8-2023

Addition of process control experiment to Unit Operations II Laboratory.

Bradley Esselman
University of Louisville

ADDITION OF PROCESS CONTROL EXPERIMENT TO UNIT OPERATIONS II LABORATORY

By

Bradley L. Esselman
B.S., University of Louisville, 2022

A Thesis
Submitted to the Faculty of the
University of Louisville
J.B. Speed School of Engineering
as Partial Fulfillment of the Requirements
for the Professional Degree

MASTER OF ENGINEERING

Department of Chemical Engineering

August 2023

ADDITION OF PROCESS CONTROL EXPERIMENT TO UNIT OPERATIONS II LABORATORY

Submitted by: Bradley Esselman Digitally signed by Bradley Esselman Date: 2023.08.02 14:49:39 -04'00'

Bradley L. Esselman

A Thesis Approved On

07/25/2023

(Date)

by the Following Reading and Examination Committee:

Vance Jaeger Digitally signed by Vance Jaeger DN: cn=Vance Jaeger, o=University of Louisville, ou=Department of Chemical Engineering, email=vance.jaeger@louisville.edu, c=US Date: 2023.08.02 14:53:54 -04'00' Adobe Acrobat Reader version: 2023.003.20244

Vance W. Jaeger, Thesis Director

Gerald A. Willing

Patricia Ralston Digitally signed by Patricia Ralston Date: 2023.08.02 15:12:30 -04'00'

Patricia A. Ralston

ACKNOWLEDGEMENTS

I would like to thank Dr. Jaeger, Dr. Willing, and Dr. Ralston for sitting on my thesis reading committee. All of their guidance, support, and expertise was instrumental in shaping the quality and depth of my thesis. I would especially like to thank Dr. Jaeger for dedicating his valuable time, including weekends, to provide insightful feedback that greatly contributed to the development of this thesis.

I also want to give thanks to the University of Louisville Chemical Engineering faculty for providing me the necessary resources for my academic growth. Additionally, I would like to thank the Spring 2023 Unit Operations II Laboratory students for their participation and feedback.

Lastly, thank you to my family and friends for their unwavering support and encouragement throughout my undergraduate and graduate careers.

ABSTRACT

Process control is an essential aspect of manufacturing, contributing to improved process safety, efficiency, product consistency, and energy optimization. Chemical engineers are often responsible for ensuring the safe, efficient, and cost-effective operation of industrial processes, and process control plays a pivotal role in accomplishing this.

Chemical engineering students at the University of Louisville complete the course, *Elements of Process Control*, during the second semester of their fourth year. This lecture-based course offers limited hands-on, practical experience. To supplement the lack of hands-on experience in the classroom, a new process control experiment was designed and implemented into the Unit Operations II Laboratory curriculum as described in this report.

The purpose of this project was to increase fourth-year chemical engineering students' understanding of process control, as well as their ability to apply process control concepts to real systems. The success of the project was assessed through the students' accomplishment of five Learning Objectives pertaining to experimental design, proportional-integral-derivative (PID) controller tuning, and other key process control concepts.

The accomplishment of the Learning Objectives was evaluated via the students' experimental results in tandem with pre- and post-assessment scores. The results confirmed that the Learning Objectives were achieved. In a post-lab survey, students indicated that the experiment was beneficial to their learning and supported the claim that the process control experiment is a valuable addition to the Unit Operations II Laboratory.

TABLE OF CONTENTS

NOMENCLATURE

Abbreviation/Symbol	Meaning
ABET	Accreditation Board for Engineering and Technology
$\bar{c}$	Controller output initial value when the controller activates
c(t)	Controller output
CV	Control variable
Δc	Controller output range
Δu	Change in process input
Δy	Change in process output
Δy_s	Sensor span
e(t)	Error from setpoint
K_C	Controller gain
K_C^D	Dimensionless controller gain
K_P	Process gain
K_U	Ultimate gain
KS	Kolmogorov-Smirnov (normality test)
MV or *u*	Manipulated variable
PB	Proportional band
PB_U	Ultimate proportional band
PID	Proportional-integral-derivative
P_U	Ultimate period
t_{ris}	Rise time
τ_D	Derivative time
τ_I	Integral time
Unit Ops Lab	Unit Operations Laboratory
Z-N	Ziegler-Nichols (tuning)

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

A. Problem Definition

Process control is the method of monitoring, regulating, and manipulating variables in a process in order to maintain a desired output. Process control is used throughout manufacturing industries to enhance process safety, optimize process efficiency, reduce product variability, and decrease energy consumption. Chemical engineers are often responsible for ensuring the safe, efficient, and cost-effective operation of industrial processes, and process control plays a key role in accomplishing this. One of the current chemical engineering curriculum criteria of the Accreditation Board for Engineering and Technology Inc. (ABET) focuses on the engineering "design, analysis, and *control of processes*...[1]" Because of the importance of process control within chemical process industries, ABET has made it a core subject for chemical engineering curriculum.

The Chemical Engineering curriculum at the University of Louisville includes Elements of Process Control and Unit Operations II Laboratory (Unit Ops II Lab) during the second semester of the fourth year. According to the Elements of Process Control Syllabus, "Upon successful completion of this course, [students] are expected to be able to design, analyze and implement process control systems on Chemical Engineering related processes.[2]" The course is primarily lecture-based, offering limited hands-on experience through the utilization of a process control simulation software called Loop-Pro. Lessons with Loop-Pro involve following pre-written procedures with guess-and-check tuning. While these lessons allow students to observe cause and effect relationships, the lessons do not adequately prepare students to accomplish the goals presented in the class syllabus.

Namely, there is a lack of design, analysis, and implementation. To supplement the lack of hands-on experience in the classroom, a new process control experiment was designed and implemented into the Unit Ops II Lab curriculum as described in this report. The experiment aims to provide students with practical, real-world exposure to process control concepts using an Armfield PCT-51 flow control module (Figure 1). Through the addition of this experiment, students were given the opportunity to engage actively in the learning process and collaborate with their peers. Active learning and cooperative learning are highly successful instructional methodologies that have demonstrated effectiveness in enhancing knowledge retention, student satisfaction, and overall academic performance[3,4].

FIGURE 1 – Armfield PCT-51 Flow Control Module

Unit Ops Laboratory courses are core chemical engineering classes where students apply what they have learned in their other courses to real chemical engineering processes on lab or pilot scale equipment. At the University of Louisville, content is divided into two courses, Unit Ops I Lab and Unit Ops II Lab. Students take one lab during each semester of their fourth year. Prior to the implementation of this experiment in the Spring of 2023, neither Unit Ops Lab courses had any experiment relating to process control. There are many chemical engineering programs that have a dedicated process control lab course as part of their core curriculum. A brief survey of peer institutions reveals that other ACC schools such as Florida State University, University of Pittsburgh, and Georgia Institute of Technology all have dedicated process control lab courses. Thus, the implementation of a process control experiment in Unit Ops II Lab will fill a gap within the University of Louisville chemical engineering curriculum and provide department graduates with a deeper understanding of process control concepts.

B. Purpose

The purpose of this project is to increase fourth-year chemical engineering students' understanding of process control, as well as their ability to apply process control concepts to real systems. This is accomplished through the design and implementation of a process control experiment that provides fourth-year chemical engineering students with practical, hands-on experience tuning a proportional-integral-derivative (PID) controller and reinforces key concepts from their process control class. The experiment was designed to accomplish five Learning Objectives. Through successful completion of the experiment, students should demonstrate the ability to:

1. Tune a controller for P, PI, and PID control

2. Design and conduct experiments relating to process control
3. Describe the impact proportional, integral, and derivative action have on the responses for various controllers and determine which controller is best suited for this process
4. Calculate key process, sensor, and controller variables such as process gain, sensor span, rise time, and overshoot
5. Determine if a controller is direct- or reverse-acting

These Learning Objectives were chosen to reflect the knowledge, skills, and abilities expected of chemical engineers in the context of process control within manufacturing. In designing the experiment, consideration was also given to the ABET Student Outcomes, which serve as benchmarks for assessing the effectiveness of engineering programs. The ABET Student Outcomes listed below are taken directly from ABET's descriptions:[1]

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
3. an ability to communicate effectively with a range of audiences
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts

5. an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies

Student Outcomes 1, 3, 5, 6, and 7 are all directly addressed by either the Learning Objectives or the nature of the Unit Ops II Lab course itself. Table I shows which Student Outcomes relate to each Learning Objective. Student Outcomes 3 and 5 are accomplished through group collaboration and report writing that is integral to Unit Ops II Lab.

TABLE I

LEARNING OBJECTIVES AND ASSOCIATED ABET STUDENT OUTCOMES

		ABET Student Outcomes						
	Learning Objectives	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	Tune a controller for P, PI, and PID control	X						X
2	Design and conduct experiments relating to process control						X	X
3	Describe the impact proportional, integral, and derivative action have on the responses for various controllers and determine which controller is best suited for this process						X	X
4	Calculate key process, sensor, and controller variables such as process gain, sensor span, rise time, and overshoot	X						X
5	Determine if a controller is direct- or reverse-acting	X						X

Furthermore, the Learning Objectives were designed to challenge the students to use higher-order thinking, as defined by the 2001 Revised Taxonomy. This revision of Bloom's Taxonomy lists the following cognitive skills: remember, understand, apply, analyze, evaluate, and create[5]. Figure 2 shows the Revised Taxonomy and describes each cognitive skill.

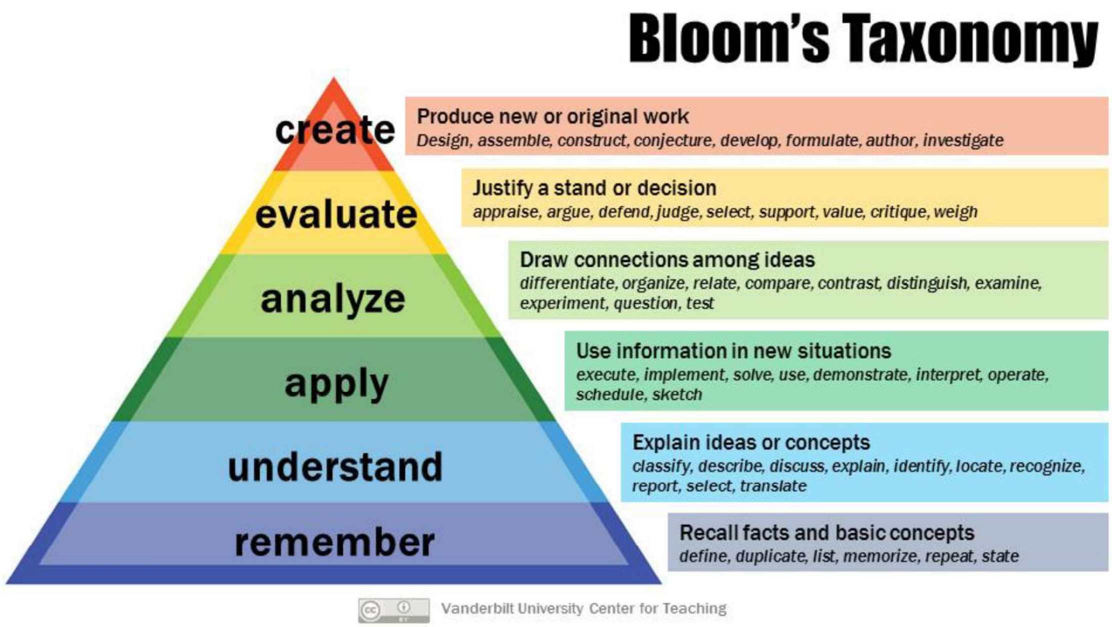


FIGURE 2 – Hierarchy of Cognitive Skills from the Revised Taxonomy[5]

The first three skills listed are commonly thought of as "lower-order" cognitive skills, while the last three skills listed are considered "higher-order" skills. Table II shows which cognitive skills are used to accomplish each Learning Objective. Throughout the lab, students use the lower-order cognitive skills of remembering, understanding, and applying what they have learned in their process control class. The second Learning Objective challenges students to use the highest cognitive skill by creating their own experiment. The third Learning Objective ensures students use the other higher-order cognitive skills of analyzing and evaluating.

TABLE II

LEARNING OBJECTIVES AND ASSOCIATED COGNITIVE SKILLS

	Revised Taxonomy Cognitive Skills					
Learning Objectives	**Remember**	**Understand**	**Apply**	**Analyze**	**Evaluate**	**Create**
1	X	X	X			
2	X	X	X			X
3	X	X	X	X	X	
4	X	X	X	X		
5	X	X	X	X		

C. Theory

The closed-loop control in this experiment manipulates the speed of a pump in to regulate the flow rate of water through a pipe. Closed-loop control, also known as feedback control, is a method of control which one or more process outputs are measured, and the controller makes automatic adjustments to keep the control variable (CV) near the setpoint. In every closed-loop control system, there is a process, sensor, controller, and actuator. The process is the system being controlled. The sensor is the device that measures changes in a process variable. The controller receives input from both the user and sensor and then sends commands to the actuator. The actuator is the device that changes the manipulated variable. In the case of this experiment, the process is the water flowing through the system, the sensor is the flowmeter, the controller is a flow controller in the form of a PC program, and the actuator is the variable speed pump itself.

This experiment uses a proportional-integral-derivative (PID) controller. PID controllers can operate using P-only, PI, or PID control. PID controllers are governed by the PID algorithm. The position form of the PID algorithm is[6]

$$c(t) = \bar{c} + K_c\left[e(t) + \frac{1}{\tau_I}\int_0^t e(t)dt + \tau_D\frac{de(t)}{dt}\right] \quad (1)$$

where c(t) is controller output, $\bar{c}$ is the initial value of the controller output when the controller is activated, K_C is the controller gain, τ_I is integral time, τ_D is derivative time, and e(t) is the error from setpoint at time, t. Controller gain, integral time, and derivative time are tuning parameters that determine the amount of proportional, integral, and derivative action that is applied in the control loop. Proportional, integral, and derivative action refer to the amount of proportional, integral, or derivative control the controller is applying to the system. As proportional, integral, or derivative action increase, the controller output increases.

Under proportional control, the controller output is proportional to e(t). This error, or offset, is almost always present with P-only control. The offset is the difference between the set point and the steady-state, closed-loop response. The closed-loop response describes how the system reacts and adapts to changes or disturbances in the process. There are many ways to analyze the closed-loop response. For the purposes of this paper, analysis of the closed-loop response will focus on examining how the CV changes over time. Under P-only control, the position form of the PID algorithm reduces to

$$c(t) = \bar{c} + K_c[e(t)] \quad (2)$$

The tuning parameter for proportional control is K_C. The higher the value of K_C, the more proportional action there is. Offset decreases as K_C increases. If K_C is too high, the closed-loop response may oscillate, and the system may become unstable.

Integral control integrates the steady-state error from setpoint over time and eliminates offset. Integral control often works with proportional control within a PI controller. Under PI control, the position form of the PID algorithm becomes

$$c(t) = \bar{c} + K_c \left[e(t) + \frac{1}{\tau_I} \int_0^t e(t)dt \right] \tag{3}$$

The tuning parameter for integral control is τ_I. The lower the value of τ_I, the more integral action there is, the faster the process responds. The main drawbacks to increased integral action are greater overshoots and more continuous oscillations[6].

Derivative control calculates the derivative of the steady-state error. The controller then works to reduce the rate of change of the error. This can help dampen oscillations and stabilize systems. The tuning parameter for derivative control is τ_D. The higher the value of τ_D, the more derivative action there is. Derivative control typically works with both proportional and integral control. PID control is often used for sluggish processes that oscillate under PI control. The main drawback of derivative control is the high sensitivity to noise. If a system has significant noise, derivative control may cause the system to become unstable.

Two metrics that can be used to evaluate the steady-state, closed-loop response for a given controller are rise time (t_{ris}), and overshoot. These metrics are most observed following a change of set point. Rise time is the amount of time it takes the control variable to cross its new steady-state value. Overshoot is the amount the response exceeds its new steady-state value divided by the difference between the old and new steady-state values. Referring to Figure 3, overshoot is calculated as $\frac{B}{D}$.

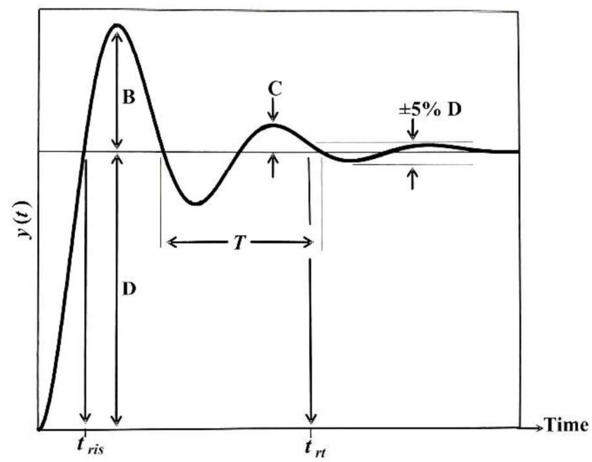


FIGURE 3 – Overshoot in a closed-loop response[6]

PID controllers can be direct- or reverse-acting. Direct-acting controllers increase output following an increase in the CV. Reverse-acting controllers decrease output following an increase in the CV. Table III displays factors that influence whether a controller is direct- or reverse-acting.

TABLE III

GUIDELINES FOR SELECTION OF DIRECT- AND REVERSE-ACTING CONTROLLERS[6]

Process Gain	Direct-Acting Actuator (Air-to-open valve actuator or a control valve with a valve positioner or a variable speed pump)	Reverse-Acting Actuator (Air-to-close valve actuator without a valve positioner)
Positive	Reverse-Acting PID	Direct-Acting PID
Negative	Direct-Acting PID	Reverse-Acting PID

The process gain (K_P) can be calculated to determine the controller type. Process gain is given by[6]

$$K_P = \frac{\Delta y}{\Delta u} \tag{4}$$

where Δy is the change in the output variable, and Δu is the change in the input variable. In a given process, a change in the manipulated variable (MV) results in a change in the CV. In a block diagram for a control loop, the MV is the input for a process and the CV is the output. For this process, the MV is the pump speed, and the CV is the water flow rate.

To finely tune a PID controller, different tuning values must be tested to find the ideal combination of controller gain, integral time, and derivative time. While this process can take a long time, there are tuning methods that can be used to calculate initial controller settings. The Ziegler-Nichols (Z-N) tuning method experimentally measures the ultimate gain (K_U) and the ultimate period (P_U) for a process[6]. This is done by alternating between two setpoints while increasing the proportional action of a P-only controller until the steady-state, closed-loop response displays sustained oscillations. The value of the controller gain during the sustained oscillations is the ultimate gain, and the period of the sustained oscillations is the ultimate period.

TABLE IV

ZIEGLER-NICHOLS PID SETTINGS[6]

Controller	K_C	τ_I	τ_D
P	0.5 K_U	--	--
PI	0.45 K_U	P_U /1.2	--
PID	0.6 K_U	P_U /2	P_U/8

Table IV shows the relationships between the ultimate parameters (K_U and P_U) and the three tuning parameters. These relationships were originally discovered and reported in *Optimum Settings for Automatic Controllers* by J. G. Ziegler and N. B. Nichols in 1942[7]. The PCT-51 unit uses proportional band (PB) instead of K_C to represent the proportional action of the controller. Proportional band is defined as[6]

$$PB = \frac{100\%}{K_c^D} \tag{5}$$

in which K_C^D is defined as[6]

$$K_c^D = K_c \frac{\Delta y_s}{\Delta c} \tag{6}$$

where Δy_s is the sensor span and Δc is the controller output range. K_C^D is dimensionless way to express controller gain. By combining Equations 5 and 6, the relationship between PB and K_C can be written.

$$PB = \frac{100\% \times \Delta c}{K_c \times \Delta y_s} \tag{7}$$

Equation 7 can similarly be written as

$$PB_U = \frac{100\% \times \Delta c}{K_U \times \Delta y_s} \tag{8}$$

where PB_U is the ultimate proportional band, which is the value of the proportional band during sustained oscillations. By combining Equations 7 and 8, the following equation can be written.

$$PB = \frac{PB_U \times K_U}{K_c} \tag{9}$$

By substituting the relationships between K_C and K_U from Table IV into Equation 9, students can use their experimentally determined PB_U to calculate their PB tuning parameter for each controller. With the data presented in Table V, Equation 7 can also be used to solve for the span of the sensor, assuming the controller output range is 100%.

TABLE V

RELATIONSHIP BETWEEN PROPORTIONAL BAND AND CONTROLLER GAIN

PB (%)	10	20	30	40	50	60	70	80	90	100
K_C (%-min)/L	133.3	66.7	44.4	33.3	26.7	22.2	19	16.7	14.8	13.3

II. METHODS

A. Experimental Design

The success of this project will be assessed through the accomplishment of the defined Learning Objectives. To facilitate the achievement of the Learning Objectives, the following student lab report deliverables were established:

- Create a properly labeled block diagram for the control loop
- Report PB, τ_I, and τ_D tuning parameters for all three controllers
- Generate a curve showing CV and setpoint vs time for a P-only, PI, and PID tuned controller
- Use disturbance test data to generate a curve showing CV, setpoint, and solenoid valve position vs time for a P-only, PI, and PID tuned controller
- Discuss which controller is best suited for this process
- Design and carry out experiments investigating:
    - The impact proportional action has on the response for a PI controller
    - The impact integral action has on the response for a PI controller
    - The impact derivative action has on the response for a PID controller
- Report qualitive and quantitative (t_{ris} and overshoot) observations when appropriate
    - Compare results with literature
- Determine if the controller is direct- or reverse-acting
    - Support conclusions with calculation of K_P (use Manual Control Test data)
- Calculate the sensor span

The process control laboratory experiment consists of five separate tests, split up between two lab periods. First, the pre-lab session is meant to make the students familiar with the equipment, to present the underlying chemical engineering theory, and to collect initial data that will be needed for the main lab session. One week later, the main lab session is meant for the students to conduct major experiments. The procedures for the pre-lab and main lab sessions of this experiment are found within the Process Control Lab Handout in Appendix II.

