - 1 = -e^{-\frac{1}{\tau}}$$

$$-0.1 = -e^{-\frac{1}{\tau}}$$

$$0.1 = e^{-\frac{1}{\tau}}$$

$$\ln 0.1 = \frac{-1}{\tau}$$

$$-2.3 = \frac{-1}{\tau}$$

$$\frac{-1}{-2.30} = \tau$$

$$\tau = 0.43$$

Transfer function development in MATLAB

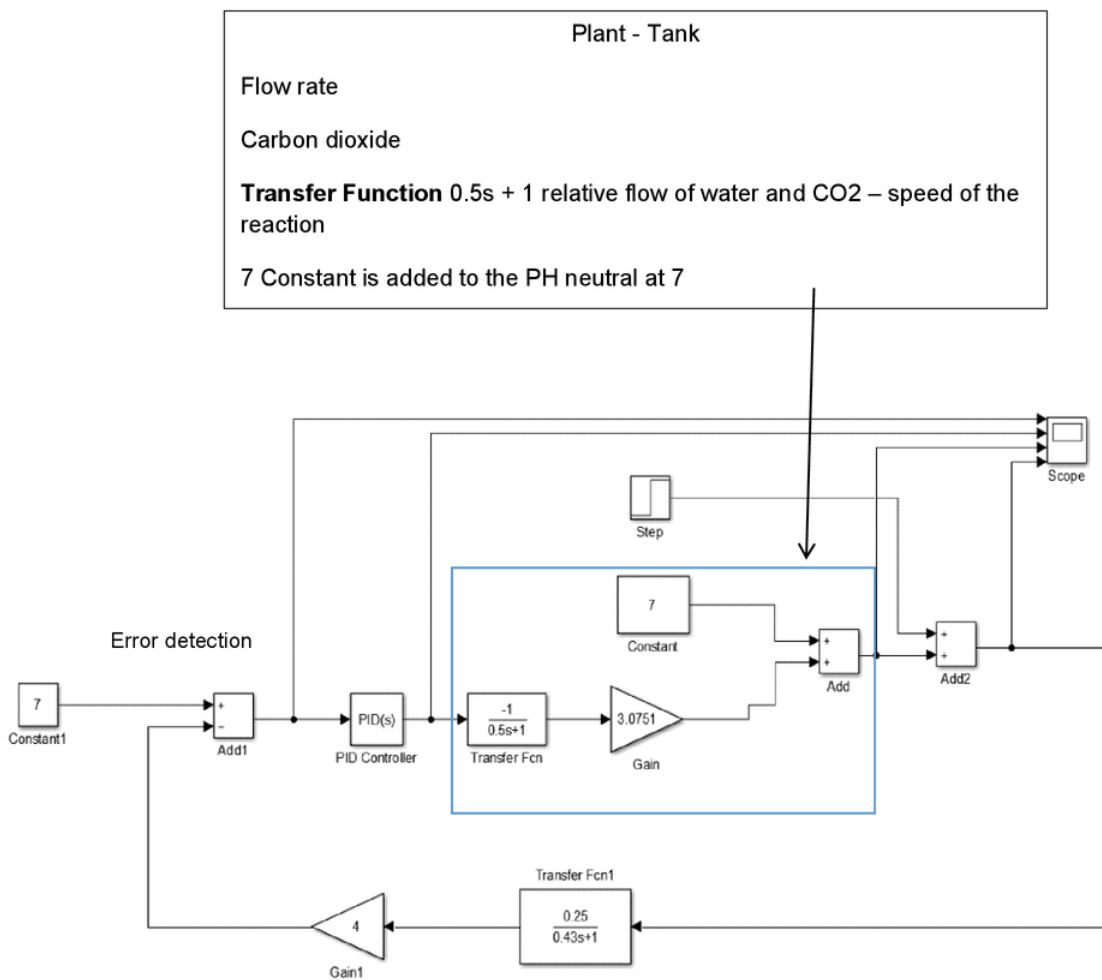


Figure 16 - MATLAB system design

Transfer Fcn1 is the transfer function for the PH sensor. The top part of the transfer function relates to the sensitivity, while the denominator is the response time. An amplifier with is added to the system to amplify the signal from the sensor. The amplifier also has a gain of 4 which is multiplied by the numerator to get the PH in volts. Finally, the step is added as the disturbance in the system. The PID controller also has a transfer function with a low pass filter inside to slow and smooth out the response.

