# ME 421L

# Automatic Controls Laboratory

# CE117

# Process Trainer

# Lab 8: Flow control by Valve

Hamilton Institute

Based on original designs by Professor P.E. Wellstead

TQ Education and Training Ltd

**REFERENCES: CE 117 Process Trainer Manual**

# 1. Introduction: The CE117 Process Trainer

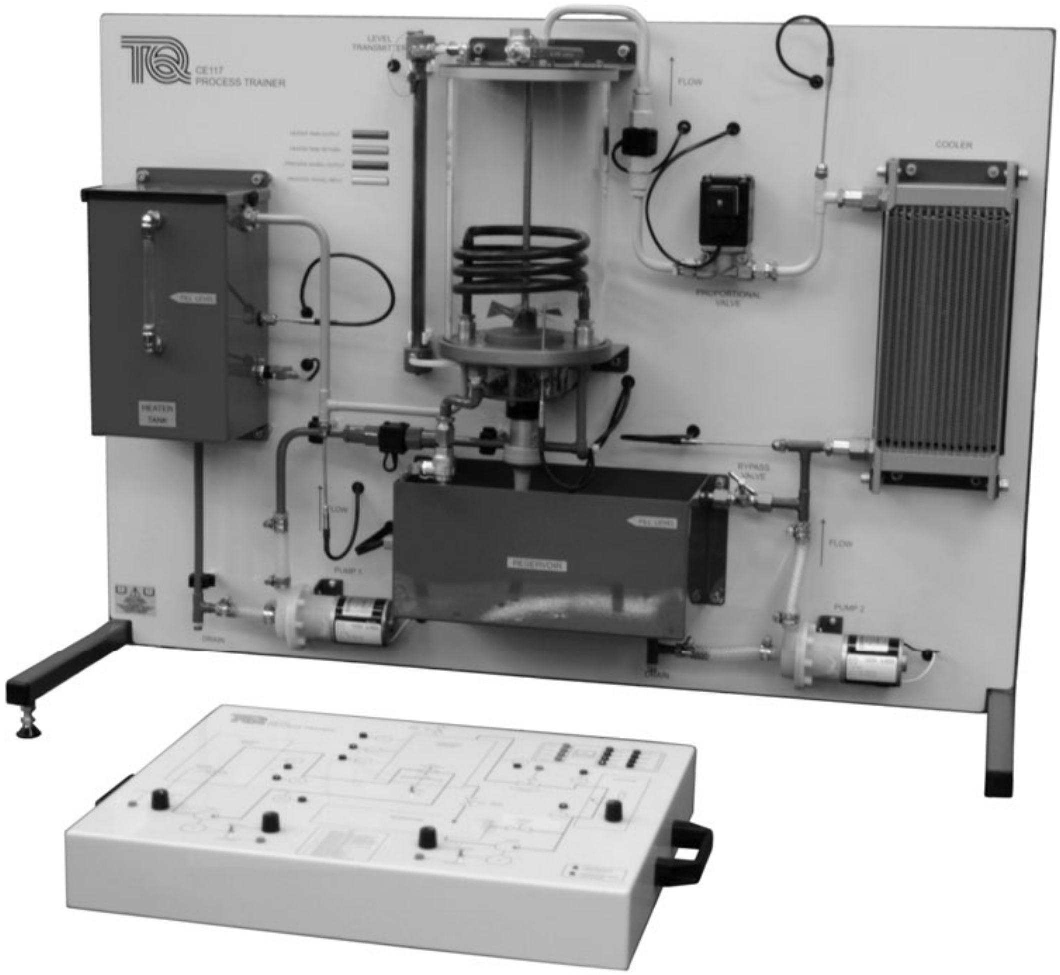


**Figure 1 The CE117 Process Trainer**

The CE117 Process Trainer is a fully integrated self-contained bench top process control apparatus. For safety reasons water is used as the working fluid. The equipment allows practical student investigations into a wide range of strategies for the control of:

• Flow
• Level
• Temperature
• Pressure

The student investigations may be the control of each of these parameters individually, or in combinations. The CE117 Process Trainer is supplied with all of the essential parts needed to allow the creation and control of fully functional process control systems. The performance of these different control systems can then be investigated and compared. The CE117 Process Trainer can be controlled by means of the built-in RS232 interface and CE2000 software (supplied) or any other suitable analogue or digital controller that may be available.

## CE2000 Control Software

The CE117 Process Trainer is supplied with Windows® based CE2000 Control Software that allows,
• Controller design and implementation
• Supervisory control
• Data acquisition, storage and display
• The setting of control parameters and gains
• Real time trend display

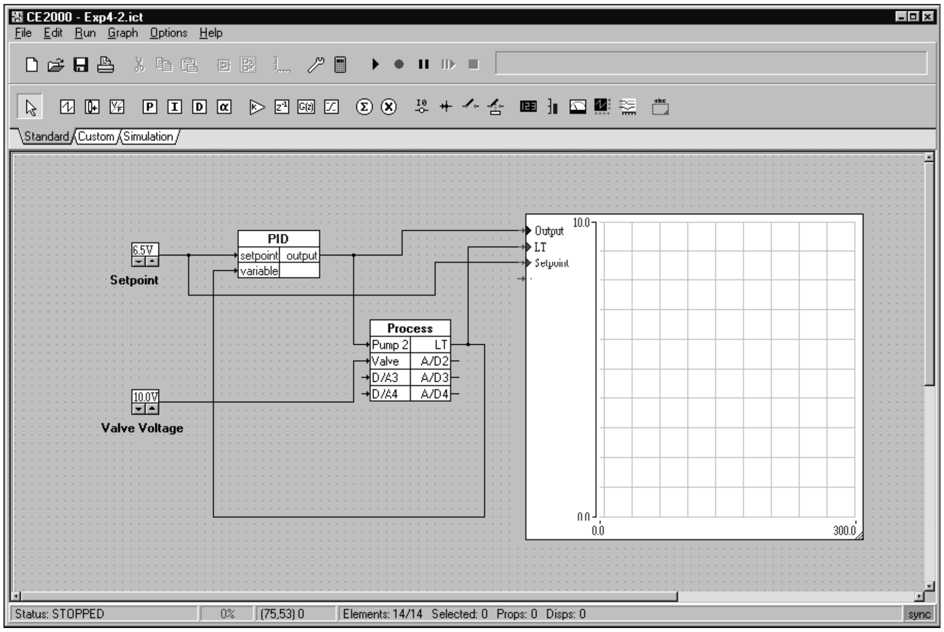


**Figure 2 Sample Screenshot of the CE2000 Control Software**

The CE2000 provides all of the tools needed to create, edit and run a wide range of data acquisition and control circuits. It also includes digital and graphical displays with built-in record functions.
The CE2000 circuits function in real time to monitor and control the CE117. They also provide visual graphical display of trends of selected parameters. The captured data can be easily and quickly exported to a word processor program to produce reports, or sent directly to a printer to produce a hard copy of tabulated or graphical results.