The first three tests all accomplish the first Learning Objective: Tune a controller for P, PI, and PID control. The students completed the first of these tests during the pre-lab. The students performed Ziegler-Nichols tuning to determine the tuning parameters for the process (see Equation 9 and Table IV). This tuning test was divided into two parts. In the first part, the students found an approximate value for the ultimate controller gain. As this part was time consuming, the sample interval was set to one second in order to reduce the number of data points collected. In the second part, the students found a more precise value for ultimate gain (K_U). The sample interval was changed to 200 msec to increase the detail of the oscillations so that the ultimate period could be determined.

The students then had a week in between the pre-lab session and the main lab session to calculate their tuning parameters. The next two tests, performed during the main lab period, were designed for the students to evaluate their tuning values by running the process during standard and upset conditions. In the fourth test, the students operated the process with manual control. The speed of the pump was gradually increased, and the linear relationship between the pump speed and water flow rate was recorded. This data was then used in Equation 4 to calculate process gain (K_P) and determine whether the controller is direct- or reverse-acting, accomplishing Learning Objective 5 and part of 4 related to the calculation of key variables.

The last part of the experiment required students to design and conduct tests investigating the impact proportional and integral action have on the closed-loop response for a PI controller and the impact derivative action has on the closed-loop response for a PID controller. In addition, the students were tasked with determining which controller is best suited for the process. Students calculated rise time and overshoot values for each test. Using these two metrics, along with qualitative observations, the students were required to discuss their findings on the impacts that controller actions have on closed-loop responses and evaluate which controller was optimal.

By designing and conducting their own tests, the second Learning Objective was accomplished. The third objective was met through the students' analysis of controller action and closed-loop response, as well as their determination of which controller was best suited for the process. Lastly, the fourth Learning Objective was met through the students' calculations of rise time and overshoot. This learning objecting was also accomplished through the students' final deliverable. The students were required to calculate the sensor span for the flowmeter using Equation 7 and the data from Table II. This deliverable was incorporated because knowing the sensor span is important when purchasing the instrument for a process, as well as when making any throughput changes to an existing system.

B. Materials, Instrumentation, and Equipment

Figure 4 shows a labeled depiction of the Armfield PCT-51 flow control module that was utilized in the process control experiment. The tank is filled with water to the zero mark on the flow indicator tube (3). The pump pushes water up the tubing, through the flowmeter, and out into the flow indicator tube. Water then drains at a constant rate through the holes in the flow indicator tube. A solenoid valve is on the line between the pump and flowmeter. When opened, water is diverted back into the tank before entering the flowmeter.

1. Electric flowmeter
2. Solenoid
3. Flow indicator tube
4. Electrical interface
5. Interchangeable solenoid orifice
6. Different size solenoid orifices
7. Drain ball valve
8. Variable speed centrifugal pump
9. Quick release connector

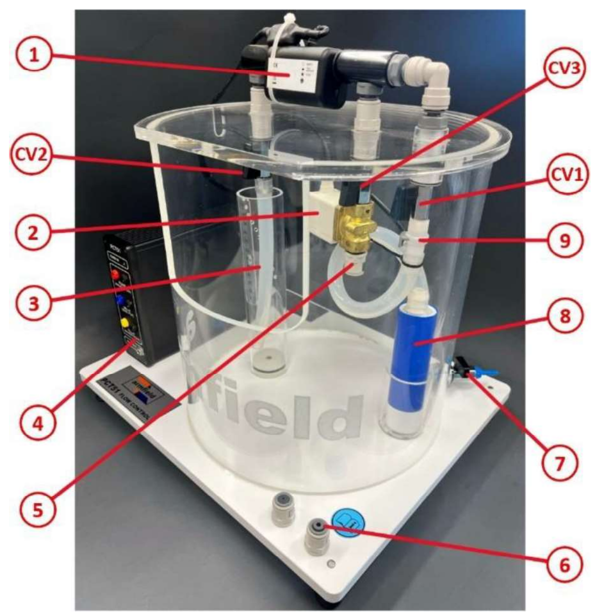


FIGURE 4 – Diagram of PCT-51 Flow Control Module

The PCT-51 module uses feedback control (closed-loop control). The flowmeter measures the flow rate of water passing through the tube. The measurement is then sent to the PID controller, which adjusts the speed of the centrifugal pump in an attempt to make the water flow rate equal to the setpoint. Figure 5 shows the block diagram for this control loop.

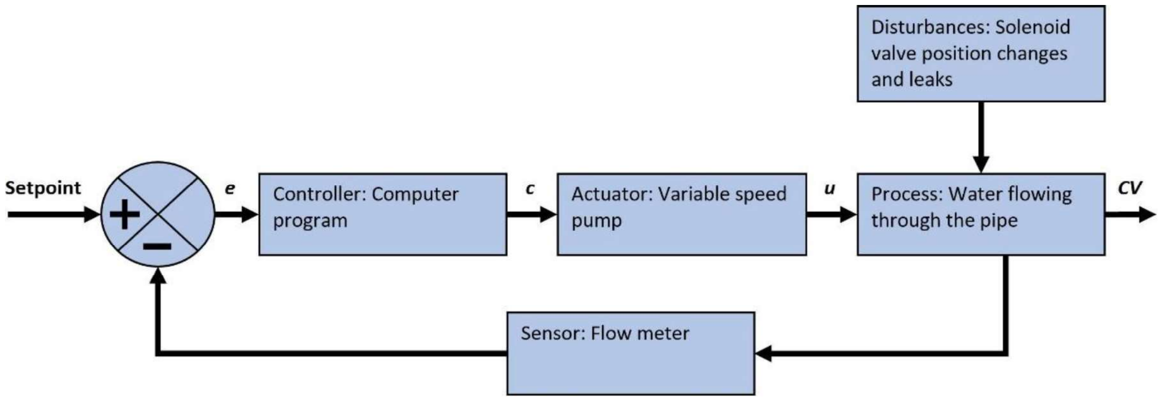


FIGURE 5 – Block Diagram of Flow Control Process

In the block diagram, *e* is the error from setpoint, *c* is the controller output, *u* represents the manipulated variable (MV), and CV means control variable. The CV is the water flowrate, the MV is the pump speed, and the controller output is a signal that tells the variable speed pump how fast to operate. Because controller output is a percentage, and the pump speed is measured in percent, the controller output happens to be the same value as the pump speed. This is not always the case for other systems.

All instrumentation is integrated within the PCT-51 unit. The only other materials and equipment needed for the experiment are about seven liters of water, the AC adaptor for the PCT-51 unit, a computer, a usb cable to connect the electrical interface to the computer, rubber tubing to connect to the drain nozzle, and a five-gallon bucket or drain to empty the water into after the experiment. In addition to physical equipment, ArmSoft PCT-51 Flow Control educational software is needed to interface with the PCT-51 module. The user interface of the software can be seen in Figure 6.

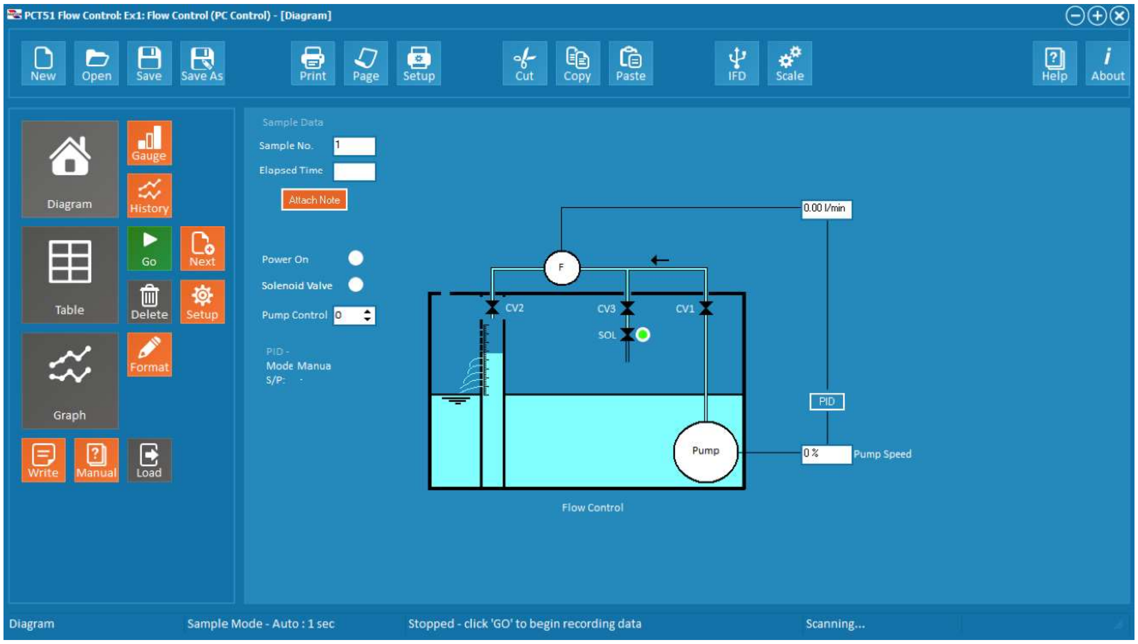


FIGURE 6 – ArmSoft PCT-51 Flow Control Educational Software User Interface

There are no major safety concerns associated with this experiment. Caution should be exercised as to not allow water to spill on any electrical equipment. All safety precautions and personal protective equipment that are required to enter the Unit Operations Lab must be adhered to.

C. Evaluation of Learning Objectives and Student Performance

Because the objectives of this report are driven by student outcomes, it is crucial to measure the change in the students' understanding of process control and ability to apply their knowledge to solve problems relating to the established Learning Objectives. On the day of the pre-lab session, before the students were formally introduced to the experiment, the students took a pre-assessment to determine their level of previous knowledge from their process control class, other engineering courses, or internship experiences. At the time of the pre-assessment, none of the students had yet received the experimental procedure provided in Appendix II. The students were given as much time as they needed to answer 13 questions listed below. This assessment was taken in the classroom using Microsoft Forms, and students were informed that the results of their pre-assessment would not affect their grades. A week after the main lab session, the students were emailed a post-assessment to take after they submitted their lab reports. This post-assessment was taken on the students' own time under no external observation. Once again, the students were informed that their scores on the post-assessment would not affect their course grades.

The post-assessment contained the same questions as the pre-assessment, along with 6 survey questions about what the students thought of the experiment. Students were not provided access to the correct answers after either assessment. This was done to prevent answer sharing among students as well as ensure students were not able to learn from their mistakes on the pre-assessment. Of the 43 students that completed the experiment, 34 completed the post-assessment and survey. The following questions were asked in both assessments to quantify what the students learned by completing the experiment (the **bold** answers are correct):

1. What chapter of Chemical and Bio-Process Control are you on in your Process Control class?
2. True or False: Controller gain is directly proportional to proportional action.
    a. **True**
    b. False
3. True or False: Proportional band is directly proportional to proportional action.

a. True

b. False

4. True or False: Integral time is directly proportional to integral action.

a. True

b. False

5. True or False: Derivative time is directly proportional to derivative action.

a. True

b. False

6. If the actuator in a process control loop is a variable speed pump, and the process gain is positive, is the controller direct- or reverse-acting?

a. Direct-Acting

b. Reverse-Acting

c. Both

d. Neither

7. To decrease the response time for a control loop under PI control, you can

a. Increase proportional band

b. Decrease proportional band

8. What can happen if the value for integral time is too high on a PI controller?

a. The closed-loop response may be sluggish

b. The closed-loop response may oscillate and become unstable

c. The closed-loop response may go to zero

d. The closed-loop response may go to infinity

9. What does integral action do on a PI controller?

a. Integral action minimizes overshoot

b. Integral action minimizes lag

c. Integral action minimizes oscillations

d. Integral action minimizes offset

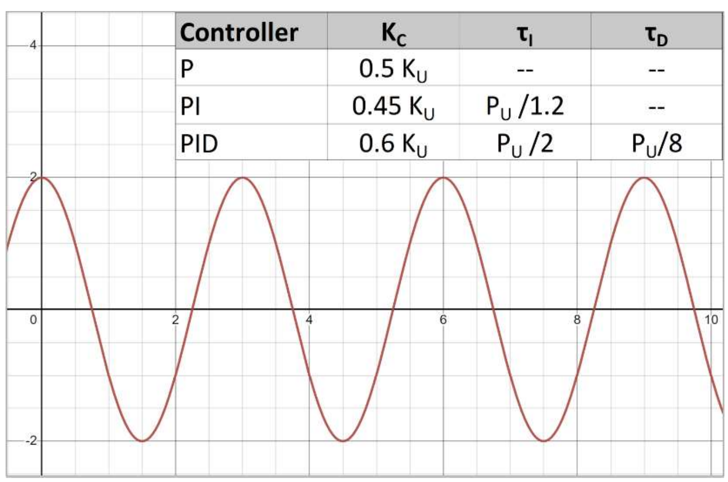
10. What type of control do you use to obtain the ultimate gain and ultimate period during Ziegler-Nichols tuning?

a. P-only

b. PI

c. PID

11. The following sustained oscillations were obtained during Ziegler-Nichols tuning. Given this data, what should the integral time be for a PID controller? **1.5 seconds**



Controller	K_C	τ_I	τ_D
P	0.5 K_U	--	--
PI	0.45 K_U	P_U /1.2	--
PID	0.6 K_U	P_U /2	P_U/8

FIGURE 7 – Theoretical Ziegler-Nichols Tuning Data

12. What is overshoot equal to based off of the following image: (Figure 3)

a. Overshoot = B

b. Overshoot = B/C

c. **Overshoot = B/D**

d. Overshoot = B-C

13. In this process control loop, the speed of a pump is changed to regulate the flow rate of water through a pipe. What is the control variable?

    a. The flow meter

    b. The pump

    c. The speed of the pump

    d. **The flow rate of water**

Question 1 was used to establish what content the students should have learned in their process control class prior to the lab as well as between their pre- and post-assessments. The Learning Objectives that each of the remaining questions targets are displayed in Table VI.

TABLE VI

ASSESSMENT QUESTIONS AND TARGETED LEARNING OBJECTIVES

Assessment Questions	Learning Objectives 1 Tune Controllers	2 Design and Conduct Experiments	3 Controller Action and Response	4 Variable Calculations	5 Direct- or Reverse-Acting
2	X				
3	X				
4	X				
5	X				
6					X
7	X		X		
8	X		X		
9			X		
10	X				
11	X				
12				X	
13				X	

Questions 2 through 5 test the students on their understanding of the relationship between tuning parameters and controller action. These questions correspond to the first Learning Objective, as these relationships must be understood to tune a controller. Question 6 directly tests the students on Learning Objective 5. Questions 7 through 9 cover Learning Objective 3. Questions 7 and 8 also require knowledge of the relationship between tuning parameters and controller action, involving Learning Objective 1. Questions 10 and 11 test the students on Learning Objective 1 and questions 12 and 13 test the students on Learning Objective 4. The accomplishment of Learning Objective 2 was not tested through the assessments. It was assessed through the results of the tests each group had to design and conduct.

Along with the post-assessment, the students answered six survey questions on a Likert scale (Table VII). The questions were used to get the students' perspective on the efficacy of the experiment.

TABLE VII

LIKERT SCALE STUDENT EXPERIENCE SURVEY

	Statements	**Strongly Agree**	**Agree**	**Neither Agree nor Disagree**	**Disagree**	**Strongly Disagree**
1)	The Process Control lab successfully taught me how to tune a PID controller.	1	2	3	4	5
2)	The Process Control lab helped develop my ability to design and carry out experiments.	1	2	3	4	5
3)	I believe the theory presented in the Process Control lab handout was sufficient.	1	2	3	4	5
4)	Performing the Process Control lab increased my understanding of Process Control and PID controllers.	1	2	3	4	5
5)	I was confused and did not know where to begin when performing calculations for my Process Control lab report.	1	2	3	4	5
6)	I believe the Process Control Experiment is a good addition to the Unit Operations II Lab Curriculum.	1	2	3	4	5

III. RESULTS AND DISCUSSION

A. Experimental Results

Each test outlined in the experimental design section was conducted three times to prove consistency prior to the implementation of the lab. These trials are referred to as Trials A, B, and C. The figures shown in this section are primarily from preliminary Trial A. The results for Trials B and C can be found in Appendix I. The experimental results collected by the students were consistent with the results from the preliminary trials.

Figure 8 shows the first part of the Ziegler-Nichols tuning test. At the start of the test, a very conservative value of 200% was chosen for proportional band. The PB was decreased in large steps until the closed-loop response became unstable at a PB of 25%. The PB was then increased by 5% and lowered in intervals of 1% until sustained oscillations developed. This behavior is expected, as by comparing Equations 2 and 7, controller output is inversely proportional to PB. Therefore, as PB decreases, the controller becomes more aggressive, which eventually leads to an oscillatory response.

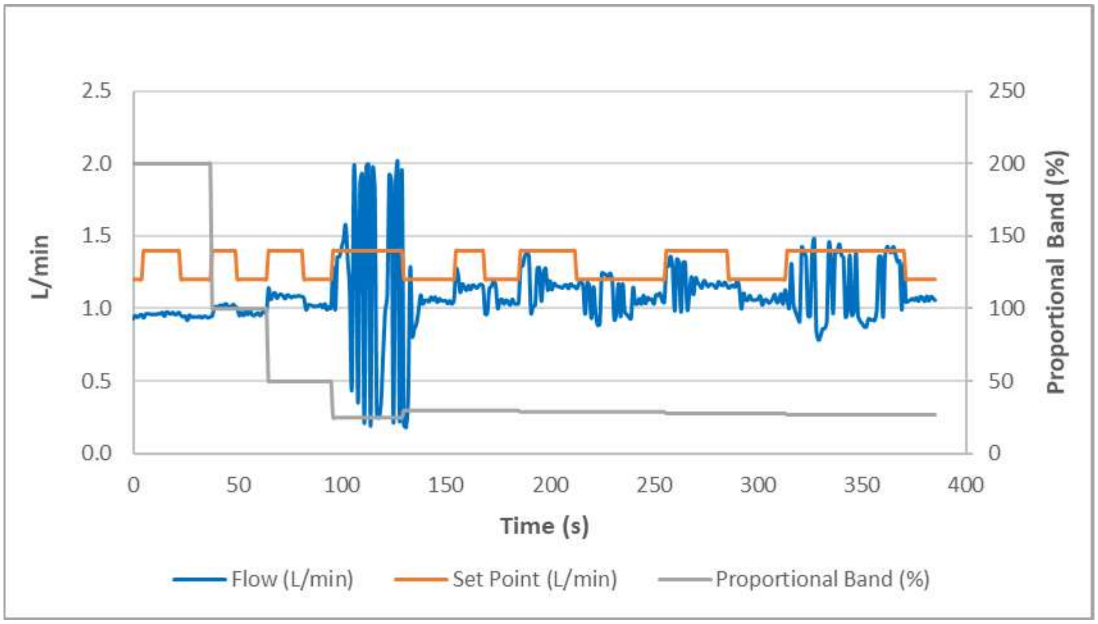


FIGURE 8 – Trial A – Ziegler-Nichols Tuning Test Part 1

The sustained oscillations appeared at a PB of 27%. Due to the large sample interval of one second, the ultimate period cannot be obtained from this part of the test. For the second part of the test, the sample interval was decreased to 200 ms. Sustained oscillations appeared again at a PB of 27%, indicating an ultimate proportional band of 27%. All preliminary trials and student tests found ultimate proportional bands of either 27% or 28%.