PID Controller Design Specifications

KP= -0.874 KI= -1.32 and KD= -0.133

PID Controller

This block implements continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking. You can tune the PID gains automatically using the 'Tune...' button (requires Simulink Control Design).

Controller: **PID** Form: **Parallel**

Time domain:

☒ Continuous-time
☐ Discrete-time

Main **PID Advanced** Data Types State Attributes

Controller parameters

Source: **internal** [Compensator formula](#)

Proportional (P): **-0.873956817258195**

Integral (I): **-1.31540758966005**

Derivative (D): **-0.133481401846942**

Filter coefficient (N): **321.827827739371**

[Tune...](#)

$$P + I \frac{1}{s} + D \frac{N}{1 + N \frac{1}{s}}$$

Figure 17 - PID Controller

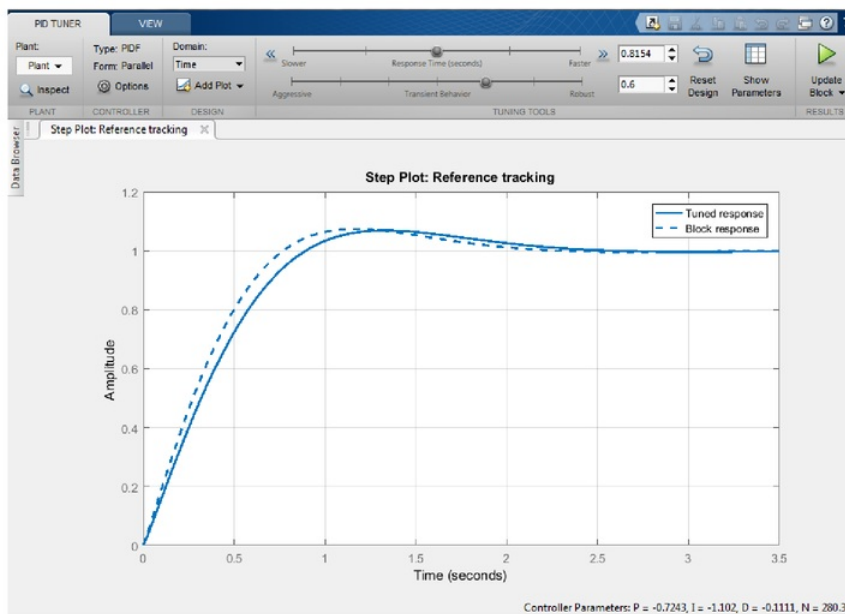


Figure 18 - Step Plot Tuned and block response

PID Tuner

Settling time less (min) than 3 seconds, Percent overshoot (%) less than 8 seconds and Closed-loop stability = stable.

Performance and Robustness		
	Tuned	Block
Rise time	0.639 seconds	0.554 seconds
Settling time	2.09 seconds	1.87 seconds
Overshoot	6.9 %	7.42 %
Peak	1.07	1.07
Gain margin	Inf dB @ Inf rad/s	Inf dB @ Inf rad/s
Phase margin	69 deg @ 2.45 rad/s	69 deg @ 2.82 rad/s
Closed-loop stability	Stable	Stable

Figure 19 - Performance and Robustness

Controller Parameters		
	Tuned	Block
P	-0.72429	-0.87396
I	-1.1021	-1.3154
D	-0.11112	-0.13348
N	280.3003	321.8278

Figure 20 - Controller Parameters

Transfer functions in MATLAB

C =

$$K_p + K_i * \frac{1}{s} + K_d * \frac{s}{T_f s + 1}$$

with $K_p = -0.724$, $K_i = -1.1$, $K_d = -0.111$, $T_f = 0.00357$

Continuous-time PIDF controller in parallel form.

