REPORT
ON

BATCHSAM Process and DeltaV

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Introduction

The BATCHSAM Process and DeltaV Closed and Open Loop Experiments were conducted on February 9, 2017. Using the DeltaV control and monitoring computer system, experimenters measured the tank level, inlet flow rate, and outlet flow rate of the feedback control system shown in Figure 1.

The purpose of the experiments is to explore and analyze the feedback control system using graphical and mathematical modeling techniques. The experiments consist of transitioning the system from one steady state to another by changing tank level set points or inlet flow rates. Results were analyzed using semi-theoretical models developed by experimenters.

Table of Contents

Figures and Tables

Discussion

Before distributed control systems were implemented in the process industry, many different versions of control systems were used. Initially, operators had to observe a process and manually control it. This was inaccurate and cumbersome, so local controllers were created. These were attached directly to the process in order to control it. This allowed operators to handle several process loops, however, making adjustments was time-consuming and unreliable. To try and reduce the number of operators required to control a system, pneumatic controls were created.

Pneumatic control systems converted process variables to pneumatic signals and transmitted to remote controllers [2]. These controllers performed simple calculations based on the set point and the process variables. This allowed the controllers to adjust the final control element. Unfortunately, it was very expensive and time-consuming to make any changes to the system, therefore analog electronic controllers replaced pneumatic ones. These analog controllers were accurate and fast-acting, but were very difficult to expand. The entire system was wired by hand, so large changes to the system required long shut down periods while extensive rewiring was being done [3]. To make expanding easier, centralized computer control systems were implemented. This system received all process inputs, performed appropriate calculations, and produced outputs to final devices all on a computer network. Even though it was easier to expand the system, it was still very expensive. These types of systems required computers with very large processing capacity and speed, so to expand the system a larger computer was required. To make controlling a process more reliable and flexible, distributed control systems were created.

This multi-level system has all of the capabilities of a centralized computer system while retaining flexibility, reliability, and rapid response of controllers [2]. This multi-level system also made it very easy to expand, and doesn't shut down the entire process if one component fails. Process where a distributed control system might be used include: chemical plants, pharmaceutical manufacturing, water treatment plants, and environmental control systems [4]. The first object-oriented distributed control system was installed in 1982 at the University of Melbourne [4]. This was critical because it was the first system that was sharing tasks and common memory and connected to a serial communication network or distributed controllers. An actual distributed control system program is called DeltaV.

The DeltaV control system was created by Emerson Process Management and was specifically created for automation engineers. Some of its applications include: model predictive control, loop monitoring and adaptive tuning, quality prediction, and constrained optimization [2]. Unlike other control systems, DeltaV is embedded in the system using the same engineering environment configuration database, and controller platform for unprecedented availability and ease of use.

Process Diagram

Figure 1 BATCHSAM process instrument. [5]

Table 1 BATCHSAM instrument description and functions.

Number	Description	Function
1	Inlet pressure gauge	Display the inlet pressure in psi
2	Inlet flow transmitter	Measure pressure and level of the inlet flow
3	Level transmitter	Continuously measure the level of the liquid
4	Flowmeter for the inlet stream	To measure the flowrate of liquid through the inlet stream
5	Switch for inlet pump	Turning inlet pump on and off
6	Inlet control valve	Valve used to control inlet fluid flow
7	Inlet pressure regulator	Maintain constant output pressure
8	Tank	To determine the liquid accumulation at certain time
9	Outlet control valve	Valve used to control outlet fluid flow
10	Outlet pressure regulator	Maintain constant output pressure
11	Switch for outlet pump	Turning inlet pump on and off
12	Flowmeter for the outlet stream	To measure the flowrate of liquid through the inlet stream
13	Outlet flow transmitter	Measure pressure and level of the outlet flow
14	Outlet pressure gauge	Display the outlet pressure in psi

Procedures

There were two parts in this lab. Part 1 involved calculating system conditions after starting at various steady states and then reaching new steady states. Part 1 is split into four parts, and will be discussed in detail below. Part 2 of the lab examined the effect of a step change in the inlet flow rate on the tank level response for an open-loop system.

Part 1 consisted of four experiments. Experiment 1 prepared the equipment by turning on the inlet and outlet pumps to ensure students knew how to manually maintain the high inlet flow rate (0.95 gpm) and low inlet flow rate (0.45 gpm).

Experiment 2 involved setting the inlet flowrate to 0.95gpm, then setting the tank level to 14”. The system was allowed to reach steady state. After the system settled, the tank level set point was changed to be 18”. The system was then allowed to reach steady state and the data was recorded.

In Experiment 3, the inlet flow rate was kept constant at 0.95 gpm, and the tank level was set to 14”. The time taken for the process to settle was recorded.

Experiment 4 involved setting the inlet flowrate to 0.95 gpm and increasing the gain of the system by an order of magnitude. The tank level was set to 18” and the time of change and the settling time of the process were recorded.

Part 2 of the experiment involved the changing of the inlet flowrate so the system reaches a new steady state. The inlet flowrate was set at 0.87 gpm and the tank level was allowed to reach 12”. When the tank level reached 12”, the manual valve draining the tank was opened and the system was allowed to stabilize. After the stability of the system was ensured for at least 15 minutes.

Then the inlet flow rate was changed to 0.97 gpm. A new steady state was allowed to reach and stabilize for 15 minutes. The data of this Part 2 was recorded and analyzed.

Discussion

Part 1

Part 1 of the BATCHSAM Process and DeltaV Experiments required tank level and set point changes under various conditions.

Experiment 1

Data of the implied valve position, or output, of the control valve was obtained using a high and low inlet flow rate. These data were collected manually during Experiment 1 by adjusting the inlet flow rate to the given values in Table 1, and recording the OUT% value as seen on DeltaV. Experiment 1 involved using a feedback and feedforward control system.

Table 2 Inlet flow rate high and low values, with resulting control valve outlet percent values for control valve 3 seen on figure 1.

