

**DEVELOPING, IMPLEMENTING, AND ASSESSING
COUPLED-TANK EXPERIMENTS IN AN
UNDERGRADUATE CHEMICAL ENGINEERING
CURRICULUM**

A Thesis

presented to

the Faculty of the Graduate School

at the University of Missouri

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

NARENDRA KUMAR INAMPUDI

Dr. Patrick J. Pinhero, Thesis Advisor

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

DEVELOPING, IMPLEMENTING, AND ASSESSING COUPLED-TANK EXPERIMENTS IN AN UNDERGRADUATE CHEMICAL ENGINEERING CURRICULUM

presented by **Narendra Kumar Inampudi**

a candidate for the degree of

Master of Science

and hereby certify that in their opinion it is worthy of acceptance.

Dr. Patrick J. Pinhero _____

Dr. Mary A. Myers _____

Dr. Matthew Bernards _____

Dr. John M. Gahl _____

.....To the Chemical Engineering Department, University of Missouri

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LIST OF ACRONYMS

CPI	Chemical Process Industries
DAC	Data Acquisition Card
DIN	Deutsches Institut für Normung
FODT	First-Order plus Dead Time
LabVIEW	Laboratory Virtual Instrumentation Engineering Workbench
LED	Light Emitting Diode
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PVC	Poly Vinyl Chloride
RCA	Radio Corporation of America
SISO	Single Input Single Output
UPM	Universal Power Module

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Narendra Kumar Inampudi

Dr. Patrick J. Pinhero, Thesis Supervisor

ABSTRACT

Five experimental modules that fit into the Undergraduate Chemical Engineering Curriculum were developed using the existing Coupled-Tank Apparatus. Students of different educational levels get an opportunity to develop practical skills like modeling, simulating and model validating, as well as real-time process control and Proportional-Integral (PI) controller tuning in a laboratory setting. These experimental modules are self-contained and each module can be used individually or in combination. These experiments developed were tested by engineering graduates and undergraduates and are ready for use in teaching. Discussions for the experimental results as well as problems encountered during the lab sessions are included so that the lab instructor can get the maximum use from this work. Finally, an outline of the project and recommendations for future work were added so that one can expand on this work starting from a firm foundation.

CHAPTER 1

INTRODUCTION

1.1 Importance of Process Dynamics and Control

Chemical processes in industries are becoming more complicated and are eventually designed with intricate control systems in modern times^[1]. Controlling these processes requires a chemical engineer who has comprehensive knowledge of the basic principles and the advanced techniques in process control design. Inadequate understanding of the concepts by the students who in turn get hired into operator, control engineer, process engineer and managerial positions may result in fatal loss of life and property. Today's control systems include more diagnostic sensors and automation, delivering increasing volumes of data. However, the gains accrued from closer process control and management can often be offset by losses due to time spent in dealing with the unexpected events in the process. Human operators/engineers continue to face the responsibility for making important and complex decisions, frequently within a very limited timeframe. Incidents such as Three Mile Island, Bhopal, and Chernobyl provide chilling examples of faults that turned into disasters, partly due to improper control actions taken by the operators^[2].

Almost every chemical process industry (CPI) employs one or more process control strategies for one or multiple reasons like safety and reliability of the process, maintaining the constant desired purity of product, maximizing the profitability of the process and environmental issues ^[3]. Some of the most common chemical process industries using process control are

- Hydrocarbon fuels
- Chemical products
- Pulp and paper products
- Agrochemicals
- Man-made fibers
- Food Industry

The importance of process control has increased in the process industries over the past 30 years, driven by global competition, rapidly changing economic conditions, more stringent environmental and safety regulations, and the need for more flexible yet more complex processes to manufacture high value-added products. A modern undergraduate course in chemical process control should reflect the diverse milieu of process control theory and applications and encompass process dynamics, computer simulation, measurement and control hardware, feedback control, and advanced control strategies. This suggests that a mere academic understanding of control principles will not suffice in industry. Students require a hands-on, practical experience in the laboratory before they step into industry.

1.2 Common Laboratory Experiments Taught in Various Universities

Some of the common laboratory experiments taught in university process control courses are as follows

- Pressure and level control^[4]
- Temperature and level control in a heated tank^[4]
- Air temperature control^[4]
- Temperature and level control in a liquid tank^[4]
- Control of a batch reactor^[4]
- Control of empty and packed bed tubular reactor^[4]
- Control of a heated bar temperature^[4]
- Double pipe heat exchanger^[4]
- Temperature control in an air bath^[5]
- Water-flow control under oscillatory load disturbances^[5]
- Single tank pH control^[5]
- Interacting water-tank control^[5]
- Temperature control with variable-measurement time delay^[5]
- Integrating tank level control^[5]
- Cascade control of temperature in a water tank^[5]

- Dye- concentration control with load disturbances^[5]
- Four-tank water level control^[5]
- Temperature and level control in a water tank^[5]
- Multitank pH control^[5]

Numerous textbooks are available for teaching the process dynamics and control course and the popular ones are listed in Table 1-1. The common topics covered in these courses are listed in Table 1-2.

Table 1-1 Process Control Textbooks^[6]

Bequette ^[7]	Marlin ^[13]
Coughanowr ^[8]	Ogunnaike and Ray ^[14]
Coughanowr and Koppel ^[9]	Riggs ^[15]
Erickson and Hedrick ^[10]	Seborg, Edgar, and Mellichamp ^[16]
Luyben ^[11]	Smith and Corripio ^[17]
Luyben and Luyben ^[12]	Stephanopoulos ^[18]

Table 1-2 Common Chemical Process Dynamics and Control Course Topics^[19]

Topics	Lecture time %
Process Dynamics and Modeling	28.1
Feedback Control and tuning	22.1
Stability and Frequency Response Analysis	14.3
Computer Simulation	8.9
Advanced Control Techniques	8.4
Control System Hardware	7.7
Computer Control Systems	4.8
Other	5.7

1.3 Motivation

The previous sections underline the importance of a competent control course in the undergraduate chemical engineering program. This project was prompted by resources in the Department of Chemical Engineering at University of Missouri and motivation to improve the laboratory experiments in the control class. The focus is on developing a practical, robust, and portable laboratory with flexibility for future development and eventually adding online access. Providing an online controls course would make the MU Chemical Engineering Curriculum much more flexible in addressing issues related to unlimited, open-schedule access and extension learning.

1.4 Objectives

- To use the existing coupled water tank apparatus in Department of Chemical Engineering–University of Missouri in the best possible manner within the Process Dynamics and Control course
- To practically demonstrate fundamental concepts like modeling and simulating a process system and validating a dynamic model
- To introduce and provide hands-on experience with Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) graphical user interface control programs

- To provide hands-on experience in tuning the Proportional-Integral (PI) controller for the apparatus
- To modify the existing experiments and their LabVIEW code for self-containment and robustness
- To develop a new laboratory which uses the same existing equipment

Integrating a laboratory experience into Process Control course allows students to model a chemical process using differential equations, which helps them better understand the chemical process, and then simulate the process in Simulink®, simulation software from the MathWorks™. Finally comparing the Simulink prediction of process with the experimental results and analyzing the reasons for any discrepancies in the results allows for validating the model. Other labs provide the students with actual hands-on experience in tuning a PI controller for the same process using the tuning rules taught in the class at later stage in semester.

1.5 Thesis Organization

Chapter 1

- Introduction
- Motivation and
- Objectives

Chapter 2

- Apparatus Description
- Software Description
- Pressure Sensor Calibration Procedure

Chapter 3

- Orifice Coefficient Determination
- Experimental Module for Modeling the Liquid Level in a Cylindrical Tank
- Experimental Module for Modeling the Liquid Level in the Second Tank of a Coupled Tank System
- Experimental Module for Tuning a PI Controller for Level Control of a Cylindrical Tank
- Experimental Module for Tuning a PI Controller for Level Control of the Second Tank in a Coupled Tank System
- Correcting Pump.VI Startup Issues

Chapter 4

Results and discussions for

- Experimental module for Orifice Coefficient Determination
- Experimental Module for Modeling the Liquid Level in a Cylindrical Tank

- Experimental Module for Modeling the Liquid Level in the Second Tank of a Coupled Tank System
- Experimental Module for Tuning a PI Controller for Level Control of a Cylindrical Tank
- Experimental Module for Tuning a PI Controller for Level Control of the Second Tank in a Coupled Tank System

Chapter 5

- Project Progression
- Outcomes
- Student Feedback
- Recommendations
- Future Work
- Miscellaneous

Appendix

- MATLAB Code for Experiment-2 Results.
- LabVIEW Block Diagrams for Pump.VI and LabPID1.VI

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CHAPTER 2

MATERIALS AND METHODS

2.1 Coupled Tank Apparatus Description ^[1]

The Quanser coupled tank apparatus is shown in the Figure 2-1. The apparatus is a bench-top model consisting of a pump, two cylindrical tanks made of plexiglas, and

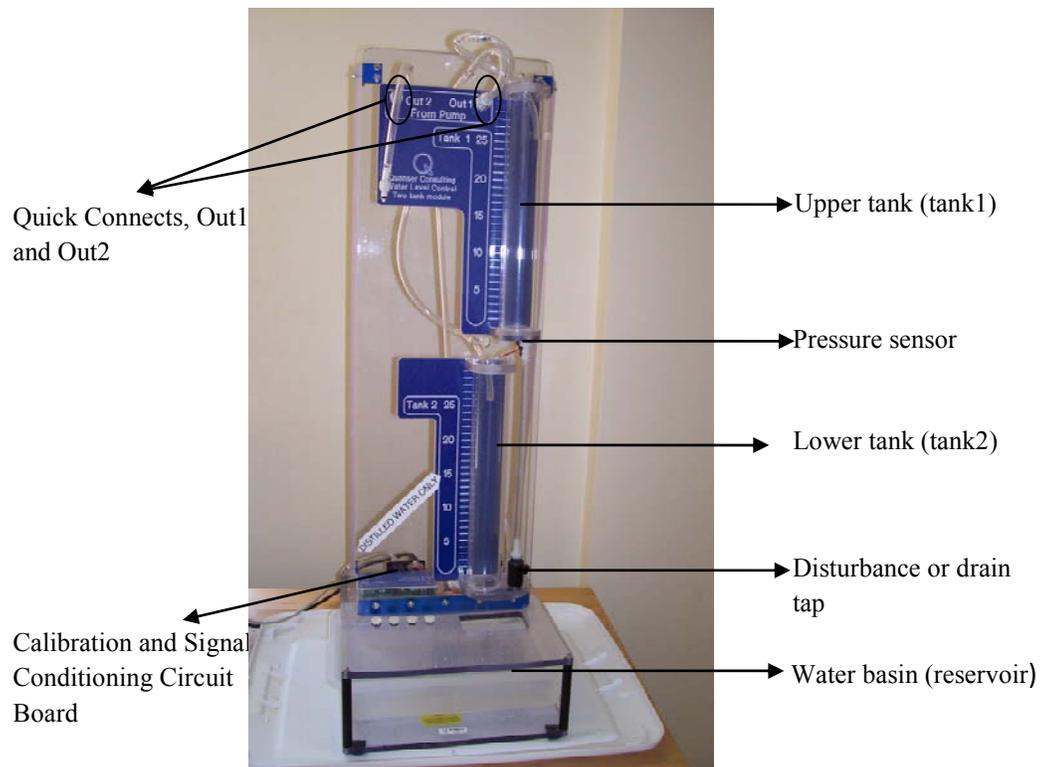


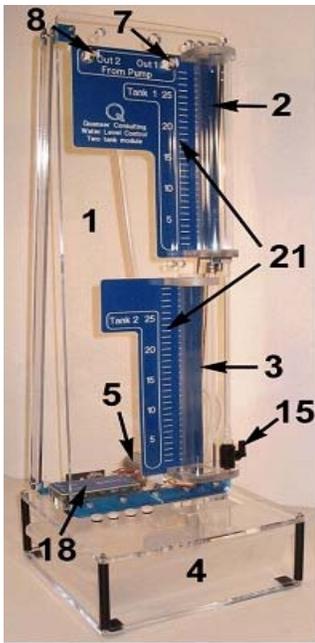
Figure 2-1 Coupled Tank Apparatus.

water basin (reservoir). These two tanks are of volume 133.35cm^3 each and are mounted on a platform with a metering scale behind each tank indicating the approximate liquid level in tank. The two tanks are vertically mounted on a platform and positioned in such a manner that outflow from the top tank (tank1) serves as inflow for the lower tank (tank2). Outflow from the lower tank goes directly into a reservoir. From each tank, fluid exits by gravity discharge through a small orifice. The resistance of this discharge can be varied by replacing the orifice inserts of different diameters into a threaded hole at the bottom of the tank. A drain tap is also provided in the apparatus to introduce disturbance flow into either tank1 or tank2. By opening the drain tap, liquid from tank1 flows directly to the reservoir. The pump propels water vertically to two quick-connect orifices "Out1" and "Out2", which are usually closed. The system is equipped with different diameters for these two orifices, for configurability. Teflon Tubing of 1/4" I.D with compatible couplings is provided to enable the pump to feed one tank or both tanks. *The water level in each tank is measured by a pressure sensor located at the bottom of each tank.*

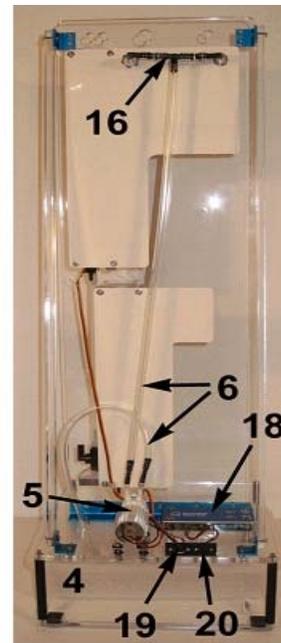
2.2 Component Description

Overall frame (Component #1)

The overall frame is made of plexiglas and dimensions for overall frame height, width and depth are 0.915 m, 0.305 m, and 0.305 m respectively ^[1].



(a)



(b)

Figure 2-2 Coupled-Tank Plant: (a) Front View and (b) Back View.

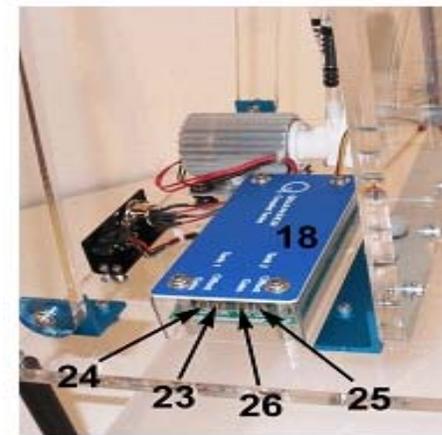
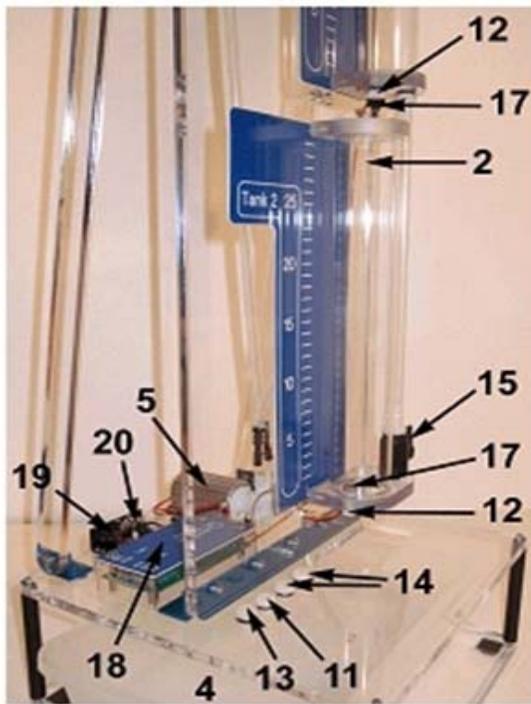
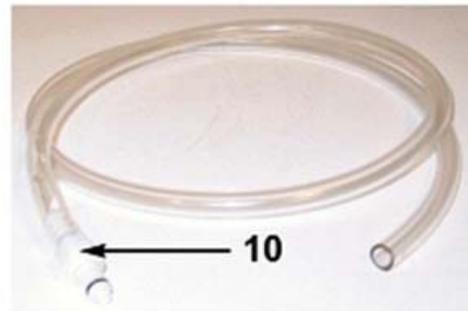
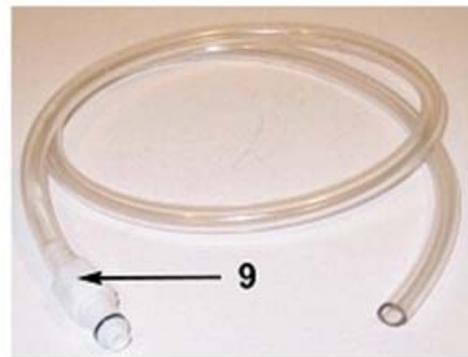


Figure 2-3 Calibration and Signal Conditioning Circuit Board.



(a)



(b)

Figure 2-4 (a) Base of Coupled-Tank Apparatus. (b) Quick connects "Out1" and "Out2" Couplings.

Water Tanks (Component #2 & #3)

The water tanks are made of plexiglas and have a uniform cross sectional area of 0.045 m each.

Water Basin (Component #4)

The water reservoir is an ordinary poly vinyl chloride (PVC) basin and is filled with ~18 MΩ distilled water from a Barnstead™ NANOpure® Diamond Life Science (UV/UF) ultrapure water system.

Pump (Component #5)

The coupled-water tank pump is a gear pump with a 12- Volt Direct Current (DC) motor and heat radiating fins. The parts of the pump that come into contact with the pumped fluid are two molded Delrin gears in a Delrin pump body, a stainless steel shaft, a Teflon diaphragm and a Buna N seal. It is also equipped with 3/16" ID hose fittings.

Rubber Tubing (Component #6)

The Tubing is made of Teflon with 1/4" ID.

Quick-Connect Inlet Orifice "Out1" & "Out2" (Component #7 & #8)

These quick-connect inlet orifices are used to bring online only tank1 or only tank2 or both with various configurations.

Quick Connects "Out1" and "Out2" Couplings (Component #9 & #10)

These are the couplings that connect quick-connect inlet orifice and the hose that run either to tank1 or tank2.

Outlet inserts (Component #11, #12, #13, #14)

Outflow from the tanks can be varied by using the different outlet inserts provided by the manufacturer. The four different inserts provided are small, medium, and large outlet inserts with diameters of 0.3175 cm, 0.4762 cm and 0.5556 cm respectively, as well as a plug.

Disturbance Tap (Component #15)

The disturbance tap (which is operated manually) serves as a drain valve in case of emergency, when the LabVIEW program is not taking control limit action for level control of tank1. To close the tap, the flap should be horizontal to the ground. For draining, the fluid flap should be in line with the drain pipe or vertical to the ground.

Flow Splitter (Component #16)

This divides the flow between "Out1" and "Out2" so that different configurations: Single Input Single Output (SISO), State –Coupled SISO and State-Coupled and input Coupled SISO configurations are possible.

Pressure Sensor (Component #17)

A pressure sensor is located at the bottom of each tank to measure the head in that tank. The sensor output voltage increases proportional to the applied pressure. The output measurement is processed through signal conditioning board (component #18) and made available as 0-5V DC signal. Sensitivity of the measurement is to be determined and is usually in the range of 6.0-6.4 cm³/ (s.V) for both pressure sensors. Calibration of each pressure sensor's offset and gain potentiometers are required to keep level measurements consistent with the liquid used in the experiment.

Calibration and Signal Conditioning Circuit Board (Component #18)

To calibrate the pressure sensors, the bottom of the Coupled-Water tank apparatus houses a signal conditioning circuit board, identified by component #18. Table 2-1 provides a list of different signal potentiometers to be tuned during sensor calibration.

Table 2-1 Calibration and Signal Conditioning Circuit Board Components

ID#	Description	ID#	Description
23	Tank1 Sensor Offset Potentiometer	24	Tank1 Sensor Gain Potentiometer
25	Tank2 Sensor Offset Potentiometer	25	Tank2 Sensor Gain Potentiometer

2.3 Coupled-Tank Model Parameters ^[1]

Table 2-2 lists and characterizes the main parameters (e.g. mechanical and electrical specifications, conversion factors, constants) associated with the two-tank specialty plant. Some of these parameters can be used for mathematical modeling of the Coupled-Tank system as well as to obtain the water level's Equation Of Motion (EOM).

Table 2-2 Coupled tank system model parameters

Symbol	Description	Value	Units
K	Pump Flow Constant	~17.9 (apparatus specific)	cm ³ /s/V
V _{p_max}	Pump maximum Continuous Voltage	12	V
V _{p_peak}	Pump Peak Voltage	22	V
D _{out1}	Out1 Orifice Diameter	0.4763	cm
D _{out2}	Out2 Orifice Diameter	0.4763	cm
L _{1_max}	Tank1 Height (i.e. Water level range)	30	cm
D _{t1}	Tank1 Inside diameter	4.4450	cm
K _{L1}	Tank1 Water level sensor sensitivity (Depending upon pressure sensor calibration)	6.1	cm/V
L _{2_max}	Tank2 height(i.e. water level range)	30	cm
D _{t2}	Tank2 Inside diameter	4.445	cm
K _{L2}	Tank2 Water level sensor sensitivity (Depending upon pressure sensor calibration)	6.1	cm/V

Symbol	Description	Value	Units
V_{bias}	Tank1 and Tank2 Pressure sensor power bias	± 12	V
P_{range}	Tank1 and Tank2 sensor pressure range	0-6.89	KPa
D_{so}	Small Outflow Orifice diameter	0.3175	cm
D_{mo}	Medium Outflow orifice diameter	0.4762	cm
D_{lo}	Large Outflow orifice diameter	0.5556	cm
D_{wo}	Diameter of orifice without any insert	0.7560	cm
g	Acceleration due to gravity	981	cm/s^2

2.4 Electrical Components and Connections

Electrical connections must be made between the three major components. The Universal Power Module (Quanser UPM 2405) which serves as a power amplifier, the Quanser Q8 terminal board (Data Acquisition and Control (DAC) Board) and the Coupled-Tank Apparatus. Figure 2-5 shows the Hardware required for the Coupled-Tank system and Figure 2-6 shows the Coupled-tank connections.

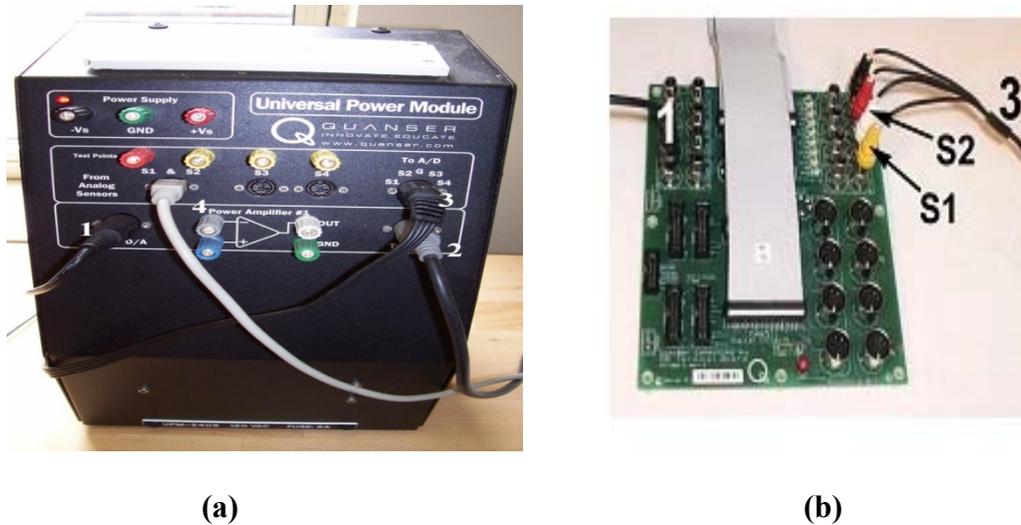


Figure 2-5 (a) Universal Power Module: UPM 2405 (b) Q8 Terminal Board Connections.

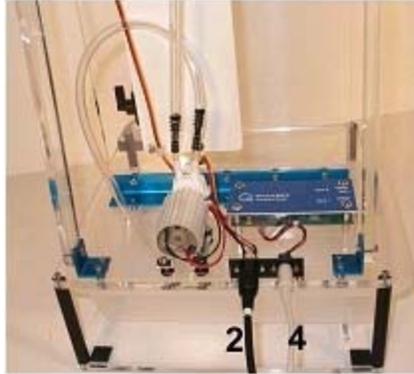


Figure 2-6 Coupled-Tank Connections.

2.4.1 Cable Nomenclature

Figure 2-7 and Figure 2-8 depicts the cables used in wiring the Coupled-Tank system.



(a)



(b)

Figure 2-7 (a)"From Digital-To-Analog" Cable (b) "To Load" Cable of Gain 5.

Figure 2-7(a) shows "From Digital-To-Analog" cable which is 5-pin- Deutsches Institut für Normung (DIN) connector to Radio Corporation of America (RCA) adapter. This cable connects an analog output of the data acquisition terminal board to the power module for proper power amplification. Figure 2-7 (b) shows "To Load" cable which is a 4-pin DIN to 6-pin DIN connector. This cable connects the output of the power module,

after amplification to the gear pump. One end of this cable contains a resistor that sets the amplification gain. When carrying a label showing "5", at both ends, the cable has that particular amplification gain.



(a)



(b)

Figure 2-8 "From Analog Sensors" Cable (b) "To-Analog-to -Digital" Cable.

Figure 2-8(a) shows "From Analog Sensors" cable which is 6-pin mini DIN to 6-pin mini DIN. This cable carries analog signals from one or two pressure sensors to the UPM, where the signals can be either monitored and/or used by an analog controller. The cable also carries a ± 12 V DC line from the UPM in order to power a sensor and/or signal conditioning board. Figure 2-8 (b) shows "To-Analog-to -Digital" cable which is 5-pin-DIN to 4 x RCA. This cable carries the analog signals, taken from the pressure sensors, unchanged, from the UPM to Digital-To-Analog input channels on the data acquisition terminal board.

2.4.2 Coupled Tank Wiring Summary

Table 2-3 describes the electrical connections necessary to run the coupled water tank system. The cable numbers are labeled in Figure 2-5(a).

Table 2-3 Coupled Tank Apparatus Wiring Summary

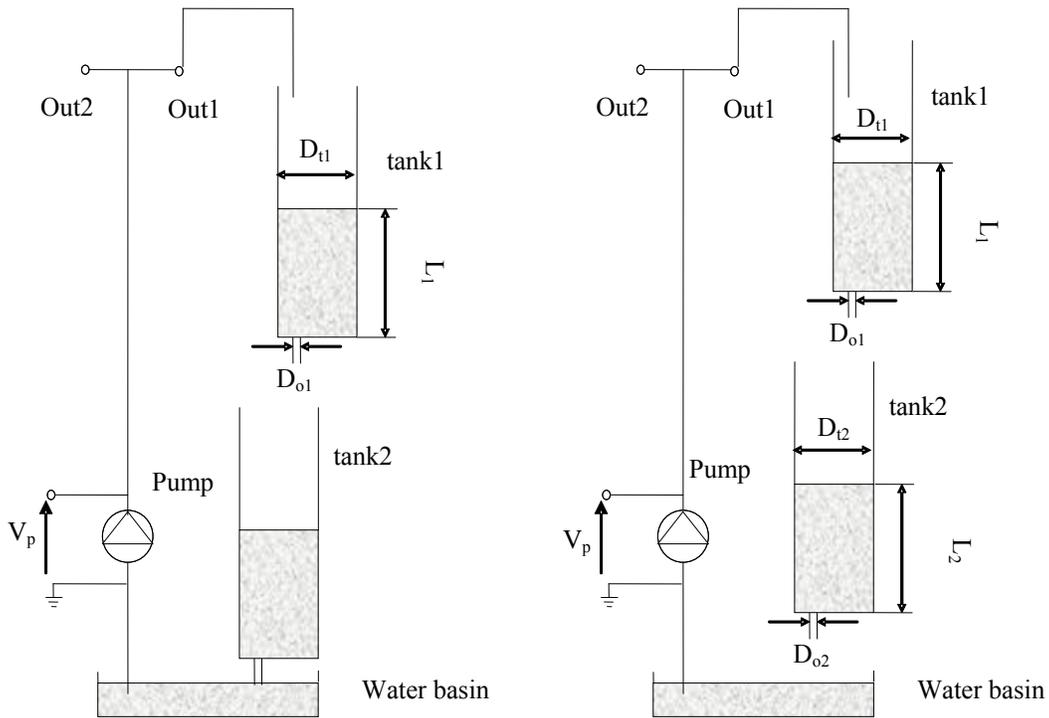
Cable#	From	To	Signal
1	DAC#0	UPM "From D/A"	Control signal to UPM
2	UPM "To Load"	Coupled-Tank's	Power leads to gear pump
3	UPM "To A/D"	Terminal Board: S1 to ADC#0 S2 to ADC#1	Tank 1 and tank 2 level feedback signals to the DAQ board through UPM
4	Coupled tank's Pressure Sensors	UPM "S1 & S2"	Liquid level feedback signal to the UPM
5	Power supply outlet	UPM power socket	UPM power supply

2.5 Configurations

A single Coupled-tank system can be used to set up different types of experiments, as described below. Each of these configurations results in a unique control problem.

Configuration#1 Single Input Single Output (SISO)

In this system, the pump feeds into tank1 and tank2 is not used at all. A controller is designed to regulate or track the level in tank1. Different inlet and outlet diameters can be used and tried in tank1.



(a)

(b)

Figure 2-9 (a) SISO Configuration (b) State-Coupled SISO Configuration.

Configuration#2 State-coupled SISO system

In this system, the pump feeds into tank1 which in turn feeds tank2. A controller is designed to regulate or track the level in tank2. Different inlet and outlet diameters can be used and tried in tank2.

Configuration # 3 State-Coupled and Input Coupled SISO system

In this system, the pump feeds into tank1 and tank2 using a split flow. tank1 also feeds into tank2. A controller is designed to regulate or track the level in tank 2. Different inlet

and outlet diameters can be used and tried in tank1 and tank2.

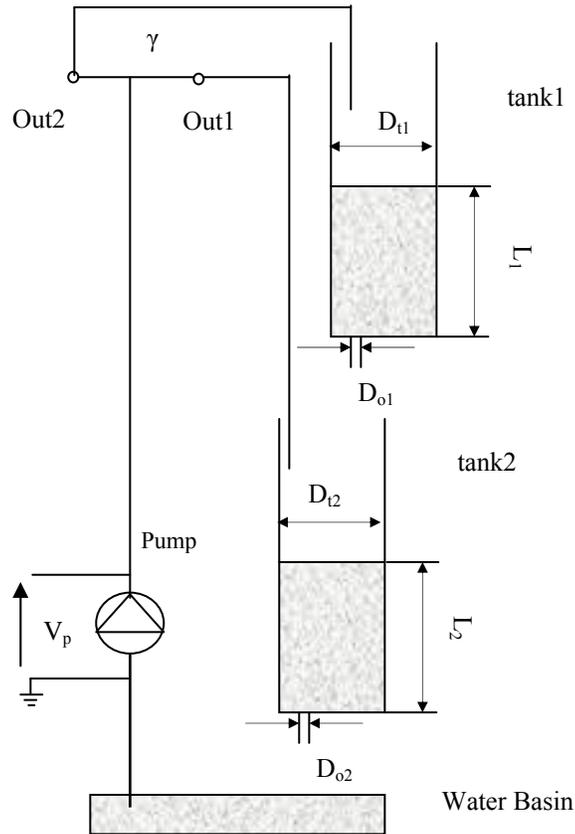


Figure 2-10 State-Coupled and Input Coupled SISO System.

2.6 Pumped Fluid

Distilled water is the pumped fluid. The reservoir water is taken from the Barnstead™ NANOpure® Diamond Life Science (UV/UF) ultrapure water system which has a resistivity of $\sim 18 \text{ m}\Omega\text{-cm}$, located in Dr. Pinheiro's laboratories.

Distilled water is recommended to fill the water in the reservoir to avoid deposits on and staining on plexiglas tubes and other equipment.

2.7 Data Acquisition and Control Software

The LabVIEW programs Pump.VI and LabPID1.VI are for control of pump speed and to acquire voltage data from the pressure transducers in either tank1 and/or tank2. LabVIEW is installed on Dell workstation running the Windows XP operating system. Pump.VI has NIDAQmx device drivers (8.0.0f0) and LabPID1.VI has Traditional Data Acquisition software (7.4.1f4) for data acquisition.

2.7.1 LabVIEW Pump.VI Program Explanation

The Pump.VI program is a LabVIEW routine that operates the open-loop tank level process and Figure 2-11 shows the controls and indicators on the Pump.VI front panel. The “PUMP VOLTAGE” vertical slider and the input box below it are used to set the pump voltage. It is advised to type a number into the input box instead of moving the slider when creating a step change. The data display boxes in the center of the screen show the time in milliseconds and tank1, tank2 pressure sensor output voltages and the pump voltage in Volts. Tank pressure sensor voltages and the pump voltage are also

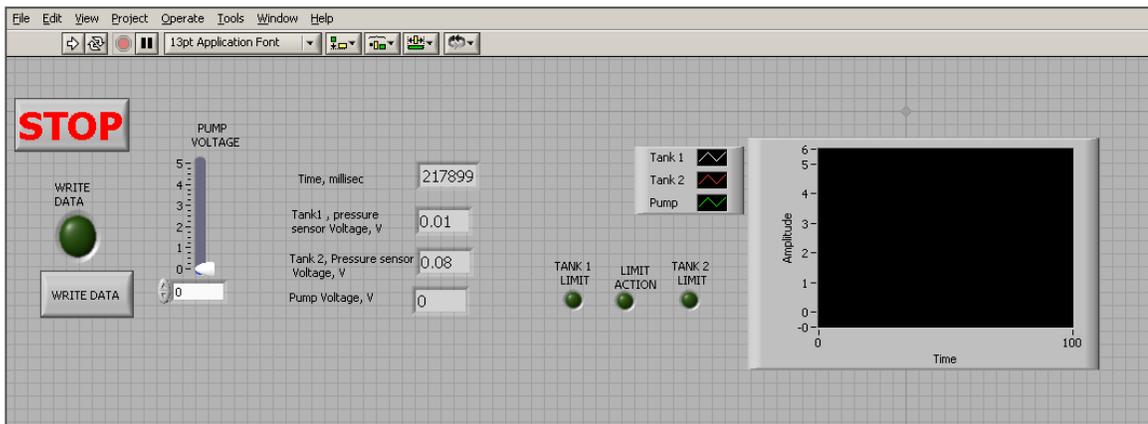


Figure 2-11 Pump.VI Front Panel.

displayed in the waveform chart on the right of the screen. “Write data” glows to indicate when the program is writing data to the user defined file. The tank1 and/or tank2 limit Light Emitting Diode (LED) glow when the tank voltages are in the range 4.3 to 4.5 V, indicating the danger of tank overflow. At this point the Safety Interlock System’s watchdog routine shuts off the pump and the pump continues to remain idle until the voltage range is again within the acceptable range (less than 4.3 Volts).

Important Note: The measured variables in tank1 & tank2 are pressure sensor voltages and not the tank volumes or liquid levels.

2.7.2 LabPID1.VI Program Explanation

The front panel of LabPID1.VI is shown in Figure 2-12. On the left side of the screen, the set point for the liquid level is entered. The “Run pump” button is used to run the pump. “Control Tank Toggle” button is used to switch level control between tank1 and tank2. “Write data” glows when the program is writing data to the user defined file.

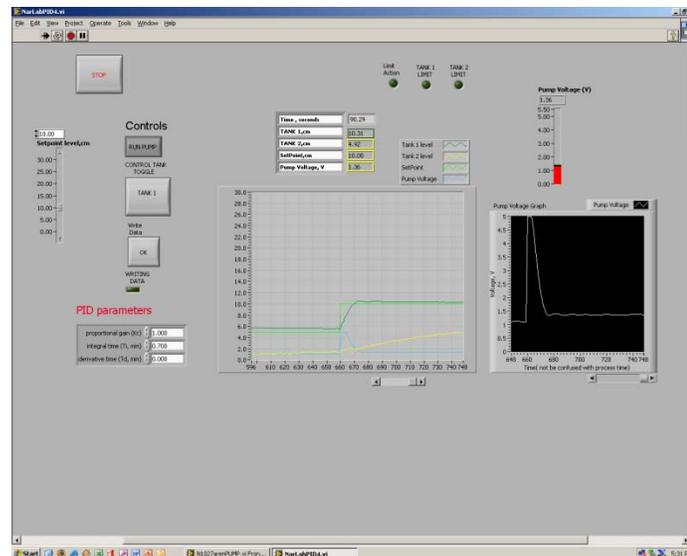


Figure 2-12 LabPID1.VI Front Panel.