Figure 21 - PID Transfer function

```
>> P= tf(Plant)
```

P =

From input "PID Controller" to output "u":
-14.3

$$\frac{-14.3}{s^2 + 4.326 s + 4.651}$$

Continuous-time transfer function.

Figure 22 - The plant Transfer function

```
>> Sensor = tf([0.25],[0.43,1])
```

Sensor =

$$\frac{0.25}{0.43 s + 1}$$

Continuous-time transfer function.

Figure 23 - PH sensor Transfer function

```

>> System=(C*P)/(1+(C*P*Sensor))
System =

    196 s^7 + 5.75e04 s^6 + 7.305e05 s^5 + 3.714e06 s^4 + 9.354e06 s^3 + 1.166e07 s^2 + 5.76e06 s
-----
    0.43 s^9 + 245.8 s^8 + 3.645e04 s^7 + 3.826e05 s^6 + 1.685e06 s^5 + 3.936e06 s^4 + 5.256e06 s^3 + 3.996e06 s^2
    + 1.44e06 s

```

Figure 24 - System Transfer function

Results

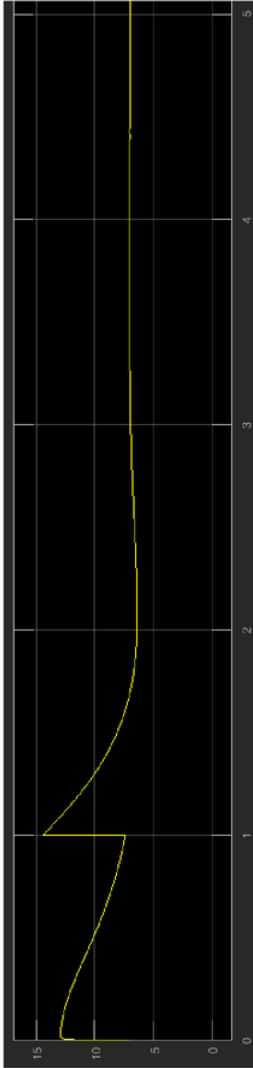


Figure 25 - PH sensor Scope Reading (a)

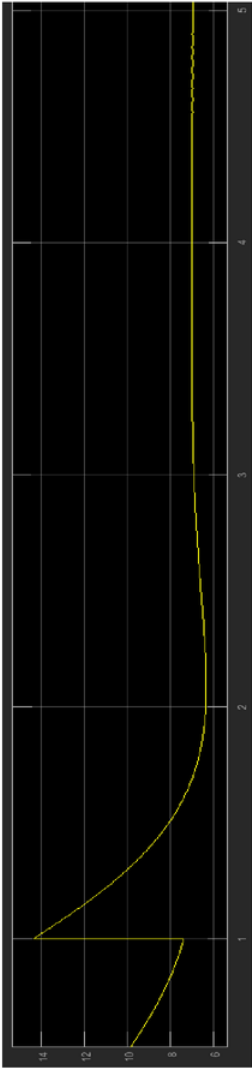


Figure 26 - PH sensor Scope Reading (b)

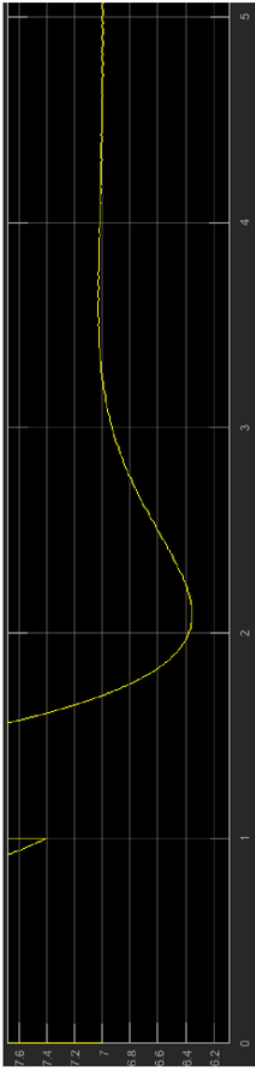


Figure 27 - PH sensor Scope Reading (c)