The CE2000 Control Software includes example data acquisition and controller circuit files that support each of the practical experiments provided in the CE117 manual. These controller files may be used exactly as supplied or modified easily and quickly using the powerful editing tools included in the CE2000 to introduce changes to the circuit. Alternatively, totally new customized data acquisition and controller circuits can be created that extend the scope of student investigations into process control principles and applications.

# 2. General Description

The CE117 Process Trainer hardware is supplied in two main parts,

- The Experiment Module
- The Control Module

Two multi-way leads (supplied) connect the two modules together

## 2.1 The Experiment Module

The Experiment Module is a bench-mounting unit that supports all of the process control hardware of the CE117 on its front panel. This module also contains the power supplies for each of the devices and circuits of the CE117, as well as the power amplifiers for the actuators and signal conditioning circuits for the transmitters. The CE117 Process Trainer includes two separate flow circuits - *a Process/Cooler Flow Circuit* and *a Heater Flow Circuit*.

**Process/Cooler Flow Circuit**

The Process/Cooler Flow Circuit includes:

- A Process Vessel with a Drain Valve and an Air Vent
- A Reservoir
- A variable speed D.C. motor driven pump (Pump 2)
- A Cooler comprising a radiator and a variable speed fan
- A servo-controlled Proportional Valve
- A Process Loop Bypass Valve

All these parts are joined by color coded pipework to form the complete Process Flow Circuit.


**Figure 3 The Experiment Module**

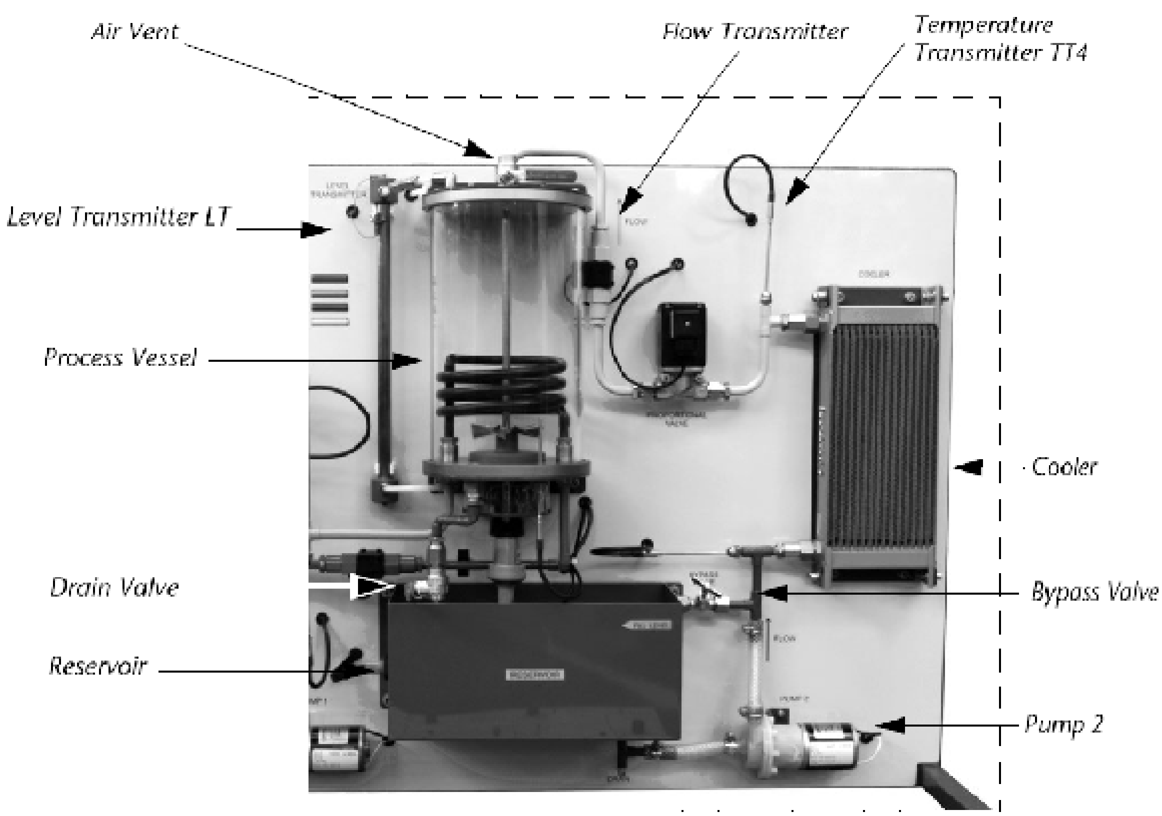


**Figure 4 The Process/Cooler Flow Circuit**

The Process Vessel is a transparent cylinder. A scale on the front of the Process Vessel allows the level of water to be accurately measured.

Pump 2 delivers water from the Reservoir to the Process Vessel via the Cooler and Proportional Valve. Water returns to the reservoir under gravity by means of a Drain Valve located in the base of the Process Vessel. The pump, and hence flow rate, are controlled by means of a potentiometer or an external voltage input at a socket on the Control Module (See “The Control Module” on page 6).

A needle type Bypass Valve is included in the Process Flow Circuit to allow the outflow from the pump to return directly to the reservoir without passing through the Cooler or the Process Vessel. This provides a secondary means of controlling or varying the flow rate of water in the Process Flow Circuit, or as a means of introducing a disturbance to the system.

An electrically controlled Proportional Valve is fitted to remotely control the flow of water in the Process Flow circuit.

The Process Vessel includes a capacitive Level Transmitter (LT) positioned to the left of the Process Vessel and mounted vertically. The transmitter is a simple parallel plate capacitor. A tapping at the base of the Level transmitter connects to the base of the Process Vessel via a short length of flexible tubing. A similar tapping connects the top of the Level Transmitter to the top of the Process Vessel.

A signal conditioning circuit measures this change in capacitance and provides an electrical signal proportional to the level of water in the Process Vessel. The output of the signal conditioning circuit of the Level Transmitter (LT) is calibrated to give 0 V when the Process Vessel is empty and 10 V when at maximum level.

The Process Vessel includes a Heat Exchanger coil mounted in the plate at the base. This coil forms part of the Heater Flow circuit. A Platinum Resistance Thermometer (TT5) is mounted in the base plate of the Process Vessel. To ensure that the temperature of the water in the Process Vessel is uniform, a rotary Stirrer is included in the base of the Process Vessel. It is driven by a magnetically coupled D.C. motor mounted beneath the Process Vessel. This arrangement minimizes the possibility of leaks, especially when the vessel is pressurized, and hence reduces the need for maintenance during the lifetime of the apparatus. A toggle switch on the Control Module allows the Stirrer to be switched ON or OFF.

An impeller type Flowmeter (FT2) is included in the flow circuit to measure the flow and provide a calibrated output signal for display or control purposes. Water flowing in the flow circuit causes the impeller to rotate. Optical sensing of the impeller produces a series of pulses. These pulses are proportional to the flow rate. A frequency-to-voltage converter produces a D.C. signal proportional to the flow rate that can be used for display or control purposes.

An Air Vent in the top of Process Vessel allows it to be sealed to allow practical investigations into pressure control in a sealed vessel. The pressure in the head space above the surface of the water in the Process Vessel increases with increase in water level.