In addition to the initialization controls described above, the PID tuning parameters are entered and displayed here. The 'STOP' button is used to stop the program.

The dynamic response of the output variables are shown in the center of the screen. The Limit action LED, along with either the tank1 Limit or tank2 Limit LED, glows when the tank voltages are in the range 4.3 to 4.5 V. In this voltage range, the Safety Interlock System takes control to avoid overflow. The levels of tank1 and tank2, along with the set point, are displayed numerically in cm. They are also plotted on a waveform chart below their numerical display. The dynamic response of the input variable is shown on the right of the screen. The pump voltage is displayed on a vertical indicator and is plotted on the waveform chart below the vertical indicator. The horizontal scroll bar below the waveform charts enables the user to view earlier responses. Use the horizontal scroll bar to note how the input and output variables respond to a step change for various tuning constants and, based on these responses, tune the process.

Appropriate values for the Proportional-Integral-Derivative (PID) parameters lead to good control - stable, snappy, and not too oscillatory. Inappropriate values leads to bad control - unstable, sluggish, and oscillatory. Adjust the PID tuning parameters as necessary so that the response to a set point change is reasonable.

2.8 Calibration Procedure for the Pressure Sensors

1. Make sure that the tanks to be calibrated are empty before starting the calibration. If not, empty it using the disturbance tap (black flap near the bottom of tank2) for tank1 and removing the plug (finger) for tank2.
2. Water can be pumped only to the tank1 by using the quick connect at “Out1”.
3. Use a finger to plug the tank1 orifice.
4. Observe the tank1 voltage on the Pump.VI front panel. If it is off from 0 V at zero cm, manually adjust offset potentiometer screw for tank1 on the calibration and signal conditioning circuit board using the potentiometer adjustment tool (flat head screw driver) to obtain 0 V. Turning the screw clockwise will decrease the voltage and vice-versa.
5. Now, fill tank1 to 25 cm and observe the voltage reading for tank1.
6. If it is off from 4.10 V, adjust the gain potentiometer screw for tank1 to obtain 4.10 V. Turning the gain potentiometer screw clockwise will increase the voltage and vice-versa.
7. Now, drain water from the tank1 using the using disturbance tap.
8. Check whether the offset is back to 0 V or not. If not, repeat steps 4-7 until you get the offset for the tank1 as 0V. (0V offset is usually achieved by 2-3 repeats of steps 4-7). If yes, check whether the voltage is 4.10 V at 25 cm of water level.

9. Double check whether voltage is reading 0 V when tank1 is empty and 4.10 V at 25 cm water level.
10. Tank2 is brought online for calibration by using quick connect at “Out2” and disconnecting quick connect on “Out1”.
11. Plug orifice of tank2 with a finger.
12. Follow steps 4-9 to calibrate the offset and gain potentiometers for tank2.
13. Now the apparatus is ready for experimentation.

2.9 Reference

1. *Coupled Water Tanks User Manual, Document Number: 557, Revision: 03, Quanser.*

CHAPTER 3

LABORATORY TEACHING MODULES

3.1 Introduction

Five experiments were designed to introduce and provide hands-on experience with the concepts of modeling, simulation, model validation, feed-back control and PI controller tuning. Different educational levels of undergraduate chemical engineering students can gain practical skills using these experimental modules. These five skills are some of the most important practical tools to graduates seeking positions in the process industry. These modules offer useful exercises in the following:

- Instrument calibration
- Finding orifice coefficient flow constant for gravity discharge
- Formulation and validation of a dynamic model for liquid level in a cylindrical tank
- Formulation and validation of a dynamic model for liquid level in the second tank of a coupled-tank system
- Fine tuning of a PI controller for level control of a cylindrical tank

- Fine tuning of a PI controller for level control of the second tank in the coupled-tank system

This chapter contains modules for five independent stand alone experiments. The modules are written such that each section represents a single, self-contained experiment. Each can be used as a laboratory procedure manual.

3.2 Experiment-1 Orifice Coefficient Determination

Objective

To find the orifice coefficient for a cylindrical tank.

Coupled Tank Apparatus Description ^[1]

The Quanser coupled tank apparatus is shown in Figure 3-1. The apparatus is a bench-top model consisting of a pump, two cylindrical tanks made of plexiglas, and water basin (reservoir). These two tanks are of volume 133.35cm^3 each and are mounted on a platform with a metering scale behind each tank indicating the approximate liquid level in tank. The two tanks are vertically mounted on platform and positioned in such a manner that outflow from the top tank (tank1) serves inflow for the lower tank (tank2), if second tank is used for experiment. Outflow from lower tank goes directly into a reservoir. From each tank, fluid exits by gravity discharge through a small orifice. The

resistance of this discharge can be varied by replacing the orifice inserts of different diameters into a threaded hole at the bottom of the tank.

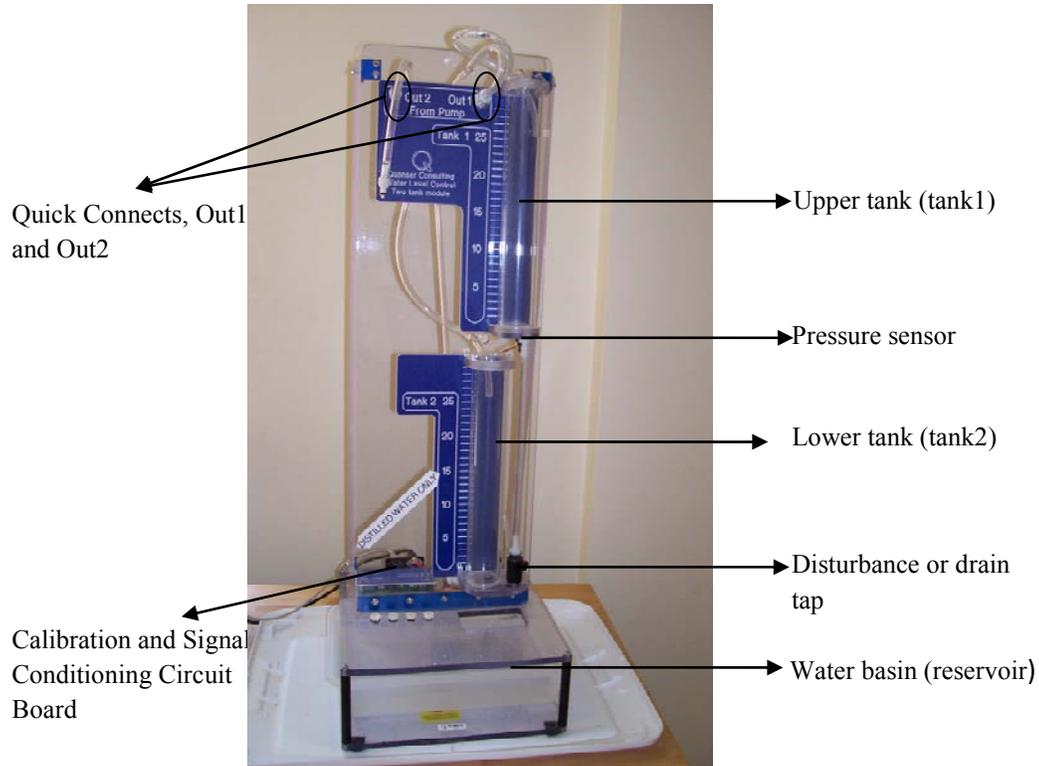


Figure 3-1 Coupled Tank Apparatus.

For this experiment use only medium inserts of diameter 0.476cm for both tanks.

A drain tap is also provided in the apparatus to introduce disturbance flow into either tank1 or tank2. By opening the drain tap, liquid from tank1 flows directly to the reservoir. The pump propels water vertically to two quick-connect orifices "Out1" and "Out2", which are usually closed. The system is equipped with different diameters for these two orifices, for configurability. Teflon Tubing of 1/4" I.D with compatible couplings is provided to enable the pump to feed one tank or both tanks. *The water level in each tank is measured by a pressure transducer located at the bottom of each tank.*

Theory^[2]

The overall material balance on the cylindrical tank is:

$$\left\{ \begin{array}{l} \text{rate of accumulation} \\ \text{of mass in system} \end{array} \right\} = \left\{ \begin{array}{l} \text{rate of mass} \\ \text{entering the system} \end{array} \right\} - \left\{ \begin{array}{l} \text{rate of mass} \\ \text{leaving the system} \end{array} \right\} \quad \mathbf{3-1}$$

$$\frac{dM}{dt} = \rho \frac{dV}{dt} = \rho F_i - \rho F_o$$

$M = \text{mass}; \rho = \text{density}; V = \text{Volume } F_i = \text{input flow rate};$

$F_o = \text{output flow rate}$

A schematic of the cylindrical tank system is shown in Figure 3-2. In this experiment, liquid is pumped from a reservoir into a cylindrical tank at a flow rate F_i (volume/time). The input flow rate is proportional to the pump voltage, i.e.

$$F_i = KV_{pump} \quad \mathbf{3-2}$$

where K [volume/(time.Volt)] is a constant and V_{pump} is the pump voltage.

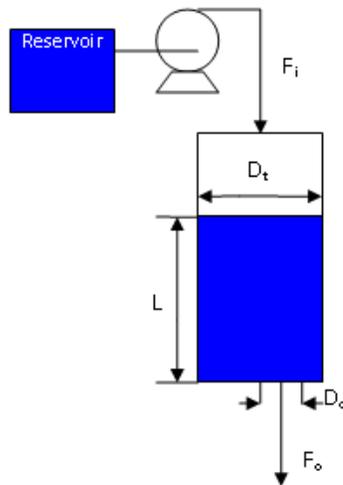


Figure 3-2 Schematic of Cylindrical Tank.

The liquid exits the tank by gravity discharge through a small orifice with cross-sectional area A_o . The tank's output velocity, v_o (length/time) is given by ^[5]

$$v_o = C_o \sqrt{\frac{2(P_1 - P_2)}{\rho \left[1 - \left(A_o/A_T\right)^2\right]}} \quad 3-3$$

C_o = orifice coefficient or discharge coefficient

$P_1 - P_2$ is nothing but head and is given by ρgL and $\left[1 - \left(A_o/A_T\right)^2\right]$ is almost equal to

1. Thus

$$v_o = C_o \sqrt{2gL} \quad 3-4$$

where g is the acceleration due to gravity and L is the tank's liquid level.

Volumetric output flow rate is

$$F_o = A_o v_o \quad 3-5$$

$$F_o = C_o A_o \sqrt{2gL}$$

At steady state, $F_i = F_o$

$$KV_{pump} = C_o A_o \sqrt{2gL} \quad 3-6$$

Pre-Lab tasks

- Prepare a spreadsheet that defines the experimental data necessary to define the gain, K , relating the pump voltage to the inlet volumetric flow rate.

- Prepare a spreadsheet that defines the experimental data necessary to calibrate the pressure sensor to the tank’s liquid level.
- Use Equation 3-5 and show how orifice coefficient can be graphically determined from the experimental data.

LabVIEW Pump.VI Program Explanation

The Pump.VI program is a LabVIEW routine that operates the open-loop tank level process and Figure 3-3 shows the controls and indicators on the Pump.VI front panel. The “PUMP VOLTAGE” vertical slider and the input box below it are used to set the pump voltage. It is suggested to type a number into the input box instead of moving

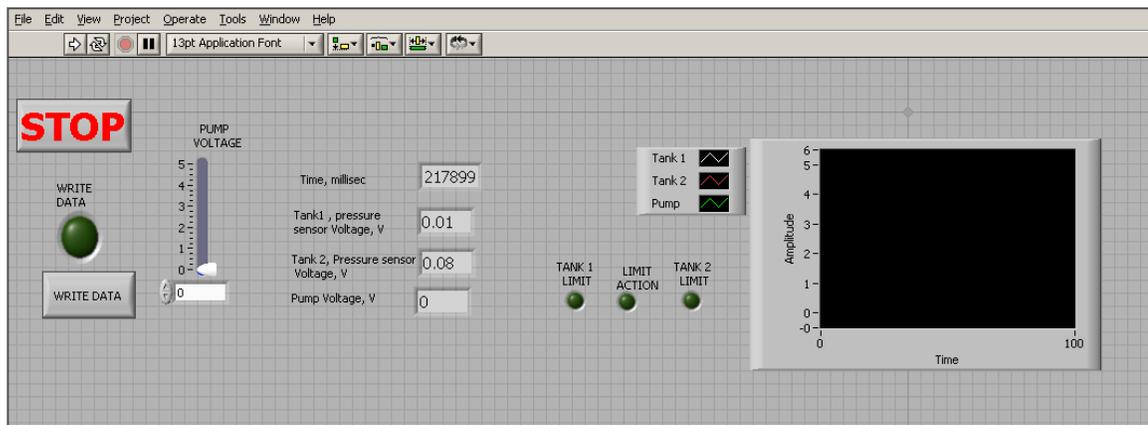


Figure 3-3 Pump.VI Front Panel.

the slider when creating a step change. The data display boxes in the center of the screen show the time in milliseconds and the tank1, tank2 pressure sensor output voltages and the pump voltage in Volts. Tank pressure sensor voltages and the pump voltage are also

displayed in the waveform chart on the right of the screen. "Write data" glows to indicate when the program is writing data to the user defined file. Tank1 and/or tank2 limit LED glow when the tank voltages are in the range 4.3 to 4.5 V, indicating the danger of tank overflow. At this point the Safety Interlock System's watchdog routine shuts off the pump and the pump continues to remain idle until the voltage range is again within the acceptable range (less than 4.3 Volts).

Important Note: The measured variables in tank1 & tank2 are pressure sensor voltages and not the tank volumes or liquid levels.

Lab Procedures

Precautions and Other Notes:

- Make sure that the reservoir's distilled water level is at least three-fourths full.
- A watchdog (software interlock) is programmed into pump.vi so that the tanks do not overflow. If the liquid level in either of the tanks reaches 25cm the pump is turned off and the pump continues to remain idle until the tank's voltage drops below 4.3 V
- Do not panic, the pump can be noisy. If it starts smoking that's another matter, you can shut off the pump by clicking "Stop" button in the program.
- Avoid parallax error while measuring the tank level; take measurements with an eye-line directly perpendicular to the level.

1) *Familiarize yourself with the apparatus and how it relates to the schematic.*

a) See Figure 3-1 and Figure 3-2.

2) *Start the pump.vi program and Open a data file*

a) Double-click the Pump.VI icon on the desktop. It opens the pump.vi program in LabVIEW. Familiarize yourself with the icons, controls and indicators on the screen shown in Figure 3-3.

b) Click the white color arrow button on the top left of the screen to start the program. A window pops up on the screen asking to define an output file.

c) Assign a file name and save it in Microsoft excel spreadsheet format, for example yourname.xls.

3) *Removal of air pockets*

a) Run the pump by giving a random pump voltage between 0.5-1 Volts in the voltage input box below the “PUMP VOLTAGE” vertical slider and watch for any air bubbles over/in the pressure sensor, located at the bottom of the top tank.

b) Air pockets will almost always form in the sensor, whether or not you see bubbles, poke the rod into sensor as shown in Figure 3-4.

Cautions: 1) Be gentle with the sensor while removing bubbles. A violent stroke on the sensor could ruin it.

2) Don't get confused with the bubbles formed and floating at the top of tank for bubbles in sensor.

- c) Once air pockets are removed, proceed to calibration of the tank pressure sensor (Step 4).



Figure 3-4 Removal of Air Pockets in Pressure Sensor.

4) *Calibrate the upper tank's pressure sensor.*

- a) Make sure that tank1 is empty by setting 0 V in “PUMP VOLTAGE” input box before starting the calibration. If not, empty it by using the disturbance tap (black flap near the bottom of tank2).
- b) Observe the pressure sensor voltage reading in the tank1 display box. If it is not 0 V, first manually adjust offset potentiometer screw for tank1 on the calibration and signal conditioning circuit board (See Figure 3-5) using the potentiometer adjustment tool (flat head screw driver) to obtain 0 Volts. Turn the offset potentiometer screw clockwise to increase the voltage reading and vice-versa.
- c) Cover the tank1 outlet with your finger.

- d) Using the quick connect at “Out1”, apply a voltage to the pump and fill the tank to 25 cm. Then turn off the pump (Apply 0 voltage to the pump).

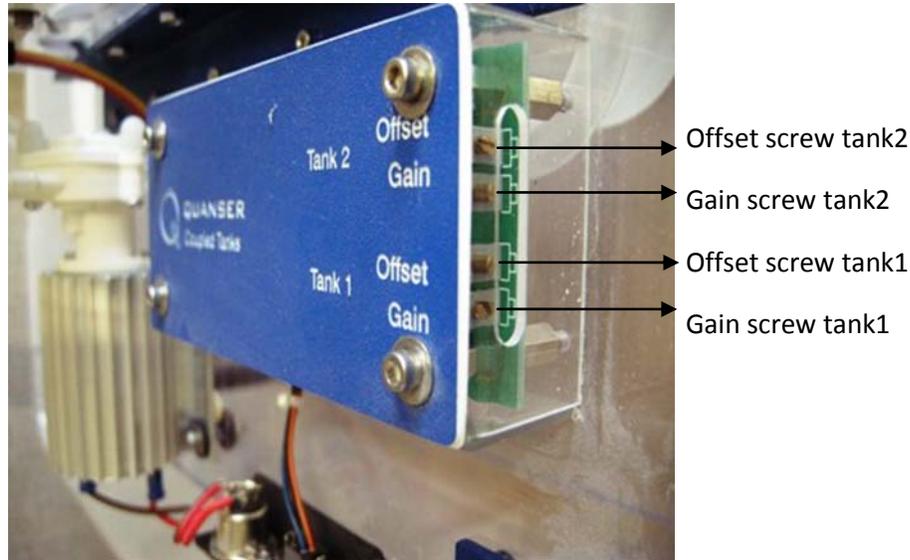


Figure 3-5 Calibration and Signal Conditioning Circuit Board.

- e) Observe the voltage reading in the tank1 display box. If it is not 4.10 V (± 0.03 of this value is okay) at 25 cm, manually adjust gain potentiometer screw for tank1 to obtain 4.10V. Turn the gain potentiometer screw clockwise to increase the voltage reading and vice-versa.

Caution: Make sure to adjust the correct potentiometer screw. For better understanding see Figure 3-5.

- f) Drain the tank.
- g) Check to see that the reading returns to 0V (readings may take 30 seconds or so to stabilize). If not, repeat 4b-4f until you get 0V at 0 cm and 4.10V at 25cm of level (This may take several trials).
- h) Record the voltage sensor readings for the tank levels of 0, 5, 10, 15, 20, 25 cm in a notebook.

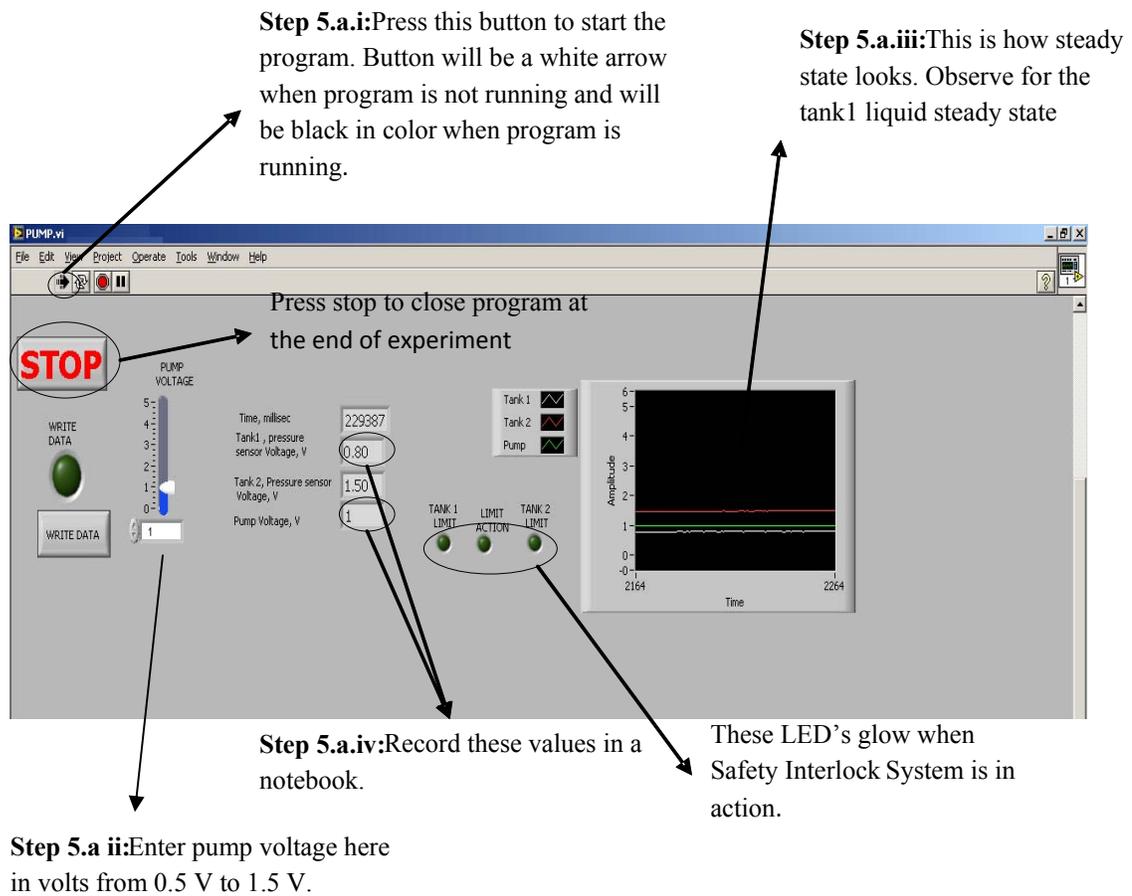


Figure 3-6 Step by Step Procedure for Experiment-1.

5) *Get the empirical data.*

Pump Flow constant, K

- a) Using a timer and graduated cylinder, obtain the data necessary to determine the gain relating the pump voltage to the inlet flow rate

Orifice coefficient

- i) Start the program
- ii) Set Pump Voltage to 1V in pump voltage input box
- iii) Wait until the liquid level reaches steady state and remains there for 1-2 minutes
- iv) Note the steady state liquid level and the steady state pressure sensor voltage. in a notebook
- v) Repeat steps 5.a.ii to 5.a.iv for 5-6 different pump voltage values equally spaced between 1 V and 1.65V

Data Analysis

1. Find the gain relating the pump voltage to the inlet flow rate
2. Find the gain relating the tank's liquid level to the pressure sensor voltage
3. Using the appropriate plot, find the orifice coefficient

3.3 Experiment-2 Modeling Liquid Level in a Cylindrical Tank

Objective

Formulate and validate a dynamic model for the liquid level in a cylindrical tank

Tasks

- Derive a dynamic model for the liquid level in a cylindrical tank.
- Obtain the necessary experimental data to validate the dynamic model.
- Solve the nonlinear dynamic model and its linearized approximation for laboratory conditions.
- Compare the theoretical model, its linearized approximation, and the empirical data obtained in the laboratory.

Coupled Tank Apparatus Description ^[1]

The Quanser coupled tank apparatus is shown in Figure 3-7, next page. The apparatus is a bench-top model consisting of a pump, two cylindrical tanks made of plexiglas and water basin (reservoir). These two tanks are of volume 133.35cm^3 each and are mounted on a platform with a metering scale behind each tank indicating the approximate liquid level in cm in the tank. The two tanks are vertically mounted on platform and positioned in such a manner that outflow from the top tank (tank1) is used as inflow for the lower tank (tank2), if the second tank is used for the experiment.

Outflow from the lower tank goes directly into a reservoir. From each tank, fluid exits by gravity discharge through a small orifice. The resistance of this discharge can be varied by replacing the orifice inserts of different diameters into a threaded hole at the bottom of the tank. *For this experiment use only the medium inserts of diameter 0.476cm for both tanks.*

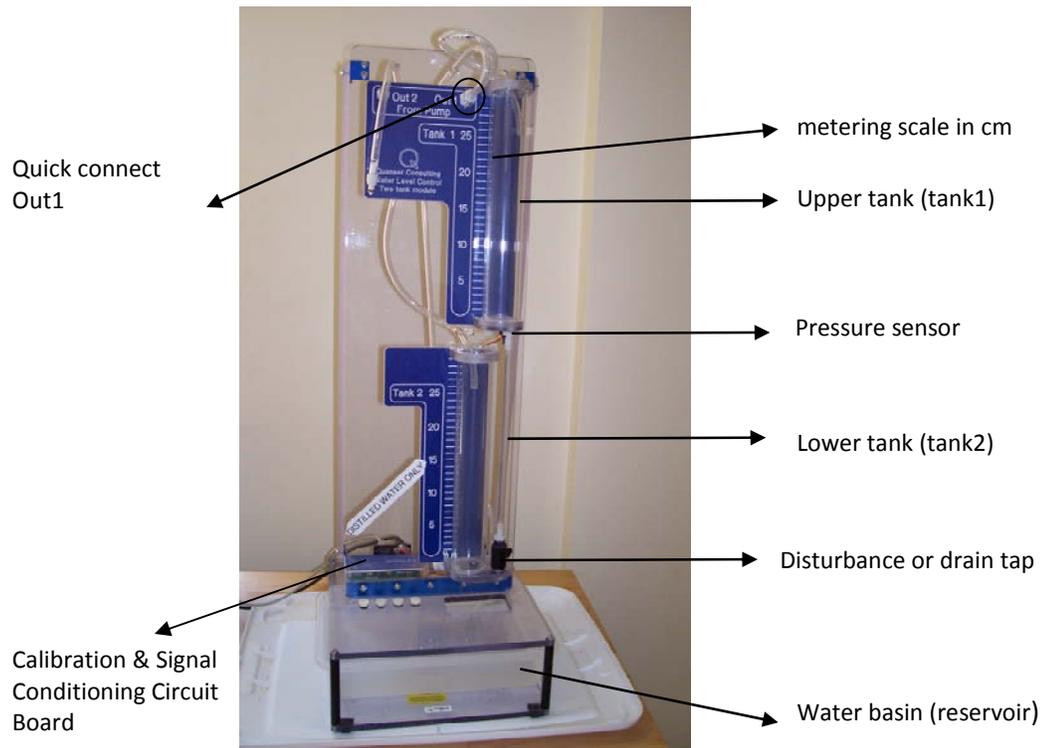


Figure 3-7 Coupled Tank Apparatus.

A drain tap is also provided in the apparatus, to introduce disturbance flow into either tank1 or tank2. By opening the drain tap, liquid from tank1 flows directly to the reservoir. The pump propels water vertically to two quick-connect orifices "Out1" and "Out2", which are usually closed. The system is equipped with different diameters for

these two orifices, for configurability. Teflon Tubing of 1/4" I.D with compatible couplings is provided to enable the pump to feed one tank or both tanks. *The water level in each tank is measured by a pressure transducer located at the bottom of each tank.*

Theory^[3, 4]

What is modeling and what is a mathematical model?

- The process of deriving the set of equations (algebraic and/or differential) that can be used to describe the response of the system to one or more inputs is called *modeling*.
- The equations which describe the system behavior are called the *mathematical models* of the system.

What are reasons for modeling?

- Improve or understand the chemical process operation is the overall objective for developing a dynamic process model.
- These models are often used to simulate the process behavior in operator training, in process design, in safety system analysis, and in process control.

How is a system modeled?

- The basis for modeling actually depends on the system. However, almost all systems important to chemical engineers can be modeled with both overall and component mass balances, energy balances, and momentum balances. Modeling a

simple situation like the liquid surge vessel requires only an overall material balance on the system. Overall material balances are sufficient to describe a system only if the roles of temperature, individual component compositions and pressure are not important. However, if there is an energy change in the system, like a temperature changes, an energy balance must be considered in modeling. An example of this situation is modeling of a heated mixing tank.

The basis for modeling a tank's dynamic liquid level is an overall material balance. It has the form:

$$\left\{ \begin{array}{l} \text{rate of accumulation} \\ \text{of mass in system} \end{array} \right\} = \left\{ \begin{array}{l} \text{rate of mass} \\ \text{entering the system} \end{array} \right\} - \left\{ \begin{array}{l} \text{rate of mass} \\ \text{leaving the system} \end{array} \right\} \quad \mathbf{3-7}$$

A more in depth explanation about modeling can be found in Chapter 2 of B. Wayne Bequette: *Process Control Modeling, Design and Simulation, Prentice Hall (2003)*^[1].

A schematic of the cylindrical tank system is shown in Figure 3-8. In this experiment, liquid is pumped from a reservoir into a cylindrical tank at a flow rate, F_i (volume/time). The input flow rate is proportional to the pump voltage, i.e.,

$$F_i = KV_{pump} \quad \mathbf{3-8}$$

where K [volume/(time.Volt)] is a constant and V_{pump} is the pump voltage.

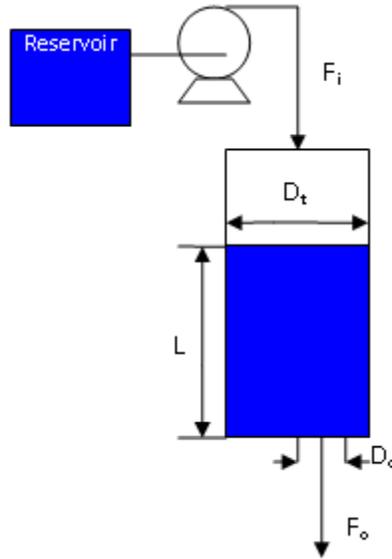


Figure 3-8 Schematic of Cylindrical Tank.

The liquid exits the tank by gravity discharge through a small orifice. The tank's outlet velocity (length/time) for small orifices is given by ^[5],

$$v_o = C_o \sqrt{\frac{2(P_1 - P_2)}{\rho \left[1 - \left(\frac{A_o}{A_T} \right)^2 \right]}} \quad 3-9$$

C_o = orifice coefficient or discharge coefficient

$P_1 - P_2$ is nothing but head and is given by ρgL and $\left[1 - \left(\frac{A_o}{A_T} \right)^2 \right]$ is almost equal to

1. Thus

$$v_o = C_o \sqrt{2gL} \quad 3-10$$

where g is the acceleration due to gravity and L is the tank's liquid level.

Pre-lab Procedures

1. Develop the nonlinear model relating the tank's liquid level to the pump voltage, i.e., find $\frac{dL}{dt} = f(L, V)$. Assume constant density. Use the parameters
 - a. Pump flow constant: $K=17.9 \text{ cm}^3/(\text{s}\cdot\text{V})$
 - b. Tank diameter: $D_t = 4.445 \text{ cm}$
 - c. Outlet orifice diameter: $D_o = 0.4762 \text{ cm}$
 - d. Gain relating water level to sensor voltage 6.0-6.4 cm/V
 - e. Acceleration due to gravity, $g = 981 \text{ cm/s}^2$
2. Find the steady state pump voltage, V_s , as a function of the steady state liquid level, L_s .
3. Define deviation variables and linearize the model about steady state.
4. Determine the transfer function for this open-loop process. What type of process model does this transfer function represent? What are the process model parameters?

LabVIEW Pump.VI Program Explanation

The Pump.VI program is a LabVIEW routine that operates the open-loop tank level process and Figure 3.9 shows the controls and indicators on the Pump.VI front panel. The “PUMP VOLTAGE” vertical slider and the input box below it are used to set the pump voltage. It is advised to type a number into the input box instead of moving the slider when creating a step change. The data display boxes in the center of the screen show the time in milliseconds and the tank1, tank2 pressure sensor output voltages and the pump

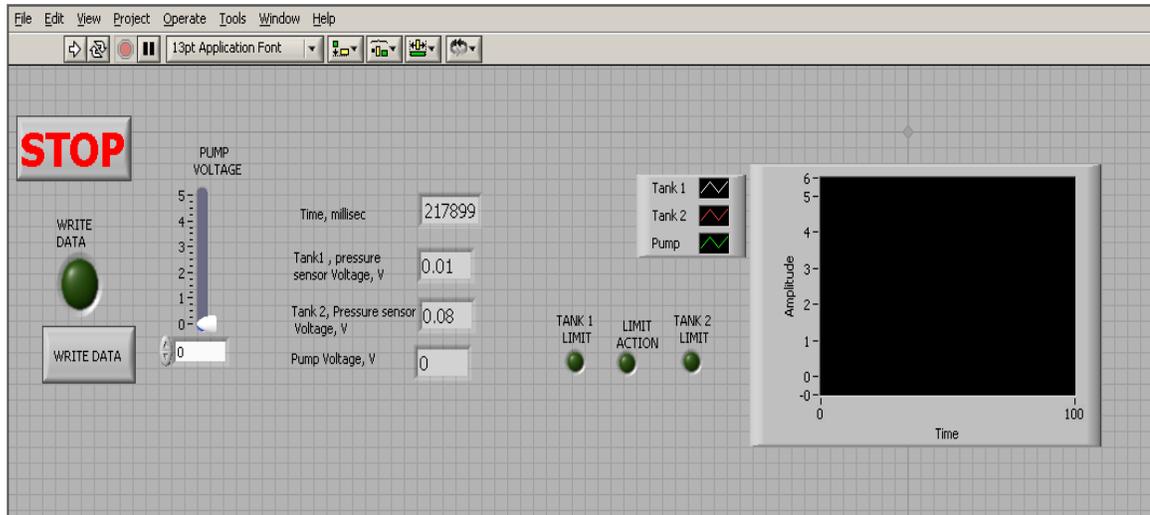


Figure 3-9 Pump.VI Front Panel.

voltage in Volts. Tank pressure sensor voltages and the pump voltage are also displayed in the waveform chart on the right of the screen. “Write data” glows to indicate when the program is writing data to the user defined file. tank1 and/or tank2 limit LED glow when the tank voltages are in the range 4.3 to 4.5 V, indicating the danger of tank overflow. At this point the Safety Interlock System’s watchdog routine shuts off the pump and the pump continues to remain idle until the voltage range is again with the acceptable range (less than 4.3 Volts).

Important Note: *The measured variables in tank1 & tank2 are pressure sensor voltages and not the tank volumes or liquid levels.*

Lab Procedures

Precautions and Other Notes:

- Make sure that the reservoir’s distilled water level is at least three-fourths full.

- A watchdog is programmed into pump.vi so that the tanks do not overflow. If the liquid level in either of the tanks reaches 25cm the pump is turned off and the pump continues to remain idle until the tank's voltage drops below 4.3 V in tanks.
- Do not panic, the pump can be noisy. If it starts smoking that's another matter. Shut off the pump by clicking "Stop" button on the Pump.VI.
- Avoid parallax error while measuring the tank level; take measurements with an eye-line directly perpendicular to the level.

1) *Familiarize yourself with the apparatus and how it relates to the schematic.*

a) See Figure 3-7 and Figure 3-8.

2) *Start the pump.vi program and Open a data file*

a) Double-click the Pump.VI icon on the desktop. It opens the pump.vi program in LabVIEW. Familiarize yourself with the icons, controls and indicators on the screen shown in Figure 3-9.

b) Click the white color arrow button on the top left of the screen to start the program. A window pops up on the screen asking to define an output file.

c) Assign a file name and save it in Microsoft excel spreadsheet format, for example yourname.xls.

3) *Removal of air pockets*

a) Run the pump by giving a random pump voltage between 0.5-1 Volts and watch for any air bubbles over/in the pressure sensor, located inside at the bottom of the top tank.

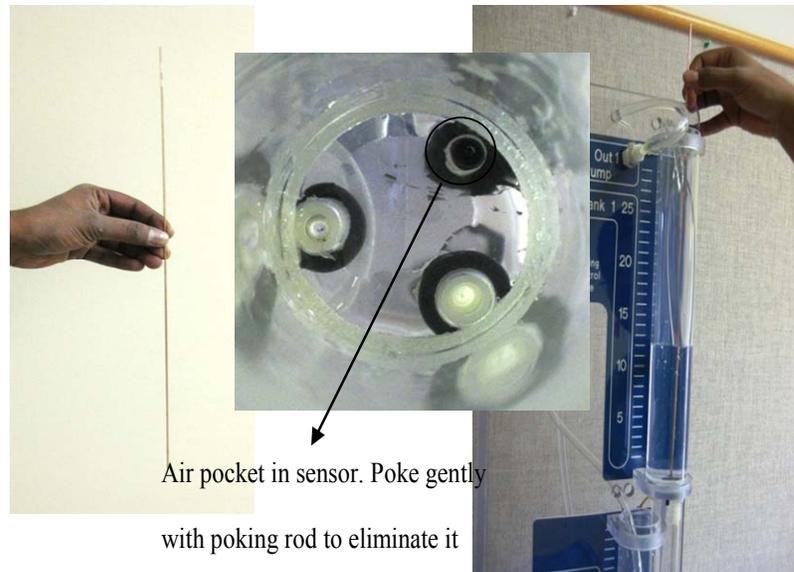


Figure 3-10 Removal of Air Pockets in Pressure Sensor.