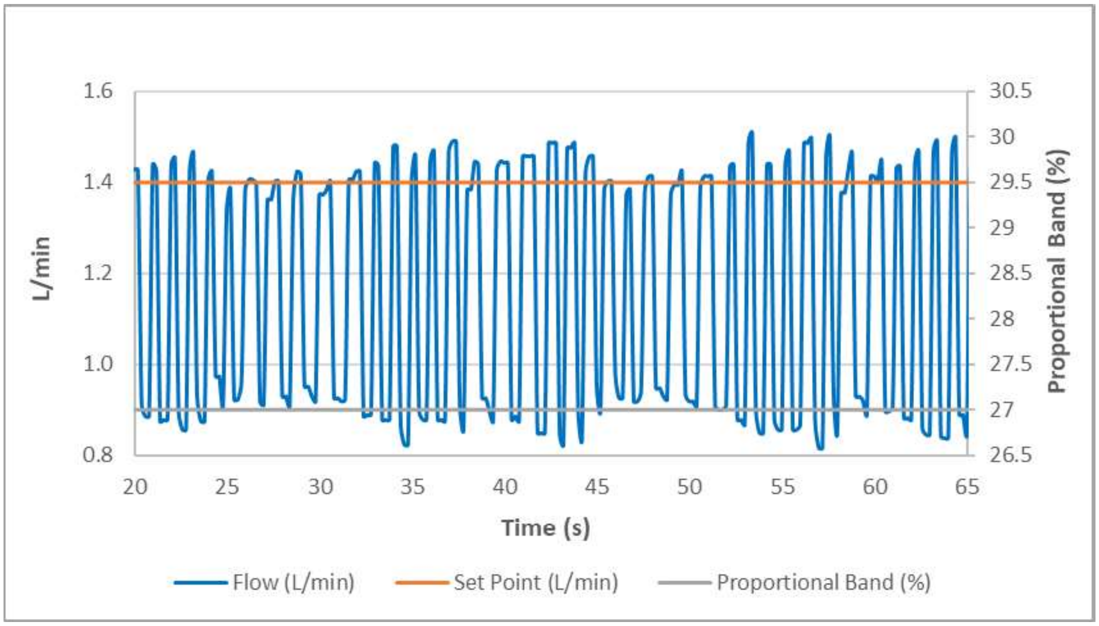


FIGURE 9 – Trial A – Ziegler-Nichols Tuning Test Part 2

An average ultimate period was found by dividing a length of time by the number of wavelengths present during the time. Figure 9 shows that in an interval of 45 seconds, there were 38 wavelengths, generating an average ultimate period of 1.18 seconds. This is consistent with the other preliminary trials, as well as the student results. The tuning parameters in Table VIII were then calculated using Table IV and Equation 9, as outlined in the Theory section.

TABLE VIII

TRIAL A – ZIEGLER-NICHOLS EXPERIMENTAL TUNING VALUES

Controller	PB	τ_I	τ_D
P	54%	--	--
PI	60%	0.99	--
PID	45%	0.59	0.15

Every lab group was able to obtain similar or identical tuning values as found in Trial A. After the tuning values were obtained, the process was operated between two setpoints under P-only, PI, and PID control. This test is important for the first Learning Objective, as evaluating tuning parameters is a key part of tuning a controller. Figure 10 shows the results of this test.

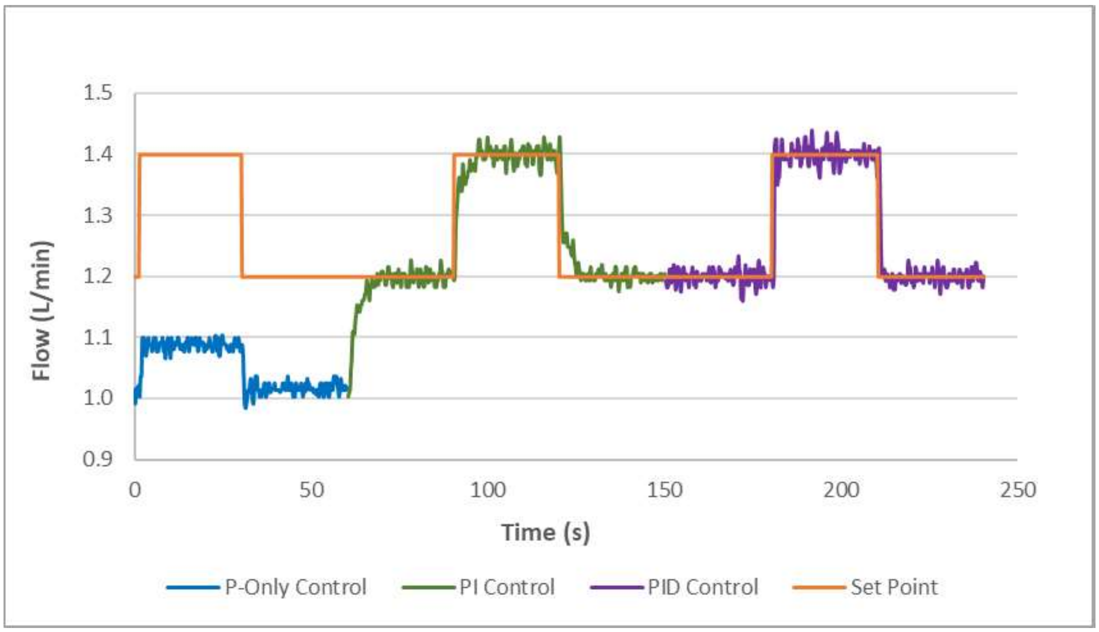


FIGURE 10 – Trial A – Tuned Controller Test

It can be seen that with P-only control, there is a large offset between the CV and the setpoint. Under PI control, the offset was eliminated, but the response time increased. When the controller was switched to PID control, the response time decreased. These results are consistent with the characteristics of proportional, integral, and derivative action, as presented in Chapter 7 of *Chemical and Bio-Process Control*[6]. Student results varied under PID control. Most student groups we able to obtain a stable closed-loop response, but four groups obtained an oscillatory response when they enabled PID control.

Three of the four were able to obtain a stable response after the oscillations. One likely explanation for the lack of stability under PID control is added noise due to a leak at the quick release connector at the outlet of the pump. Derivative control is very sensitive to noise and can cause a noisy system to become unstable.

The disturbance test yielded similar results. P-only control was fast but allowed for offset. Under PI control, the offset was eliminated, but it took more time for the CV to return to steady state after the change in valve position. PID control had inconsistent results. Figure 11 shows an unstable response after the solenoid valve was closed. Trial B had the same result, but Figure 12 shows the stable response obtained in Trial C.

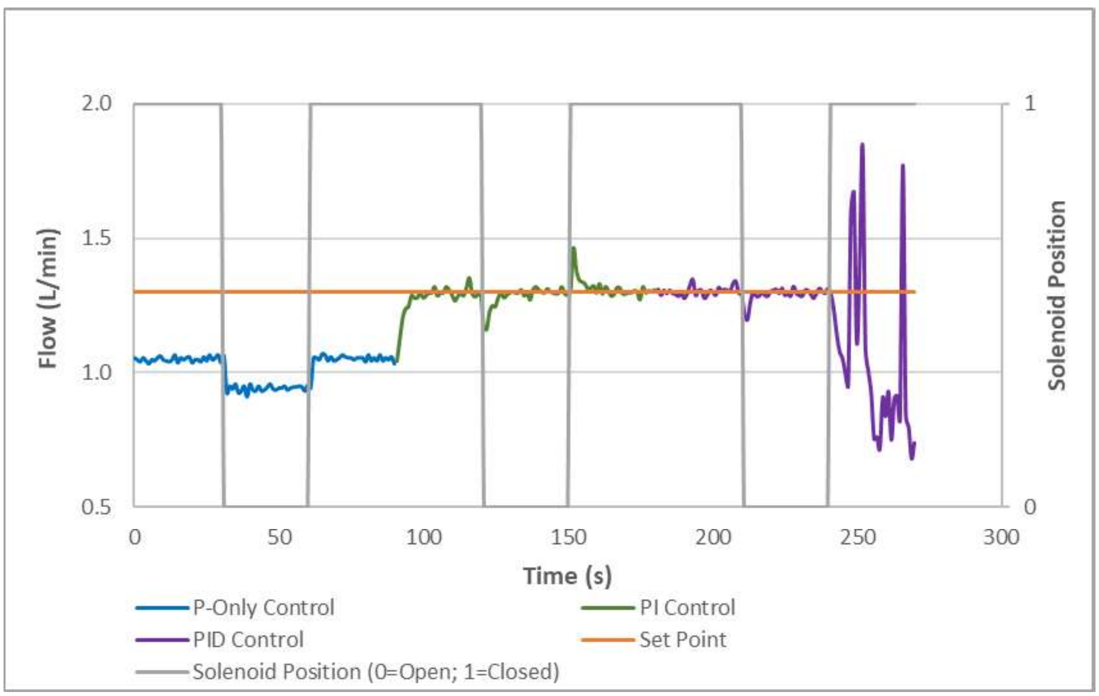


FIGURE 11 – Trial A – Disturbance Test

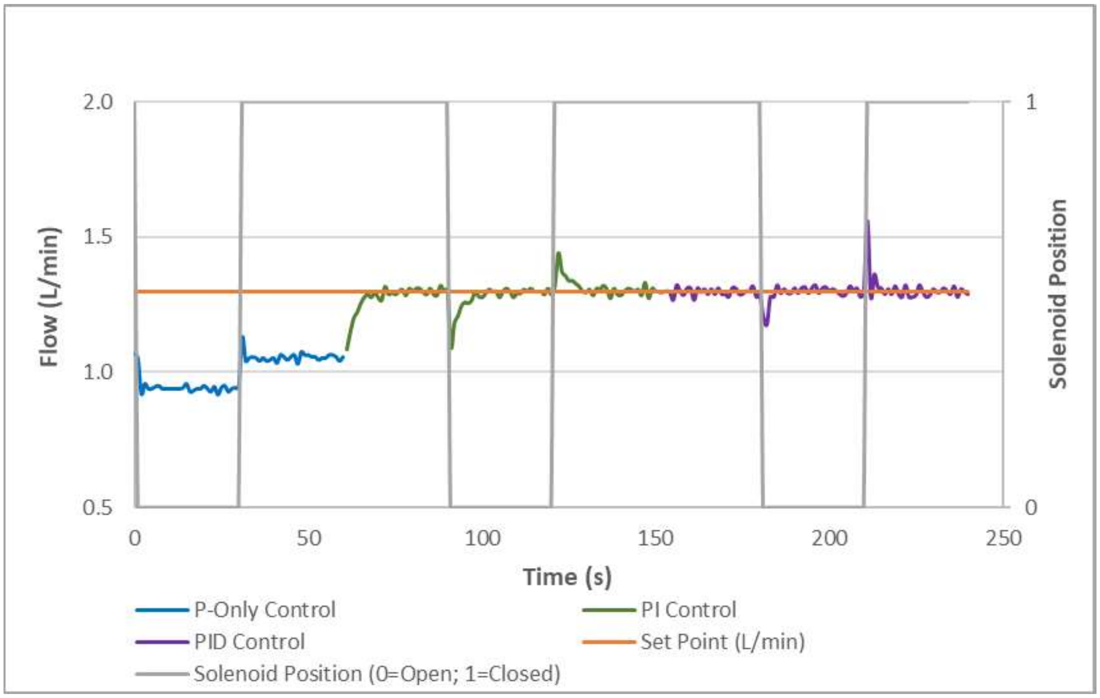


FIGURE 12 – Trial C – Disturbance Test

This same trend held for the student data. Five of the ten lab groups had graphs like Figure 11, while the other half had graphs more similar to Figure 12. As discussed before, it is likely that the leak at the outlet of the pump added noise to the system. Derivative control works to reduce the rate of change of the error from setpoint. As a result, rapid and unpredictable variations from setpoint can cause a controller with derivative action to amplify the noise and lead to erratic control.

The next test demonstrated the linear relationship between the CV (water flow rate) and the MV (pump speed). According to Equation 4, the process gain is equal to the slope of the line in Figure 13. The process gain can be obtained using the formula for the slope of a line or by using a linear trendline in MS Excel. The bottom equation in Figure 13 is for a trendline that was forced through the origin, while the trendline for the top equation was not. Regardless of the calculation method used, K_P is about 0.2 $\frac{L\%}{min}$. Solving for K_P relates to the fourth Learning Objective, regarding the calculation of key variables.

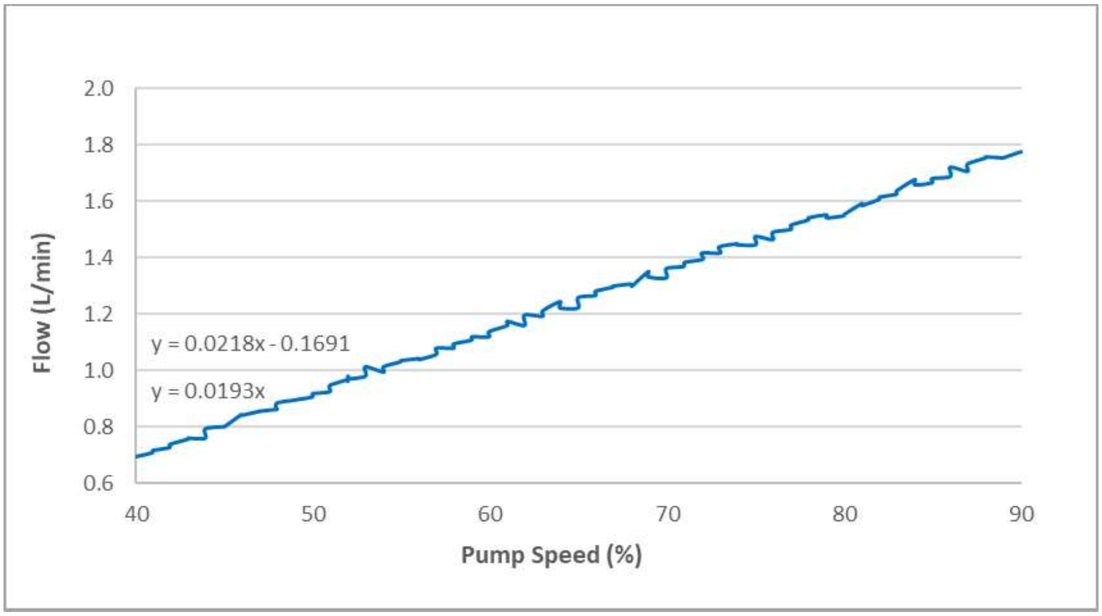


FIGURE 13 – Trial A – Manual Control Test

With the K_P calculated, Table III can be used determine whether the controller is direct- or reverse-acting. With a variable speed pump and a positive K_P, the students were able to successfully classify the controller as reverse-acting, accomplishing the fifth Learning Objective.

The last part of the experiment required students to design and conduct three tests to determine the impact proportional and integral action have on the closed-loop response for a PI controller and the impact derivative action has on the closed-loop response for a PID controller. The students were then required to determine which controller is best suited for this process. These requirements directly relate to Learning Objectives 2 and 3, regarding designing and conducting experiments, and describing the impact controller actions have on closed-loop responses. In addition to the results from Trial A, the student results from Lab Group 1 are shown below.

Figure 14 shows the preliminary results for the test investigating the impact proportional action has on the closed-loop response for a PI controller. Figure 15 shows the same results, with the oscillations at the end of the test cut off in order to show the closed-loop response at a larger visual scale. Figure 16 displays the results obtained by lab group 1.

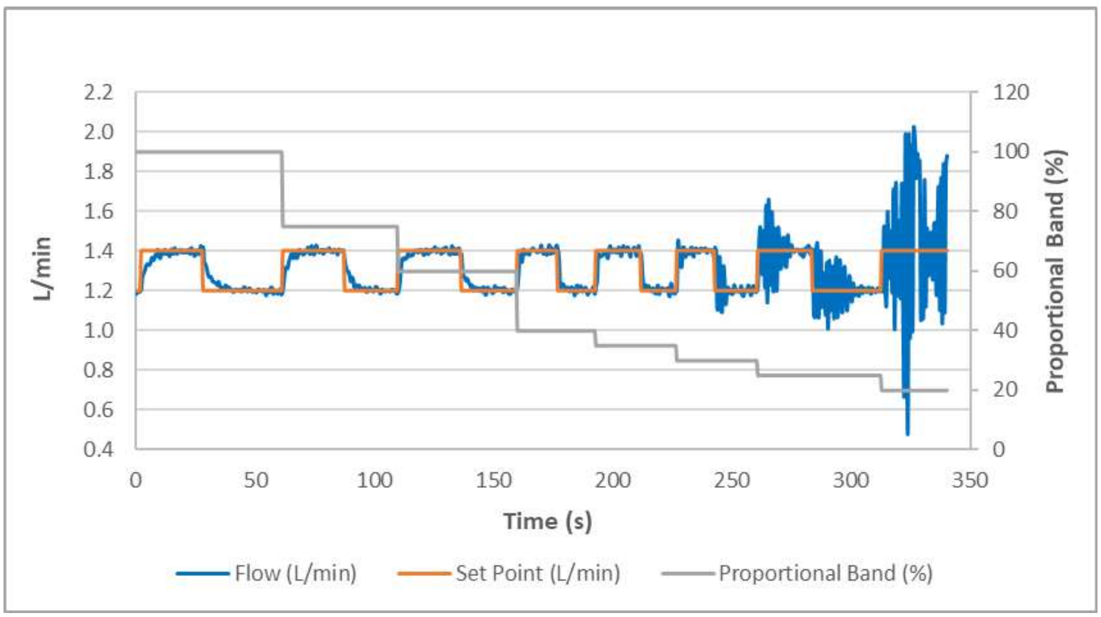


FIGURE 14 – Trial A – Effect of Proportional Action on a PI Controller

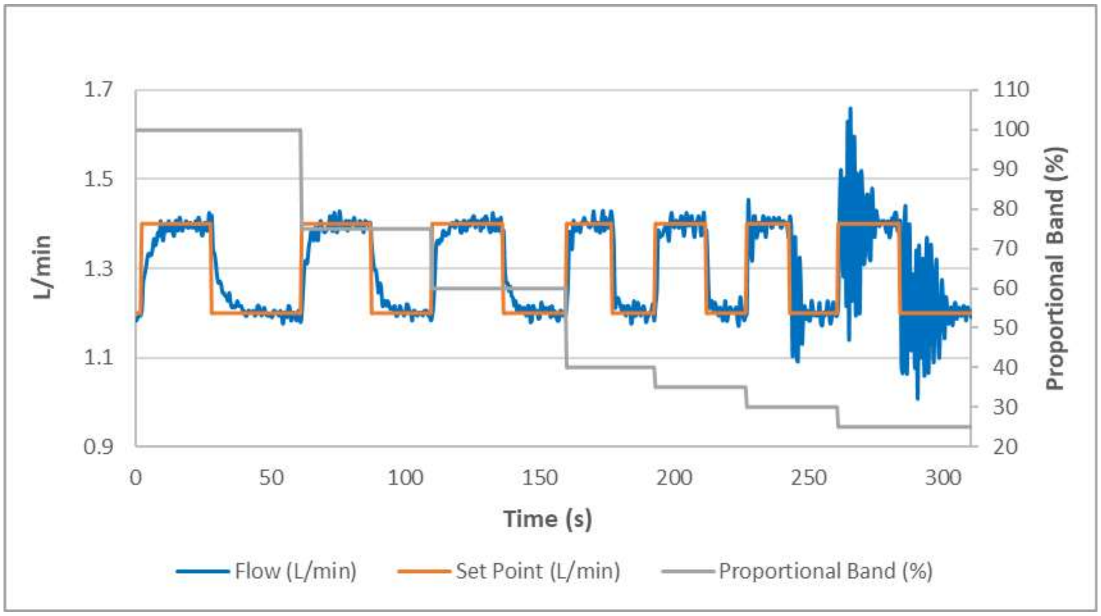


FIGURE 15 – Trial A – Effect of Proportional Action on a PI Controller; Cropped

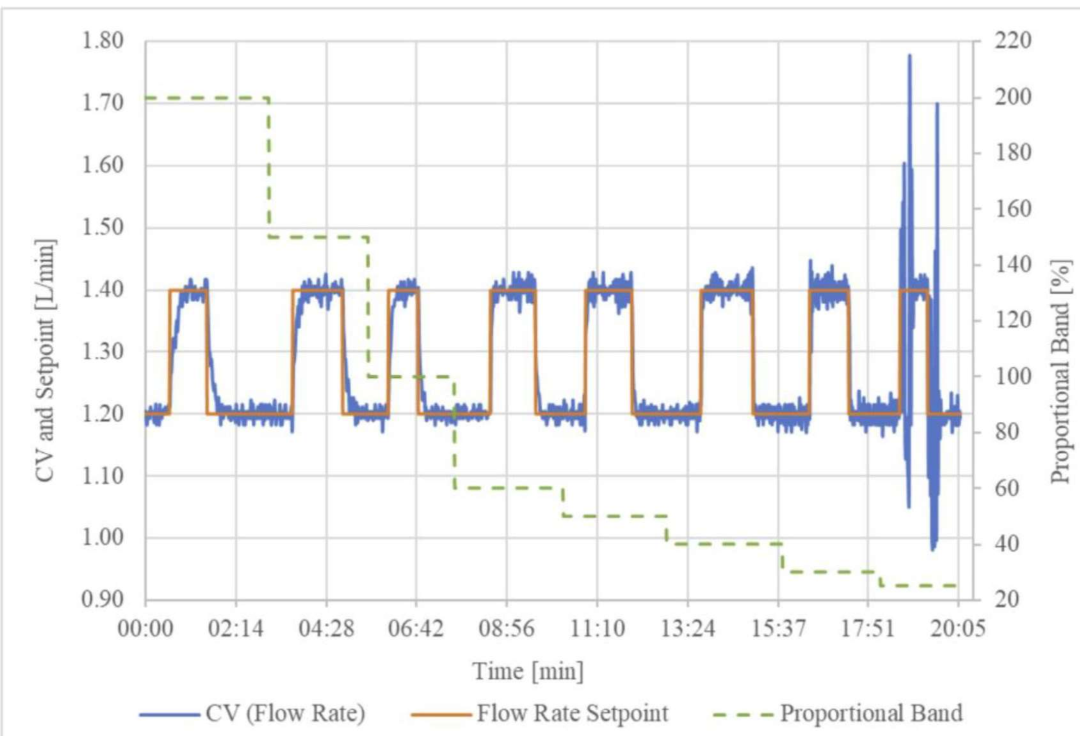


FIGURE 16 – Student Group 1 – Effect of Proportional Action on a PI Controller

As discussed above in Ziegler-Nichols tuning, proportional action increases as proportional band decreases. All three figures show that as PB decreases on a PI controller, rise time decreases. This is expected, as when the PB decreases, the controller becomes more aggressive, resulting in a faster response. When there is too much proportional action, large overshoots can occur, and the closed-loop response can become unstable. Lab group 1 ended their test before the response became truly unstable. Regardless, they were still able to observe the impact proportional action has on the closed-loop response for a PI controller. This holds true for most of the lab groups, demonstrating both their ability to design and conduct experiments as well as their successful investigation on how proportional action impacts the closed-loop response for a PI controller (Learning Objectives 2 and 3). Additionally, the students were successful in calculating rise time and overshoot values (Learning Objective 4) and using them as metric to compare the closed-loop response at different PB values.

