Chemical Engineering Teaching Across the Atlantic

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Abstract — *Chemical Engineering students at the University of Cambridge, UK, have performed an experiment on process dynamics and control located at the Massachusetts Institute of Technology, USA, over the Internet. Using material taught in lectures on process control, the students tuned a controller to maintain a constant inlet water temperature to a heat exchanger. The control and observation of its response was done via a LabVIEW web interface, which is widely used in industry. In the first part of the experiment, the students made observations of a system under P, PI, and PID (proportional-integral-derivative) control using parameters obtained by applying the Cohen-Coon method to open loop test data. In the next part they improved these parameters by observing the response of the system to disturbances and applying knowledge of the equations governing PID control. Finally, the students recorded the responses to three different step changes. The equipment and interface performed technically without fault during the duration of the course (ten three-hour sessions). Feedback was obtained by issuing questionnaires; the students very much appreciated doing a real experiment and being able to see, firsthand, the effects on the system of each of the control parameters.*

Index Terms — *web based experiment, LabVIEW, distance learning, process control, PID*

INTRODUCTION

Remote experimentation is an increasingly used industrial and research technique, whereby a process can be analyzed and controlled, and data can be recorded and processed, via a web interface, removing the need to be in the same physical location as the equipment itself. Making use of this technology, a collaboration has been launched between the University of Cambridge (CU) and Massachusetts Institute of Technology (MIT), where CU chemical engineering students perform experiments located on the other side of the Atlantic. In the first such collaboration, chemical engineering students in Cambridge studied a fast responding system (located at MIT) using their theoretical knowledge of process control to fine tune a set of control parameters, trying to achieve and maintain a constant inlet water temperature to a heat exchanger.

Technically, the equipment performed without failure during the course and an evaluation of the students' response shows high appreciation of the instant feedback from the experiment allowing them to test their ideas, experiment with altering the settings, and study the response in real time, thus helping them to understand the practicalities of process control.

THE EXPERIMENT

The experiment used, developed as part of the MIT iLabs project [1], is a heat exchanger for online use within the "Transport Processes" and "Process Dynamics and Control" subjects [2]. The experiment is located in a laboratory in the Department of Chemical Engineering at MIT and has been used in the education of MIT chemical engineering students since November 2001. The equipment is manufactured by Armfield, Ltd. (Ringwood, England) and consists of a service unit (HT30XC) supplying hot and cold water, and a shell and tube heat exchanger (HT33) mounted on the service unit. The service unit is connected to a computer through a universal serial bus (USB) port. The experimental setup is controlled and broadcasted to the internet by LabVIEW software from National Instruments (Austin, Texas). For communication during the experimental session between the students, who can collaborate online at different locations, and between the students and the tutor, a Java-based chat capability is included. The experiment can be accessed from any internet connected computer after registering and installing Java and LabVIEW plug-ins.

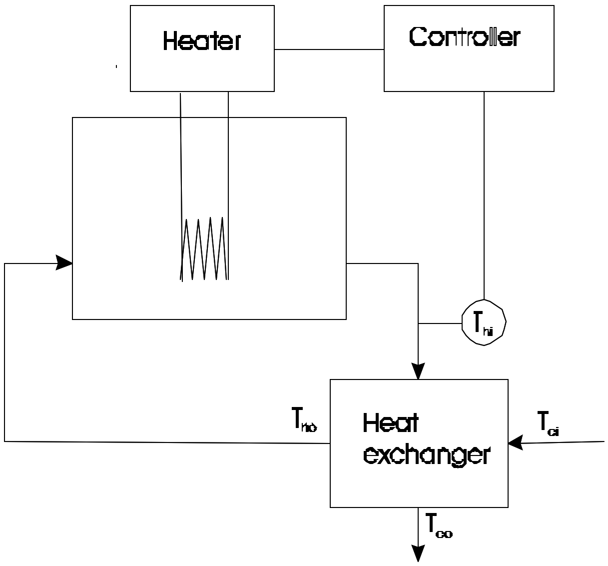

FIGURE 1.
SIMPLIFIED EXPERIMENTAL SETUP.

The experiment was originally set up to study the principles of heat transfer, and its application was broadened to study transient dynamics and control. In this initial collaboration, the focus has been on the controller for the hot water inlet temperature; the actual heat exchanger was only treated as a black box (Figure 1). The cold water to the heat exchanger was from the tap, whereas the hot water was circulated through a heated tank. The students' task was to achieve and maintain constant a desired water temperature into the heat exchanger, T_{hi}, under varying flow conditions. This temperature was also used as the input to the controller.

