Board 23: Add a Real Experience on Process Control Lab to your Students . . . for Free!

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Introduction.

The most recent survey on teaching Process Control in the chemical engineering curriculum, conducted by the AIChE Education Division, pointed out that more than 50% of respondents require no lab reports [1], confirming the common perception that no lab is associated with most of these courses. In fact, Process Control courses have a long tradition of being considered too theoretical by chemical engineers [2]. However, there is substantial evidence that lab experiences improve student learning, specifically in Process Control [3], but the implementation of lab experiences in process control courses have been largely constrained in many higher-education institutions by several factors like lack of equipment and technical support [4]. Several initiatives have been reported to compensate for this deficiency including classroom lab kits [3], remote labs [4], [5], [6], virtual lab simulators [6], [7], [8], [9], and the use of data from unit operation experimental modules [10] among others.

Our chemical engineering curriculum includes a capstone senior course on Process Control, 5 credit units, with a companion laboratory course (1 credit hour). The lab includes six fully automated experimental setups, three for liquid level control and three for temperature control as described below. Experiments are designed to run on “open loop” for developing first-principles derived process models and on “closed loop” to synthetize, test, and evaluate PID controllers. Data is collected in EXCEL spreadsheets. We processed and analyzed the data on Matlab and Simulink. Our intention is to offer our documentation and data to institutions with limited or no access to process control lab facilities, offering to their students an enriching practical experience to complement their education in a critical and promising area for chemical engineering careers. Faculty can organize the information (videos, manuals, EXCEL data files, MATLAB codes, Simulink block simulations) to the extent that better fits the course and assignments. Every single experiment provides abundant material to illustrate main process control topics (dynamics, models, controller synthesis, performance, tuning) and they can choose or combine the six available experiments.

Experimental setups.

The process control lab referred to here is currently operating six experimental setups. A summary description of each experiment is provided below with more detailed information on the lab manuals available upon request.

“Small tank” liquid level equipment. This experimental setup is depicted in Figure 1, and the main components of equipment are described in Table 1. This is a self-regulating liquid level (control variable) tank system, where flow comes into the tank by a pump (manipulated variable) and leaves the tank by a drainpipe with a valve. Another drainpipe with a valve is included to provide an additional flow outlet (disturbance variable). The liquid level in the tank is measured by a pulley system in contact with the top liquid surface. The PID controller acts upon the electric signal that regulates the speed of the peristaltic pump to establish the water flow rate.

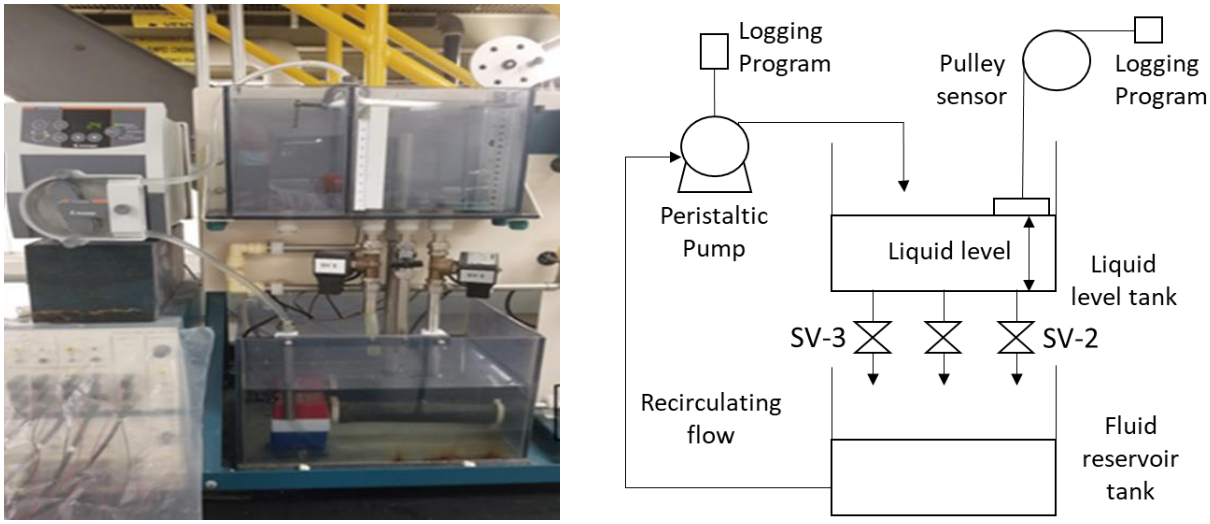

Figure 1. "Small tank" liquid level setup: picture and basic diagram

Table 1. "Small tank" main equipment components

Fluid reservoir to hold the water used in the experiment. Made of Plexiglas, with a rectangular base 40 x 20 inches and 20 inches high, located at the bottom
Recirculating pump to recirculate water between the reservoir and the small tank. Peristaltic pump, variable speed rotor, plastic piping, located left. It is automatically operated by the computer system to adjust the desired water flow into the tank (manipulated variable)
"Small tank" for the liquid level control Made of Plexiglas, with a rectangular base of 35 x 10 inches and 15 inches high, located on top. It is provided with three orifices at the bottom for the connection of discharge metal pipes. It includes a graded level indicator for direct observation of the liquid level
Float height sensor to record the liquid level. A floating cylindrical plastic piece connected by wire to a pulley system mounted on a metal wheel where the tension of the wire has been calibrated to record the liquid level below the floating piece. It is connected to the computer interface to register values every second
Solenoid valve (SV-2) to allow or restrict flow from the small tank into the reservoir tank. Mounted in one of the drainpipes at the bottom of the small tank. It is actioned by the computer to the "on" or "off" position, to allow or block water flow. It is used as a disturbance variable
Solenoid valve (SV-3) to allow or restrict flow from the small tank into the reservoir tank. Mounted in one of the drainpipes at the bottom of the small tank. It is actioned by the computer to the "on" or "off" position, to allow or block water flow. It is intended to remain open during the experiment providing for the gravity discharge flow from the small tank.
Manual valve to allow or restrict flow from the small tank into the reservoir tank. Mounted in one of the drainpipes at the bottom of the small tank. It is done manually for maintenance purposes. It is intended to remain closed during the experiment.
Computer interface, software and PID controller A desktop station includes a rotating knob to adjust the amperage to the peristaltic pump correlated with the flow rate. It also provides a small screen to visualize the actual and previous level measurements (line). In the "open loop" model, the system records the time, the pump amperage, the flow rate, and the liquid level, all EXCEL spreadsheet columns. For the closed loop operation, digital buttons allow to introduce a desired value for the set point liquid level (cm), for the proportional gain (mA/cm), the integral time (s) and the derivative time (s) by independent activation of every controller component acting on the flowrate delivered by the peristaltic pump. All these values are recorded at time readings in the EXCEL spreadsheet

The liquid level in the tank adjusts according to the model derived from mass and energy balances as given by equation (1)

$$\frac{dh}{dt} = \frac{1}{A_c}\left(F_{in} - C_{V3}h^{p_{V3}} - C_{V2}h^{p_{V2}}\right) \qquad (1)$$

where,

h = liquid level in the tank (cm)
A_c = transversal area of the tank (cm^2)
F_{in} = inlet flow rate (cm^3/s)
C_{V3} = valve constant (for solenoid vale SV3), units to match power factor
p_{V3} = power factor for valve SV3 for gravity discharge flow rate from a tank (Bernoulli model)
C_{V2} = valve constant (for solenoid vale SV2), units to match power factor
p_{V2} = power factor for valve SV2 for gravity discharge flow rate from a tank (Bernoulli model)

The analysis of the system dynamics is used to determine the values for C_{V2}, C_{V3}, p_{V2}, p_{V3} that better fit real data, as it is explained later in the section on software. The analysis of the process control targets to track set point changes in the liquid level (h) and synthetize PID controllers (acting on the pump delivered flow rate) for optimal performance, including the impact of disturbance variable (on/off activation of valve SV2)

"Large tank" liquid level equipment. This experimental setup is depicted in Figure 2, and the main components of equipment are described in Table 2. This is a self-regulating liquid level (control variable) tank system, where flow comes into the tank by a pneumatically operated flow control valve (manipulated variable) connected to the building circulating water and leaves the tank by a side drain with a valve. Another drainpipe with a valve is included at the bottom of the tank to provide an additional flow outlet (disturbance variable).

