# PERFORMING PROCESS CONTROL EXPERIMENTS
## *Across the Atlantic*

Anders Selmer, Mike Goodson, Markus Kraft, Siddhartha Sen[1], V. Faye McNeill[2], Barry S. Johnston[3], Clark K. Colton[3]
*University of Cambridge • Cambridge CB2 3RA, United Kingdom*

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, which are increasingly being used in industry and research, allow a process to be analyzed and controlled—and data recorded and processed via a Web interface—without the need to be in the same physical location as the equipment itself.

Likewise, Internet-based experiments offer possibilities for students to use up-to-date technologies for remote operation and communication on a *real* system. Perhaps more importantly, they will give students essential training for what they're likely to encounter professionally.

The purpose of this paper is to report on the development, usage, and evaluation of a new exercise in process dynamics and control that incorporates 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.

## EXPERIMENTAL SETUP

The experimental equipment is a heat exchanger, set up for online use within the subjects of transport processes and process dynamics and control. This was done as part of the MIT iCampus project, where a number of Web-accessible experiments—iLabs—have been developed.[1] The experiment, contained in a laboratory in the Department of Chemical Engineering at MIT, has been used in the education of MIT chemical engineering students since November 2001. The equipment is manufactured by Armfield, Ltd. in Ringwood, England, and consists of a service unit (HT30XC) supplying hot and cold water, with a shell and tube heat exchanger (HT33) mounted on it. 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). A Java-based chat capability is included, allowing communication during the experimental session among the students (who can collaborate online at different locations) as well as between the students and the tutor. The experiment

***Anders Selmer*** *studied chemistry and chemical engineering at the Lund Institute of Technology, Sweden, and obtained a master's degree in 1993. After nine years in industry he is now working with Web-based experiments for chemical engineering students at the University of Cambridge.*
***Mike Goodson*** *studied chemical engineering at the University of Cambridge and started his Ph.D. on population balance modeling in 2000. Since January 2004 he is also the department Teaching Fellow, assisting students with continuously assessed coursework.*
***Markus Kraft*** *obtained the academic degree "Diplom Technomathematiker" at the University of Kaiserslautern in 1992 and completed his "Dr. rer. nat." at the Department of Chemistry at the same university in 1997. Since 1999 he is a lecturer in the Department of Chemical Engineering at the University of Cambridge. His main research interests are in the field of computational chemical engineering.*
***Siddhartha Sen*** *obtained his bachelor's degrees in computer science and engineering and mathematics from the Massachusetts Institute of Technology in 2003, and went on to get a master's degree in computer science in 2004. Sid is currently working as a software design engineer in the Network Load Balancing group at Microsoft Corp.*
***Vivian Faye McNeill*** *graduated from the Massachusetts Institute of Technology with her Ph.D. in chemical engineering in February 2005. Her thesis was entitled "Studies of Heterogeneous Ice Chemistry Relevant to the Atmosphere." She is currently a research associate in the Department of Atmospheric Sciences at the University of Washington, Seattle.*
***Barry S. Johnston*** *studied chemical engineering at Alabama, Clarkson, and Northwestern universities. He has worked in the chemical and nuclear industries. At MIT, he teaches undergraduate courses in process control, equipment design, and laboratory, and occasionally directs Practice School stations.*
***Clark K. Colton*** *received the B.ChE. degree from Cornell University in 1964 and a Ph.D. degree from Massachusetts Institute of Technology in 1969. He joined the faculty of MIT thereafter, becoming full professor in 1976. He was deputy head of the chemical engineering department 1977-78 and Bayer Professor of Chemical Engineering 1980-86. His research interests are in bioengineering.*



[1]*Currently at Microsoft Corp., headquarters at One Microsoft Way, Redmond, WA 98052*
[2]*Currently at University of Washington, Seattle, WA 98195-1750*
[3]*Massachusetts Institute of Technology, Cambridge, MA 02139-4307*

can be accessed from any Internet-connected computer after registering and installing Java and LabVIEW plug-ins. For a detailed description of the hard- and software environment, refer to Colton, *et. al*.[2]

The experimental setup is shown in Figure 1; the heat exchanger is to the bottom right. The cold water flow, $F_c$, uses mains cold water from a tap in the laboratory and is controlled by a flow controller operating a valve. 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.