Stability In control system

Stability analysis is the nature of the response of a system to transient disturbance. The analysis determine whether or not the system is stable, if a control system is designed to meet a time domain specification using empirical frequency response data. Then it is necessary to be able to predict how the closed loop system will behave in the time domain. In addition, small changes in the characteristics of the controller or the system can determine how robust the design is in term of the sensitivity of the control system performance. [5]

Pole-zero plot

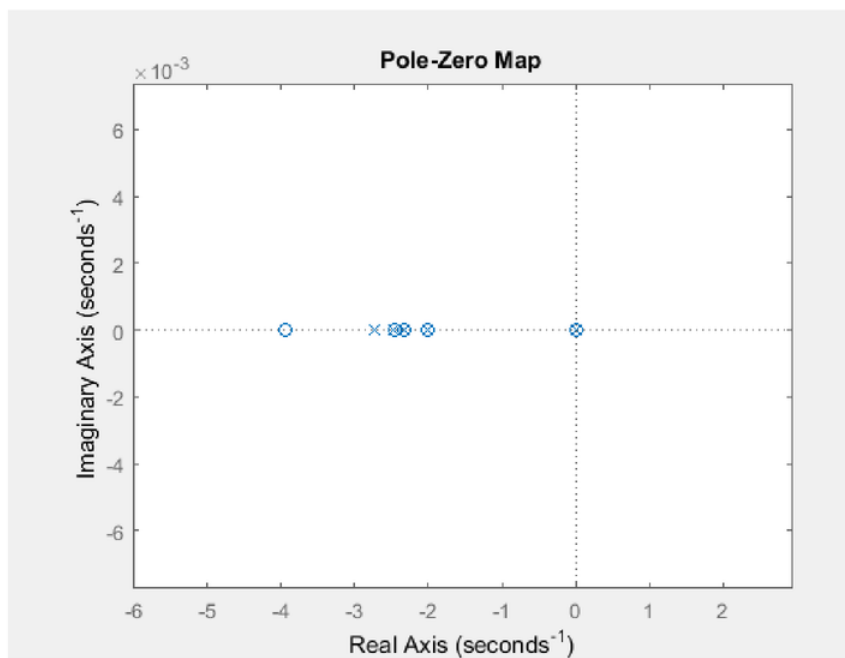


Figure 28 - Pole – Zero

Figure 26, shows the pole-zero output response which is fundamental to the analysis of the system. The zeros and poles generate the amplitude for both the forced and natural responses. Thus the farther to the left a pole is on the negative real axis, the faster the exponential transient response will decay to zero. This is known as the effect of a real-axis pole upon transient response. [9]