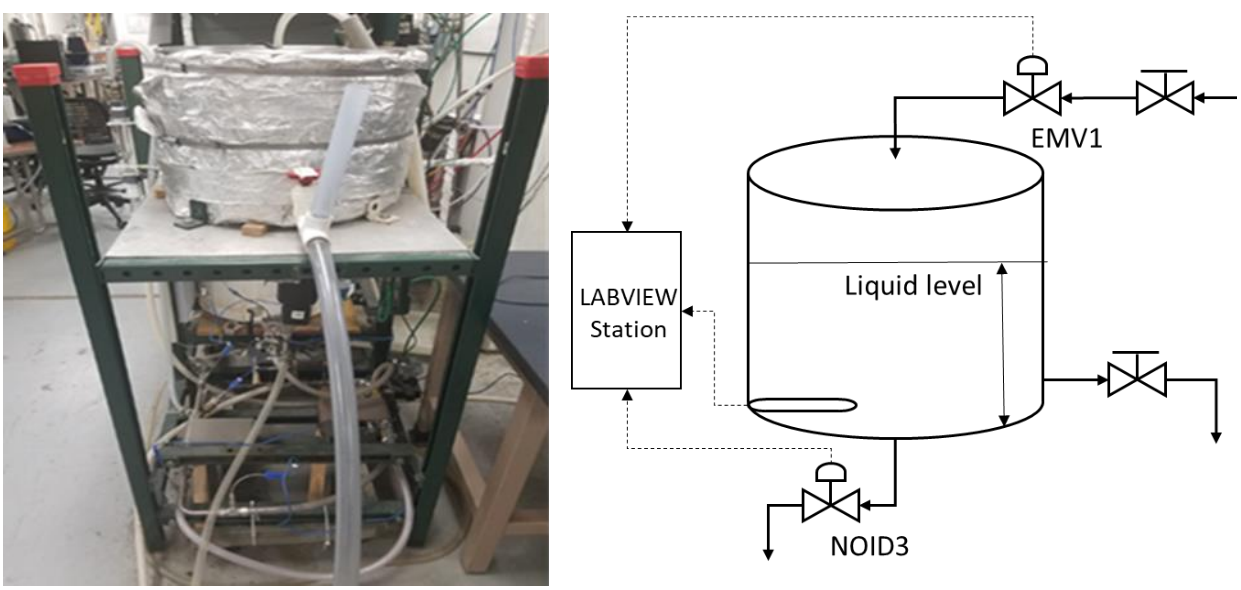

Figure 2. "Large tank" liquid level setup: picture and basic diagram

Table 2. "Large tank" main equipment components

A stainless steel 15 gallons tank, 18 inches ID, with one side port and one bottom port. Water is discharged through a plastic hose at the top of the tank. The side orifice (1 inch ID) is located 1.5 inches above the bottom of the tank and connected to a plastic hose with a manual valve to discharge. The bottom orifice (1 inch ID) is located at the bottom of the tank and connected to a solenoid valve
A globe flow control valve (EMW1) pneumatically operated (3-15 psig) and actioned by a current-to-pressure (IP) transducer (4-20 mA) at the interface with the computer system. This valve regulates the incoming flow to the tank
A volumetric flowrate sensor integrated with the valve (EMV1) measures the incoming flowrate to the tank that is recorded in the computer system.
A side drain manual gate valve to allow or restrict the flow from the tank. The valve is adjusted to a fixed position for the experiments.
An automated ball valve (NOID3) connected at the bottom drain of the tank. This valve is automatically operated on the on/off position, with a pre-established opening adjusted by a needle valve.
A submersible pressure transducer located on the inside of bottom of the tank measuring the gauge pressure (0-1 psig) in relation with the volume of liquid inside the tank
A desktop station includes visual panel with a rotating knob to adjust the amperage to the globe control valve (EMV1) that adjusts the % open of the valve (displayed) correlated with the flow rate entering the tank. An active simplified flow diagram displays the flow rate to the tank and the liquid level inside. It also provides a small screen to visualize the actual and previous liquid level measurements (line). In the "open loop" model, the system records the time, the % open of the valve (%), the amperage to the control valve (mA), the inlet flow rate (gpm), and the liquid level (inches), all in EXCEL spreadsheet columns. For the closed loop operation, digital buttons allow to introduce a desired value for the set point liquid level (inches), for the proportional gain (mA/in), the integral time (s) and the derivative time (s) by independent activation of every controller component acting on the inlet flow rate to the tank. It also records the on/off status for the bottom valve. All these values are recorded at time readings every second in the EXCEL spreadsheet

The liquid level in the tank adjusts according to the model derived from mass and energy balances as given by equation (2)

$$\frac{dh}{dt} = \frac{1}{A_c}\left(F_{in} - C_{Vside}(h-d)^{p_{Vside}} - C_{Vbottom}h^{p_{Vbottom}}\right) \qquad (2)$$

Variables in equation (2) are like the variables shown in equation (1) above, where the sub index Vside applies to the side discharge and Vbottom applies to the bottom discharge. In addition, the parameter "d" is the height (inches) for the side orifice where the side discharge pipe and valve are connected.

The analysis of the system dynamics is used to determine the values for C_{Vside}, $C_{Vbottom}$, p_{Vside}, $p_{Vbottom}$ that better fit real data. The analysis of the process control targets to track set point changes in the liquid level (h) and synthetize PID controllers (acting on the inlet flow rate) for optimal performance, including the impact of disturbance variable (on/off activation of valve NOID3)

"Cascade-tanks" liquid level experiment. This experimental setup is depicted in Figure 3, and the main components of equipment are described in Table 3. This is a dual set of two tanks in series (top and bottom) with two peristaltic pumps to deliver water into each tank, respectively. This is a self-regulating liquid level (control variable) tanks system, where flow comes into the top tank (manipulated variable) and discharges through a bottom orifice into a bottom tank. The bottom tank may get additional flow from another peristaltic pump (disturbance variable), and discharge though a bottom orifice into a reservoir tank where the pumps take the water for recirculation.

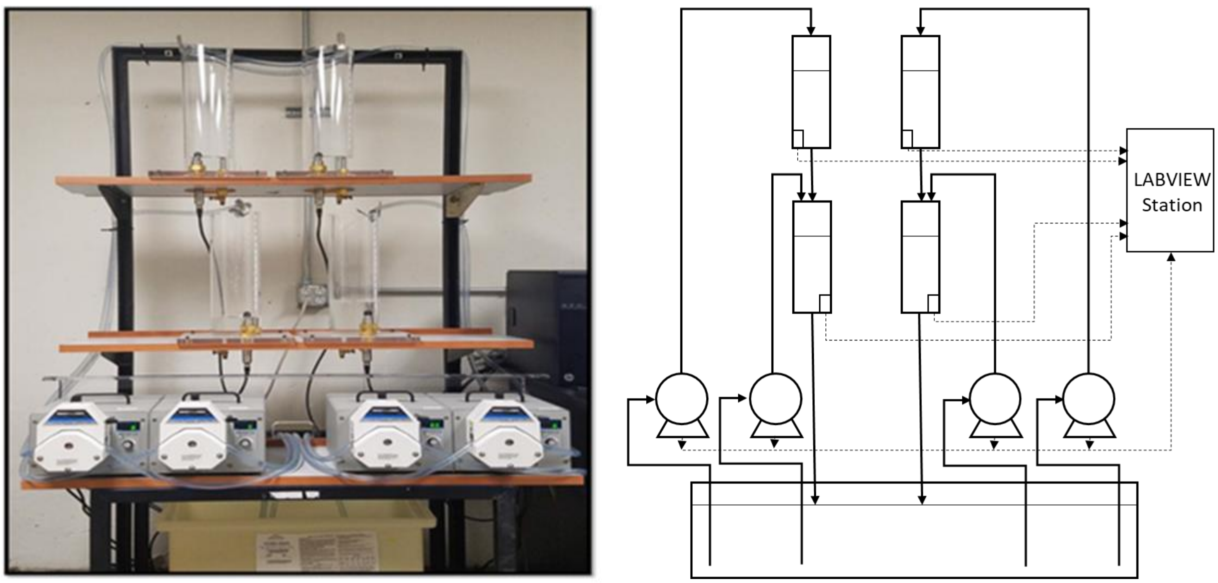

Figure 3. “Cascade tanks” liquid level setup: picture and basic diagram

The liquid level in the tanks adjusts according to the model derived from mass and energy balances as given by equations (3 and 4)

$$\frac{dh_1}{dt} = \frac{1}{A_{c1}}\left(F_{in1} - C_{V1} h_1^{p1}\right) \quad (3)$$

$$\frac{dh_2}{dt} = \frac{1}{A_{c2}}\left(F_{in2} + C_{V1} h_1^{p1} - C_{V2} h_2^{p2}\right) \quad (4)$$

where,

h_1 = liquid level in the top tank (in)
A_{c1} = transversal area of the top tank (in^2)
F_{in1} = inlet flow rate to top tank (in^3/s)
C_{V1} = valve constant (for top tank discharge), units to match power factor
p_1 = power factor for valve in gravity discharge pipe from top tank in a relaxed Bernoulli type model for gravity discharge flow rate from top tank
h_2 = liquid level in the bottom tank (in)
A_{c2} = transversal area of the bottom tank (in^2)
F_{in2} = inlet flow rate to bottom tank (in^3/s)
C_{V2} = valve constant (for bottom tank discharge), units to match power factor

p_2 = power factor for valve in gravity discharge pipe from top tank in a relaxed Bernoulli type model for gravity discharge flow rate from bottom tank

Table 3. "Cascade tanks" main equipment components

A fluid reservoir 100 L rectangular plastic tank located on the floor, beneath the platform for the pumps. Suction plastic hoses take the water to the pump inlet lines. Bottom tanks gravity discharge lines are located above the fluid reservoir for direct discharge.
A set of four similar peristaltic pumps, arranged in two similar sets: one pump discharge flow in the top tank, the other into the bottom tank. Each set is provided with a splitter to distribute the flow between both pumps in the set, according to a selected splitter coefficient α. For a splitter value of 0% ($\alpha = 0$), all flow is sent to the bottom tank, for a splitter value of 100% ($\alpha = 1$), all flow is sent to top tank, any other intermediate value distributes a set flow between both tanks. Pump-set flowrate (lpm) is adjusted by a voltage signal in the 0-10 V range by the computer interface.
Two split setting blocks. Each split setting block sets the ratio of flow for the corresponding pumps, fixing the flowrate to the interconnected tanks.
Two similar sets of two tanks each. Each tank is a 5 inches ID by 17 inches height, clear acrylic cylinder with a graduated level plastic label. Each tank is provided with two bottom orifices. One orifice holds a pressure transducer calibrated to measure the liquid level inside the tank. The other orifice holds a metal pipe with a manual valve by gravity discharge.
Four pressure transducers. Each Omega transducer is located at the bottom of the corresponding tank. The transducer outputs a current in the 4-20 mA range depending on the fluid column pressure on the transducer's wafer plate. The current signal is transformed into an equivalent liquid level height (in) by an internal calibration in the computer interface.
A desktop station includes a visual panel with a simplified flow diagram to locate the liquid level automatic readings of the liquid levels in the four tanks, and a set of four adjustable indicators to set the zero-levels (offsets). It includes two actionable windows to set the flow rate and the splitter ratio to each tank system and provides one dial (0-100) for pump power and input voltage input and delivered flowrate for each pump. It also provides a small screen to visualize the actual and previous liquid level measurements of each tank (lines). In the "open loop" model, the system records the time (every three s), the liquid level in each tank (inches), the flowrate (lpm) of each pump, the total flow rate (lpm) for each set of tanks, the splitter ratio for each set of tanks (%), and the input voltage (V) to each pump all in EXCEL spreadsheet columns. For the closed loop operation, digital buttons allow to introduce a desired value for the set point (liquid level, inches) for each of the bottom tanks, for the proportional gain (mA/in), the integral time (s) and the derivative time (s) by independent activation of every controller component (acting on the flowrate to the top tank). All these values are recorded at time readings every second in the EXCEL spreadsheet.

