Simulation and Experiment in

AN INTRODUCTORY PROCESS CONTROL LABORATORY EXPERIENCE

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There are several advantages to integrating classroom and laboratory exposure. For many students, understanding concepts taught in the classroom improves significantly when they have the opportunity to gain hands-on experience in a laboratory. A laboratory exercise also provides an opportunity to apply the theory they have learned in the classroom to an actual engineering problem. Finally, comparing experimental data and dynamic simulation results is an effective way to reinforce process dynamics education in a laboratory exercise. The wider incorporation of process dynamics into the curriculum is considered to be a key component in process control education of chemical engineering students.[1]

There are a number of simulation-based chemical process dynamics experiments presented in the engineering education literature. They range from modules incorporated into a commercial process control computer system,[2] case studies illustrating various process control concepts programmed using MATLAB/SIMULINK,[3-5] and workshops based on real-time simulation of industrial unit operations.[6] Although there are benefits of simulation-based experiments, a major disadvantage is the lack of an actual physical process that the students can watch, hear, and touch while it is operating. Understanding the dynamic behavior of a process is greatly enhanced by observing the physical process operation. Visualization provides a significant benefit to many students as they attempt to apply the theoretical concepts taught in the classroom.[7,8] This aspect was one of the main motivations for developing the experience documented in this work.

A review of the equipment-based chemical process dynamics experiments presented in the engineering education literature reveals a wide range of complexity in the processes considered. They range from relatively simple liquid-level[9] and stirred-tank[10] systems, multiple tank systems,[11] quite complex reaction[12] and distillation[13] systems, and combinations of simple, more complex, and simulated systems.[14] Because this experience is intended to be an introductory exposure to process dynamics, simulation, and control, using an easily modeled, simple, physical process that incorporates the introductory concepts from the process control and simulation course is appropriate. For this reason, a single-tank liquid-level system was chosen.

Feedback control is performed using a proportional-only controller. Proportional control provides two benefits for this introductory experience. The first is that a proportional controller is easily simulated. The additional complexity required in the simulation of integral action in the controller provides little, if any, benefit to the understanding of process dynamics and dynamic simulation in an introductory experience. The second benefit is that proportional control results in steady-state offset of the tank level. This concept is often difficult for some students to initially grasp in the classroom. The ability to observe this phenomenon on a real physical system can be very helpful for these students.

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LABORATORY EQUIPMENT

The experiment is carried out using a 50-gallon gravity-drained tank equipped with liquid level and outlet flow sensors. Liquid level is controlled by a valve on the inlet water pipe. There is an additional inlet water pipe with a manual valve. The outlet flow rate can be adjusted by a manual valve on the outlet pipe of the tank. A steam heater is connected to the tank but not used in this experiment. The tank is 2.5 feet in height and 1.8 feet in diameter. The tank system is shown in Figure 1.

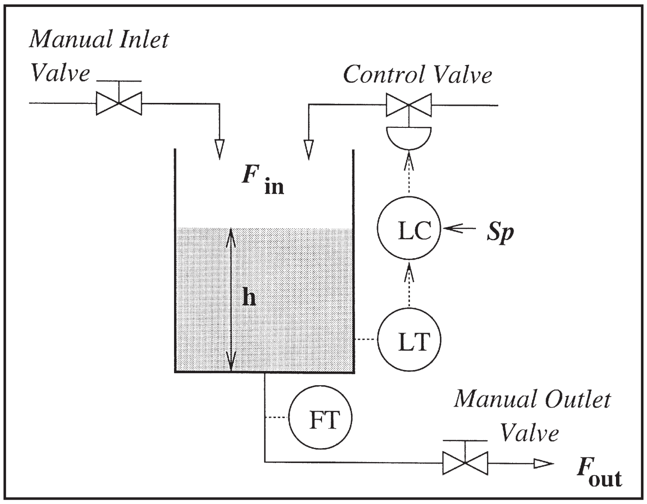

Figure 1. *Experimental tank system.*

Liquid level control is provided by a single-loop electronic controller. There is also a distributed computer control system connected to the tank. Because we believe there is value in exposing the students to both the single-loop electronic and computer control systems, we have the ability to switch between the two systems on this tank. The single-loop controller is used for this introductory experiment, while the computer control system is used for temperature-control experiments and a model predictive control experiment in the senior laboratory course.[15]

LABORATORY EXERCISE

The exercise comprises two three-hour laboratory sessions. During the first session, the student groups become familiar with the tank system and perform the experimental work. In the second session, they develop their dynamic simulation model, compare their simulated results with those obtained experimentally, and document their findings in a short memo report to the instructor.

