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Process Dynamics and Control Experiment Performed Across the Atlantic

Anders Selmer, Mike Goodson, Markus Kraft ¹, Sidharta Sen,

V.Faye McNeill, Barry S. Johnston and Clark K. Colton ²

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¹ Department of Chemical Engineering
University of Cambridge
Pembroke Street
Cambridge CB2 3RA
UK
E-mail: mk306@cam.ac.uk

² Department of Chemical Engineering
M.I.T.
Cambridge
MA 02139
U.S.A.
E-mail: ckcolton@mit.edu

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Edited by

Cambridge Centre for Computational Chemical Engineering
Department of Chemical Engineering
University of Cambridge
Cambridge CB2 3RA
United Kingdom.

Fax: + 44 (0)1223 334796

E-Mail: c4e@cheng.cam.ac.uk

World Wide Web: <http://www.cheng.cam.ac.uk/c4e/>

Abstract

At the University of Cambridge, UK, we have developed, used, and evaluated a new exercise in Process Dynamics and Control incorporating a web-based experiment physically located at MIT. We describe the experimental equipment, the interface used, the new exercise, and report on the student evaluation. The successful realization of this exercise shows that the technology is available and sufficiently stable to perform complex educational experiments over the Internet. The exercise was appreciated by the students, as was shown by positive responses to the course evaluation questionnaire.

1 Introduction

Process control has increased in importance in the process industries over the past decades, driven by global competition, rapidly changing economic conditions, more stringent environmental and safety regulations, and the need for more flexible yet more complex processes to manufacture high value products. Remotely controlled processes are increasingly used in industry and research, 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.

The Process Dynamics and Control course gives the students a solid foundation of theoretical knowledge but for a chemical engineer it is also an important professional skill to be able to put understanding into practice. A well designed practical exercise, using up to date technologies for remote operation and communication, on a real system, will give the students essential training for what they are likely to encounter in their professional life.

The purpose of this paper is to report on the development, usage, and evaluation of a new exercise in Process Dynamics and Control incorporating a web-based experiment physically located at MIT. We first describe the experimental equipment and interface used, then the new exercise, and finally the results of the student evaluation.

2 The Experiment

The experimental equipment is a heat exchanger, set up for online use within the “Transport Processes” and “Process Dynamics and Control” subjects [1]. This was done as part of the MIT iCampus project, where a number of web accessible experiments, iLabs, have been developed [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 broadcast 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.

The experimental setup is shown in Figure 1; the heat exchanger is to the bottom right. For the cold water flow, F_c , mains cold water, controlled by a flow controller

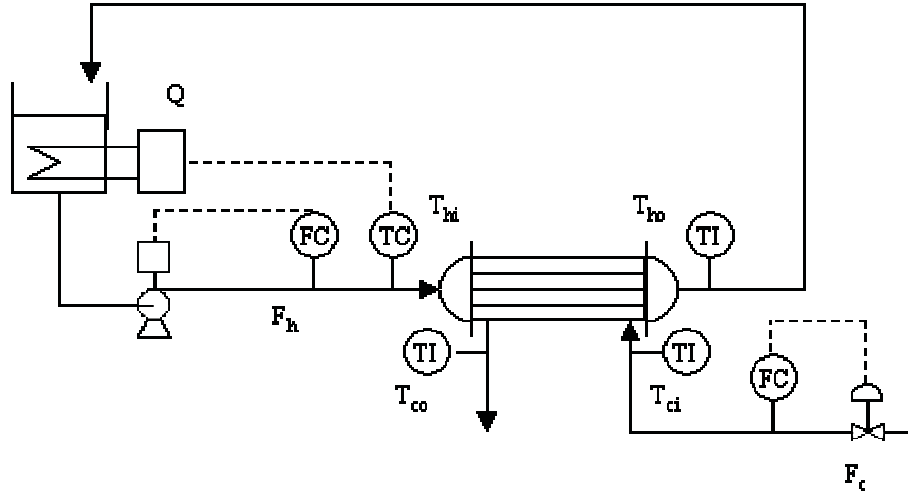


Figure 1: *The experimental setup*

operating a valve, is used. Temperature indicators measure the cold water inlet and outlet temperatures, T_{ci} and T_{co} . For the hot water flow, F_h , a pump, controlled by a flow controller, pumps water through a heated tank (to the top left) where a heater, controlled by a temperature controller, heats the water. Temperature indicators measure the hot water inlet and outlet temperatures, T_{hi} and T_{ho} . T_{hi} is also used as the input to the temperature controller. The heat exchanger was originally built to study the principles of heat transfer; its application was then 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. The students' task was to achieve and maintain constant a desired water temperature into the heat exchanger, T_{hi} , under varying flow conditions.