The analysis of the system dynamics is used to determine the values for C_{V1}, C_{V2}, p_1, p_2 that better fit real data. The analysis of the process control targets to track set point changes in the liquid level (h_2) of the bottom tank and synthetize PID controllers (acting on the flowrate to the top tank) for optimal performance, including the impact of disturbance variable (input flow rate to the bottom tank)

"Large tank" temperature experiment. This experimental setup is depicted in Figure 4, and the main components of equipment are described in Table 4. This is a liquid tank where the temperature (controlled variable) is regulated by an internal coil heat exchanger operating with high temperature steam (manipulated variable) inside. The insulated tank is charged with water to a fixed level (overflow line with orifice avoids any level increase). Steam is introduced into the copper coil through a pressure regulating valve (manipulated variable) establishing the inlet steam temperature. The tank is provided with a bottom orifice connected to a water recirculating pumping system exchanging heat with two plate heat exchangers with cooling water. The recirculating flowrate (manipulated variable) back to the tank can be adjusted by the openness of an electrically actuated flow control valve (EMV1) and the cooling water flow rate can be adjusted by a manual ball valve (can be selected as disturbance variables).

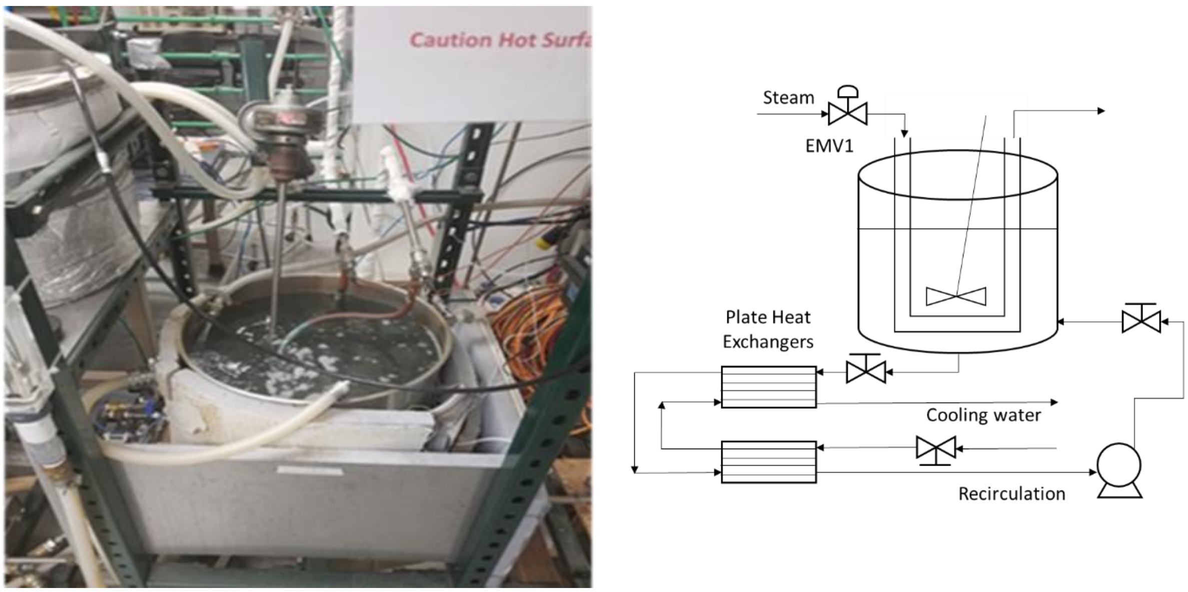

Figure 4. "Large tank" (coil heat exchanger) temperature setup: picture and basic diagram

The temperature in the tank adjusts according to the model derived from mass and energy balances as given by equation (5)

$$\frac{dT}{dt} = \left(\frac{F}{V}\right)(T_{in} - T) + \left(\frac{U_{A1}}{\rho C_p V}\right)(T_{steam} - T) + \left(\frac{U_{A2}}{\rho C_p V}\right)(T_{env} - T) \quad (5)$$

where

T = temperature of the liquid inside the tank (°C)
F = flow rate of the recirculating water (lpm)
V = liquid volume inside the tank (l)
T_{in} = temperature of the recirculating water returning to the tank (°C)
U_{A1} = heat transfer coefficient based on the external area of the steam coil inserted in the tank (cal/(°C min))
ρ = density of the water inside the tank (kg/l)
C_p = heat capacity of the water (cal/kg-°C)
T_{steam} = temperature of the steam inside the coil, assumed to be constant for saturated steam, but significant sub cooling alters this assumption (°C)
U_{A2} = heat transfer coefficient based on the open area of the tank to the environment (cal/°C-min))
T_{env} = ambient temperature (°C)

Table 4. “Large tank” (coil heat exchanger) main equipment components

A stainless steel 15 gallons tank, 18 inches ID, with an overflow line orifice to discharge any excess in the liquid volume, and a bottom orifice connected to a solenoid valve regulating the access to a recirculating flow system.
An electrical stirrer inserted in the tank to homogenize the liquid content of the tank with the blades located near the bottom of the tank.
A thermocouple inserted into the tank in a steel sheath to measure a one-point temperature in the tank, located about the middle of the tank, and connected to the computer interface.
A steam pressure-regulating valve (EMV1) connected to the steam generator in the building sets the steam temperature to the cooper coil inserted in the tank fluid. Condensed steam is discharged in the water drain of the building.
Two identical plate heat exchangers in series for the recirculating water to the tank to be cooled with cooling water. The circuit is connected to the building cooling water through a manual valve and a rotameter.
A centrifugal pump for the recirculation of water into the tank
An electrically actuated flow control valve at the pump discharge to regulate the recirculating water flow rate
A desktop station includes a visual panel with a simplified flow diagram to locate signal measurements in the system. It includes a dial indicator with a numerical window for the openness (%) of the steam valve and the corresponding amperage (mA) of the signal to the actuator. Three numerical indicators for the steam temperature (°C) at the source, at the inlet of the coil, and at the outlet of the coil. A numerical indicator for the temperature (°C) of the fluid inside the tank. Two temperature (°C) indicators for the recirculating water after each plate heat exchanger. A flowrate (gpm) indicator for the recirculating water flowrate. A numerical regulator/indicator for the openness (%) of the valve (EMV2) in the recirculating circuit. Three temperature (°C) indicators for the cooling water at the entrance of each plate heat exchangers and at the discharge to the drain. All these values are recorded in EXCEL spreadsheet columns every two s. For the closed loop operation, digital buttons allow to introduce a desired value for the set point temperature (°C) inside the tank, and for the proportional gain (mA/°C), the integral time (s) and the derivative time (s) by independent activation of every controller component (acting on the steam valve). All these values are recorded at time readings every second in the EXCEL spreadsheet.

The analysis of the system dynamics is used to determine the values for U_{A1} and U_{A2} that better fit real data. The analysis of the process control targets to track set point changes in the tank temperature (T) of the tank and synthetize PID controllers (acting on the steam pressure regulator) for optimal performance, including the impact of disturbance variables (recirculating water flowrate, cooling water flow rate)

Double pipe heat exchanger experiment. This experimental setup is depicted in Figure 5, and the main components of equipment are described in Table 5. A storage tank contains a 50/50 blend of ethylene glycol and water. The blend is pumped towards a heating section consisting of three double pipe heat exchangers in series with co-current high temperature saturated steam in the outer pipe. The hot blend is directed to a cooling section of five double pipe heat exchangers in series with counter-current cooling water in the outer pipe. The cooled water returns to the blend storage tank. The experiment is designed to control the temperature of the cooled blend (control variable) returning to the storage tank. A steam pressure regulator sets the temperature of the saturated steam to the heating section. A pneumatic control ball valve regulates the flow of the cooling water (manipulated variable). A pneumatic control ball valve regulates the flow of the blend (disturbance variable). Twenty-two temperatures are monitored and recorded across the system at strategic points of the flow diagram (Figure 5).