The laboratory exercise begins with the tank operating at steady state under proportional-only feedback control with a water level setpoint of 50%. The instructor reviews the physical operation of the tank, goes over each component comprising the feedback control loop, and leads a short discussion concerning the options to remove steady-state offset with the student group. The students are then instructed to adjust the controller bias to remove the steady-state offset in the tank level. They may either put the controller in manual and adjust the control valve position or adjust the bias directly to eliminate the offset. The value of this exercise is gaining an appreciation for the response time of a real physical system. The students are prompted to estimate both the time constant of the system, which is on the order of five minutes, and the open-loop response time of the tank in order to determine how long it should take for the tank level to reach steady state after a change to the inlet water valve position is made. Although process simulators provide valuable training experience for the students, a major drawback is that those experiences are in "simulation" time. The first part of this laboratory exercise demonstrates that real process dynamics are not on this same simulation time scale.

After the students have adjusted the bias to eliminate the steady-state offset in the tank level, the system is returned to closed-loop control and they are allowed to choose one disturbance from a list in the laboratory instructions. This list contains the following disturbances:

- *Simultaneously dump two small buckets of water into the tank*
- *Dump one large bucket of water into the tank*
- *Change the inlet flow rate by opening the manual disturbance flow valve*
- *Change the outlet flow rate by opening or closing the manual outlet valve*
- *Change the level setpoint*
- *Change one of the level controller tuning parameters*

where the two small buckets are each two gallons, resulting in an impulse disturbance that is approximately 20% of the liquid volume; the large bucket is 25 gallons, resulting in an impulse disturbance when full that is about the same as the liquid volume; and the disturbance flow results in a step disturbance that is about the same as the initial steady-state inlet flow rate.

From the instructor's perspective, it is desirable to have as much variation in the selected disturbances between groups as possible to make the students' semester-end oral reports on this experiment more interesting. In practice, other than discouraging the one large bucket, prompting by the instructor in order to provide this variation has seldom been necessary.

Prior to implementing their chosen disturbance, the tasks of time keeper, data logger, and disturbance initiator are distributed by the group members among themselves. Their selected disturbance is then implemented on the tank system under closed-loop level control. The initial data point is collected after the disturbance has been completed. In the case of the buckets, this point is the time when all of the water has been emptied into the tank. Because two students (and sometimes the instructor) are required to empty the bucket contents into the tank, the time-keeping and data-logging tasks are performed by one student at the beginning of the experiment. For the other disturbances, the initial data point is taken immediately after the valve position or controller tuning parameter has been changed. Data is collected at intervals of ten to twenty seconds until the tank level reaches steady state. The experimental phase of this exercise is typically completed well within the three-hour laboratory period.

PROCESS SIMULATION

The second phase of this exercise involves the dynamic simulation of the closed-loop tank system with the disturbance chosen by the group. This phase is carried out during the laboratory period immediately following the experimental session. Process simulation begins with an unsteady-state material balance over the tank. Assuming a constant cross-sectional area of the tank, A_c, and the same constant density for all water streams, a macroscopic mass balance results in

$$A_c \frac{dh}{dt} = F_{in} - F_{out} \qquad (1)$$

where h is the height of water in the tank, F_{in} is the inlet volumetric flow rate, and F_{out} is the outlet volumetric flow rate.

The inlet volumetric flow rate of water is determined by the position of the control valve. Although this control valve is linear, the inlet flow rate is not a linear function of valve position over the entire valve position range due to variation in the water supply pressure as the valve position changes. The students are given a calibration curve, shown in Figure 2, that is used to relate the inlet flow rate to the control valve position. Over the linear operating range of the valve, the following correlation can be used to determine the inlet flow rate

$$F_{in} = 0.171\left(V_p\right) - 1.03 \qquad 10 \le V_p \le 60 \qquad (2)$$

where F_{in} is the flow rate in units of gpm and V_p is the control valve position in units of % open. If the disturbance flow was selected, there is a second constant inlet flow rate that must be added to this relationship.

The outlet volumetric flow rate is assumed to be proportional to the square root of the pressure drop across the manual outlet valve due to the static head of fluid in the tank

$$F_{out} = K_v \sqrt{h + \frac{19}{12}} \qquad (3)$$

where F_{out} is the flow rate in units of gpm, K_v is the proportionality constant, h is the height of the water in the tank in units of feet, and the bottom of the tank is 19 inches above the outlet valve. The proportionality constant K_v is determined from the measured outlet flow rate and water height when the tank level is at steady state.

