



## Temperature and Level Control of a Multivariable Water Tank Process

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# Temperature and Level Control of a Multivariable Water Tank Process

## Abstract

The project is concerned with the design of a water tank process and experimental evaluation of feedback control structures to achieve water level and temperature control at desired set point values. The manipulated variables are the pump power, on the water outflow line, and heat supply to the tank. Detailed, first principles-based, dynamic models as well as empirical models for this interactive and multivariable process have been developed and used for controller design. Furthermore, this experimental study entails and discusses the design of the water tank process and associated instrumentation, real time data acquisition and control using the DeltaV distributed control system (DCS), process modeling, controller design, and evaluation of the performance of tuning methodologies in a closed loop manner. This student work was submitted in partial fulfillment of the requirements for the Senior Project in Controls and Instrumentation course at the Engineering Technology department of the University of Houston - Downtown.

## 1. Introduction

The Control and Instrumentation program at the University of Houston - Downtown includes a number of courses on process control, process modeling and simulation, electrical/electronic systems, computer technologies, and communication systems. To meet graduation requirements for the degree of Bachelor of Science in Engineering Technology, students must work in teams and complete a capstone project. This project, also called Senior Project in our terminology, provides students with an opportunity to work on complex control problems, similar to ones encountered in the industry, and employ a number of technologies and methods to provide a practical solution.

In general, the Senior Project entails the design and construction of a process, identification of key control objectives, specification and implementation of required instrumentation for process variable(s) monitoring and control, real time data acquisition and storage methods, modeling of the process using empirical and/or analytical methods, design and tuning of controllers, and closed loop control performance evaluation.

Equally important to these technical requirements are a number of non-technical requirements focusing on project management, technical writing, presentation of technical topics, teamwork and communication. This paper presents the results from a senior project which aims to simultaneously control the level and temperature of water in a tank. Such objectives are important to the process industries concerned with materials and energy control.

The remaining of the paper is organized as follows. Section 2 discusses the process under consideration and the control objectives. Section 3 refers to the instrumentation required to measure and control key process variables. Section 4 presents the computing platform which is a distributed control system (DCS). Section 5 presents the dynamic modeling results based on first principles. Section 6 presents empirical modeling, tuning and closed loop results for the water level and temperature. Section 7 summarizes main results and is followed by references.

## 2. The Process and Control Objectives

A schematic of the process is shown in Figure 1. The water tank has a constant cross sectional area. The water height is being affected by the flow in and the flow out. The flow in to the tank is not available for control purposes but can be manually adjusted to simulate a process disturbance. The water outflow depends on the power supplied to the pump which is available for manipulation and control of the water level in the tank. A heating element provides the required energy to maintain a desired water temperature by adjusting the electrical power to it.

The control objective is to maintain the water level (measured by transmitter LT) and temperature (measured by transmitter TT) at desired setpoint values using closed loop feedback control strategies which employ PI controllers (LC and TC, respectively) on a Delta V distributed control system. Figure 2 shows the control strategy to achieve this objective.