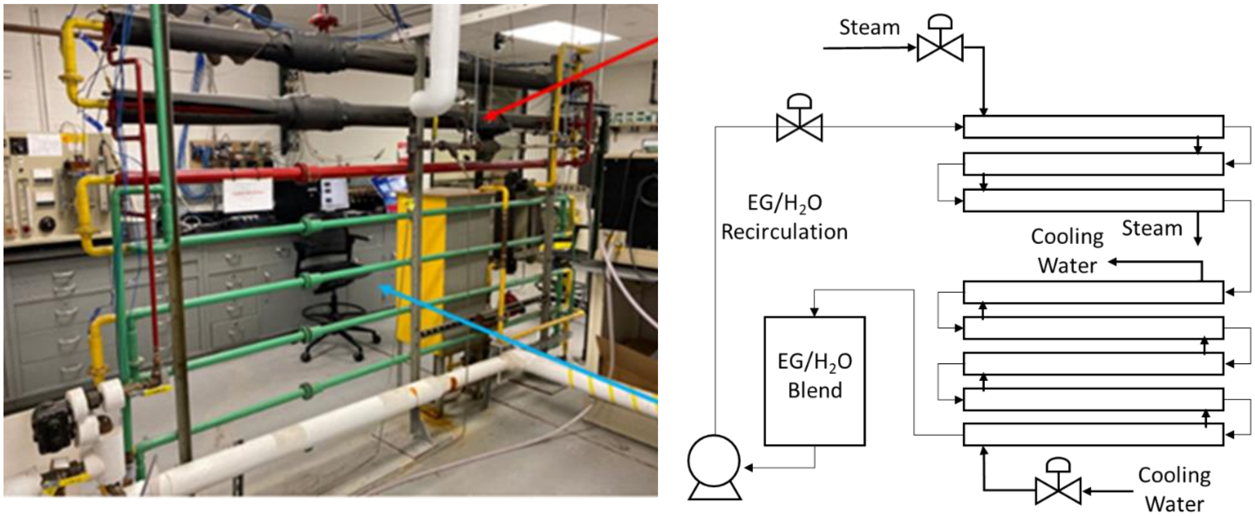

Figure 5. Double-pipe heat exchanger setup: picture and basic diagram

Table 5. Double pipe heat exchanger main equipment component

A carbon steel 0.5 x 0.5 x 1 m tank containing the 50/50 blend of ethylene glycol and water, with a bottom orifice connected to a pipe with a pump, and a top cover with an orifice connected to the discharge of the cooled blend
A reciprocating pump to recirculate the blend of ethylene glycol through the system
A feed line for the ethylene glycol to be delivered to the heating section, with a rotameter for visual inspection of the flow rate and a flowrate sensor connected to the computer interface
A pneumatic control valve to regulate the flow of the ethylene glycol/water blend
A pressure regulator to regulate the pressure/temperature of saturated steam into the heating section
Three steel double pipe heat exchangers in series, 2.82 m long each, with steam flowing through the outer pipe (0.0286 m OD) and the ethylene glycol/water blend through the inner tube (0.0286 m OD). The two hotter pipes are insulated.
Five steel double pipe heat exchangers in series, 2.82 m long each, with cooling water flowing through the outer pipe (0.0413 m OD) and the ethylene glycol/water blend through the inner tube (0.0286 m OD).
A reciprocating pump to circulate cooling water into the cooling section of the system
A water line for the cooling water, with a rotameter for visual inspection of the flow rate and a flowrate sensor connected to the computer interface
Twenty-two thermocouples distributed at strategic points in the system to record the temperature of the steam, ethylene glycol/water blend, and cooling water at inlet/outlet points
A desktop station includes a visual panel with a simplified flow diagram to locate signal measurements in the system. It includes a rotating knob to set the flow rate (0-35 lpm) of the ethylene glycol/water blend, a rotating knob to set the flow rate (0- 20 lpm) of the cooling water, and a rotating knob to set the voltage (0-10 V) to the steam pressure regulator. It also displays the values for twenty-two temperature indicators. All these values are recorded in EXCEL spreadsheet columns every two s. For the closed loop operation, digital buttons allow to introduce a desired value for the set point temperature (°C) of the cooled ethylene glycol/water blend before returning to the storage tank and for the proportional gain (mA/°C), the integral time (s) and the derivative time (s). Every controller component can be independently activated (acting on the cooling water flow control valve). All these values are recorded at time readings every second in the EXCEL spreadsheet.

The temperatures in the pipes adjust according to an approximate discretized model derived from mass and energy balances as given by equations (6 and 7) for each double pipe heat exchanger.

$$\frac{dT_{h,out}}{dt} = (\frac{F_h}{V_h})(T_{h,in} - T_{h,out}) - (\frac{UA_i}{\rho_h Cp_h V_h})(T_{h,out} - T_{c,out}) \quad (6)$$

$$\frac{dT_{c,out}}{dt} = (\frac{F_c}{V_c})(T_{c,in} - T_{c,out}) + (\frac{UA_i}{\rho_c Cp_c V_c})(T_{h,out} - T_{c,out}) \quad (7)$$

where,

$T_{h,out}$ = exit temperature of the hot stream (°C)
F_h = flow rate of the hot stream (lpm)
V_h = liquid volume of the hot stream in the pipe (l)
$T_{h,in}$ = inlet temperature of the hot stream (°C)
UA_i = heat transfer coefficient for the i^{th} double pipe based on the average heat area between the pipes (cal/(°C min))
ρ_h = density of the hot stream (kg/l)
Cp_h = heat capacity of the hot stream (cal/kg-°C)
$T_{c,out}$ = exit temperature of the cold stream (°C)
F_c = flow rate of the cold stream (lpm)
V_c = liquid volume of the cold stream in the pipe (l)
$T_{c,in}$ = inlet temperature of the cold stream (°C)
ρ_c = density of the cold stream (kg/l)
Cp_c = heat capacity of the hot stream (cal/kg-°C)

This set of two equations is replicated for each one of the five double pipe heat exchangers with the proper interconnecting variables, where the outlet temperatures from one heat exchanger become the inlet temperatures for the heat exchanger connected in series. The analysis of the system dynamics targets to determine the values for the five average UA_i parameters that better fit real data. The analysis of the process control targets to track set point changes in the cooled blend temperature (T) and synthetize PID controllers (acting on the cooling rate flow rate) for optimal performance, including the impact of disturbance variables (ethylene glycol/water blend flowrate)

Shell-and-tube heat exchanger experiment. This experimental setup is depicted in Figure 6, and the main components of equipment are described in Table 6. One of the three shell-and-tube heat exchangers (with different number of baffles for the shell side) is selected for the experiment, isolating the other two from circulating fluids, by closing the manual valves at the inlet lines. At the top, cold water from the building cold water system is directed through a rotameter and a flow control valve to the inner tubes (10) in four passes of a shell-and-tube heat exchanger (condenser) with high temperature saturated steam on the shell side. The hot water (liquid) is directed to the set of double-pass (U-shape) internal tubes in the shell-and-tube heat exchangers. Cold water from the building cold water system is directed to the baffled shell side of the heat exchanger through a rotameter and a flow control valve. The experiment has been designed for dual operation. In one mode of operation, the outlet temperature of the hot water (control variable) flowing inside the tubes of the heat exchanger is regulated by the flowrate of the hot water (manipulated variable) with the cooling water flowrate to the shell side acting as a disturbance variable. In another mode of operation, the outlet temperature of the cold water (control variable) flowing inside the shell of the heat exchanger is regulated by the flowrate of the cold water (manipulated variable) with the hot water flowrate inside the tubes acting as the disturbance variable. In both instances, the high temperature steam used to heat the water circulating inside the tubes of the shell-and-tube heat exchanger can be acting as a disturbance variable.

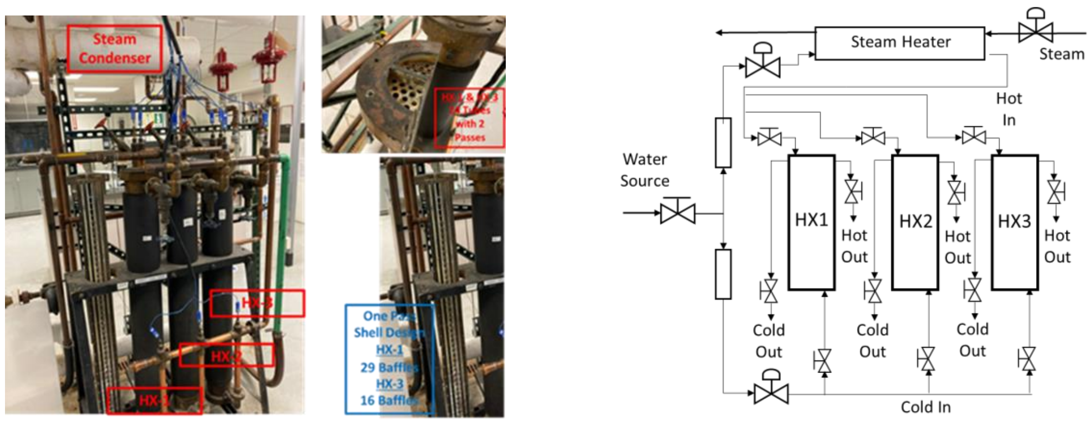

Figure 6. Shell-and-tube heat exchanger setup: picture and basic diagram

Table 6. Shell-and-tube heat exchanger main equipment components

Three stainless steel shell-and-tube heat exchangers, each with the same number of tubes (24) in a two-pass configuration (U-shape), 0.25 inches ID and 48 inches long per pass. The shell side is a 4 inches ID and 48 inches long chamber, with 16, 22 and 29 baffles, respectively.
A shell-and-tube heat exchanger (condenser) with 10 inner tubes in 4 passes for the cold water and a shell chamber for high temperature saturated steam
A steam pressure regulator in the steam feed to the condenser
A flow control needle valve in the feed line of the cold water to the condenser, directed to the inner tubes of the shell-and-tube heat exchanger
A rotameter for visual inspection of the cold-water flow rate to the condenser
A flow control needle valve in the feed line of the cold water to the shell side of the shell-and-tube heat exchanger
A rotameter for visual inspection of the cooling water flowrate to the shell side of the shell-and-tube heat exchanger
Six manual valves at the inlets and outlets of each shell-and-tube heat exchangers
A desktop station includes a visual panel with a simplified flow diagram to locate signal measurements in the system. It includes a rotating knob to adjust the water flow rate (0-40 lpm) to the shell side, a rotating knob to adjust the water flow rate to the tube side (0-40 lpm) and a rotating knob to set the steam pressure (0-10 psig). Fourteen temperature (°C) indicators at strategic points (inlet and outlet streams) in addition to the steam source temperature (°C). Two screens display the tube side and the shell side inlet temperatures (°C), and two screens display the tube side and the shell side exit temperatures (°C). Two panels provide for the action of controllers in both the tube side temperature control and the shell side temperature control, with actuator/indicator for the set point temperature (°C), indicator for current temperature (°C), indicator for the temperature error (°C), and the independent indicator/actuator of the proportional control gain (mV/°C), integral time (s), and derivative time (s). All the referred values are recorded every 4 s in EXCEL spreadsheet columns.