The next test was done to investigate the impact integral action has on the closed-loop response for a PI controller. Figures 17 and 18 show the preliminary results and Figure 19 shows the students' results.

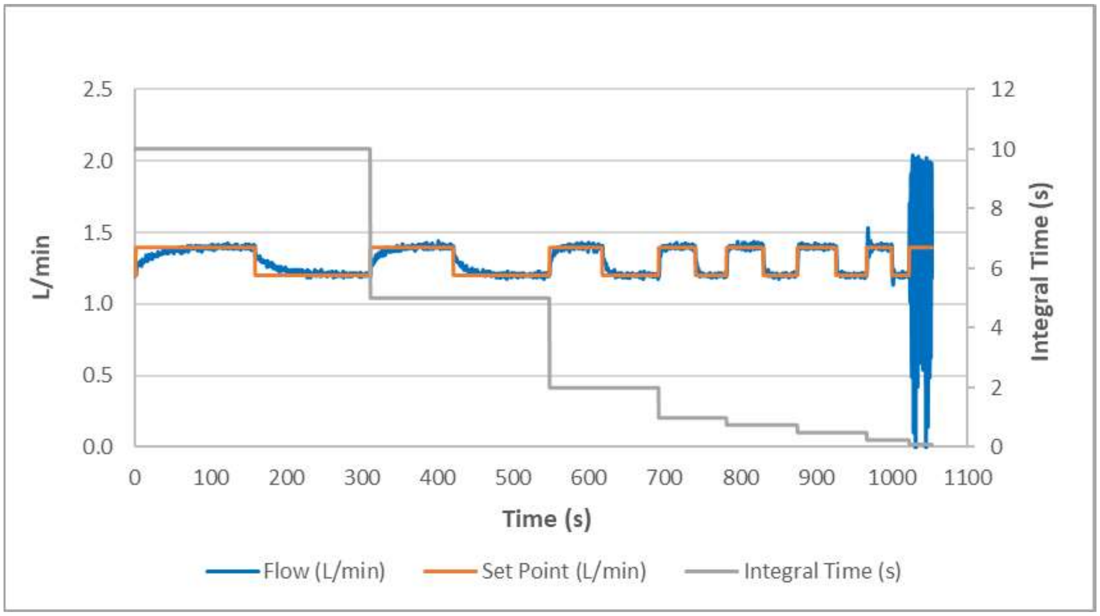


FIGURE 17 – Trial A – Effect of Integral Action on a PI Controller

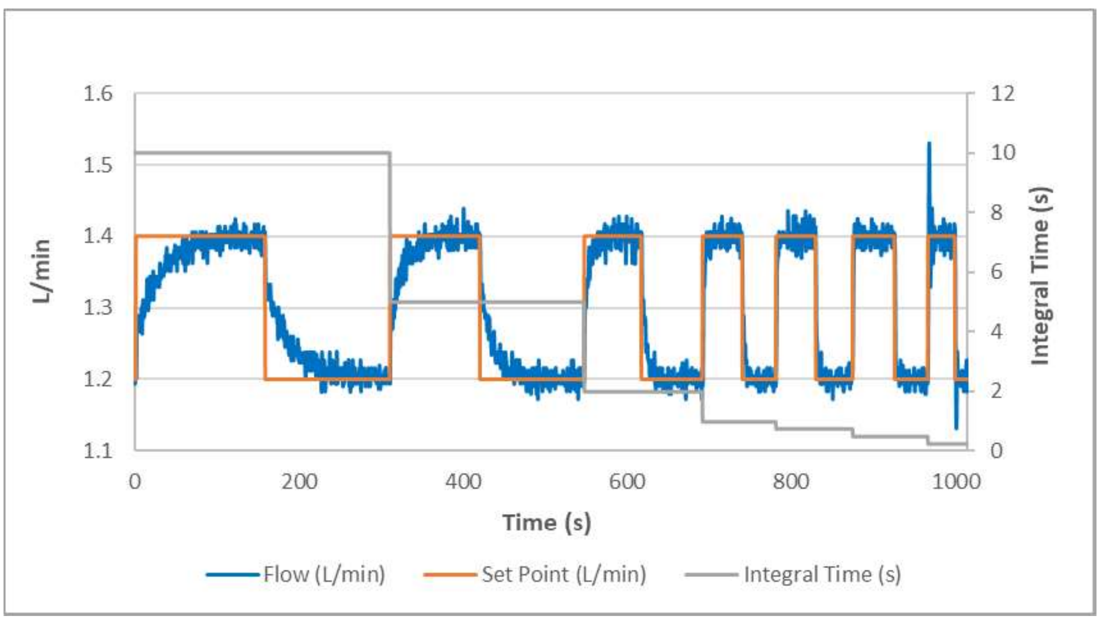


FIGURE 18 – Trial A – Effect of Integral Action on a PI Controller; Cropped

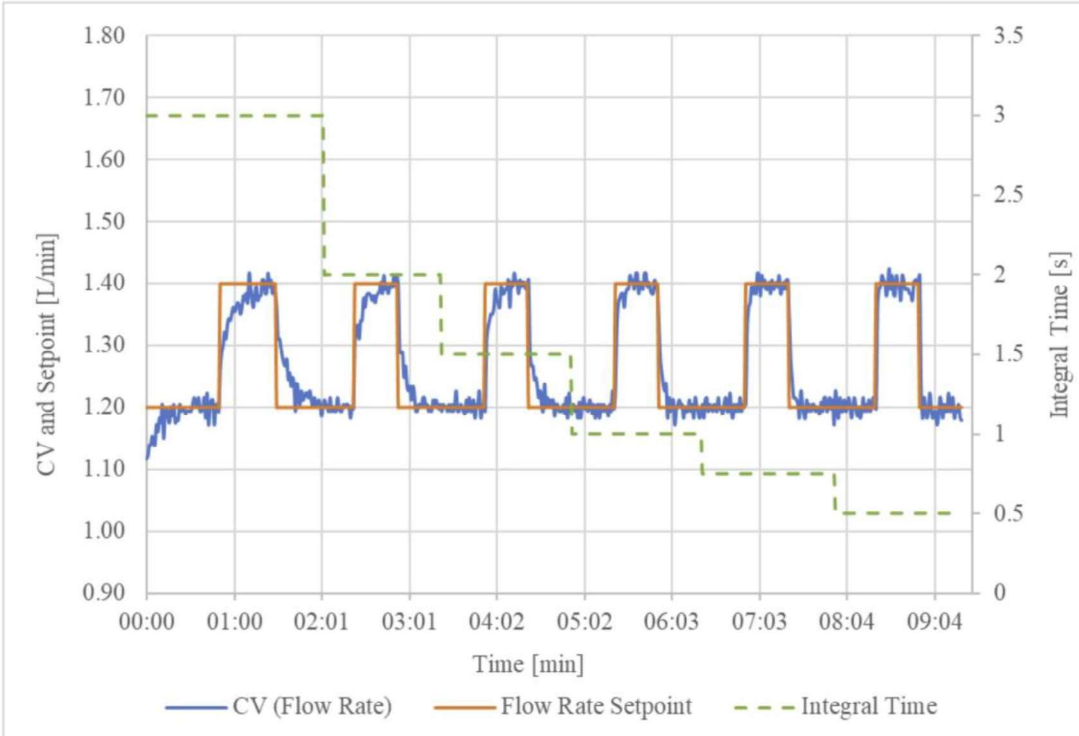


FIGURE 19 – Student Group 1 – Effect of Integral Action on a PI Controller

Equation 3 shows that as integral time decreases, controller output and the amount of integral action increases. Both tests show that as integral time decreases on a PI controller, rise time decreases. This is expected, as when integral time decreases, the controller becomes more aggressive, resulting in a faster response. When there is too much integral action, large overshoots can occur, and the closed-loop response can become unstable. Similar to the PB test above, this group of students did not observe the oscillatory response that can occur when the integral action is too aggressive. Nevertheless, they, along with most of the lab groups, were able to design and conduct an effective experiment to observe the impact integral action has on the closed-loop response for a PI controller, achieving Learning Objectives 2 and 3. Additionally, their observations were supported by calculations of rise time and overshoot, accomplishing Learning Objective 4.

The next test was done to investigate the impact derivative action has on the closed-loop response for a PID controller. Figures 20 and 21 show the preliminary results and Figure 22 shows the student results.

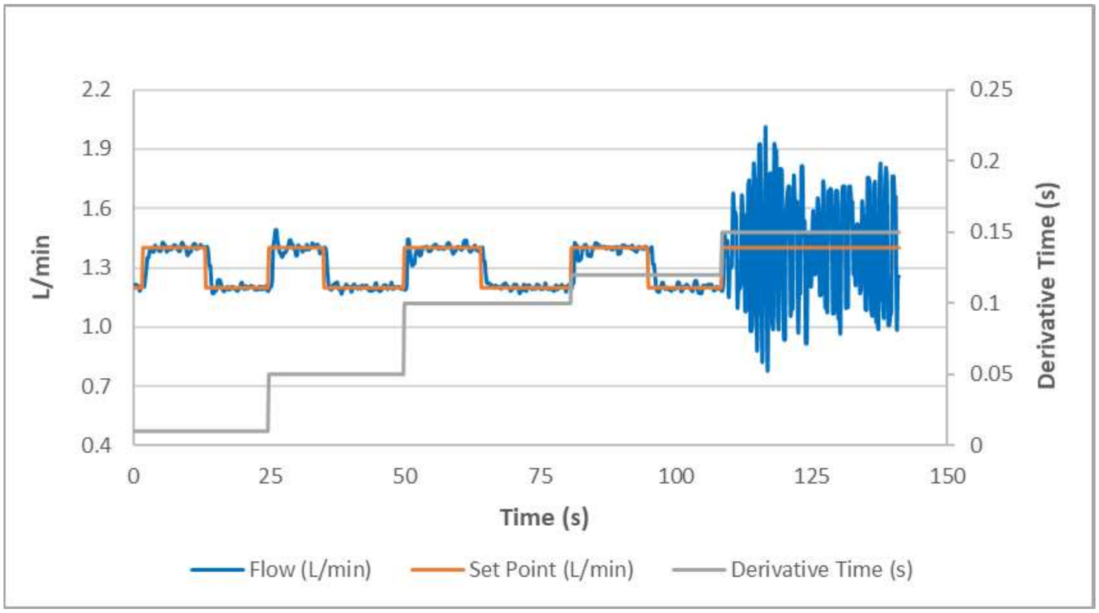


FIGURE 20 – Trial A – Effect of Derivative Action on a PID Controller

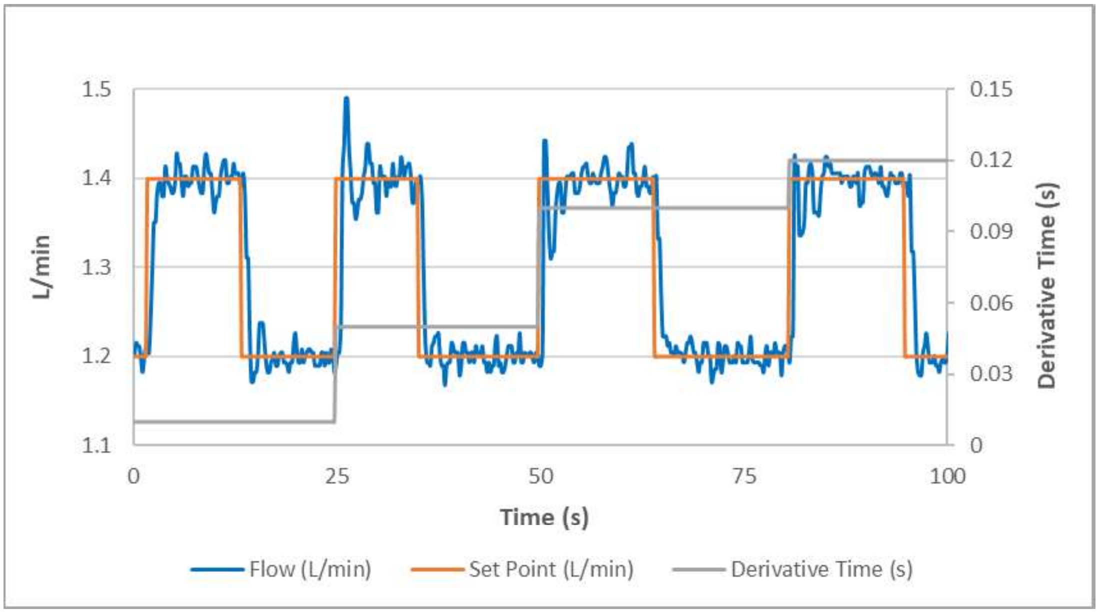


FIGURE 21 – Trial A – Effect of Derivative Action on a PID Controller; Cropped

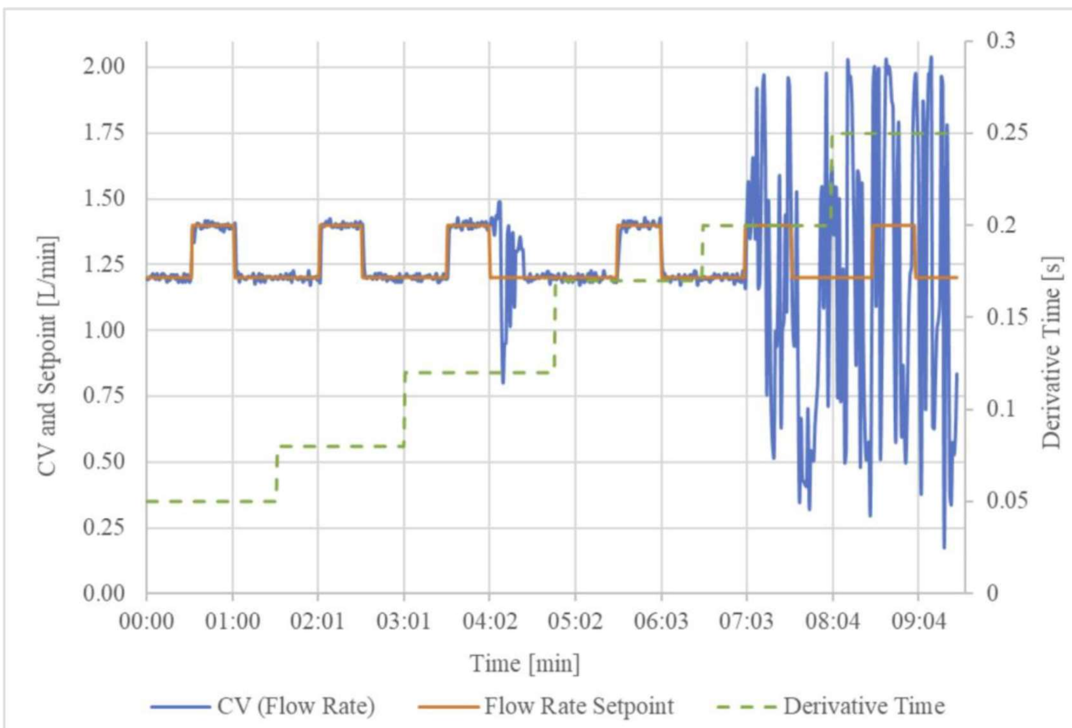


FIGURE 22 – Student Group 1 – Effect of Derivative Action on a PID Controller

Equation 1 shows that as derivative time increases, controller output and the amount of derivative action increases. None of the figures display any clear and consistent relationship between derivative action and rise time or overshoot. The range over which derivative time could be tested before the closed-loop response became unstable was very narrow. This may be due to the leak in the tubing discussed earlier. The narrow testing range may have limited the observation of significant trends with rise time and overshoot.

The last deliverable required in the students' lab reports was a calculation of sensor span. The correct value for the span of the sensor is $7.5 \frac{L}{min}$. The students were able to successfully calculate this value, further achieving Learning Objective 4.

Overall, the students' experimental results were consistent and aligned with the preliminary results. The students achieved the first Learning Objective by obtaining ultimate tuning parameters, calculating tuning values, and testing them with P-only, PI, and PID control. While not all groups were successful in maintaining a stable response under PID control, they were able to learn about the limitations of derivative control. The second Learning Objective was accomplished, as the students successfully designed and conducted experiments investigating the impact proportional, integral, and derivative action have on the closed-loop responses under different types of control.

Most students argued that PI control was best suited for this process, as the closed-loop response was stable and had no offset. Some students discussed the strengths and weaknesses of each type of control and argued that the optimal controller depends on the desired outcome. There is no correct or incorrect answer for which type of control is optimal, if the students were able to defend their choice. Viewed together, the students were highly successful in both identifying the impact controller actions have on the closed-loop response and defending their stance on which controller is optimal for this system, accomplishing the third Learning Objective. The fourth Learning Objective was accomplished through the students' successful calculations of K_P, rise time, overshoot, and sensor span. Lastly, through the calculation of K_P, the students were able to identify the controller as reverse-acting, achieving the last Learning Objective.

B. Student Assessment Results

In Unit Ops II Lab, students complete three experiments over the course of the semester. Due to this, some students conducted the process control experiment near the beginning of the semester, while others performed it towards the end. For the data presented in this section, the students' results are grouped under Lab 1, Lab 2, and Lab 3 based off whether it was their first, second, or third lab of the semester. Table IX displays the course schedule.

TABLE IX

UNIT OPS LAB II PROCESS CONTROL EXPERIMENT TIMELINE

Course Schedule	**Week 1-3**	**Week 4**	**Week 5**	**Week 6**	**Week 7**	**Week 8**	**Week 9**	**Spring Break**	**Week 11**	**Week 12**	**Week 13**	**Week 14**	**Week 15**
Lab 1 Pre-Lab & Pre-Assessment		X											
Lab 1 Main Lab			X										
Lab 1 Post-Assessment and Report Due					X								
Lab 2 Pre-Lab & Pre-Assessment					X								
Lab 2 Main Lab						X							
Lab 2 Post-Assessment and Report Due									X				
Lab 3 Pre-Lab & Pre-Assessment									X				
Lab 3 Main Lab										X			
Lab 3 Post-Assessment and Report Due												X	

This lab was designed to be conducted by the students once they have covered chapter two in their process control textbook, *Chemical and Bio-Process Control*[6]. Furthermore, for this project to be successful, students must accomplish the Learning Objectives and benefit from the experiment regardless of process control class progress.

In addition to the students' performance in the experiment and on their lab reports, their performance on the pre- and post-assessments was used to assess whether the Learning Objectives were met. Table X contains descriptive statistics for the students' performance on both assessments.

TABLE X

STUDENT ASSESSMENT PERFORMANCE DESCRIPTIVE STATISTICS

Statistic	Pre-Assessment	Post-Assessment
Mean	34.30%	55.88%
Standard Error	2.17%	3.33%
Median	33.33%	54.17%
Mode	41.67%	41.67%
Standard Deviation	14.23%	19.41%
Sample Variance	2.02%	3.77%
Range	66.67%	75.00%
Minimum	8.33%	25.00%
Maximum	75.00%	100.00%
Students	43	34

Across all three lab groups, the average score on the pre-assessment was a 34.30% and the average score on the post-assessment was a 55.88%. This shows an absolute improvement of 21.58% and a 62.91% increase relative to the pre-assessment average. For the remainder of the results, any improvement between assessment scores will be discussed in absolute terms rather than relative.

The results for each lab group are shown in Table XI. The mean pre-assessment scores for each lab group are within a few percentage points of each other. The last lab group only scored 0.23% higher than the first lab group, despite having seven weeks of additional time in their process control class. This provides evidence that the increase in score between assessments is due to the completion of the experiment rather than the content in their process control course. The average score on the pre-assessment was slightly better than the average score a student would obtain by guessing on each question (~34%). This indicates that students likely have difficulty applying theoretical knowledge from their process control class to practical scenarios.

TABLE XI

STUDENT ASSESSMENT PERFORMANCE SUMMARY

Lab	Pre-Assessment	Post-Assessment	Absolute Change	Relative Change	Number of Students (Pre/Post)	Chapter in Process Control Textbook (Pre/Post)
Lab 1	35.19%	58.85%	23.67%	67.27%	18/16	4/6
Lab 2	32.05%	43.75%	11.70%	36.50%	13/12	6/8
Lab 3	35.42%	72.22%	36.81%	103.92%	12/6	8/11
Overall	34.30%	55.88%	21.58%	62.91%	43/34	

The average post-assessment scores varied more, with Lab 3 performing the best and Lab 2 performing the worst. While Lab 2 had the smallest improvement between the two assessments, the average score still increased by 11.7%. The data show that on average, regardless of when students conducted the experiment over the course of the semester, completing the experiment led to an increase in score between their two assessments.