An integrated circuit type Pressure Transmitter (PT) is located in the top of the Experiment Module and *connects via a pipe to the top of the Process Vessel. The Pressure Transmitter measures the pressure in the* head space of the Process Vessel when the Air Vent is closed.

The Water Reservoir includes a Float Switch mounted in the left-hand side of the tank. If the level of the water in the Reservoir drops below a minimum level, the Float Switch disables the pump (Pump 2) to prevent it running dry. An indicator light on the Mimic Panel of the Control Module illuminates when the Float Switch has sensed low water level. Once the level of water has risen above the minimum level, the Float Switch closes and the pump supply is enabled once more and the indicator light on the Mimic Panel switches off.

Water passes from Pump 2 to the Cooler and then enters the Process Vessel. The Cooler comprises a compact series of passages. These passages are thermally connected to a honeycomb of metal fins that increase the effective surface area of the Cooler. A variable speed Fan forces air through the Cooler and so removes energy (heat) from the water flowing through it. With continuous circulation of water through the Cooler, the temperature of the water in the Process Vessel (and the Water Reservoir) can be reduced.

Platinum Resistance Thermometers are mounted at the inflow and outflow of the Cooler. These can be used to measure the temperature differential between the water flowing in and out of the Cooler so that the heat energy removed from the water can be determined.

Table 1 provides the technical data for the hardware used on the CE117 Process Trainer.

| Item | | Analogue Signal | Conversion Details |
|---|---|---|---|
| **PRT Temperature Transmitters** (Platinum Resistance Thermometers) | **TT1 TT2 TT3 TT4 TT5** | 0 - 10 V Output Linear | 10°C per Volt<br>0 V = 0°C<br>10 V = 100°C |
| **Flow Transmitters** | **FT1 FT2** | 0 - 10 V Output | 1 L/min per Volt<br>0 V = No flow |
| **Level Transmitter** | **LT** | 0 - 10 V Output Non Linear | 0 V = Empty Vessel<br>10 V = Maximum Level |
| **Pressure Transmitter** | **PT** | 0 - 10 V Output | 100 mbar per Volt<br>0 V = 0 mbar (gauge) |
| **Electric Heater** | | 0 - 10 V Input | 75 W per Volt<br>0 V = Heater Off<br>10 V = 750 W Maximum Power (Nominal) |
| **Proportional Valve** | **S** | 0 - 10 V Input | 0 V = Closed<br>10 V = Open |
| **Pump 1 Pump 2** | | 0 - 10 V Input | 0 V = No Flow<br>10 V = Maximum Flow |

**Table 1 Analogue Signal Sockets on the Mimic Panel**

## 2.2 The Control Module

The Control Module provides access to all of the actuator and transmitter circuits contained in the Experimental Module. It also provides the interface between the CE117 Process Trainer and the PC for up to 4 channels of analogue-to-digital conversion (AD) and eight channels of digital-to-analogue conversion (DA).

**The Control Module Mimic Panel**

The front panel of the Control Module includes a Mimic Panel that provides schematic detail of the layout and functionality of the complete CE117 Process Trainer. It also provides the means to physically access the inputs and outputs of the transmitters and actuators of the CE117.

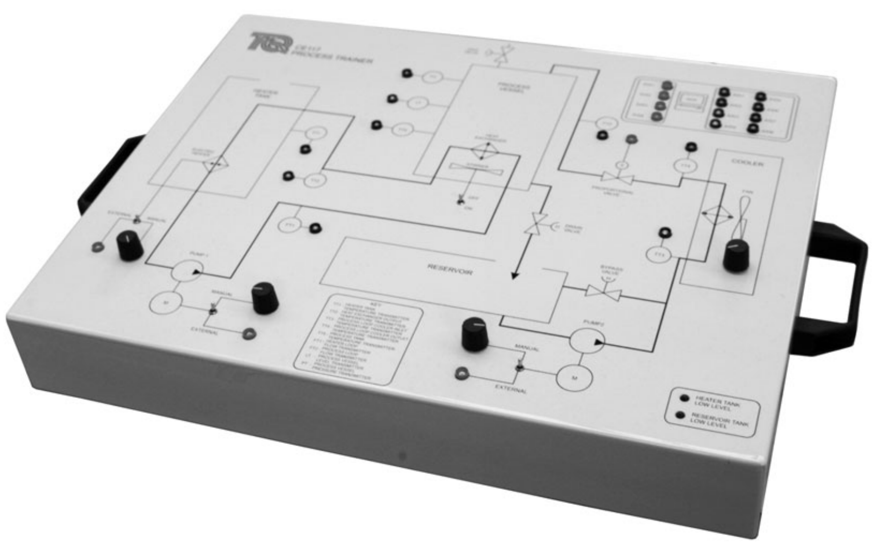

**Figure 5 The Control Module**

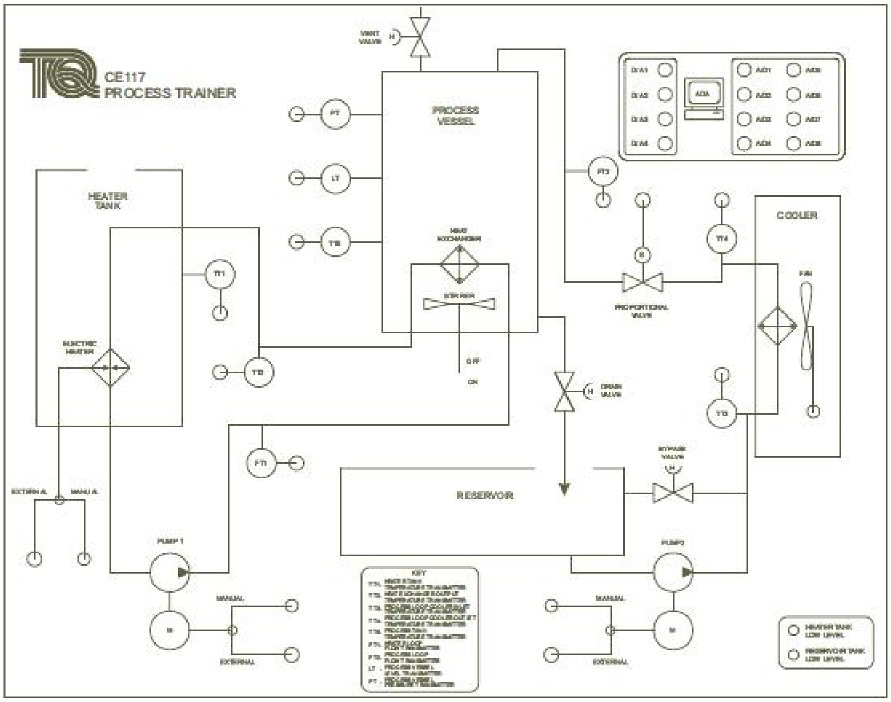


**Figure 6 The Control Module Mimic Panel**

**Process Vessel Section**

This section of the Mimic Panel includes sockets for the:
• Input to the Proportional Valve (S) to control its degree of opening - open, closed or some intermediate setting
• Output signal from the Pressure Transmitter (PT)
• Output signal from the Level Transmitter (LT)
• Output signal from the Temperature Transmitter (TT5)
• Output signal from the Flow Transmitter (FT2) measuring the flow rate into the Process Vessel
A toggle switch labeled ON/OFF controls the Stirrer mounted in the base of the Process Vessel.