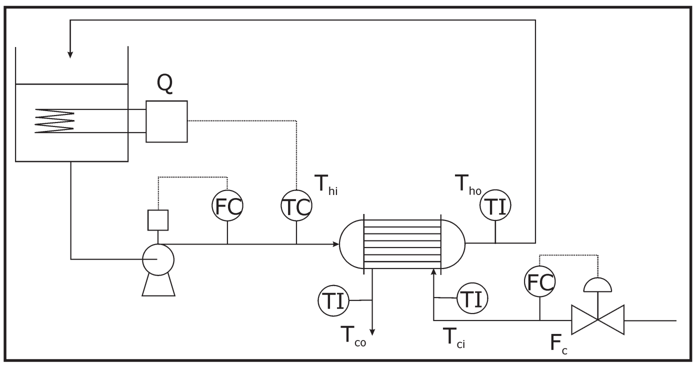


***Figure 1.*** *Experimental setup (described in the text).*

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 a desired water temperature into the heat exchanger, $T_{hi}$, under varying flow conditions.

## CONTROLLER INTERFACE

The graphical user interface, shown in Figure 2, allows the user to change setpoint temperature, change hot and cold water flow rates, switch between co- and countercurrent flow patterns, and set the proportional (P), integral (I), and derivative (D) parameters. It also shows real-time values of temperatures, flowrates, and controller output. Temperatures and flowrates 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 rescaled by double clicking and entering new extreme values on an axis.