A one-tailed, paired student t-test was used to determine the statistical significance of the increase in performance between assessments. Prior to the t-test, Kolmogorov-Smirnov (KS) normality tests were conducted for both assessment distributions. The results indicated that neither data set significantly diverges from a normal distribution, validating the normality assumption for the t-test. The p-value for the paired t-test was 2.80E-06, which is lower than the most common significance level of 0.05. This supports the claim that the mean score on the post-assessment was greater than the mean score on the pre-assessment.

The paired student t-test is most appropriate for analyzing the data, as the same students took the pre- and post-assessments. However, nine students did not complete the post-assessment. Consequently, the paired t-test excludes the pre-assessment scores from those nine students. Because of this, an unpaired, two-sample t-test was completed to ensure the results are statistically significant when including all of the data collected. A homoscedastic test was chosen after a Levene's test found no significant difference in variances between the pre- and post-assessment scores. The p-value for the two-sample, homoscedastic t-test was 1.50E-07, which is lower than the most common significance level of 0.05. This provides evidence that the mean score on the post-assessment was greater than the mean score on the pre-assessment.

Table X shows the mean and median are within one percentage point of each other for the pre-assessment and two percentage points for the post-assessment. The median is less sensitive to extreme values compared to the mean. Both measures of central tendency are close in value and show similar increases between tests. This indicates that the overall improvement between the assessments is likely robust and not excessively influenced by a few exceptionally high or low scores. Additionally, this provides evidence that the improvement is representative of the overall performance of the students and is not solely driven by a particular subgroup. This claim is further supported by Figure 23.

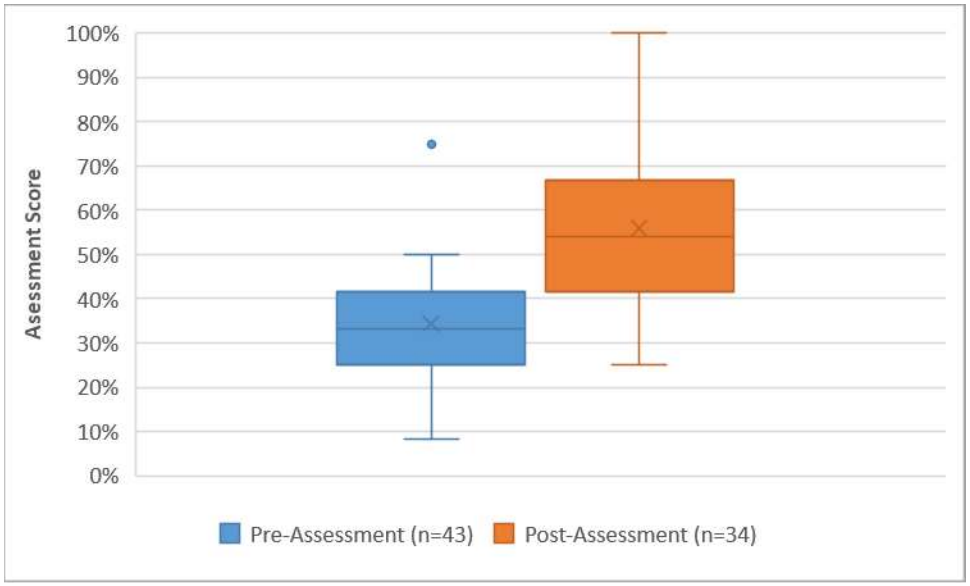


FIGURE 23 – Student Pre- and Post-Assessment Performance

This box and whisker plot shows that each quartile in the post-assessment results is significantly higher than the same quartile for the pre-assessment results. The minimum score for the post-assessment is the same point (25%) as the lower quartile for the pre-assessment. This trend continues, as the lower whisker for the post-assessment has the same range as the entire interquartile range for the pre-assessment. Only one score on the pre-assessment is higher than the median of the post-assessment.

Across the 34 students that took the post-assessment, only three scored worse than their pre-assessment by one question each. After excluding the nine students' data who did not complete the post-assessment, the mean and median score on the pre-assessment are 36.03% and 41.67% respectively. The nine excluded pre-assessment scores were on average lower than the rest of the data, with a mean score of 27.78% and a median score of 25%. The difference in score between the post-assessment and the pre-assessment for each student was plotted in Figure 24.

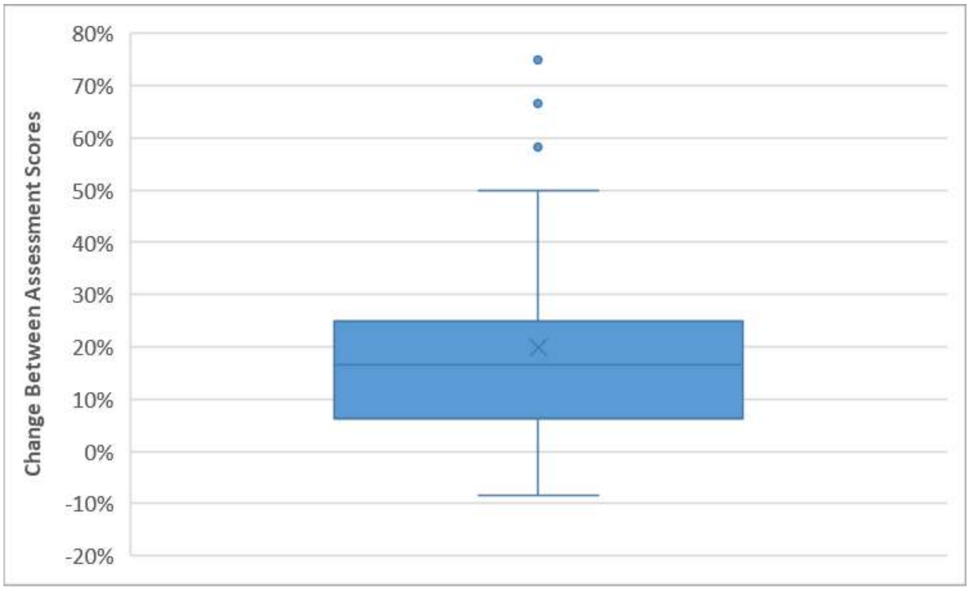


FIGURE 24 – Change in Student Performance Between Pre- and Post-Assessments

This box and whisker plot only includes data from students who completed both assessments. Because the nine excluded scores were lower on average compared to the rest of the scores, the mean and median improvement are lower than the overall absolute change reported in Table XI. The mean and median improvement between the two assessments are 19.85% and 16.67% respectively.

In addition to overall improvement, the average change in performance for each question was calculated. The questions can be seen in Table XII and the results are displayed in Figure 25. Question 1 was omitted from the table and figure below, as it relates to what chapter the students were on in their process control class and was worth no points.

TABLE XII

PRE- AND POST-ASSESSMENT QUESTIONS

	Assessment Questions
2.	True or False: Controller gain is directly proportional to proportional action.
3.	True or False: Proportional band is directly proportional to proportional action.
4.	True or False: Integral time is directly proportional to integral action.
5.	True or False: Derivative time is directly proportional to derivative action.
6.	If the actuator in a process control loop is a variable speed pump, and the process gain is positive, is the controller direct- or reverse-acting?
7.	To decrease the response time for a control loop under PI control, you can
8.	What can happen if the value for integral time is too high on a PI controller?
9.	What does integral action do on a PI controller?
10.	What type of control do you use to obtain the ultimate gain and ultimate period during Ziegler-Nichols tuning?
11.	The following sustained oscillations were obtained during Ziegler-Nichols tuning (Figure 7). Given this data, what should the integral time be for a PID controller?
12.	What is overshoot equal to based off of the following image (Figure 3):
13.	In this process control loop, the speed of a pump is changed to regulate the flow rate of water through a pipe. What is the control variable?

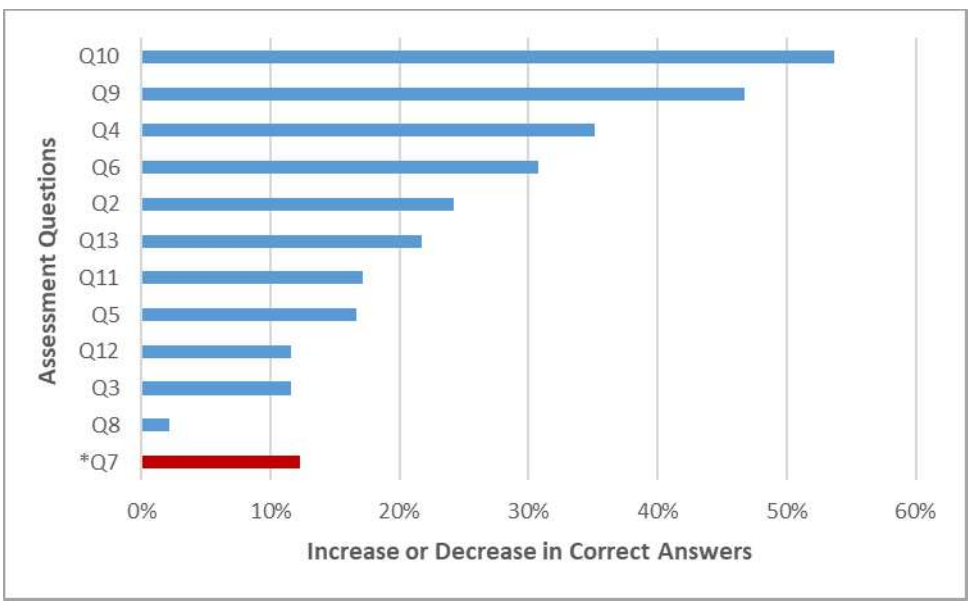


FIGURE 25 – Change in Question Performance Between Pre- and Post-Assessments
*Question 7 in red had a decrease of about 12% in performance

This plot includes the data from the nine students who did not take the post-assessment. The values were obtained by finding the difference between the percentage of students who correctly answered a specific question on the post-assessment and the percentage of students who answered same question correctly on the pre-assessment. The students improved the most on questions 10 and 9. Question 10 covers a key aspect of Ziegler-Nichols tuning, and question 9 is about the relationship between integral action and the closed-loop response. These questions support the accomplishment of Learning Objectives 1 and 3.

Students improved the least on questions 7 and 8. Just over 12% more students got question 7 wrong on the post-assessment than the pre-assessment. Questions 7 and 8 are both more challenging and test the students' capability of using higher level processes of analyzing by forming relationships between different concepts. Table VI shows that these questions target both Learning Objectives 1 and 3. Both questions required knowledge of the relationship between tuning parameters, controller action, controller aggression, and the closed-loop response of the system. The students had to connect all of these ideas in order to know the answer to both questions.

The intention for questions 7 and 8 was to assess the students' understanding of concepts from Learning Objective 3. These questions should be redesigned, as they require knowledge beyond the scope of Learning Objective 3. While there was not a notable improvement on questions 7 and 8, the students markedly increased their scores on the remaining questions.

In addition to the pre- and post-assessment, a post-lab, Likert scale survey was used to evaluate if the students believed the experiment was beneficial. The results are displayed in Table XIII.

TABLE XIII

LIKERT SCALE STUDENT SURVEY EXPERIENCE RESULTS

	Statements	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree	Average Score (1 = Strongly Disagree, 5 = Strongly Agree)
1)	The Process Control lab successfully taught me how to tune a PID controller.	13	20	1	0	0	4.35
2)	The Process Control lab helped develop my ability to design and carry out experiments.	6	24	4	0	0	4.06
3)	I believe the theory presented in the Process Control lab handout was sufficient.	15	16	3	0	0	4.35
4)	Performing the Process Control lab increased my understanding of Process Control and PID controllers.	15	19	0	0	0	4.44
5)	I was confused and did not know where to begin when performing calculations for my Process Control lab report.	0	10	7	17	0	2.79
6)	I believe the Process Control Experiment is a good addition to the Unit Operations II Lab Curriculum.	13	19	2	0	0	4.32

The average scores for statements 1, 2, 3, 4, and 6 were all between four and five. This indicates that students, on average, agree or strongly agree with the statements. No students selected disagree or strongly disagree for these statements. The results for statements 1, 2, and 4 show that students believe that performing the experiment had a positive impact on their learning. The results for statement 3 show that the theory section presented in the lab handout sufficiently prepared even the first lab group for the experiment. The results for statement 6 show that the students believe the process control experiment is a good addition to the Unit Ops II Lab curriculum.

The average score for statement five was 2.79, indicating that on average, students were neutral or disagreed with the statement provided. No students selected strongly agree or strongly disagree. This is a positive result, as it shows that the students were appropriately challenged with the calculations in the lab report.

IV. CONCLUSIONS

Process control is an essential aspect of manufacturing used to enhance process safety, optimize process efficiency, reduce product variability, and decrease energy consumption. A thorough understanding of process control is crucial for chemical process engineers. In recognition of its significance, ABET has designated process control as a core subject for chemical engineering curriculum. Thus, it is necessary that chemical engineering graduates from the University of Louisville possess the knowledge and skills required to apply process control concepts to manufacturing systems. To ensure this, a hands-on process control laboratory experiment was designed and implemented as part of the Unit Ops II Lab Course.

The experiment uses an Armfield PCT-51 flow control module to provide fourth-year chemical engineering students with practical, hands-on experience tuning a proportional-integral-derivative (PID). Furthermore, the experiment reinforces key concepts from their process control class. Through the successful completion of the experiment, students are expected to demonstrate the ability to: tune a controller for P, PI, and PID control; design and conduct experiments relating to process control; describe the impact proportional, integral, and derivative action have on the closed-loop responses for various controllers and determine which controller is best suited for the given process; calculate key process, sensor, and controller variables, such as process gain, sensor span, rise time, and overshoot; and determine if a controller is direct- or reverse-acting. The accomplishment of these Learning Objectives was assessed via pre- and post-assessments in tandem with the students' experimental results.

Prior to the implementation of the lab, three preliminary trials were conducted in order to confirm the experiment's repeatability. In general, the students' experimental results were in line with the preliminary data, further demonstrating the experiment's repeatability. Moreover, the students' consistent and accurate results substantiate the accomplishment of the Learning Objectives.

The students were given a pre- and post-assessment with identical questions based on the Learning Objectives to quantify what they learned through the completion of the lab. Students were not given access to the results after they had completed either assessment. This was done to ensure answers could not be shared and also students would not learn from their mistakes on the assessment. On average, the students' scores increased by 22 percentage points between assessments. Additionally, an increase in score was observed across all lab groups, regardless of when in the semester the lab was completed. These results provide compelling evidence that the students successfully achieved the Learning Objectives through their completion of the experiment, thus confirming the overall success of the project.

After the students submitted their lab reports, they were given a Likert scale survey. The survey results were positive and indicated that the students found the process control lab to be appropriately challenging, beneficial to their learning, and a valuable addition to the Unit Ops II Lab curriculum.

V. RECOMMENDATIONS

If the process control laboratory experiment is incorporated into the Unit Ops II Lab curriculum, a few recommendations can be implemented to enhance its effectiveness and better measure the accomplishment of the Learning Objectives:

1. Replace assessment questions 7 and 8
2. Remove Learning Objective 4
3. Remove the calculations of overshoot and sensor span
4. Discuss derivative control's sensitivity to noise in the lab handout
5. Contact Armfield to fix data collection issues
6. Utilize the other Armfield process control tabletop modules

The first recommendation is to replace questions 7 and 8 on the assessments. These questions are ineffective at assessing the students' understanding of specific Learning Objectives. Both questions require applying knowledge from Learning Objectives 1 and 3. On average, the students did not show any improvement on these questions between the two assessments. Because the questions required knowledge from outside the scope of a single Learning Objective, the point of failure cannot be identified.

As many of the assessment questions focus on the first Learning Objective, revised versions of questions 7 and 8 should only relate to Learning Objective 3. Instead of asking what can happen if the value for integral time is too high on a PI controller, question 8 should ask what can happen if there is not enough integral action on a PI controller. Question 7 asks how to decrease the response time for a control loop under PI control. The correct answer should be "increase proportional action," rather than "decrease proportional band." These changes will allow the assessments to more effectively identify areas for improvement with respect to the Learning Objectives.

The next recommendation is to remove Learning Objective four. With the exception of sensor span, all calculations in the lab are integrated within the other Learning Objectives. For example, Learning Objective 1 requires the calculation of Ziegler-Nichols tuning parameters. Additionally, process gain must be calculated to know whether the controller is direct- or reverse-acting for Learning Objective 5. Lastly, the calculation of rise time and overshoot are utilized in the analysis for Learning Objective 3. Learning Objective 4 does not add value to the experiment and can be removed.

Furthermore, it is advised to exclude the calculations for overshoot and sensor span from the deliverables. Overshoot can be qualitatively observed from the closed-loop response, eliminating the need for explicit calculations. While the calculation of sensor span is important, it does not relate to the other deliverables, nor does it add any hands-on aspect to the lab. The students gain sufficient experience calculating the sensor span within their process control class.

The fourth suggestion stems from the most common recommendation in the students' lab reports. There was a leak at the connection between the tubing and the pump. Several students recommended that this leak be fixed to increase the accuracy of the collected data. The only discrepancy in accuracy due to the leak was that the flowmeter did not measure all of the water being pumped. However, this difference should have no impact on the students' ability to obtain tuning values and consistent results.

While the flow rate discrepancy did not impact the students' success, the added noise from the leak might have. Noise refers to unpredictable variations in the control variable from setpoint. These deviations can be from many sources, including measurement errors and true disturbances, such as a leak. Derivative control attempts to reduce the rate of change of the error from setpoint. As a result, rapid and unpredictable variations from setpoint can cause a controller with derivative action to amplify the noise and lead to erratic control. Approximately half of the disturbance tests conducted, including the preliminary trials, produced an unstable closed-loop response under PID control. If the leak was not present to generate additional system noise, PID control may have been a more effective and consistent method of control.

This leak was noticed before the implementation of the lab. Noise is an inherent part of many systems, and it can impact what methods of control are viable. For this reason, the leak was not repaired, and it is not advised that the leak be repaired. It is recommended that this weakness of derivative control be discussed in the theory section of the lab handout, so that students are more aware of it and can identify the issue that the leak poses to derivative control.

Another recommendation mentioned in several students' lab reports was update the process control software on the computer. The newest version of the software was installed at the beginning of the semester. However, some data collection issues arose shortly after. Occasionally, the data would not entirely clear, and it would prevent more data from being recorded. The procedure in the lab handout for clearing data was revised in an attempt to eliminate this issue. With some students still having problems with it, groups were advised to check if their data was being recorded at the start of each test. It is recommended that Armfield is contacted for assistance troubleshooting this issue.

While this experiment gives students valuable hands-on experience, process control is dependent on the process being controlled. What method of control works well for one process may be ineffective for another. The University of Louisville Chemical Engineering Department has two other Armfield PCT desktop modules. One unit is for level control and the other is for pressure control. It would be valuable to the students if they were able to interact with both of the other units and learn about how process control can vary from system to system. Future graduate student(s) could create complimentary experiments to this one. If students are eventually able to interact with all three units, it may be best to integrate the experiments into the Elements of Process Control course rather than the Unit Ops II Lab.

REFERENCES CITED

1. "Criteria for Accrediting Engineering Programs." *ABET*, 2022, www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2023-2024/.

2. Fu, Xiao-An. Syllabus for Elements of Process Control. Spring 2023, University of Louisville.

3. Doug Tougaw. "Integration Of Active Learning Exercises into a Course on Probability and Statistics". 2005 Annual Conference, Portland, Oregon, 2005, June. ASEE Conferences, 2005.

4. Svinicki, Marilla, and Wilbert J Mckeachie. "Active Learning: Group-Based Learning." *McKeachie's Teaching Tips: Strategies, Research, and Theory for College and University Teachers* , 13th ed., Wadsworth, Cengage Learning, Belmont, CA, 2011, pp. 190–201.

5. Armstrong, Patricia. "Bloom's Taxonomy." *Vanderbilt University Center for Teaching*, 2010, cft.vanderbilt.edu/guides-sub-pages/blooms-taxonomy/.

6. Riggs, James B., and M. Nazmul Karim. *Chemical and Bio-Process Control*. 4th ed., Ferret Publishing, 2016.

7. Ziegler, J. G., and N. B. Nichols. "Optimum Settings for Automatic Controllers." *Journal of Fluids Engineering*, vol. 64, no. 8, 1942, pp. 759–765.