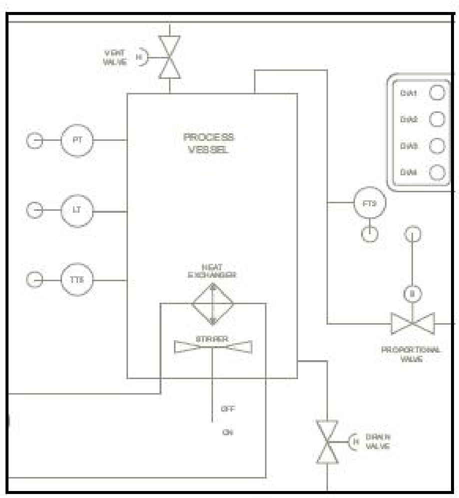


**Figure 7 Process Vessel Section of the Mimic Panel**

**Reservoir Section**

This section of the Mimic Panel includes:
• A 2 mm socket and a potentiometer to provide control over the delivery of Pump 2 in the Process Flow Loop.
• A toggle switch to select whether the pump speed is controlled manually (Manual), or whether it is controlled using an external source (External).

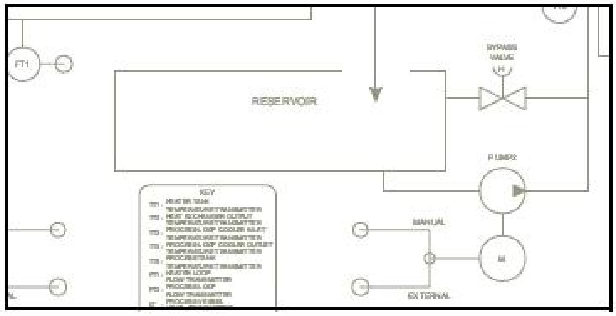


**Figure 8 The Reservoir Section**

**Low Water Level Switches and Indicators**

The bottom right-hand corner of the Control Module includes two LED indicators.

If the level of water in either the Heater Tank or the Process Vessel falls below a minimum level, then the Float Level Switches included in both tanks will open and disable the respective pump (Pump 1 or 2 respectively). The specific action will be indicated by the relevant indicator LED illuminating. The Heater in the Heater Tank is also turned off if the water level becomes too low. Once the level in the tank increases above the minimum, then the Float Level Switch closes, the pump supply is re-enabled and the LED indicator goes out.

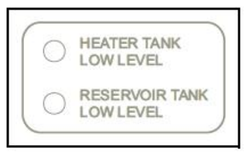


**Figure 9 Low Water Level Indicators**

**The ADA Section**

The ADA Section of the Mimic Panel is the interface between the transmitters and actuators of the CE117 Process Trainer and a PC running the CE2000 Control Software supplied. It provides all of the facilities required to be a multi-channel data acquisition and control system.

The ADA facilities provided are;

- 8 A-D Inputs - 12 bit, ±10 V.
- 4 D-A Outputs - 12 bit, ±10 V.

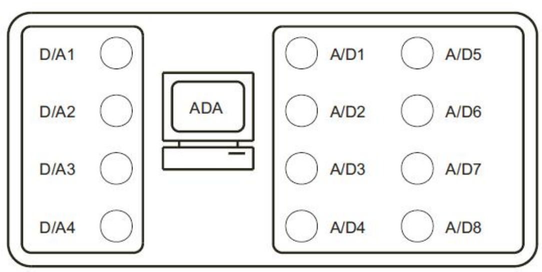


**Figure 10 The ADA Section**

# 3. System Dynamics

This section describes the dynamics of the Process Trainer. For more details, we recommend a popular book: "Process Dynamics and Control" by Seborg, Edgar and Mellichamp, (Wiley). Where possible, the symbols and notation used in the book are also used in this manual.

## Notation

| Symbol | Units | Description |
|---|---|---|
| $C$ | J/kg K | Heat capacity of the fluid |
| $A$ | $m^2$ | Area |
| $V$ | Litre | Volume of fluid in the process vessel |
| $V_h$ | Litre | Volume of fluid in the heater tank |
| $T$ | Celsius (°C) | Temperature of the fluid in the vessel |
| $T_i$ | Celsius (°C) | Inflow temperature |
| $T_h$ | Celsius (°C) | Temperature in the heater tank |
| $T_o$ | Celsius (°C) | Outlet temperature from the heat exchanger |
| $T_{ref}$ | Celsius (°C) | Reference temperature |
| $P$ | Watts (W) | Heater input electrical power |
| $w_i$ | kg/s | Inlet mass flow rate |
| $w$ | kg/s | Outlet mass flow rate |
| $Q$ | J/kg | Heat input to the process vessel from the heat exchanger |
| ρ | $kg/m^3$ | Fluid density |
| $q_i$ | L/min or $m^3/s$ | Volumetric flow rate into the vessel |
| $q$ | L/min or $m^3/s$ | Volumetric flow rate out of the vessel |
| $q_h$ | L/min or $m^3/s$ | Flow rate through the heat exchanger. |
| $K$ | | A constant for the cooler |
| $U_{fan}$ | V | Cooler fan speed input voltage |

## The Process Vessel

The heat exchanger in the process vessel supplies an input heat flow rate $Q$. The fluid feed to the system is at temperature $T_i$ and mass flow rate $w_i$. The outflow temperature is $T$ and mass flow rate $w$. The control variables are the fluid input flow rate, the outflow rate and the heat input to the heater. The general control objective is to control the temperature $T$ and the volume of fluid ($V$) in the vessel. This type of system is the basis of many chemical process systems.

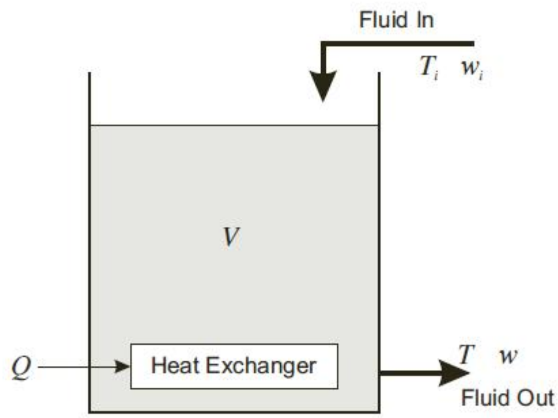


**Figure 11 Process System Model**

For the process vessel of volume $V$ filled with water of density ρ, the mass of water in the vessel is given by $V\rho$. From Figure 11, the law of conservation of mass gives the mass balance:

(Rate of mass accumulation) = (Rate of mass into the vessel) – (Rate of mass out of the vessel)

The mass balance equation is then

$$\frac{d(V\rho)}{dt} = w_i - w$$

Equation (1) can be rewritten as:

$$\frac{dV}{dt} = \frac{1}{\rho}(w_i - w) = q_i - q$$

The flow rate through the process loop is given by the relationship between the pump characteristics, the losses in the pipes and cooling systems, and the proportional valve. This is usually given by a set of curves which relate the pump input to the flow rate for various proportional valve positions.