Inlet Flow rate (gpm)	**Control Valve Output %**
0.95	65.35
0.45	54.4

Experiment 2

During Experiment 2 of Part 1, two steady states were achieved – one at 14" and another at 18". As shown in Figure 2, the first steady state was reached within 5 minutes. This is the settling time of the first steady state. Figure 2 also shows that the settling time of the second steady state is 3 minutes.

The system involved setting the tank level and keeping the inlet flow rate constant. The height was maintained by manipulating the outlet flowrate. Therefore, the control variable is the tank height and the manipulated variable is the outlet flowrate. It was seen in OUT% data that the inlet OUT% is a higher value than the outlet OUT% shown in Figure 2. The pattern of a constant, higher inlet valve OUT% continued through Experiments 2, 3 and 4. This is attributed to a larger valve resistance of the inlet control valve.

Figure 2 and Figure 3 show that the system is constantly overshooting and then undershooting the level until a constant value is reached. This is what is known as an oscillating system. The oscillation in tank level also shows how the process is a feedback control system as the level must change from a set point before the manipulated variable is altered.

A semi-theoretical model was designed and the transfer function, the gain, and the time constant for the system was calculated (Refer Appendix A).

The dynamic mass balance for the system is given is follows:

$$\frac{d(\rho Ah(t))}{dt} = \rho q_1(t) - \rho q_2(t) \tag{1}$$

Where:

ρ = fluid density

A = Area

h = tank height

q_1 = inlet flow rate

q_2 = outlet flow rate.

The transfer function was found and the expression is given as follows:

$$H'(S) = \frac{1}{A*S}(Q_1'(S) - Q_2'(S)) \tag{2}$$

If the characteristic equation of the system is investigated, it is seen that the roots of the equation are zero. When the root is zero, it is seen that the system is oscillatory. Therefore, the theoretical model matched with the experimental data. The transfer function also tells us that as the root of the equation is zero, the process is not self-regulating.

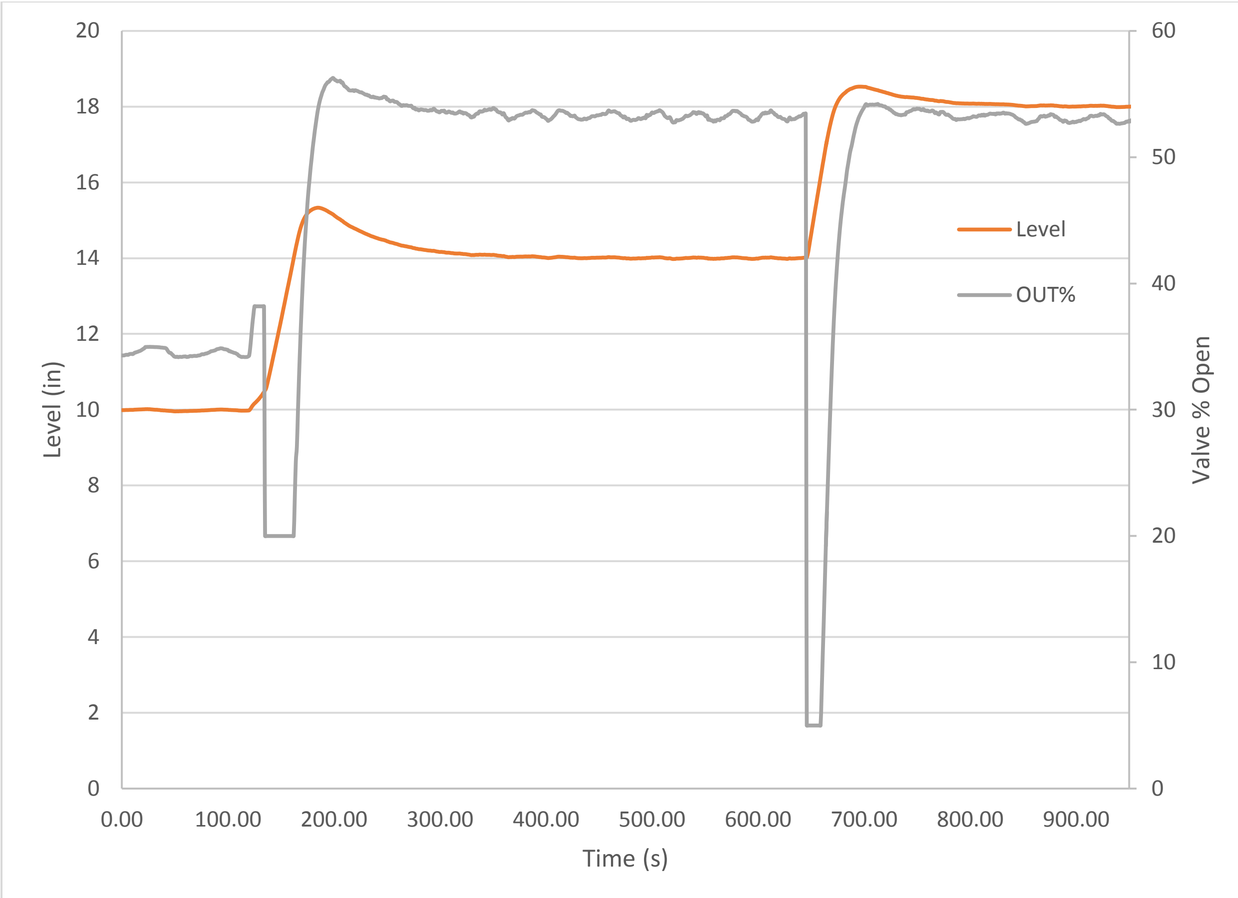

Figure 2 Tank level and OUT% data plotted versus time shows an initial steady state at a height of 10”. The system is transitioned to a first and second steady state at 14” and 18”. When the level is transitioning to the final steady state level, the valve opening percentage drops from 55% open to 5% open, and sharply returns to the original OUT% value. The OUT% behavior shown on Figure 2 provides support for the system to be not self-regulating.