The temperature changes are modeled by discretized structure shown in Figure 7 for a four-compartment structure (extended number of compartments have been explored with increasing number resulting in longer computational times) as given by equations (8-15)

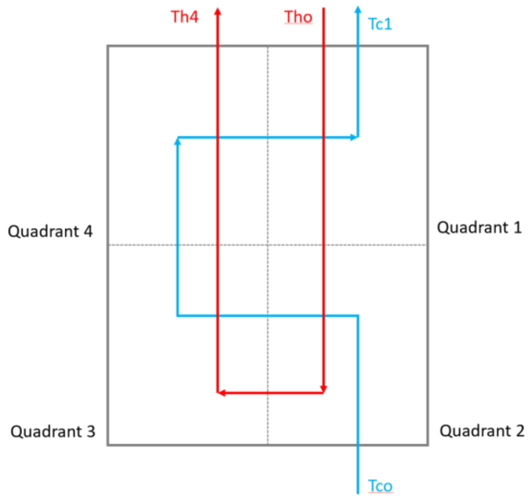

Figure 7. A four-compartment model to approximate temperature changes on the shell-and-tube heat exchanger

Shell Side (Cold)

$$\frac{dT_{c1}}{dt} = \left(\frac{F_c}{V_c}\right)(T_{c4} - T_{c1}) + \frac{UA_{c1}}{\rho C_p V_c}(T_{h1} - T_{c1}) \quad (8)$$

$$\frac{dT_{c2}}{dt} = \left(\frac{F_c}{V_c}\right)(T_{c0} - T_{c2}) + \frac{UA_{c2}}{\rho C_p V_c}(T_{h2} - T_{c2}) \quad (9)$$

$$\frac{dT_{c3}}{dt} = \left(\frac{F_c}{V_c}\right)(T_{c2} - T_{c3}) + \frac{UA_{c3}}{\rho C_p V_c}(T_{h3} - T_{c3}) \quad (10)$$

$$\frac{dT_{c4}}{dt} = \left(\frac{F_c}{V_c}\right)(T_{c3} - T_{c4}) + \frac{UA_{c4}}{\rho C_p V_c}(T_{h4} - T_{c4}) \quad (11)$$

Tube side (Hot)

$$\frac{dT_{h1}}{dt} = \left(\frac{F_h}{V_h}\right)(T_{h0} - T_{h1}) + \frac{UA_{h1}}{\rho C_p V_h}(T_{h1} - T_{c1}) \quad (12)$$

$$\frac{dT_{h2}}{dt} = \left(\frac{F_h}{V_h}\right)(T_{h1} - T_{h2}) + \frac{UA_{h2}}{\rho C_p V_h}(T_{h2} - T_{c2}) \quad (13)$$

$$\frac{dT_{h3}}{dt} = \left(\frac{F_h}{V_h}\right)(T_{h2} - T_{h3}) + \frac{UA_{h3}}{\rho C_p V_h}(T_{h3} - T_{c3}) \quad (14)$$

$$\frac{dT_{h4}}{dt} = \left(\frac{F_h}{V_h}\right)(T_{h3} - T_{h4}) + \frac{UA_{h4}}{\rho C_p V_h}(T_{h4} - T_{c4}) \quad (15)$$

The analysis of the system dynamics is used to determine the values for the eight UA_i parameters that better fit real data. The analysis of the process control targets to track set point changes in the exit tube side temperature (Th_4) or the exit shell side temperature (Tc_1) by synthetizing PID controllers (acting on the tube side flow rate or the shell side flow rate) for optimal performance. The impact of disturbance variables (either the shell-side flow rate or the tube-side flow rate) are also included in the analysis. The steam temperature can also be used as a disturbance variable in either control mode.

Supporting software.

This section illustrates the use of the software for the analysis of the dynamics and the synthetizing of PID controllers for the “small tank” liquid level experiments. Similar tools accompany all other experiments.

Data from every experiment is collected by LABVIEW software and stored in EXCEL spreadsheets. A sample is presented in Table 7 for the “small tank” liquid level experiment where the time column shows results every 5 s, with the corresponding amperage signal to the peristaltic pump, the liquid level in the tank, and the flowrate delivered by the pump. In this example, when the experimental run reaches 3280 s (column A) the pump signal changes from 0.0100 amps to 0.0105 amps (column B). This action leads to a change in the flow rate from 1.453 lpm to 1.619 lpm (column D), forcing the system to depart from the previous state in the liquid level at 5.76 cm increasing this level progressively (column C). It will end up reaching a new steady state (not shown in the Table) of 7.63 cm by the time of 4780 s (25 min later).

Table 7. Sample of recorded data for the “small tank” liquid level experiment

	A	B	C	D	E	F	G	H	I	J
1	Time (s)	Pump Signal (Amps)	Tank Height (cm)	Flow Rate (L/min)						
651	3245	0.01000	5.757	1.453						
652	3250	0.01000	5.759	1.453						
653	3255	0.01000	5.756	1.453						
654	3260	0.01000	5.759	1.453						
655	3265	0.01000	5.757	1.453						
656	3270	0.01000	5.757	1.453						
657	3275	0.01000	5.756	1.453						
658	3280	0.01050	5.758	1.619						
659	3285	0.01050	5.753	1.619						
660	3290	0.01050	5.762	1.619						
661	3295	0.01050	5.798	1.619						
662	3300	0.01050	5.831	1.619						
663	3305	0.01050	5.869	1.619						
664	3310	0.01050	5.901	1.619						
665	3315	0.01050	5.931	1.619						
666	3320	0.01050	5.964	1.619						
667	3325	0.01050	6.003	1.619						
668	3330	0.01050	6.029	1.619						
669	3335	0.01050	6.056	1.619						
670	3340	0.01050	6.084	1.619						
671	3345	0.01050	6.111	1.619						
672	3350	0.01050	6.145	1.619						
673	3355	0.01050	6.168	1.619						
674	3360	0.01050	6.198	1.619						
675	3365	0.01050	6.227	1.619						
676	3370	0.01050	6.254	1.619						
677	3375	0.01050	6.282	1.619						
678	3380	0.01050	6.305	1.619						
679	3385	0.01050	6.329	1.619						

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MATLAB is used to visualize and analyze the data, though EXCEL can be also used for the same purpose, or some other software handling EXCEL inputs. With a simple MATLAB plotting subroutine, the data can be displayed as the sample presented in Figure 8.

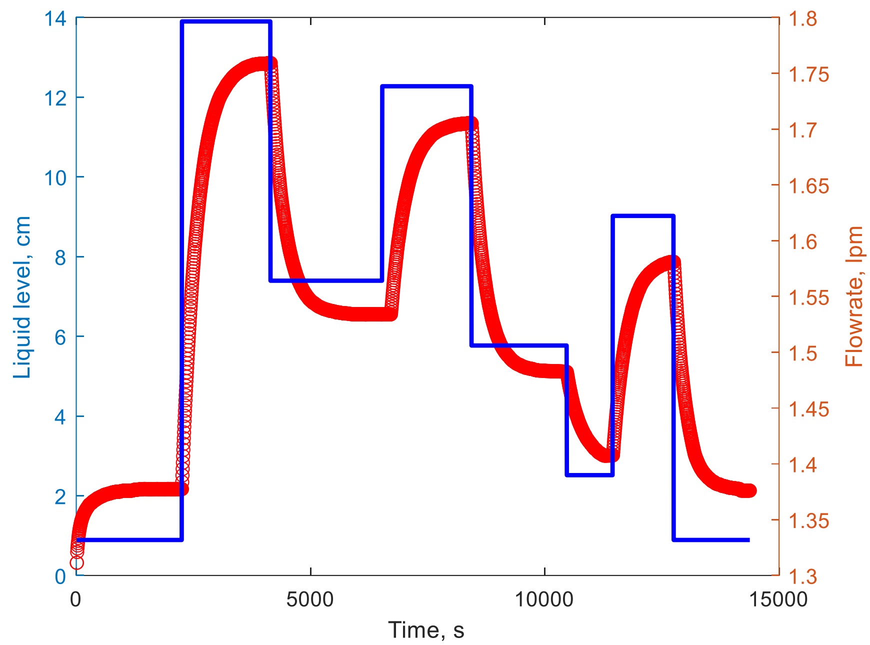

Figure 8. Sample of data collected for the “small tank” liquid level experiment. Step changes in the flow rate (square shape) force variations in the liquid level of the tank (curve shape)

The plotting subroutine can be modified to display only one specific step change reactive course as displayed in Figure 9.

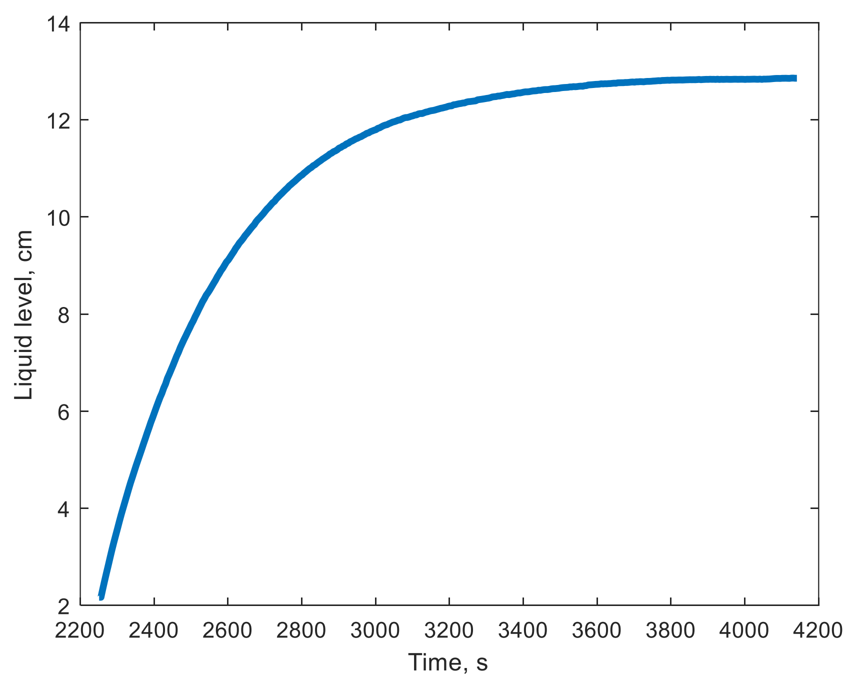

Figure 9. Sample of an isolated step change reactive curve for the “small tank” liquid level experiment.

A characteristic first-order transfer function can be derived from any single step-change reactive curve (see reference [11] for concepts and procedures) as exemplified by equation (16)

$$G(s) = \frac{K}{\tau s + 1} = \frac{23.00}{334s + 1} \qquad (16)$$

where the value of K ("gain") is obtained by dividing the variation in the liquid level (from the previous steady state of 2.156 cm high to the new steady state of 12.857 cm high, equal to 10.69 cm) by the change in the flowrate (0.4646 lpm for this step as recorded in the data), with units of $\frac{cm-min}{l}$. The value of τ ("time constant") is calculated as the time difference to reach 63.2% of the final steady value. In this example that point is given by 2.156 + 0.632 * (12.857 - 2.156) = 8.919 cm, that is reached at the time 2590 s, with the step change starting at 2256 s, resulting in a time difference of 334 s. The experimental values for each step change result in variations for these parameters opening the opportunity for a statistical analysis.