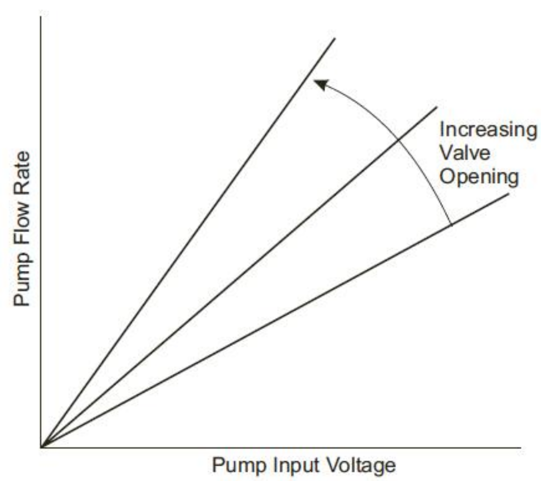


**Figure 12 Typical Linear Pump Characteristic**

# 4. Process Control Theory

The dynamics and control of process systems is an important subject. Properly configured and effectively tuned control systems have a major influence on the efficiency and safety of a process plant. In this section the main process control topics are reviewed and their application described in terms of the CE117 Process Trainer. The popular and widely used book “Process Dynamics and Control” by Seborg, Edgar and Mellichamp, (Wiley) is again recommend for more background and details.

## Feedback Control of Flow

The control of flow rate through a pipeline occurs in process engineering when fluid, gas or a mixture of both is pumped through a pipeline or process network. The flow of fluid can be controlled in the Process Trainer in both the heater and process loops by:

- Control of pump speed (heater and process loop).
- Control of the proportional valve position (process loop only).
- A combination of the pump speed and valve position.
- Adjustment of the process loop by pass valve.

The control schemes for the pump speed and valve control are shown in Figure 13. Both methods of control are used in practical situations, depending upon the process system being considered. In some complex systems a mix of both schemes is used. For example, in a gas distribution network, pumps are used as the primary actuator. They move gas through the network from the source to the user. Local valves control the amount of gas taken from the network by users at various locations around the network.

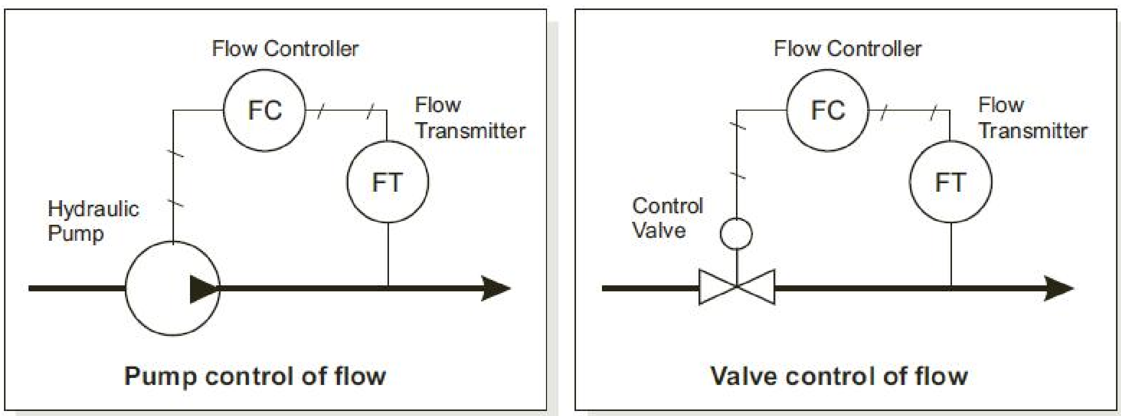


**Figure 13 Two Methods of Flow Control**

# 5. Experiments

## Experiment 1: Basic Control, Hardware and Software Familiarization

### Object

To perform basic control and measurement tests to become familiar with the Process Trainer.