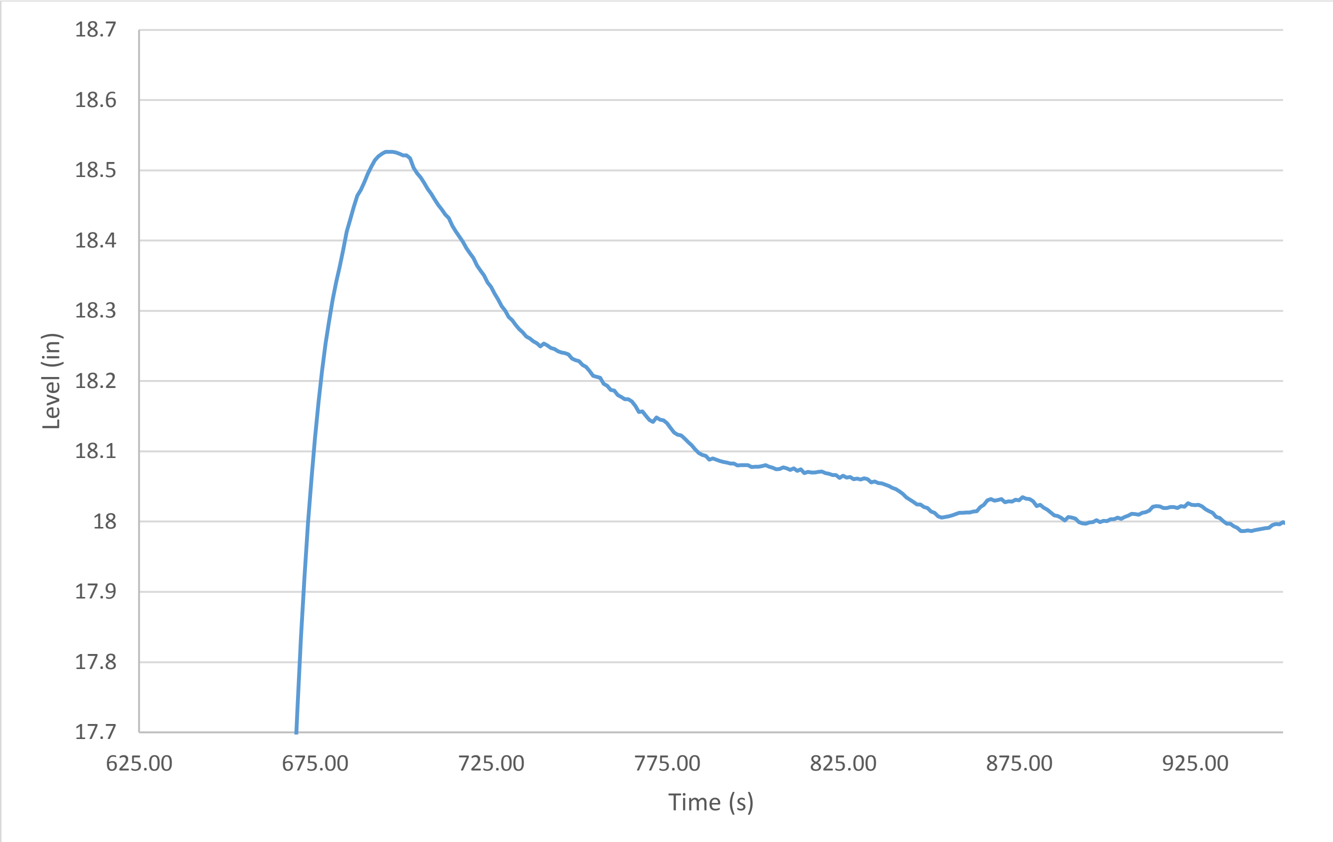

Figure 3 A magnified plot of the tank level response transitioning to the final steady state at 18" from Figure 2. An effect of the feedback control system is seen as the level rises to 18.5” before descending to the set value. The oscillations shown as the level reaches 18” are significant, as they further support the conclusion that our system is an integrating process.

Experiment 3

This experiment involved setting the tank level and keeping the inlet flow rate constant. The height was maintained by manipulating the outlet flowrate. Therefore, the control variable is the height and the manipulated variable is the outlet flowrate.

Figure 4 and Figure 5 shows that the system is constantly undershooting and then overshooting the level until a constant value is reached. This implies this experiment also involves an oscillating system. The oscillation in tank level also shows how the process is a feedback control system as the level must change from a set point before the manipulated variable is altered.

The semi-theoretical model developed for experiment 2 was used and compared to experimental data. The model showed that the root is zero which states the system is oscillatory. Therefore, the experimental data matched the theoretical model.