- b) Air pockets will almost always form in sensor, whether or not you see bubbles poke the rod into sensor as shown in Figure 3-10.

Caution: 1) Be gentle with the sensor while removing bubbles. A violent stroke on the sensor could ruin it.

2) Don't get confused with the bubbles formed and floating at the top of tank for bubbles in sensor.

- c) Once air pockets are removed, stop the pump by setting 0V as the pump voltage and observe the voltage for the tank1 on Pump.VI front panel. If the voltage value is within ± 0.1 Volts of 0 V when the tank1 is empty, proceed to generate empirical data (Step 5). Otherwise proceed with the calibration of the tank pressure sensor (Step 4).

4) *Calibrate the upper tank's pressure sensor.*

- a) Make sure that tank1 is empty before starting the calibration. If not, empty it by using the disturbance tap (black flap near the bottom of tank2).

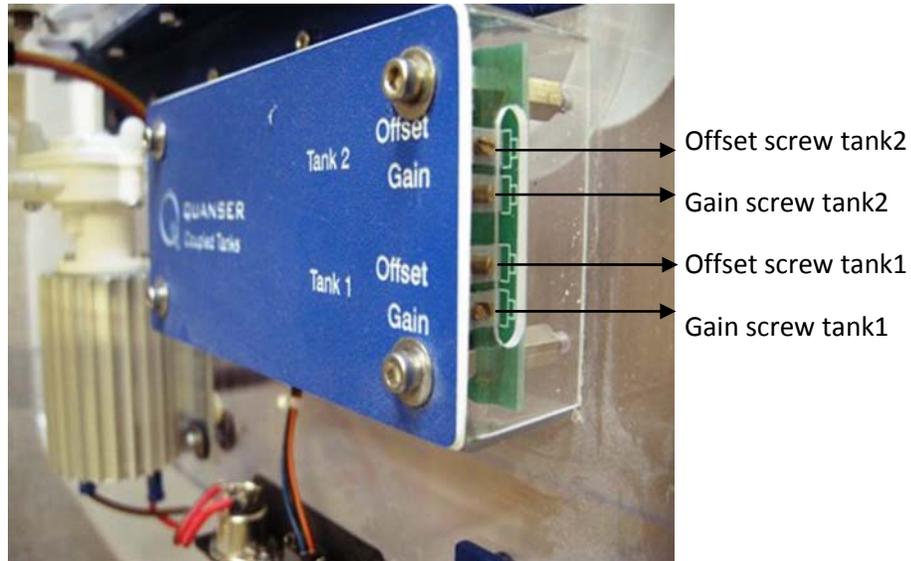


Figure 3-11 Calibration and Signal Conditioning Circuit Board.

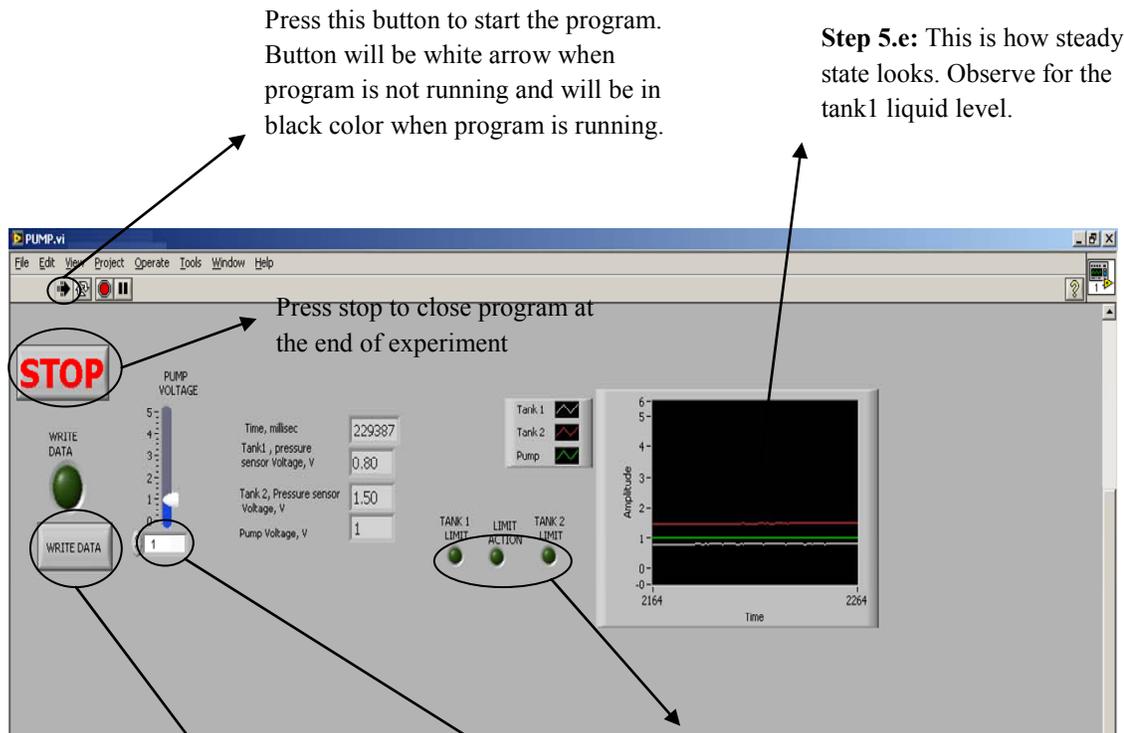
- b) Observe the pressure sensor voltage reading in the tank1 display box. If it is not 0 V, first manually adjust offset potentiometer screw for tank1 on the calibration and signal conditioning circuit board (See Figure 3-11) using the potentiometer adjustment tool (flat head screw driver) to obtain 0 Volts. Turn the offset potentiometer screw clockwise to increase the voltage reading and vice-versa.
- c) Cover the tank outlet with your finger.
- d) Using the quick connect at “Out1”, apply a voltage to the pump and fill the tank to 25 cm. Then turn off the pump (Apply 0 voltage to the pump).
- e) Observe the voltage reading in the tank1 display box. If it is not 4.10 V (± 0.03 of this value is okay) at 25 cm, manually adjust gain potentiometer screw for tank1

to obtain 4.10V. Turn the gain potentiometer screw clockwise to increase the voltage reading and vice-versa.

Caution: Make sure to adjust the correct potentiometer screw. For better understanding see Figure 3-11.

- f) Drain the tank.
 - g) Check to see that the reading returns to 0V (readings may take 30 seconds or so to stabilize). If not, repeat 4b-4f until you get 0V at 0 cm and 4.10V at 25cm of level (This may take several trials).
- 5) *Generate the empirical data*
- a) See detailed step by step procedure shown in Figure 3-12.
 - b) Record the pressure sensor voltage readings for tank1 liquid levels of 0, 5, 10, 15, 20, 25 cm in a notebook
 - c) Set the pump voltage (usually around 0.7 Volts) so that the steady state liquid level in tank1 is around 3 cm. Note the pump voltage at steady state.

Note: If you had to calibrate the sensor again, make sure there are no air bubbles over the sensor before you start recording data. If there are bubbles repeat step 3b.
 - d) Click the “WRITE DATA” button.
 - e) Make a positive step change (between 1 to 1.5 Volts) in the pump voltage by entering a number into the “PUMP VOLTAGE” input box and pressing enter. Do not make the step change so large that the Safety Interlock System’s watchdog program kicks off. Wait for the liquid level to reestablish steady state.



Press this button to start the program. Button will be white arrow when program is not running and will be in black color when program is running.

Step 5.e: This is how steady state looks. Observe for the tank1 liquid level.

Press stop to close program at the end of experiment

Step 5.d: Click "Write data" to write data into the file.

These LED's glow when Safety Interlock System is in action.

Step 5.g: Click "Writing Data" to stop recording to file.

Step 5.c: Enter a voltage value between 0.5-0.75Volts here to get initial steady state value.

Step 5.e: Enter a voltage value between 1 and 1.5Volts.

Step 5.f: Step change pump voltage back to 0.5-0.75 Volts of step 5.b.

Figure 3-12 Step by Step Procedure for Experiment #2.

- f) Once steady state is established, step change the pump voltage to its original steady-state value from step 5c.
 - g) Click the “WRITING DATA” to stop recording data.
 - h) Repeat steps 5c-5g three more times for same pump voltages.
- 6) *Press “STOP” button to stop the program.*

Data Analysis

- 1) Compute the gain relating the tank voltage to the tank level using the calibration data from step 5.b.
- 2) Solve the nonlinear model using MATLAB for the step changes in pump voltage you performed in the lab.
- 3) Solve the linearized approximation of the nonlinear model using MATLAB for the step changed you performed in the lab.
- 4) Graphically compare the nonlinear model, its linearized approximation and the lab data.
- 5) Determine the transfer function relating the output variable (liquid level) to the input variable (pump voltage) as first order plus dead time model. Give the confidence interval for each of the model parameters ^[6].

3.4 Experiment -3 Modeling Liquid Level in a Coupled-Tank System

Objective

Formulate and validate a dynamic model for the liquid level in the second tank of a coupled-tank system.

Tasks

- Derive a linearized dynamic model for the liquid level in the second tank of the coupled-water tank apparatus.
- Obtain the necessary experimental data to validate the linearized dynamic model.
- Derive a first-order plus dead time (FODT) model from the laboratory data.
- Compare the linearized model, FODT model, and the empirical data obtained in the laboratory.

Coupled Tank Apparatus Description ^[1]

The Quanser coupled tank apparatus is shown in Figure 3-13, next page. The apparatus is a bench-top model consisting of a pump, two cylindrical tanks made of Plexiglas and water basin (reservoir). These two tanks are of volume 133.35cm^3 each and are mounted on a platform with a metering scale behind each tank indicating the approximate liquid level in cm in the tank. The two tanks are vertically mounted on platform and positioned in such a manner that outflow from the top tank (tank1) is used

as inflow for the lower tank (tank2), if second tank is used for experiment. Outflow from the lower tank goes directly into a reservoir. From each tank, fluid exits by gravity discharge through a small orifice. The resistance of this discharge can be varied by replacing the orifice inserts of different diameters into a threaded hole at the bottom of

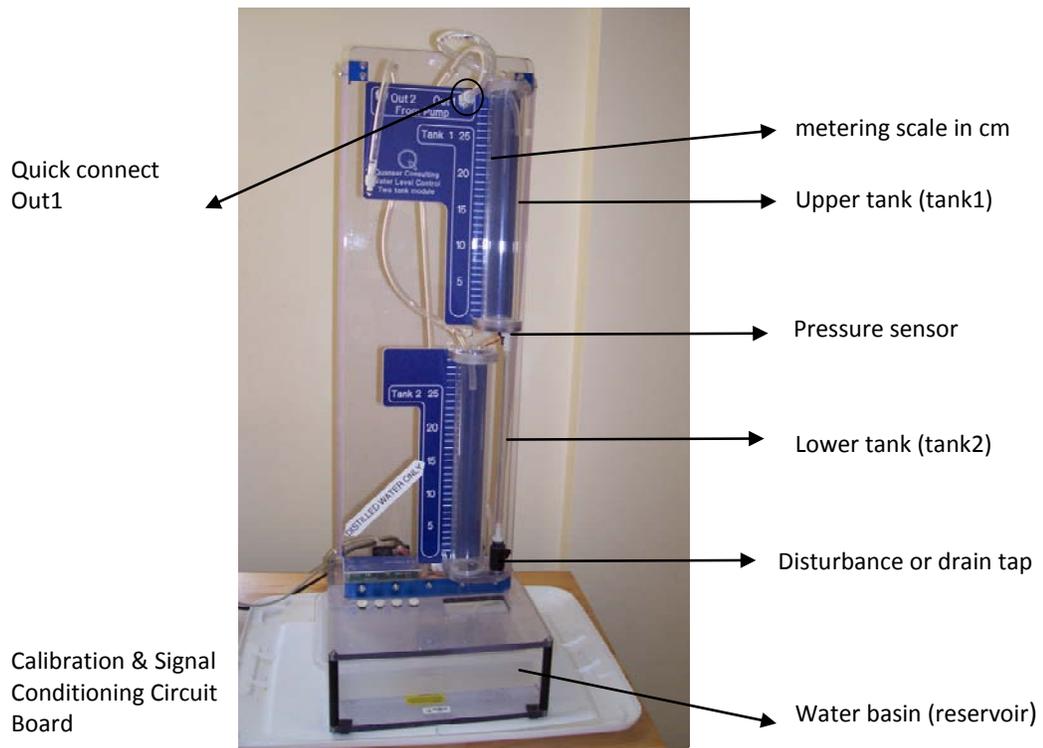


Figure 3-13 Coupled Tank Apparatus.

the tank. *For this experiment use only the medium inserts of diameter 0.476cm for both tanks.* A drain tap is also provided in the apparatus, to introduce disturbance flow into either tank1 or tank2. By opening the drain tap, liquid from tank1 flows directly to the reservoir. The pump propels water vertically to two quick-connect orifices "Out1" and "Out2", which are usually closed. The system is equipped with different diameters for

these two orifices, for configurability. Teflon Tubing of 1/4" I.D with compatible couplings is provided to enable the pump to feed one tank or both tanks. *The water level in each tank is measured by a pressure transducer located at the bottom of each tank.*

Theory^[3, 4]

What is modeling and what is a mathematical model?

- The process of deriving the set of equations (algebraic and/or differential) that describe the response of the system to one or more inputs is called *modeling*.
- The equations which describe the system behavior are called the *mathematical models* of the system.

What are reasons for modeling?

- Improve or understand chemical process operation is the overall objective for developing a dynamic process model.
- These models are often used to simulate the process behavior in operator training, in process design, in safety system analysis, and in process control.

How a system is modeled?

- The basis for modeling actually depends on the system. However, almost all systems important to chemical engineers can be modeled with both overall and component mass balances, energy balances, and momentum balances. Modeling a simple situation like the liquid surge vessel requires only an overall material

balance on the system. Overall material balances are sufficient to describe a system only if the roles of temperature, individual component compositions, and pressure are not important. However, if there is an energy change in the system, like a temperature changes, an energy balance must also be considered in modeling. An example of this situation is modeling of a heated mixing tank.

The basis for modeling a tank's dynamic liquid level is an overall material balance. It has the form:

$$\left\{ \begin{array}{l} \text{rate of accumulation} \\ \text{of mass in system} \end{array} \right\} = \left\{ \begin{array}{l} \text{rate of mass} \\ \text{entering the system} \end{array} \right\} - \left\{ \begin{array}{l} \text{rate of mass} \\ \text{leaving the system} \end{array} \right\} \quad \mathbf{3-11}$$

A more in depth explanation about modeling can be found in Chapter 2 of B. Wayne Bequette: *Process Control Modeling, Design and Simulation*, Prentice Hall (2003)¹.

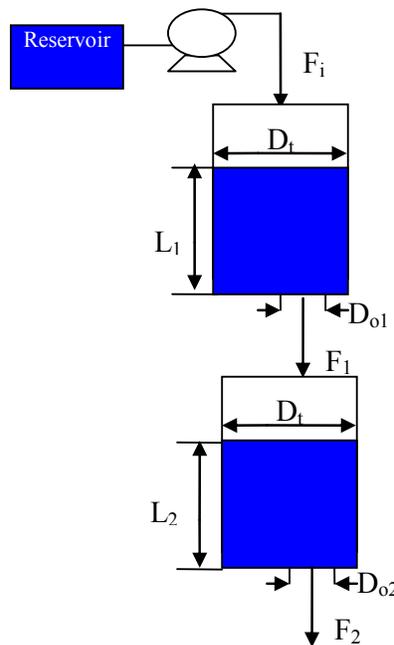


Figure 3-14 Schematic of Coupled-tank system.

Suppose two identical cylindrical tanks are arranged in series as shown schematically in Figure 3-14. The input flow rate is proportional to the pump voltage, i.e.,

$$F_i = KV_{pump} \quad \mathbf{3-12}$$

where K [volume/(time.Volt)] is a constant and V_{pump} is the pump voltage.

The liquid exits the tank by gravity discharge through a small orifice. The outlet velocity (length/time) of each tank small orifices is given by ^[5],

$$v_o = C_o \sqrt{\frac{2(P_1 - P_2)}{\rho \left[1 - \left(A_o/A_T\right)^2\right]}} \quad \mathbf{3-13}$$

C_o = orifice coefficient or discharge coefficient

$P_1 - P_2$ is nothing but head and is given by ρgL and $\left[1 - \left(A_o/A_T\right)^2\right]$ is almost equal to

1. Thus

$$v_o = C_o \sqrt{2gL} \quad \mathbf{3-14}$$

where g is the acceleration due to gravity and L is the tank's liquid level.

Pre-lab Procedures

1. Assuming constant density, find the nonlinear model relating the liquid level in the second tank to the liquid level in the first tank. That means, find

$$\frac{dL_2}{dt} = f(L_2, L_1) . \text{ Use the parameters}$$

- a. Pump flow constant: $K = 17.90 \text{ cm}^3/(\text{s}\cdot\text{V})$
 - b. Tank diameter: $D_t = 4.445 \text{ cm}$
 - c. Outlet orifice diameter: $D_{01} = D_{02} = 0.4762 \text{ cm}$
 - d. Gain relating water level to sensor voltage 6.0-6.4 cm/V
 - e. Acceleration due to gravity: $g = 981 \text{ cm/s}^2$
2. Determine the upper tank's steady state level as a function of the lower tank's steady state level.
 3. Define deviation variables and linearize the model around steady state to determine the transfer function relating the lower tank's liquid level to the upper tank's liquid level.
 4. Draw a block diagram for the open-loop, two tank process. Include all appropriate transfer functions and label all information signal streams.
 5. Use this block diagram to find the transfer function relating the flow out of the second tank to the pump voltage. What kind of process mode does this transfer function represent? What are the model parameters?

LabVIEW Pump.VI Program Explanation

The Pump.VI program is a LabVIEW routine that operates the open-loop tank level process and Figure 3-15 shows the controls and indicators on the Pump.VI front panel. The "PUMP VOLTAGE" vertical slider and the input box below it are used to set

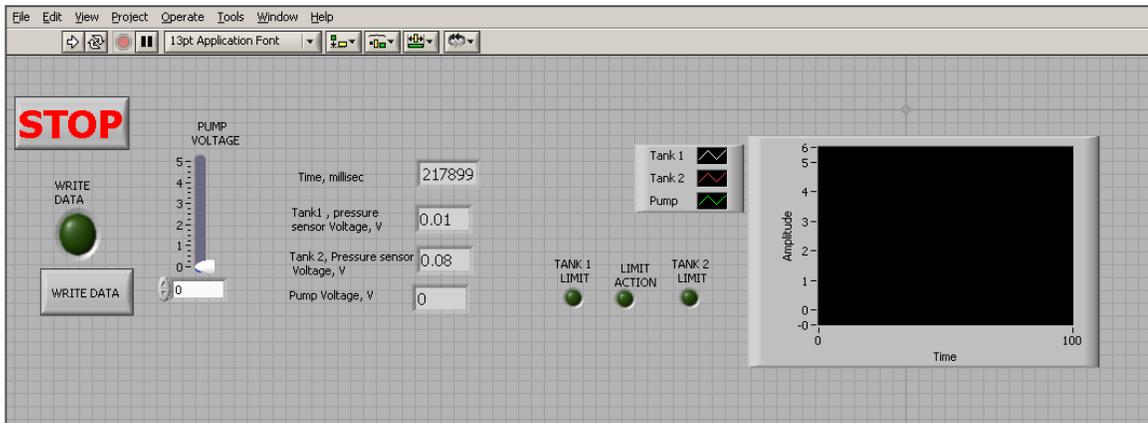


Figure 3-15 Pump.VI Front Panel.

the pump voltage. It is advised to type a number into the input box instead of moving the slider when creating a step change. The data display boxes in the center of the screen show the time in milliseconds and tank1, tank2 pressure sensor output voltages and the pump voltage in Volts. Tank pressure sensor voltages and the pump voltage are also displayed in the waveform chart on the right of the screen. “Write data” glows to indicate when the program is writing data to the user defined file. The tank1 and/or tank2 limit LED glow when the tank voltages are in the range 4.3 to 4.5 V, indicating the danger of tank overflow. At this point the Safety Interlock System’s watchdog routine shuts off the pump and the pump continues to remain idle until the voltage range is again within the acceptable range (less than 4.3 Volts).

Important Note: The measured variables in tank1 & tank2 are pressure sensor voltages and not the tank volumes or liquid levels.

Lab Procedures

Precautions and Other Notes:

- Make sure that the reservoir's distilled water level is at least three-fourths full.
- A watchdog (software interlock) is programmed into pump.vi so that the tanks do not overflow. If the liquid level in either of the tanks reaches 25cm the pump is turned off and the pump continues to remain idle until the tank's voltage drops below 4.3 V.
- Do not panic, the pump can be noisy. If it starts smoking that is another matter. Shut off the pump by clicking "Stop" button on the Pump.VI.
- Avoid parallax error while measuring the tank level; take measurements with an eye-line directly perpendicular to the level.

1) *Familiarize yourself with the apparatus and how it relates to the schematic*

- a) See Figure 3-13 and Figure 3-14.

2) *Start the pump.vi program and Open a data file*

- a) Double-click the pump.vi icon on the desktop. It opens the pump.vi program in LabVIEW. Familiarize yourself with the icons, controls and indicators on the screen shown in Figure 3-15.
- b) Click the white color arrow button on the top left of the screen to start the program. A window pops up on the screen asking user to define an output file.

c) Assign a file name save it in Microsoft excel spreadsheet format, for example yourname.xls.

3) *Removal of air pockets*



Figure 3-16 Removal of Air Pockets in Pressure Sensor.

a) Run the pump by giving a random pump voltage between 0.5-1 and watch out for air bubbles over/in the pressure sensors located at the bottom of each tank for both tank1 and tank2.

b) Air pockets will form in the sensors most of the time, whether or not you see bubbles, poke the rod into sensors of both tank1 and tank2 as shown in

Figure 3-16.

Caution: 1) Be gentle with the sensor while removing bubbles. A violent stroke on the sensor could ruin it.

2) Don't get confused with the bubbles formed and floating at the top of tank for bubbles in sensor.

- c) Once air pockets are removed, stop pump by setting 0 V as the pump input and observe for the tank1 and tank2 voltages on Pump.VI front panel. If the tank voltage value is within ± 0.1 Volts of 0 V for both tanks when they are empty proceed to generate empirical data (Step 6). Otherwise head to calibration of the both tanks pressure sensors (Step 4 and 5).
- 4) *Calibrate the upper tank's pressure sensor*
- a) Make sure that tank1 is empty before starting the calibration. If not, empty it using the disturbance tap (black flap near the bottom of tank2).
- b) Observe the pressure sensor voltage reading in the Tank1 display box. If it is not 0 V, manually adjust offset potentiometer screw for Tank 1 on the calibration and signal conditioning circuit board (See Figure 3-17) using the potentiometer adjustment tool (flat head screw driver) to obtain 0 V. Turn the offset potentiometer screw clockwise to increase the voltage reading and vice-versa.
- c) Cover the tank outlet with your finger.
- d) Using the quick connect at "Out1", apply a voltage to the pump and fill the tank to 25 cm. Then turn off the pump. (Apply 0 V to the pump.)
- e) Observe the voltage reading in the tank1 display box. If it is not 4.10 V (± 0.03 is okay) at 25 cm, manually adjust gain potentiometer screw for tank1 to obtain

4.10V. Turn the gain potentiometer screw clockwise to increase the voltage reading and vice-versa.

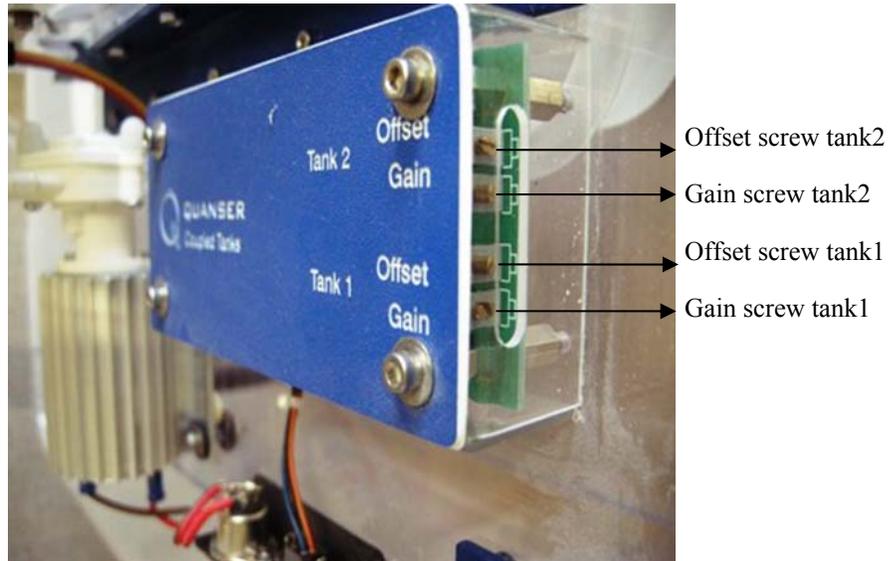
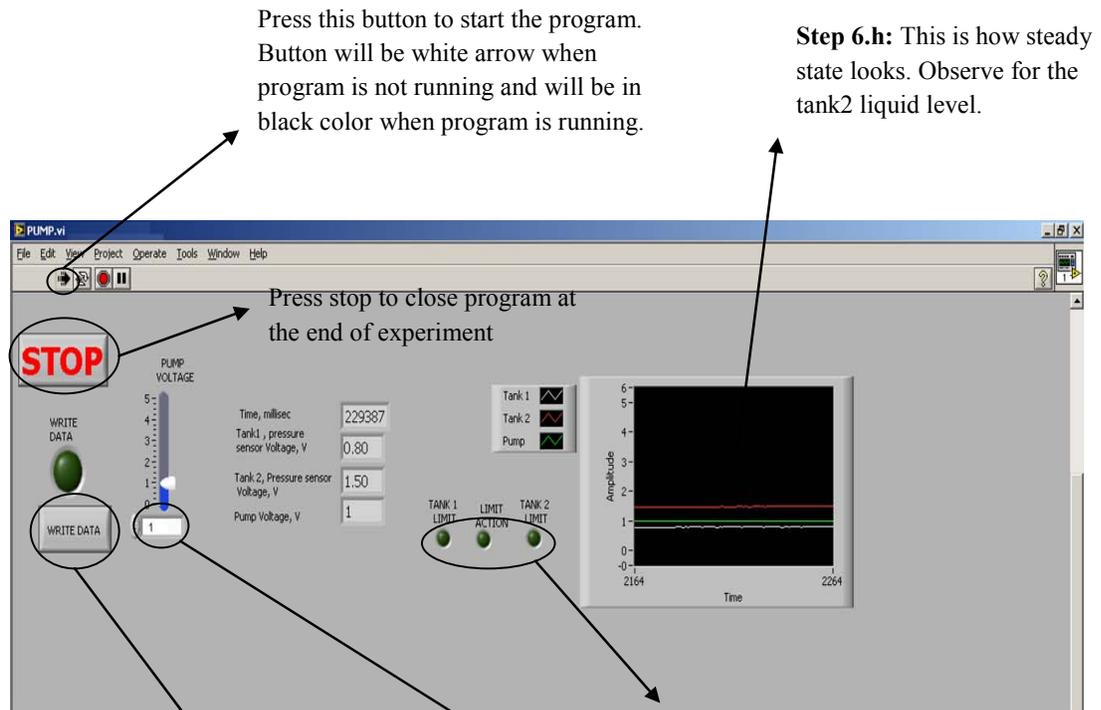


Figure 3-17 Calibration and Signal Conditioning Circuit Board.

- f) Drain the tank.
 - g) Check to see that the reading returns to 0V (Readings may take 30 seconds or so to stabilize). If not, repeat 4b-4f until you get 0V at 0cm and 4.10V at 25cm of level. (This may take several trials).
- 5) *Calibrate lower tank's pressure sensor*
- a) Repeat the same procedure described from 4a-4g for tank2 by bringing tank2 using quick connect "Out2". Make sure you disconnect "Out1" while calibrating tank2.



Press this button to start the program.
Button will be white arrow when
program is not running and will be in
black color when program is running.

Step 6.h: This is how steady
state looks. Observe for the
tank2 liquid level.

Press stop to close program at
the end of experiment

Step 6.f: Click "Write data" to write
data into the file.

Step 6.j: Click "Writing Data" to stop
recording to file.

These LED's glow when
Safety Interlock System is
in action.

Step 6.e: Enter a voltage value between 0.5-
0.75Volts here to get initial steady state
value.

Step 6.g: Enter a voltage value between 1
and 1.5Volts.

Step 6.i: Step change pump voltage
back to zero

Figure 3-18 Step by Step Procedure for Experiment #3.

6) *Generate the empirical data*

- a) Record the pressure sensor voltage readings for tank1 liquid levels of 0,5,10,15,20,25 cm in notebook. While doing this step, hold the tank level by blocking orifice (insert) with finger. Make sure you connect “Out1” and disconnect “Out2”.
- b) Repeat 6.a for tank2. Make sure you connect “Out2” and disconnect “Out1” this time.
- c) Before starting the experiment plug in only “Out1” using quick connect. Make sure “Out2” is disconnected before you start taking data.
- d) See Figure 3-18 for step by step procedure.
- e) Set the pump voltage so that the steady state liquid level in tank2 is around 3 cm. Note the pump voltage (will be usually around 0.8 V) and liquid level in tank1 at steady state.

Note : If you had to calibrate the sensor(s) again, make sure there are no air bubbles over/in the sensor before you start recording data. If there are bubbles repeat step 3b.
- f) Click the “WRITE DATA” button.
- g) Make a positive step change (to 1.25-1.5 Volts) in the pump voltage by entering a number into the “PUMP VOLTAGE” input box and pressing enter. Do not make the step change so large that the Safety Interlock System’s watchdog program kicks off.
- h) Wait for the tank2 liquid level to reestablish steady state.

- i) Once steady state is established, step change the pump voltage to steady state value from 6.g.
 - j) Click the “WRITING DATA” to stop recording data.
 - k) Repeat steps 6e-6j three more times for same pump voltage.
- 7) *Press “STOP” button to stop the program.*

Data Analysis

- 1) Find the sensitivities for pressure sensor voltages to tank levels from the calibration data in steps 6.a and 6.b.
- 2) Solve the linearized approximation model using MATLAB for the step change you performed in the laboratory.
- 3) Determine a First order plus dead time (FODT) model from the empirical data.
- 4) Graphically compare the linearized approximation, the FODT model and the lab data.

3.5 Experiment-4 Tuning a PI Controller for Level Control of a Cylindrical Tank

Objective

To gain hands-on experience in tuning a PI controller for level control of cylindrical tank.

Pre-lab Tasks

- Calculate level control tuning parameters using the Ciancone method for a PI control algorithm and a set point change. (Use the appropriate graph from Marlin Thomas E., *Process Control: Designing Processes and Control Systems for Dynamic Performance*, McGraw-Hill, New York 2nd edition, page 286).

Note: The model parameters will vary slightly among the apparatus because they have different pump flow constants. Use values of process gain, time constant and dead time corresponding to the apparatus on which you do tuning experiment to calculate the tuning parameters.

Coupled Tank Apparatus Description ^[1]

The Quanser coupled tank apparatus is shown in Figure 3-19. The apparatus is a bench-top model consisting of a pump, two cylindrical tanks made of Plexiglas and water basin (reservoir). These two tanks are of volume 133.35cm^3 each and are mounted on a

platform with a metering scale behind each tank indicating the approximate liquid level in tank. The two tanks are vertically mounted on platform and positioned in such a manner that outflow from the top tank (tank1) serves as inflow for the lower tank (tank2), if second tank is used for experiment. Outflow from lower tank goes directly into reservoir. From each tank, fluid exits by gravity discharge through a small orifice.

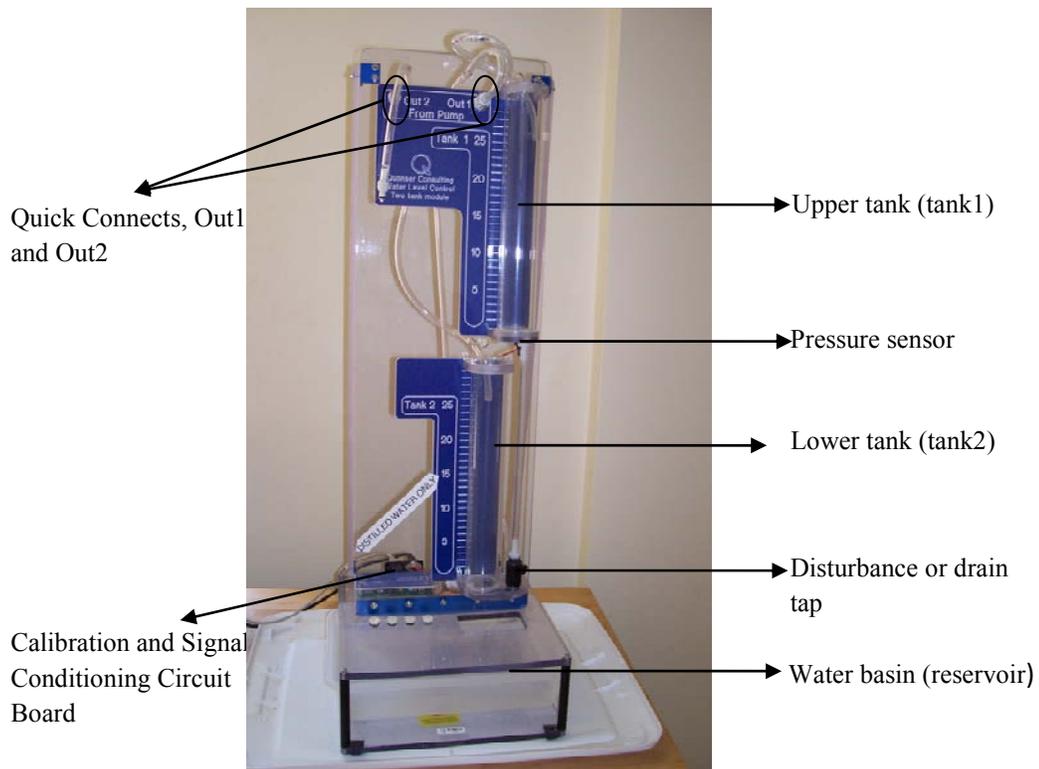


Figure 3-19 Coupled Tank Apparatus.

The resistance of this discharge can be varied by replacing the orifice inserts of different diameters into a threaded hole at the bottom of the tank. *For this experiment use only the medium inserts of diameter 0.476cm for both tanks.* A drain tap is also provided in the apparatus to introduce disturbance flow into either tank1 or tank2. By opening the drain tap, liquid from tank1 flows directly to the reservoir. The pump propels water vertically

to two quick-connect orifices "Out1" and "Out2", which are usually closed. The system is equipped with different diameters for these two orifices, for configurability. Teflon Tubing of 1/4" I.D with compatible couplings is provided to enable the pump to feed one tank or both tanks. *The water level in each tank is measured by a pressure transducer located at the bottom of each tank.*

Theory

PID Controller Algorithm

The Proportional-Integral-derivative (PID) controller is the mostly commonly used feedback algorithm in control systems. Due to robustness and simplicity in operation, about 95% of closed-loop industrial processes use PID controllers ^[7]. A PID controller attempts to reduce the error, which is calculated as the difference between the controlled variable's set point and its measured value. A PID controller takes corrective action on the process input according to the algorithm shown in Figure 3.20, to keep the error to a minimum ^[8].

The PID controller algorithm has three components: proportional, integral and derivative. A proportional-only controller reacts to and accounts for the current error. However, a P-only controller cannot drive the steady error to zero. A PI controller reacts to and accounts for the current error as well as its history. A PI controller drives the steady state error to zero. However, the integral component adds to instability if k_I is improperly tuned. A PID controller reacts to and compensates for the current error, its

history and its future direction [8]. The derivative component adds to stability and speed of the response if properly tuned.