Nyquist Diagram

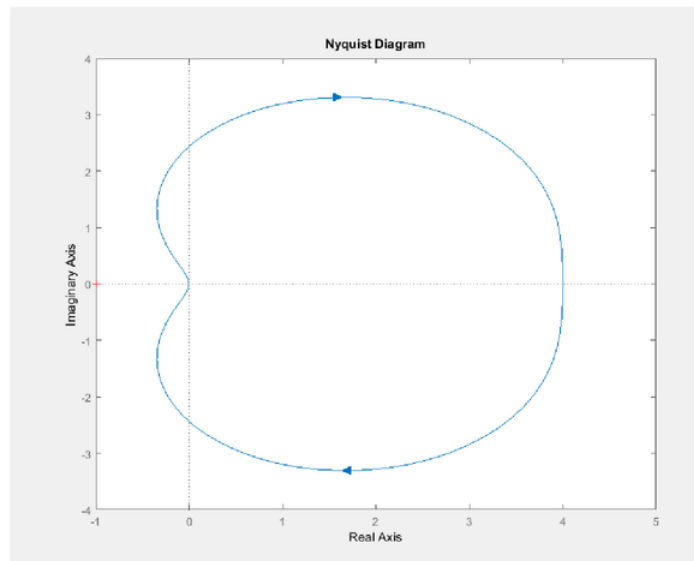


Figure 29 - Nyquist Diagram

Figure 27, shows the systems output response in a Nyquist diagram. The diagram defines two quantitative measures of how a system is. The two quantities are called gain and phase margin. If a system has greater gain, this means the phase margin can withstand greater changes in the system parameters before becoming unstable. Thus, the Nyquist diagram above shows that the system is stable. As previously explained in a system whose poles are farther from the imaginary axis have a greater degree of stability. [9]

Bode Diagram

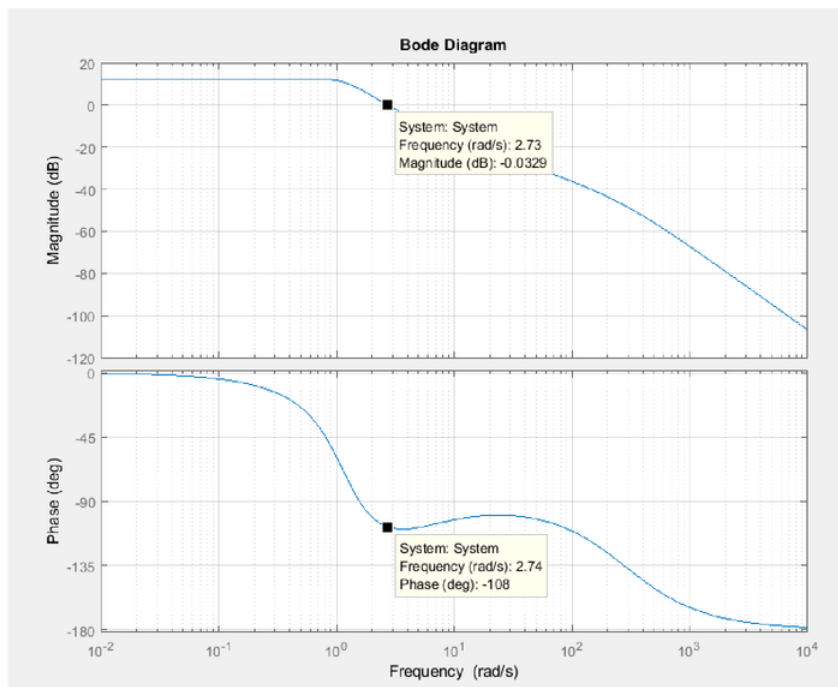


Figure 30 - Bode Diagram (a)