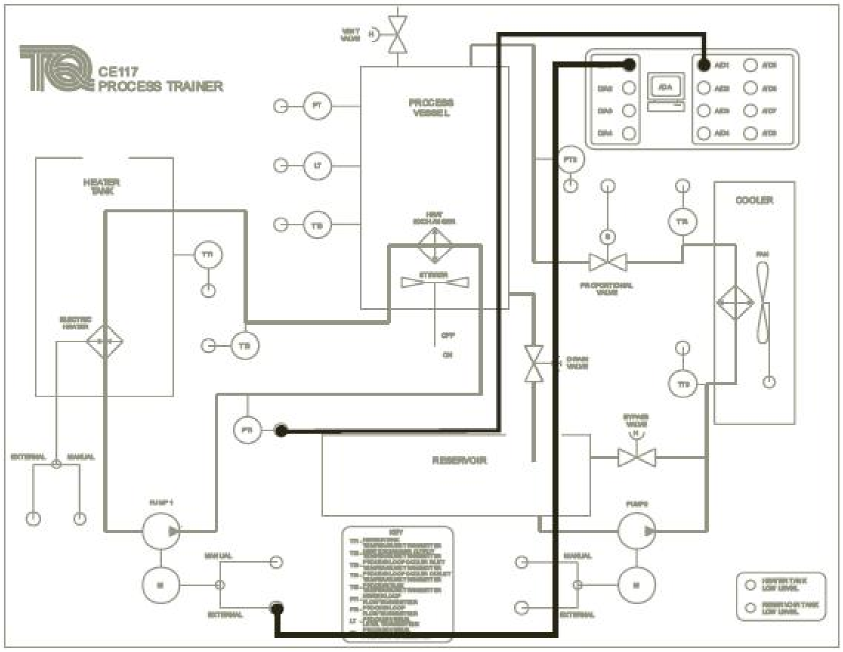


**Figure 14 Connections For Experiment 1 Procedure 1**

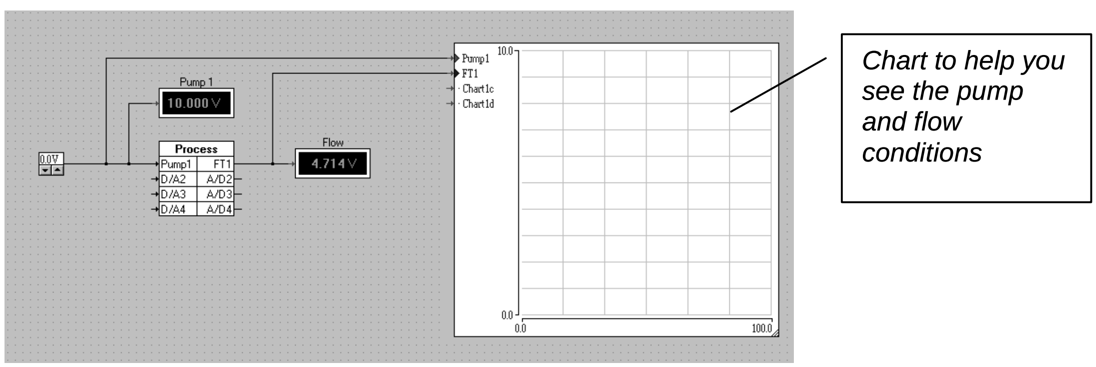


**Figure 15 Screenshot of Experiment 1 Procedure 1.**

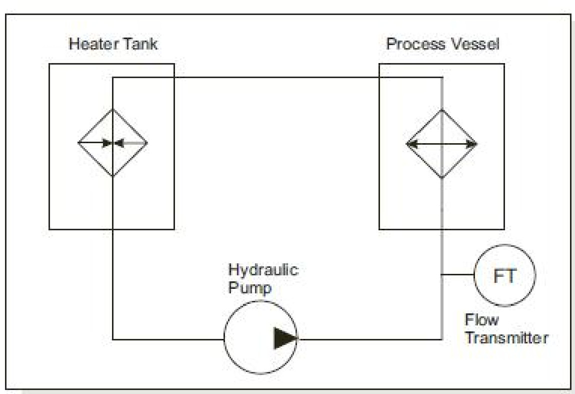


**Figure 16 Schematic of Experiment 1 Procedure 1**

## Experiment 1 - Procedure 1 - Heater Loop Pump Characteristic

1) Create a blank results table similar to Table 2.
2) Start the CE2000 software (double click on the CE2000 icon on your computer desktop). Use the CE2000 software to open the circuit file ‘exp1-1.ict’ from the default CE2000/CE117 folder (see Figure 17).

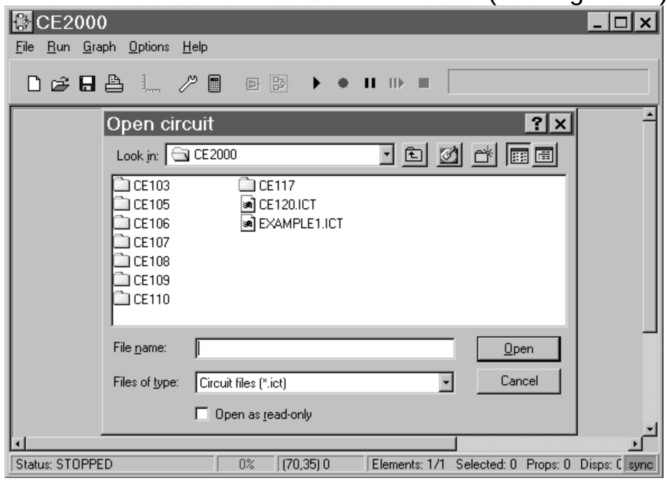


**Figure 17 Start the CE2000 Software and Use File - Open - CE2000 - CE117 - exp1-1.ict**

3) Connect the CE117 Mimic Panel as shown in Figure 14. Set Pump 1 switch to ‘External’. Analogue signals will pass from the ADA section to Pump 1 and from flow transmitter FT1. The software will display and record the flow through the heater loop.
4) You will use the ‘Run’, ‘Record’ and ‘Stop’ buttons on the software. You will also use the chart recorder. Make sure that you are familiar with these items (read the CE2000 Help Files or User Guide).
5) On the software set the Pump voltage to 0 V. Run the software and click on the record button to record the results.
6) In 1 V steps, increase the pump voltage from 0 to 10 V. After each voltage increase, wait for the flow to stabilize, the chart on the software will help to show you this. Use your blank table to record the corresponding flow transmitter voltages.
7) Convert the flow transmitter voltage into flow rate in Litre per minute. Table 1 on page 6 gives details of voltage and flow rate conversions.
8) Draw a block diagram of the control system. Create a graph of Flow (volt) on the vertical axis against Pump (volt) on the horizontal axis. The CE2000 software can do this for you - you must set the graphing options (see Figure 18), then click on the ‘Draw graph’ button. (Read the ‘Graphing’ details in the CE2000 Help Files or User Guide). Your curve is the pump flow characteristic.
9) You may also use the the ‘Export Data File’ function in the CE2000 software to export your data to other programs to create charts (read the CE2000 Help Files or User Guide).

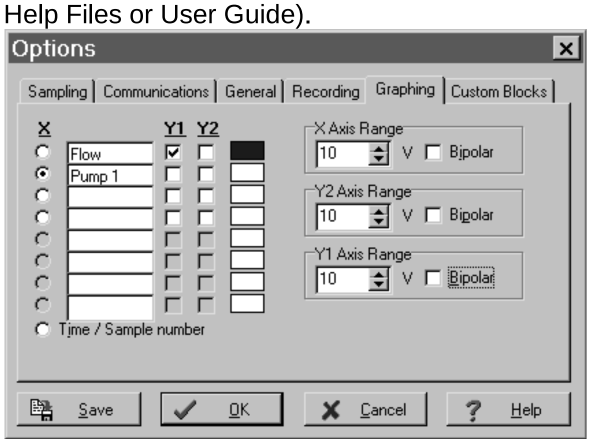


**Figure 18 Use the Options - Graphing Dialogue Box to Make the CE2000 Create Your Graph.**

## Questions

• Is the pump flow characteristic linear?
• At what voltage does the pump start to create a reasonable flow?

| Pump (Volt) | Flow Transmitter (Volt) | Flow Rate (Litre/minute) |
|---|---|---|
| 0 | | |
| 1 | | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | | |
| 6 | | |
| 7 | | |
| 8 | | |
| 9 | | |
| 10 | | |