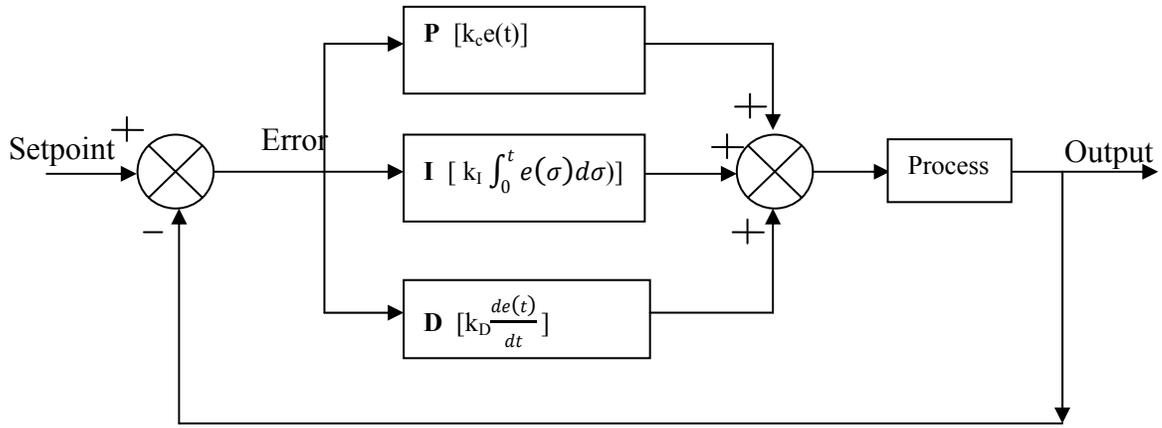


Figure 3-20 PID Controller Block Diagram in a Feedback Loop.

The weighted sum of these three actions is used in a PID controller to take corrective action. The corrective action taken by a PID controller algorithm is computed as follows^[8]

$$u(t) = k_c \left[e(t) + \frac{1}{\tau_I} \int_0^t e(\sigma) d\sigma + \tau_D \frac{de(t)}{dt} \right] \quad 3-15$$

where k_c is proportional gain, τ_I is integral time and τ_D is derivative time.

For PI control there is no derivative term, so

$$u(t) = k_c e(t) + \frac{k_c}{\tau_I} \int_0^t e(\sigma) d\sigma \quad 3-16$$

where k_c is proportional gain, τ_I is integral time.

Tuning

If PID controller parameters (k_c , τ_i , τ_D) are chosen incorrectly, then the controlled output can become unstable, i.e. the process output diverges with or without oscillation. Adjusting the control parameters to get the desired output response is called *tuning*. The desired behavior of the process output differs depending on the application. For some processes, overshoot is allowed. For other processes overshoot is not tolerable. For example, in the process of manufacturing plastic gloves, the positioning of a double plastic film is necessary. If an overshoot occurs, the plastic films wrinkle unacceptably^[9]. Except in applications where oscillations cannot be tolerated, processes are usually tuned to respond as second-order under-damped system with a damping factor between 0.4 and 0.8^[10]. This gives a sufficiently fast response. Smaller values for the damping factor yield excess overshoot and larger values yield sluggish (slow) response.

Second- Order Underdamped Response Definitions

Overshoot:

Overshoot is the distance between the first peak and the new steady state.

Rise time:

It is the amount of time it takes to first reach the new steady-state value.

Settling time^[4]:

The time it takes the process to “nearly” attain its steady state value, usually within 2% or 5% of its final value.

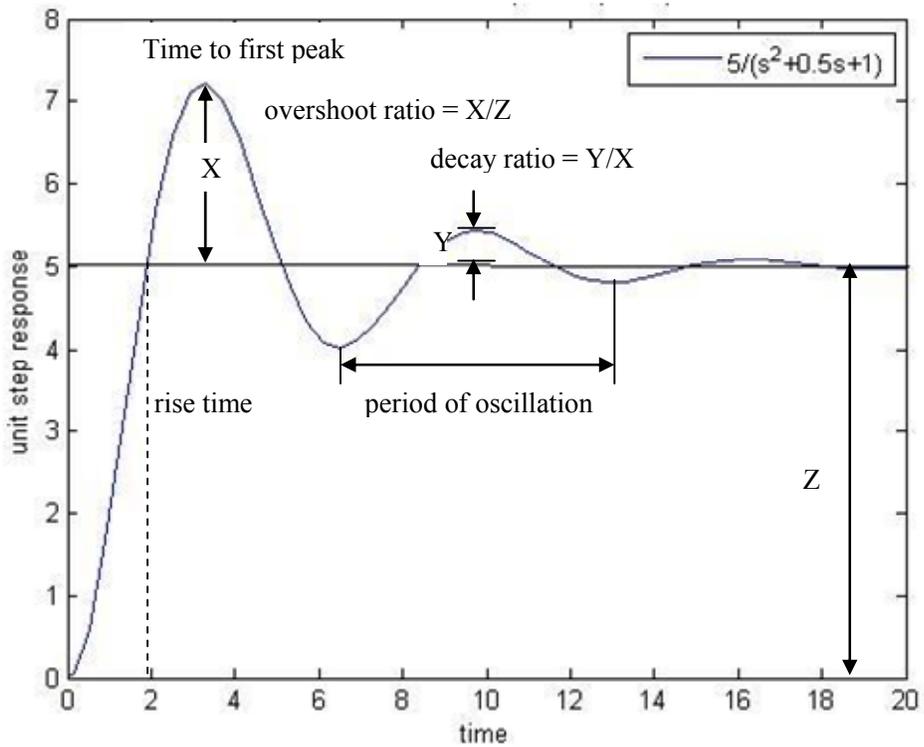


Figure 3-21 Step Response Characteristics of Underdamped Second-Order Processes.

Offset:

The error (discrepancy between the setpoint and the process output) at steady state is called offset.

Decay ratio:

Decay ratio is defined as the ratio of the sizes of successive peaks.

Calculation of Initial Tuning Parameters

There are three general methods for calculating PID tuning parameters. Classic closed-loop methods force the closed-loop system to the edge of stability by inducing sustained oscillation in the output. The closed-loop Ziegler-Nichols method ^[11] and Tyres-Luyben method ^[12] are classic examples. The direct synthesis method ^[8] derives both a controller and its parameters from the transfer functions of a known process model and a defined closed-loop output response. Open-loop methods, such as the open-loop Ziegler-Nichols ^[11] method, the Cohen-Coon method ^[13], and the Ciancone method ^[14], are based on the parameters of a first-order plus dead time (FODT) process model. The open-loop Ciancone method will be used to determine initial estimates (swags) of controller tuning parameters in this experiment.

Open-Loop Methods

Ciancone Method ^[14]

Ciancone and Marlin created an open-loop method of tuning controllers based on a single parameter called '*fraction dead time*'. Fraction dead times ranges between 0.0 and 1.0 and is calculated from the FODT parameters. It represents the fraction of the total time needed for the open-loop process step response to reach 63.2% of its final value that is due to dead time. Determining PI controller parameters using Ciancone correlations is a three step procedure.

1. From the FODT model (k_p , τ_p , and θ), calculate the fractional dead time as $\theta/(\tau_p + \theta)$.

2. Use the appropriate graph from Marlin Thomas E., *Process Control: Designing Processes and Control Systems for Dynamic Performance*, McGraw-Hill, New York 2nd edition, page 286. to determine the dimensionless tuning values: $K_c K_p, T_I / (T_p + \theta)$.
3. Calculate the dimensional controller tuning values from the dimensionless tuning values and the FODT parameters.

$$k_c = \frac{(K_c K_p)}{k_p} \quad \text{3-17}$$

$$\tau_I = \left(\frac{T_I}{\theta + T_p} \right) (\theta + T_p) \quad \text{3-18}$$

Fine Tuning

The values for controller tuning constants determined by correlation methods are just swags to be applied to the physical system initially and improved based on empirical performance during fine tuning. See Figure 3-22 for the well tuned, PI controlled process.

Fine Tuning of a PI Controller

Use the previously determined control parameter initial guesses and fine tune the PI controller using the rules ^[15] that follow

Three important features relating to the manipulated variable are notable from the well behaved process in Figure 3-22.

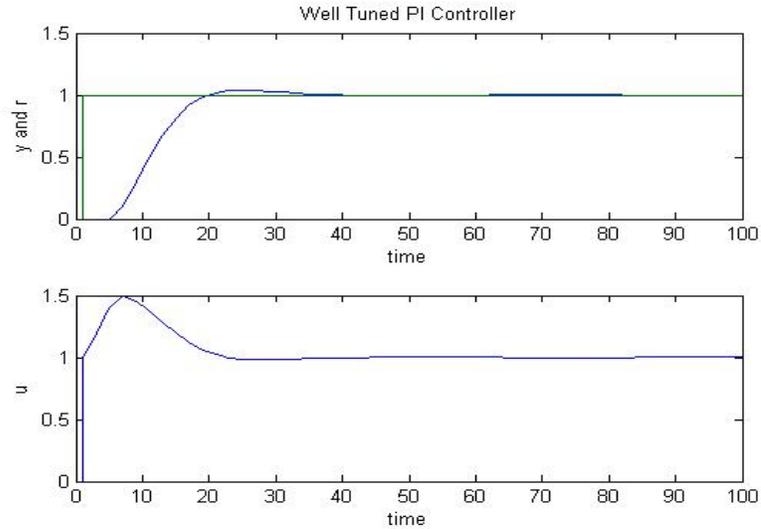


Figure 3-22 Well-Behaved Process Controller.

1. The manipulated variable changes immediately when the set point is changed. This change is due to the proportional mode and is equal to $k_c \Delta E(t) = [k_c R(t)]$. This initial change is typically restricted to 70 to 150 percent of the change at the final steady state.
2. There is a delay between the *time the manipulated variable changes* and the time when the controlled variable responds. This delay is due to process dead time and no controller can reduce this delay to less than the process dead time.
3. During the delay time the manipulated variable increases linearly. This is due to the integral mode. During this period the error is constant so the proportional term does not change but the integral term increases linearly with slope equal to $\frac{k_c E(t)}{\tau_I}$.

After the controlled variable begins its transient response, the proportional term decreases while the integral term continues to increase. At steady state (the end of the

transient response) the proportional term is zero because the error is zero and the integral term has adjusted the manipulated variable to a value that reduces the offset to zero. These three features are very useful for recognizing maladjusted tuning parameters when fine tuning.

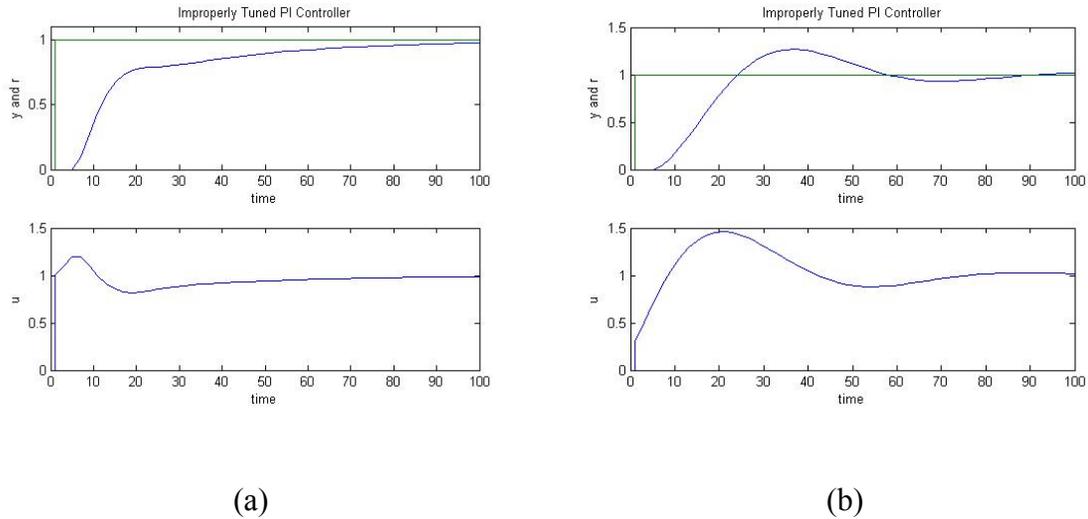


Figure 3-23 Improperly Tuned Controllers (a) sluggish response due to too little integral action, needs smaller (τ_I) integral time, (b) sluggish response due to too little proportional action, needs larger gain (k_c).

Figure 3-23 gives examples of improperly tuned responses. Figure 3-23(a) has a sluggish response due to too little integral action. To speed up the response lower τ_I . Proportional gain is not raised to speed up the response because the initial change manipulate variable is within 70-150% of final steady state value. Figure 3-23 (b) has a sluggish response due to too little proportional gain k_c . To speed up the response, increase k_c . When fine tuning a PI controller, adjust the proportional gain, k_c , first and then adjust the integral time, τ_I .

Effect of Tuning Parameters on Output Response to a Setpoint Step Change

The above discussion involved only a PI controller. Tuning a PID controller requires knowledge of the effects of all three tuning parameters. A general guide follows

Table 3-1 Effect of Controller Tuning Parameters on Higher Order Processes.

Parameter	Rise Time	Overshoot	Settling Time	Offset
Increasing k_c	Decreases	Increases	No effect	Decreases
Decreasing (τ_I)	Decreases	Increases	Increases	Eliminated
Increasing (τ_D)	Small Decrease	Decreases	Decreases	No effect

Proportional gain (k_c)

An increase in absolute value of controller gain $|k_c|$ will speed up the response but at the expense of system stability.

Integral Gain (τ_I)

An increase in integral time (τ_I) tends to slow down the response and decrease the overshoot, while the lower τ_I speeds up the response and increases overshoot. Too low of a value for τ_I , can lead to instability.

Derivative time (τ_D)

An increase in derivative time helps system stability. However, this control action is very sensitive to measurement noise. Usually only PI control is used for loops where there is measurement or output noise.

Three Laws of Feedback Controller Tuning

- 1 Control performance must be defined with respect to all important plant operating goals. The desired behavior of the controlled variable and the manipulated variable must be defined for expected disturbances, model errors, and noisy measurements.
- 2 The dynamic behavior of both the controlled variable and the manipulated variable must be observed when analyzing the performance of feedback control systems. Complete diagnosis is not possible without information on both variables.
- 3 When tuning a feedback controller, where you start is not as important as where you finish! The values for controller tuning constants determined by correlation methods are just swags to be applied to the physical system initially and improved based on empirical performance during fine tuning.

After completing this experiment, you will have hands-on experience with laws two and three and a better understanding of the issues involved in law one.

LabPID1.VI Program Explanation

The front panel of LabPID1.VI is shown in Figure 3-24. On the left side of the screen, the set point for the liquid level is entered. The “Run pump” button is used to run the pump. “Control Tank Toggle” button is used to switch level control between tank1 and tank2. “Write data” glows when the program is writing data to the user defined file.

In addition to the initialization controls described above, the PID tuning parameters are entered and displayed here. The ‘STOP’ button is used to stop the program.

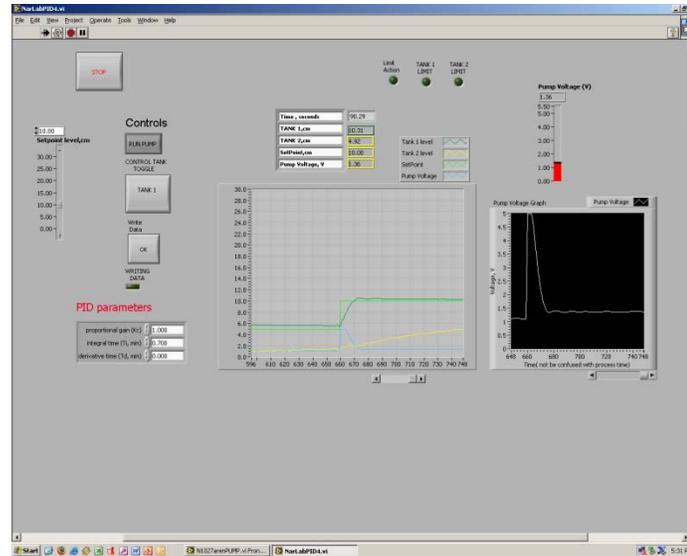


Figure 3-24 LabPID1.VI Front Panel.

The dynamic response of the output variables are shown in the center of the screen. The Limit action LED, along with either the tank 1 Limit or tank2 Limit LED, glows when the tank voltages are in the range 4.3 to 4.5 V. In this voltage range, the safety interlock system takes control to avoid overflow. The levels of tank1 and tank2, along with the set point, are displayed numerically in cm. They are also plotted on a waveform chart below their numerical display. The dynamic response of the input variable is shown on the right of the screen. The pump voltage is displayed on a vertical indicator and is plotted on the waveform chart below the vertical indicator. The horizontal scroll bar below the waveform charts enables the user to view earlier responses. Use the horizontal scroll bar to note how the input and output variables

respond to a step change for various tuning constants and, based on these responses, tune the process.

Appropriate values for the PID parameters lead to good control - stable, snappy, and not too oscillatory. Inappropriate values leads to bad control - unstable, sluggish, and oscillatory. Adjust the PID tuning parameters as necessary so that the response to a set point change is reasonable.

Lab Procedure

Precautions and Other Notes:

- Make sure that the reservoir's distilled water level is at least three-fourths full.
- A watchdog is programmed into LabPID1.vi so that the tanks do not overflow. If the liquid level in either of the tanks reaches 25cm the pump is turned off and the pump continues to remain idle until the tank's voltage drops below 4.3 V.
- Do not panic, the pump can be noisy. If it starts smoking that's another matter. Shut off the pump, by clicking "Stop" on the LabPID1.VI program.

1) Start up of experiment/program

- a) Familiarize yourself with the apparatus. See Figure 3-19.
- b) Double-click the LabPID1.VI icon on the desktop. It opens the LabPID1.VI program in LabVIEW. Familiarize yourself with the icons, controls and indicators and what they do on the screen. See Figure 3-24.

- c) Click the white arrow button on the top left of the screen to start the program. A window pops up on the screen asking user to define an output file.
- d) Assign a file name and save it in Microsoft Excel spreadsheet format (e.g. : yourname.xls). The output file records PID parameters and tank levels, set point and pump voltage as a function of time.
- e) Use “Control Tank Toggle” to switch to tank1. This will bring tank1 online for level control.

2) *Remove the air pockets*

- a) Press ‘Run pump’ and then enter a random set point ≤ 10 cm and watch for any air bubbles over/in the pressure sensor for the tank your tuning.

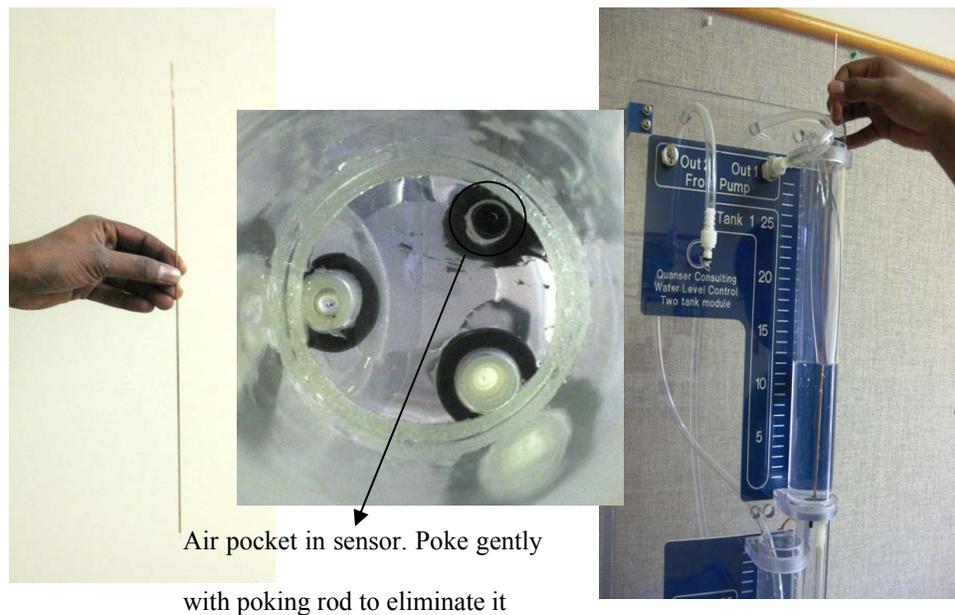


Figure 3-25 Removal of Air Pockets in Pressure Sensor.

- b) Air pockets will form in the sensors most of the time. Whether or not you see bubbles, poke the rod into tank1 sensor cavity as shown in Figure 3-25 to remove them

Caution: 1) Be gentle with the sensor while removing bubbles. A violent stroke on the sensor could ruin it.

2) Don't get confused with the bubbles formed and floating at the top of tank for bubbles over/in sensor.

- c) Once air pockets are removed, click "Run Pump" to stop pump.

3) *Generate empirical data (See Figure 3-26)*

- a) For initial Ciancone PI parameters

- i. Enter the initial Ciancone PI parameters (SWAGs calculated from the theoretical settings) in the PID parameters input box.

Note: 1) *Enter the integral time and derivative time in **minutes**.*

2) *Make sure $\tau_D = 0$ for PI control.*

- ii. Enter the set point of 3 cm.
- iii. Press "Run pump" to start the pump.
- iv. Once the steady state liquid level is reached on tank1 (See tank1 level in waveform chart on screen), click "write data" button and then change the set point to the value given to your group.
- v. *Note the initial pump voltage change and observe the pump voltage response along with tank1 level response as the system reaches the new steady state.*

- vi. Once the new steady state is reached, click “write data” to stop recording and “run pump” to stop the pump.

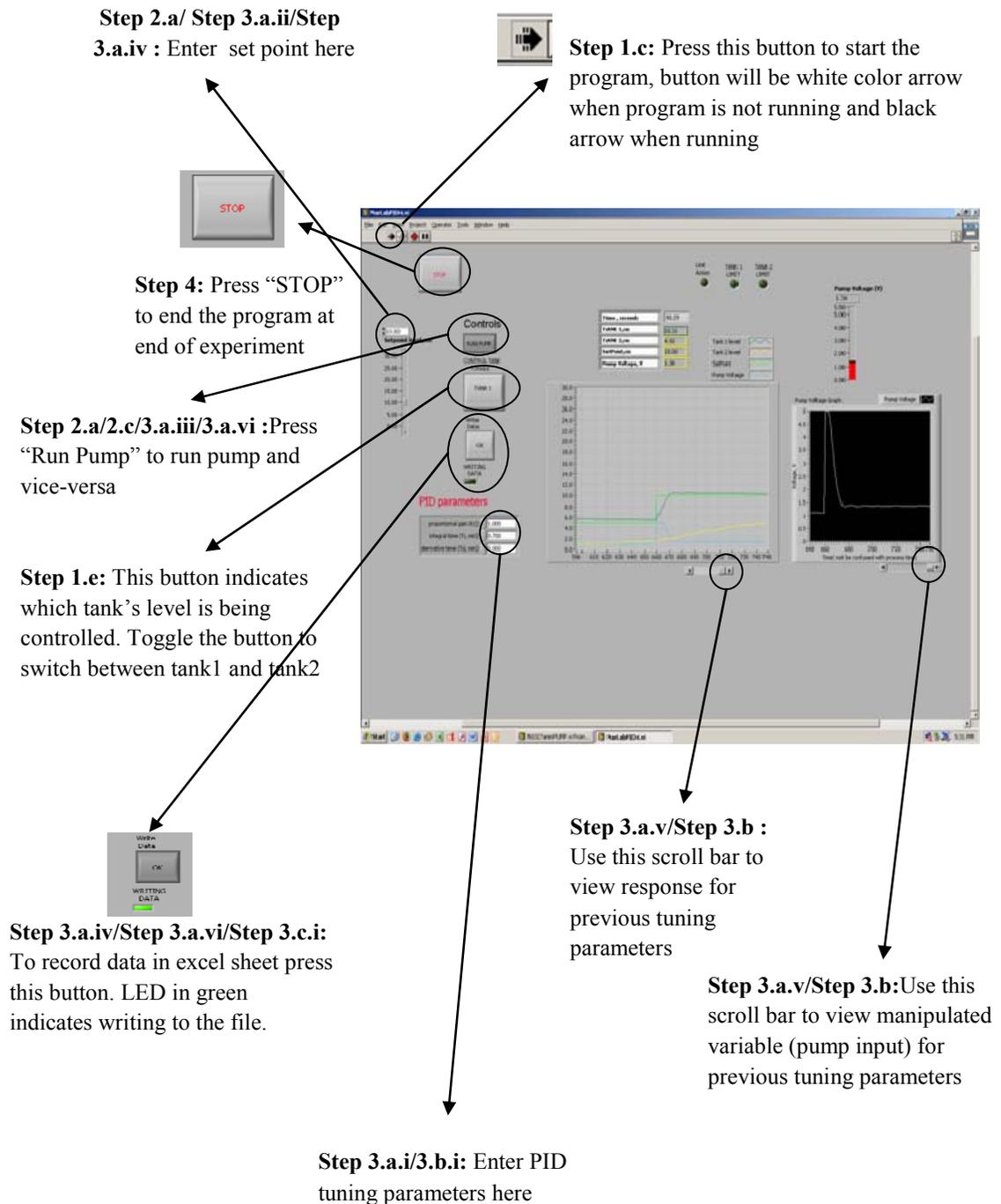


Figure 3-26 Detailed Explanation of Step by Step Procedure for Tuning.

b) Fine Tuning

- i. Use scroll bars below tank level and voltage vs. time plots to view response for previous tuning parameters.
- ii. Adjust the k_c and τ_I for best closed-loop response. Use a trial and error method based on PI controller tuning and parametric effect topics in the theory section. Parametric effects are listed in Table 3-1 for assistance.
The allowable percent overshoot is 10%.
- iii. Repeat steps 3.a.i to 3.a.vi without recording data until you get desired closed-loop response for both the output and input variables. Use scroll bars below tank level and voltage vs. time plots to view response for previous parameters.
- iv. Once desired response is attained go 3.c.

c) Final PI parameters

- i. Repeat steps 3.a.i to 3.a.vi with final tuning parameters. Make sure you record data this time.

4) *Press “STOP” button at the end of the experiment.*

Data Analysis

1. Graphically compare the empirical set point responses of tank1 for both sets (initial Ciancone and fine tuned) of PI tuning parameters.

2. Compare each of the empirical closed-loop responses, both its input and output, with its SIMULINK equivalent. Discuss any discrepancies. Why might there be any discrepancies?

3.6 Experiment-5 Tuning a PI Controller for Level Control of the Second Tank in Coupled Tank System

Objective

To gain hands-on experience in tuning a PI controller for level control of the second tank in a coupled tank system.

Pre-lab Tasks

1. Calculate level control tuning parameters using the open-loop Ziegler-Nichols method for a PI control algorithm (Use Table 3-2).
2. Calculate level control tuning parameters using the Ciancone method for a PI control algorithm and a setpoint change. (Use the appropriate graph from Marlin Thomas E., *Process Control: Designing Processes and Control Systems for Dynamic Performance*, McGraw-Hill, New York 2nd edition, page 286).

Note:

- The model parameters will vary slightly among the apparatus because they have different pump flow constants. Use values of process gain, time constant and dead time corresponding to the apparatus on which you do the tuning experiment to calculate the tuning parameters.
- For calculating τ , θ , K_p , use the output tank level response for step change in pump voltage (graph obtained in experiment 3), assuming a pseudo first order process for the second tank.

Coupled Tank Apparatus Description ^[1]

The Quanser coupled tank apparatus is shown in Figure 3-27. The apparatus is a bench-top model consisting of a pump, two cylindrical tanks made of Plexiglas and water basin (reservoir). These two tanks are of volume 133.35cm^3 each and are mounted on a platform with a metering scale behind each tank indicating the approximate liquid level in tank. The two tanks are vertically mounted on platform and positioned in such a manner that outflow from the top tank (tank1) serves as inflow for the lower tank (tank2), if second tank is used for experiment. Outflow from lower tank goes directly into reservoir. From each tank, fluid exits by gravity discharge through a small orifice. The resistance of this discharge can be varied by replacing the orifice inserts of different diameters into a threaded hole at the bottom of the tank. *For this experiment use only the medium inserts of diameter 0.476cm for both tanks.* A drain tap is also provided in the apparatus to introduce disturbance flow into either tank1 or tank2. By opening the drain

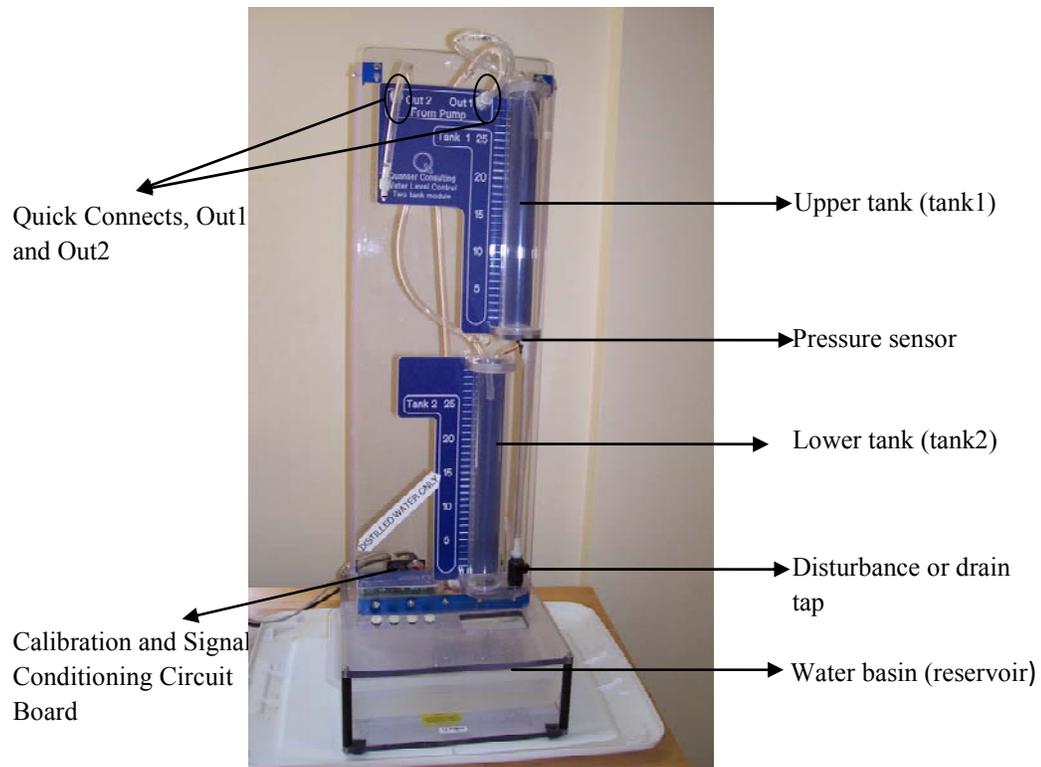


Figure 3-27 Coupled Tank Apparatus.

tap, liquid from tank1 flows directly to the reservoir. The pump propels water vertically to two quick-connect orifices "Out1" and "Out2", which are usually closed. The system is equipped with different diameters for these two orifices, for configurability. Teflon Tubing of 1/4" I.D with compatible couplings is provided to enable the pump to feed one tank or both tanks. *The water level in each tank is measured by the pressure transducer located at a bottom of each tank.*

Theory

PID Controller Algorithm

The Proportional-Integral-derivative (PID) controller is the mostly commonly used feedback algorithm in control systems. Due to robustness and simplicity in operation, about 95% of closed-loop industrial processes use PID controllers ^[7]. A PID controller attempts to reduce the error, which is calculated as the difference between the controlled variable's set point and its measured value. A PID controller takes corrective action on the process input according to the algorithm shown in Figure 3-28, to keep the error to a minimum ^[8].

The PID controller algorithm has three components: proportional, integral and derivative. A proportional-only controller reacts to and accounts for the current error. However, a P-only controller cannot drive the steady error to zero. A PI controller reacts to and accounts for the current error as well as its history. A PI controller drives the steady state error to zero. However, the integral component adds to instability if k_I is improperly tuned. A PID controller reacts to and compensates for the current error, its history and its future direction ^[8]. The derivative component adds to stability and speed of the response if properly tuned.

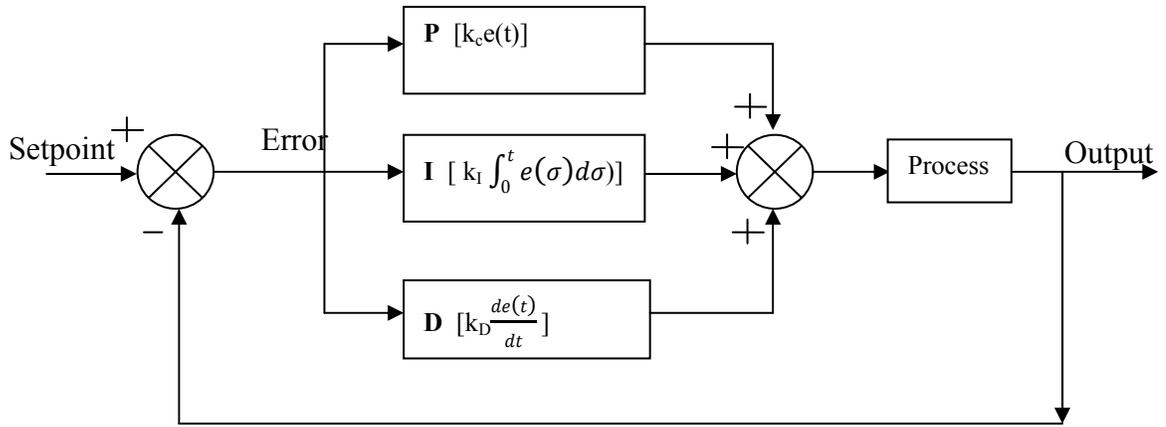


Figure 3-28 PID Controller Block Diagram in a Feedback Loop.

The weighted sum of these three actions is used in a PID controller to take corrective action. The corrective action taken by a PID controller algorithm is computed as follows ^[8]

$$u(t) = k_c \left[e(t) + \frac{1}{\tau_I} \int_0^t e(\sigma) d\sigma + \tau_D \frac{de(t)}{dt} \right] \quad \mathbf{3-19}$$

where k_c is proportional gain, τ_I is integral time and τ_D is derivative time.

For PI control there is no derivative term, so

$$u(t) = k_c e(t) + \frac{k_c}{\tau_I} \int_0^t e(\sigma) d\sigma \quad \mathbf{3-20}$$

where k_c is proportional gain, τ_I is integral time.

Tuning

If PID controller parameters (k_c , τ_I , τ_D) are chosen incorrectly, then the controlled output can become unstable, i.e. the process output diverges with or without

oscillation. Adjusting the control parameters to get the desired output response is called *tuning*. The desired behavior of the process output differs depending on the application. For some processes, overshoot is allowed. For other processes overshoot is not tolerable. For example, in the process of manufacturing plastic gloves, the positioning of a double plastic film is necessary. If an overshoot occurs, the plastic films wrinkle unacceptably^[9]. Except in applications where oscillations cannot be tolerated, processes are usually tuned to respond as second-order under-damped system with a damping factor between 0.4 and 0.8^[10]. This gives a sufficiently fast response. Smaller values for the damping factor yield excess overshoot and larger values yield sluggish (slow) response.

Second- Order Underdamped Response Definitions

Overshoot:

Overshoot is the distance between the first peak and the new steady state.

Rise time:

It is the amount of time it takes to first reach the new steady-state value.

Settling time^[4]:

The time it takes the process to “nearly” attain its steady state value, usually within 2% or 5% of its final value.

Offset:

The error (discrepancy between the setpoint and the process output) at steady state is called offset.