THE GRAPHICAL USER INTERFACE

The graphical user interface (Figure 2) allows the user to change set-point temperature, hot and cold water flow rates, switch between co- and counter-current flow pattern, and set proportional (P), integral (I), and derivative (D) parameters. It also shows real time values of temperatures, flow rates, and controller output. Temperatures and flow rates are also displayed in a scrolling graph and in tabular form which is observed by clicking the "Data Table" tab, and the interface allows the user to record these data to a file for later retrieval. The charts can be re-scaled by double clicking and entering new extreme values on an axis.

The desired values for flow rates (1), set point temperature (2), and PID parameters (3) are simply entered into the boxes. For the flow rates, there are also options to use the turning knobs or the arrow buttons. To save experimental data, which can later be retrieved from the website, a file name is entered and the "record data" button clicked (4). To use only P control, zero can be entered for the D parameter, but this is not appropriate for the I parameter, since the control signal is proportional to the inverse of I. To overcome this, a "reset integral error" button (5) was added to make it possible to switch off the integral control. The contribution of each control parameter to the control signal is shown in the output boxes (3) as a help for fine tuning. The hot and cold water flow rates are shown in the two charts (6, 7) with the instantaneous values in boxes. The inlet and outlet temperatures to/from the heat exchanger are shown in the chart (8) with instantaneous values in boxes in the schematic heat exchanger drawing (9). The dial (10) shows the heater output.

Several students can be logged in to the experiment at the same time, but for obvious reasons only one person can control the parameters. The right to control can be passed between the students by requesting and releasing control of the experiment.

On the same page is also a Java chat facility for communication between the students and between the students and the tutor. A message is typed, and after the "send" button is clicked the message is visible to all logged in to the chat facility.