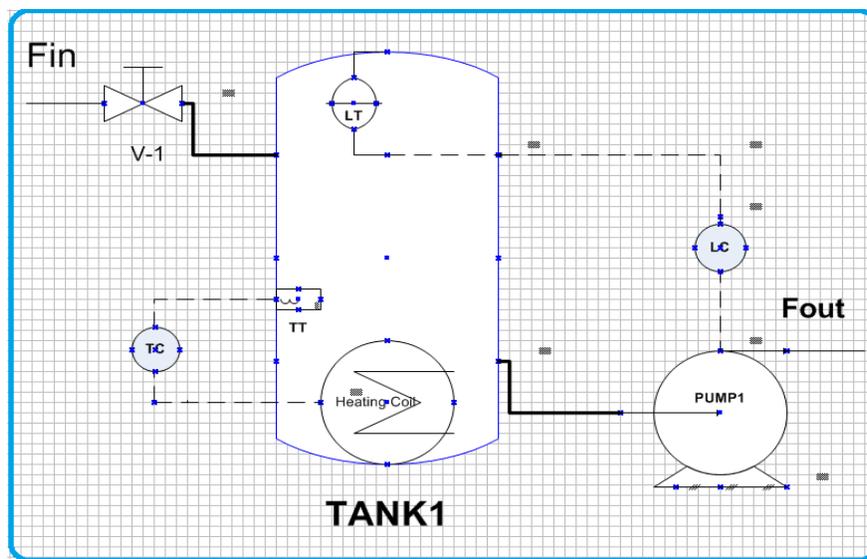


Fig. 1: Schematic of the Water Tank

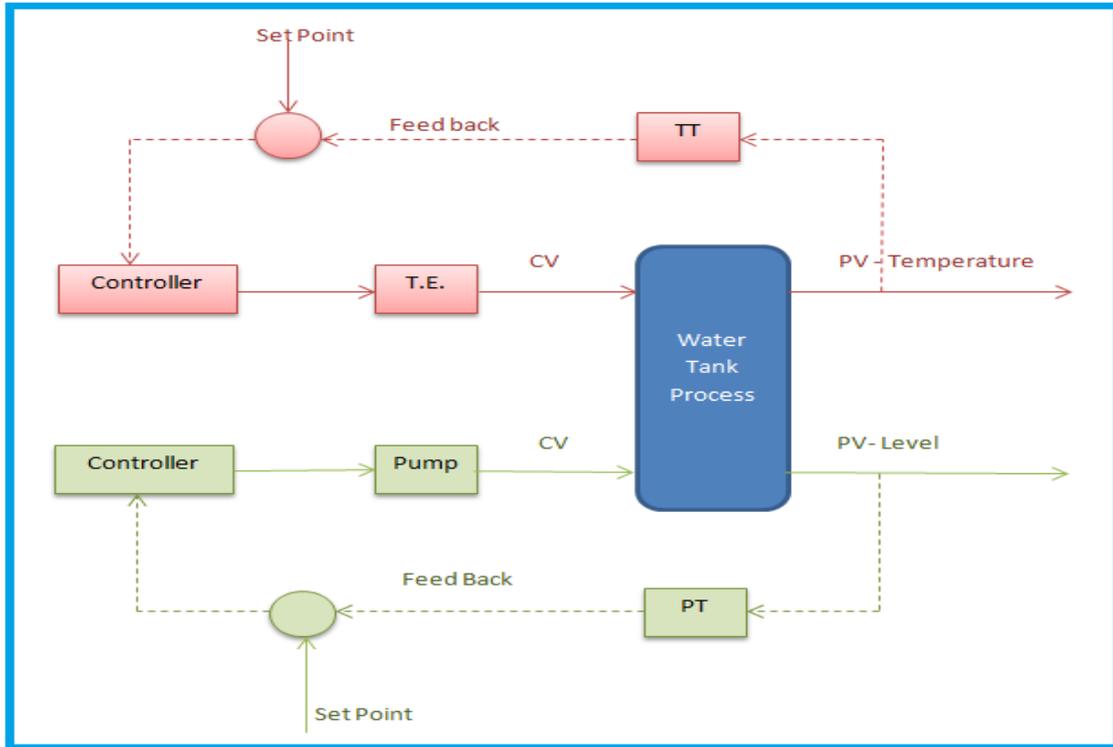


Fig. 2: Control Strategy for the Water Tank

As shown in Figure 2, one PI controller is used to maintain material inventory (i.e. water level) in the tank by adjusting the power to the pump. Also, another PI is used to control the water temperature at a desired setpoint value by adjusting the power to the heating element.

### 3. Process Instrumentation

A metal tank of 39 gallon capacity is used to hold water. To achieve water level and temperature control, a number of instruments are used. Water level is measured using a general purpose EchoPod DL14 sensor with 4-20mA signal output. For the purpose of this project the level transmitter is calibrated to read up to 25 inches maximum. The level transmitter is connected to the DCS input card. Figure 3 shows a picture of the level sensor.



Fig. 3: Echo Pod DL14 Level Sensor

To control the water level, by adjusting the flow out from the tank, a pump is used. The particular pump for this project is an Attwood Tsunami Aerator pump (Figure 4). The Attwood Tsunami pump uses a 12-volt, 3-amp DC power supply.



Fig. 4: Attwood Tsunami Aerator Pump

A pulse width modulation (PWM) circuit is used to adjust the speed of the DC motor to manipulate the flow out from the tank, which in turn controls the level of the tank. A LM324 IC based PWM circuit is used to control the speed of the motor. The PWM circuit converts in coming 1 to 5 volt signal to an average 0 to 12 volt output to control the speed of the motor. The 4 to 20 mA output from the DeltaV is converted to a 1 to 5 volt signal using a resistor in parallel with the output. This 1 to 5 volt signal serves as the reference voltage for the PWM circuit. The circuit compares the reference voltage to an internally generated saw tooth voltage to control the average output to the motor. The average voltage output to the motor depends on the width of the 12 volt pulses that are send to the motor.

Water temperature is measured using a Type K thermocouple with a sensitivity of approximately  $41 \mu\text{V}/^\circ\text{C}$  (Figure 5)



Fig. 5: HTTC36-K-18G-6 K Type Thermocouple

The power to the heating element is controlled using a zero crossing Watlow controller (Figure 6). The Watlow controller takes 4 to 20 mA as input and determines the number of cycles reaching the heating element from a 60 Hz alternating current depending on the input to achieve continuous control of the heater. The power for the heating element comes from a 20 Amps, 220 Volt, 2 Phase disconnect switch. The maximum power that can be drawn by the heater is limited by the disconnect switch.