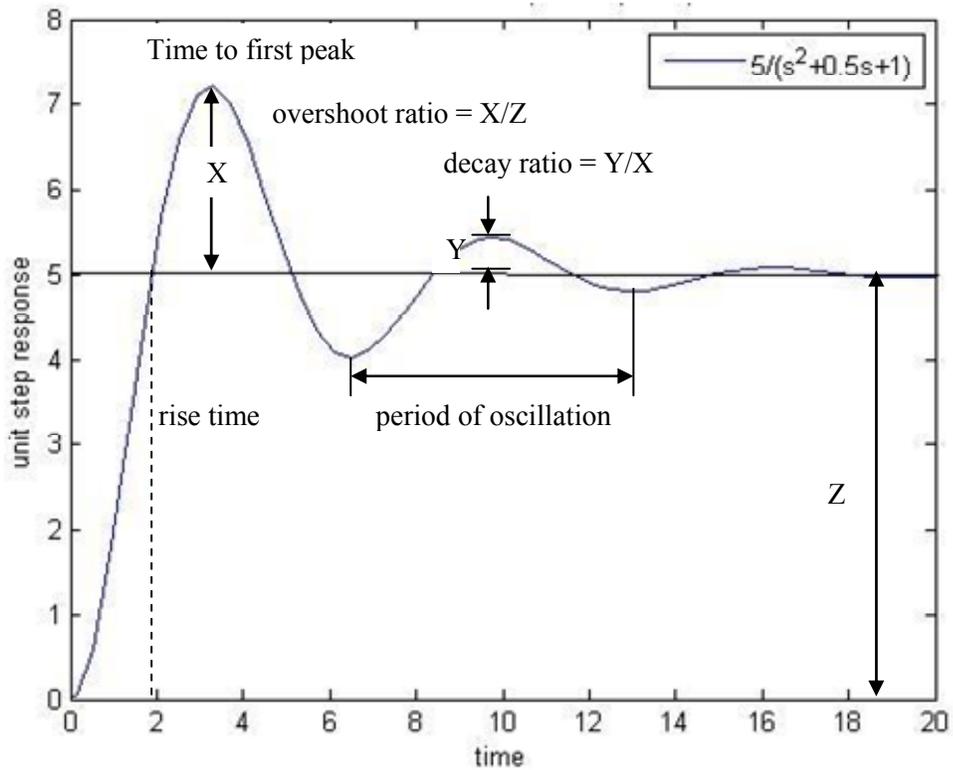


Figure 3.29 Step Response Characteristics of Underdamped Second-Order Processes.

Decay ratio:

Decay ratio is defined as the ratio of the sizes of successive peaks.

Calculation of Initial Tuning Parameters

There are three general methods for calculating PID tuning parameters. Classic closed-loop methods force the closed-loop system to the edge of stability by inducing sustained oscillation in the output. The closed-loop Ziegler-Nichols method ^[11] and Tyres-Luyben method ^[12] are classic examples. The direct synthesis method ^[3] derive both a controller and its parameters from the transfer functions of a known process model and a defined closed-loop output response. Open-loop methods, such as the open-loop Ziegler-Nichols ^[11] method, the Cohen-Coon method ^[13], and the Ciancone-Marlin method ^[14], are based on the parameters of a first-order plus dead time (FODT) process model. The open-loop Ziegler-Nichols and Ciancone methods will be used to determine initial estimates (swags) of controller tuning parameters in this experiment.

Open-Loop Methods

Ziegler-Nichols Method

Ziegler-Nichols developed a tuning method based on a FODT model that produces approximate quarter-wave damping ^[16]. Given a first-order plus dead time (FODT) process model whose transfer function is

$$G_p(s) = \frac{k_p e^{-\theta_s}}{\tau_p s + 1} \quad \mathbf{3-21}$$

use formulae given in Table 3-2 to calculate Ziegler-Nichols swags.

Table 3-2 Ziegler-Nichols Open-Loop Tuning Parameters^[3]

<i>Controller Type</i>	k_c	τ_I	τ_D
P-only	$\tau_p/k_p\theta$	-	-
PI	$0.9 \tau_p/k_p\theta$	3.3θ	-
PID	$1.2 \tau_p/k_p\theta$	2θ	0.5θ

Ciancone Method:

Ciancone and Marlin created an open-loop method of tuning controllers based on a single parameter called *'fraction dead time'*. Fraction dead times ranges between 0.0 and 1.0 and is calculated from the FODT parameters. It represents the fraction of the total time needed for the open-loop process step response to reach 63.2% of its final value that is due to dead time. Determining PI controller parameters using Ciancone correlations is a three step procedure.

1. From the FODT (k_p , τ_p , and θ) model, calculate the fractional dead time as $\theta/(\tau_p + \theta)$.
2. Use the appropriate graph from Marlin Thomas E., *Process Control: Designing Processes and Control Systems for Dynamic Performance*, McGraw-Hill, New York 2nd edition, page 286.to determine the dimensionless tuning values: K_cK_p , $T_I/(T_p + \theta)$.

Calculate the dimensional controller tuning values from the dimensionless tuning values and the FODT parameters.

$$k_c = \frac{(K_c K_p)}{k_p} \quad 3-22$$

$$\tau_I = \left(\frac{T_I}{\theta + T_p} \right) (\theta + T_p) \quad 3-23$$

Fine Tuning

The values for controller tuning constants determined by correlation methods are just swags to be applied to the physical system initially and improved based on empirical performance during fine tuning. See Figure 3-30 for the well-tuned PI controlled process.

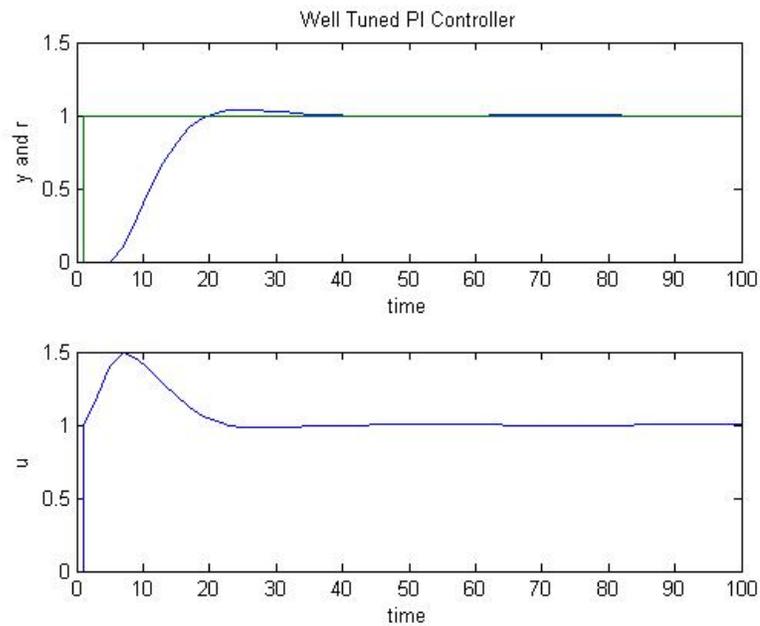


Figure 3-30 Well Behaved Process Controller.

Fine Tuning of a PI Controller

Use the previously determined control parameter initial guesses and fine tune the PI controller using the rules that follows ^[15].

Three important features relating to the manipulated variable are notable from the well-behaved process in Figure 3-30.

1. The manipulated variable changes immediately when the set point is changed. This change is due to the proportional mode is equal to $k_c \Delta E(t) = [k_c R(t)]$. This initial change is typically restricted to 70 to 150 percent of the change at the final steady state.
2. There is a delay between the time the manipulated variable changes and the time when the controlled variable responds. This delay is due to process dead time and no controller can reduce this delay to less than the process dead time.
3. During the delay time the manipulated variable increases linearly. This is due to the integral mode. During this period the error is constant so the proportional term does not change but the integral term increases linearly with slope equal to $\frac{k_c E(t)}{\tau_I}$.

After the controlled variable begins its transient response, the proportional term decreases while the integral term continues to increase. At steady state (the end of the transient response) the proportional term is zero because the error is zero and the integral term has adjusted the manipulated variable to a value that reduces the offset to zero. These three features are very useful for recognizing maladjusted tuning parameters when fine tuning.

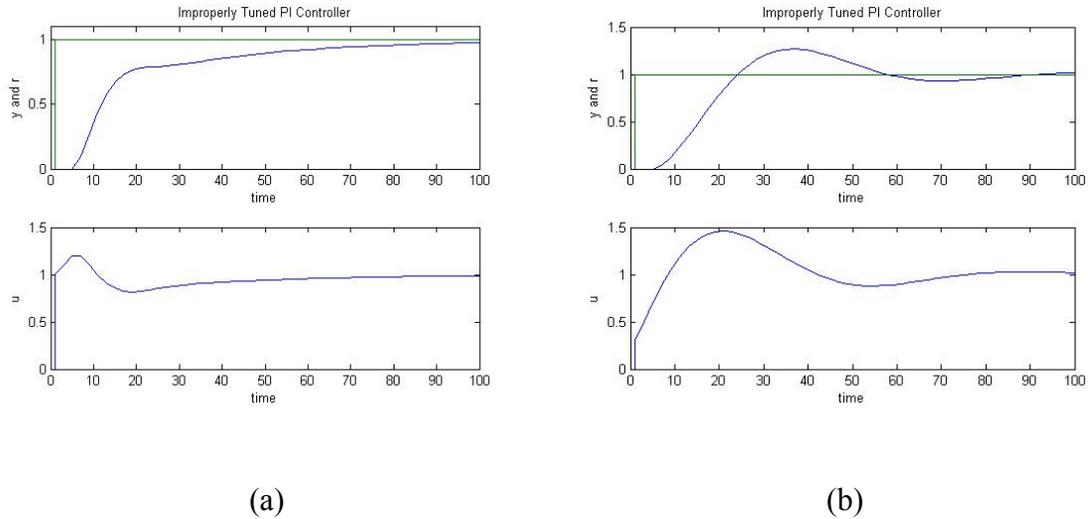


Figure 3-31 Improperly Tuned Controllers (a) sluggish response due to too little integral action, needs smaller (τ_I) integral time, (b) sluggish response due to too little proportional action, needs larger gain(k_c).

Figure 3-31 gives examples of improperly tuned responses. Figure 3-31(a) has a sluggish response due to too little integral action. To speed up the response lower τ_I . Proportional gain is not raised to speed up the response because the initial change manipulate variable is within 70-150% of final steady state value. Figure 3-31(b) has a sluggish response due to too little proportional gain k_c . To speed up the response, increase k_c . When fine tuning a PI controller, adjust the proportional gain, k_c , first and then adjust the integral time, τ_I .

Table 3-3 Effect of Controller Tuning Parameters on Higher Order Processes

Parameter	Rise Time	Overshoot	Settling Time	Offset
Increasing k_c	Decreases	Increases	No effect	Decreases
Decreasing (τ_I)	Decreases	Increases	Increases	Eliminated
Increasing (τ_D)	Small Decrease	Decreases	Decreases	No effect

Proportional gain (k_c)

An increase in absolute value of controller gain $|k_c|$ will speed up the response but at the expense of system stability.

Integral Gain (τ_I)

An increase in integral time (τ_I) tends to slow down the response and decrease the overshoot, while the lower τ_I speeds up the response and increases overshoot. Too low of a value for τ_I , can lead to instability.

Derivative time (τ_D)

An increase in derivative time helps system stability. However, this control action is very sensitive to measurement noise. Usually only PI control is used for loops where there is measurement or output noise.

Three Laws of Feedback Controller Tuning

- 1 Control performance must be defined with respect to all important plant operating goals. The desired behavior of the controlled variable and the manipulated variable must be defined for expected disturbances, model errors, and noisy measurements.
- 2 The dynamic behavior of both the controlled variable and the manipulated variable must be observed when analyzing the performance of feedback control systems. Complete diagnosis is not possible without information on both variables.
- 3 When tuning a feedback controller, where you start is not as important as where you finish! The values for controller tuning constants determined by correlation

methods are just swags to be applied to the physical system initially and improved based on empirical performance during fine tuning.

After completing this experiment, you will have hands-on experience with laws two and three and a better understanding of the issues involved in law one.

LabPID1.VI Program Explanation

The front panel of LabPID1.VI is shown in Figure 3-32. On the left side of the screen, the set point for the liquid level is entered. The “Run pump” button is used to run the pump. “Control Tank Toggle” button is used to switch level control between tank1 and tank2. “Write data” glows when the program is writing data to the user defined file. In addition to the initialization controls described above, the PID tuning parameters are entered and displayed here. The ‘STOP’ button is used to stop the program.

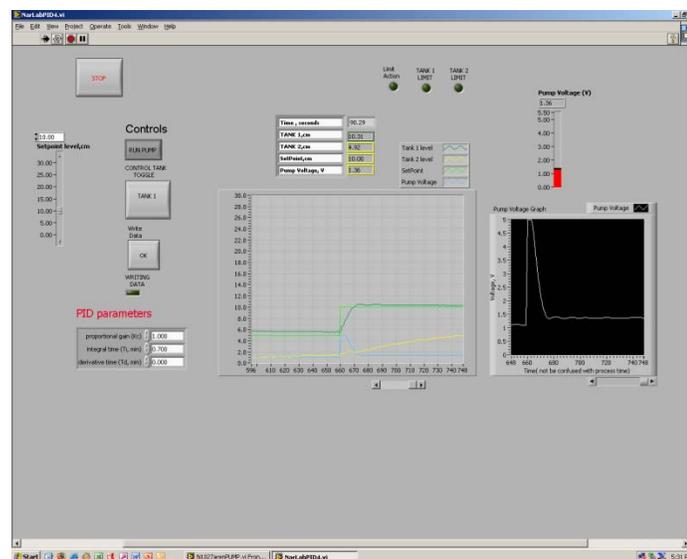


Figure 3-32 LabPID1.VI Front Panel.

The dynamic response of the output variables are shown in the center of the screen. The Limit action LED, along with either the tank1 Limit or tank2 Limit LED, glows when the tank voltages are in the range 4.3 to 4.5 V. In this voltage range, the Safety Interlock System takes control to avoid overflow. The levels of tank1 and tank2, along with the set point, are displayed numerically in cm. They are also plotted on a waveform chart below their numerical display. The dynamic response of the input variable is shown on the right of the screen. The pump voltage is displayed on a vertical indicator and is plotted on the waveform chart below the vertical indicator. The horizontal scroll bar below the waveform charts enables the user to view earlier responses. Use the horizontal scroll bar to note how the input and output variables respond to a step change for various tuning constants and, based on these responses, tune the process.

Appropriate values for the PID parameters lead to good control - stable, snappy, and not too oscillatory. Inappropriate values leads to bad control - unstable, sluggish, and oscillatory. Adjust the PID tuning parameters as necessary so that the response to a set point change is reasonable.

Lab Procedure

Precautions and Other Notes:

- Make sure that the reservoir's distilled water level is at least three-fourths full.

- A watchdog is programmed into LabPID1.VI so that the tanks do not overflow. If the liquid level in either of the tanks reaches 25cm the pump is turned off and pump continues to remains idle until the tanks voltage drops below 4.3 V.
- Do not panic, the pump can be noisy. If it starts smoking that is another matter. Shut off the pump by clicking "Stop" on the LabPID1.VI program.

1) *Start up of experiment/program*

- Familiarize yourself with the apparatus. See Figure 3-27.
- Double-click the LabPID.VI icon on the desktop. It opens the LabPID.VI program in LabVIEW. Familiarize yourself with the icons, controls and indicators and what they do on the screen. See Figure 3-32.
- Click the white arrow button on the top left of the screen to start the program. A window pops up on the screen asking to define an output file.
- Assign a file name and save it in Microsoft Excel spreadsheet format (e.g.: yourname.xls). The output file records PID parameters and tank levels, set point and pump voltage as a function of time.
- Use "Control Tank Toggle" to switch to tank2, if it is not the online tank for level control.

2) *Remove the air pockets*

- Run pump for a random set point ≤ 10 cm and watch for any air bubbles over/in the pressure sensor for the both tank1 and tank2.
- Air pockets will form in the sensors most of the time. Whether or not you see bubbles, poke the rod into sensor cavity of both tank1 and tank2 as shown in

Figure 3-33 to remove them.

Caution: 1) Be gentle with the sensor while removing bubbles. A violent stroke on the sensor could ruin it.

2) Don't get confused with the bubbles formed and floating at the top of tank for bubbles in sensor.



Figure 3-33 Removal of Air Pockets in Pressure Sensor.

c) Once air pockets are removed click “Run Pump” to stop the pump.

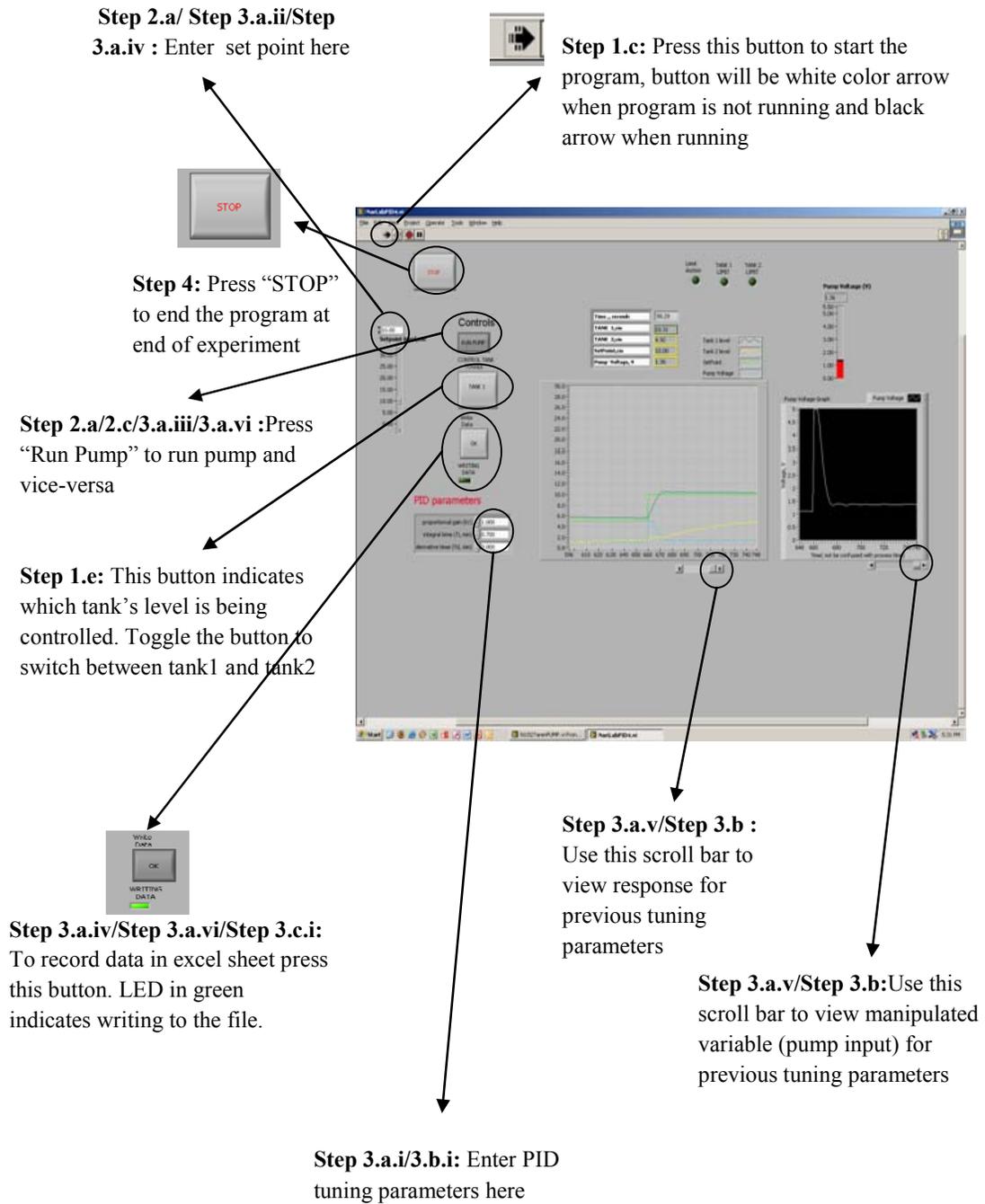


Figure 3-34 Detailed Explanation of Step by Step Procedure for Tuning.

3) *Generate empirical data (See Figure 3.34 for step by step explanation)*

a) For initial PI parameters

- i. Enter the instructor specified initial PI parameters (SWAGs calculated from the theoretical settings) in the PID parameters input box.

Note: *1) enter the integral time and derivative time in **minutes**.*

2) Make sure $\tau_D = 0$ for PI control.

- ii. Enter the set point of 3 cm.
- iii. Press “Run pump” to start the pump.
- iv. Once the steady state liquid level is reached on tank2 (See tank2 level graph), click “write data” button and then change the set point to the value given to your group.
- v. *Note the initial pump voltage change and observe the pump voltage response along with tank2 level response as the system reaches the new steady state.*
- vi. Once the new steady state is reached, click “write data” to stop recording and “run pump” to stop the pump.

b) Fine Tuning

- i. Use scroll bars below tank level and voltage vs. time plots to view response for previous tuning parameters.
- ii. Adjust the k_c and τ_I for best closed-loop response. Use a trial and error method based on PI controller tuning and parametric effect topics in the theory section. Parametric effects are listed in Table 3.3. for assistance.

The allowable percent overshoot is 10%.

- iii. Repeat steps 3.a.i to 3.a.vi without recording data until you get desired closed-loop response for both the output and input variables. Use scroll bars below tank level and voltage vs. time plots to view response for previous parameters.
 - iv. Once desired response is attained go 3.c.
- c) Final PI parameters
- i. Repeat steps 3.a.i to 3.a.vi with final tuning parameters. Make sure you record data this time.
- 4) *Press “STOP” button at the end of the experiment.*

Data Analysis

1. Graphically compare the empirical set point responses of tank2 for all three sets (initial Ziegler-Nichols and Ciancone guesses and fine tuned) of PI tuning parameters.
2. Compare each of the empirical closed-loop responses, both its input and output with its SIMULINK equivalent. Discuss any discrepancies. Why might there be any discrepancies?

3.7 Correcting Pump.VI Start-up Issues

The two LabVIEW programs, Pump.VI and LabPID1.VI, are written in different versions. This can cause device driver conflict issues. To counter this problem:

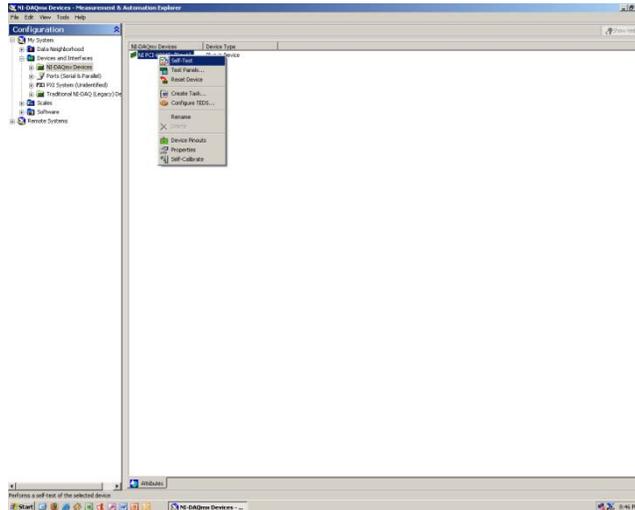


Figure 3-35 Issues with the LabVIEW Program Start Up.

1. Click Measurement and automation icon on the desktop or access it from the programs in the windows menu.
2. Expand NI-DAQmx devices in the expanded devices and interfaces.
3. Right click on NI-DAQmx devices and then do self test and reset the device.
4. The screen display shows now the “device has successfully tested” for self test and “device has been reset successfully” for reset.

3.8 References

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- 4) Donald R. Coughnour *Process Systems Analysis and Control, 2nd edition*, McGraw-Hill International editions, 1991.
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- 9) Basilio J. C., and S. R. Matos “*Design Of PI and PID Controllers with Transient Performance Specification*,” IEEE Transactions on Education, Vol. 45, No. 4, November 2002.
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- 11) Ziegler, J.G., and N.B. Nichols, “*Optimum Settings for Automatic Controllers*,” Trans. ASME, 64,759-768(1942).
- 12) Luyben, M.L., and W.L. Luyben, *Essentials of Process Control*, McGraw-Hill, New York (1997).
- 13) Cohen, G.H., and G.A. Coon, “*Theoretical Considerations of Retarded Control*,” Trans. ASME, 75, 827(1953).
- 14) R Ciancone and T Marlin, *Tune controllers to meet plant objectives*, Control, 5, 50-57, 1992.
- 15) Marlin Thomas E., *Process Control: Designing Processes and Control Systems for Dynamic Performance*, McGraw-Hill, New York 2nd edition.

- 16) B.W. Bequette, *Process Control—Modeling, Design and Simulation*, page 202, Prentice Hall (2003).

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter has five subsections. Each subsection has pre-lab tasks, experimental results, data analysis solutions and discussion of the results for each of the five experiments in the Chapter 3.

4.2 Experiment-1 Orifice Coefficient Determination

4.2.1 Pre-Lab Tasks

(c) Determining Orifice Coefficient

The orifice coefficient is found from the steady state relation

Flow in = Flow out

$$KV_{pump} = \alpha\sqrt{L} \quad 4-1$$

$$\alpha = C_0 A_0 \sqrt{2g} \text{ (from Equation 3-6)}$$

The relation between level in the tank and its pressure sensor voltage is determined from calibration of pressure sensor. So Equation 4-1 becomes

$$KV_{pump} = \beta\sqrt{V_{sensor}} \quad 4-2$$

In this experiment V_{pump} is used as the independent variable

Applying log on both sides gives

$$\log V_{sensor} = 2 \log \frac{K}{\beta} + 2 \log V_{pump} \quad 4-3$$

The graph, $\log V_{pump}$ Vs $\log V_{sensor}$, is a line with slope 2 and intercept = $2 \log \frac{K}{\beta}$

Since K is determined by calibrating, β can be calculated as $\frac{K}{10^{\frac{\text{intercept}}{2}}}$

Combining Equations 4-1 and 4-2 gives

$$\beta\sqrt{V_{sensor}} = \alpha\sqrt{L}$$

But, from the calibration of the pressure sensor, L is proportional to V_{sensor} , i.e.,

$L=mV_{sensor}$. Therefore

$$\beta \sqrt{\frac{L}{m}} = C_0 A_0 \sqrt{2g\sqrt{L}}$$

and $C_0 \alpha$ can be computed as

$$C_0 = \frac{\beta}{A_0 \sqrt{2g\sqrt{m}}} \quad 4-4$$

4.2.2 Calibration of Pump Voltage to Flow Rate

The relation between the pump voltage and flow rate is found measuring the volumetric flow rate in a 250 ml graduated cylinder. For six pump voltages, the time for the liquid to move from 50 ml to 210 ml was recorded. The results are tabulated in Table 4-1 through Table 4-4 for all the apparatus.

Table 4-1 Experimental Data Relating Pump Voltage and Flow Rate for Apparatus-1

pump voltage V	Time in seconds							Flowrate ml/s
	Trial 1	Trial 2	Trial 3	Trail 4	Trial 5	Trial 6	Average	
0.50	20.88	20.47	20.22	20.18	20.19	20.34	20.38	7.85
0.65	14.56	14.53	15.12	14.62	14.41	14.28	14.59	10.97
0.75	12.28	12.81	12.69	12.78	12.78	12.87	12.70	12.60
1.00	9.37	9.28	9.31	9.22	9.15	9.03	9.23	17.34
1.25	7.25	7.43	7.25	7.19	7.25	7.25	7.27	22.01
1.50	5.91	6.03	5.91	6.18	6.03	6.04	6.02	26.59

Table 4-2 Experimental Data Relating Pump Voltage and Flow Rate for Apparatus-2, Trial-1

pump voltage V	Time in seconds							Flowrate ml/s
	Trial 1	Trial 2	Trial 3	Trail 4	Trial 5	Trial 6	Average	
0.50	18.40	19.22	17.97	18.16	18.12	17.81	18.28	8.75
0.65	13.38	13.34	13.53	14.03	13.50	13.56	13.56	11.80
0.75	11.38	11.37	11.72	11.63	11.65	11.40	11.53	13.88
1.00	8.69	8.56	8.63	8.69	8.71	8.56	8.64	18.52
1.25	7.18	7.09	7.00	7.07	7.03	7.05	7.07	22.63
1.50	5.87	5.94	6.12	6.00	6.12	6.06	6.02	26.59

Table 4-3 Experimental Data Relating Pump Voltage and Flow Rate for Apparatus-3

pump voltage V	Time in seconds							Flowrate ml/s
	Trial 1	Trial 2	Trial 3	Trail 4	Trial 5	Trial 6	Average	
0.50	22.16	22.34	21.59	21.97	21.82	21.53	21.90	7.31
0.65	14.72	14.71	15.06	14.91	15.78	15.81	15.17	10.55
0.75	12.40	12.50	12.62	12.60	12.31	12.63	12.51	12.79
1.00	8.94	8.69	8.91	8.66	8.88	8.93	8.84	18.11
1.25	7.06	7.00	7.10	7.09	6.97	7.13	7.06	22.67
1.50	6.03	5.90	5.85	5.75	5.78	5.90	5.87	27.26

Table 4-4 Experimental Data Relating Pump Voltage and Flow Rate for Apparatus-4

pump voltage V	Time in seconds							Flowrate ml/s
	Trial 1	Trial 2	Trial 3	Trail 4	Trial 5	Trial 6	Average	
0.50	18.75	18.97	19.15	18.66	18.34	18.66	18.76	8.53
0.65	13.43	13.85	13.66	13.47	13.62	13.91	13.66	11.72
0.75	11.53	11.38	11.47	11.56	11.50	11.47	11.49	13.93
1.00	8.63	8.43	8.59	8.53	8.62	8.63	8.57	18.67
1.25	6.85	7.03	6.87	7.09	6.78	6.94	6.93	23.10
1.50	5.94	5.88	5.82	5.88	5.78	5.79	5.85	27.36

The data from Table 4-2 is plotted in Figure 4-1.

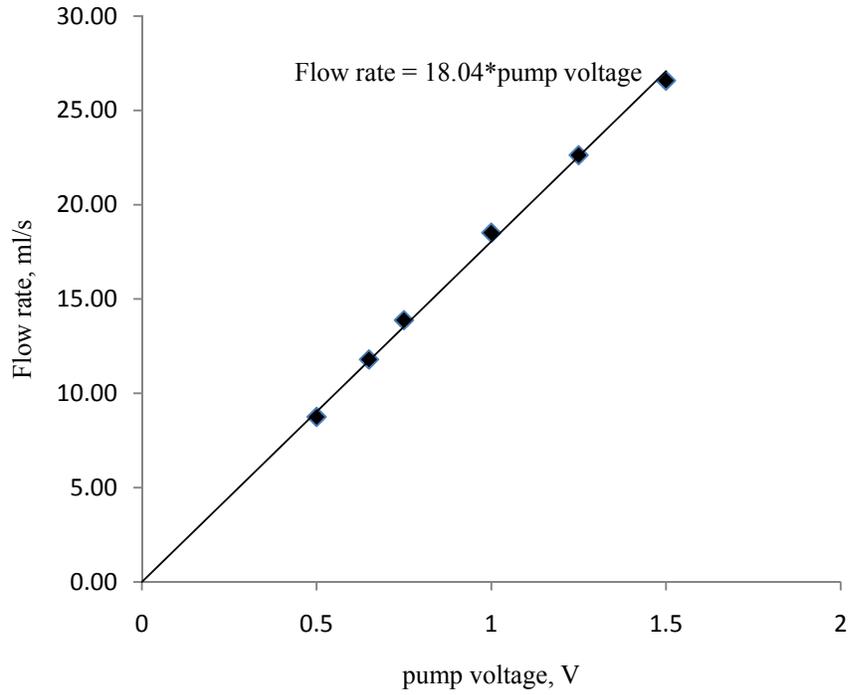


Figure 4-1 Pump Voltage and Flow Rate Calibration for Apparatus-2, Trial-1.

Pump flow constant (K) across apparatus

K varies slightly across the apparatus and is determined by the procedure described in section 4.2.2. The K values are tabulated in Table 4-5.

Table 4-5 Pump Flow Constants for the Different Apparatus

Apparatus	K, cm ³ /s.V
Apparatus-1	17.40
Apparatus-2	17.99*
Apparatus-3	17.76
Apparatus-4	18.33

* average of three trials

Pump flow constant (K) with time on the same apparatus

The pump flow constant (K) remains almost constant for an individual apparatus over time. The test described in section 4.2.2 was performed on three different days. Over these three days the values of K on apparatus-2 were 18.04, 18.04 and 17.91 cm³/ (s.V). The mean and standard deviation of K are 17.99 cm³/ (s.V) and 0.07 cm³/ (s.V), respectively. The standard deviation of 0.07 can be attributed to experimental error and therefore K can be assumed constant with respect to time. The data for the trials are tabulated in Table 4-2, Table 4-6 and Table 4-7.

Table 4-6 Experimental Data Relating Pump Voltage and Flow Rate, Apparatus-2, Trial-2

pump voltage V	Time in seconds							Flowrate ml/s
	Trial 1	Trial 2	Trial 3	Trail 4	Trial 5	Trial 6	Average	
0.50	18.82	18.34	18.75	18.28	18.38	18.53	18.52	8.64
0.65	13.69	13.53	13.56	13.54	13.50	13.60	13.57	11.79
0.75	11.69	11.59	11.75	11.59	11.68	11.91	11.70	13.67
1.00	8.81	8.97	8.84	8.72	8.78	8.69	8.80	18.18
1.25	7.09	7.00	7.28	7.19	7.00	7.03	7.10	22.54
1.50	6.16	6.00	6.10	5.93	6.07	5.97	6.04	26.50

Table 4-7 Experimental Data Relating Pump Voltage and Flow Rate, Apparatus-2,
Trial-3

pump voltage V	Time in seconds							Flowrate ml/s
	Trial 1	Trial 2	Trial 3	Trail 4	Trial 5	Trial 6	Average	
0.50	18.62	18.15	18.57	18.44	18.15	18.41	18.39	8.70
0.65	13.62	13.56	13.41	13.60	13.37	13.40	13.49	11.86
0.75	11.56	11.59	11.56	11.72	11.53	11.56	11.59	13.81
1.00	8.82	8.87	8.69	8.60	8.62	8.94	8.76	18.27
1.25	6.97	7.19	6.97	7.22	6.97	7.22	7.09	22.57
1.50	5.97	6.12	5.94	5.90	5.94	5.94	5.97	26.81

4.2.3 Calibration of Pressure Sensor Voltage to Tank Liquid Level

Table 4-8 shows the experimental data relating pressure sensor voltage (tank voltage) to liquid level in the tank1 apparatuses. The data for tank1 is acquired in step 4.h of the lab procedure in experiment-1.

Table 4-8 Pressure Sensor Calibration Data Tank1

Liquid level	Pressure Sensor Voltage, V			
	Apparatus-1	Apparatus-2	Apparatus-3	Apparatus-4
0	-0.03	-0.03	0.00	0.03
5	0.84	0.75	0.83	0.82
10	1.66	1.56	1.64	1.65
15	2.50	2.36	2.48	2.48
20	3.30	3.14	3.31	3.29
25	4.07	3.89	4.10	4.12

Each apparatus has similar readings for both tanks. A calibration chart is drawn with Tank Sensor Voltage as independent variable and Liquid Level as dependent

variable. This gives an equation of the form $y = mx + c$ where the slope, m , gives the gain value.

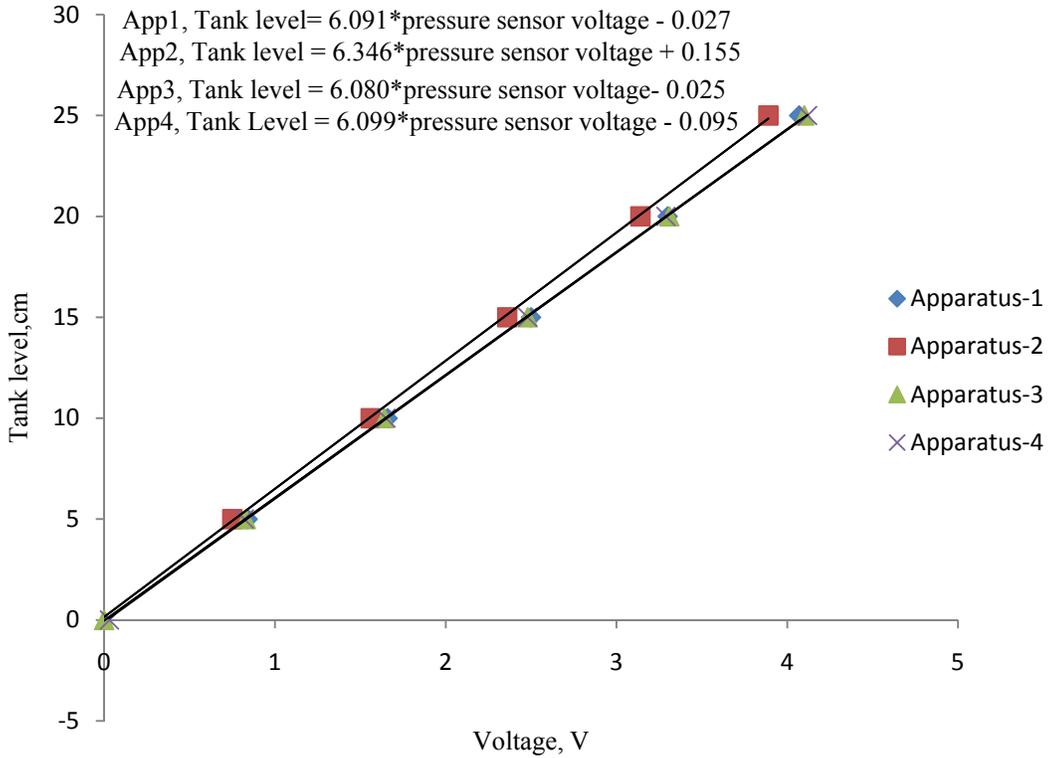


Figure 4-2 Calibration Chart, Pressure Sensor Voltage Versus Level in the Tank1.