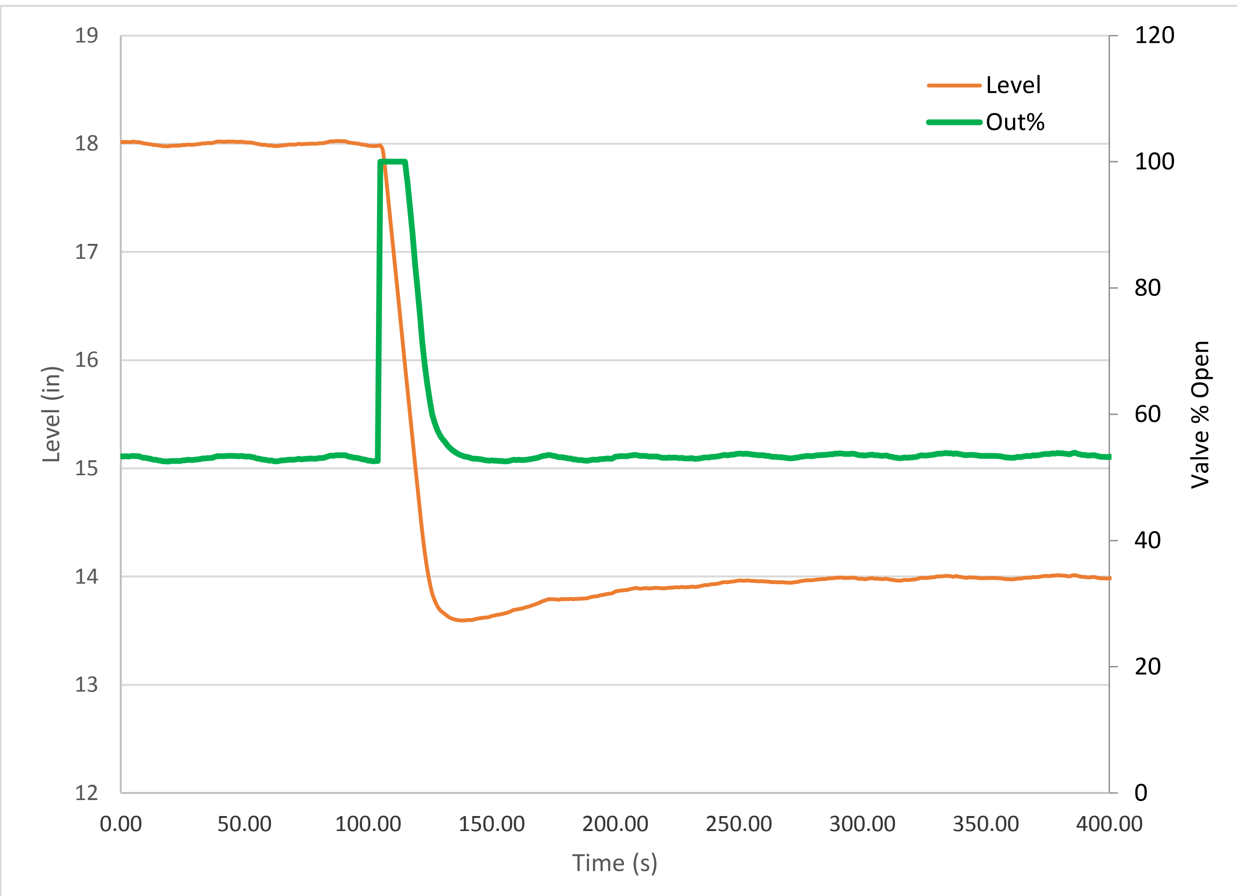

Figure 4 Tank level plotted with the outlet valve open percentage against time. Figure 4 shows a decrease in tank level from 18" to 14", with a simultaneous increase of the OUT% value to 100% open. Once the level value of 14" is reached, the OUT% decreases sharply back to its level from the initial steady state.

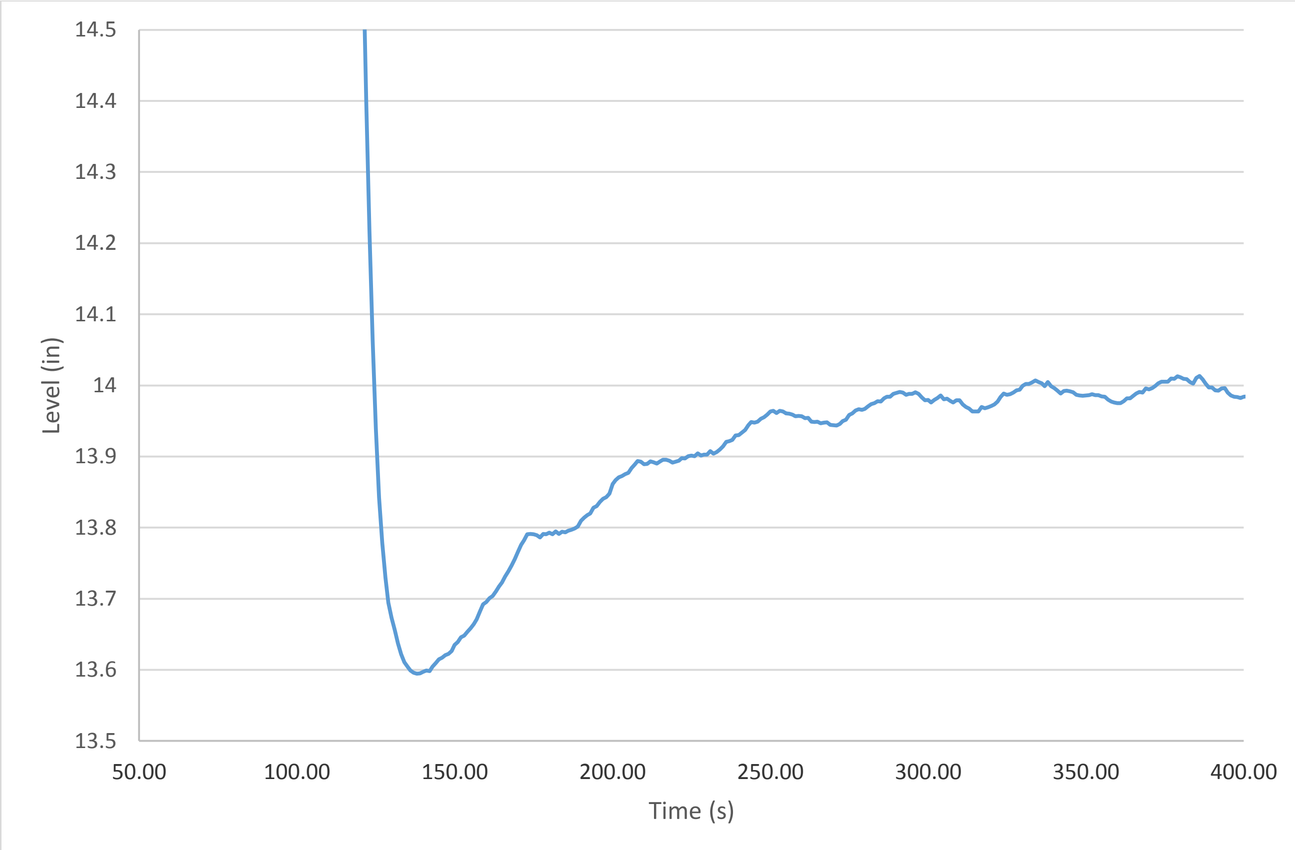

Figure 5 An enhanced view of Figure 4 level as it approaches the new steady state. Oscillations can be seen as the level approaches the new steady state, which are a result of the integrating process.