Fig. 6: Watlow DIN-A-MITE Power Controller

#### 4. The Control Platform

The control system used for this project is Emerson DeltaV Distributed Control System. This control system uses a standard PC hardware for user interfaces, paired with proprietary controllers and I/O modules to control numbers of control loops. This hardware can be distributed throughout a process plant connected through Foundation Fieldbus modules. The I/O cards used for this process are analog input cards, analog output card and one thermocouple card. A basic DeltaV system overview is shown in Figure 7. Detailed information for this type of DCS can be found at Emerson's website ([www.emerson.com](http://www.emerson.com))

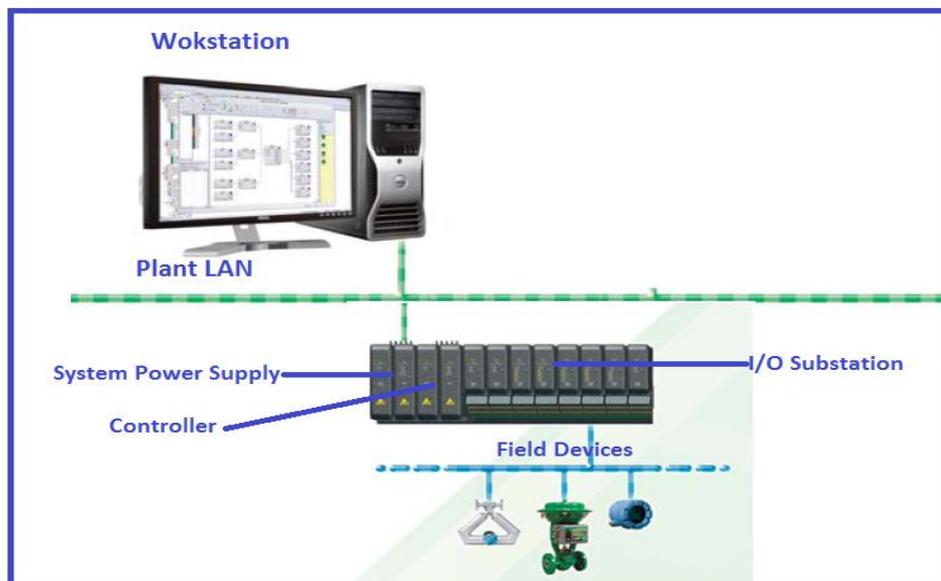


Fig. 7: DeltaV System Overview <sup>1</sup>

The strategy for level and temperature control has been implemented using two PI controllers. Part of the system configuration and implementation is the development of a user interface which allows the user to oversee the control of the tank process. Figure 8 shows this user interface along with the faceplates of the level and temperature controllers. Using these faceplates, the user can change the mode of the controllers (Auto/Manual), adjust the setpoint of the controllers (in auto mode) or the controller output (when in manual mode), and even fine tune the controllers by specifying the values for the proportional gain and integral time (or reset in DeltaV terminology). Details on system configuration and interface development are beyond the scope of this work and thus omitted.

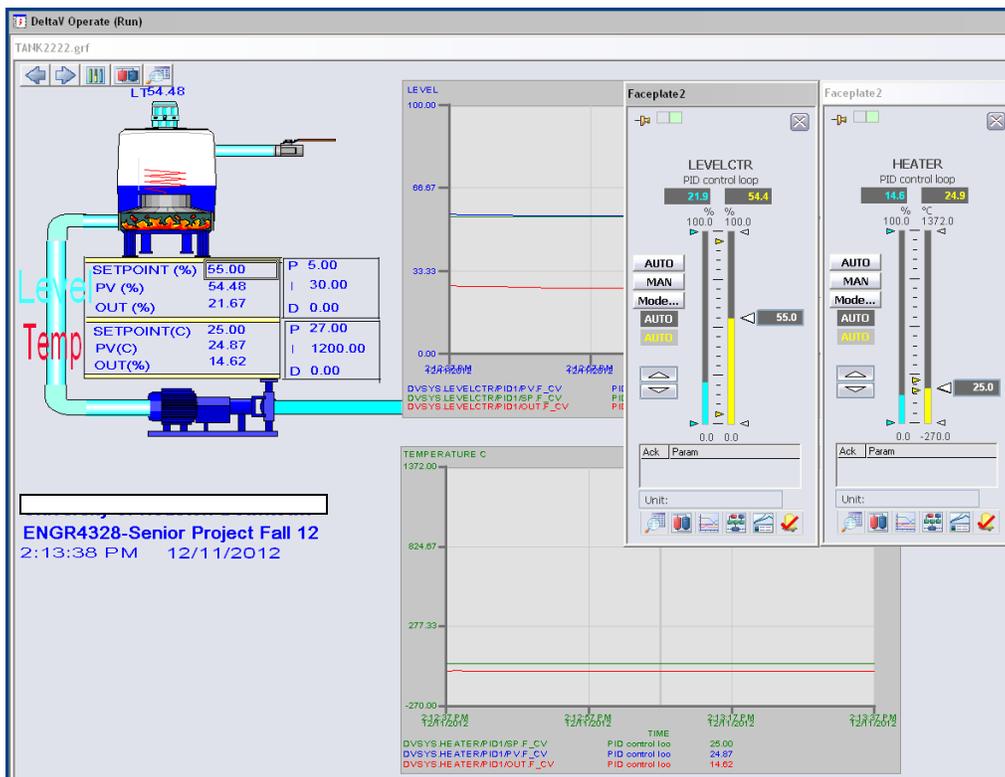


Fig. 8: Operator Interface with Controller Faceplates and Trending Capabilities

## 5. Analytical Modeling

In order to design and tune the level and temperature controllers, models describing the impact of pump power on level and heating element power on temperature are required. Such models can be developed using empirical methods (i.e. step testing the process) or analytically using material and energy balances. The development of the analytical models is described in the following for the water level and temperature.