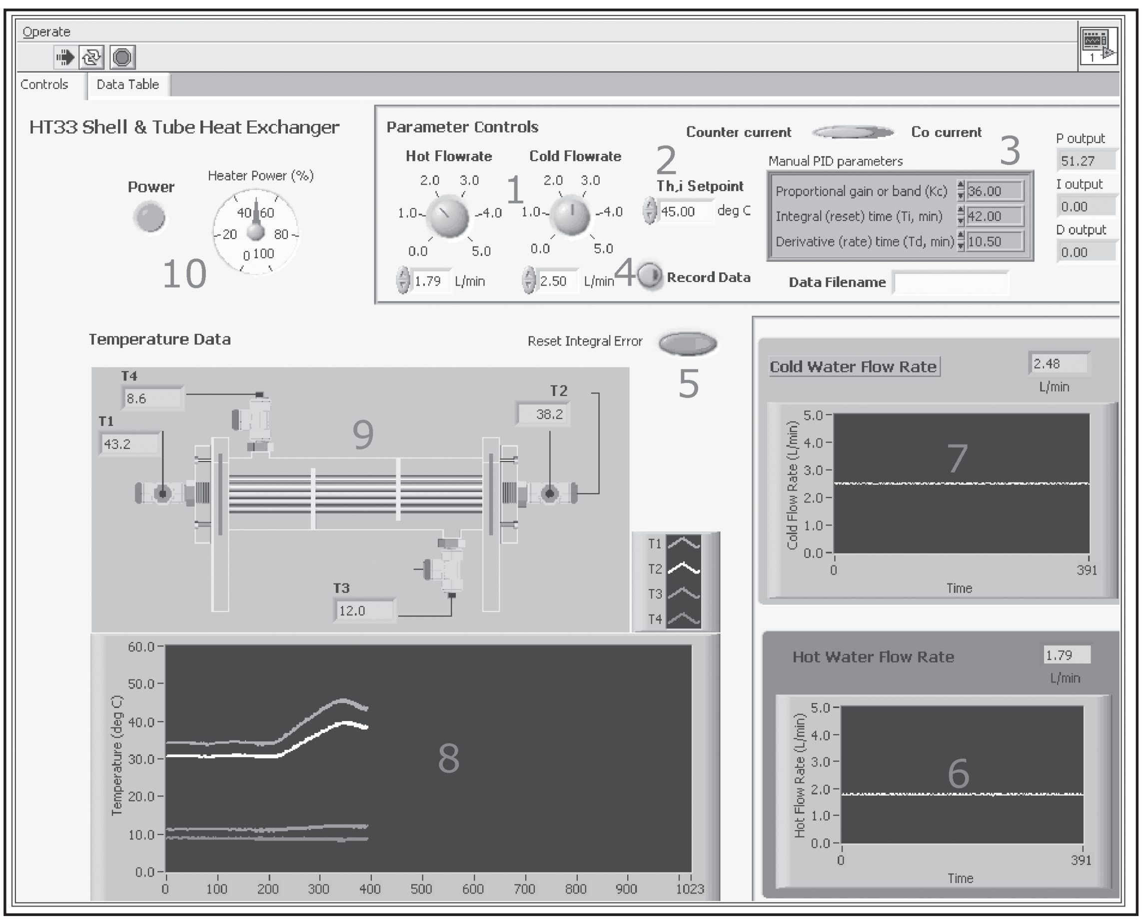


***Figure 2.*** *The graphical user interface (numbers refer to text description).*

The desired values for (1) flowrates, (2) setpoint temperature, and (3) PID parameters are simply entered into the boxes. For the flowrates, there are also options to use the turning knobs or the arrow buttons. To save experimental data, which can later be retrieved from the Web site, a file name is entered and the "record data" button clicked (4). By entering appropriate values for the parameters, and using the "reset integral error" button (5) when necessary, students can run the experiment under P, PI, or PID control as required. The hot and cold water flowrates 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.

The interface looks and operates in exactly the same way if it is used to control an experimental setup next to the computer or if the setup is somewhere else. What the students do not see when performing the experiment over the Internet is the actual equipment. Maybe more importantly, they do not *hear* the noise of pumps and stirrers. To reduce this disadvantage, a Webcam has now been added to allow the students to see and hear the equipment when running the experiment.

Since we had the opportunity to use a real experiment we have not investigated the possibility of using a simulation. Simulations might be of good use when teaching control, but if students are to be trained for a real world with errors and irregularities, it is our view that a real system is preferable to a simulated one. This view is also supported by Ang and Braatz,[3] and Bencomo in his review of process control education.[4] From an interface point of view, running a simulation would not differ from running a real experiment, but the behavior of the system is likely to be more predictable.

On the same page as the interface is a Java chat facility (Figure 3) for communication among 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 users logged in to the chat facility.

## THE EXERCISE

"Process Dynamics and Control[5]" is the title of a one-term course of 16 lectures taught in the second year of chemical engineering at the University of Cambridge. It aims to give students a variety of skills, such as how to write correctly formulated mass and energy balances and how to analyze and design controllers. Other institutions such as Rensselaer[6] and Illinois[3] have more lecture time to cover the topic and also have their students run a case study over several weeks[6] or spend several hours every week in the laboratory.[3] The course at the University of Cambridge is accompanied by an exercise that is an extended activity, undertaken individually, designed to test the students' knowledge of ideas covered in lectures. The exercise, although based on the course material, aims to challenge the students and extend their understanding. To practice presenting work clearly and concisely, each student writes a report on the exercise.

Unlike schools such as Utah[7] and Illinois,[3] the University of Cambridge has no huge experimental facilities to use for control experimentation. Further, space and time restrictions do not allow for a hands-on laboratory experiment to be added to the course. By incorporating the MIT iLabs heat exchanger operated over the Internet, the new exercise met course goals and gave Cambridge students the traditional benefits of a laboratory experiment. It also exposed them to remote-control software—much in line with the future predictions on remotely operated processes made by Skliar, *et. al.*,[7]