Experiment 4

Experiment 4 involved changing the gain of the system by an order of magnitude. The gain of the system tells us the degree of influence the input has on the output. Comparing Figure 2 and Figure 6, we can see that as gain increases, the amount of overshoot increases, as does the settling time. The increased oscillations show an apparent decrease in system stability, which is also an effect of an increase in gain.

Since the system is still stable, we can see that increasing the gain value did not reveal conditional stability. Further increases in the gain may reveal the gain stability threshold value, and cause the system to become unstable.

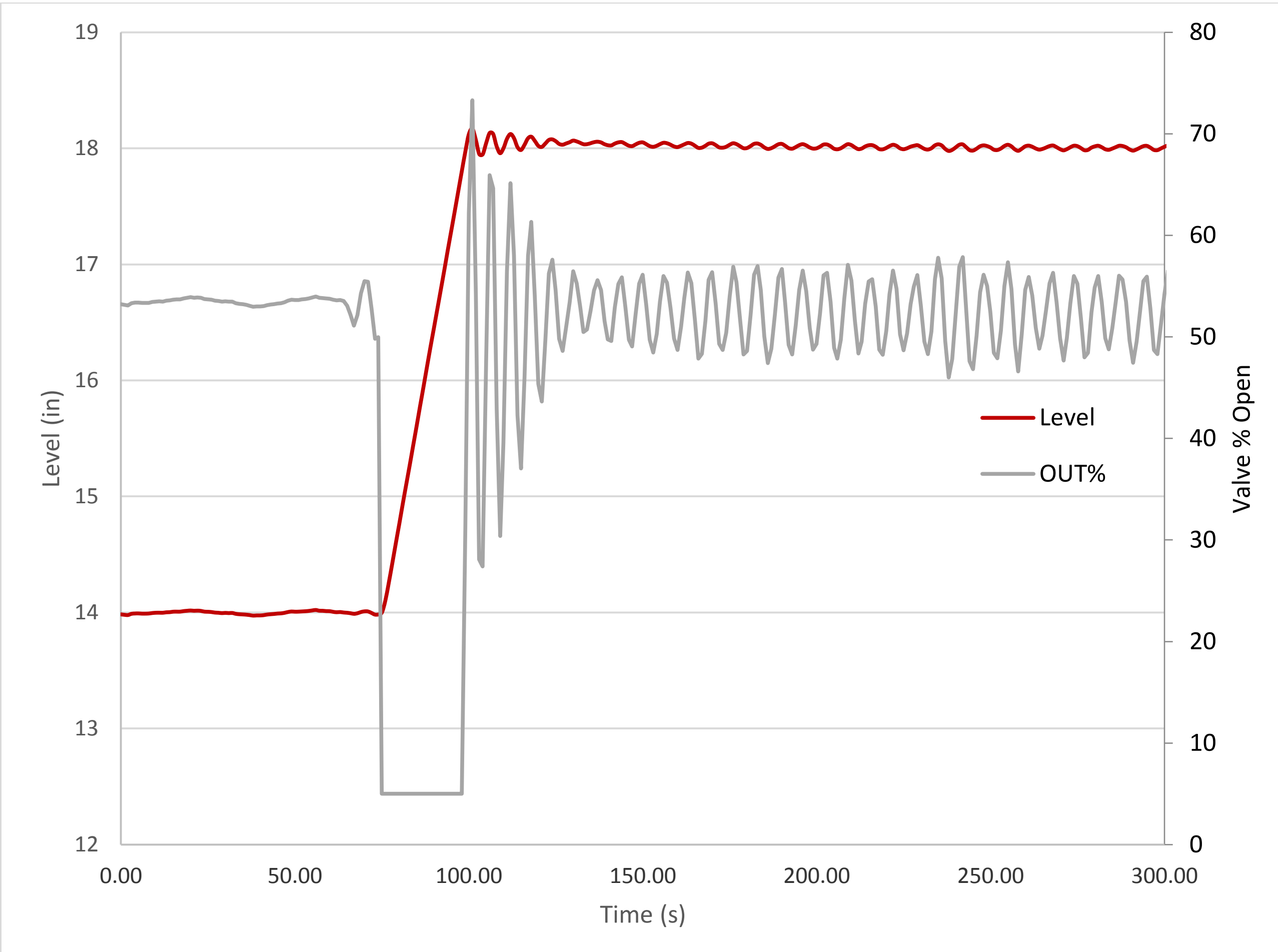

Figure 6 Tank level and OUT% plotted against time shows both values oscillating as the level reaches a new steady state at 18” and the OUT% returns to its original steady state value after a sharp decrease when the higher tank level was set. The large oscillations are a result of an increase in the Gain on the DeltaV system.