In addition, students are provided with a SIMULINK [12] basic model (Figure 10) based on the ordinary differential equation (ODE) (equation 1), using a conventional S-function [13]. Students can experiment with different values for a change in flow rate, and guess values for the valve constant and the power factor trying to replicate experimental results, with characteristic results as presented in Figure 11.

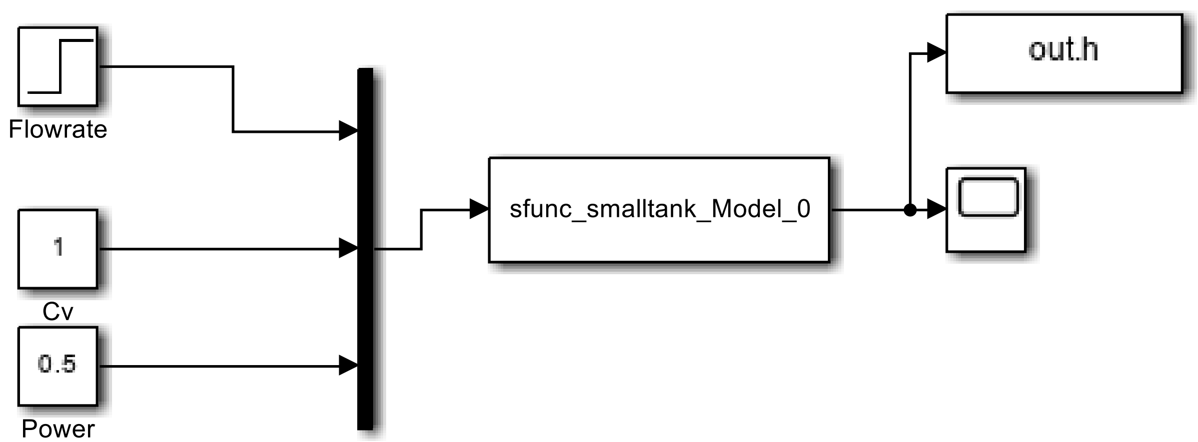

Figure 10. Basic Simulink model, S-function based, to experiment with "guess" values for the flowrate change, valve constant, and power factor (refer to equation 1)

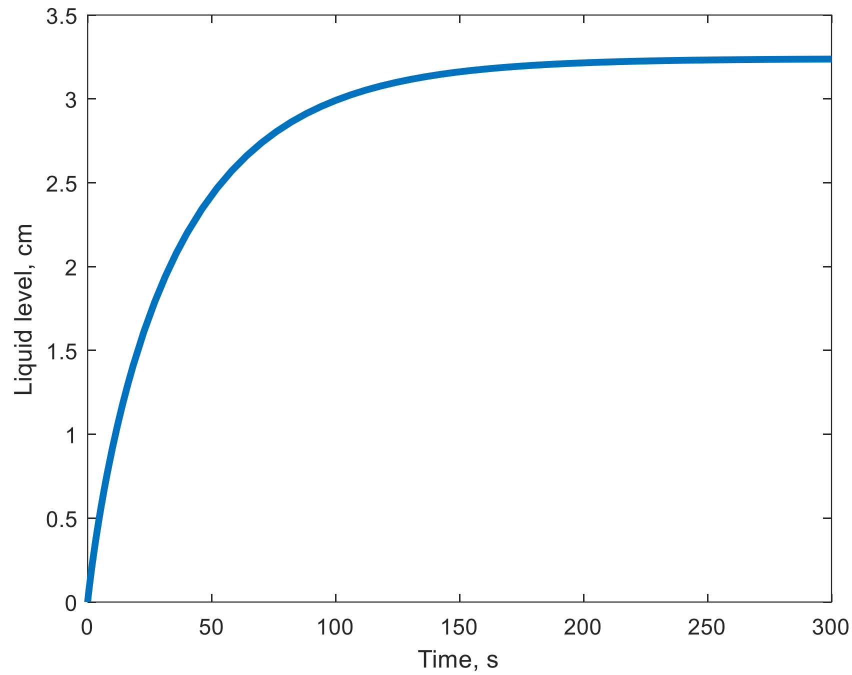

Figure 11. Characteristic reactive curve for a single step-change (i.e. “small tank” liquid level, referred above) generated with a model.

The same SIMULINK model is slightly modified (Figure 12) (see inlet/outlet ports “1” at the bottom) to allow a MATLAB statistical subroutine to estimate “best values” for fitting the data (Figure 13). In this example, the software reports C_{V3} = 1.0833, and p_{V3} = 0.1971. Certainly, this fitting can be performed with alternative software, including EXCEL Solver.

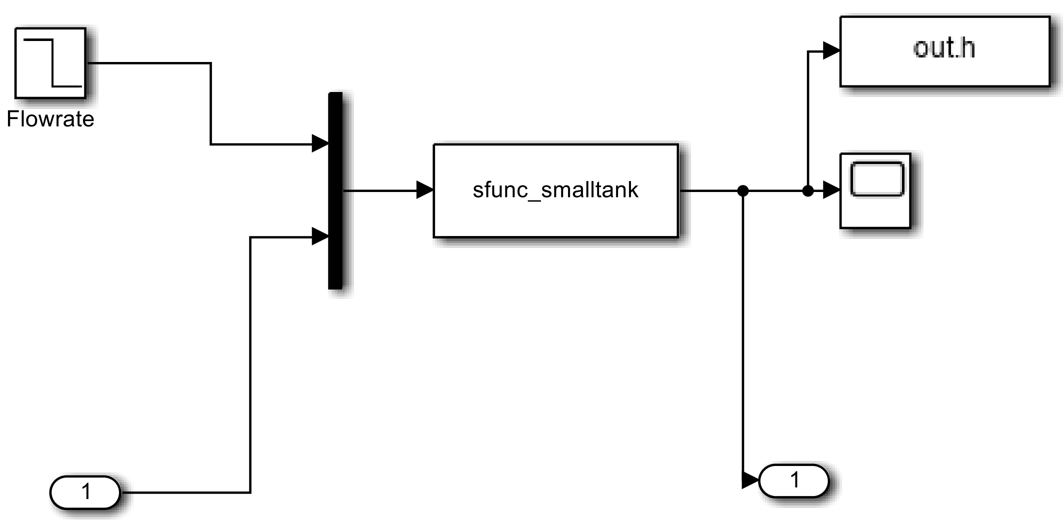

Figure 12. Simulink model to allow a statistical subroutine to estimate “best” values for the parameters (i.e., C_{V3}, p_3 in equation 1)

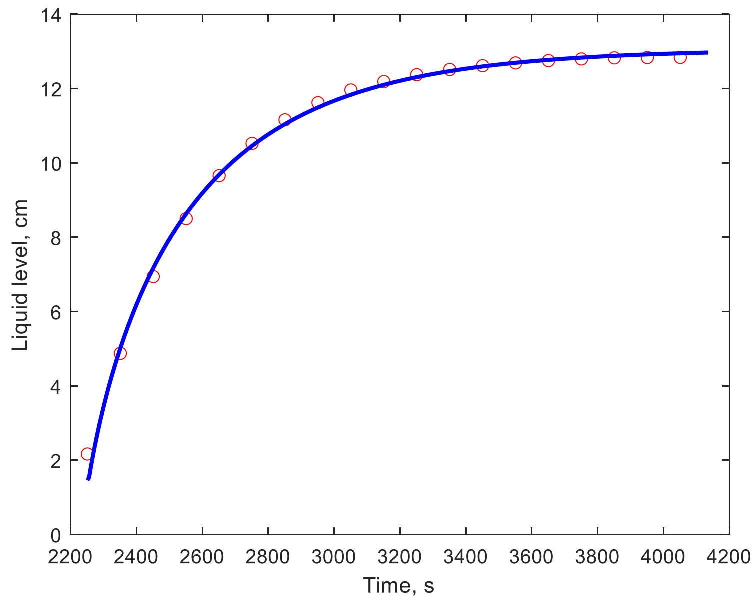

Figure 13. MATLAB statistical subroutines and SIMULINK S-function model fit the reactive curve for a single step change (small tank liquid level experiment). Red circles correspond to experimental data point; continuous blue line corresponds to adjusted model.

The same set of MATLAB subroutines and SIMULINK model can also estimate the “best value” for an entire experimental session with multiple sequential step changes, as illustrated in Figure 14.

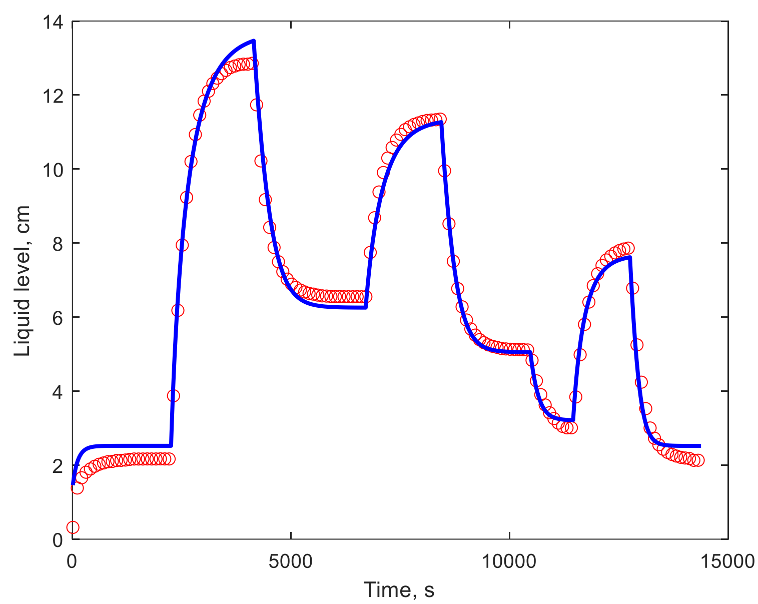

Figure 14. MATLAB statistical subroutines and SIMULINK S-function model fit the reactive curve for multiple step changes in sequence (small tank liquid level experiment). Red circles correspond to experimental data point; continuous blue line corresponds to adjusted model.

This analysis of the system dynamics is used to estimate the parameters in the models presented in equations 1-15, for ODE models and for Transfer function models, which can be interrelated by linearization (Taylor series expansion) of the ODE equations [11]. Experimental data presents some challenges to the uniqueness of the values and opens opportunities for discussion and analysis of the variations.