The control valve position is determined by the level controller on the tank. For the proportional-only controller, the valve position is determined from the controller equation

$$V_p = B + K_c\left(S_p - L\right) \qquad (4)$$

where V_p is the valve position in units of % open, B is the controller bias in units of % open, K_c is the proportional gain in units of % open/% level, S_p is the water level setpoint in units of % level, and L is the level of the water in the tank in units of % level. In practice, the controller gain is kept at a value around 1 %/% to prevent the control valve position from moving out of its linear operating range during the transient response due to the disturbance.

Simulation of the process is carried out by numerical solution of Eqs. (1) through (4). Before they can be solved, however, the units must be made consistent throughout all of the

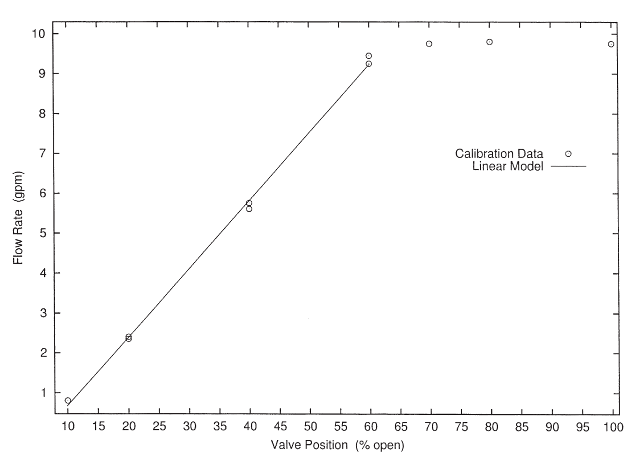

***Figure 2.** Inlet water control valve calibration curve.*

relationships. The controlled variable for the controller is configured to be in units of % while the tank dimensions are given to the students in units of feet and the flow rate calibrations are given in units of gpm. This variation in the units given to the students is intentional. Numerical solution is typically carried out by the student groups using MathCad, which is used by the department in the introductory material balance and the numerical methods prerequisite courses, although they are free to use any of the other mathematical software packages such as MATLAB, EXCEL, and Maple that are available on the engineering college server.

EXAMPLES AND DISCUSSION OF RESULTS

Example experimental and simulation results are shown in Figures 3 and 4. Figure 3 presents the results for the large bucket impulse disturbance. In this example, the large bucket was only about half full. Figure 4 presents the results for a reduction in the outlet flow rate from closing the manual outlet valve. In both cases, the experimental and simulated responses are very similar. These results are typical for most of the student lab groups.

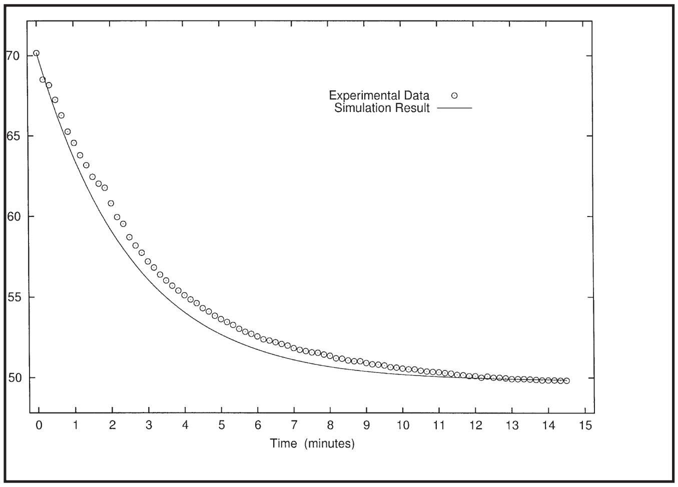

Figure 3. *Experimental and simulated closed-loop tank level for the large bucket impulse disturbance.*