**Table 2 Blank Results Table**

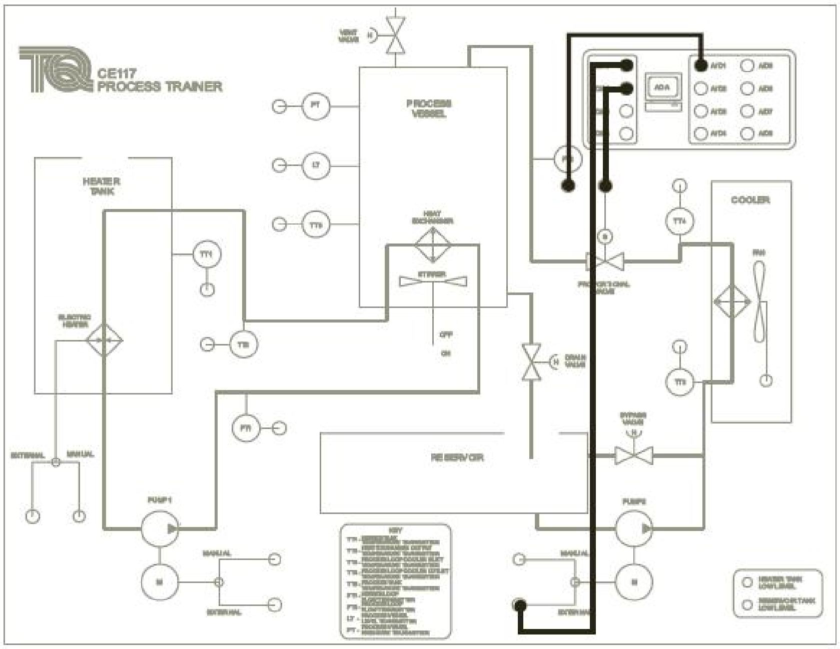


**Figure 19 Connections for Experiment 1 Procedure 2.**

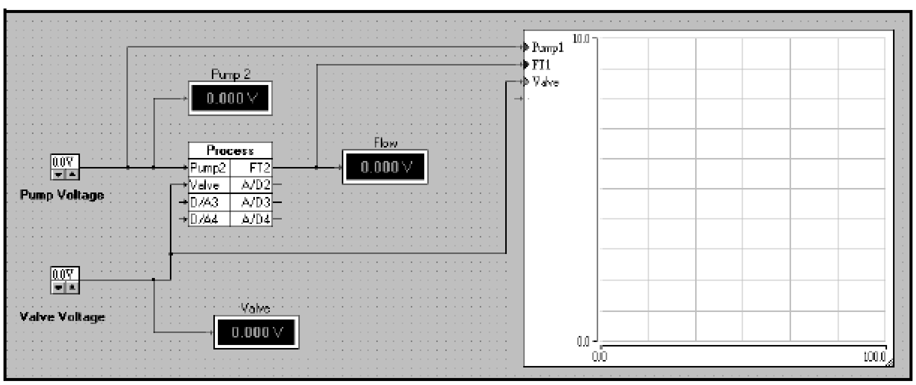


**Figure 20 Screenshot of Experiment 1 Procedure 2**

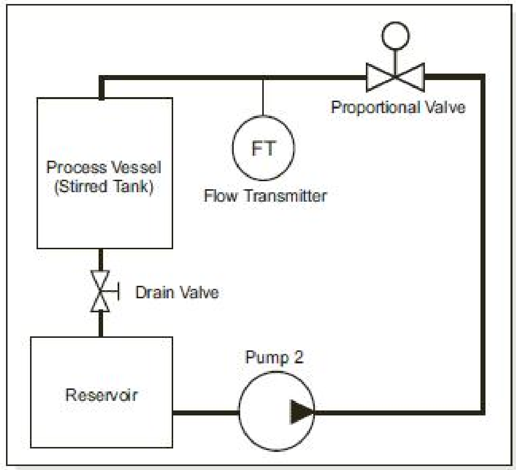


**Figure 21 Schematic of Experiment 1 Procedure 2**

## Experiment 1 - Procedure 2 - Process Loop Pump and Valve Characteristics

1) Create two blank results tables similar to Table 3 and Table 4.
2) Start the CE2000 software and load file ‘exp1-2.ict’.
3) Close the process loop bypass valve, fully open the process vessel drain valve and open the air vent valve.
4) Connect the CE117 Mimic Panel as shown in Figure 19. Set Pump 2 switch to ‘External’. Analogue signals will pass from the ADA section to Pump 2, the proportional valve S and from flow transmitter FT2. The software will display the flow through the process loop.

**Pump Characteristic**

5) On the software, set the **pump** voltage to 0 V and apply a full 10 V to the **valve** (fully open). Run the software. In 1 V steps, increase the **pump** voltage from 0 to 10 V. After each voltage increase, wait for the flow to stabilize, the chart will help. Use your blank table to record the corresponding flow transmitter voltages. You may also use the record button on the software to record your readings.
6) Convert the flow transmitter voltage into flow rate in Litre per minute. Table 1 on page 6 gives details of voltage and flow rate conversions.
7) Draw a block diagram of the control system. Create a chart of Flow (volt) on the vertical axis against **Pump** (volt) on the horizontal axis. You may use the CE2000 software to do this for you. Your curve is the **pump** flow characteristic.

**Valve Characteristic**

8) On the software, set the **valve** voltage to 0 V and apply a full 10 V to the **pump** (full flow). Run the software. In 1 V steps, increase the **valve** voltage from 0 to 10 V. After each voltage increase, wait for the flow to stabilize, the chart will help. Use your blank table to record the corresponding flow transmitter voltages. You may also use the record button on the software to record your readings.
9) Convert the flow transmitter voltage into flow rate in Litre per minute. Table 1 on page 16 gives details of voltage and flow rate conversions.
10) Draw a block diagram of the control system. Create a chart of Flow (volt) on the vertical axis against **Valve** (volt) on the horizontal axis. You may use the CE2000 software to do this for you. Your curve is the **valve** characteristic.

## Questions

• Is the pump flow characteristic linear?
• At what voltage does the pump start to create a reasonable flow?
• Is the valve characteristic linear?
• At what voltage does the valve allow a reasonable flow?

| Pump (Volt) | Flow Transmitter (Volt) | Flow Rate (Litre/minute) |
|---|---|---|
| 0 | | |
| 1 | | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | | |
| 6 | | |
| 7 | | |
| 8 | | |
| 9 | | |
| 10 | | |

**Table 3 Blank Results Table for Pump Flow Characteristics**

| Valve (Volt) | Flow Transmitter (Volt) | Flow Rate (Litre/minute) |
|---|---|---|
| 0 | | |
| 1 | | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | | |
| 6 | | |
| 7 | | |
| 8 | | |
| 9 | | |
| 10 | | |

**Table 4 Blank Results Table for Valve Characteristics**

# Experiment 2: Basic Proportional Control - Flow Control by Valve

## Object

To investigate the use of the proportional valve position to control flow rate in the process loop.