Although typical gain values range from 6.1 – 6.4, it need not be in this range because the gain values depend on how the potentiometer screws are adjusted. Moreover, it doesn't need to be regressed the origin because sometimes there will be slight offset from zero at zero level in the tank.

4.2.4 Orifice Coefficient

Following the procedure described in step 5 in lab procedure of section 3.2 produces the data tabulated in Table 4-9 and plotted in Figure 4-3.

Table 4-9 Experimental Data $\log V_{\text{pump}}$ vs. $\log V_{\text{sensor}}$, Apparatus-2

Vpump	Vsensor	log Vpump	Log Vsensor
1.10	1.16	0.04	0.06
1.25	1.57	0.10	0.20
1.40	2.03	0.15	0.31
1.55	2.50	0.19	0.40
1.70	3.02	0.23	0.48
1.85	3.63	0.27	0.56

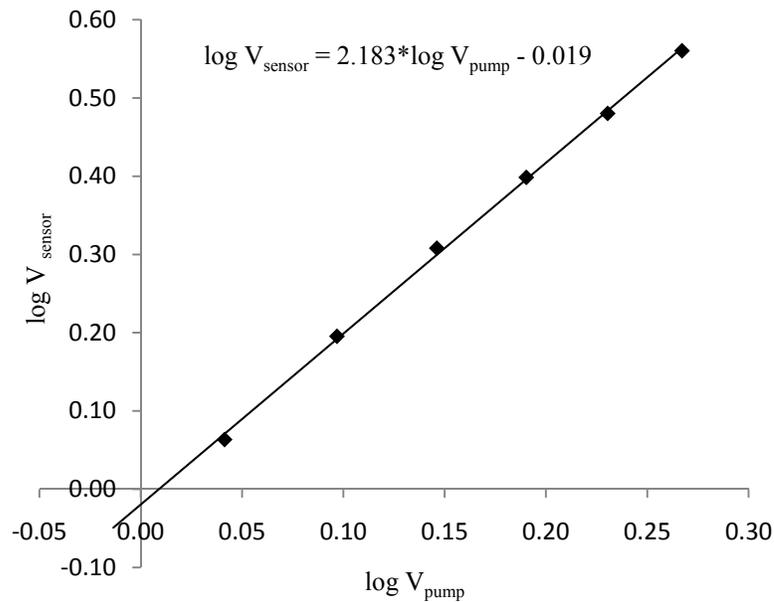


Figure 4-3 $\log V_{\text{pump}}$ vs. $\log V_{\text{sensor}}$ for Apparatus-2.

The intercept of Figure 4-3 yields the value of orifice coefficient as shown below and described in section 4.2.1. Note that m for Equation 4-4 comes from Figure 4-2 and is the slope of the line between pressure sensor voltage and tank level for apparatus-2 for this example calculation.

$$2 \log \frac{K}{\beta} = -0.019$$

$$\beta = 17.99/10^{\frac{-0.019}{2}}$$

$$\beta = 17.99 * 1.02 = 18.36 \frac{cm^3}{s \cdot \sqrt{V}}$$

$$\alpha = C_0 A_0 \sqrt{2g} = 18.36 / \sqrt{6.346}$$

$$C_0 = 18.36 / (3.1415 * \left(\frac{0.4763}{2}\right)^2 * \sqrt{6.346 * 2 * 981})$$

$$C_0 = 0.9235$$

The experimental data verify that resistance flow is proportional to the square root of the tank level because the slope of the regressed line is very close to 2 considering experimental error as predicted by Equation 4-3 and shown in Figure 4-3.

4.3 Experiment-2 Modeling Liquid Level in a Cylindrical Tank

4.3.1 Pre-lab Tasks

$$(1) \frac{dL}{dt} \text{ as } f(L, V)$$

Material balance on the tank:

$$\left\{ \begin{array}{l} \text{rate of accumulation} \\ \text{of mass in tank} \end{array} \right\} = \left\{ \begin{array}{l} \text{rate of mass} \\ \text{entering in tank} \end{array} \right\} - \left\{ \begin{array}{l} \text{rate of mass} \\ \text{leaving out of tank} \end{array} \right\} \quad 4-5$$

In the following equations, M = mass of water; V = Volume of water;

ρ = density of water ; F_i = Flow into cylindrical tank;

F_o = Flow out from the cylindrical tank;

A_T = cross sectional area of the tank;

A_o = cross sectional area of the outlet orifice; K = pump flow constant;

ϑ_o = velocity of water at outlet orifice; g = acceleration due to gravity

$$\frac{dM}{dt} = \rho \frac{dV}{dt} = \rho F_i - \rho F_o \quad 4-6$$

$$A_T \frac{dL}{dt} = F_i - F_o$$

$$F_i = KV_{pump} \text{ gives}$$

$$A_T \frac{dL}{dt} = KV_{pump} - A_o \vartheta_o$$

$$\frac{dL}{dt} = \frac{K}{A_T} V - C_o \sqrt{2g} \frac{A_o}{A_T} \sqrt{L} = f(L, V) \quad 4-7$$

$$\text{Note that } A_T = \pi \left(\frac{D_T}{2} \right)^2 \text{ and } A_o = \pi \left(\frac{D_o}{2} \right)^2$$

(2) Steady state pump voltage, V_s , as a function of steady state liquid level, L_s

At steady state, the change in height with time is zero so Equation 4-7 is equal to zero.

$$\left. \frac{dL}{dt} \right|_s = 0$$

$$C_o \sqrt{2g} \frac{A_o}{A_T} \sqrt{L_s} = \frac{K}{A_T} V_s$$

where L_s is height at steady state and V_s is pump voltage at steady state

$$\sqrt{L_s} = \frac{K}{\sqrt{2g} A_o C_o} V_s \quad \mathbf{4-8}$$

(3) Deviation variables and linearized model at steady state:

$$X = L - L_s \text{ and } u = V - V_s$$

$$\frac{dX}{dt} = f(L_s, V_s) + \left. \frac{\partial f}{\partial L} \right|_s X + \left. \frac{\partial f}{\partial V} \right|_s U$$

(4) By definition of steady state $f(L_s, V_s) = 0$. So,

$$\frac{dX}{dt} = -\sqrt{\frac{g}{2}} \left(\frac{A_o}{A_T} \right) C_o \frac{1}{\sqrt{L_s}} X + \frac{K}{A_T} U$$

$$\text{let } c_1 = \sqrt{\frac{g}{2L_s}} \left(\frac{A_o}{A_T} \right) C_o \text{ and } c_2 = \frac{K}{A_T}$$

$$Y = X$$

$$\Rightarrow \frac{dY}{dt} = \frac{dX}{dt} = -c_1 Y + c_2 U$$

$$sY(s) = -c_1 Y(s) + c_2 U(s)$$

$$(s + c_1)Y(s) = c_2U(s)$$

$$\frac{Y(s)}{U(s)} = \frac{c_2}{s + c_1}$$

$$\frac{Y(s)}{U(s)} = \frac{\left(\frac{c_2}{c_1}\right)}{(1/c_1)s + 1} \quad \mathbf{4-9}$$

This is first order system with gain = (c_2/c_1) and time constant = $(1/c_1)$

4.3.2 Experiment-2 Results

Carrying out the experimental procedures described in Section 3.3 produces a graph similar to Figure 4-4. The curves show how the tank level changes when there is a step change in input pump voltage from 0.7 V to 1.25 V for different trials. This graph yields the parameters for first order plus dead time (FODT) model for the particular process. The final height of upper tank is not same for each apparatus for same step change in pump voltage because the flow rate is not same for a particular pump voltage across all the apparatuses.

All the graphs in this subsection are for step changes in input pump voltage from 0.7 volts to 1.25 volts and only for the upper tank in each apparatus. Doing a step change from one steady-state level to another eliminates dead time and start-up effects in each apparatus. The plots are ten repeated experimental procedures. The red curves indicate the 95 % confidence interval (C.I.) and the black line indicates the mean for the upper tank liquid level as a function of time. The yellow curves are the actual data collected on the apparatus. The MATLAB code for the graphs is attached in Appendix – 1.

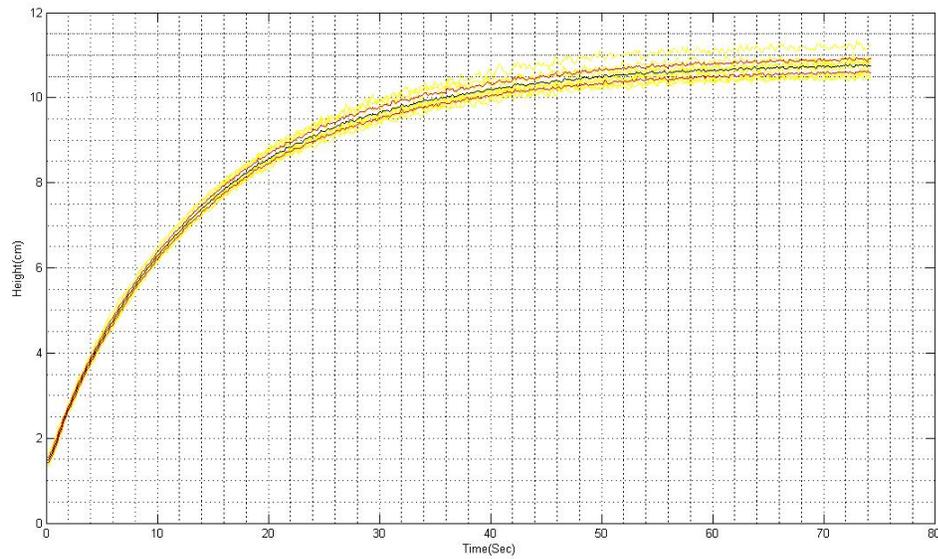


Figure 4-4 Experiment-2 Data for Apparatus-1.

Graphs analogous to Figure 4-4 for apparatus-2, apparatus-3 and apparatus-4 are plotted in Figure 4-5 through Figure 4-7, respectively. The final steady state level is not same for the same step change because there is a slight difference in pump flow constant (K) across the apparatus. The spread among the trials may be attributed to pressure sensor hysteresis which did allow the return to the original voltage level.

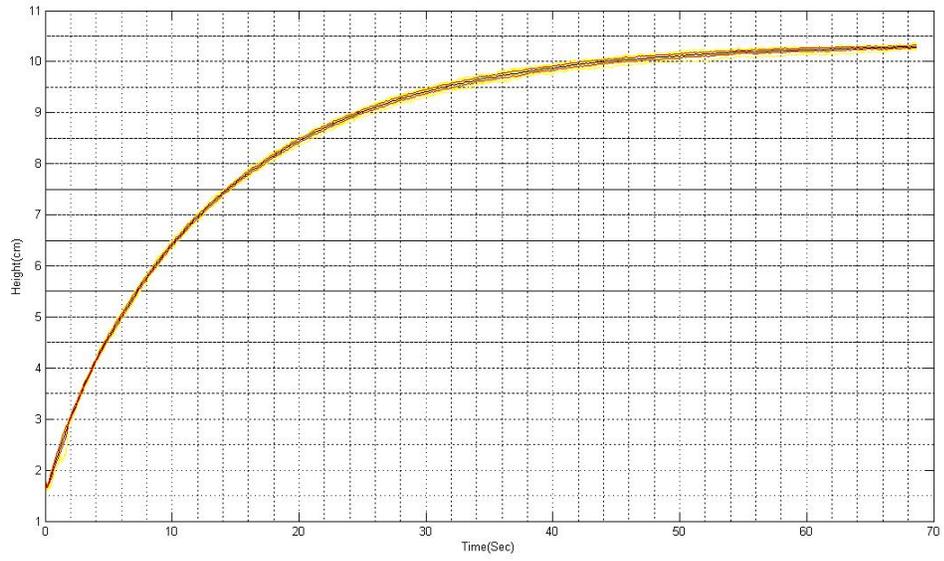


Figure 4-5 Experiment-2 Data for Apparatus-2.

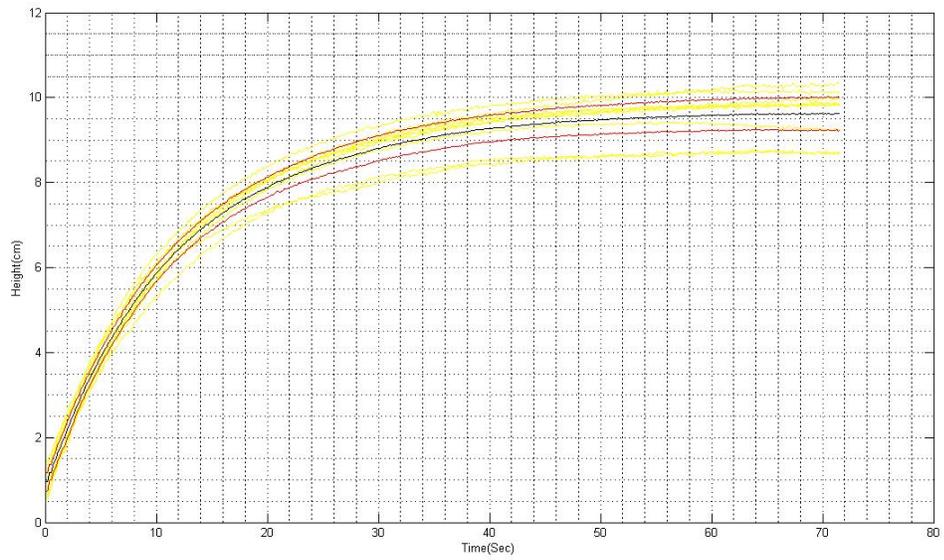


Figure 4-6 Experiment-2 Data for Apparatus -3.

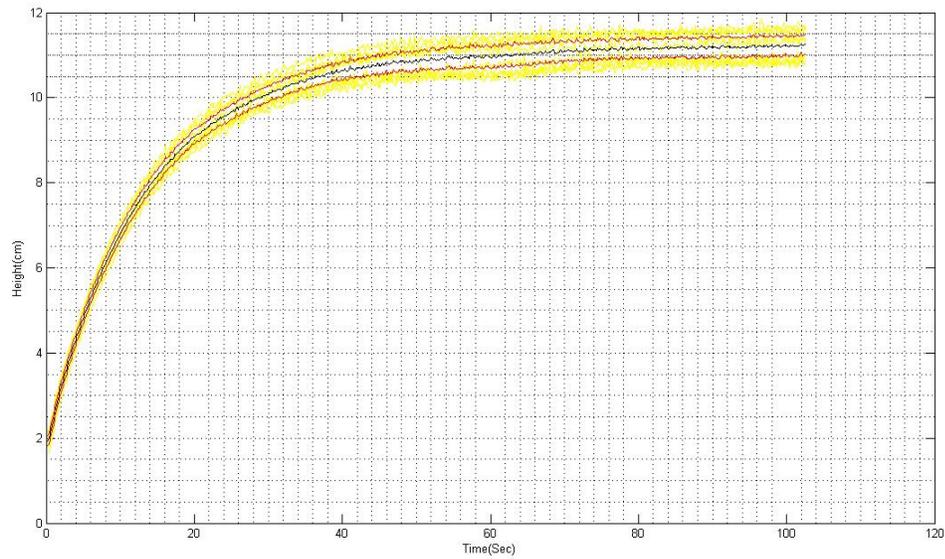


Figure 4-7 Experiment-2 Data for Apparatus-4.

Sample Calculation for Process gain (K_p), Process Time Constant (τ_p), and Process with Dead Time (θ).

The process gain is computed as the steady-state change in the output variable divided by the change in manipulated variable. Figure 4-4 is used for calculations.

Initial height in the tank = 1.45 cm

Final height reached in the tank = 10.75 cm

Initial input pump voltage = 0.7 V

Final input pump voltage = 1.25 V

$$\begin{aligned}
 \text{Process gain } (K_p) &= \text{change in liquid level / change in pump voltage} \\
 &= (10.75 - 1.45) / (1.25 - 0.7) \\
 &= 16.909 \text{ cm/V}
 \end{aligned}$$

The process time constant is determined as the time it takes the mean curve to reach 63.2% of the output variable change.

τ_p is time taken for tank level at reach $0.632*(10.75-1.45)+1.45$ cm= 7.32cm. From Figure 4-4, this time is 13.8 s.

The process dead time is the amount of time it takes the output variable to react after the manipulated variable is changed. Since the manipulated variable is changed at time = 0 s and the level starts changing at time = 0 s, there is no dead time in the upper tank process.

\therefore The FODT parameters are $K_p = 16.909$ cm/V, $\tau_p = 13.8$ s, and $\theta = 0$ s for the upper tank of apparatus-1.

4.3.3 Data Analysis

(1) Calibration Chart

Table 4-10 shows pressure sensor voltage (tank voltage) versus liquid level in the tank1, Apparatus-1. This data are acquired in step 5.b in Experiment-2. Each apparatus has similar readings for both tanks.

Table 4-10 Calibration Chart Readings for Tank

Tank Voltage, V	Liquid level in tank, cm
0	0
0.85	5
1.69	10
2.5	15
3.3	20
4.09	25

A calibration chart is drawn with tank voltage as independent variable and liquid level as dependent variable. Plotting these two variables gives an equation of the form $y = mx + c$ where the slope, m , gives the gain value as shown in Figure 4-8.

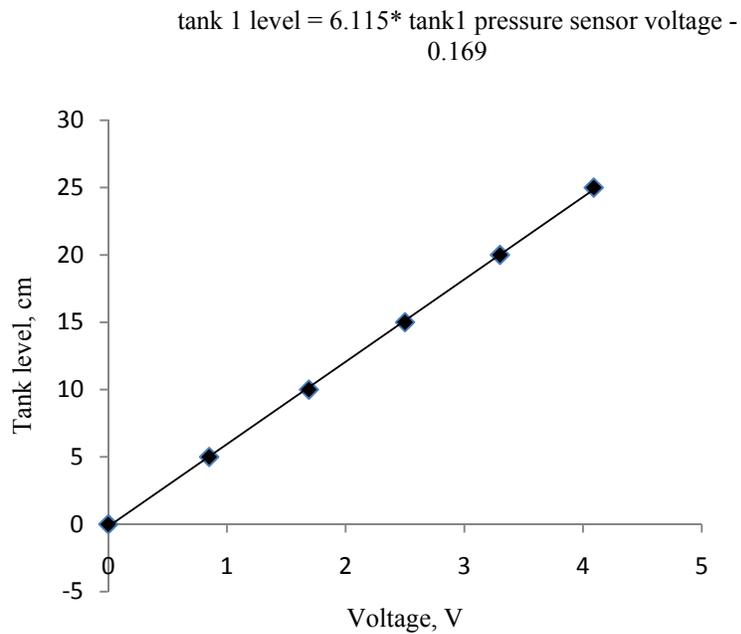


Figure 4-8 Calibration Chart, Pressure Sensor Voltage vs. Level in the Tank, Apparatus-1.

Although typical gain values range from 6.1 – 6.4, it need not be in this range because the gain values depend on how the potentiometer screws are adjusted. Moreover, it doesn't need to be regressed through the origin because sometimes there will be slight offset from zero at zero level in the tank.

(2) Comparison with experimental data

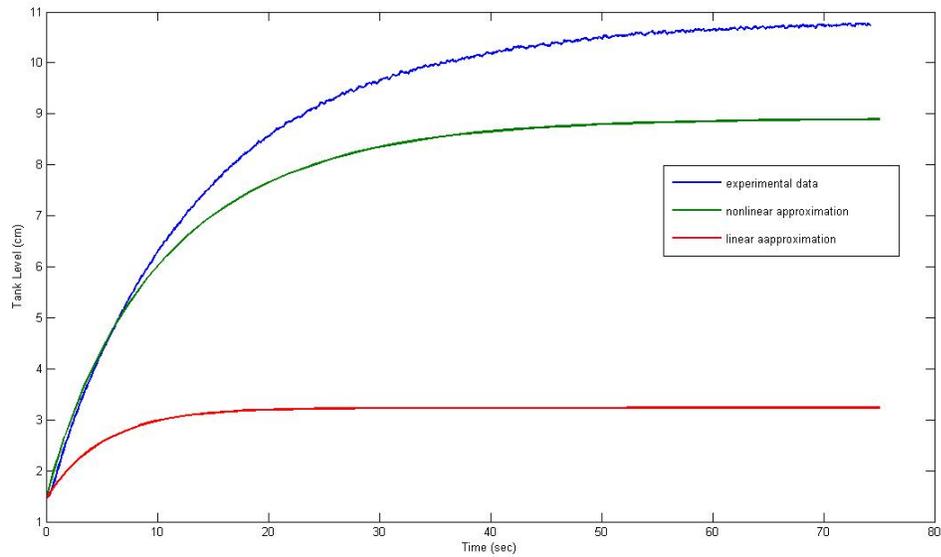


Figure 4-9 Comparison of experimental data with Simulink non-linear and linear approximations for apparatus-1.

Figure 4-9 shows the comparison of experimental data with Simulink non-linear and linear approximations for apparatus-1. The reason for deviation of experimental data from non-linear approximation might be attributed to the sensor voltage not being at zero at start of the experiment. This offset is not adjusted if it is within ± 0.1 V of zero. The linear approximation is way off even from the non linear approximation because the step change is almost 80% of initial steady state about which the model is linearized. Linear approximation holds good only for small input changes from the point about which the model is linearized. This is shown in the exercise problem 2.8, B.W. Bequette, *Process Control—Modeling, Design and Simulation*, Prentice Hall (2003).

4.4 Experiment -3 Modeling the Liquid Level in the Second tank of a Coupled-Tank System

4.4.1 Pre-Lab Tasks

(1) Material balance on the lower tank:

$$\left\{ \begin{array}{l} \text{rate of accumulation} \\ \text{of mass in tank} \end{array} \right\} = \left\{ \begin{array}{l} \text{rate of mass} \\ \text{entering in tank} \end{array} \right\} - \left\{ \begin{array}{l} \text{rate of mass} \\ \text{leaving out of tank} \end{array} \right\}$$

$$\frac{dM_2}{dt} = \rho \frac{dV_2}{dt} = \rho F_1 - \rho F_2$$

$$A_{T2} \frac{dL_2}{dt} = C_o A_{o1} \vartheta_{o1} - C_o A_{o2} \vartheta_{o2}$$

$$\text{where } A_{T2} = A_{T1} = A_T = \pi \left(\frac{D_T}{2} \right)^2$$

$$A_{o1} = \pi \left(\frac{D_{o1}}{2} \right)^2 \quad \& \quad A_{o2} = \pi \left(\frac{D_{o2}}{2} \right)^2$$

$$\vartheta_{o1} = C_o \sqrt{2gL_1} \quad \& \quad \vartheta_{o2} = C_o \sqrt{2gL_2}$$

$$f(L_2, L_1) = \frac{dL_2}{dt} = -\sqrt{2g} \frac{A_{o2}}{A_T} C_o \sqrt{L_2} + \sqrt{2g} \frac{A_{o1}}{A_T} C_o \sqrt{L_1} \quad \mathbf{4-10}$$

$$\frac{dL_2}{dt} = -\sqrt{2g} C_o \left(\frac{D_{o2}}{D_T} \right)^2 \sqrt{L_2} + \sqrt{2g} C_o \left(\frac{D_{o1}}{D_T} \right)^2 \sqrt{L_1}$$

$$= -0.4697\sqrt{L_2} + 0.4697\sqrt{L_1} = f(L_2, L_1)$$

(2) At steady state, the change in height with time is zero so Equation 4-10 is equal to zero.

$$\left. \frac{dL_2}{dt} \right|_s = 0$$

$$C_o \sqrt{2g} \frac{A_{o2}}{A_T} \sqrt{L_{2s}} = C_o \sqrt{2g} \frac{A_{o1}}{A_T} \sqrt{L_{1s}}$$

$$\Rightarrow L_{1s} = \left(\frac{A_{o2}}{A_{o1}} \right)^2 L_{2s}$$

$$L_{1s} = L_{2s}$$

(3) Define the deviation variables as

$$\text{Let } X = L_2 - L_{2s} \text{ and } U = L_1 - L_{1s}$$

$$\frac{dX}{dt} = f(L_{2s}, L_{1s}) + \left. \frac{\partial f}{\partial L_2} \right|_s X + \left. \frac{\partial f}{\partial L_1} \right|_s U$$

By definition of steady state, $f(L_{2s}, L_{1s}) = 0$. So,

$$\frac{dX}{dt} = -\sqrt{\frac{g}{2}} \left(\frac{A_{o2}}{A_T} \right) C_o \frac{1}{\sqrt{L_{2s}}} X + \sqrt{\frac{g}{2}} \left(\frac{A_{o1}}{A_T} \right) C_o \left(\frac{1}{\sqrt{L_{1s}}} \right) U$$

$$\text{Let } \left. \frac{\partial f}{\partial L_2} \right|_s = \sqrt{\frac{g}{2}} \left(\frac{A_{o2}}{A_T} \right) C_o \frac{1}{\sqrt{L_{2s}}} = \frac{0.2348}{\sqrt{L_{2s}}} = \alpha$$

$$\text{and } \left. \frac{\partial f}{\partial L_1} \right|_s = \sqrt{\frac{g}{2}} \left(\frac{A_{o1}}{A_T} \right) C_o \left(\frac{1}{\sqrt{L_{1s}}} \right) = \frac{0.2348}{\sqrt{L_{1s}}} = \beta$$

$$Y = X$$

$$\therefore \frac{dY}{dt} = \frac{dX}{dt} \Rightarrow \frac{dY}{dt} = -\alpha Y + \beta u$$

$$\frac{Y(s)}{u(s)} = \frac{\beta}{s + \alpha}$$

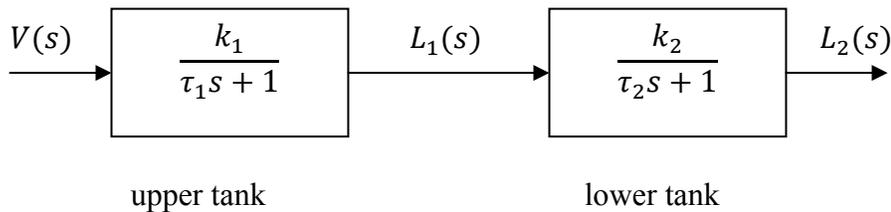
$$\frac{Y(s)}{u(s)} = \frac{\left(\frac{\beta}{\alpha}\right)}{(1/\alpha)s + 1} = \frac{k_2}{\tau_2 s + 1}$$

$$k_2 = \frac{0.2348/\sqrt{L_{1s}}}{0.2348/\sqrt{L_{2s}}} = \sqrt{\frac{L_{2s}}{L_{1s}}} \quad 4-11$$

$$\tau_2 = \frac{1}{0.2348/\sqrt{L_{2s}}} = 4.2582\sqrt{L_{2s}} \quad 4-12$$

$$\frac{Y(s)}{U(s)} = \frac{\left(\sqrt{\frac{L_{2s}}{L_{1s}}}\right)}{(4.2582\sqrt{L_{2s}})s + 1} = \frac{k_2}{\tau_2 s + 1} \quad 4-13$$

(4)



$$(5) \quad \frac{L_2(s)}{V(s)} = \frac{k_1 k_2}{\tau_1 \tau_2 s^2 + (\tau_1 + \tau_2)s + 1}$$

This is a second order system with gain = $k_1 k_2$, natural period

$$\tau = \sqrt{\tau_1 \tau_2}, \text{ and damping factor } \zeta = \frac{\tau_1 + \tau_2}{2\tau}$$

As shown in section 4.3.1, the top tank process gain is computed as follows for apparatus

1.

$$\begin{aligned}
k_1 &= \frac{\frac{K}{A_T}}{\sqrt{\frac{g}{2L_{1s}}} C_o \left(\frac{A_{o1}}{A_T}\right)} = \frac{K\sqrt{2L_{1s}}}{\sqrt{g} C_o A_{o1}} \\
&= \frac{17.4 * \sqrt{2} * \sqrt{L_{1s}}}{\sqrt{981}\pi * 0.9235 \left(\frac{0.4763}{2}\right)^2} \\
&= 4.7748\sqrt{L_{1s}}
\end{aligned}$$

$$\begin{aligned}
\tau_1 &= \sqrt{\frac{2L_{1s}}{g}} \left(\frac{A_T}{C_o A_{o1}}\right) = \sqrt{\frac{2}{g}} \left(\frac{D_T}{C_o D_{o1}}\right)^2 \sqrt{L_{1s}} \\
&= \sqrt{\frac{2}{981}} \left(\frac{4.4450}{0.4763}\right)^2 * \frac{1}{0.9235} \sqrt{L_{1s}} \\
&= 4.2582\sqrt{L_{1s}}
\end{aligned}$$

From Equation 4-13,

$$\frac{Y(s)}{U(s)} = \frac{\left(\sqrt{\frac{L_{1s}}{L_{2s}}}\right)}{(4.2582\sqrt{L_{2s}}s + 1)} = \frac{k_2}{\tau_2 s + 1}$$

$$\tau_2 = 4.2582\sqrt{L_{2s}}$$

For a second order system,

$$\text{gain} = k_1 k_2 = 4.7748\sqrt{L_{1s}} * \sqrt{\frac{L_{2s}}{L_{1s}}} = 4.7748\sqrt{L_{2s}}$$

$$\therefore \tau = \sqrt{4.2582 * \sqrt{L_{1s}} * 4.2582 * \sqrt{L_{2s}}}$$

$$\tau = 4.2582 * \sqrt{\sqrt{L_{1s}} * \sqrt{L_{2s}}}$$

$$\zeta = \frac{4.2582 * \sqrt{L_{1s}} + 4.2582 * \sqrt{L_{2s}}}{2 \left(4.2582 * \sqrt{\sqrt{L_{1s}} * \sqrt{L_{2s}}} \right)}$$

$$\zeta = \frac{0.5 * (\sqrt{L_{1s}} + \sqrt{L_{2s}})}{\sqrt{\sqrt{L_{1s}} * \sqrt{L_{2s}}}}$$

4.4.2 Experiment-3 Results

Carrying out the experimental procedures described in section 3.4 yields graphs plotted in Figure 4-10 through Figure 4-14 for each of the four apparatus respectively. These are the empirical models for the particular process. The curves show how the lower tank level changes when there is a step change in input pump voltage from 0.8 V to 1.35 V for different trials. The final height in the lower tanks is not same for all the apparatus for same step change in pump voltage because the flow rate is not same for a particular pump voltage across the apparatuses as each one have a different pump flow constant.

All the graphs in this section are for step changes in input pump voltage from 0.8 volts to 1.35 volts and only for tank2 in all apparatuses. Doing a set change from one level to another level eliminates start-up effects in these apparatuses. The graphs are

plotted by repeating the experimental procedures 10 times. Red color line indicates the 95% confidence interval (C.I.) and the black color one is mean for the entire set of values. Data set in yellow color is actual data collected on the apparatus. The MATLAB code similar to generate these graphs is attached in Appendix – 1.

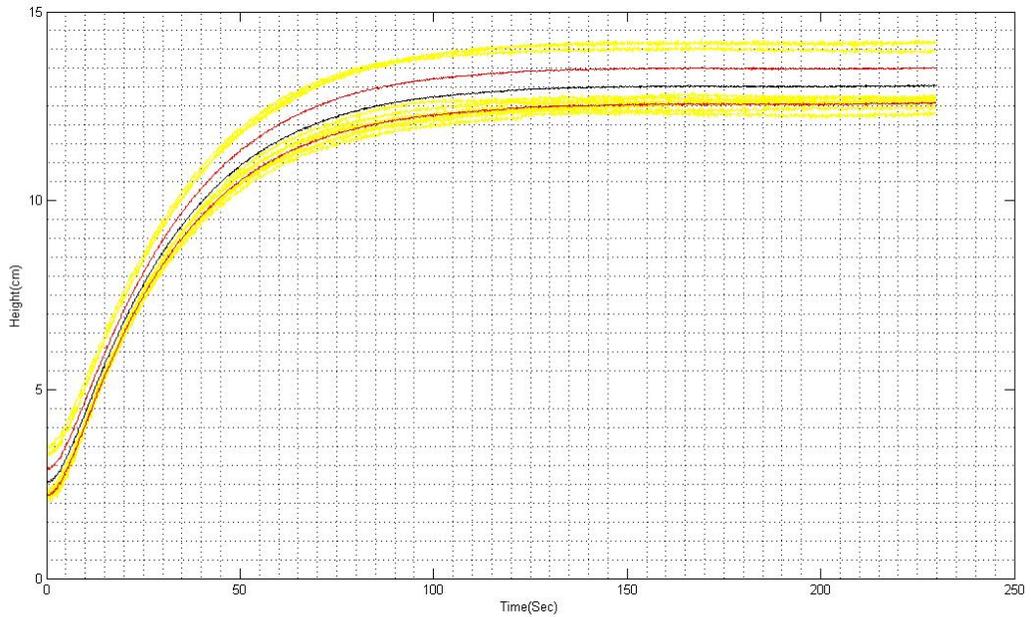


Figure 4-10 Experiment-3 Data Tank2, Apparatus-1.

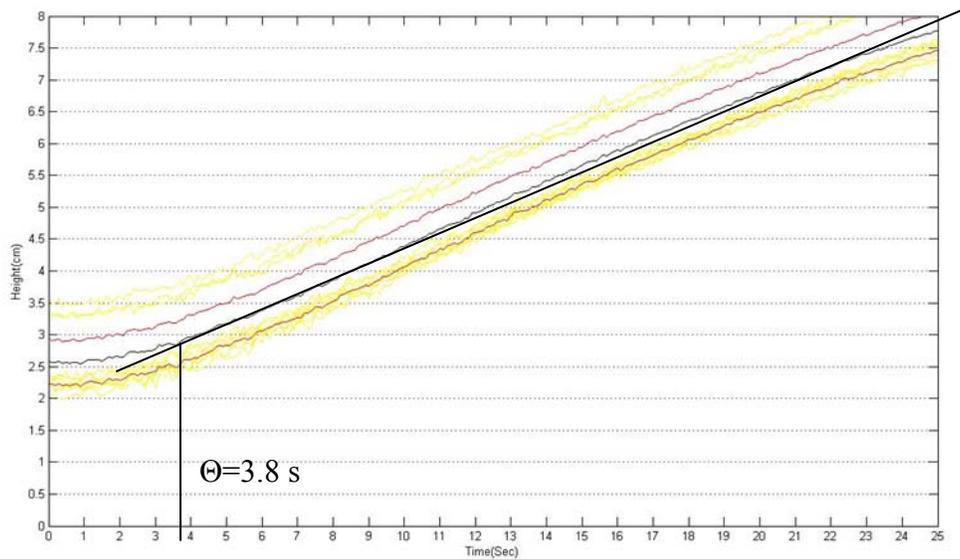


Figure 4-11 Enhanced View in Initial Stages of Experiment-3 Data for Apparatus-1.

Sample Calculation for Process gain (K_p), Process Time Constant (τ_p) and Process Dead Time, $\theta^{[1]}$.

First order + dead-time process is represented by

$$y(s) = \frac{K_p e^{-\theta s}}{\tau_p s + 1} u(s)$$

$$\begin{aligned} \text{Process gain } K_p &= \text{change in output variable / change in input variable} \\ &= (13.0 - 2.58) / (1.35 - .8) \quad (\text{from Figure 4-10}) \\ &= 18.9454 \text{ cm/V} \end{aligned}$$

From Figure 4-11 dead time is 3.8 sec

Time to approach 63.2% of the new steady state is $0.632 * (13 - 2.58) + 2.58 = 9.16 \text{ cm}$

In Figure 4-10, the value for a height of 9.15 cm is $\tau_p = 33.6$ seconds

Transfer function $G_p(s) = \frac{18.9454e^{-3.8s}}{33.6s+1}$ represents the FODT model of the process pictured in Figure 4-10.

