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A Unit Operations Laboratory Experiment Combined with a Computer Simulation to Teach PID Controller Tuning

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Introduction

A process control course is not required for graduation from our department and only about half of our students take one. Recognizing the value of process control in the chemical industry we wanted to give all our students at least some exposure to it. We encourage students to take our second semester senior course that includes control theory, but also recognized that some knowledge of the practical aspects of PID controller tuning could serve all our students well. This paper describes a unit operations laboratory experiment that we implemented to provide our first semester seniors some experience with controller tuning. In our implementation we found that a laboratory exercise to learn tuning methods can be time consuming and taxing on the equipment. We felt that an alternative of a purely equation-based, virtual controller tuning exercise might not be interesting or seem relevant to real world processes. Instead, we developed and implemented a laboratory experiment that combines a physical process with a computer model to teach the practical aspects of PID controller tuning. The computer model allowed students to run virtual experiments to discover the effect of changing each control parameter and to test various controller tuning methods. The virtual experiments were tied to reality and learning was strengthened by applying the knowledge gained to control the physical experiment.

Physical Experiment

The objective of the experiment, shown schematically in Figure 1, was to control the temperature inside a jacketed, well-stirred vessel containing 200 ml of water. The vessel was heated and cooled by circulating water through the jacket surrounding the vessel. The temperature of the circulating water was controlled with a PID controller acting on a temperature bath containing a heater and a refrigeration unit. The process studied was a simple one where we started with the contents of the vessel at room temperature (about 20 ^{o}C) and tried to efficiently raise the temperature and control it at a new set point value of 30 ^{o}C. The reactor vessel and associated temperature bath was purchased from Syrris, Ltd as part of a biodiesel reactor system, shown in Figure 2, that we use in a separate lab course[1].

The number of physical runs that could be made in a four hour lab period was limited because it took about 30 minutes to heat the water and another 30 minutes to cool it and start over with a new set of control parameters. The range of studies on controller tuning methods that could be made on the physical experiment was also limited, because of the need to avoid boiling or freezing of the process and circulating water and the desire to avoid taxing the heating and cooling equipment.

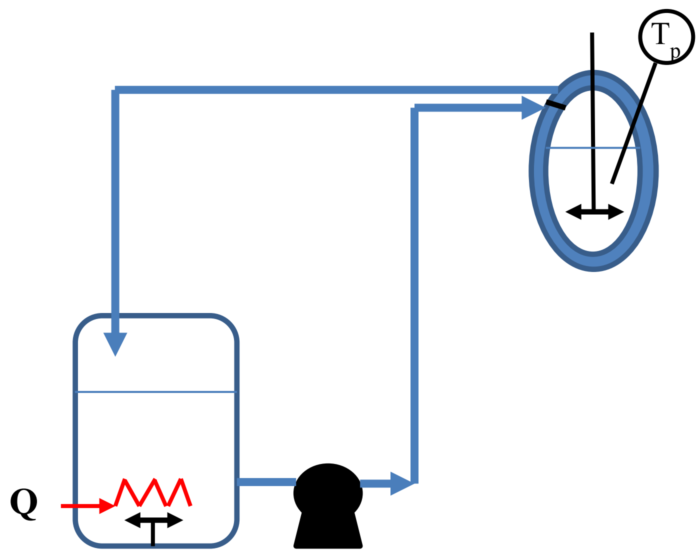

Figure 1. Temperature controlled reactor vessel schematic.

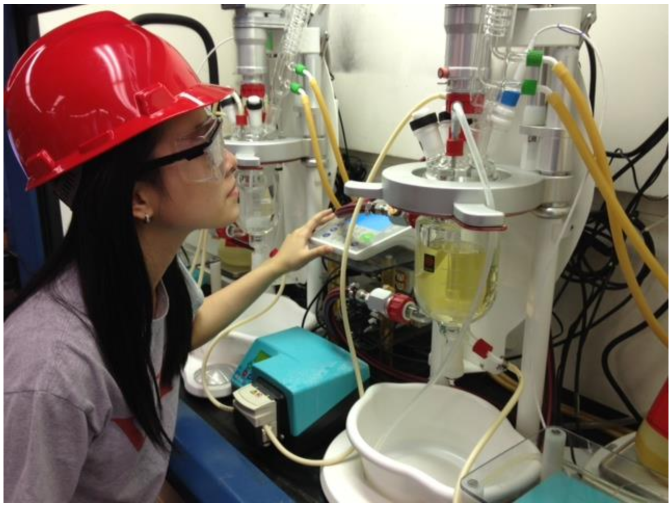

Figure 2. Temperature controlled reactor system from Syrris, Ltd also used for biodiesel reaction studies.

Computer Simulation

As indicated above, at this point in the curriculum, few of our students knew control theory. We could have used an excellent Matlab control tutorial[2] if we wanted a purely equation-based model using transfer functions and time constants, but it was not our aim to teach control theory and Laplace transforms. Instead we wanted a computer simulation of the process and controller that could be seen as clearly representing the physical experiment, but would allow more "experiments" covering a wider range of variables in a shorter time frame.