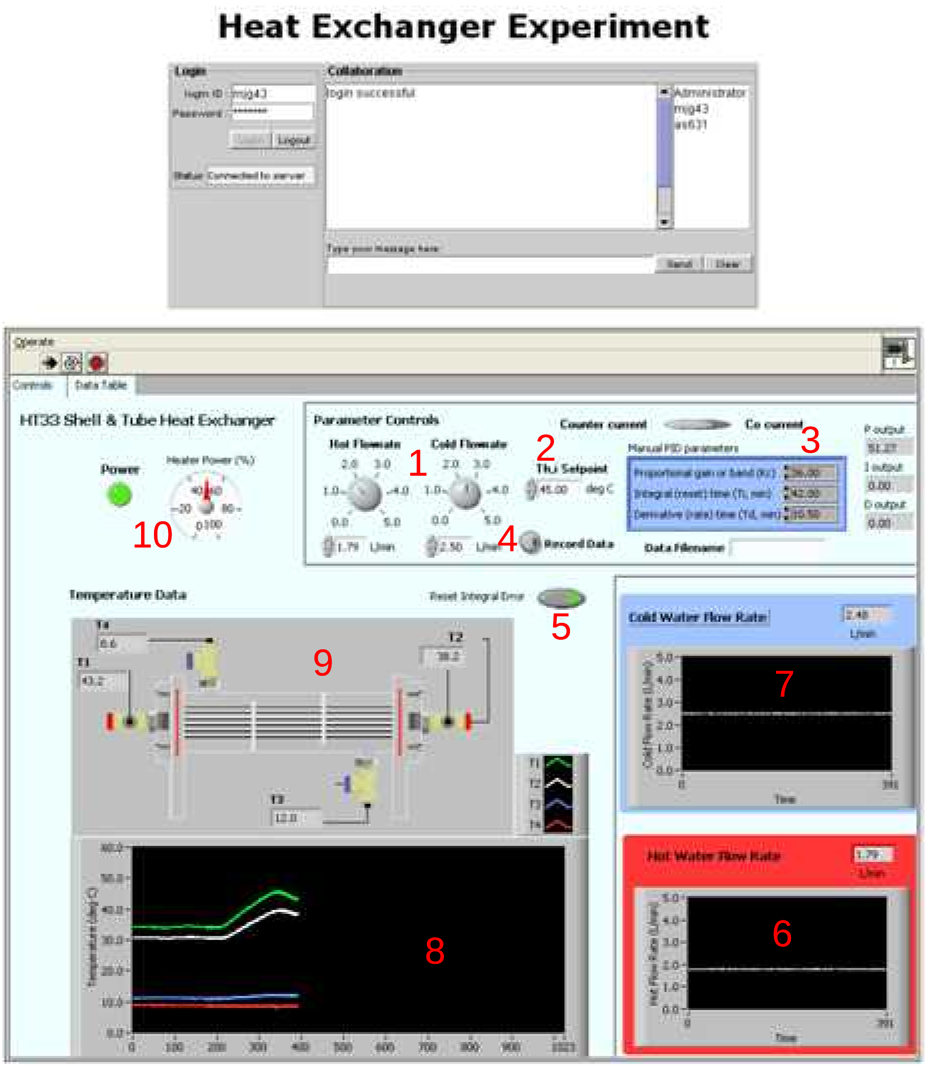

FIGURE 2.
THE GRAPHICAL USER INTERFACE (NUMBERS REFER TO TEXT DESCRIPTION). THE CHAT FACILITY IS AT THE TOP.

THE EXERCISE

"Process Dynamics and Control" is a subject taught in the second year of chemical engineering at CU and aims to give the students a variety of skills, such as how to write correctly formulated mass and energy balances and to analyze and design controllers. The course is accompanied by an exercise that is designed to be an intermediate step between idealized, exam-style questions and long-term, large-scale projects. In previous years, the exercise contained a simulation of a flash tank where the numerical solution of the control equations often occupied more of the students' time and thought than the actual control part. In order to allow the students to focus more successfully on the practicalities of control, the previous exercise was eliminated, and a new one incorporating the MIT heat exchanger was developed.

The new exercise is divided in three parts:

1. A few preparatory questions on control enabling the students to identify the relevant variables and to calculate control parameters from open loop test data.
2. An experimental session with observations of a real system under P, PI, and PID-control, followed by fine tuning of the control parameters and testing the response of the system to disturbances.
3. Processing of data obtained during the experimental session and follow up questions penetrating deeper into the matter.

For the first part, the students were given a piping and instrumentation diagram of the experimental setup and four sets of real data obtained from open loop tests (the reaction of the system to a step change in the process variable with the controller disconnected). From the piping and instrumentation diagram, the students should identify: a) the controlled variable, b) the process variable and c) any disturbance variables. From the data supplied, the students should first identify which set was best suited and then apply the method of Cohen and Coon [3] to calculate an initial set of PID parameters to be used in the experimental session. Because the data was real and non-ideal, the resulting PID parameters could vary by at least a factor of three depending on how slope, final temperature, and dead time were interpreted from the data. Many students commented on this, and it was a useful experience on the difficulties that can arise when dealing with real data. After presenting acceptable answers for the first part to a tutor, username and password were issued to enable the student to log in to the experiment.

In groups of three or four at their allocated time slots, the students logged in to the experiment at http://heatex.mit.edu using a LabVIEW interface. The Java chat facility was used for communication between the students and the tutor. After agreeing on initial PID parameters, the students' first task was to make qualitative observations of the system under P, PI, and PID control, noting phenomena such as offset and stability in the controlled variable. If the system did not stabilize, the students had to make changes to one or more of the parameters, using their theoretical knowledge of control, to obtain a stable system. Once happy with the steady state behavior, the students tested their parameters by applying, and recording the response to, step changes in the hot and cold water flow rates and in the set point temperature. Some groups needed to further adjust their parameters to ensure the system was stable in response to the disturbances. Most groups completed the experimental session within two hours, but some groups spent more time playing and testing responses to changes in the parameters and spent up to three hours.

Following the experimental session, the students wrote individual reports on their observations and changes to the parameters during the experiment. They also had to (1) process their data by choosing (and justifying the choice of) an error response criterion and calculating its value for each disturbance, (2) suggest methods for further fine tuning, and (3) discuss the differences between the experimental system and an idealized stirred tank. For the error response criterion, some students chose the integral of the square error and others the integral of the absolute error, and both criteria were accepted as long as the choice was justified. Because the students had just calculated the value of an error response criterion, we expected a suggestion to minimize that for further fine tuning, but quite a few suggested other routes like minimizing overshoot, rise time, or decay ratio and also pointed out that different aspects are important to different systems. Finally, the comparison to an idealized stirred tank was a useful exercise, since the students were used to doing this the other way around by dealing with idealized systems and thinking about how a real system would behave.

EVALUATION

The equipment is designed to run over long periods of time with minimal maintenance, and once set up by the MIT staff it could be run for the complete course with only occasional supervision. Technically, the equipment and interface performed without fault during the duration of the course (ten three-hour sessions).