3 The Graphical User Interface

The graphical user interface, shown in 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 the 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 help for fine-tuning. The hot and cold water flow rates are shown in the two charts (6 and 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.

Heat Exchanger Experiment

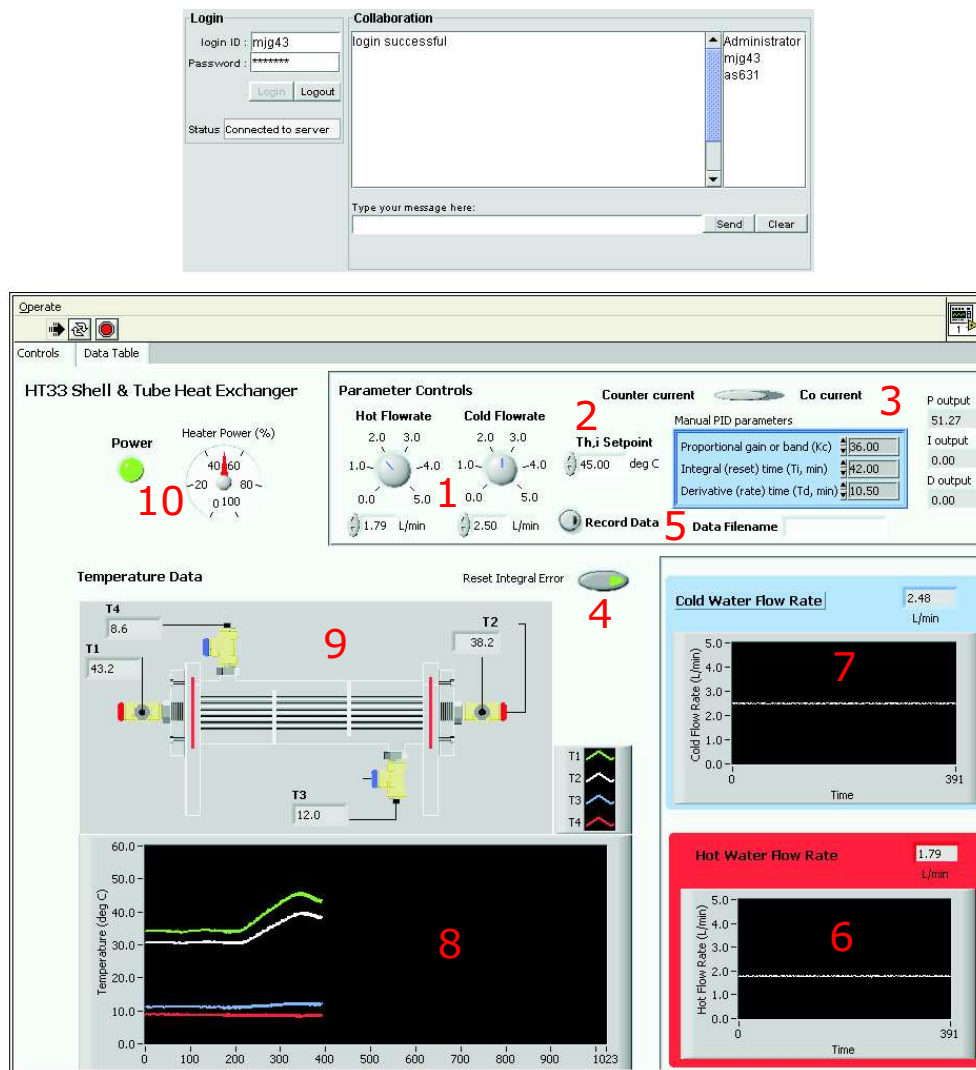


Figure 2: *The Graphical User Interface (Numbers refer to text description). The chat facility is at the top.*

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.