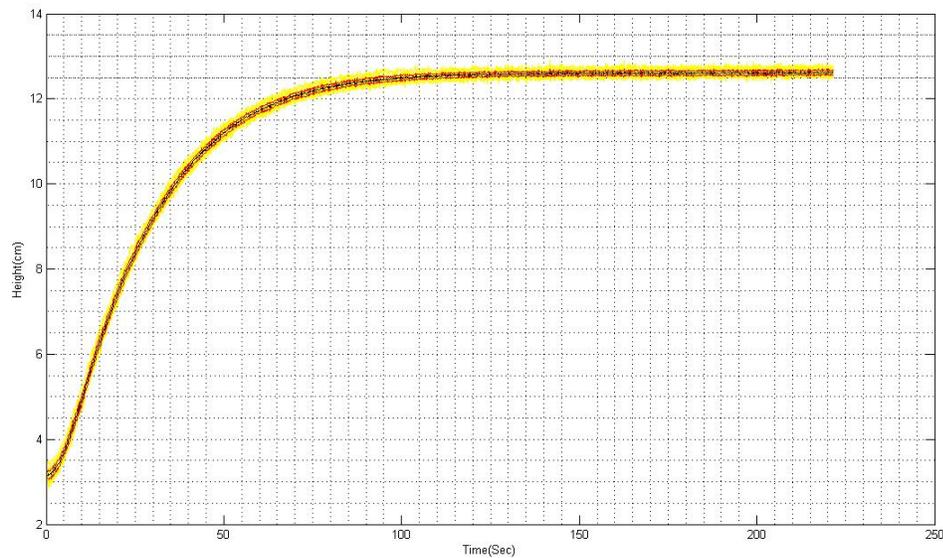


Figure 4-12 Experiment-3 Data Tank2, Apparatus-2.

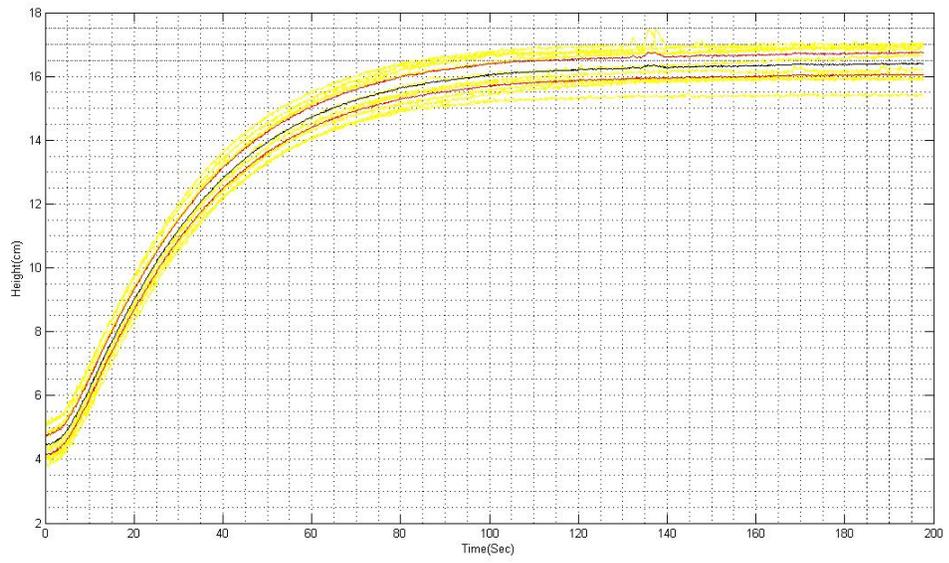


Figure 4-13 Experiment-3 Data Tank2, Apparatus-3.

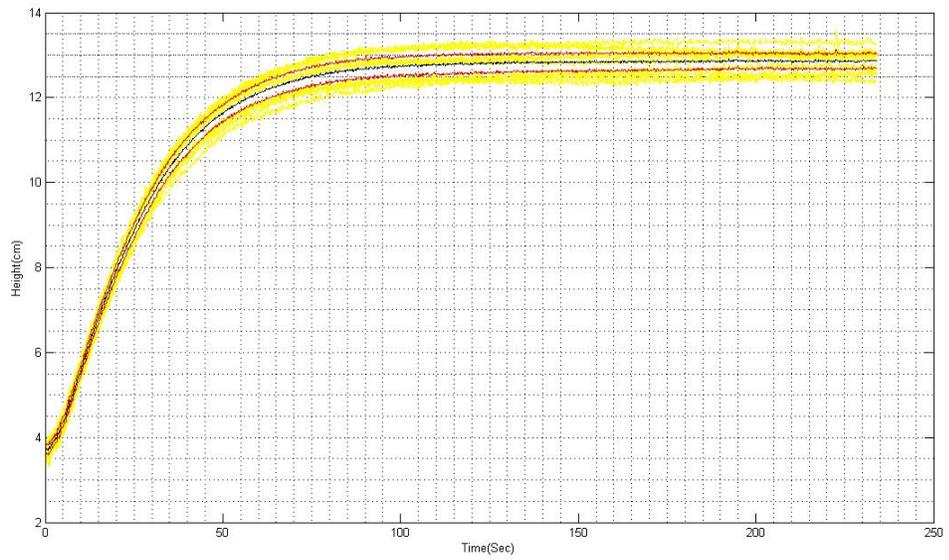


Figure 4-14 Experiment-3 Data Tank2, Apparatus-4.

4.4.3 Data Analysis

(1) Calibration Data

Results will be similar to the one documented in section 4.3.3.

(2) For the second order process

L_{1s} and L_{2s} are the initial steady state value before step change in tank1 and tank2 respectively for apparatus-1. L_{1s} and L_{2s} are 3.75 and 2.58 cm respectively. Actually L_{1s} and L_{2s} should be equal but because of the allowable calibration limits of ± 0.1 around 0 V after calibration there will be differences in heights.

$$\text{gain, } k = k_1 k_2 = 4.7748 \sqrt{L_{2s}} = 4.7748 * \sqrt{2.58} = 7.6695$$

$$\tau = \text{natural period} = 4.2582 * \sqrt{\sqrt{L_{1s}} * \sqrt{L_{2s}}} = 7.5100s$$

$$\text{Damping factor, } \zeta = \frac{0.5 * (\sqrt{L_{1s}} + \sqrt{L_{2s}})}{\sqrt{\sqrt{L_{1s}} * \sqrt{L_{2s}}}} = 1.0044$$

The Transfer function of the second order system is^[2]

$$\frac{Y(s)}{X(s)} = \frac{k}{\tau^2 s^2 + 2\zeta\tau s + 1}$$

$$\begin{aligned} \text{Transfer function} &= \frac{7.6695}{(7.5100)^2 s^2 + 2 * 1.0044 * 7.5100 * s + 1} \\ &= \frac{7.6695}{56.4001s^2 + 15.0861s + 1} \end{aligned}$$

(3) Comparison of Experimental Data and Simulink Linear Approximation

Experimental Data is obtained by following the lab procedure in section 3.4. The Simulink approximation is obtained from the model shown in Figure 4-15 and block parameters in Figure 4-16.

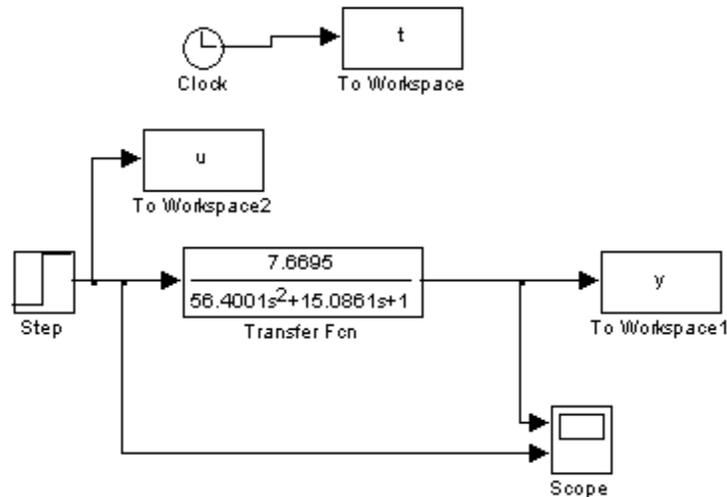


Figure 4-15 Simulink Model for Experiment-3, Apparatus-1.

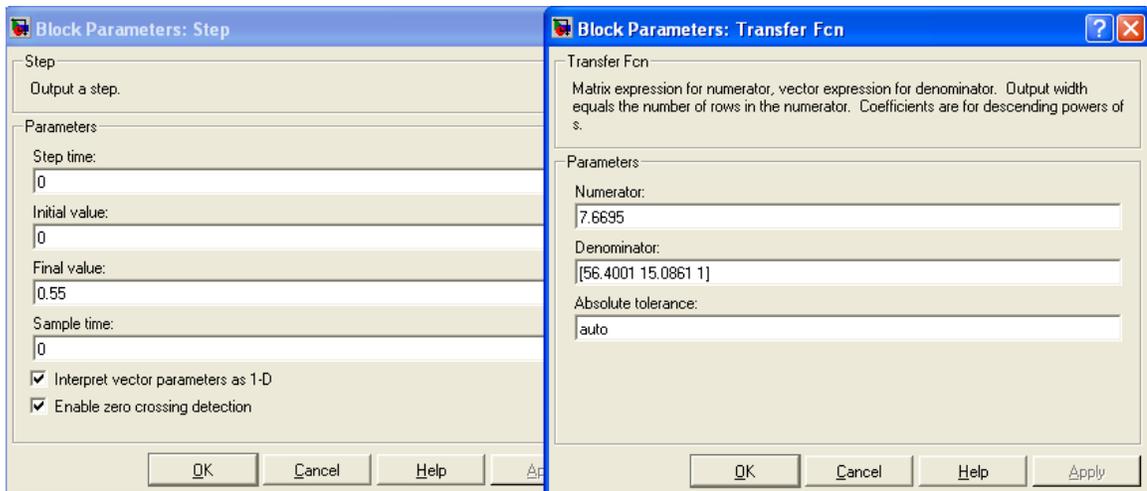


Figure 4-16 Block Parameters for Simulink Model, Apparatus-1, and Experiment-3.

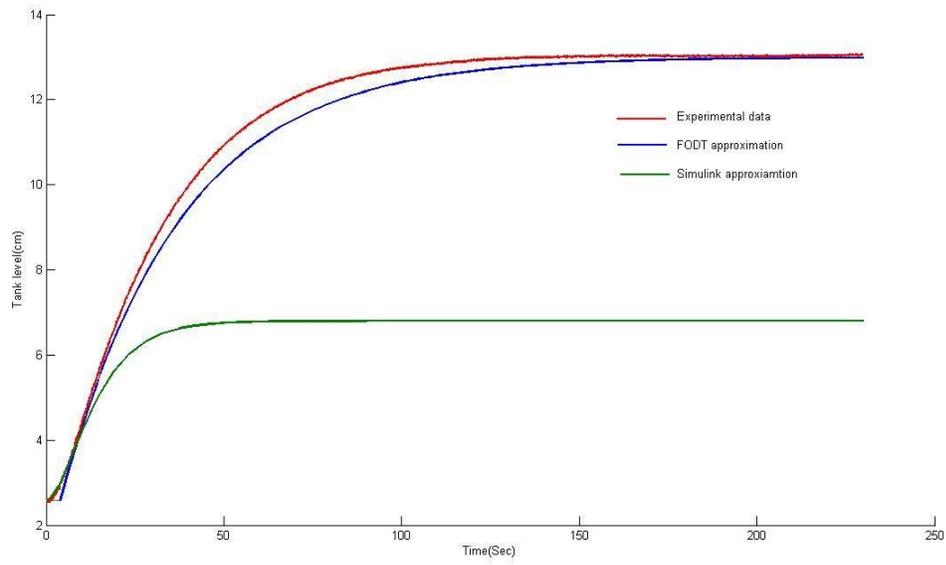


Figure 4-17 Comparison of Experiment-3 Data, Simulink and FODT Approximations for Tank2, Apparatus-1.

The FODT approximation, Simulink approximation and empirical data are all plotted in Figure 4-17 for comparison. The experimental and Simulink linearized model approximation deviates from the process because of the accuracy limits of linearization. A linearization is only approximate near the point it is linearized about and that was its initial steady state. FODT approximation closely follows the experimental data because the FODT parameters are taken from experimental data itself.

4.5 Experiment-4^[3] Tuning a PI controller for Level Control of Cylindrical Tank

4.5.1 Pre-Lab tasks

- (1) Calculations similar to the one described in section 4.3.2 yield the FODT parameters for the upper tank process of each apparatus. Summary of results for all the apparatus are tabulated in Table 4-11.

Table 4-11 Upper Tank Model Parameters for Experiment-4

Tank1	Process Gain, K_P	Time constant, τ_P	Dead time, θ
	(cm/Volt)	(s)	(s)
Apparatus-1	16.909	13.8	0
Apparatus -2	15.727	12.5	0
Apparatus-3	15.727	12.0	0
Apparatus-4	16.909	13.5	0

Table 4-12 Ciancone PI Tuning Parameters for Tank1, Experiment-4

Tank1	$\theta/(\theta+\tau_p)$	$K_c K_p$	$T_I/(T_p+\theta)$	k_c	τ_I
				(Volt/cm)	(min)
Apparatus-1	0	1.5	0.74	0.089	0.170
Apparatus -2	0	1.5	0.74	0.095	0.154
Apparatus-3	0	1.5	0.74	0.095	0.148
Apparatus-4	0	1.5	0.74	0.089	0.167

4.5.2 Data Analysis

Table 4-12 gives the Ciancone parameters for upper tank level control for all the apparatus. Following tuning rules stated in section 3.5, the results for this experiment were obtained. The desired output response for a fine tuned process is almost achieved with the Ciancone parameters. These parameters were slightly conservative. So, the proportional gain is slightly increased and integral time is slightly decreased to complete fine tuning. Initial estimates were $k_c=0.095$ and $\tau_I=0.148$ and the final tuning parameters were $k_c=0.1$ and $\tau_I=0.15$ for apparatus-3. Figure 4-18 shows the Simulink model for the experiment and block parameters are tabulated in Table 4-13. Figure 4-19 depicts the output (tank1 level) response to a set point change from 3 cm to 15 cm for PI level controller for initial and final tuning parameters and Figure 4-20 depicts the input response to the set point change from 3 to 15 cm for the same process and controller parameters. To aid in analysis, Simulink simulation data are also added in Figure 4-19 and Figure 4-20. *Note:* The PID algorithm used in PID controller in Simulink is

$$u(t) = k_c \left[e(t) + \frac{1}{\tau_I} \int_0^t e(\sigma) d\sigma + \tau_D \frac{de(t)}{dt} \right]$$

So, Proportional parameter, $k_c = 0.095$ for initial guess

Integral parameter = $k_c / \tau_I = 0.095 / (0.148 * 60) = 0.0106$ s

Derivative parameter, $\tau_D = k_c \tau_D = 0$ for this experiment.

It is important to make sure that units are consistent for all the block parameters.

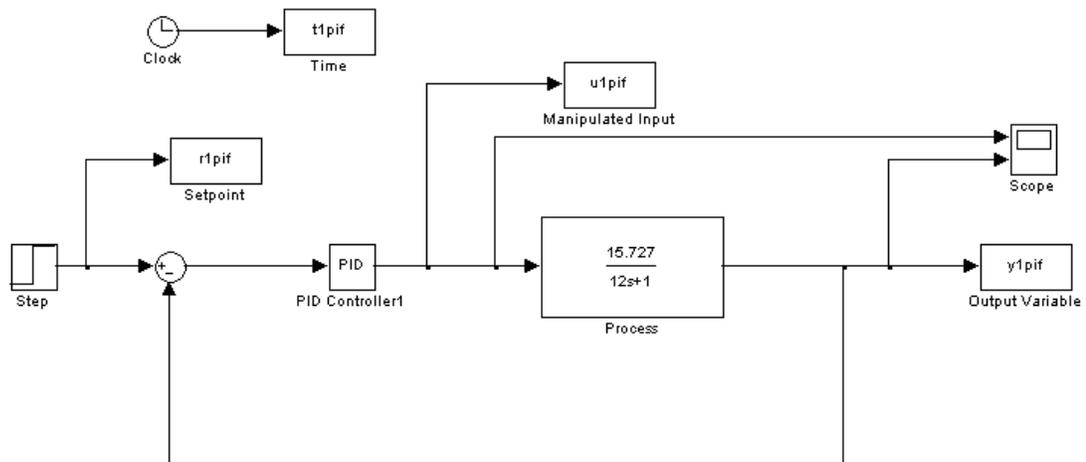


Figure 4-18 Simulink Model for Experiment-4, Apparatus-3.

Table 4-13 Block Parameters for Simulink Model Experiment-4, Apparatus-3

Block Parameter: Step	Ciancone parameters	Fine tuned
Step	0	0
Initial Value	0	0
Final Value	12	12
Sample	0	0
Block Parameter: PID controller	Ciancone Parameters	Fine tuned
Proportional Gain, k_c	0.095	0.100
Integral time, τ_I	0.0106	0.0144
Derivative time, τ_D	0	0

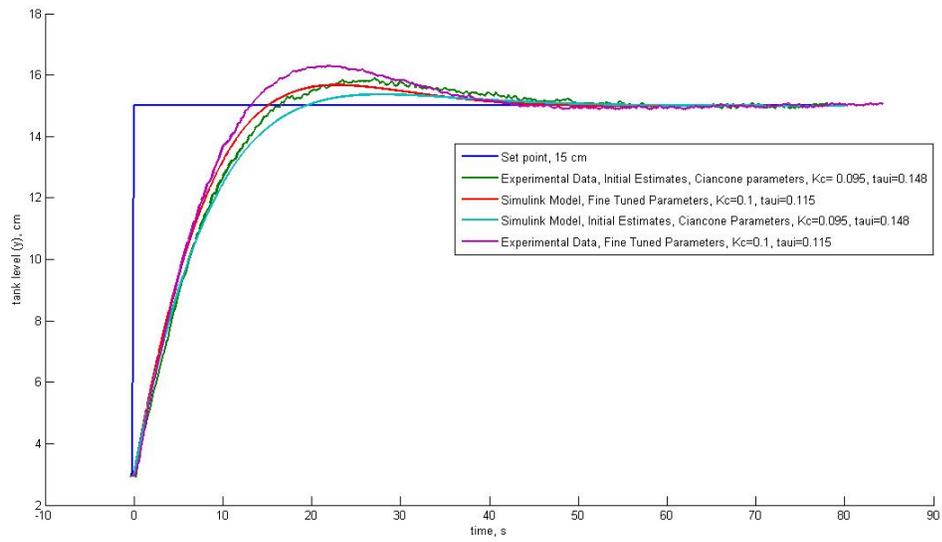


Figure 4-19 Comparison of Tank Level Response between Experimental Data and Simulink Simulation for Setpoint change in Tank1 Ciancone Method and Fine Tuned PI Control Parameters.

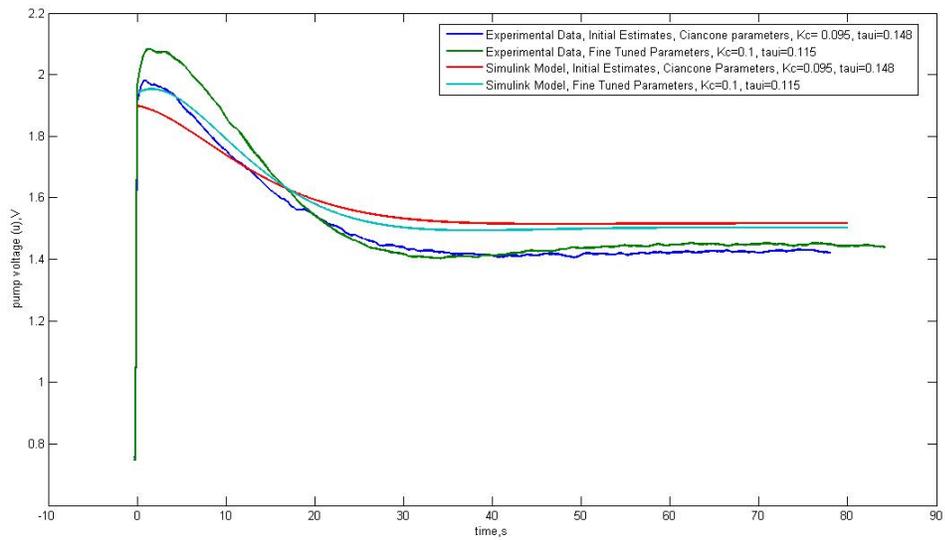


Figure 4-20 Input Voltage Response Comparison between Experimental Data and Simulink Model for Setpoint Change in Tank1 Ciancone Method and Fine Tuned PI Control Parameters.

The closeness of experimental output response and the Simulink output response indicate that the model parameters given in Table 4-12 are good. The slightest deviation between the experimental data and simulink data approximation may be due to sensor hysteresis and non-linearity. The fined tuned output response obeys the given tuning rules: no more than 10% overshoot and an initial input response is within 70-150% of its steady change. (For this experiment the students have input response within 50-200% of its steady state).

4.6 Experiment-5^[3] Tuning a PI Controller for level control of the Second Tank in a Coupled-Tank System

4.6.1 Pre-Lab Tasks

Calculations similar to the one described in section 4.4.2 yield the FODT parameters for the lower tank process of each apparatus. Summary of results for all the apparatus are tabulated in Table 4-14.

Table 4-14 Tank2 Model Parameters for Experiment-5.

Tank2	Process Gain, K_p	Time constant, τ_p	Dead time, θ
	(cm/Volt)	(s)	(s)
Apparatus-1	18.945	33.6	3.8
Apparatus -2	17.182	29.5	4.5
Apparatus-3	21.691	34.6	4.5
Apparatus-4	16.618	28.9	3.8

Open loop methods use the values in the Table 4-14 to generate PI tuning parameters. Ziegler-Nichols and Ciancone parameters are listed in Table 4-15 and Table 4-16 respectively..

Table 4-15 Second Tank, Ziegler-Nichols PI tuning parameters for FODT model.

Tank2	Ziegler-Nichols PI Tuning Parameters	
	K_c	τ_I
	(V/cm)	(min)
Apparatus-1	0.420	0.209
Apparatus -2	0.343	0.248
Apparatus-3	0.319	0.248
Apparatus-4	0.412	0.209

Table 4-16 Ciancone PI Tuning Parameters for Tank2, Experiment-5.

Tank2	$\theta/(\theta+\tau_p)$	$K_c K_p$	$T_I/(T_p+\theta)$	k_c	τ_I
				(Volt/cm)	(min)
Apparatus-1	0.102	1.50	0.74	0.079	0.461
Apparatus -2	0.132	1.40	0.77	0.081	0.436
Apparatus-3	0.115	1.45	0.75	0.067	0.489
Apparatus-4	0.116	1.45	0.75	0.087	0.409

4.6.2 Data Analysis

Following tuning rules stated in section 3.6, the results for this experiment were obtained. The output response from Ziegler-Nichols parameters applied to the PI level controller yields an oscillatory response. Using tuning rules the PI controller is detuned for the desired response. The initial guesses, Ziegler-Nichols parameters were $k_c=0.391^*$

and $\tau_I = 0.193$ and the fine tuned parameters were $k_c = 0.06$ and $\tau_I = 0.325$. Figure 4-21 shows the Simulink model for the experiment initial guesses. Figure 4-22 depicts the output response for PI control using Ziegler-Nichols and the final tuning parameters for a set point change from 3 cm to 13cm. Figure 4-23 depicts the input response to the set point change from 3 to 13 cm for the same process. To aid in analysis, Simulink simulation data is also added to the plot.

* Students used a different initial guess different from the values given in Table 4-15.

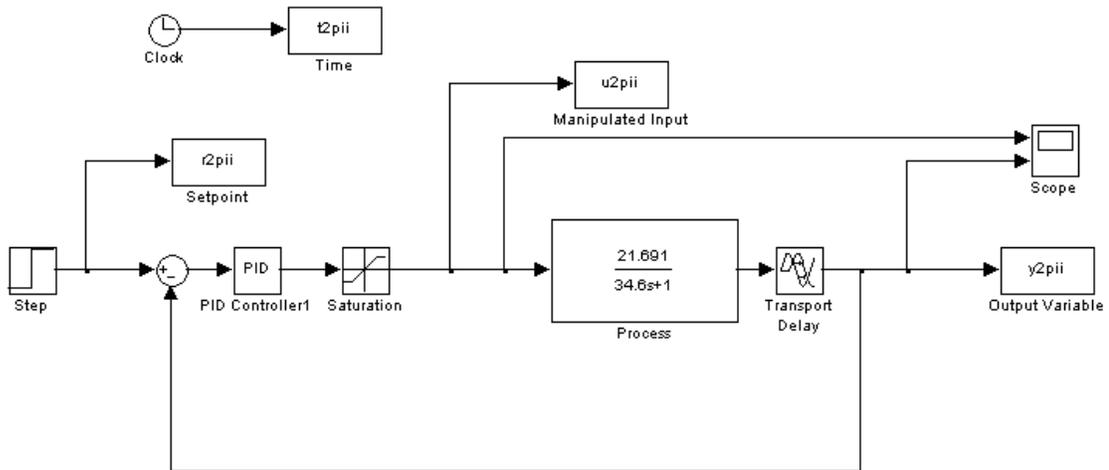


Figure 4-21 Simulink Model for Experiment-5, Apparatus-3.

Table 4-17 Block Parameters for Simulink Model Experiment-5

Block Parameter: Step	Ziegler-Nichols parameters	Fine tuned
Step	0	0
Initial Value	0	0
Final Value	10	10
Sample	0	0

Block Parameter: PID controller	Ziegler-Nichols parameters	Fine tuned
Proportional Gain, k_c	0.391	0.06
Integral time, τ_I	0.034	0.003
Derivative time, τ_D	0	0
Block Parameter: Transport Delay	Ziegler-Nichols parameters	Fine tuned
Time Delay	4.5	4.5
Input	0	0
Block Parameter: Transport Delay	Ziegler-Nichols parameters	Fine tuned
Initial buffer size	1024	1204
Pade order(for linearization)	0	0
Block Parameter: Saturation	Ziegler-Nichols parameters	Fine tuned
Upper limit	5	Not applicable
Lower limit	0	Not applicable
Sample time	-1	Not applicable

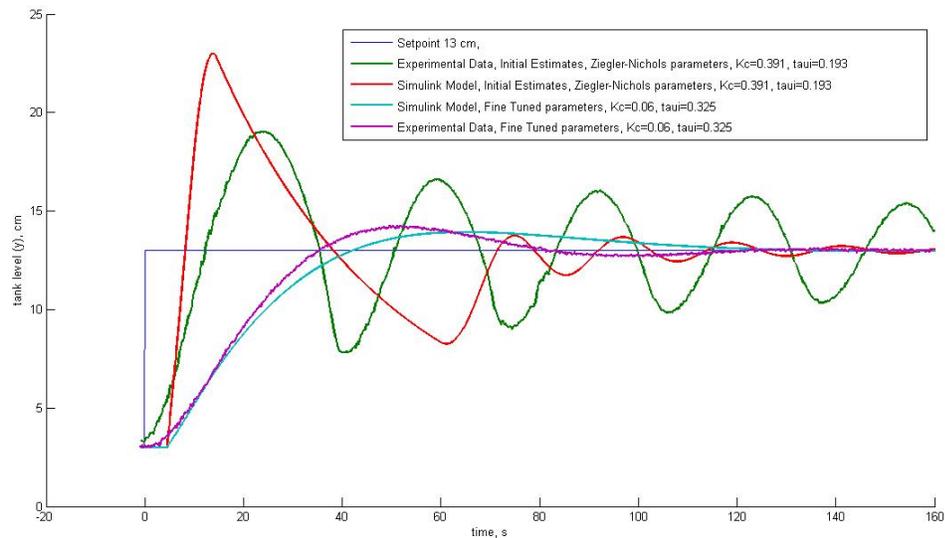


Figure 4-22 Comparison of Output Response between Experimental Data and Simulink Approximation for Ziegler-Nichols and Fine Tuned PI Tuning Parameters for Setpoint Change from 3 to 13 cm in Tank2 Apparatus-3.

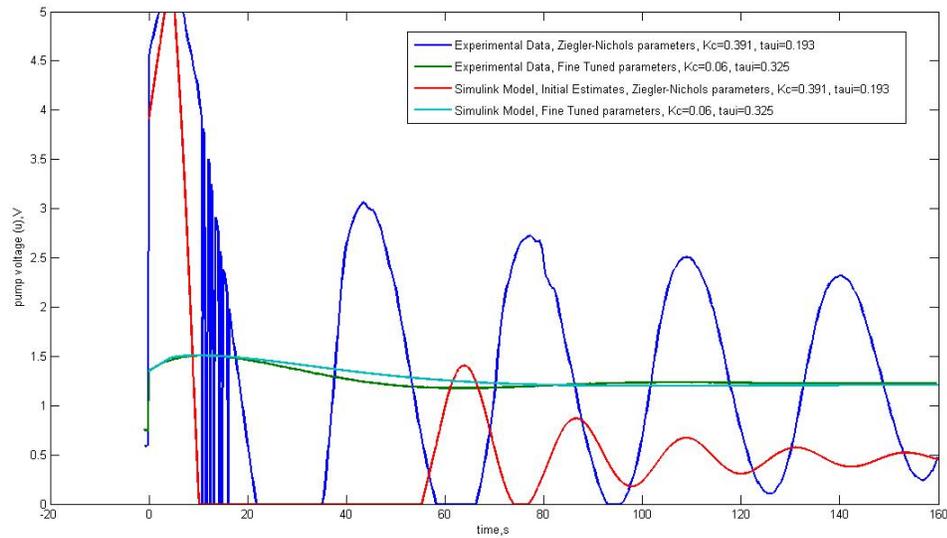


Figure 4-23 Comparison of Input Response between Experimental Data and Simulink Approximation for Ziegler-Nichols and Fine Tuned PI Tuning Parameters for Setpoint Change from 3 to 13 Cm in Tank2 Apparatus-3.

In the Simulink model, a saturation block is added to the model because it was observed that the pump behaved like on-off controller initially. This means the Ziegler-Nichols parameters are too aggressive for the system and the safety interlock system came into action. The Simulink data for input response is off from the experimental data for the Ziegler –Nichols parameters. The safety interlock system injected more oscillation than it is predicted by adding a saturation block in the Simulink model to account for the effect of the safety interlock system. The fined tuned output response obeys the given tuning rules: no more than 10% overshoot and an initial input response is within 70-150% of its steady change. (For this experiment the students have input response within 50-200% of its steady state).

4.7 References

- 1) B.W. Bequette, *Process Control—Modeling, Design and Simulation*, Prentice Hall (2003).
- 2) D.R. Coughanowr, *Process Systems Analysis and Control*, 2nd ed. New York: McGraw-Hill, 1991.
- 3) These experiments are done by students following Chapter 3.3 and 3.4 in this thesis

CHAPTER 5

STUDENT FEEDBACK AND FUTURE WORK

5.1 Progression of the Project

This project was started in May 2008 to sort out and fix issues with the existing Process Control Lab. This section narrates, in chronological order and with respect to the individual experiments, how the project progressed to create a more practical and streamlined laboratory experience for the students.

Summer 2008

Time was taken to understand the coupled tank apparatus, learn LabVIEW basics, and to comprehend the LabVIEW code for the existing programs. The Process Control Lab has four matching bench-top experiments designated Apparatus #1, Apparatus #2, Apparatus #3, and Apparatus #4, respectively. Each includes the Quanser coupled tank apparatus and a computer running LabVIEW. Apparatus #4 was running an evaluation copy of LabVIEW and therefore a licensed version of LabVIEW was installed.

5.1.1 Experiments 2 and 3: Modeling Liquid Levels in the Tanks

Spring 2008

According to Dr. Myers, the four experiments were not setup and available in a high bay area until very late in the semester due to space issues related to construction. Students were able to run the experiments using the literature available from Quanser and hands-on instruction from Dr. Myers. However, the data were unusable for model validation.

Fall 2008

After evaluating the experimental apparatus and computer programs during summer 2008, a one-page procedural handout was prepared for running the modeling experiments. Fall 2008, ChE 4370 students were the first to do the process modeling experiments on the Coupled-tank system using this handout. They performed the upper tank level modeling experiment (experiment #2) twice. Incoherent pressure sensor voltage readings necessitated the second experimental trial.

(i) First Trial of Experiment 2

For the first trial, students performed the experiment without calibrating the pressure sensors. At that point, student handouts were rewritten to be more self-contained. A theory section on modeling was added to the procedures for guiding the students through the experiment. However, sensor calibration was not included in those procedures. At that time, calibration was performed by the Teaching Assistant four (4) days before the experiment was run rather than having the students doing it during the

lab. Even with calibrated pressure sensors, students got inconsistent readings for the pressure sensor voltage and were in a total confusion about how to do data analysis for the experiment.

Students were also confused by the Pump.VI front panel. The section circled in Figure 5-1 was the cause of this confusion. They thought the data collected and displayed were for tank volumes instead of pressure sensor voltages.

Students in Fall 2008 were confused with this section of the Pump.VI front panel.

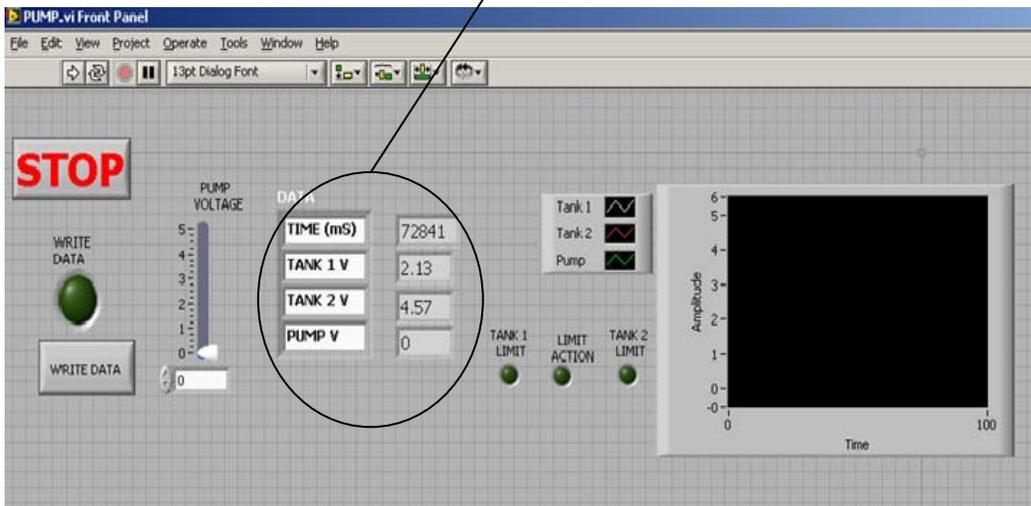


Figure 5-1 Screenshot of How the Pump.VI Front Panel looked in Spring 2008.

(ii) Response to the First Trial of Experiment 2

Incoherent pressure sensor voltage readings drew attention to the Pump.VI LabVIEW code, to the potentiometer calibration screws, and to the pressure sensors as the possible root causes of the problem. After critically analyzing the LabVIEW code, it

was removed from the list of probable causes. Focus shifted to the potentiometer screws and the pressure sensors for root cause analysis.

By a series of experiments, it was determined that the voltage readings changed dynamically even with no liquid inflow to the tank. Figure 5.2 depicts this phenomenon.

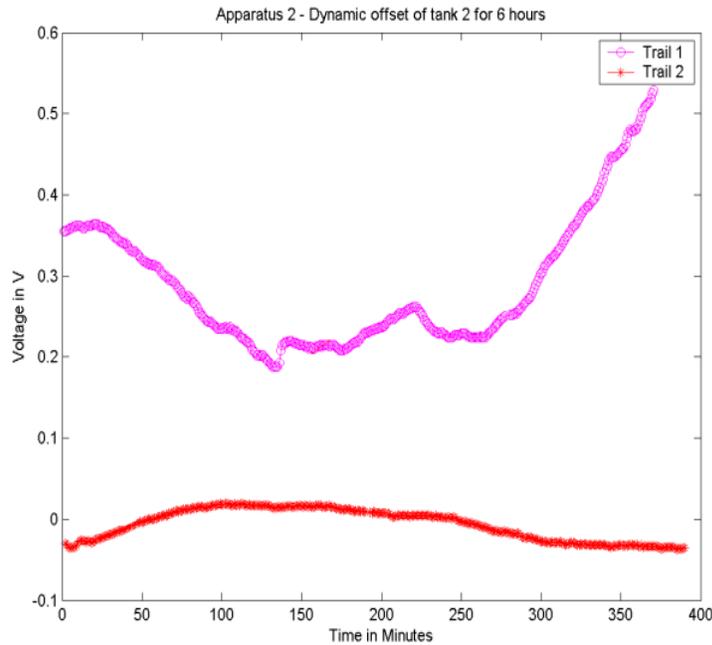


Figure 5-2 Dynamic Change in Pressure Sensor Reading for No Pump Voltage.