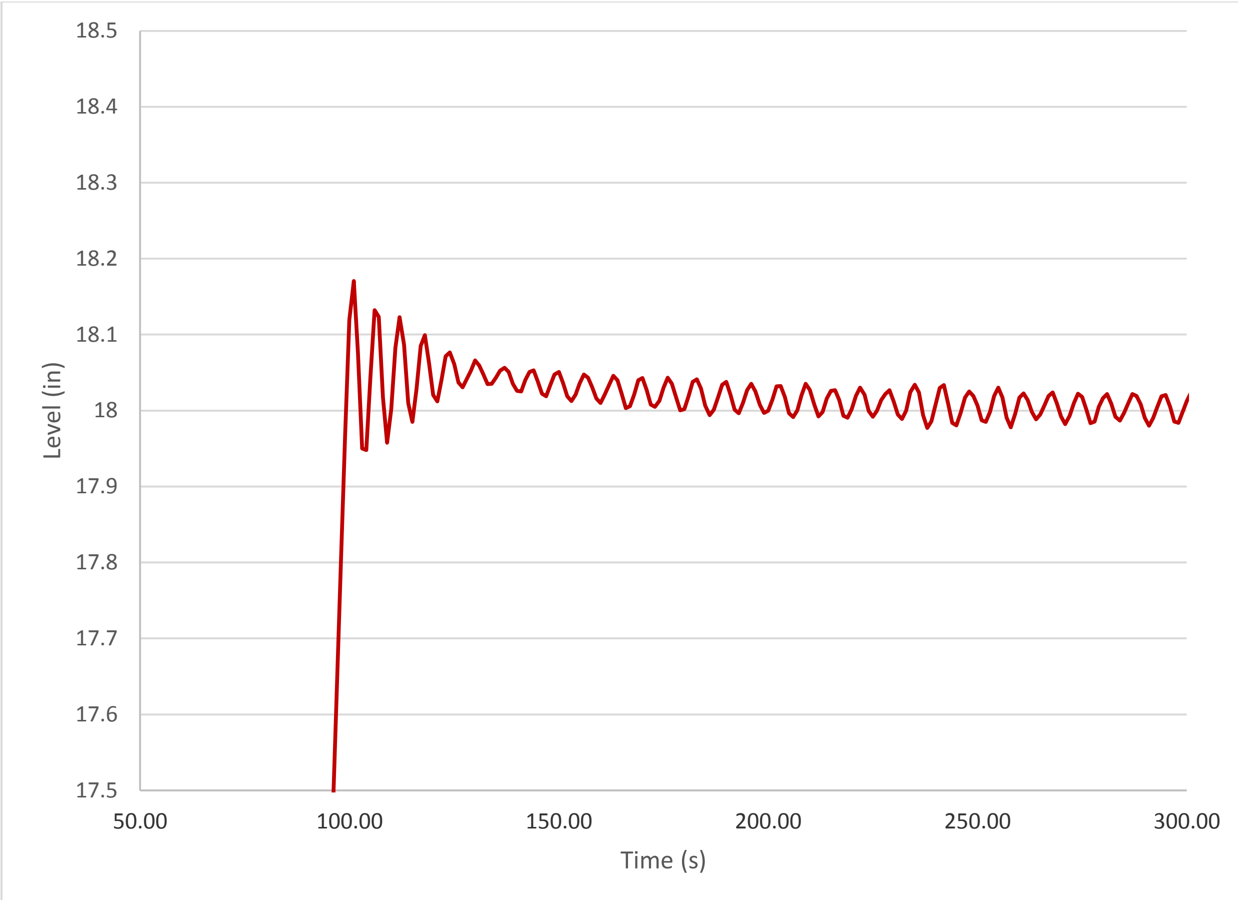

Figure 7 An enhanced view of Figure 6 shows the tank level approaching the new set point of 18". As it approaches the new steady state, oscillations are seen as a result of the integrating process. Overshoot values of Figure 7 are significantly larger than in Figure 3 or Figure 5, due to the Gain value increase in Experiment 4.

Part 2

Part 2 of the BATCHSAM Process and DeltaV Experiments involved reaching a steady state tank level, changing the inlet flow rate, and reaching a new steady state tank level. The experiment was run by first attaining a steady state tank level, with the tank outlet valve fully opened. Once steady state was reached, at about 13 inches, the inlet flow rate was changed from 0.87 gpm to 0.97 gpm, and a new steady state tank height of about 21 inches was reached. Figure **8** below shows the experimental data obtained from the experiment.

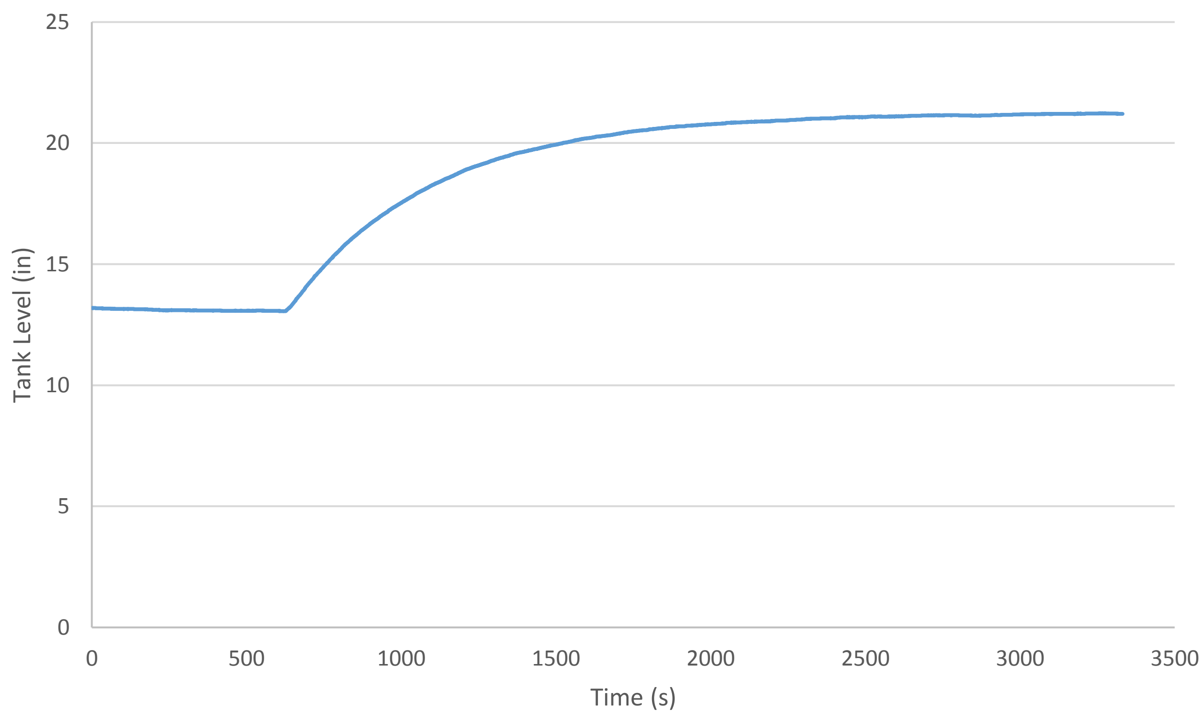

Figure 8 – The tank level change from an initial steady state and a second steady state caused by a change in the inlet flow rate.