4 The Exercise

“Process Dynamics and Control” [3] is the title of a one term course, taught in the second year of chemical engineering at the University of Cambridge 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, which is an extended activity, undertaken individually, designed to test the student’s knowledge of the ideas covered in lectures. The exercise, although based on the course material, aims to extend and challenge the student. The exercise is written up by the student in a report style, which gives them practice in presenting their work clearly and concisely to the examiners. 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 (see Figure 1) 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. Most students identified the controlled and process variables correctly as T_{hi} and Q respectively. The disturbance variables here are T_{ho} and F_c since this is what enters the heater bath but T_{ho} is a function of F_c , F_h , T_{ci} and also T_{hi} which complicates the matter and also confused the students and illustrates why real life is more interesting than idealized systems. From the data supplied, the students should first identify which set was best suited and then apply the method of Cohen and Coon [4] to calculate an initial set of PID parameters

to be used in the experimental session. Because the data were 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 another useful experience on the difficulties that can arise when dealing with real data.

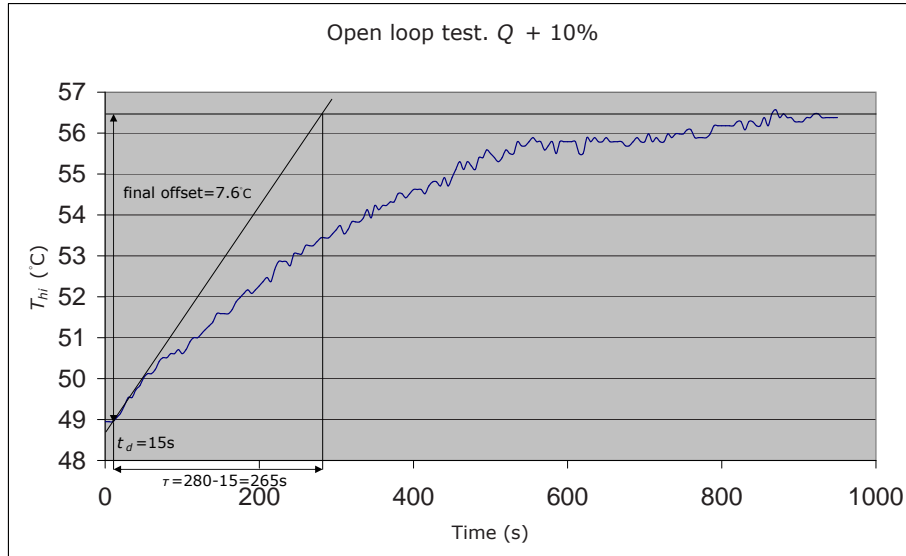


Figure 3: *Open Loop Test Data Plotted for Obtaining P, I and D Parameters According to Cohen and Coon [4].*

Figure 3 shows the recorded response to a step change in Q of +10 %. The final offset is $56.5 - 48.9 = 7.6$ °C (or Kelvin), the dead time, $t_d = 15$ s and $t = 280 - 15 = 265$ s. To be able to use the Cohen and Coon formulas we also need K , the final offset divided by the step change. Total heater power is 2 kW so $K = 7.6(\text{K})/0.2(\text{kW}) = 38$ K/kW or in %: $K = 7.6(\text{K})/10(\%) = 0.76$ K/%. The P, I and D parameters can then be estimated using the equations shown in Table 1:

Table 1: *Equations to estimate P, I and D parameters according to Cohen and Coon [4].*

P (%/K)	I (s)	D (s)
$\frac{1}{K} \frac{\tau}{t_d} \left(\frac{4}{3} \frac{t_d}{4\tau} \right) = 31$ %/K	$t_d \left(\frac{32 + 6t_d/\tau}{13 + 8t_d/\tau} \right) = 36$ s	$t_d \left(\frac{4}{11 + 2t_d/\tau} \right) = 5.4$ s

After presenting reasonable estimates of the P, I, and D parameters 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, or trial and error, to obtain a stable system. Once happy with the steady state behavior, the students tested their parameters by applying, and recording the response to, three step changes: a) F_h step change of -1 L/min, b) T_{hi} , set point step change of $+5$ °C and c) F_c step change of $+2$ L/min. 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, each student wrote an individual technical report, including his/her observations and changes to the parameters during the experiment. They also had to process their data by choosing (and justifying the choice of) an error response criterion and calculating its value for each disturbance, suggest methods for further fine-tuning, and 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 (emphasizing large errors) and others the integral of the absolute error (treating all errors equally), 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 and the students noted things like: the presence of dead times for the measurements in the real system, signal noise in the measured values for temperatures and flow rates, the real system being too complex to treat mathematically and the mixing being non perfect in the real system. Usually the students are used to doing this the other way around by dealing with idealized systems and thinking about how a real system would behave.