A computer model that captured all the necessary physics was developed using COMSOL Multiphysics software. The model included a circulation hose connecting a reaction vessel to a temperature bath. The circulation hose was made continuous by connecting the outlet to the inlet through a periodic boundary condition. The fluid flow was modeled with the k-ε turbulent flow equations. The heat input to the process was simulated as a volume heat source inside the temperature bath and was adjusted to drive the process temperature to the set point using the standard proportional, integral, derivative control equation.

$$Q(t) = Q_o[K_p E(t) + K_i \int_0^t E(t)dt + K_d \frac{dE(t)}{dt}] \qquad (1)$$

where $E(t) = T_{set} - T_p$. The fluid flow equations were first solved in a stationary study using an average temperature. The resulting velocity field was then assumed to be constant in a time dependent study of the heat transfer.

The output for both the simulated and physical experiments included temperature response curves for the circulating bath, jacket, and reactor and the integral absolute error (IAE) providing a measure of the deviation of the process temperature from the set point.

$$IAE = \int_0^\infty |E(t)|dt \qquad (2)$$

A typical response curve is shown in Figure 3.

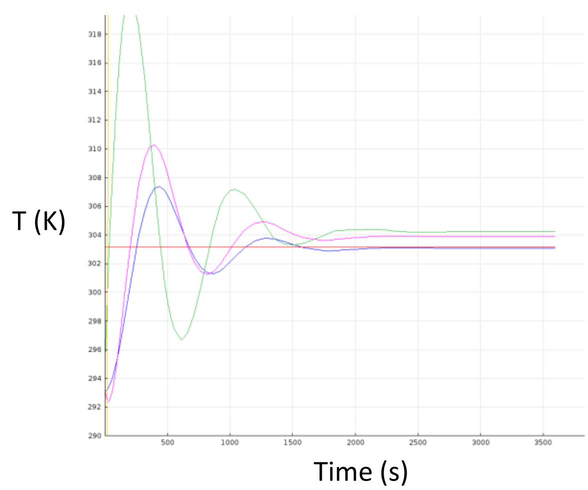

Figure 3. Temperature (K) in the reactor (blue), bath (green) and hose (magenta) as a function of time in seconds. Set point temperature is in red.

Student Experience

Some students may have encountered controllers in operation in research labs or at summer jobs, but few had any knowledge of how to tune them. At the pre-lab stage, we provided notes on the basics of PID control including typical response curves and definitions of terms like rise time, overshoot, decay ratio, etc., and an explanation of tuning criteria and several tuning methods. Step by step procedures for following the Ziegler-Nichols[3], Tyreus-Luyben[4], and Riggs[5] tuning methods were also provided as well as a tutorial on using the simulation of our process.

In the pre-lab exercise, students used the simulation to observe the effect of increasing the proportional control parameter for P-only control. They also answered questions about how they would continue using the simulations to study the various tuning methods and investigate the effect of changing each control parameter independently. They also explained how they would run the physical experiment to verify how changing the P and I parameters affected the control during the lab. Computers were available in the lab, for continued exploration of the tuning methods and of the effect of changing control parameters, K_p, K_i, and K_d, using the simulations while waiting for the physical experiments to run. An unspecified "prize" was offered to the group that obtained the lowest IAE when tuning the simulated controller.

Most groups came to the lab having made a number of simulation runs beyond the required P-only control ones and having determined the ultimate gain and period for use in the Z-N and T-L methods already. By the beginning of the lab they had all discovered that the Z-N and T-L methods cannot be used on the physical system because finding the ultimate gain would exceed the low and high temperature limits on the bath. During the lab, three or four physical experiments were conducted to observe the effect of changing one parameter at a time starting with a low K_p value in P-only control that gave an over damped response. Our original goal was to have the simulation match the experiment well enough that "optimal" parameters, determined on the simulation, could be demonstrated directly on the physical experiment. That is, one physical run could be made with poor control, and then a second run with excellent control could be made using the parameters optimized from the simulation. Due to imperfections in estimates of flow rates, heat transfer rates, mixing effects, and heat losses in the computer model this has not yet been fully achieved, but students did use the knowledge gained in tuning the simulation to demonstrate and explain the effect of changes in the parameters in their physical runs.

After the lab, students wrote a report explaining what they learned about the various tuning methods, the main effect that each control parameter had on the response curves and how they were able to minimize the IAE.

Assessment

Thirty six students assembled in nine groups of four completed the controller tuning experiment in the initial offering. Assessment of the initial offering included a pre and post diagnostic quiz with 9 multiple choice questions on PID controller tuning and a final survey to gage student satisfaction and gain feedback on the experience. There was marked improvement in the overall percent of correct answers to the diagnostic quiz as this value increased from 33 % in the pre quiz to 49 % in the post quiz. While the percent of correct answers is not a high as we would like, the non-stellar performance can be attributed to the inherent difficulty of the questions and the timing and preparation for the quiz. The pre quiz was taken on the first day of class without warning or preparation. Most students had essentially no knowledge of PID tuning and were simply guessing at answers. The post quiz was taken on the last day of class, with no prior warning, no studying, no consequence on the course grade, and varying time (from days to weeks) after the lab was completed by the students. Figure 4 indicates that some of the 9 questions were better understood by the students than others. In the future, adjustments will be made in the pre-lab notes, the lab exercise, and in the clarity of the quiz to try to improve the post quiz results.