### 5a. Level Model

Referring to Figure 1, the two inputs to this model are the water flow in,  $F_i$ , and flow out,  $F_o$ , from the tank. Assuming constant water density,  $\rho$ , and tank cross sectional area,  $A$ , a material balance around the tank yields:

$$\{\text{Accumulation of mass}\} = \{\text{mass in}\} - \{\text{mass out}\}$$

$$\frac{d(m)}{dt} = \rho * F_i - \rho * F_o$$

But,

$$m = \rho * V = \rho * A * h$$

Then,

$$\begin{aligned} \frac{d(\rho * A * h)}{dt} &= \rho * F_i - \rho * F_o \\ \rho * A * \frac{d(h)}{dt} &= \rho * F_i - \rho * F_o \\ \frac{d(h)}{dt} &= \frac{F_i}{A} - \frac{F_o}{A} \end{aligned}$$

If,

$$F_o = K_v V_v$$

where  $K_v$  is the pump constant and  $V_v$  is the pump power in % of scale

then

$$\frac{d(h)}{dt} = \frac{F_i}{A} - \frac{K_v V_v}{A} \quad (1)$$

Equation (1) is the time domain model between the water level,  $h$ , and the flow in and pump power (in % of scale). To develop the transfer function, equation (1) is Laplace transformed which yields:

$$S * h(s) = \frac{1}{A} F_i(s) - \frac{K_v}{A} * V_v(s)$$

or

$$h(s) = \frac{1}{A*s} F_i(s) - \frac{K_v}{A*s} V_v(s) \quad (2)$$

From equation (2), the transfer function between tank level,  $h$ , and pump power is:

$$\frac{h(s)}{V_v(s)} = -\frac{K_v}{A \cdot s} \quad (3)$$

Since data is gathered every 5 seconds, a time delay of 5 sec (or 0.083 min) is added to the level transfer function. Thus, to tune the PI controller, the transfer function in equation (4) is used:

$$\frac{h(s)}{V_v(s)} = -\frac{K_v \cdot e^{-0.083s}}{A \cdot s} \quad (4)$$

For the water tank, the following operating data applies:

Cross sectional area, A:	225 in <sup>2</sup>
Maximum level, h:	25 in
Max pump flow, F <sub>o,max</sub> :	100 gph = 1.67 gpm
Pump constant, K <sub>v</sub> :	0.0167 gpm/% speed = 3.85 in <sup>3</sup> /min/%speed

Using this data, equation (4) yields:

$$G_{PL,A}(s) = \frac{h(s)}{V_v(s)} = -\frac{K_v \cdot e^{-0.083s}}{A \cdot s} = -\frac{0.0684 \cdot e^{-0.083s}}{s} \quad (5)$$

Thus, Equation (5) gives the transfer function between the water level (in %) and the pump power (in %). It can be used to tune the level PI controller according to any chosen tuning methodology.

### 5b. Temperature Model

The model describing the effect of power to the heating element on the water temperature is derived by combining material and energy balances. Also, the following assumptions are being made:

- Water density and heat capacity remain constant
- There is perfect water mixing in the tank
- The water level is kept constant (i.e. flow in = flow out)
- The tank cross sectional area is constant
- The inlet water temperature is constant
- Heat losses to the surroundings are minimal

Then, using the previous assumptions, an energy balance around the tank gives:

$$\frac{d(m \cdot c_p \cdot T)}{dt} = \rho \cdot c_p \cdot F_i \cdot T_i - \rho \cdot c_p \cdot F_o \cdot T + K_h \cdot P_h$$

where:

m:	water mass in tank
c <sub>p</sub> :	water heat capacity
ρ:	water density
F <sub>i</sub> :	water flow in
T <sub>i</sub> :	inlet water temperature
F <sub>o</sub> :	water flow in
T:	water temperature
K <sub>h</sub> :	gain of power to heating element
P <sub>h</sub> :	power to heating element (in % of scale)

Since:

$$m = \rho \cdot A \cdot h$$

Then:

$$\rho \cdot c_p \cdot A \cdot h \cdot \frac{dT}{dt} = \rho \cdot c_p \cdot F_i \cdot T_i - \rho \cdot c_p \cdot F_0 \cdot T + K_h \cdot P_h$$

or

$$A \cdot h \cdot \frac{dT}{dt} = F_i \cdot T_i - F_0 \cdot T + \frac{K_h}{\rho \cdot c_p} \cdot P_h$$

or

$$\frac{A \cdot h}{F_0} \cdot \frac{dT}{dt} = \frac{F_i}{F_0} \cdot T_i - T + \frac{K_h}{\rho \cdot c_p \cdot F_0} \cdot P_h$$

Since, it is assumed that the level is held constant,  $F_i = F_0$ . Then,

$$\frac{A \cdot h}{F_0} \cdot \frac{dT}{dt} = T_i - T + \frac{K_h}{\rho \cdot c_p \cdot F_0} \cdot P_h$$