5 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.

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

Students were provided with 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. 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”.

5.2 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. When it came to group size, the students’ opinions fell into two categories: either seeing little or no reason to have smaller groups, or thinking that a smaller group would have been good. Three students commented that three students would be the ideal group size.

Student feedback on group work: “No problem - useful to be able to discuss things”, “Beneficial having a group of people to discuss/explain ideas”, “Very useful to have people to talk it through with”.

5.3 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, see Figure 4.

5.4 Comparison to other exercises

The other exercises were purely theoretical and performed individually. This exercise offered a change by being partly performed in a group and in providing a challenge to use theoretical knowledge to tune a real system. This was very positively received by most students, see Figure 5.

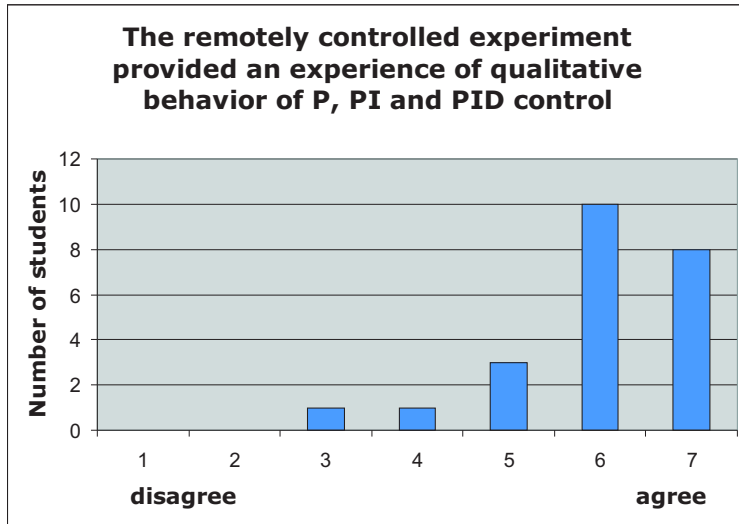


Figure 4: *“The remotely controlled experiment provided an experience of qualitative behavior of P, PI and PID control”*

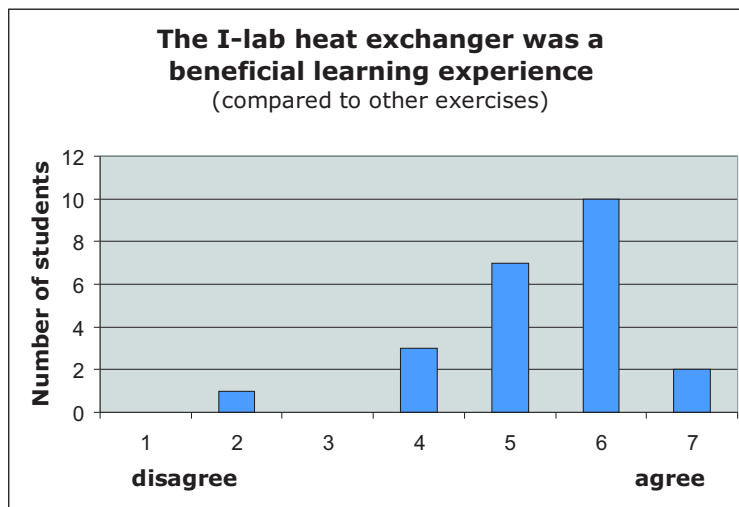


Figure 5: *“The I-lab heat exchanger was a beneficial learning experience (compared to other exercises)”*

Student feedback on comparison: “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”.

6 Summary

We have developed, used, and evaluated a new exercise in Process Dynamics and Control incorporating a web-based experiment physically located at MIT. We describe the experimental equipment, the interface used, the new exercise, and report on the student evaluation.

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

The authors at University of Cambridge are now in the process of developing assignments and hardware for a new experiment on chemical reactors for broadcasting to the Internet.

7 Acknowledgements

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