For the synthesis of PID controllers, data are collected in a similar way as illustrated in Table 8 for the small tank liquid level experiment. The steady state at time 5584 s (3.993 cm level high) is subjected to a set-point change from the 4 cm level to a level of 7 cm, tracked by a PI controller with a proportional gain (Kc) of 2 Amps/cm and an integral time (τ_I) of 50 s (and no derivative action) acting on the flowrate. A graphical representation is illustrated in Figure 15.

Table 8. Data sample from a small tank liquid level experiment under PI control. The status of the controllers (P: proportional, I: integral, D: derivative) are indicated as 0 for the off position and 1 for the on, Kc is the proportional gain, τ_I the integral time, and τ_D the derivative time constant)

Time (s)	Pump Amps	Height cm	Flowrate lpm	P on/off	I on/off	D on/off	Set point	Kc Amps/cm	τ_I s	τ_D s
5574	0.0100	3.9930	1.4230	1	1	0	4	2	50	0
5579	0.0100	3.9930	1.4240	1	1	0	4	2	50	0
5584	0.0100	3.9930	1.4240	1	1	0	4	2	50	0
5589	0.0160	4.1570	3.5050	1	1	0	7	2	50	0
5594	0.0160	4.6640	3.3370	1	1	0	7	2	50	0
5599	0.0150	5.0870	3.1930	1	1	0	7	2	50	0
5604	0.0150	5.4700	3.0510	1	1	0	7	2	50	0
5609	0.0140	5.7940	2.9240	1	1	0	7	2	50	0
5614	0.0140	6.0910	2.7950	1	1	0	7	2	50	0
5619	0.0140	6.3510	2.6710	1	1	0	7	2	50	0
5624	0.0130	6.5930	2.5440	1	1	0	7	2	50	0
5629	0.0130	6.8000	2.4250	1	1	0	7	2	50	0
5634	0.0130	6.9960	2.3000	1	1	0	7	2	50	0
5639	0.0120	7.1670	2.1800	1	1	0	7	2	50	0
5644	0.0120	7.3110	2.0670	1	1	0	7	2	50	0
5649	0.0120	7.4300	1.9620	1	1	0	7	2	50	0
5654	0.0110	7.5130	1.8760	1	1	0	7	2	50	0
5659	0.0110	7.5730	1.7990	1	1	0	7	2	50	0
5664	0.0110	7.6060	1.7380	1	1	0	7	2	50	0
5669	0.0110	7.6230	1.6850	1	1	0	7	2	50	0
5674	0.0110	7.6320	1.6380	1	1	0	7	2	50	0
5679	0.0100	7.6310	1.5960	1	1	0	7	2	50	0
5684	0.0100	7.6270	1.5570	1	1	0	7	2	50	0
5689	0.0100	7.6320	1.5120	1	1	0	7	2	50	0
5694	0.0100	7.6300	1.4720	1	1	0	7	2	50	0
5699	0.0100	7.6210	1.4360	1	1	0	7	2	50	0
5704	0.0100	7.5680	1.4320	1	1	0	7	2	50	0
5709	0.0100	7.5070	1.4370	1	1	0	7	2	50	0
5714	0.0100	7.4490	1.4440	1	1	0	7	2	50	0
5719	0.0100	7.3930	1.4540	1	1	0	7	2	50	0

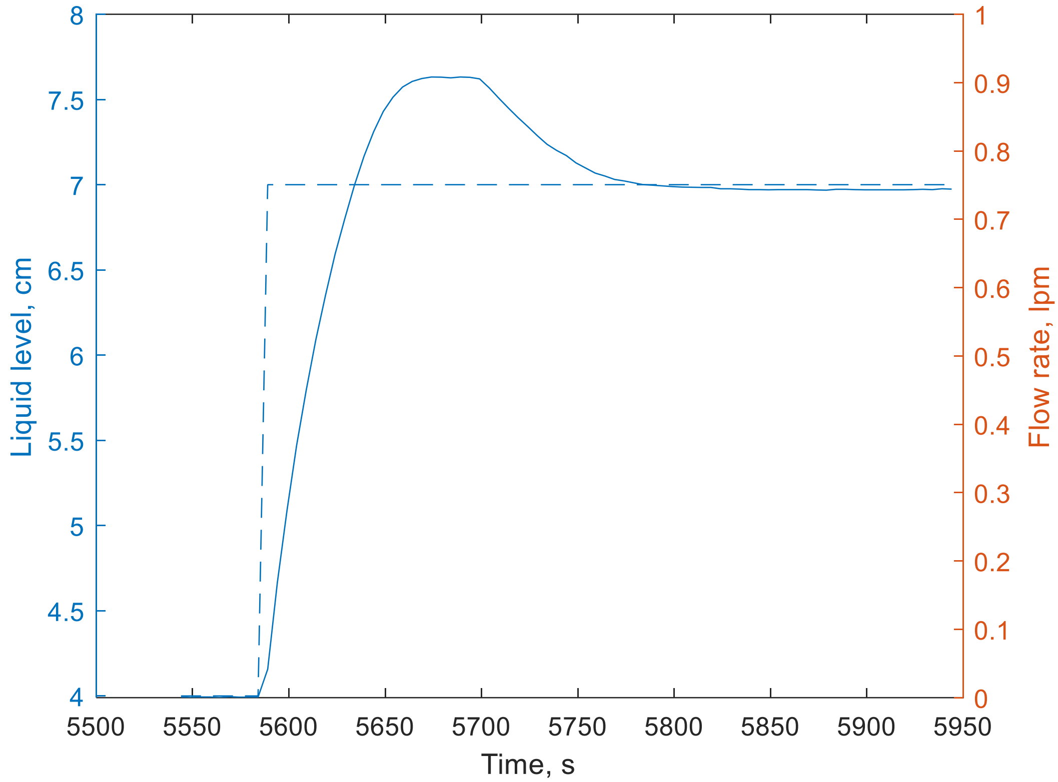

Figure 15. Experimental data for set-point change in liquid level of the small tank liquid level experiment under the action of a PI controller (Values reported in Table 8. The liquid level is the continuous curve, and the flowrate is the dashed line)

Students are then provided with a working SIMULINK model for the process control analysis. An example is depicted in Figure 16. The ODE model with the "best values" for the model parameters obtained in the previous analysis of dynamics is incorporated in the S-function included in the model. The control element (control valve, variable speed pump) is simulated by a polynomial P(u) derived from the calibration of the instrument. The mathematical performance of the polynomial is constrained with input and output saturation blocks corresponding to the range of the controller's signal (i.e., 0-10 mA) and to the physical limits of delivery of the control element (i.e., 0-4 lpm), and adjusted with a bias factor to replicate the baseline. The PID block allows for testing values for the proportional gain, integral and derivative time. The model in Figure 16 includes a step change block for the set point and another block for the disturbance variable, corresponding in this case to the second drain (see description of the equipment above). Another version of this model replaces the S-function with the corresponding transfer function also derived in the analysis of the dynamics, referred to above.

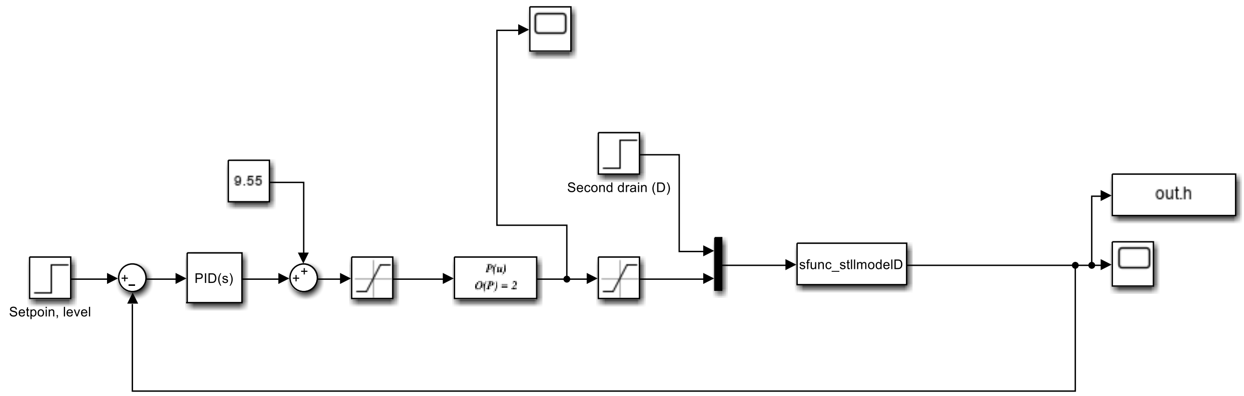

Figure 16. SIMULINK model for process control analysis of the small tank liquid level experiment

The SIMULINK models report the performance of the system under control as illustrated in Figure 17.