The figure clearly shows the change in inlet flow rate and the tank height response to that change. The response appears to be smooth and self-regulating. This is due to the fact that the outlet flow is controlled by the height of the tank. As the tank height increases, the increased mass of the liquid in the tank causes the outlet flow rate to also increase. This process continues until the outlet flow rate is equal to the set inlet flow rate, due to the tank height.

The dynamic mass balance of the system is given by Equation 3 below.

$$\frac{d(\rho A h(t))}{dt} = \rho q_1(t) - \rho q_2(t) \tag{3}$$

Where:

ρ = fluid density
A = Area
h = tank height
q_1 = inlet flow rate
q_2 = outlet flow rate.

The dynamic mass balance can be manipulated to define a first order differential model of the system, given by Equation 4.

$$\frac{KAd\left(h'(t)\right)}{dt} + h'(t) = Kq_1' \tag{4}$$

Where:

$K = \frac{h(\infty) - \bar{h}}{q_1(final) - q_1(o)}$
$h' = h(t) - \bar{h}$
$q_1' = q_1(t) - \bar{q}_-$

$$G_2(S) = \frac{K}{(\tau S + 1)} = \frac{\frac{h(\infty) - \bar{h}}{q_1(final) - q_1(o)}}{(AKS + 1)} \tag{5}$$

Using the transfer function from equation 5, the theoretical model of the tank height can be derived. To get the theoretical model the inverse Laplace operator is applied to the product of the inlet change and the transfer function.

The theoretical model is a piecewise function shown in Equation 6 below. Using the piecewise function theoretical model will become Equation 7 below.

$$h(t) = \begin{cases} \bar{h}, & t < tstep \\ \bar{h} + 0.1K(1 - e^{-\frac{t}{\tau}}), & t \geq tstep \end{cases} \tag{6}$$

$$h(t) = \bar{h}Ş(t) + \ 0.1K(1 - e^{-\frac{t-tstep}{\tau}})Ş(t - tstep) \tag{7}$$

Where:

$K = \frac{h(\infty) - \bar{h}}{q_1(final) - q_1(o)}$

$\bar{h} = the\ average\ height\ of\ the\ liquid\ before\ the\ step\ change$

$t = \ the\ time$

$tstep = the\ time\ at\ which\ the\ change\ in\ the\ inlet\ flow\ occured$

Using the theoretical model with the data that was received in the experiment can be used to compare the model to the experiment. Figure 9 below shows the tank height from the experimental data, and the height from the theoretical model.

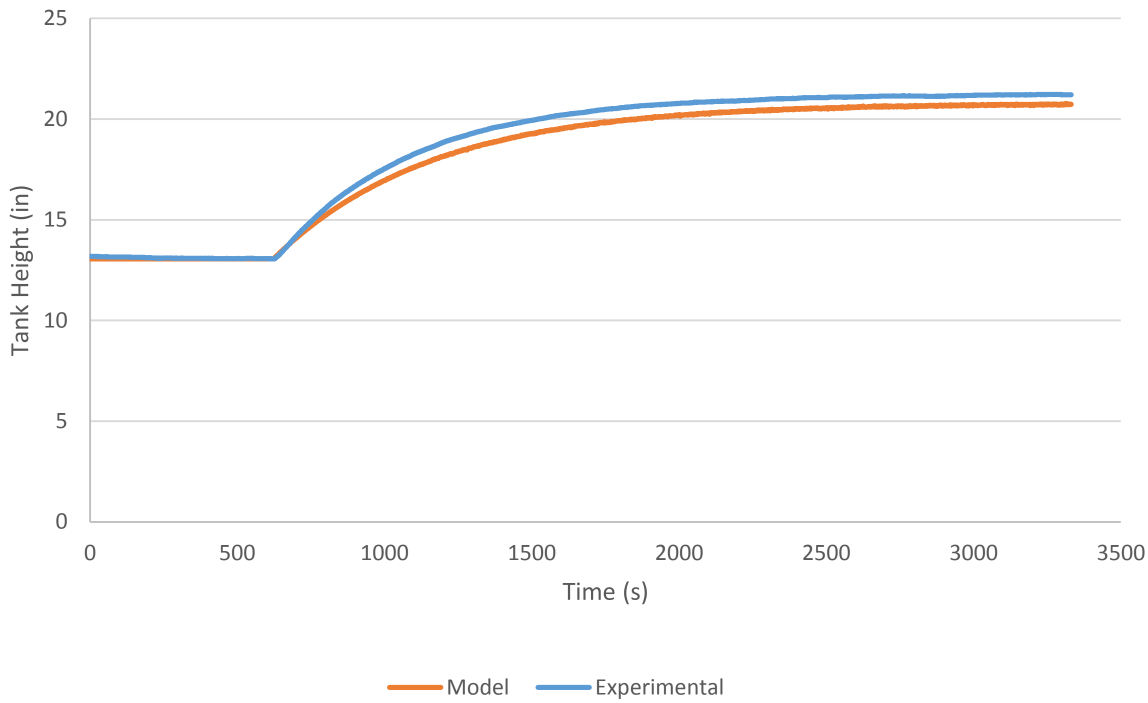

Figure 9 - The tank level change from an initial steady state and a second steady state caused by a change in the inlet flow rate plotted against a modeled response of the same function.

Figure 9 shows that the theoretical model differs slightly when compared to the experimental data. This can be attributed to modeling error. With modeling error present it will lead to a model that will not give the exact value of the tank height; however, the model that was derived provides a very accurate estimation to the tank height based on the time.

Conclusion and Recommendations

The experiments that were completed by Group 3, show many concepts learned in class. Part 1 experiment 2 shows that going from one steady state to another at a higher level with a feedback control system in a first order differential equation will be oscillatory and non-self regulating since the root of the transfer function is zero. Part 1 experiment 3 shows that changing from one steady state to another with a first order differential equation with a feedback control system is not dependent on the direction of the change, and is going to be oscillatory and non-self regulating. Part 1 experiment 4 shows how the gains affect the overshoot and settling time. Part 2 includes modeling of a first order differential equation. The differential equation from part 2 is self-regulating and smooth since it has a real root in the left hand plane. When the equation was modeled theoretically it was slightly off from the experimental data due to modeling error.