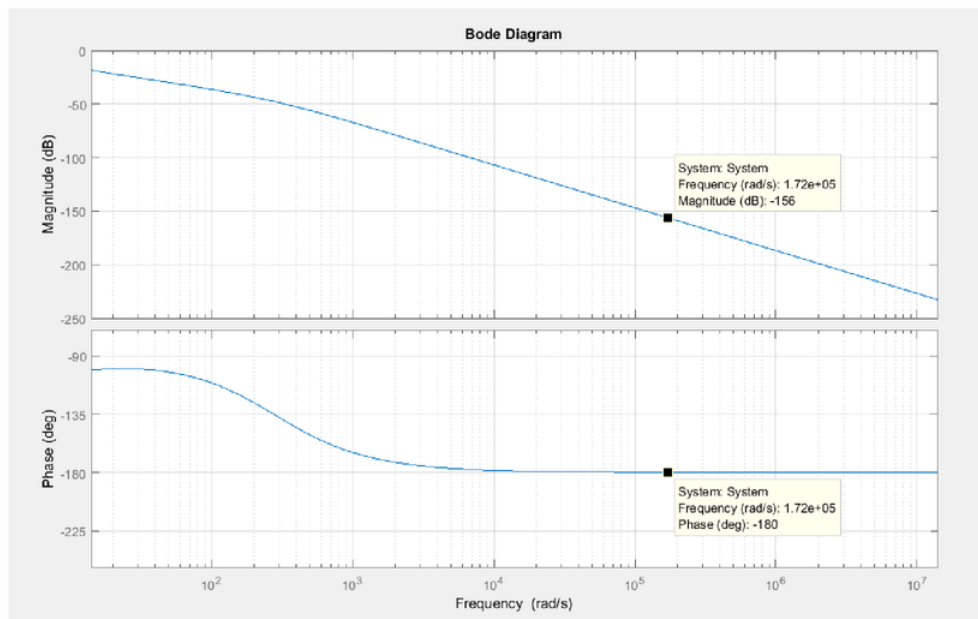


Figure 31 - Bode Diagram (b)

Both Figure 28 (a) and (b), shows the systems output response in a Bode diagram. Bode plots are subsets of the complete Nyquist diagram but just in another form. The Bode plots are an alternate ways of visualising and implementing the theoretical concepts of the system. Thus, all the calculations still applied to stability can also be derived from the Nyquist stability criterion. [9]

The gain margin is determined by looking at the phase plot and finding the frequency where the phase is 180 degree. At this frequency, we determine from the magnitude plot how much the gain can be increased before reaching 0dB. **Figure**, the phase angle is 180 at approximately $1.72e+0.5$ rad/s.

The phase margin can be determined by looking at the phase plot of the diagram and finding out the frequency where the phase is 180 degrees. At this frequency, we look on the phase plot to find the difference between the phase and 180 degrees. This difference is the phase margin, figure (b) shows that the difference between the two is:

$$-108 - (-180) = 72^\circ.$$

Conclusion

Based on the results, the system managed to regulate the acidity of the water leaving the plant to a safe level. Thus, the pH value of the water was also reduced from 13pH to 7ph.

The system was designed to incorporate any possible disturbance that could have an effect on its performance. Possible disturbances, such as changes in plant o/p pH, changes in plant o/p flow, changes in temperature o/p and any temperature changes of the incoming CO₂ gas. Figure 29, below shows the pH value of the water decreasing and a sudden spike in the system which represents any possible disturbances. Although, the pH value increases for a short period of time it, the system is acknowledges this and deals with it and pH value continues to decrease shortly after the spike.

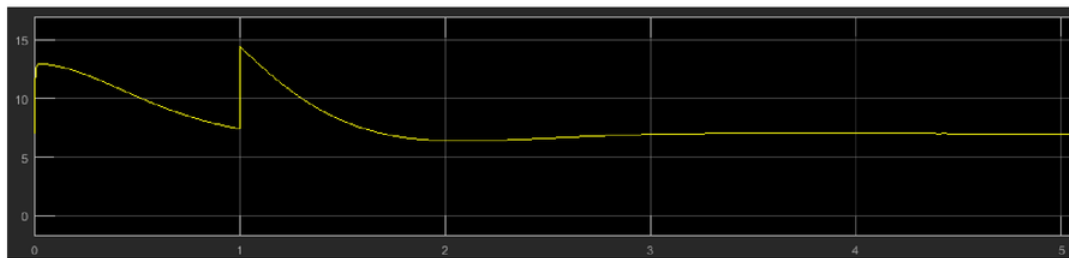


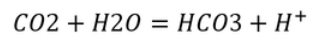
Figure 32 - PH sensor Scope Final Reading (d)

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Appendices

The fact that the CO₂ dosing system consist a tank of carbon dioxide gas, several calculation were done to determine the correct PH sensor, Co₂ in the water and gas diffuser for the project. However, at the end of these calculation it was proven that difficult to achieve, because the logarithms equations were not satisfied.