APPENDIX I: PRELIMINARY DATA

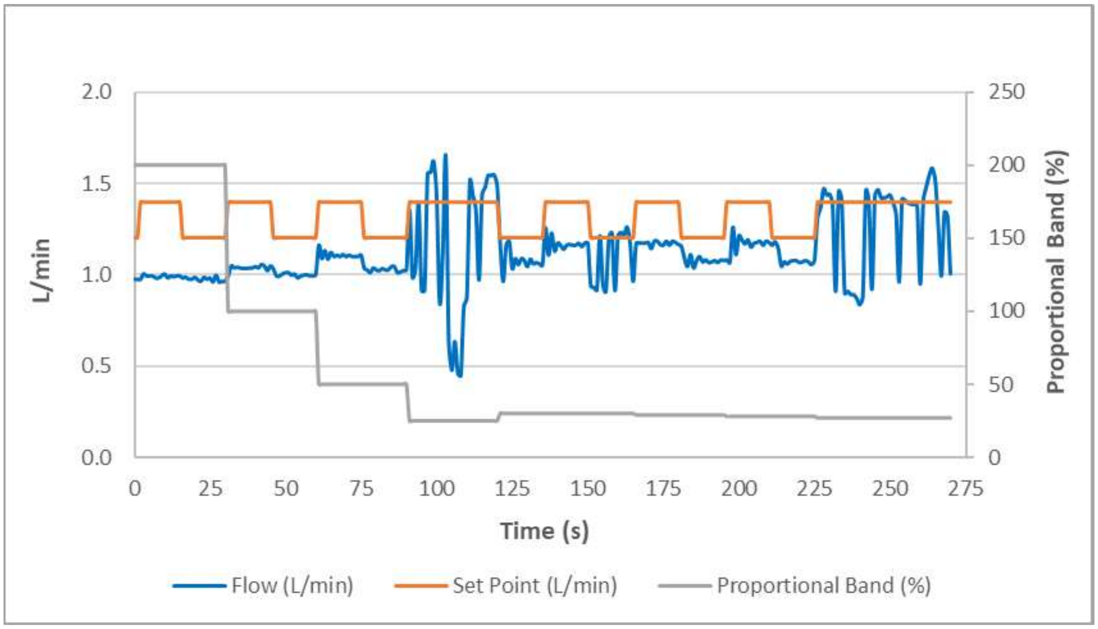


FIGURE 26 – Trial B – Ziegler-Nichols Tuning Test Part 1

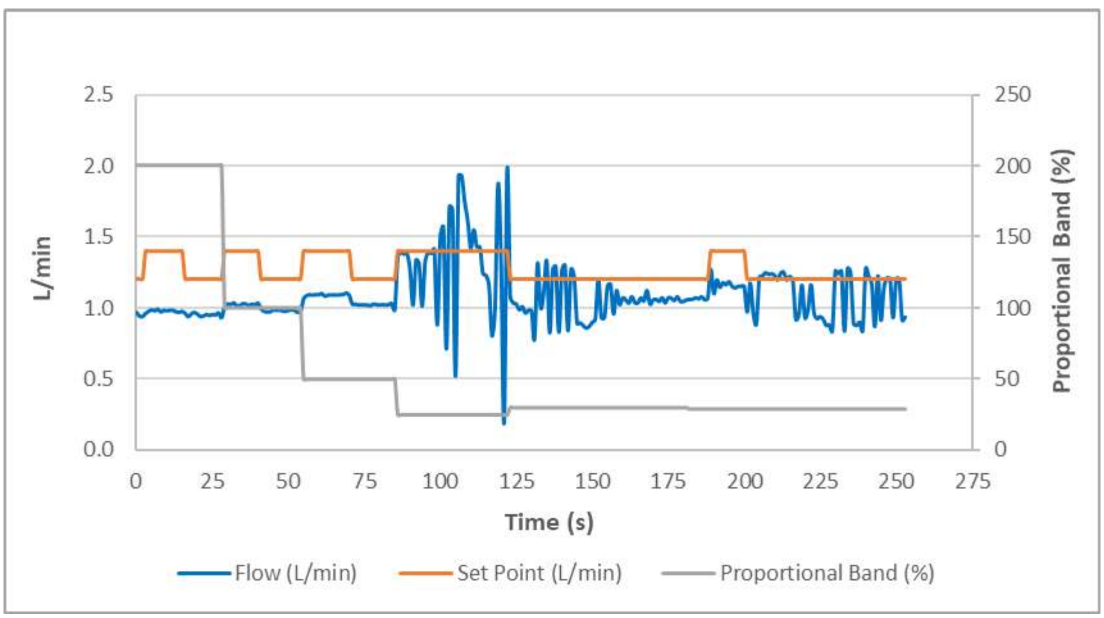


FIGURE 27 – Trial C – Ziegler-Nichols Tuning Test Part 1

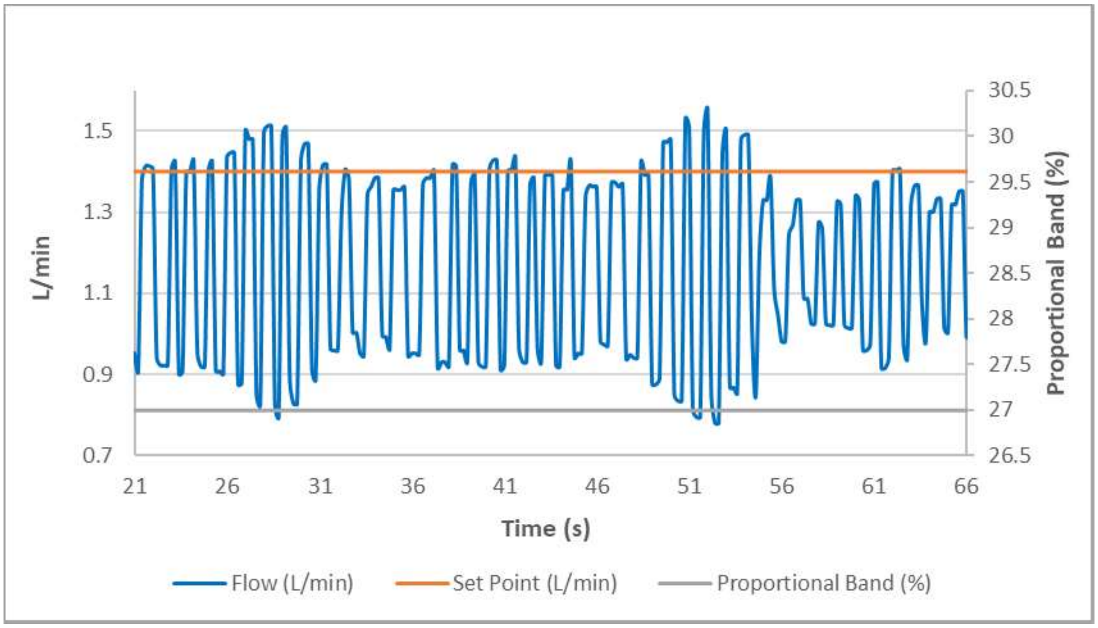


FIGURE 28 – Trial B – Ziegler-Nichols Tuning Test Part 2

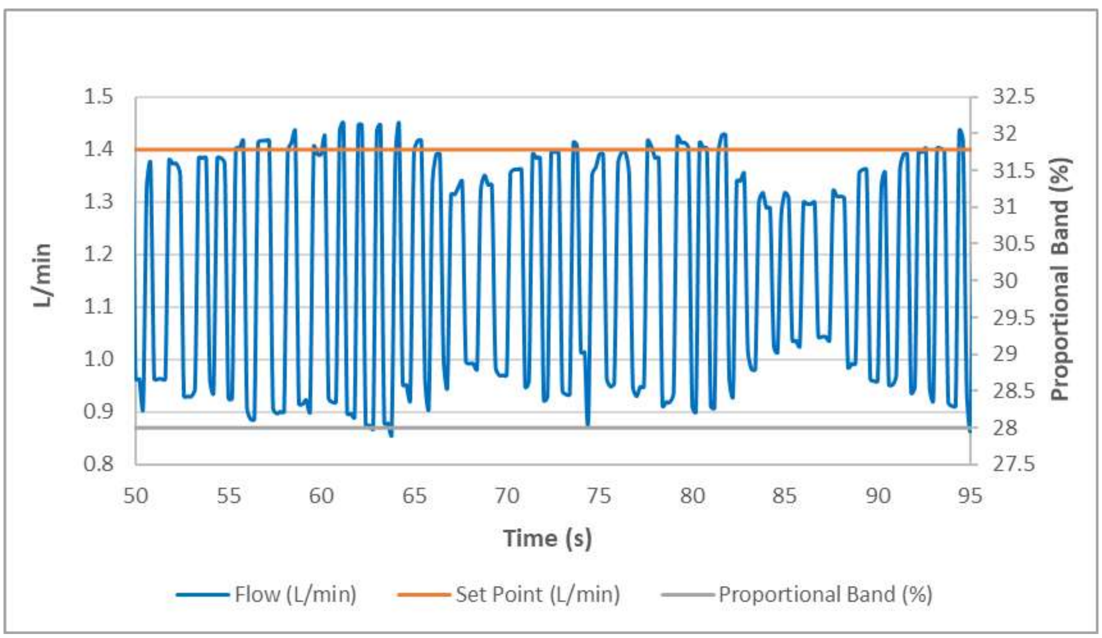


FIGURE 29 – Trial C – Ziegler-Nichols Tuning Test Part 2

TABLE XIV

TRIAL B – ZIEGLER-NICHOLS EXPERIMENTAL TUNING VALUES

Controller	PB	τ_I	τ_D
P	54%	--	--
PI	60%	0.96	--
PID	45%	0.58	0.14

TABLE XV

TRIAL C – ZIEGLER-NICHOLS EXPERIMENTAL TUNING VALUES

Controller	PB	τ_I	τ_D
P	56%	--	--
PI	62%	1.01	--
PID	47%	0.61	0.15

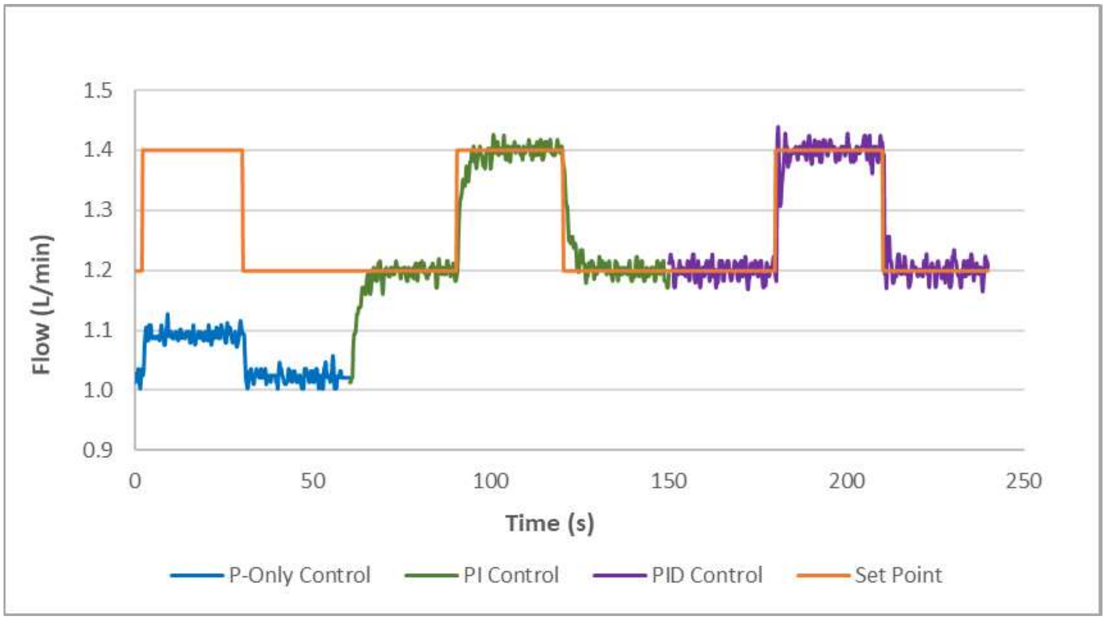


FIGURE 30 – Trial B – Tuned Controller Test

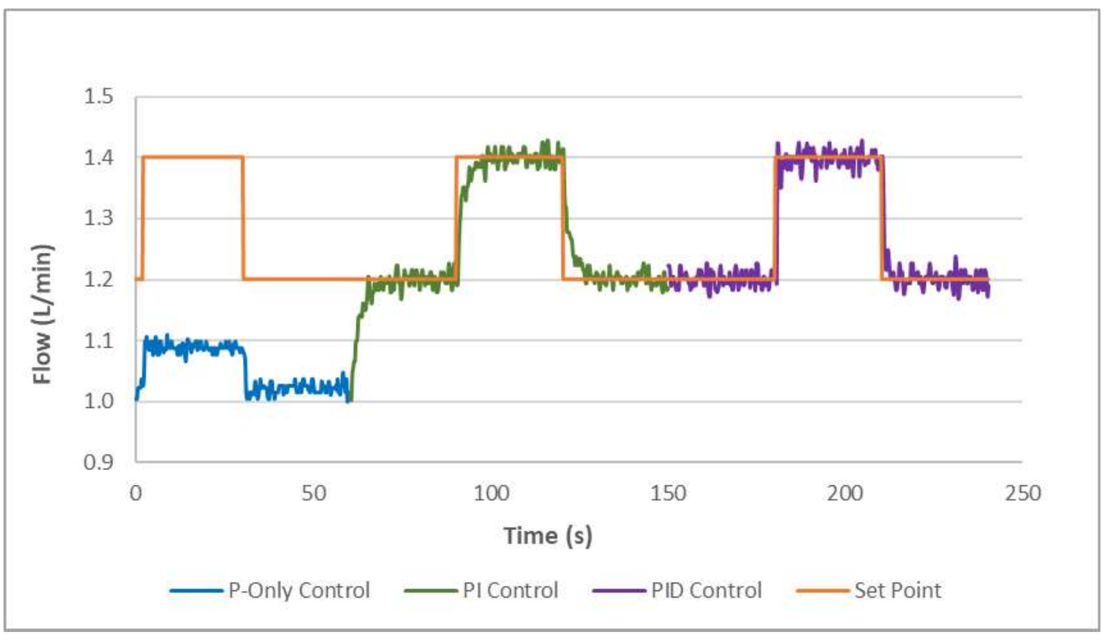


FIGURE 31 – Trial C – Tuned Controller Test

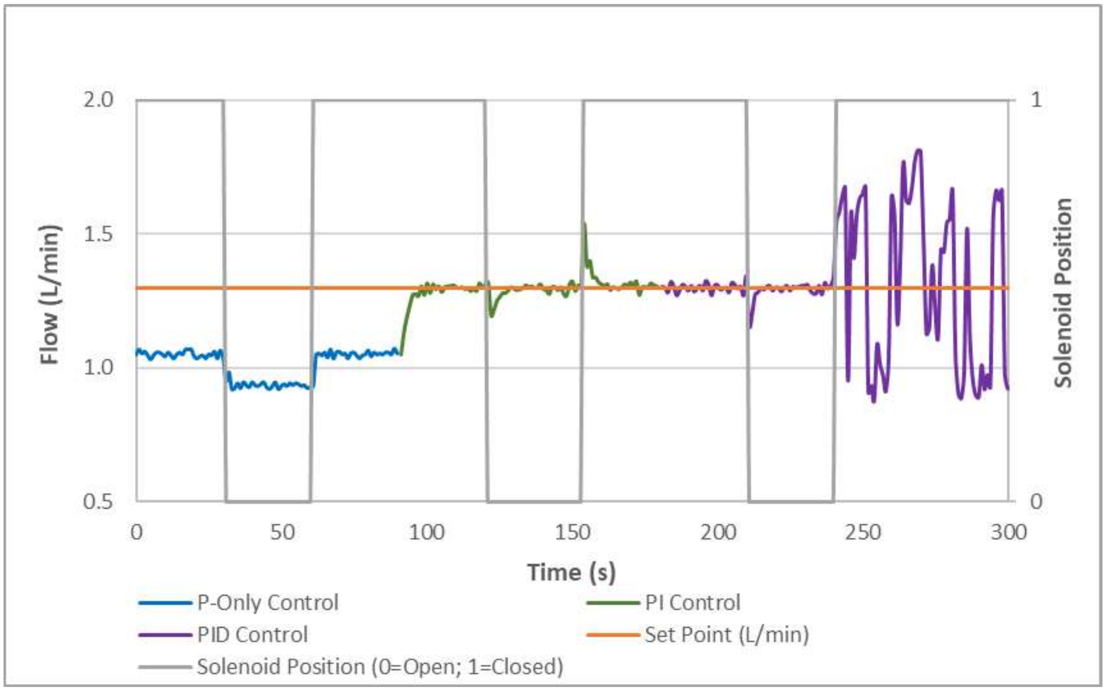


FIGURE 32 – Trial B – Disturbance Test

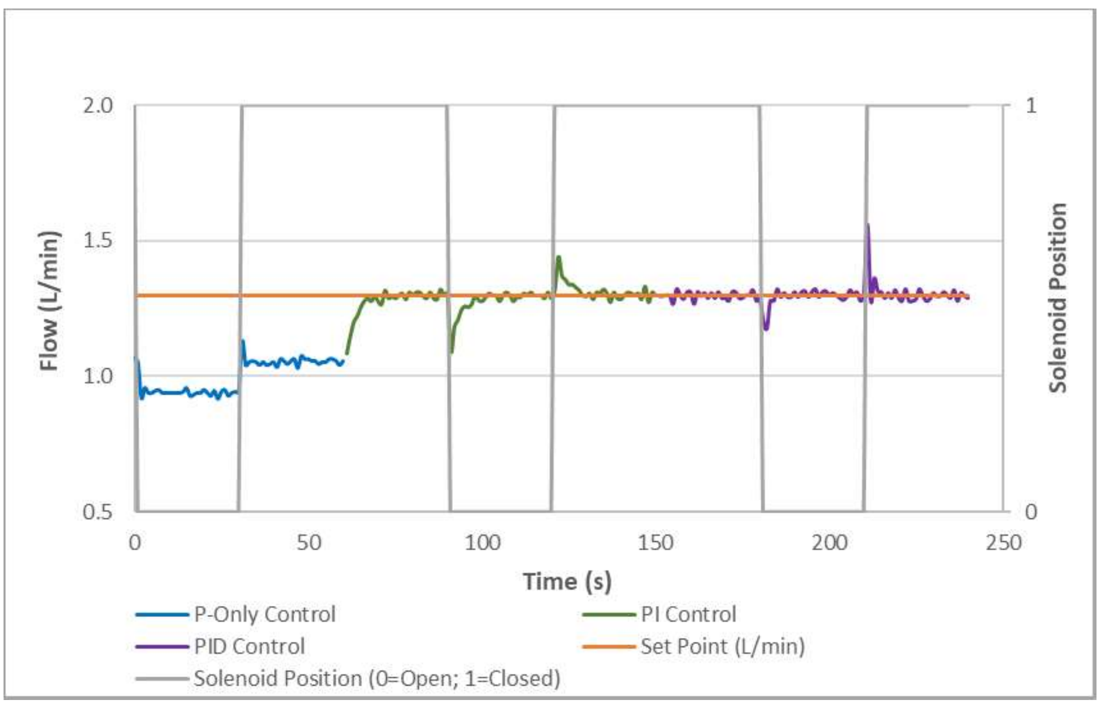


FIGURE 33 – Trial C – Disturbance Test

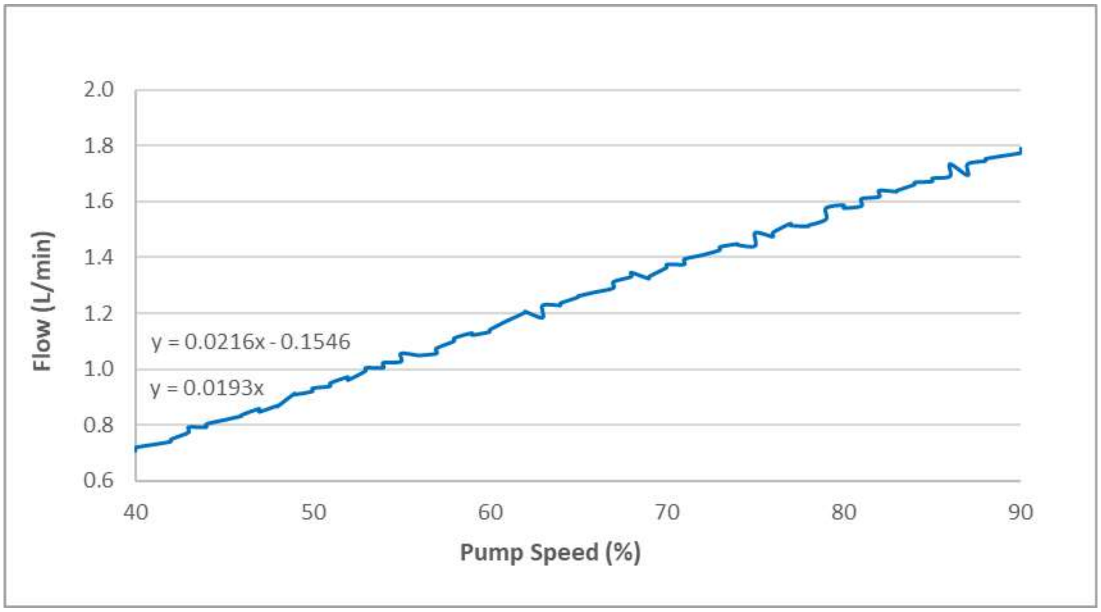


FIGURE 34 – Trial B – Manual Control Test

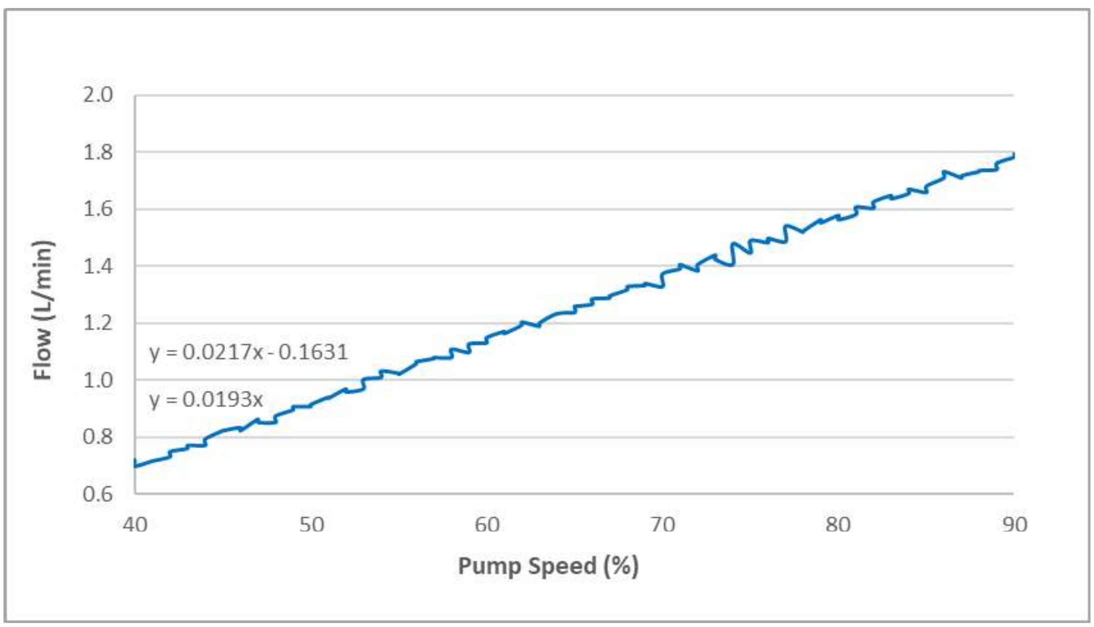


FIGURE 35 – Trial C – Manual Control Test

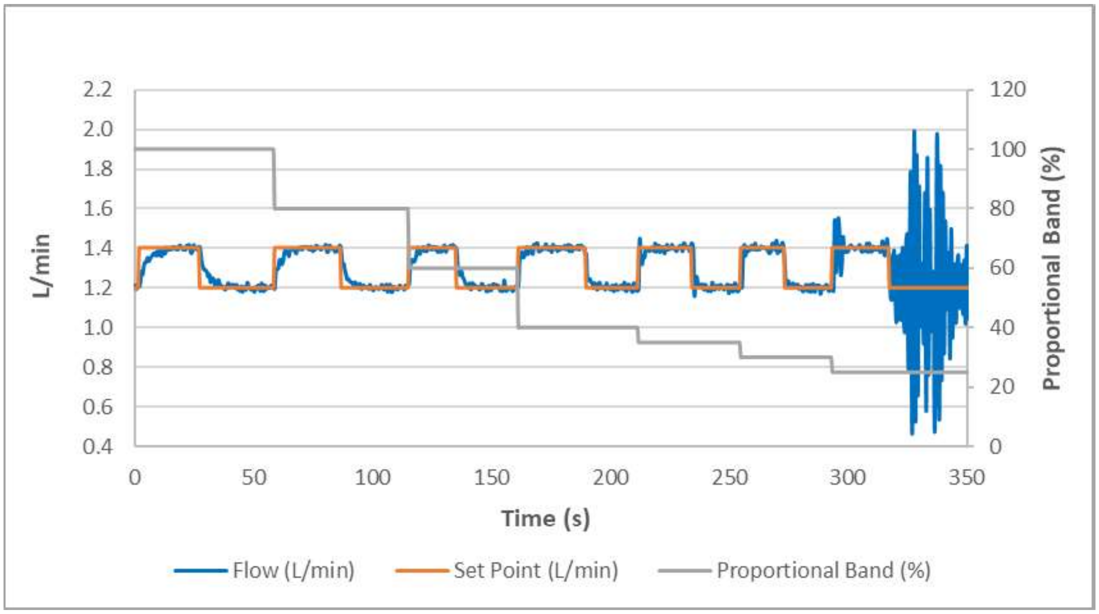


FIGURE 36 – Trial B – Effect of Proportional Action on a PI Controller

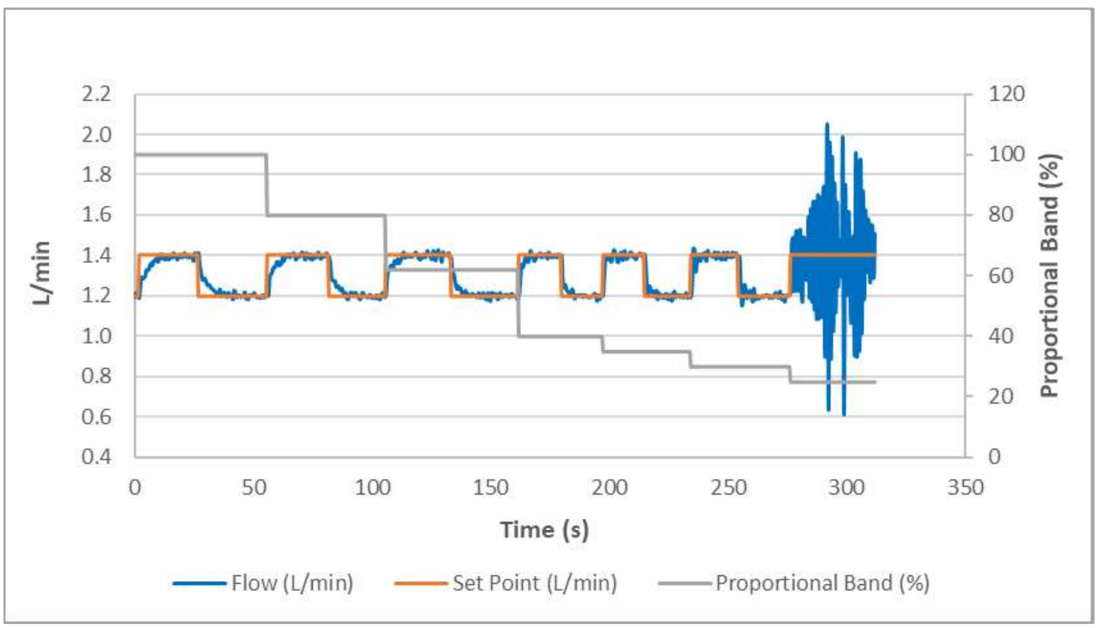


FIGURE 37 – Trial C – Effect of Proportional Action on a PI Controller

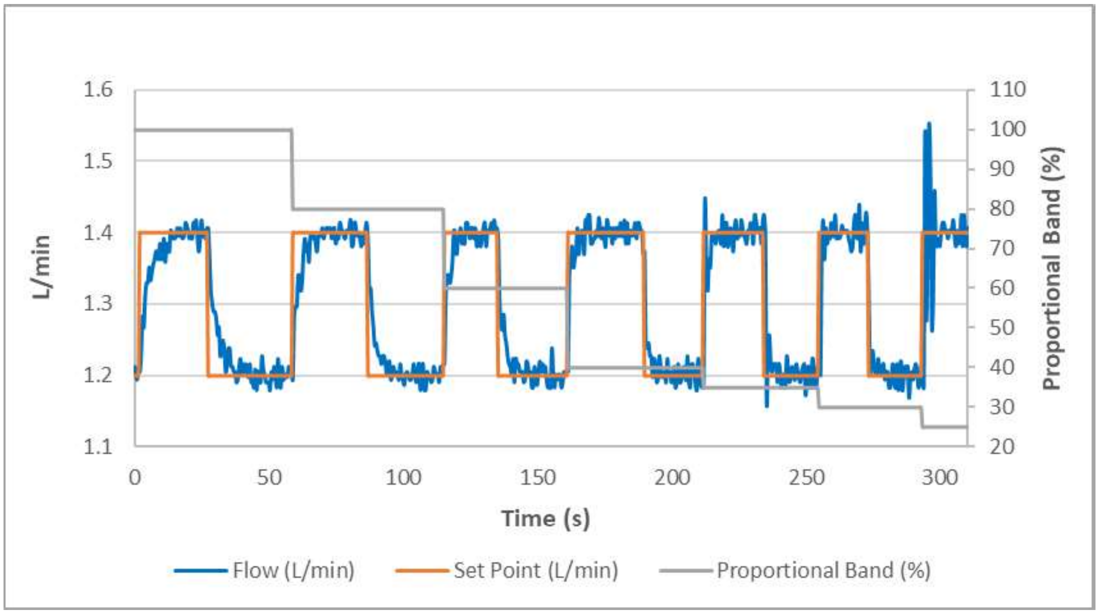


FIGURE 38 – Trial B – Effect of Proportional Action on a PI Controller; Cropped

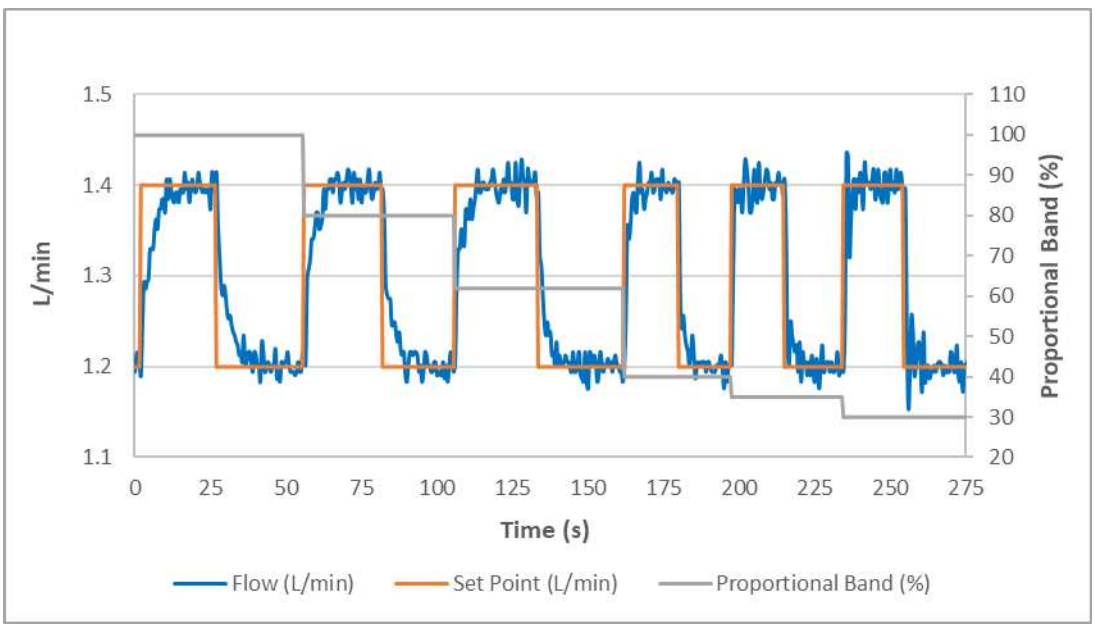


FIGURE 39 – Trial C – Effect of Proportional Action on a PI Controller; Cropped

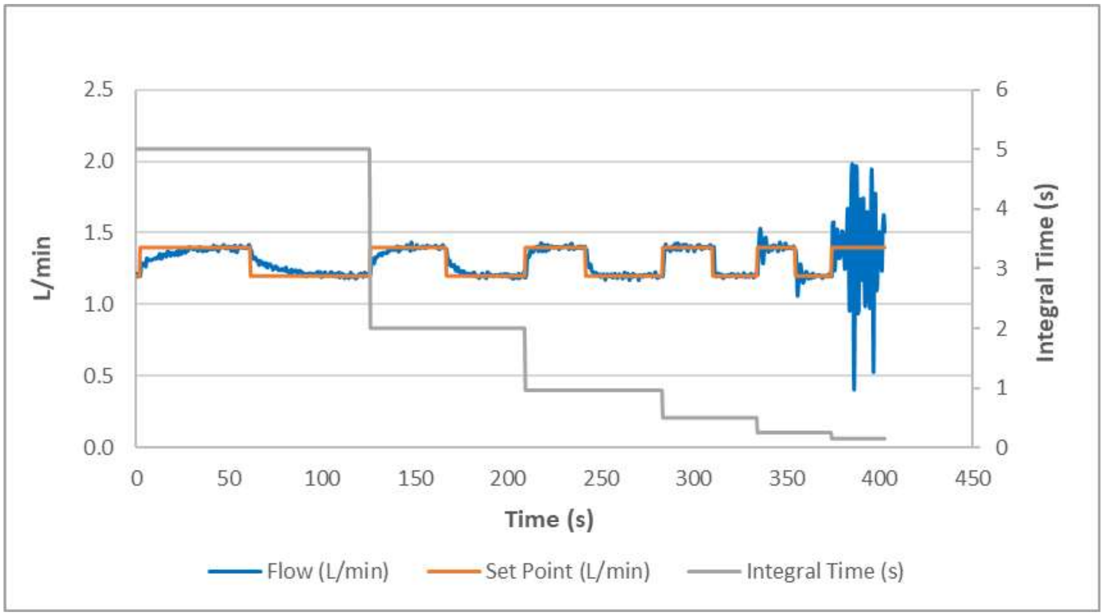


FIGURE 40 – Trial B – Effect of Integral Action on a PI Controller

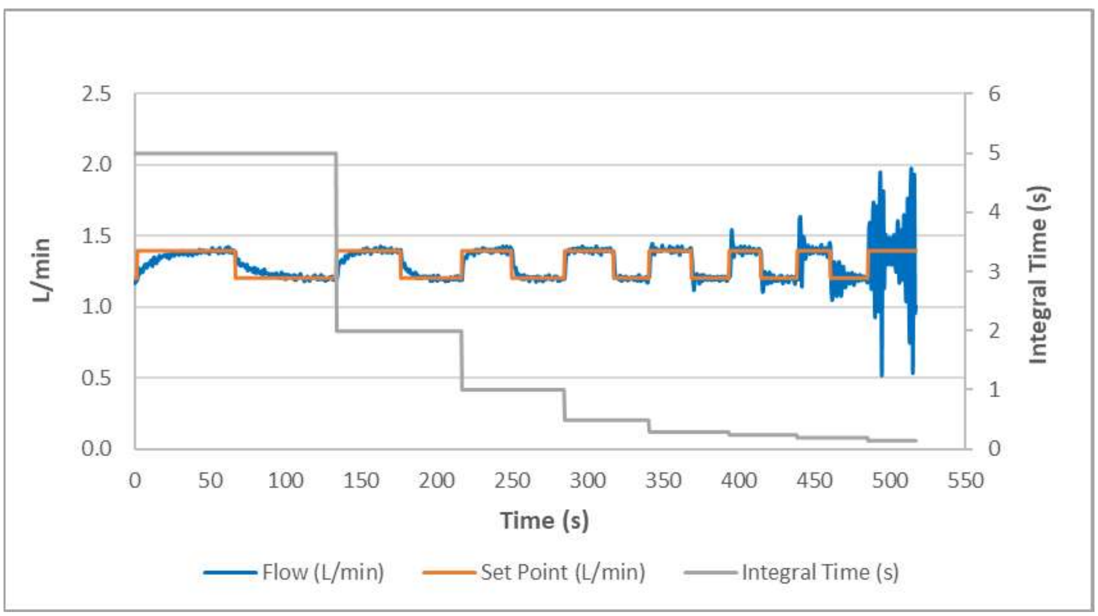


FIGURE 41 – Trial C – Effect of Integral Action on a PI Controller

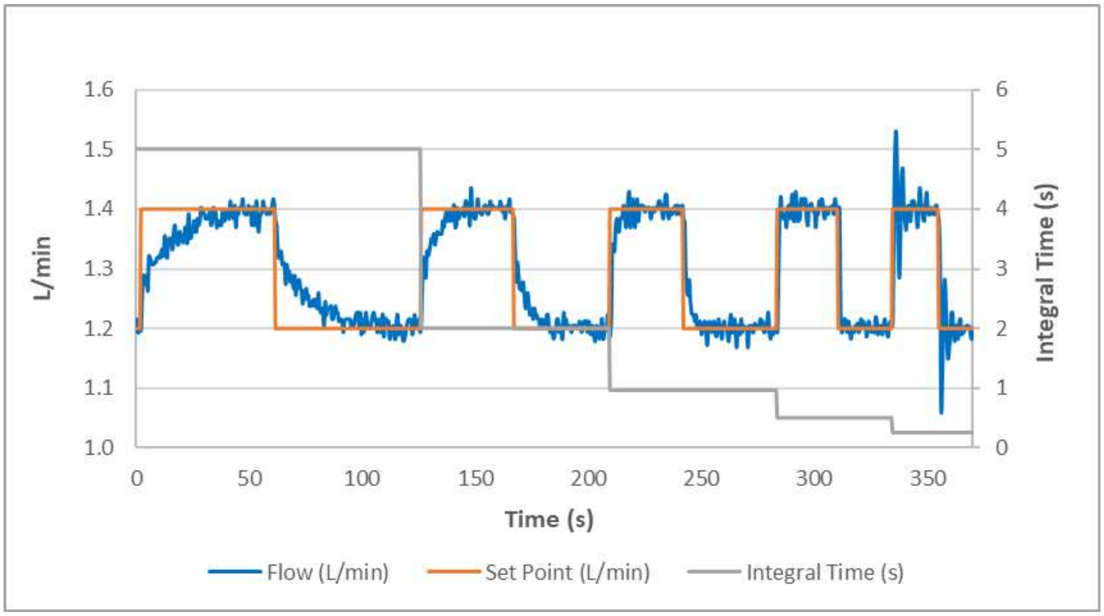


FIGURE 42 – Trial B – Effect of Integral Action on a PI Controller; Cropped

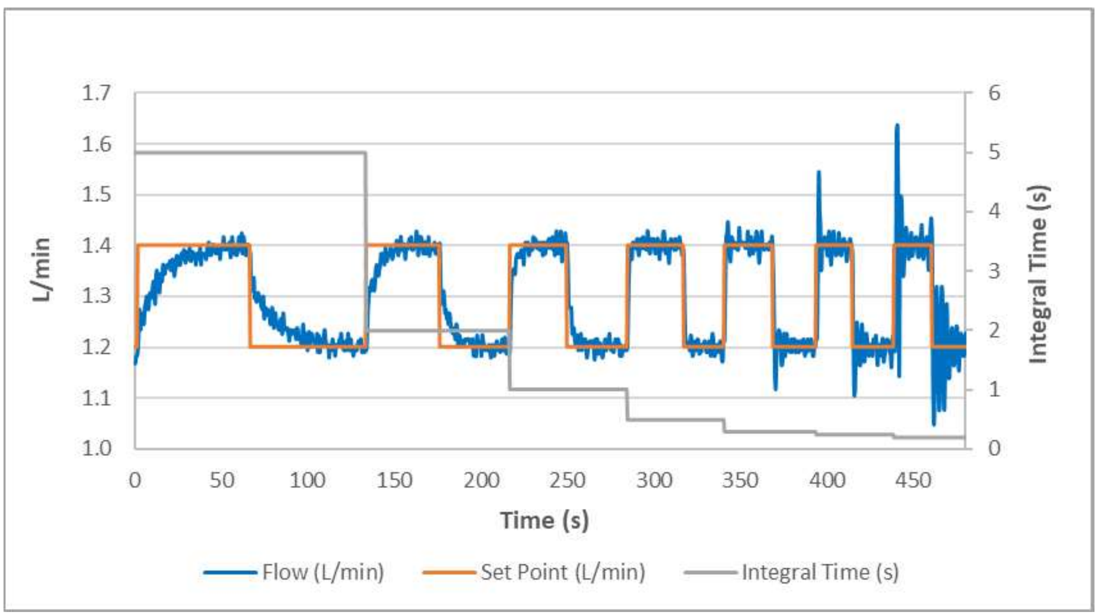


FIGURE 43 – Trial C – Effect of Integral Action on a PI Controller; Cropped

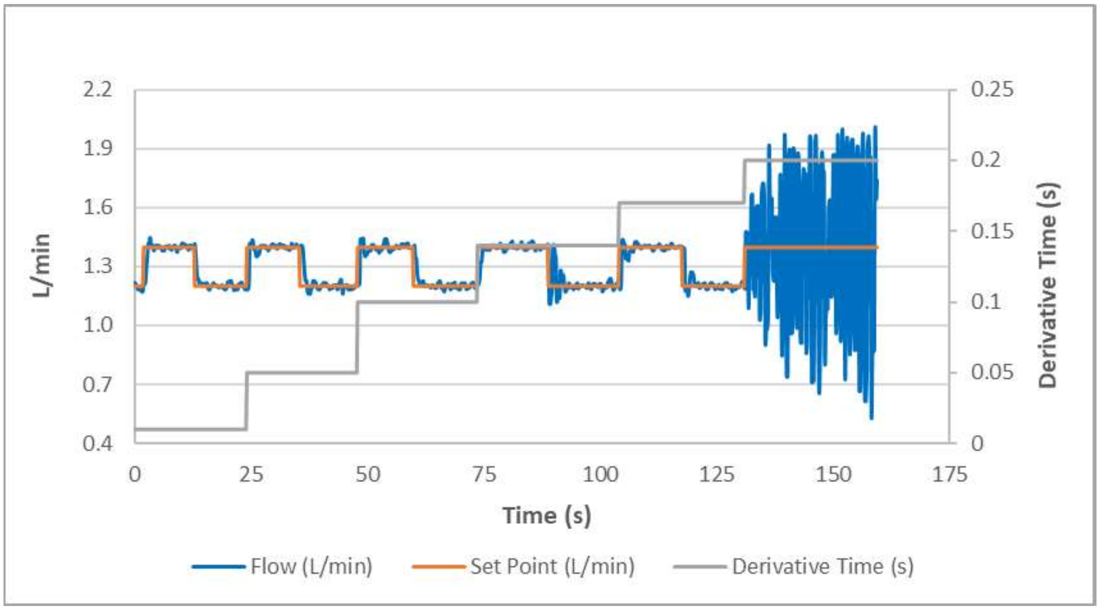


FIGURE 44 – Trial B – Effect of Derivative Action on a PID Controller

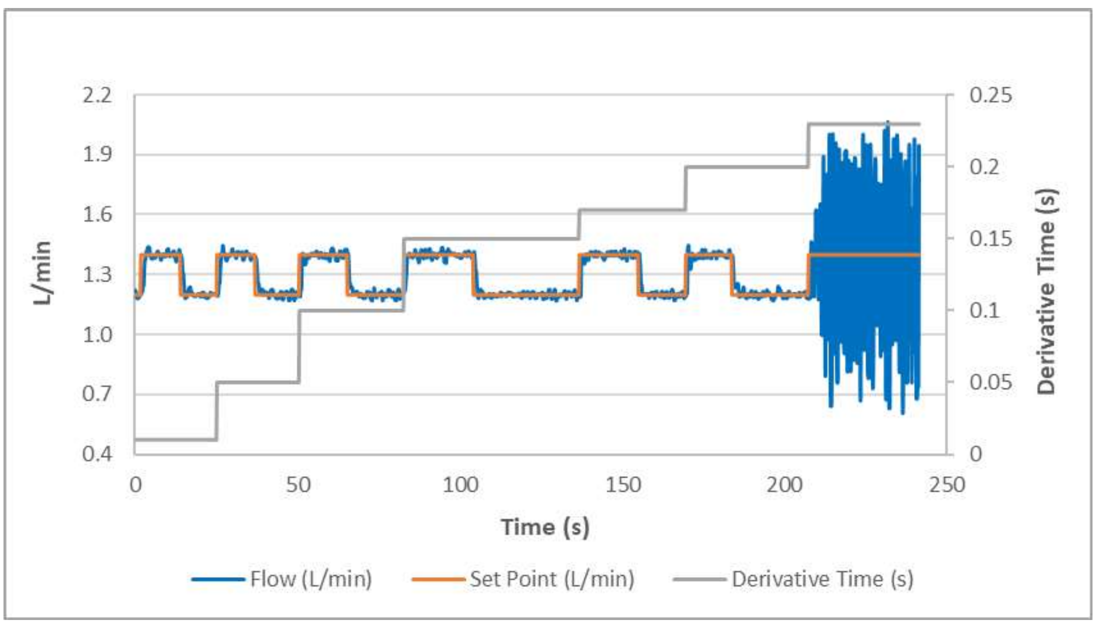


FIGURE 45 – Trial C – Effect of Derivative Action on a PID Controller

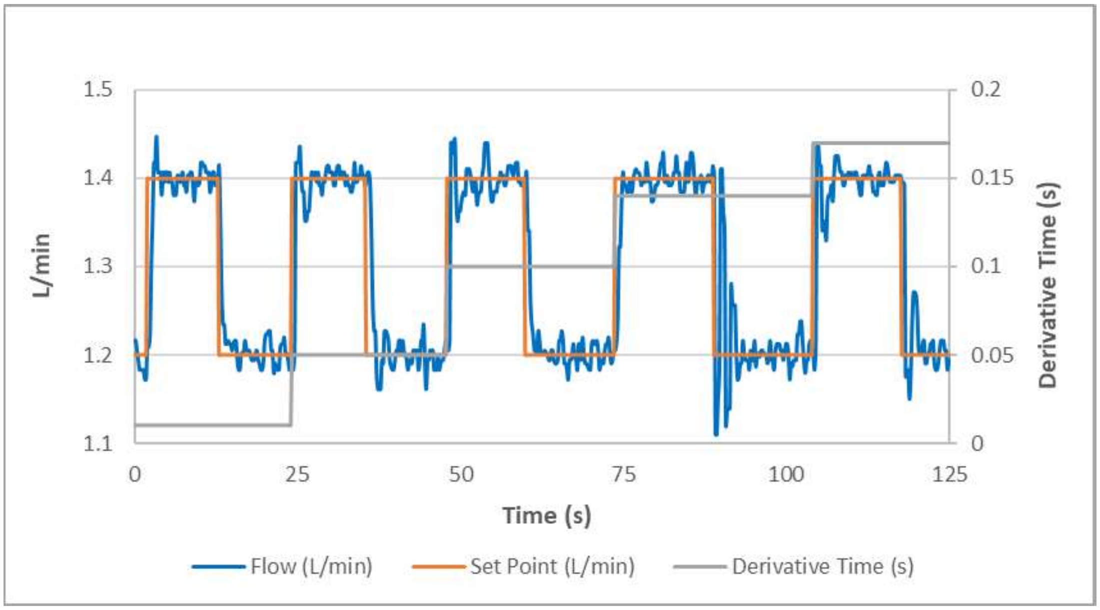


FIGURE 46 – Trial B – Effect of Derivative Action on a PID Controller; Cropped

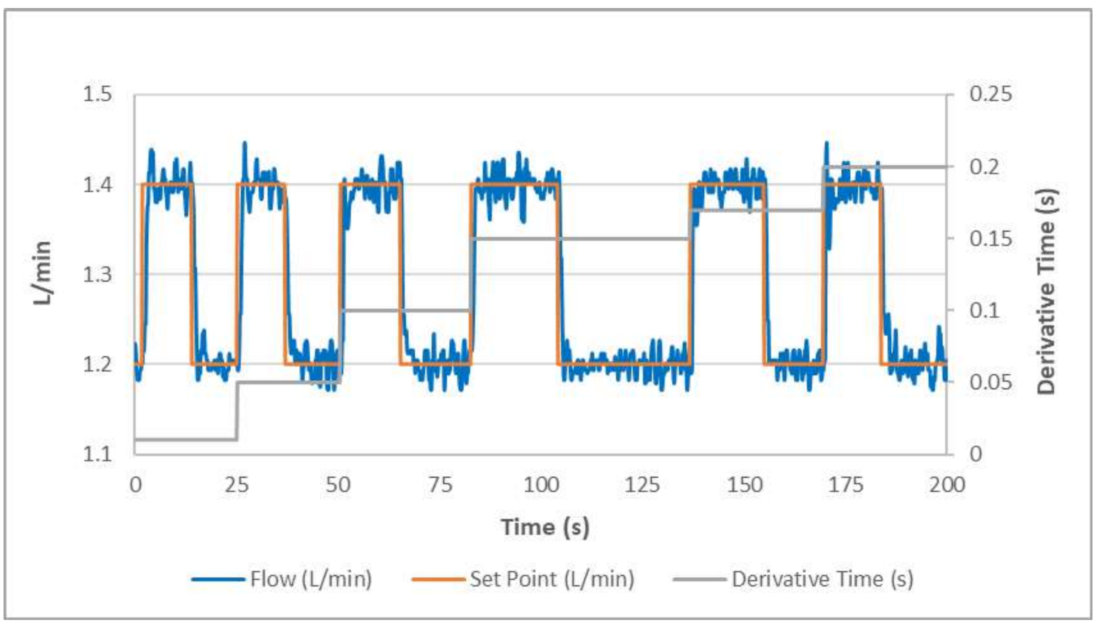


FIGURE 47 – Trial C – Effect of Derivative Action on a PID Controller; Cropped

APPENDIX II: PROCESS CONTROL LAB HANDOUT

Process Control Experiment

Experimental Objectives

- Tune a controller for P, PI, and PID control
- Practice designing and carrying out experiments
- Describe the impact proportional, integral, and derivative action have on the responses of various controllers
- Determine if a controller is direct- or reverse-acting
- Calculate key process, sensor, and controller variables such as process gain, sensor span, rise time, and overshoot

Prelab Activity

The goal of pre-lab day is to prepare for running your experiment. Before leaving on pre-lab day, each group must:

- Sketch P&ID of equipment
- Discuss the operation of the PCT-51 unit with the TA
- Carry out Ziegler-Nichols tuning and calculate key tuning parameters
- Discuss lab requirements with the TA
- Complete the task list

Theory

The process control loop in this experiment uses a proportional-integral-derivative (PID) controller to manipulate the speed of a pump in order to control the flow rate of water through a pipe. PID controllers can operate using P-only, PI, or PID control. PID controllers are governed by the PID algorithm. The position form of the PID algorithm is[6]

$$c(t) = \bar{c} + K_c\left[e(t) + \frac{1}{\tau_I}\int_0^t e(t)dt + \tau_D\frac{de(t)}{dt}\right] \tag{1}$$

where c(t) is controller output, $\bar{c}$ is the initial value of the controller output when the controller is activated, K_C is the controller gain, τ_I is integral time, τ_D is derivative time, and e(t) is the error from setpoint at time, t. K_C, τ_I, and τ_D are tuning parameters that determine the amount of proportional, integral, and derivative action that are applied in the control loop.

Under proportional control, the controller output is proportional to e(t). This error, or offset, is almost always present with P-only control. The offset is the difference between the set point and the steady-state closed-loop response. Under P-only control, the position form of the PID algorithm reduces to

$$c(t) = \bar{c} + K_c[e(t)] \tag{2}$$

The tuning parameter for proportional control is K_C. The higher the value of K_C, the more proportional action there is. Offset decreases as K_C increases.

Integral control integrates the steady-state error from setpoint over time. The controller then works to eliminate this offset. Under PI control, the position form of the PID algorithm becomes

$$c(t) = \bar{c} + K_c\left[e(t) + \frac{1}{\tau_I}\int_0^t e(t)dt\right] \tag{3}$$

The tuning parameter for integral control is τ_I. The lower the value of τ_I, the more integral action there is, the faster the process responds.

Derivative control calculates the derivative of the steady-state error. The controller then works to reduce the rate of change of the error. This can work to dampen oscillations and stabilize systems. The tuning parameter for derivative control is τ_D. The higher the value of τ_D, the more derivative action there is.

Two metrics that can be used to evaluate the steady-state, closed-loop response for a given controller are rise time (t_{ris}), and overshoot. These metrics are most commonly observed following a change of set point. Rise time is the amount of time it takes the control variable to cross its new steady-state value. Overshoot is the amount the response exceeds its new steady-state value divided by the difference between the old and new steady-state values. A visual explanation of overshoot can be seen on page 213 of *Chemical and Bio-Process Control*[6].