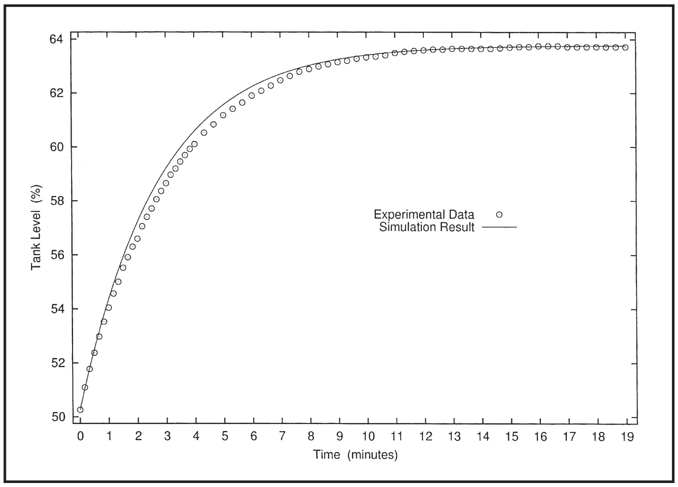

Figure 4. *Experimental and simulated closed-loop tank level for a change in the outlet valve position.*

In addition to presenting their experimental and simulation results, the student groups are asked to discuss the sources of error in this experiment in their group memo report. Examination of the experimental and simulated dynamic responses reveals that the simulation leads the experimental response. Because there are dynamics associated with the level sensor and control valve that are not included in the simulation model, this result would not be unexpected. The effects of valve friction, sensor noise, and the precision of the liquid level value displayed by the controller can also contribute to error as well as the assumption of a perfect square root relationship and a constant K_v value for the outlet flow rate that may not be valid over the liquid level ranges encountered in the experiments. Experimental error in the timing of the collected level data samples is also present. Almost every student group mentions the valve, sensor noise, and sampling error as sources of error in their report. Some groups also mention the outlet flow relationship used in the simulation model. Few groups discuss the dynamic effect of the valve and sensor.

STUDENT RESPONSE

As part of the student evaluation of the process simulation and control course, a number of supplemental questions concerning the value of the text and controller simulation software used in the course, the laboratory experience documented here, and the preparation received in the required prerequisite courses are included. The evaluation scores ranged from 5=Very Effective to 1=Very Ineffective. The average scores from the last four years are: presentation and explanation of concepts in the textbook, 3.04; use of CStation for class examples, 3.25; use of CStation for homework problems, 2.96; process control experiment in Lab II, 4.02.

CStation[16] is the process control simulation software package used in the course, *Essentials of Process Control*[17] was the course text at the time of these evaluations, and the process control experiment in Lab II is the experience documented in this work.

The average score given by the students for this laboratory experience is considerably higher than for the text and process control simulation package and is essentially the same as the average score of 4.10 for the value of the process control and simulation course over the same period. It should be noted that a number of students have provided somewhat negative comments concerning the length of the loop tuning homework assignments requiring the use of CStation. These feelings may have had some influence on the CStation scores. It should also be noted that only one

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valuable in industry and could be useful in academe (*e.g.,* which centers should the university compete for?). Asking questions is valuable—how long do professors need for different tasks, what can be done to improve the process, if students aren't the customers, who is, etc. Industrial faculty members can help ask the questions and help search for answers.

SUMMARY

Many chemical engineering departments have been criticized for a lack of industrial experience in their faculty. One approach to partially solving this problem is to hire early retirees from industry. As shown by the experiences related in this paper, these returning professors will probably experience some degree of cultural shock. Their transition to becoming productive contributors can be eased by providing both formal training in teaching and informal mentoring.

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student provided written comments about the text and that no student provided written comments about the laboratory experience over the four-year period. Because there are no formal course evaluations for laboratory courses, student response data from the second-semester junior laboratory course concerning the laboratory course and this experiment is not available. Qualitative assessment of this experience based on comments received from the students during and after the experiment indicate that this experience has been generally well received by the students.

CONCLUSIONS

An introductory laboratory experience in process dynamics and control that is conducted concurrently with the process simulation and control course at Villanova University has been presented here. The experience is intended to reinforce the introductory concepts of dynamic simulation and feedback control presented in the classroom by using a simple liquid-level process. Based on quantitative and qualitative student responses in the laboratory and process simulation and control courses, the students found the experience a valuable addition to their process simulation and control education.

ACKNOWLEDGMENTS

A curriculum revision grant to the Villanova University Chemical Engineering Department from Air Products and Chemical Co. that supported development of this laboratory experience, and the contributions of Professor Robert Sweeney in the design and construction of the experimental system are gratefully acknowledged. I would also like to thank the Villanova University chemical engineering students over the past four years for their active participation in the continuing development and improvement of this experience, and Ami Badami and Jenny Papatolis of the class of 2003 for supplying their respective group's experimental and simulation results that are presented in this paper.

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