Assuming deviation variables,  $T_i$  to remain constant, and Laplace transforming the above equation, it yields:

$$\left(\frac{A \cdot h}{F_0}\right) \cdot s \cdot T(s) = -T(s) + \frac{K_h}{\rho \cdot c_p \cdot F_0} \cdot P_h(s)$$

or

$$\left[\left(\frac{A \cdot h}{F_0}\right) \cdot s + 1\right] \cdot T(s) = \frac{K_h}{\rho \cdot c_p \cdot F_0} \cdot P_h(s)$$

or

$$G_{PT,A}(s) = \frac{T(s)}{P_h(s)} = \frac{\frac{K_h}{\rho \cdot c_p \cdot F_0}}{\left(\frac{A \cdot h}{F_0}\right) \cdot s + 1}$$

The above equation gives the analytically derived transfer function between the power to the heating element (in % of scale) and water temperature. Using the steady state conditions for the water tank as shown in Table 1, the following analytical process model is obtained:

Table 1: Water Tank Data

Water Tank Steady State Conditions		
Variable	Value	Units
Water flow out	61.6	in <sup>3</sup> /min
Water heat capacity	4.18	J/(g K)
Water density	1	g/cm <sup>3</sup>
Water height (%)	50	%
Tank cross sectional area	225	in <sup>2</sup>
Maximum power to heating element	840	W
Heating element power gain	504	J/(min %)

$$G_{PT,A}(s) = \frac{T(s)}{P_h(s)} = \frac{0.12}{45.65 \cdot s + 1} \quad (6)$$

Thus, the process gain is 0.12 C/% while the time constant is 45.65 min.

## 6. Empirical Modeling, Tuning, and Closed Loop Control

Empirical models between controlled and manipulated variables are being developed by collecting and analyzing process data gathered under controlled, open loop conditions by stepping the manipulated variables. Using such models and certain tuning methods, initial tuning parameters for the water level and temperature PI controllers are calculated. Finally, the closed loop performance of the PI controllers is tested for setpoint changes and the interaction of the two control loops is being accessed.

### 6a. Empirical Modeling for Level Controller

The water tank level is held constant by equalizing the water flow out and the flow in. Then, the flow out is changed in a step wise manner and the level response is being observed. A series of step changes is introduced while the water level is maintained within range. As expected, the level behaves like an integrating (or ramp) process. Using step test data, an average time delay (in min) and gain ( in % of level/min per % of power) were calculated. These values are as follows:

Level Process Gain:

$$K_{PL} = 0.073 \frac{\%level / min}{\% power}$$

Level Time Delay:

$$\theta_L = 8.5 \text{ sec} = 0.14 \text{ min}$$

Thus the empirical transfer function between the tank level and the pump speed is:

$$G_{PL,E}(s) = -\frac{K_{PL} \cdot e^{-\theta_L \cdot s}}{s} = -\frac{0.073 \cdot e^{-0.14 \cdot s}}{s} \quad (7)$$

By comparing the analytical transfer function, equation (5), and the empirical transfer function, equation (7), there is good agreement between both methods for this particular process. To tune the PI level controller the model given by equation (7) is used.

### 6b. Tuning the Level PI Controller and Closed Loop Results

Using the IMC tuning method<sup>2</sup>, and for various values of the closed loop time constant,  $\square_c$ , the tuning parameters are shown in Table 2 with the integral time in seconds as required by DeltaV.

Table 2: Level Controller Tuning using the IMC Method

$\tau_c$ (s)	$K_{CL}$ (%speed/%level/min)	$T_{I_{CL}}$ (s)
8.5	73.32	25.2
17	54.35	42.0
25.5	42.80	58.8
34	34.5	76.5
42.5	29.89	92.4
51	25.95	109.2

Based on the data shown in Table 2, it is concluded that as the desired closed loop time constant increases, the tuning of the controller is less aggressive (lower gain and longer integral time). Figure 9 shows the closed loop control of the tank level for various tuning parameters which correspond to different values of the closed loop time constant that varies from 8.5 to 51 seconds. Note that the horizontal axis represents process time in military time units while the vertical axis goes from 0% to 100% and can be used both for the level and the pump power. Thus, in Figure 9, it is demonstrated that as the desired closed loop time constant increases, the level response to a step change in the level setpoint is more sluggish while the movement of the manipulated variable (pump power) is reduced.



Fig. 9: Level Control for Different  $\tau_c$  Values

By comparing the different system responses, it seems that when  $K_c = 34.5$  and  $\tau_I = 76.5$ , the level responds very well to setpoint changes. However, the manipulated variable response is still very noisy. By filtering the level measurement using a filter with time constant of 10 seconds, the closed system response is improved (Figure 10). The reduction in the movement of the manipulated variable (pump power) is noticeable.