PID controllers can be direct- or reverse-acting. Direct-acting controllers increase output following an increase in the control variable (CV). Reverse-acting controllers decrease output following an increase in the CV. Table 7.1 in *Chemical and Bio-Process Control*[6] displays factors that influence whether a controller is direct- or reverse-acting. The process gain (K_P) can be calculated to determine the controller type. Process gain is given by[6]

$$K_P = \frac{\Delta y}{\Delta u} \tag{4}$$

where Δy is the change in the output variable, and Δu is the change in the input variable. In a given process, a change in the manipulated variable (MV) results in a change in the CV. In a block diagram for a control loop, it can be seen that the MV is the input for a process and the CV is the output.

To finely tune a PID controller, different tuning values must be tested to find the ideal combination of controller gain, integral time, and derivative time. While this process can take a long time, there are tuning methods that can be used to calculate initial controller settings. The Ziegler-Nichols (Z-N) tuning method experimentally measures the ultimate gain (K_U) and the ultimate period (P_U) for a process[6]. This is done by increasing the proportional action of a P-only controller until the steady-state, closed-loop response displays sustained oscillations. The value of the controller gain during the sustained oscillations is the ultimate gain, and the period of the sustained oscillations is the ultimate period.

Table 1: Ziegler-Nichols PID Settings[6]			
Controller	**K_C**	**τ_I**	**τ_D**
P	0.5 K_U	--	--
PI	0.45 K_U	P_U /1.2	--
PID	0.6 K_U	P_U /2	P_U/8

Table 1 shows the relationships between the ultimate parameters (K_U and P_U) and the three tuning parameters. The PCT-51 unit uses proportional band (PB) instead of K_C to represent the proportional action of the controller. Proportional band is defined as[6]

$$PB = \frac{100\%}{K_c^D} \tag{5}$$

in which K_C^D is defined as[6]

$$K_c^D = K_c \frac{\Delta y_s}{\Delta c} \tag{6}$$

where Δy_s is the sensor span and Δc is the controller output range. K_C^D is dimensionless way to express controller gain. By combining equations 5 and 6, the Z-N relationship between K_u and K_C can be converted to a relationship between PB_u and PB. With the data presented in Table 2, equations 5 and 6 can also be combined to solve for the span of the sensor. Assume the controller output range is 100%.

Table 2: Relationship Between Proportional Band and Controller Gain										
PB (%)	10	20	30	40	50	60	70	80	90	100
K_C	133.3	66.7	44.4	33.3	26.7	22.2	19.0	16.7	14.8	13.3

PCT-51 Start-Up Procedure:

1. Ensure the tank drain valve is closed, and then fill the tank with water up to the 0 mark on the flow indicator tube.
2. Check that the three ball valves within the tank are fully open.
3. Plug the PCT-51 unit into an outlet so that the "POWER ON" light turns green.
4. Open the PCT-51 Flow Control software on a PC, select "Ex1: Flow Control (PC Control)," and click "Load."
5. Connect the USB cable from the back of the PCT-51 console box to the PC so that the "Scanning…" text at the bottom right of the PC interface changes to "OK: IFD# on COM#."
6. Click "Power On" on the main diagram screen.
7. Press the latch on the quick release connector to disconnect the pump outlet tube from the rest of the system.
8. Point the outlet of the disconnected tube downwards into the tank. Repeatedly click the up arrow next to the pump control box to gradually increase the pump speed to 50% and remove any trapped air from within the pump.

9. Use the down arrow to reduce the pump speed to 0% and reconnect the pump outlet tube.
10. Use the arrows to gradually increase the pump speed to 100% and expel any trapped air within the system.
11. Quickly lower the pump speed to 50% and ensure the water level in the flow indicator tube lowers with pump speed and then remains at a constant level.
12. The pump speed can be reduced to 0%. The PCT-51 unit is ready for use.

Recording, Saving, and Clearing Data Procedure

1. To begin recording data, press the green “Go” button.
2. Press “Graph” to view live process trends and press “Diagram” to return to the control screen.
3. To stop recording data, press the red “Stop” button.
4. To export data, press “Save As” and choose “Excel 5.0 file (*.xls)” as the file type.
5. To clear data, press “Delete” and then “New.” Check that the Sample No. is 1 on the diagram page and there are no data points on the graph.

Ziegler-Nichols Tuning Procedure

Part I

1. Press the “Setup” button and ensure the sample interval is set at 1 sec.
2. Set the pump speed at 50%.
3. Click on the PID button to access the control loop settings.
4. Change the set point to 1.2 L/min, the proportional band to 200%, delete the values for integral time and derivative time, and press “Apply.”
5. Change the mode of operation to automatic.
6. Give the system at least 1 minute to stabilize and then begin recording data.
7. Change the setpoint to 1.4 L/min.
8. Watch the flow rate in both the box on the top right of the diagram screen and also the level in the flow indicator tube. Once the flow rate has been stable for at least 10 seconds, change the setpoint back to 1.2 L/min.
9. Once the flow rate has been stable for at least 10 seconds, lower the proportional band to 100% and change the set point to 1.4 L/min.
10. Repeat steps 8 and 9, lowering the proportional band to 50%, 25%, 10%, and then 5%.
11. At one of the proportional band settings, the flow rate will not stabilize after 30 seconds. Once this happens, increase the proportional band by 5%, and change the set point to 1.2 L/min.
12. Give the system a maximum of one minute to stabilize. If the flow rate has not stabilized, increase the proportional band in 5% increments until the flow rate stabilizes within a minute.
13. Change the setpoint to 1.4 L/min.
14. Repeat steps 8 and 9, lowering the proportional band in the latter step in increments of 1%.