Multiple new experiments can be performed to enhance the experience of the students. Two potential experiments that will be discussed are using the same system, but with different liquids, and having two tanks in series to turn the experiment into a second order system.

The experiment with changing liquids would show that the densities of the liquid would not matter because they cancel out; however, it would allow the students to see if the viscosities would affect the system. This would give the students a better understanding of a first order system, and provide a wonderful learning opportunity.

The experiment with changing the system to second order would allow the students to see different conceptual components to the class. The second order system can show the students the concepts of overshooting and dampening. Different sections of the experiment would be changing ζ to be between zero and one, equal to one, and greater than one. Having the different zeta values will show the system being under-damped, critically-damped, and over-damped. Another part of the experiment would be to show how the change of gains will affect the overshoot value, the period, the rise time, and the peak time.

Literature Cited

[1] Seborg, D.E., T.F. Edgar and D.A. Mellichamp, *Process Dynamics and Controls, 3rd edition*, Wiley, New York, 2011.

[2] Fisher Controls. *PROVOXplus Instrumentation System Overview*. USA.

[3] V. R. Segovia and A. Theorin, *History of Control History of PLC and DCS*, 2013.

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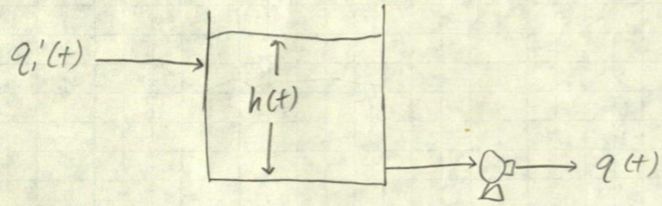
[5] Rollins, K.D., *BatchSam Process*. 2017. JPEG file.

Appendix

APPENDIX A



Outputs: $h(t)$

inputs: $q_1(t)$, $q(t)$

(1) $$\frac{d\rho A h(t)}{dt} = \rho q_1(t) - \rho q(t)$$

$$A\,\frac{dh(t)}{dt} = q_1(t) - q(t)$$

$\downarrow$ prop 1

(2) $$\mathcal{L}\left\{A\,\frac{dh'(t)}{dt} = q_1'(t) - q'(t)\right\}$$

$$AS\,H'(S) = Q_1'(S) - Q'(S)$$

(3) $$H'(S) = \frac{1}{AS}\,Q_1'(S) - \frac{1}{AS}\,Q'(S)$$

(4) $$\boxed{H'(S) = G_1(S)\,Q_1'(S) - G_2(S)\,Q'(S)}$$

Theoretical Model | Appendix B

DOMBTC: (lbm/min)

Assumptions: $q_2 = \frac{h(t)}{RV}$

(1) $\frac{d(\cancel{\rho} A h(t))}{dt} = \cancel{\rho} q_1(t) - \cancel{\rho} q_2(t)$

(2) $q_2 = \frac{h(t)}{RV}$

(4) $\frac{A d(h(t))}{dt} = q_1(t) - \frac{h(t)}{RV}$

(3) $RV = \frac{h(\infty)-h(0)}{q_1(\infty)-q_1(0)}$

output: $h(t)$ Input: $q_1(t)$

Using prop 1 for a first order system with a step order change you get the following:

(5) $A\frac{d(h'(t))}{dt} = q_1'(t) - \frac{h'(t)}{RV}$

$K = RV$

$K = \frac{h(\infty)-h(0)}{q_1(\infty)-q_1(0)} \therefore$

$\frac{A d(h'(t))}{dt} = q_1'(t) - \frac{h'(t)}{K}$

(6) $k = \frac{h(\infty)-\bar{h}}{q_1(t)-q_1(0)}$

$\bar{h} = \langle h(0) \rangle$

(7) $\frac{A d(h'(t))}{dt} + \frac{h'(t)}{K} = q_1'(t)$

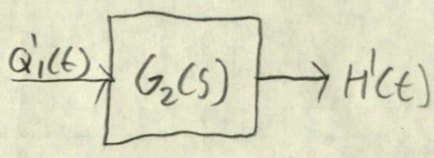
$\mathcal{L}\left(\frac{KA\, d(h'(t))}{dt} + h'(t) = K q_1'(t)\right)\mathcal{L}$

$\tau = AK$ (8)

(9) $\tau s H'(s) + H'(s) = K Q_1'(s)$

$(\tau s+1)H'(s) = K Q_1'(s)$

(10) $\frac{H'(s)}{Q_1'(s)} = \frac{K}{\tau s+1} = G_2(s)$



$G_2(s) = \frac{K}{(\tau s+1)}$ root! $s = \frac{-1}{\tau}$

Since τ can't be negative the root is in the LHP and real $\therefore$ this equation is smooth and is stable

Experimental Calculated Appendix B

$D = 5.75\,in$ $h(\infty) \approx 21.21\,in$ $h(0) \approx 13.06\,in$

$q_1(f) = .97\,\frac{gal}{min}$ $q_1(0) = .87\,\frac{gal}{min}$

$A = \frac{\pi D^2}{4} = \frac{\pi(5.75\,in)^2}{4} = 25.96\,in^2$

$K = \frac{21.21\,in - 13.06\,in}{.97\,\frac{gal}{min} - .87\,\frac{gal}{min}} = 81.5\,\frac{in\,min}{gal} \cdot \frac{60\,sec}{1\,min} \cdot \frac{1\,gal}{231\,in^3} = 21.17\,\frac{sec}{in^2}$

$\tau = AK = 25.96\,in^2\left(81.5\,\frac{in\,min}{gal}\right) = 2116.33\,\frac{in^3\,min}{gal}$

$2116.33\,\frac{\cancel{in^3}\,\cancel{min}}{\cancel{gal}} \cdot \frac{60\,s}{1\,\cancel{min}} \cdot \frac{1\,\cancel{gal}}{231\,\cancel{in^3}} = 549.70\,sec$

$\tau = 549.70\,sec$

"settling" time $= 5\tau$

$5\tau = 5(549.7\,sec)$

settling time $= 2748.5\,sec$