The attitude survey indicated that the students were very pleased with the lab exercise and that they appreciated the chance to use the simulation and the physical experiment together to learn about controller tuning. Some students particularly enjoyed the friendly competition of trying to find the lowest IAE. Table 1 presents some of the survey questions with the percent of students selecting each answer. There were also short answer, open-ended, response questions that yielded numerous positive comments about the value of the simulation allowing them to quickly and easily observe the effect of each parameter by adjusting them one at time. Although nearly all the students indicated that the simulations were highly effective in helping them learn the material, there was an understandable desire on the part of some students to conduct more physical experiments and to seek to bring the simulation in closer agreement with the physical experiment as we had originally planned. Overall this new experiment was well received by the students, and seems to have made a positive impact in introducing them to practical aspects of process control. Enrollment in our second semester control course increased from less than half of seniors in years prior to the introduction of this experiment to about 2/3 of seniors this year.

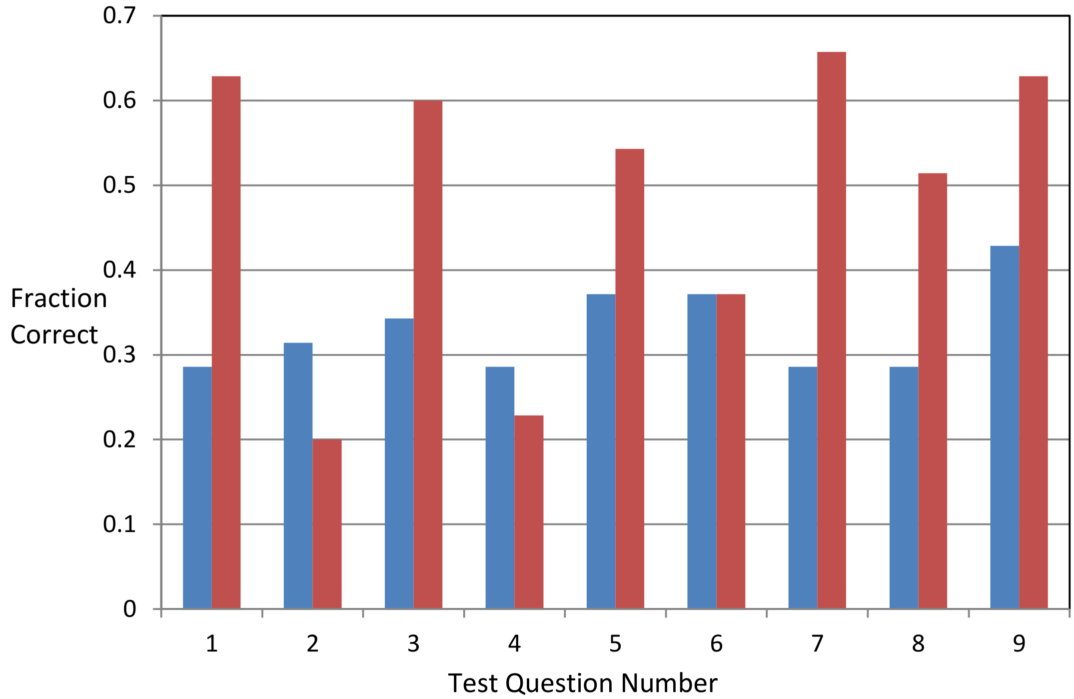

Figure 4. Fraction of correct answers on individual questions on the diagnostic quiz, pre (blue) and post (red).

Table 1. Final survey questions and percent of students providing each answer.

Question	a	b	c	d	e
1. If you were to do this again, would you rather run:	only physical experiments	only simulations	one physical experiment and many simulations	3 physical experiments and many simulations	more than 3 physical experiments and fewer simulations than we did
	3 %	3 %	22 %	53 %	19 %
2. Using the simulation software was:	very difficult	difficult	neither difficult nor easy	easy	very easy
	0 %	0 %	44 %	42 %	14 %
3. The simulation helped me to understand PID control, in general:	not at all	just a little	somewhat	much	very much
	0 %	0 %	28 %	53 %	19 %
4. The simulation helped me to understand PID tuning methods:	not at all	just a little	somewhat	much	very much
	0 %	3 %	44 %	30 %	22 %

Conclusion

In a new unit operations laboratory experiment students used a combination of three or four physical experiments and extensive computer simulations to discover the main effect of changing the proportional, integral, and derivative control parameters, to evaluate three parameter tuning methods, and to obtain "optimal" control by minimizing the integral absolute error. Combing a computer simulation that captures the essential physics with a physical experiment appears to be interesting, enjoyable, and effective in teaching practical aspects of process control.

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