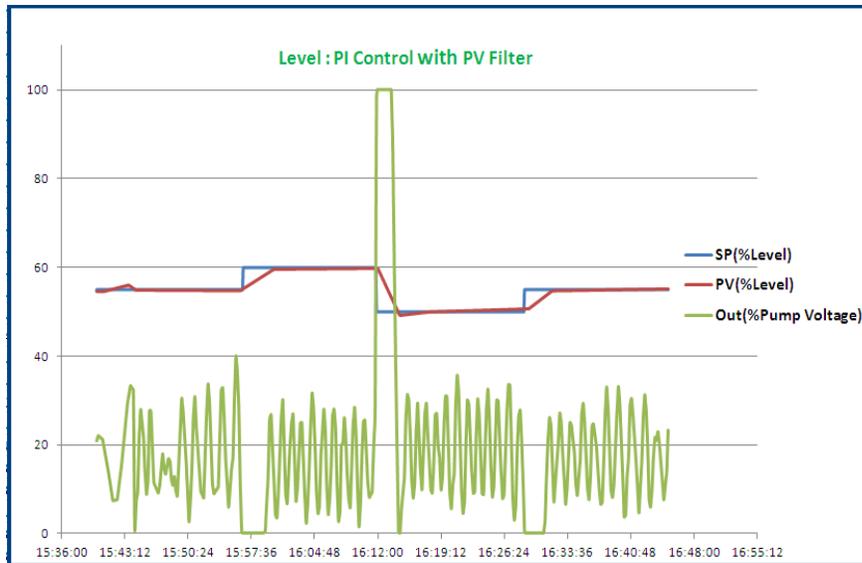


Fig. 10: Level response when  $K_c = 34.5$  and  $\tau_I = 76.5$  with level filter of 10 s

In spite of the performance improvement achieved, as shown in Figure 10, by filtering the controlled variable (level), it appears that the controller is still tightly tuned. Further manual adjustments to the tuning parameters yield the response shown in Figure 11. The conclusion is that using modeling techniques and appropriate tuning methods, good initial tuning parameters can be obtained. However, final manual adjustments may be required to further improve closed loop control performance.

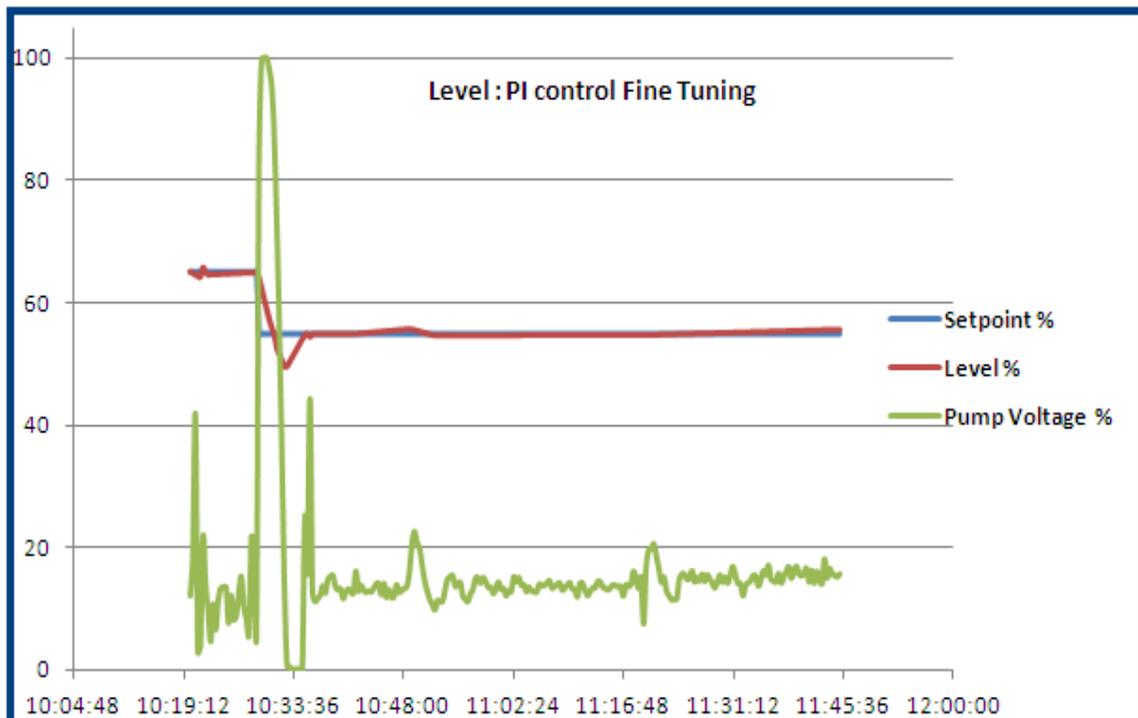


Fig. 11: Level response with manual tuning ( $K_c = 5$  and  $\tau_I = 30$  s)

### 6c. Empirical Modeling of Water Temperature

A number of step changes are made to the power to the heating element and the water response is observed. The response was modeled as that of a self-regulating process as shown in Figure 12.