Eventually, formation of air pockets was observed in the pressure sensors. These air pockets would reduce the tank voltage reading because they are less dense than water and would absorb some of the water head pressure as shown in Figure 5-2. Proceeding with the assumption that these air pockets might be the root cause for the incoherent readings, a procedure for removal of air pockets was developed. The teaching assistant performed the procedure for removing the air pockets before calibrating the sensors. Then a series of 10 trials for both experiment 2 and experiment 3 was performed to make

sure students would get consistent readings. Consistent readings were observed for Apparatus #1, Apparatus #2, and Apparatus #3. However, Apparatus 4 has some pump start-up issues as shown in Figure 5-3(a). One problem solved; another problem noted.

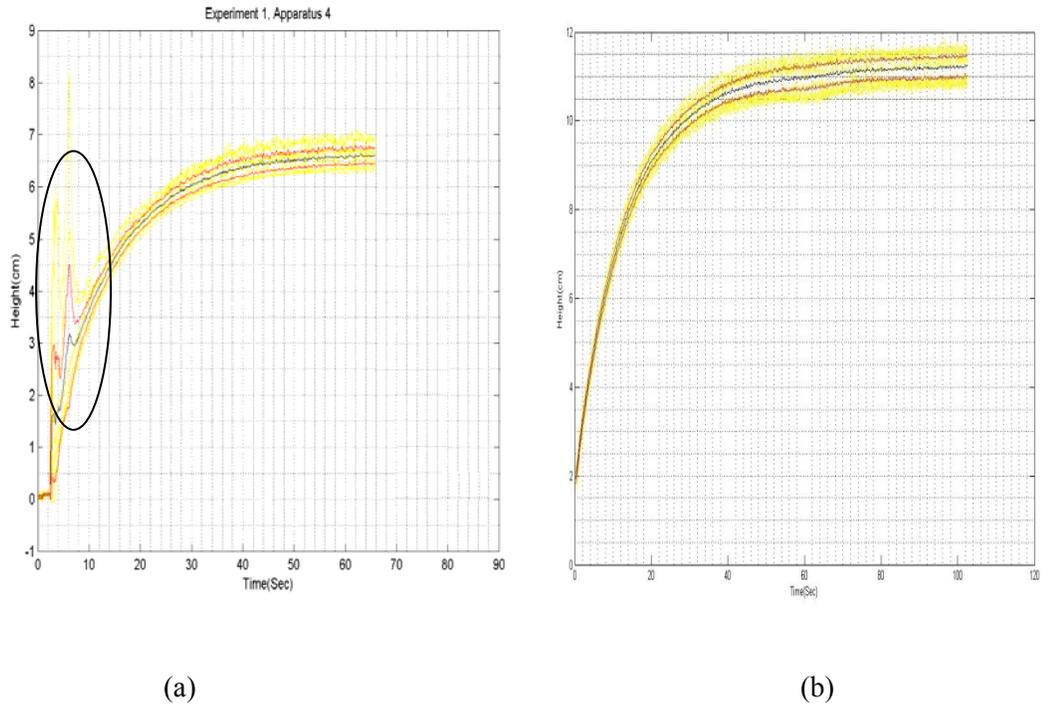


Figure 5-3 Experimental Data **(a)** with pump start-up effect **(b)** without pump start-up effects

To address the confusion associated with the Pump.VI front panel, the LabVIEW program was modified. The resulting alteration to the Pump.VI front panel is shown in Figure 5-4.

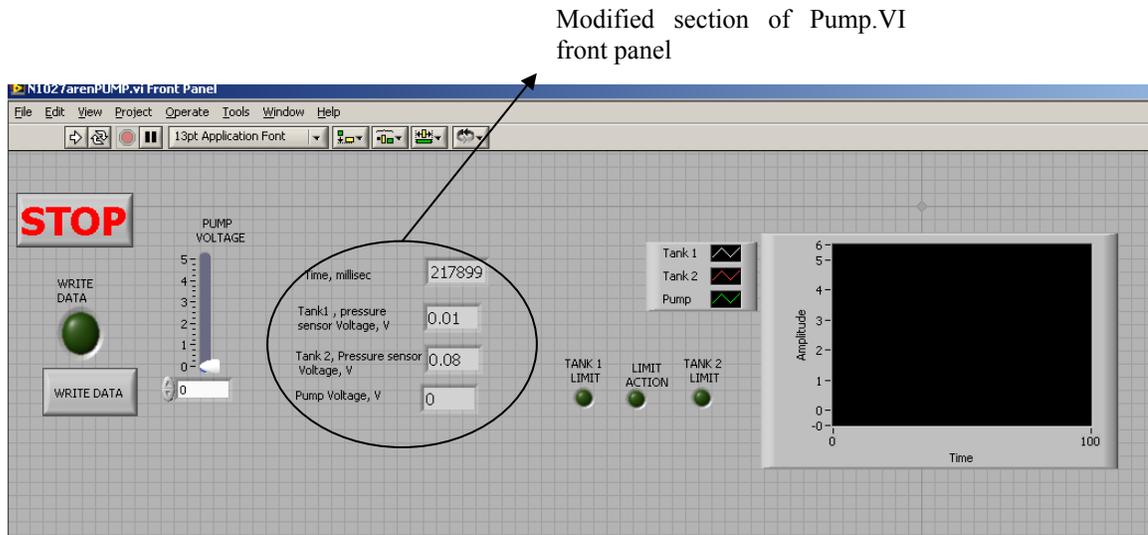


Figure 5-4 Modified Pump.VI Front Panel.

(iii) Second Trial of Experiment 2

The experimental procedure was modified so that removing the deleterious air pockets preceded calibrating the pressure sensors. Both of these steps occurred right before collecting the data. During this lab period, the students produced consistent, coherent data for further analysis. However, due to time constraints, they did not compare the experimental results with a Simulink simulation of the process.

The pump start-up issue with Apparatus #4 was not addressed directly. During this second trial of experiment 2, a student broke the upper tank orifice by over tightening the insert while calibrating the pressure sensor. This rendered Apparatus #4 unavailable for rest of the semester. While this allowed postponing addressing the pump problem, it necessitated a more equipment friendly calibration procedure.

Spring 2009

Handouts for experiment 2 and experiment 3 were rewritten to address all of the issues encountered to date. The pump start-up issues were addressed by making the step change in pump voltage from one steady state to another steady state instead of from the pump's rest state to a new steady state. With this change, no pump start-up anomaly was observed as one can see in Figure 5-3 (b).

Several graduate students volunteered to perform the experiments and evaluate the handouts. All of their comments were edited into the final edited version of the handouts shown in sections 3.2 and 3.3. Unfortunately, the handouts were not finished in time for the Spring 2009, ChE 4370 students to perform these experiments.

The data produced by the graduate students surfaced another issue. The FODT parameters were off by approximately 300% even after the pump start-up effects were ameliorated. Furthermore, when comparing the experimental data with a Simulink simulation of the process, model validation was not possible. The output responses showed a much larger gain than predicted by either the model equations or the Simulink simulation. The cause of this discrepancy must be either bugs in the Pump.VI program or incorrect modeling. Pump.VI was thoroughly checked and found to be in good order. That meant that incorrect modeling was the root cause. Checking the models for accuracy led to the conclusion that the models were mathematically correct. At that point, each of the model parameters was investigated. Eventually it was determined that the pump flow constant supplied by the manufacturer was wrong. A simple experiment,

involving a timer and graduated cylinder, showed this value to be in the range of 17.4 to 18.4 cm³/ (s.V) where as the Quanser user manual gave the value 3.3 cm³/ (s.V).

Incorporating this new pump flow constant into the model produced experimental results that compared well with both the nonlinear model produced by integration within MATLAB and the linearized model produced using Simulink. Model validation is now achievable. Considering the limitations of experimental error in the lab and model linearization for use within Simulink, these experiments provide a valuable learning experience for developing skills in process modeling.

5.1.2 Experiments 4 & 5: Controlling Liquid Levels in the Tank

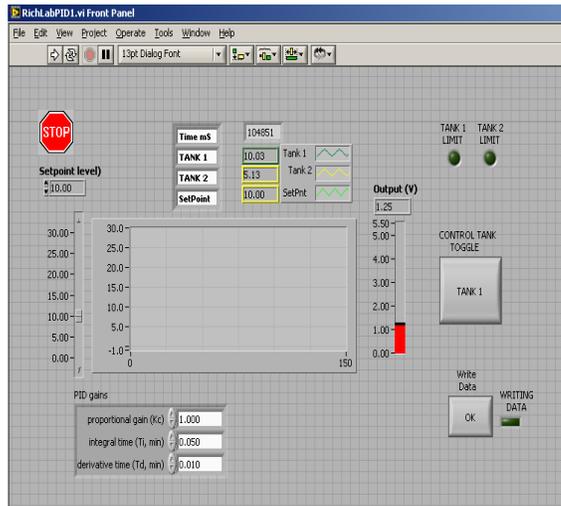
Spring 2008

The LabVIEW program, LabPID1.VI, was written to perform data acquisition and PID level control for the coupled tanks apparatus. Figure 5-5 (a) shows the front panel screen displayed by LabPID1.VI and Figure 5-5 (b) shows the tab delimited data file recorded by LabPID1.VI. This program, as it existed during the Spring 2008 semester, was totally unsuitable for executing the tasks it was written to perform.

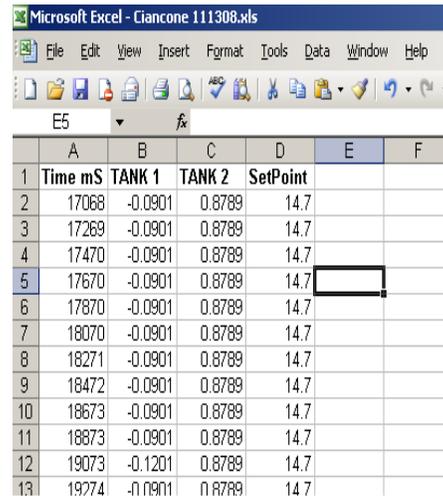
The particular issues with the LabPID1.VI program are enumerated as follows.

1. Input boxes for entering the tuning parameters, the button for switching between tanks for level control, as well as the slider and input box for establishing and/or changing the set point seem randomly placed around the screen as shown in Figure 5-5 (a). This was quite confusing for students. The front panel must be

reorganized to help students, most of who have never seen the panel of a control system, understand the basic elements of a control system.



(a)



(b)

Figure 5-5 (a) Front Panel of Old LabPID.VI Program **(b)** Data File Recorded by Old LabPID.VI Program

2. Although there was a button for switching level control between tank 1 and tank 2, the control function within LabPID.VI did not work for the lower tank in the coupled-tank system.
3. A watchdog subroutine was written into LabPID1 .VI program to perform the Safety Interlock System function of a control system which takes corrective action when unacceptable operating conditions are approached. For this experiment, the watchdog subroutine acts to avoid tank overflow. As written, the subroutine abruptly halted the program and aborted the experiment. Instead, the watchdog subroutine should idle the pump when overflow conditions are

approached and then resume normal control actions when acceptable operating conditions resume.

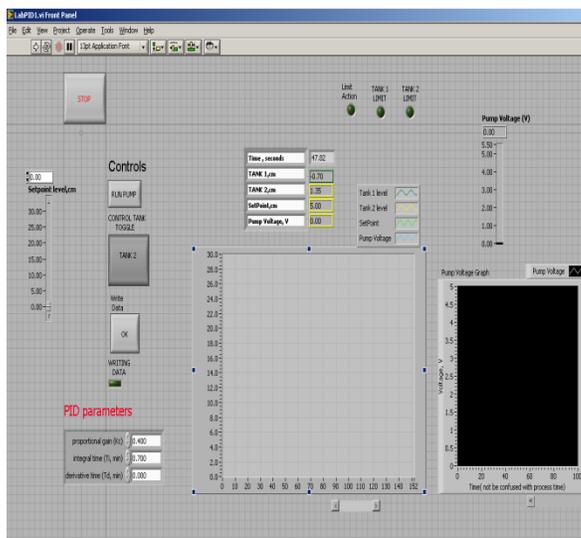
4. Tuning a controller is a trial and error process of changing the values of the controller's tuning parameters based on the dynamic responses of the manipulated input and the measured output. As written, the LabPID1.VI screen provided no way for the students to view the dynamic responses for previously chosen tuning parameter values.
5. Properly tuning a controller requires knowledge of both the manipulated input and the measured output as the system moves from one steady state to another. As shown in Figure 5-5 (b), only the dynamic values for the pressure sensor voltages, which indicate the path of the measured output (tank liquid level), are displayed and recorded. The dynamic values for the pump input voltage, which indicate the path of the manipulated input (inlet flow rate), must also be displayed and recorded.
6. LabPID.VI only recorded dynamic data in tab delimited columns for time, tank1 level, tank2 level and set point. Students also need pump input voltage readings, as noted previously, and PID tuning parameter values for post experiment analysis. Because of this data omission within LabPID1.VI, students were unable to compare the experimental input response with that predicted from Simulink model simulation.
7. There were no handouts for documenting the experimental procedures for these experiments. Students were in a dilemma about how to run these experiments.
8. Experiments are not streamlined for efficient use of the students' lab time.

9. During the trial and error tuning process, when overly aggressive tuning parameters are chosen the controller drives the pump in an on/off fashion. In this circumstance, water was spilled on the floor and workbench making the work space a messy safety hazard.
10. Due to the fact that Pump.VI and LabPID.VI were written in different versions of LabVIEW, driver conflict issues arose as the LabVIEW programs were started.

Fall 2008

The first six issues described above were fixed by changing the LabPID1.VI code. Changing the control programming within LabPID.VI, addressed the first four issues. Upon implementing the control programming changes, the front panel was functionally reorganized as shown in Figure 5-6 (a); level control for the lower tank was established; proper watchdog actions were instituted; and views for previous dynamic responses was provided. Changing the tab delimited output file written by LabPID1.VI addressed issues five and six described above as shown in Figure 5-6 (b).

Lab module handouts were written to address issues seven, eight and nine. A procedure for addressing the issues with starting the LabVIEW program is provided in section 3.7.



(a)

The screenshot shows an Excel spreadsheet with the following data:

Time, seconds	TANK 1, cm	TANK 2, cm	SetPoint, cm	Pump Voltage, V	Kc	Integral time, min	Derivative time, min
224.697	3.457	3.063	3	0.8613	0.3	0.7	0
224.297	3.457	3.093	3	0.8625	0.3	0.7	0
224.497	3.457	3.123	3	0.8611	0.3	0.7	0
224.698	3.457	3.1531	3	0.8496	0.3	0.7	0
224.899	3.457	3.093	3	0.8404	0.3	0.7	0
225.1	3.457	3.1531	3	0.8363	0.3	0.7	0
225.3	3.4277	3.093	3	0.8354	0.3	0.7	0
225.5	3.4277	3.123	3	0.8368	0.3	0.7	0
225.701	3.4277	3.063	3	0.8398	0.3	0.7	0
225.902	3.4277	3.093	3	0.842	0.3	0.7	0
226.103	3.4277	3.093	3	0.8446	0.3	0.7	0
226.303	3.4277	3.093	3	0.8452	0.3	0.7	0
226.503	3.4277	3.1531	3	0.843	0.3	0.7	0

(b)

Figure 5-6 (a) Modified LabPID1.VI front panel (b) data filed recorded by new LabPID.VI

FODT parameters, calculated without accounting for pump startup effects, were given to the students for determining initial swags for controller tuning parameter via open-loop methods for both experiments 4 and 5. Since these FODT parameters were about 300% off, due to pump startup effects, the initial swags the students calculated for experiments 4 and 5 were also way off. When tuning a controller, the starting tuning parameter values are almost immaterial compared to the ending tuning parameter values but choosing the most appropriate swags certainly expedites the tuning process. Fall 2008, ChE 4370 students were provided with a significant learning experience in the Process Control Lab. With their inappropriate swags, students got a feel for tuning because they were provided a considerable hands-on opportunity for developing skills in controller tuning.

Spring 09

Lab Module Handouts for experiments 4 and 5 were modified based on all of the lessons learned to date. These self-contained modules provide the information necessary to perform these experiments. Specifications for pre-lab preparation, laboratory operation, post-lab data analysis, and references are all included. The final version of these handouts modules are provided in sections 3.5 and 3.6.

Seniors taking ChE 4370 used these handouts to perform experiments 4 and 5. FODT parameters, calculated taking into account the pump start up effects, were given to the students for determining initial swags using open-loop methods. This time the students found much more appropriate values for the initial PI controller tuning parameters. As a consequence, level control performance was much better. The burden of tuning the controller from unacceptable performance was lifted. The lab experience involved fine tuning instead of retuning. These students were asked to assess the handouts and their comments are listed in section 5.3.2. The experimental results compared favorably with the Simulink simulation. Hence the students got to experience essence of tuning.

5.1.3 Experiment#1

Discrepancies between the experimental results for experiments 2 and 3 and their Simulink approximations lead to the development of a new experiment. As described in the *Spring 2009* subsection of section 5.1.1, experiments were performed to prove that the pump flow constant, K , documented by manufacturer was only 17-18% of the true

value. As a consequence of the root cause analysis and verification, a simple experiment was designed that could be used in a freshmen class for a variety of engineering disciplines. The experiment, to determine orifice coefficient, comprises several learning experiences for basic engineering skills. These learning experiences include design of experiment, data acquisition using LabVIEW programs, calibration of sensors. The handout module for this experiment is given in section 3.1. It has not yet been tested by students.

5.2 Outcomes

- Experiment 1 provides students with the opportunity to get a feel for laboratory, calibrate sensor instrumentation, experience graphical user interface programs for data acquisition, and develop critical thinking.
- Experiments 2 and 3 offer students foundational learning experiences in formulating a dynamic model from material balances, validating system models, solving a model's differential equations using MATLAB[®], using Simulink[®] to simulate a system, comparing experimental results with approximations, and understanding the limits of accuracy.
- Experiments 4 and 5 supply hands on experience in fine tuning a PI controller for level control.

5.3 Student Feedback on Laboratory Modules

5.3.1 Experiment-2 and Experiment-3

To assess the usability of the module handouts, seven undergraduate juniors in chemical engineering and three masters' students in electrical engineering performed the experiments with little or no supervision. None of the students had taken the ChE Process Control course prior to performing the experiment. They were all able to get through the experiments with little or no difficulty. Their reviews of the modules were taken into consideration when the modules were modified and all of their concerns were addressed. Some of their comments and the actions to address their concerns follow.

Comment-1: "It will be a nice idea to have figure for calibration and signal circuiting board"

This was addressed by creating Figure 3-11 and annotating it appropriately.

Comment-2: "I have difficulty in figuring out where the pressure sensor is at the time of removal of air-pockets"

This was taken into account and Figure 3-10 is included at the removal of air pockets procedure explanation.

Comment-3: "I like the figure explaining step-by step procedure with screenshot. It is extremely useful especially at the time of figuring out how a steady-state of level looks like on the screen".

Comment-4: I don't have any problem getting through this experiment.

To sum up, all the subtle things that students encountered during the lab sessions are addressed in the module write-up.

5.3.2 Experiment-4 and Experiment-5

These two tuning experiments were tested by 21 senior chemical engineering students in ChE 4370 during the Spring 2009 semester. Students worked in a group of two and were asked to comments on the laboratory sessions and the module handouts. Their comments are as follows:

Comment-1: "The lab module handouts were very clear and concise. We had problems with apparatus-4. During our experiment the set point of tank2 was set at 3 cm and the software reads 3 cm, but there was no water in the tank. We had to fiddle around with apparatus with settings and we ended up changing the offset on the calibration and signal circuiting board."

Sometimes even the removal of air pockets also does not eliminate the offset. The solution to this problem is to adjust the offset to zero by turning the potentiometer screws on the calibration board.

Comment-2: The apparatus seemed to be in good working order and was properly calibrated. No issues occurred. The handout was very detailed and helpful for the experiment and we especially liked Table 3-1, effect of tuning parameters on response to a step change in set point".

Comment-3: “While completing the lab all the equipment worked properly and efficiently. The Lab module handout is very clear and concise”

Comment-4: “Overall lab was very practical and lab module handout was helpful.”

Comment-5: “Curious about how the air pockets affect the pressure sensor readings”

This is addressed in page 153.

Comment-6: “The lab handout was easy to follow and explained everything very well, so there are no additional recommendations for it particular.”

Comment-7: “As noted in the lab, there are some start-up issues that cause the system to overshoot the set point and reach the maximum tank level. This is probably to do with background setting not being reset, as a complete reset of the program solves the problem. The Lab Module handout was very helpful. Not only did it contain step by step instructions along with corresponding photos and screenshots, but also contained the theory behind the lab. This was particularly helpful in understanding why the system behave the way it did when the setting was changed.”

5.3.3 Experiment #1

This experiment was not tested by students as most sections were taken from experiment #2 which was tested earlier by students and should be sufficient for the freshmen to go through this experiment.

5.4 Recommendations

Having performed experiments 2,3,4,5 in the Chemical Engineering Process Control course for two semesters, they have been streamlined for optimal use of lab time. This is essential if they are to be used in the new undergraduate laboratory. Furthermore, a better understanding where these learning experiences fit into the Chemical Engineering curriculum has been gained.

Experiment-1 can be added to a freshman level course of almost any engineering discipline. Experiment-2 could easily be integrated into ChE 2225, the sophomore year material and energy balance course. Experiment 3 is most appropriate for integration into ChE 4370, the senior year process control course because knowledge of Laplace transforms is necessary to solve the pre-lab tasks. Experiments 4 and 5 are only appropriate to ChE 4370. However, Experiments 4 and 5 could be combined into a single, hands-on, 2-hour lab experience in controller tuning.

5.5 Future Work

- The Pump.VI and LabPID1.VI programs are not written in same version of LabVIEW. This causes start-up issues related to drive conflicts. This can be eliminated by having the two LabVIEW programs written in the same version of LabVIEW. Pump.VI is already in the new version of LabVIEW so rewriting the LabPID1.VI in new version is the logical choice to solve these startup issues. This needs to be done.

- The existing LabPID1.VI uses a feedback control mechanism to maintain a tank's liquid level. A new LabVIEW program using a feed forward mechanism in combination with the feedback mechanism could be written and tested. Eventually a new experiment illustrating the effect of adding the feed forward mechanism could be added to the existing modules.
- Connecting LabVIEW to the internet would be a notable project. Then these experiments could be made available to distance-education students, providing access to the laboratory experiments even without requiring physical presence.

5.6 Miscellaneous

The following are the specifications for parts of the experimental apparatus that will eventually require replacement.

The orifices and o-rings are supplied by McMaster Carr.

Orifice

- Nylon Hex Head Cap Screw
- 3/8" -16 thread , 1/2" length
- off-white, fully threaded
- Vendor name: McMaster Carr
- Catalog code: 91244A620
- Price – USD 6.09 per 25
- The orifices can be machined according to the desired orifice diameter.

O-ring

- Type : o-ring
- C/S shape : round
- I.D : 3/8"
- O.D : 9/16"
- Width : 3/32"
- Material : EPDM (Ethylene Propylene)
- Durometer : Hard
- Color : Black
- Vendor name : McMaster Carr
- Catalog code : AS568A Dash No. : 110
- Price : USD 3.57 per 25

Pressure sensor

Pressure sensor is manufactured by Honeywell S & C and supplied by Newark Electronics.

- Operating Pressure Max : 1psi
- Sensor Output : Voltage
- Port Size : 0.04"
- Port Style : Straight
- Pressure Measure Type : Differential
- Sensor Terminals : Through Hole

- Manufacturer name : Honeywell S& C
- Vendor name : Newark electronics
- Newark part number :16F3194
- Manufacturer part no :24PCAFA6D
- Price : 21.08 per piece

APPENDIX-1

MATLAB CODE FOR EXPERIMENT-2

The following is the MATLAB code for Figure 4-4. Similar code was written for Figure 4-5 to Figure 4-7. Using the almost the same program Figure 4-10 through Figure 4-13 and Figure 5-3 were plotted.

```
load C:\MATLAB7\work\Mfiles\a1e1.txt
t = a1e1(:,1);% time column in data file
B = a1e1(:,2);% tank1 voltage
C = a1e1(:,3);% tank2 voltage
D = a1e1(:,4);% pump voltage
n = 1;
m = 2;
Max = 10; % total number of trials for the experiment
calib1 = 6.091; % calibration factor for level in the tank to pressure sensor voltage
reft = 110; % Usually the time between each data point is 99-101 millisecond. So 110
seconds is taken as reference to split the trials.
datahead(1)=1;

while m < Max % splitting the entire data into 10 different trials
    if (t(n+1) - t(n)) > reft
        datahead(m)= n+1;
        m = m +1;
```

```

        end
        n = n + 1;
end
m = 1;
datahead (Max) = length(t); % finding the length of datasets
while m <Max % finding the dataset from t=0(time of step input) to time at steady state
    head = datahead(m);
    while head < rear
        if D(head) == 0.7 && D(head+1) == 1.25% Step change is made from 0.7 to 1.25.
        Step change is point were a change in input voltage is observed.
            datastart(m) = head+1;
        end
        head = head + 1;
    end
    m = m + 1;
end
m = 1;
c = 1;
        while c < length(newsetwo)+1
            serrset(c) = std(newsetwo(:,c))/sqrt(Max-1); % finding standard deviation
            meanset(c) = mean(newsetwo(:,c)); % finding mean
            ciover = meanset + (1.96*serrset);% finding the 95% Confidence interval
            cidown = meanset - (1.96*serrset); % finding the 95% Confidence
interval
            c = c + 1;
        end
figure (1)
m = 1;

```

```

tnew = 0:0.1:74.29;
while m < Max
    plot (tnew,newsetwo(m,:), 'y');
    m = m +1;
    hold on;
end
title ('Experiment-2 data, Apparatus 1');
xlabel ('Time(Sec)');
ylabel ('Height(cm)');
hold on
plot (tnew,meanset,'k',tnew,ciover,'r', tnew,cidown,'r');
grid minor
hold off

```

Experiment-2 MATLAB Code for Solving Differential Equations for Linear and Non-Linear Approximations

Linear Approximation (Should be in a separate file)

```
function xdot = tank1l(t,L)
```

```
% Parameters
```

```
L0 = 1.45;
```

```
K = 17.8;
```

```
g = 981;
```

$$D_{o1} = 0.47625;$$

$$D_{\text{tank}} = 4.445;$$

$$A_{\text{tank}} = (\pi/4)*D_{\text{tank}}^2;$$

$$A_{o1} = (\pi/4)*D_{o1}^2;$$

% Step change in Pump Voltage Deviation Variables

$$V_0 = 0.7;$$

$$\text{delV} = 0.55;$$

$$V = \text{delV};$$

% Linear State Equation

$$\dot{x}_{\text{dot}} = (K/A_{\text{tank}})*V - (0.9245*A_{o1}/A_{\text{tank}})*\text{sqrt}(g/2/L_0)*L;$$

For Solving Non-Linear Differential Equation (This should be in a separate file)

function $\dot{x}_{\text{dot}} = \text{tank1n}(t,L)$

% Parameters

$$K = 17.4;$$

$$g = 981;$$

$$D_{o1} = 0.47625;$$

$$D_{\text{tank}} = 4.445;$$

$$A_{\text{tank}} = (\pi/4)*D_{\text{tank}}^2;$$

$$A_{o1} = (\pi/4)*D_{o1}^2;$$

% Step change in Pump Voltage

$$V_0=0.7;$$

$$\text{delV}= 0.55;$$

$$V = V_0 + \text{delV};$$

% Nonlinear State Equation

$$x_{\text{dot}} = (K/A_{\text{tank}})*V - 0.9235*(A_{o1}/A_{\text{tank}})*\text{sqrt}(2*g)*L^{0.5};$$

The above two MATLAB files should in the same folder as this one

%% Tank1 Simulation (Separate m.file)

%% Function File for Non-Linear Model

% function $x_{\text{dot}} = \text{tank1nlin}(t,L)$

% Parameters

$$\% K = 17.8;$$

$$\% g = 981;$$

$$\% D_{o1} = 0.47625;$$

$$\% D_{\text{tank}} = 4.445;$$

```

% Atank = (pi/4)*Dtank^2;

% Ao1 = (pi/4)*Do1^2;

% Step change in Pump Voltage

% V0 = 0.7;

% delV = 0.55;

% V = V0 + delV;

% Nonlinear State Equation

% xdot = (K/Atank)*V - (Ao1/Atank)*sqrt(2*g)*L^0.5;

%% Function File for Linear Model

% function xdot = tank11(t,L)

% Parameters

% L0 = 1.45;

% K = 17.4;

% g = 981;

% Do1 = 0.47625;

% Dtank = 4.445;

% Atank = (pi/4)*Dtank^2;

```

```

% Ao1 = (pi/4)*Do1^2;

% Step change in Pump Voltage (Deviation Variables)

% V0=0.7;

% delV=0.55;

% V = delV;

% Linear State Equation

% xdot = (K/Atank)*V - (Ao1/Atank)*sqrt (g/2/L0)*L;

%% Tank 1 Simulation Main Calling Program and Output

% Get numerical integration for the nonlinear process

tspann = [0,100];

Lnlino = 1.45;

[tnlin,Lnlin] = ode45(@tank1n,tspann,Lnlino);

% Get numerical integration for the linear process

tspanl = [0,100];

Llino = 1.45;

[tlin,Llin] = ode45(@tank1l,tspanl,Llino);

```

```
figure(1)
```

```
plot(tnlin,Lnlin,tlin,Llin)
```

```
title('Tank 1 Simulation Comparison for Apparatus 1')
```

```
xlabel('Time (sec)')
```

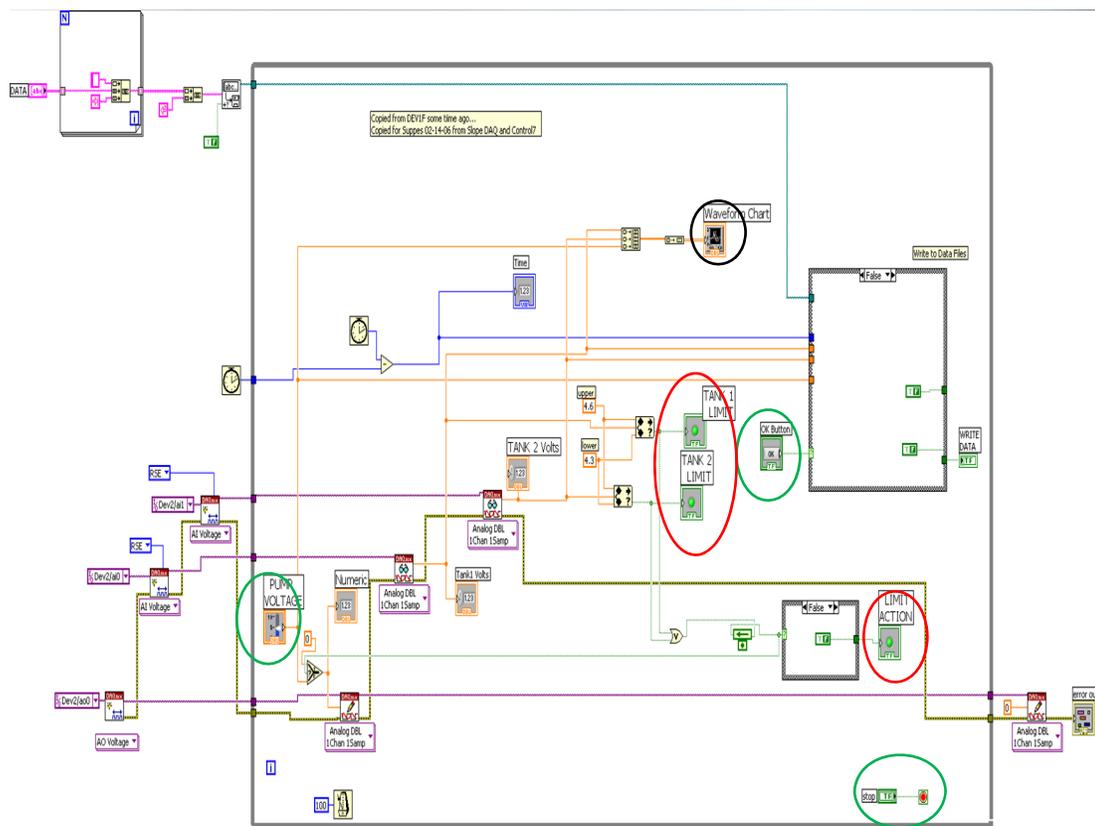
```
ylabel('Tank Level (cm)')
```

```
legend ('nonlinear','linear')
```

APPENDIX-2

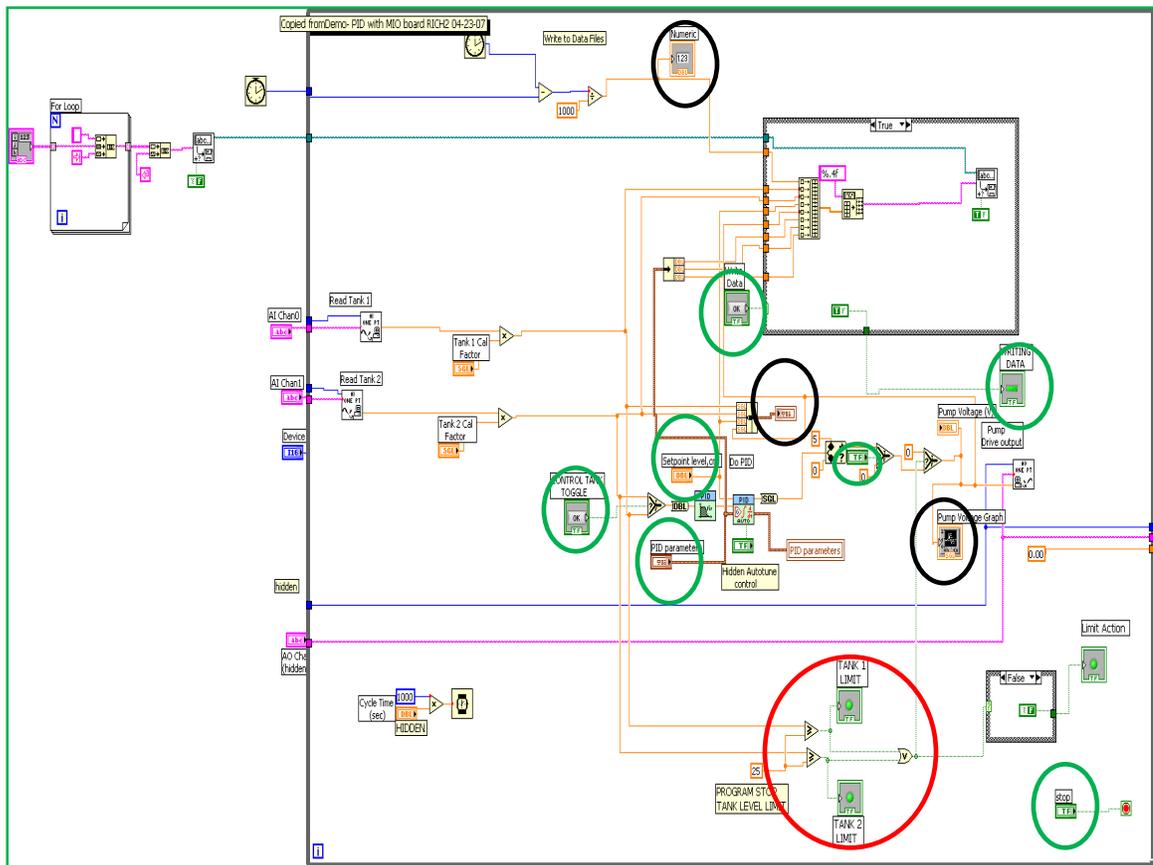
BLOCK DIAGRAMS OF LABVIEW PROGRAMS

1) Block Diagram of Pump.VI



- The Green circles are the inputs (controls), red color circles are safety interlock system and the black one is the indicator

2) Block Diagram of LabPID1.VI



- The Green circles are the inputs (controls), red color circles are safety interlock system and the black one is the indicator