Student feedback was obtained by issuing questionnaires assessing usability of experiment and interface, group work experience, meeting educational objectives, and experience in comparison to exercises in other subjects. In the questionnaire the students had to state to what extent they agreed with a number of statements on a Likert scale from 1, “I strongly disagree” to 7 “I strongly agree”. A total of 36 students performed the exercise, and 23 of them handed in a completed questionnaire.

Usability when carrying out the experiment on the web (Instructions, operation, time needed, and retrieval of data)

Students were provided a web based exercise sheet and detailed instructions on how to carry out the experiment. Time spent with the experiment varied from 90 to 180 minutes. The students were satisfied with the instructions and managed well to use the LabVIEW interface and chat window and to download their experimental data after the session (Figure 3). Various suggestions for minor improvements of the interface were received.

Student feedback on usability:

“The interface was plain and simple - very easy to operate and the use of the chat window was also very helpful”
“Interface was clear and easy to use. Instructions good”
“Quite user friendly system. Good instruction etc available”

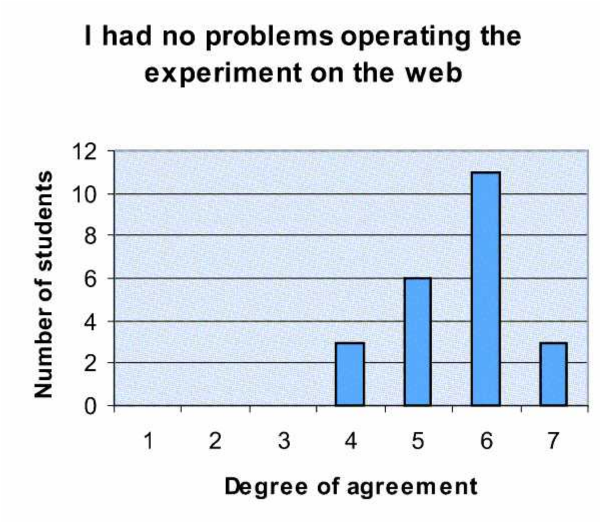

FIGURE 3.
"I HAD NO PROBLEMS OPERATING THE EXPERIMENT ON THE WEB."

Working in a group (Group size, actual and preferred, contribution to group)

This exercise was one out of seven, with the others being performed individually. This one was performed in groups of four but the reports were written individually as usual. The students very much liked working in groups and felt that they could contribute to the group (Figure 4). When it came to group size, the students' opinions fell into two categories: one seeing no or little reason to have smaller groups and one that thought a smaller group would have been good (Figure 5). Three students commented that three students would be the ideal group size.

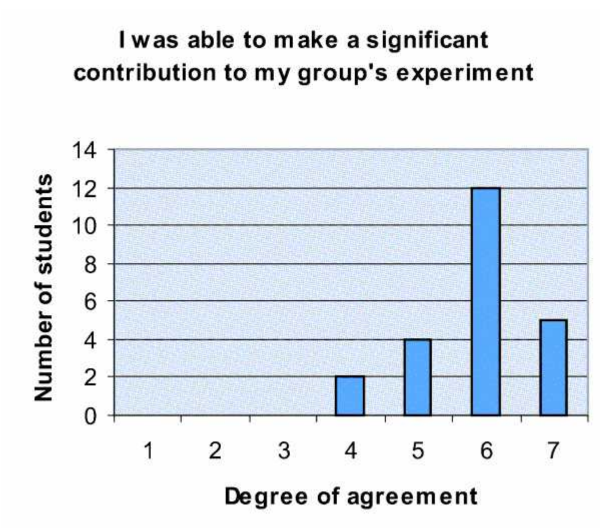

FIGURE 4.
"I WAS ABLE TO MAKE A SIGNIFICANT CONTRIBUTION TO MY GROUP'S EXPERIMENT."

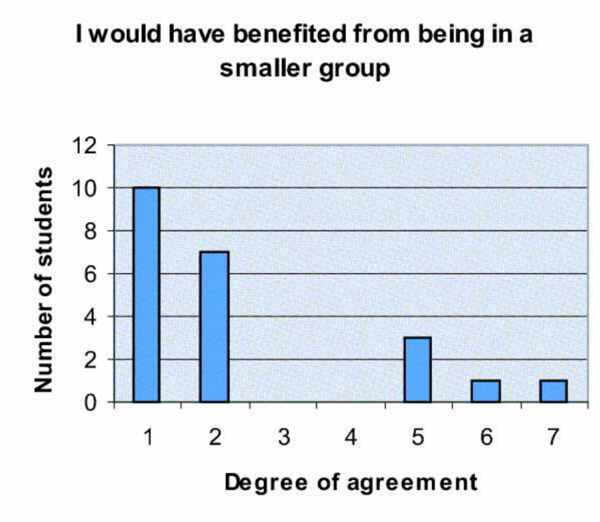

FIGURE 5.
"I WOULD HAVE BENEFITTED FROM BEING IN A SMALLER GROUP."