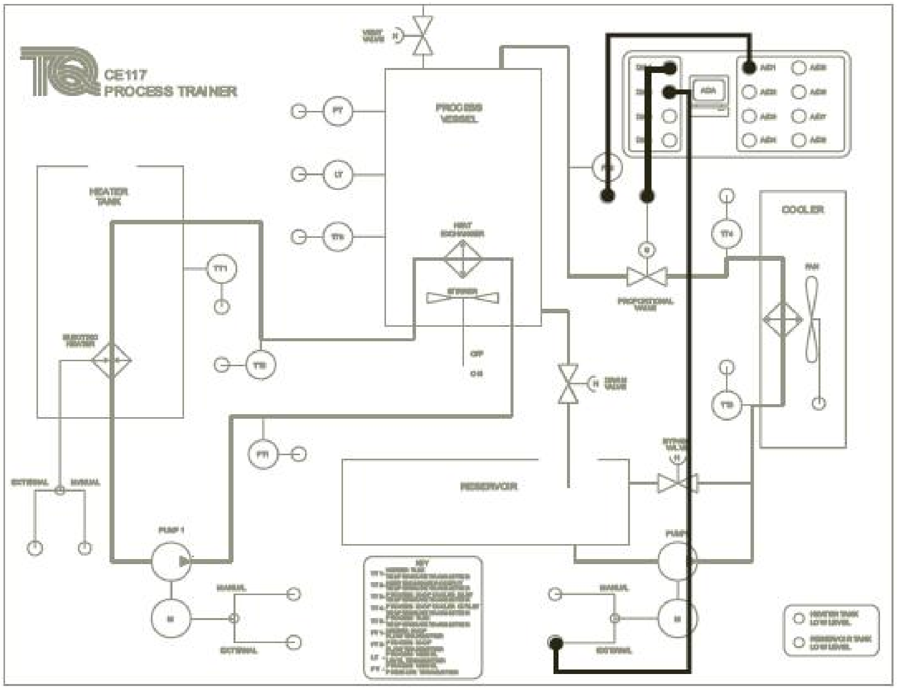


**Figure 22 Connections for Experiment 2 Procedure 1**

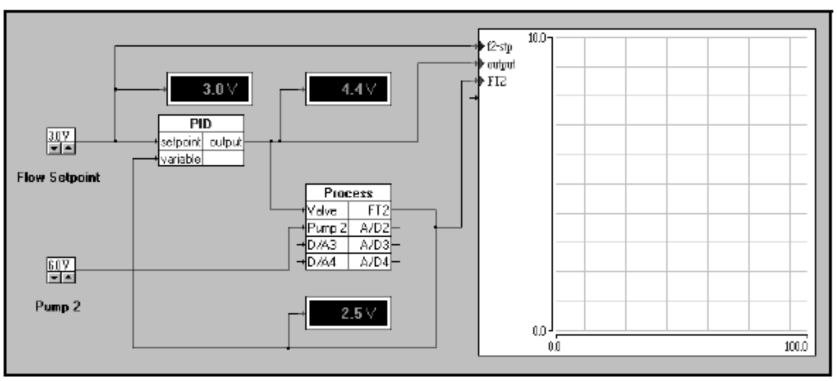


**Figure 23 Screenshot of Experiment 2 Procedure 1**

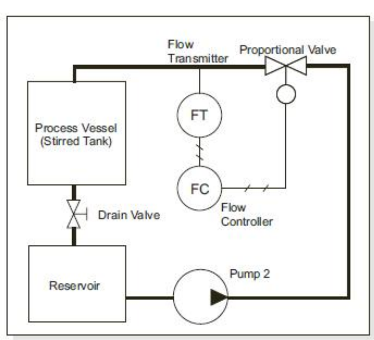


**Figure 24 Schematic of Experiment 2 Procedure 1**

## Experiment 2 Procedure

1) Start the CE2000 software and load file ‘exp2-1A.ict’.

2) Close the loop bypass valve, fully open the process vessel drain valve and the air vent.

3) Connect the CE117 Mimic Panel as shown in Figure 22. Set Pump 2 switch to ‘External’. Analogue signals will pass from the ADA section to Pump 2, the proportional valve S and from flow transmitter FT2.

4) On the software, the block titled ‘PID’ is a three term controller that controls the valve voltage. You may adjust the controller’s values of Proportional gain, Integral and Derivative. Set the PID controller to:

**Proportional gain - 0.5**
**Integral - 0.5**
**Derivative - 0 (zero)**

5) Run the software and use it to record the flow response. Adjust the flow setpoint to 0.5 V and Pump 2 voltage to 6 V and wait for the flow to stabilize.

6) Increase the flow setpoint in steps of 0.5 V up to a maximum of 3 V. At each step change, allow the flow to stabilize (should take less than 20 seconds). Adjust the flow setpoint back to 0.5 V and wait for the flow to stabilize should take less than 20 seconds). ***You may use the software to record and create a chart of the results, Figure 25***.

7) Save at least one of the responses data, regenerate them by excel and *roughly* estimate the time constant for the valve using graphical methods, ***show your work***.

NOTE *This experiment does not control level, so at setpoints above 2 V the reservoir can run low and switch off the pump. To avoid this, perform this part of the experiment as quickly as possible.*

8) Increase the flow setpoint to 2 V and wait a few seconds for the flow to stabilize.

9) *Part-open* the process loop bypass valve to reduce the loop flow. Close the bypass valve, wait for the flow to stabilize. Reduce the pump voltage by 2 V to reduce the flow, ***show the resulting chart***.

10) Draw a block diagram of the control system.

- **How well does the system respond to changes in setpoint?**
- **How well does the system respond to disturbances?**

**11) Fixing Pump 2 voltage at 6 V, repeat the experiment with different values of the proportional and integral gains, add at least 4 cases. Record your results in a table similar to Table 5. In each trial roughly estimate and record your system peak time, overshoot, if any, and the steady state error values. What do you notice about the system response for a change in each of these gains? Support your answer with the proper charts / screenshots.**

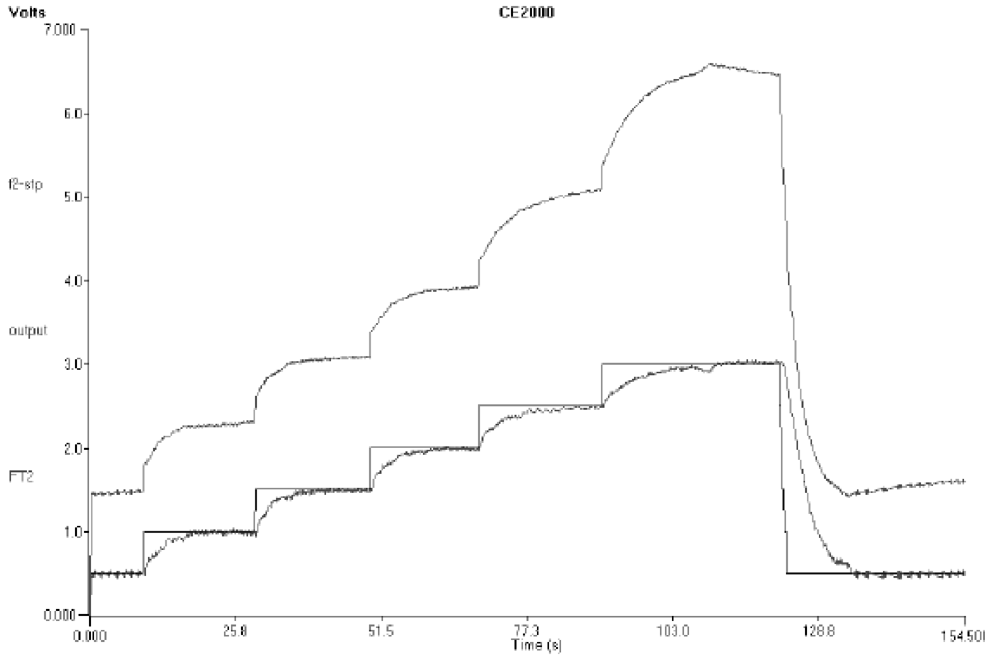


**Figure 25 Sample Results for Experiment 2 - Setpoint Adjusted**

| $K_p$ | $K_i$ | $t_p$ | $\% M_p$ | $e_{ss}$ | |
|---|---|---|---|---|---|
| 0.5 | 0.5 | | | | |
| 0.5 | 0 | | | | |
| 5 | 0 | | | | |
| 0 | 0.5 | | | | |
| 0 | 1 | | | | |
| 0 | 5 | | | | |
| | | | | | |

**Table 5 Blank Results Table for control gains effect**