$$K = ([H^+][HCO_3]) \div [CO_2]$$

$$pH = \frac{1}{2} (pK + pCO_2)$$

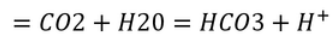
$$Pk = \log(k) \quad PCO_2 = \log[CO_2]$$

$$[CO_2] = \frac{20mol}{dm^3}$$

$$[H_2O] = \frac{55.5mol}{dm^3}$$

$$75\% \text{ of } CO_2 \text{ which } 20mol = 15mol$$

$$75\% \text{ of } 20mol = 15mol/dm^3 + 15mol/L$$



$$55.5 - 15 = 40.5mol/L \text{ Pure water (Unreacted water)}$$

$$20 - 15 = 5mol/L \text{ CO}_2 \text{ (Unreacted CO}_2\text{)}$$

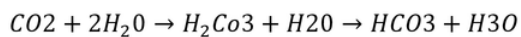
$$15 + 15 = 30mol/L \text{ CO}_2 [H^+][HCO_3]$$

$$K = \frac{30}{5} = 6$$

$$pK = -\log(6) = -0.778$$

$$KW = [H^+][OH^{-1}] = 1 \times 10^{-14} \text{ at } 25^\circ\text{C}$$

$$pKw = -\log(kw) = 14$$



Carbon acid

$$pK_a = 6.367 \quad K_a = 10^{-6.367}$$

$$[CO_2] = 44.01\text{g/mol}$$

Solubility of CO₂ 14 H₂O 15 1.45g/L (which will change with pressure)

$$1.45\text{g (Co}_2) \frac{1\text{mol}}{44.01\text{g}} = 0.03297 \text{ mol Co}_2$$

$$K_a \frac{[H^+][HCO_3]}{[Co_2(aq)]} \rightarrow 10^{-6.367} = \frac{x \cdot x}{0.03297}$$

$$10^{-6.367} = \frac{x^2}{0.03297}$$

$$x^2 = 10^{-6.367} \times 0.03297 = 1.41317 \times 10^{-8}$$

$$= \sqrt{1.41317 \times 10^{-8}}$$

$$= 1.18877 \times 10^{-4} [H^+]$$

$$pH = -\log(\sqrt{10^{-6.367}} \times \frac{Sol}{44.01})$$

$$\text{Co}_2 \text{ in water} = 392 \times 10^{-4} \text{ Mol/L. atm Henry's law}$$

Rearrange the equation to get pressure

$$pH = -\log(\sqrt{10^{-6.367}} \times 392 \times 10^{-4} \times Pressure)$$

$$\text{Log } (ABC) = \log A + \log B + \log C$$

$$\sqrt{ABC} = \sqrt{A} \times \sqrt{B} \times \sqrt{C}$$

$$-pH = \log(\sqrt{10^{-6.367}} \times \sqrt{392 \times 10^{-4}} \times \sqrt{Pressure})$$

$$-pH = \log\left(\sqrt{10^{-6.367}} \times \sqrt{392 \times 10^{-4}}\right) + \log\sqrt{Pressure}$$

$$-pH = \log -3.89 + \log\sqrt{Pressure}$$

CO2 Dosing system

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

70/100

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GRADING FORM: SMU GENERIC_GJ

FERAN KANDA

69.70

RESEARCH-INFORMED LITERATURE



A range of research informed literature has been used. Information presented is accurate. More references would have strengthened this section.

10.65

KNOWLEDGE AND UNDERSTANDING



Knowledge is accurate. Good understanding of the field. This is evidenced through the work presented on the control system development

17

ANALYSIS



A very good analysis performed on the simulated data. I think that if you had taken information from the pole-zero plot about the effect each had on the transient response of the system and compared it with the time domain traces then your analysis would have been much stronger.

17.5

PRACTICAL APPLICATION AND DEP.



Very good application of the available methods, tools and techniques. Good consideration of the context of the application.

18.75

SKILLS FOR PROFESSIONAL PRAC.



Can communicate clearly to specialist audiences with some room for improvement. Minor spelling and grammatical errors have reduced your marks in this section.

5.8