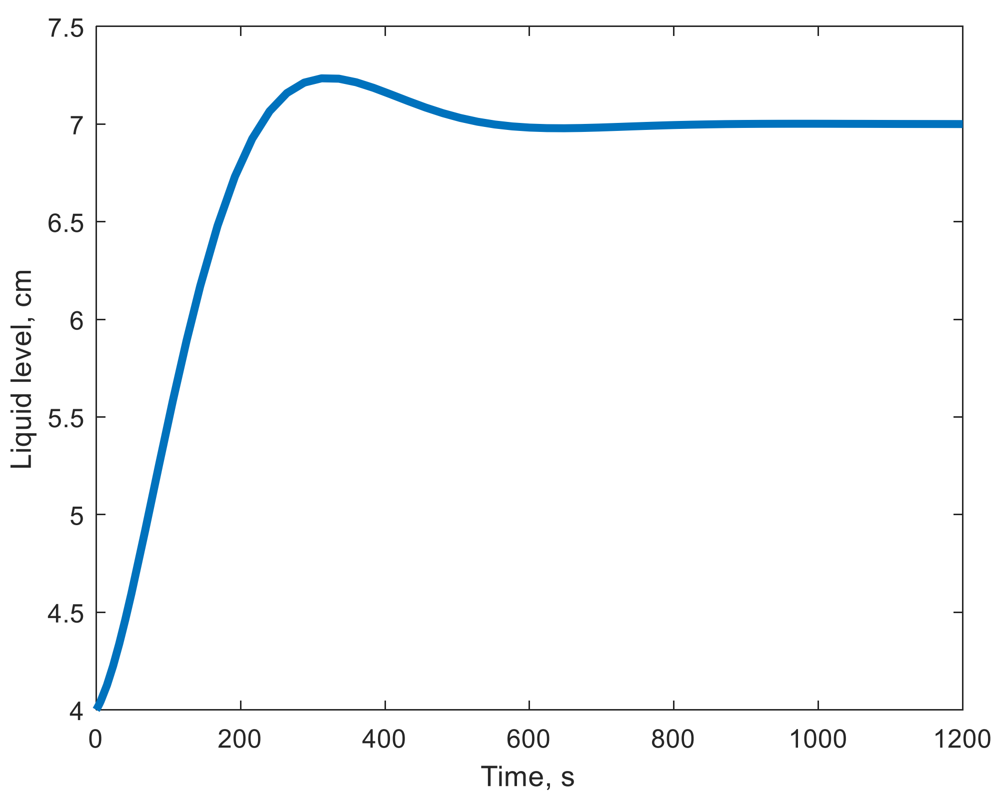

Figure 17. Performance of the SIMULINK model for the small tank liquid level experiment under control

Experimental data and model results can be analyzed for typical performance parameters (overshoot, rising time, settling time, period, etc.) and they can be used to synthesize PID controllers using model-based design methods, controller tuning relations, and on-line controller tuning [11], providing students with practical applications of the theoretical content in the process control course.

Teamwork strategies.

Our current strategy consists of establishing six teams of 5-6 members each. Each team is assigned one experiment for dynamics analysis during the first half of the term. In the second half of the term, the teams are focused on process control. Teams switch the type of experiment (liquid level or temperature control) by this second rotation, receiving the report on dynamics analysis from a previous team. Teams provide a critical review of the received report and decide on carry on with the models (Transfer function, ODE) derived by the previous team or adjust before moving into the process control analysis. Teams are also advised to structure leadership and work in three areas: (1) documentation on equipment, instrumentation, and industrial applications, (2) experimental plans, operation, data gathering, and analysis of results, and (3) computational modeling. Leadership roles need to rotate from the first to the second project. Teams are requested to develop a team contract at the beginning of the term. Teams are also asked to prepare a plan for each of the two projects (dynamics and process control) and to monitor each plan weekly. Peer grading and assessment is included at the end of both projects. Students deliver a self-assessment report at the end of the course with data on weekly time investment, main contributions, peer assessment, areas for improvement, and self-grade [14].

Assignments.

Student teams submit a comprehensive report at the end of each project. The report includes:

(a) introduction to the industrial applications related to the experiment,
(b) description of the laboratory process and equipment,
(c) development of the first principles derived theoretical model,
(d) collection and analysis of experimental data,
(e) fitting of the data with the developed models and the estimation of model parameters (i.e., valve constants, heat transfer coefficients) for the project on dynamics analysis,
(f) synthesis of PID controllers from various methods (model-based, tuning relations, on-line controller tuning) and comparisons,
(g) conclusions and recommendations
(h) appendices with exhibits of Matlab subroutines, Simulink block diagrams, and examples of software results

Teams are also requested to prepare a 15-minute presentation on the technical report.

Teams document the project management with the team contract, the monitored plan, and peer grading and assessment. In addition, individual students submit their self-assessment reports.

These assignments are selected to comply with three student outcomes in ABET Criterion 3:

- Outcome (5) "Ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives",

- Outcome (6) “Ability to develop and conduct appropriate experimentation, analyze, and interpret data, and use engineering judgment to draw conclusions”, and
- Outcome (7) “Ability to acquire and apply new knowledge as needed, using appropriate learning strategies.”

Summary of the assessment on consolidated learning.

This laboratory course has been designed to accompany a process control course where concepts, methods, and applications are presented to the students before they put them into practice in the lab. It is always a challenge to synchronize the two courses when taught by different professors. To allow for some initial progress in the process control course, the first week of the lab sessions is focused on team building strategies [15], and the second week focuses on the presentation of the Simulink software and the Matlab statistical subroutines, with detailed tutorials. During these first two weeks, students complete the self-selection of team members and advance the team contract and plan, following some recommended templates. Teams are randomly assigned with the corresponding experiments and provided with access to the lab manuals. Students also get access to the Matlab subroutines and Simulink models for initial exploring before starting lab experiments. The lab experiments for the project on dynamics analysis (conventionally referred to as the “open loop project”) run in the weeks 3-5 of the semester. Two additional weeks are provided to work on the reports and the presentations.

In week seven, after the completion of the first project on the dynamics analysis there is one lab session focused on explaining control instrumentation and the modeling of the final control element (control valve, variable speed pump). It is also the opportunity to introduce the “closed loop” models. Students get access to the software tools, and they are also provided with the reports from the teams who developed the dynamics analysis, with their proposed models and fitting parameters. The student teams review these documents, provide some professional critique, and decide on any adjustment to the models before further proceeding with the process control project (also referred to as the “closed loop project”).

Four weekly experimental sessions are available for student teams to generate data on controller synthesis and performance analysis. By the time they start with these sessions, generally they have not been exposed to controller synthesis by model-base, or on-line tuning, so they start experimenting with “guess” values, implementing in sequence online adjustments for the proportional gain, integral time, and derivative time. The progress in the process control course allows them to integrate the theory on process controller synthesis with lab results, and even to try some adjusted values in controller parameters derived from this knowledge into lab experiments. The final two weeks of the course are scheduled to complete the corresponding project reports, presentations, and team and individual teamwork assessments.

We have been evolving the approach for this lab course from an entirely open-ended team-based learning project (where students developed their experimental plans, models, and scope) into a more guided instructional approach (where students are presented with models and strategies for data collection and analysis, as presented above). The first approach is significantly more time demanding, with students reporting over seven weekly hours of work outside the lab. The second approach has been targeting one weekly hour of work outside the lab (currently around 2 hours). The first approach has shown more limited scope than the second approach, particularly in terms of methods to synthetize PID controllers.

Table 9 reports some selected assessments from students. In general, students report a satisfactory understanding of process control theory based on the work in the lab, improved skills at modeling processes, and being acquainted with process controller parameters and operation.

Table 9. Selected student assessments

"I did the Simulink and MATLAB models and compared with plots I made from the experimental data. I also wrote about the analysis of the experimental data and helped write about the model validation in the report. I feel like I did best in explaining some of the concepts behind what we observed in the lab because I am getting the opportunity to apply what I learned in class to real-world scenarios."
"My role in the project was computational leader, so I spent most of the time in lab understanding the S-function and SIMULINK models and discussing with the team what PID parameters may be best for the system based on the models. I could have done better getting a complete understanding of the model and knowing how to troubleshoot the errors exactly. Knowing exactly how to change the gain to get a better response for example or how to deal with complex transfer functions would go a long way for verifying the model. A major takeaway is to stay on top of everything and to integrate information quickly between the classes. Learning about PID controllers in CHE 0500 got delayed compared to the closed loop project, so taking what we learned in class and immediately applying it to lab would have helped me get a better understanding of what to do faster."
"My goal in the closed loop project was to thoroughly understand the Matlab and Simulink codes for the P, PI, and PID controllers. Not only would this help with my understanding in lab, but also with my understanding in class material since I am a hands-on learner. I worked on the results, model validation, and analysis sections of the report. I think what I did best was figuring how to connect all the codes, especially the R^2 code we used to analyze the predicted vs experimental data. I could have understood debugging issues with the S-Function Simulink better, and that is something I can do better next time is asking for help with that."
"Using the guess and check method is much less efficient. The major takeaways of this project are the sensitivity of the integral action and the importance of team feedback. Adjusting the integral component of the controller revealed how much the controller response would vary in terms of inverse responses, overshoot, and settling time. When first tuning the integral action, we noticed a significant settling time increase compared to proportional only action. Additionally, there was much more team input and feedback on this project compared to the open-loop project especially when discussing parameters and step changes to test. Requiring input from everyone led to better trials to collect specifics on each parameter."
"My goal was to have a working understanding of the experimental system and of the Matlab and Simulink applications of the transfer function and mathematical models. After in-lab troubleshooting, developing a plan of action, and observing the system's response, alongside leaning about controller tuning in class, and then reading over the last team's open-loop project report, I do feel that I gained this understanding. I also tackled the closed loop report more promptly than the open-loop report, which led to better success and less stress. The team distribution of work was also more even this report."

Proposal for collaboration.

This paper intends to offer a collaborative space (it could be named PCGAP for short of "Process Control Global Academic Partnership"). The authors propose to share data from experimental runs (supported by videos, pictures, and manuals), and the supporting software tools (Matlab subroutines, Simulink models), with process control faculty teaching courses to students with limited or no access to a process control lab. All this information brings students to a very close lab experience, only missing the actual handling of the equipment, but provided with visuals and data for a full understanding of the process, dynamics, and control. Faculty can adapt extensively these materials to the scope and time constraints of their courses. Faculty can select the choice of experiments and the extension of the work to request from students, from using the data and models for demonstration or requesting the development of models from scratch (depending on students' previous code training). Faculty can also decide on the various methods for the synthesis of PID controllers and the analysis of comparisons.

The data is available in EXCEL spreadsheets. Statistical subroutines and models are available in Matlab and Simulink. Faculty can take their students to develop similar approaches with other software (i.e., Python).

It is also possible to arrange for student teams at various colleges to explore collaborative work, and to run experimental plans on demand to validate or explore specific conditions. There is certainly room for improvement in the strategies for the teamwork, scope of assignments, structure of assessments, etc., for faculty to collaborate.

Conclusions.

Six experimental process control setups (three for liquid level control and three for temperature control) have been presented. They include tanks (single, cascade) and heat exchangers (internal coil, double-pipe, shell-and-tube). They are designed to train students in process dynamics and control, covering the scope of college engineering courses in process control, providing hands-on experience for process modeling and process controller synthesis that has been proved to be a major concern on engineering education in this field.

An initiative is proposed to share the available experimental data, documentation, and software tools to make this experiential learning available to faculty teaching students with limited or no access to process control lab. Faculty can explore extensive room for selection and adaptation in content and scope, to better fit this experience to their course plans.

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