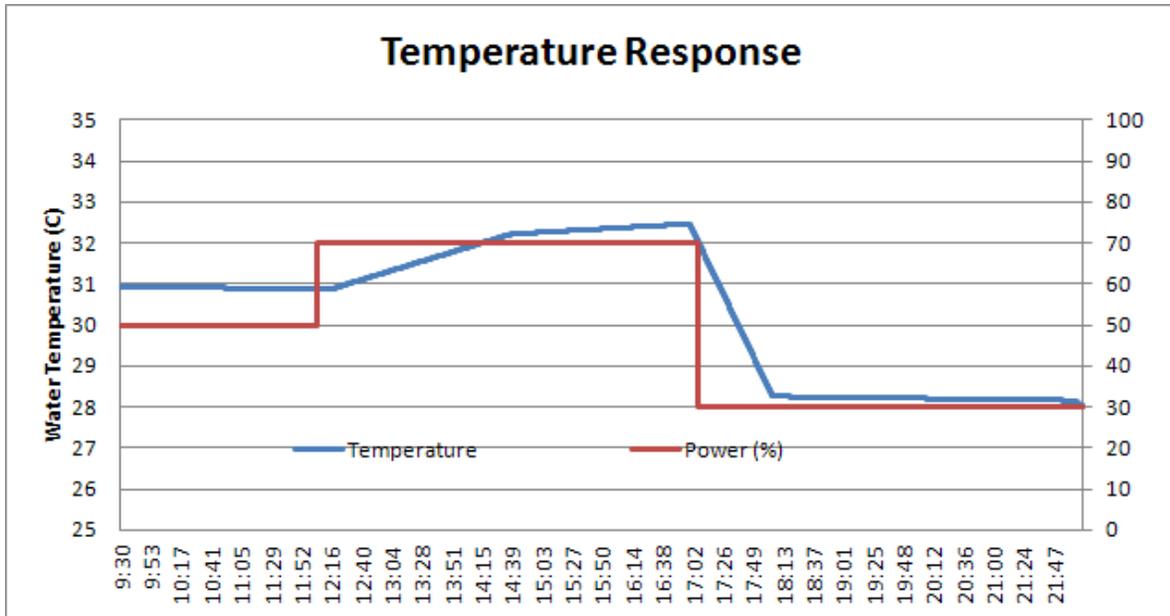


Fig. 12: Temperature response to heating element power changes

Using the process reaction curve method<sup>3</sup>, the calculated parameter values for a first order plus dead-time model, as shown in equation (8), are:

$$G_{PT,E}(s) = \frac{T(s)}{P_h(s)} = \frac{K_p \cdot e^{-\theta \cdot s}}{\tau_p \cdot s + 1} \quad (8)$$

Process gain:	$K_p = 0.0938 \text{ C/\% power}$
Time constant:	$\tau_p = 54 \text{ min}$
Time delay:	$\theta = 3 \text{ min}$

Comparing the analytical and empirical temperature models from equations (6) and (8), respectively, it is concluded that there is good agreement.

### 6c. Tuning the Temperature PI Controller and Closed Loop Results

Table 3 shows tuning parameters for a PI controller using the IMC tuning method for various values of the desired closed loop time constant when the empirical model is used.

Table 3: Tuning Results for Temperature Control Loop Using Empirical Model

$\tau_C$ (min)	k	$\theta$ min	$\tau_{MIN}$	$k_c$	$\tau_{lmin}$	$\tau_{Isec}$
3	0.093821406	3	54.45748	96.73961	54.45748	3138
6	0.093821406	3	54.45748	64.49308	54.45748	3138
12	0.093821406	3	54.45748	38.69585	54.45748	3138
18	0.093821406	3	54.45748	27.63989	54.45748	3138
24	0.093821406	3	54.45748	21.49769	54.45748	3138

Based on the open loop transfer of the temperature, it is expected that the temperature loop will respond slowly. Indeed, using the tuning parameters,  $K_C = 96.7$  and  $\tau_I = 3138$  seconds, the response of the temperature to setpoint changes is very slow. By adjusting the integral time from 3138 seconds to 850 seconds, the closed loop response of the temperature to setpoint changes is improved considerably as shown in Figure 13. The temperature reaches its new setpoint of 26 C in about 30 minutes. Again, the point is that the modeling and tuning of the temperature controller yields suitable initial tuning parameters but manual fine tuning may still be required. Especially, this is important for industrial applications. Tuning results from commercial tuning packages cannot blindly be used on the real process. Fine tuning of the online controller and evaluation of its closed loop performance by a knowledgeable engineer is typically required.

Also, in Figure 13, the water level is shown. The level PI controller maintains tight level control. When a level setpoint change from 55% to 60% is introduced at time equal to 16:50pm, the temperature control loop is being affected. The temperature, initially, drops but the PI controller responds quickly to bring it back to its setpoint of 26 C. Thus, there is interaction between the two control loops but the controllers have been tuned such that this interaction is acceptable.