Student feedback on group work:

"It was really fun"
"No problem - useful to be able to discuss things"
"Beneficial having a group of people to discuss/explain ideas"
"More enjoyable to work together, more ideal + discussion possible"
"Very useful to have people to talk it through with"

Meeting educational objectives (Measurement and analysis of real data, qualitative behavior)

Even though some students commented on a lack of sense of reality when performing the experiment, most agreed that it provided an experience of measurements and analysis of real data and the qualitative behavior of P, PI, and PID control (Figure 6).

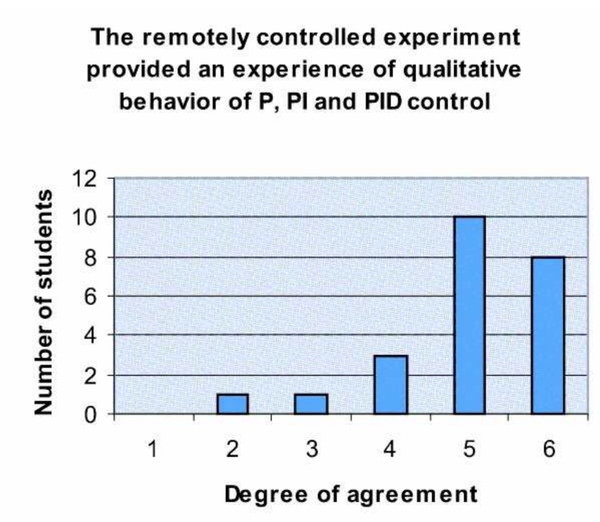

FIGURE 6.
"THE REMOTELY CONTROLLED EXPERIMENT PROVIDED AN EXPERIENCE OF QUALITATIVE BEHAVIOR OF P, PI, AND PID CONTROL."

Comparison to other exercises

The other exercises were purely theoretical and performed individually. They were simulations of systems based on equations or literature surveys. This exercise offered a change in providing a challenge to use theoretical knowledge to tune a real system. This was very positively received by most students (Figure 7).

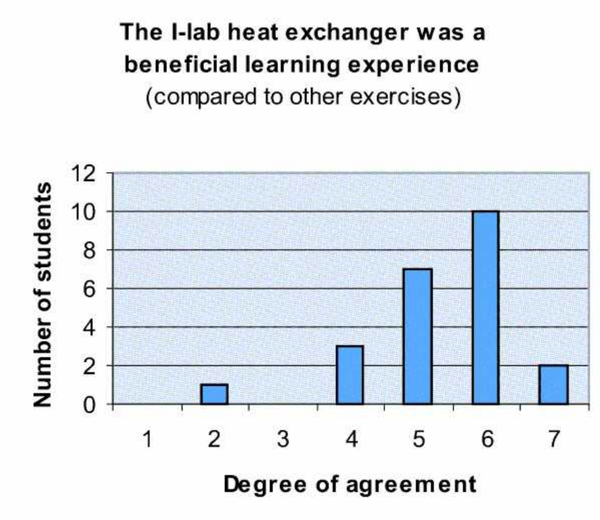

FIGURE 7.
"THE ILAB HEAT EXCHANGER WAS A BENEFICIAL LEARNING EXPERIENCE (COMPARED TO OTHER EXERCISES)."

Student feedback on comparison:

"Good to do an exercise on something real"
"It was really fun"
"Useful to experience a system that is close to reality than ideal systems studied in lectures"
"More hands on. I had control of a real experiment and was able to see the responses to adjustments I made, in real time"
"Good to obtain and analyze real data, not just theoretical exercises"
"Good level of complexity. Good fun. Good to use the web in that way. Enjoyed it…"

SUMMARY

As the first part of a new web-based teaching collaboration between the University of Cambridge and MIT, chemical engineering students in Cambridge have performed a process control experiment on equipment located at MIT. Students were able to gain hands-on experience of a system under feedback control and were able to see, firsthand, the effects on the system of altering the control parameters.

The successful realization of this web based experiment shows that the technology is available and sufficiently stable to perform complex experiments over the internet. The user friendly graphical user interface and the fast responding process were appreciated by the students, as was shown by positive responses to the course evaluation questionnaire.

ACKNOWLEDGEMENT

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