15. Once the flow rate takes longer than 45 seconds to stabilize at either set point, stop recording data, switch to manual control, and lower the pump speed to 0%.

16. Export the data and then clear the data.

Part II

1. Press the "Setup" button and change the sample interval to 200 msec.
2. Set the pump speed at 50%.
3. Change the set point to 1.2 L/min and delete the values for integral time and derivative time.
4. Change the proportional band to 3% higher than the final proportional band value from Part I.
5. Change the mode of operation to automatic.
6. Give the system at least 1 minute to stabilize and then begin recording data.
7. Lower the proportional band by 3% and increase the setpoint to 1.4 L/min.
8. If the flow rate stabilizes within 60 seconds, lower the set point to 1.2 L/min.
9. If the flow rate stabilizes within 60 seconds, lower the proportional band by 1% and increase the set point to 1.4 L/min.
10. Repeat steps 8 and 9 until the flow rate does not stabilize within 60 seconds.
11. Once the flow rate does not stabilize within 60 seconds, stop recording data, switch to manual control, and lower the pump speed to 0%.
12. Export the data and then clear the data.

Tuned Controller Test Procedure

1. Press the "Setup" button and change the sample interval to 250 msec.
2. Set the pump speed at 50%.
3. Change the set point to 1.2 L/min, delete the values for integral time and derivative time, and set the proportional band equal to the calculated Ziegler-Nichols value for P-only control.
4. Change the mode of operation to automatic.
5. Give the system at least 1 minute to stabilize and then begin recording data.
6. Change the setpoint to 1.4 L/min and wait 30 seconds.
7. Change the setpoint back to 1.2 L/min and wait 30 seconds.
8. Change the tuning values to those calculated for PI control and wait 30 seconds.
9. Repeat steps 6 and 7.
10. Change the tuning values to those calculated for PID control and wait 30 seconds.
11. Repeat steps 6 and 7.
12. Stop recording data, switch to manual control, and lower the pump speed to 0%.
13. Export the data and then clear the data.

*Note: If the controller becomes unstable during PID control, consider reducing the proportional or derivative action and run the test again.

Disturbance Test Procedure

1. Press the "Setup" button and change the sample interval to 1 sec.
2. Ensure the 3mm orifice is fitted underneath the solenoid valve.
3. Set the pump speed at 50%.

4. Change the set point to 1.3 L/min and delete the values for integral time and derivative time. Set the proportional band equal to the calculated Ziegler-Nichols value for P-only control.
5. Change the mode of operation to automatic.
6. Give the system at least 1 minute to stabilize and then begin recording data.
7. Press the “Solenoid Valve” button on the main diagram screen to open the solenoid valve and then wait 30 seconds.
8. Press the “Solenoid Valve” button again to close the solenoid valve and wait 30 seconds.
9. Change the tuning values to those calculated for PI control and wait 30 seconds.
10. Repeat steps 7 and 8.
11. Change the tuning values to those calculated for PID control and wait 30 seconds.
12. Repeat steps 7 and 8.
13. Stop recording data, switch to manual control, and lower the pump speed to 0%.
14. Export the data and then clear the data.

Manual Control Test Procedure

1. Set the pump speed at 40%.
2. Begin recording data.
3. Slowly increase the pump speed up to 90% (increase by 1% about every 2 seconds).
4. Stop recording data and lower the pump speed to 0%.
5. Export the data and then clear the data.

PCT-51 Shut-Down Procedure

1. De-select the “Power On” button on the main diagram screen.
2. Disconnect the USB cable from the PC.
3. Unplug the PCT-51 unit from the outlet.
4. Press the latch on the quick release connector to disconnect the pump outlet tube from the rest of the system.
5. Fit a tube over the PCT-51 drain nozzle and lay the tube outlet in a 5-gallon bucket.
6. Open the PCT-51 drain valve so that all of the water drains from the tank.
7. Dispose of the water down a drain.
8. Use paper towels to dry and clean out the inside of the PCT-51 unit.

Lab Report Deliverables

- Create a properly labeled block diagram for the control loop
- Report PB, τ_I, and τ_D tuning parameters for all three controllers
- Generate a curve showing CV and setpoint vs time for a P-only, PI, and PID tuned controller
- Use disturbance test data to generate a curve showing CV, setpoint, and solenoid valve position vs time for a P-only, PI, and PID tuned controller
- Discuss which controller is best suited for this process
- Design and carry out experiments investigating:
    - The impact proportional action has on the response for a PI controller

    - The impact integral action has on the response for a PI controller
    - The impact derivative action has on the response for a PID controller
- Report qualitive and quantitative (t_{ris} and overshoot) observations when appropriate
    - Compare results with literature
- Determine if the controller is direct- or reverse-acting
    - Support conclusions with calculation of K_P (use Manual Control Test data)
- Calculate the sensor span

VITA

Bradley L. Esselman

EDUCATION

Master of Engineering in Chemical Engineering, University of Louisville, Louisville, KY, August 2023. Thesis title: "Addition of Process Control Experiment to Unit Operations II Laboratory"

Bachelor of Science in Chemical Engineering, University of Louisville, Louisville, KY, May 2022.

ACADEMIC EMPLOYMENT

Graduate Student Assistant, Resources for Academic Achievement, University of Louisville, August 2022 – May 2023.

Engineering Calculus Exam Grader, Department of Engineering Fundamentals, January 2019 – December 2019

EMPLOYMENT

Project Engineering Co-Op, Carrier Vibrating Equipment, Louisville, KY, January 2020 – August 2021.

Quality Process Engineer, American Synthetic Rubber Company, Louisville, KY, August 2023 – Present.

ACADEMIC HONORS AND AWARDS

Honors student, *summa cum laude,* May 2022

Engineering Design & Innovation Showcase ChE Dept. Award, April 2022

Henry Vogt Scholarship Recipient, August 2018