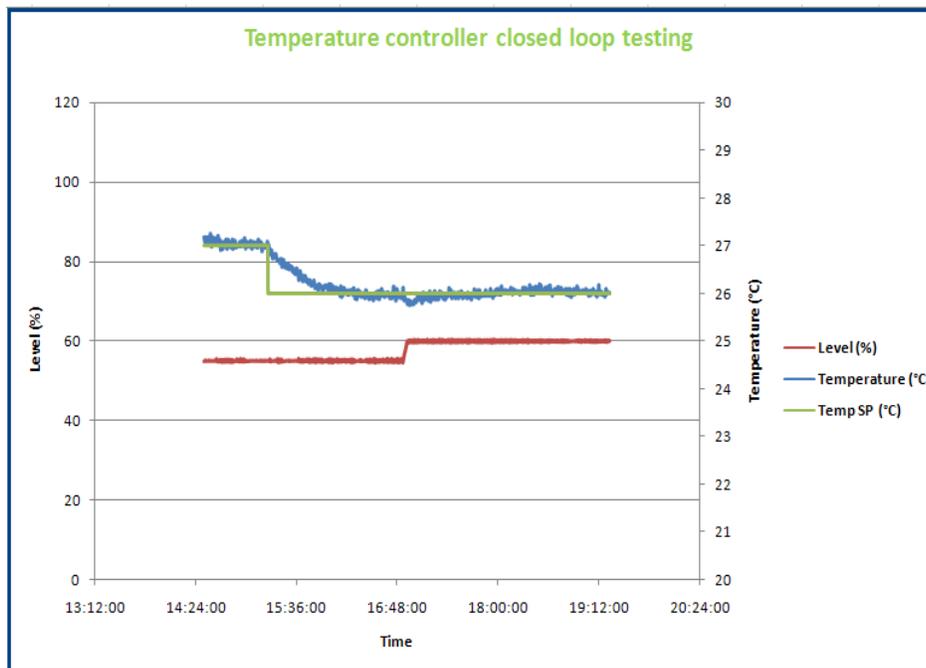


Fig. 13: Temperature Response when  $K_c = 95$  and  $\tau_I = 850s$

If the temperature controller were tuned using the analytical model, the tuning parameters would be:  $K_c = 63$  and  $\tau_i = 720s$ . Figure 14 shows the closed loop temperature response to a setpoint change of 1.5 C when the tuning is done using the empirical model (red line) and the analytical model (green line). Even though the response using the analytical model is slower compared to that when using the empirical model, it is apparent that both models yield tuning parameters which result in acceptable closed loop temperature control.

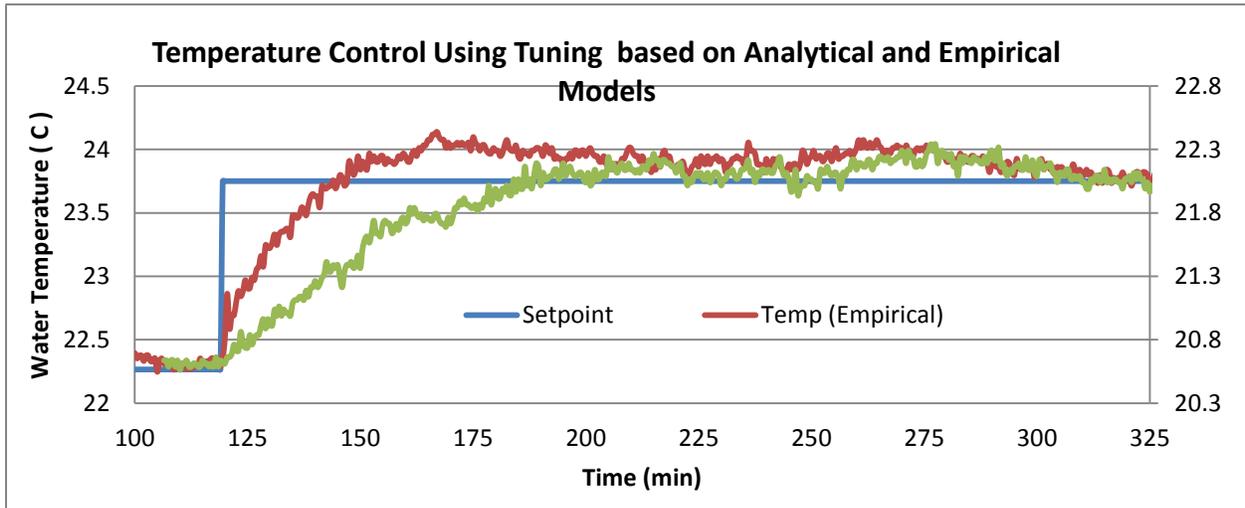


Fig. 14: Temperature Response with Tuning based on the Empirical and Analytical Models.

## 7. Conclusions

The paper was concerned with the design of two feedback, single input/single output control structures to control an interactive, multivariable, experimental process. The controlled variables are the tank water level and temperature. Modeling results using analytical, first principles based methods, and empirical, step test based, approaches were presented. There was close agreement between the analytical and empirical models. Tuning of the PI controllers was done using the IMC method. For improved closed loop performance, fine tuning of the PI controllers was required.

This work was performed in partial fulfillment of the requirements of the Senior Project course in Controls and Instrumentation of the Engineering Technology department at the University of Houston – Downtown. The work was completed in a semester’s time. By completing this work, students demonstrated proficiency in a number of technologies and methods including: process design, instrumentation, DeltaV distributed control systems, process modeling, controller tuning, and closed loop control systems implementation.

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