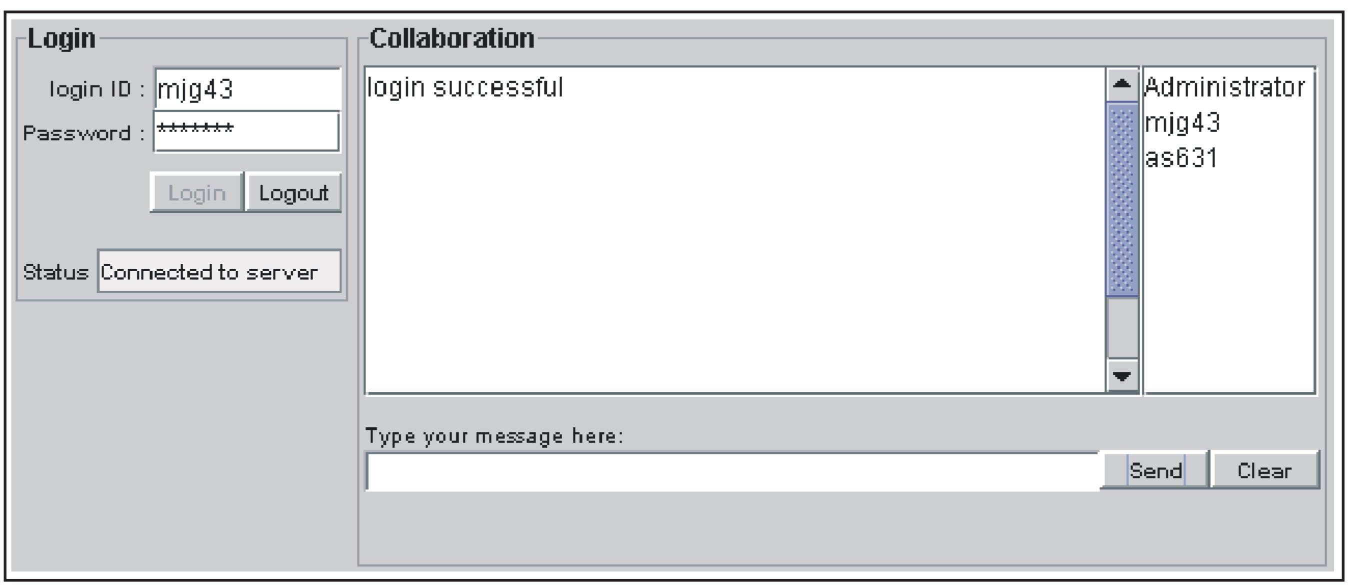


***Figure 3.*** *The chat facility.*

and described by Bencomo.[4] The advantages of this exercise are therefore twofold: experiments can easily be performed on real systems (as opposed to simulations) where equipment would otherwise be unavailable, and students gain knowledge of remote-control software such as that used in research and industry.

The new exercise is divided into three parts.

- ▲ *A few preparatory questions on control, enabling the students to identify the relevant variables and to calculate control parameters from open-loop test data*
- ▲ *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*
- ▲ *Processing of data obtained during the experimental session and follow-up questions penetrating deeper into the matter*

For the first part, 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 (*i.e.*, 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 were asked to 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 $F_h$ since this stream is what enters the heater bath, but $T_{ho}$ is a function of $F_c$, $F_h$, $T_{ci}$, and $T_{hi}$, which complicates the matter. It also confused the students—thus illustrating the truism that real life is more interesting than idealized systems.

From the data supplied, the students were told to first identify which set was best suited to the desired operating conditions and then to apply the method of Cohen and Coon[8] to calculate an initial set of PID parameters to be used in the experimental session.

Cohen and Coon is one of the tuning methods covered in the lectures and is known to be nonrobust, but the method was deliberately chosen because we did not want the students to start their experiments with a perfect set of PID parameters. The main focus of the exercise is *not* choosing PID parameters from experimental data. Rather, the focus is the practical experiment itself, and during the experiment we wanted students to experience instabilities and have to further fine tune the system using their theoretical knowledge of control. 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 with the difficulties that can arise when dealing with real data, as well as some shortcomings of the Cohen and Coon method.

After presenting reasonable estimates of the PID parameters to a tutor, each student was issued a username and password to log in to the experiment. During allocated time slots, students in groups of three or four 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) $T_{hi}$ setpoint 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 distur-

***Since we had the opportunity to use a real experiment we have not investigated the possibility of using a simulation. Simulations might be of good use when teaching control, but if students are to be trained for a real world with errors and irregularities, it is our view that a real system is preferable to a simulated one.***

bances. 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.

***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.***

Following the experimental session, each student wrote an individual technical report, including his or her observations and changes to the parameters during the experiment. The reports showed that the students had gained understanding of the effects of the PID parameters on the controlled variable and how to adjust the parameters to mitigate for undesired effects such as slow or unstable responses under servo or regulator control. They also had to process their data by: choosing (and justifying the choice of) an error-response criterion, calculating its value for each disturbance, suggesting methods for further fine tuning, and discussing 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). 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 such as minimizing overshoot, rise time, or decay ratio. They also pointed out that different aspects are important to different systems.

Finally, students ranked the comparison to an idealized stirred tank as a useful exercise. They noted things such as 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 nonperfect in the real system. Typically, students are 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 for the duration of the course (ten three-hour sessions).

Student feedback was obtained by issuing questionnaires assessing the usability of the experiment and interface, the group work experience, the meeting of educational objectives, and the experience in comparison to exercises in other subjects. In the questionnaire, students had to state to what extent they agreed with a number of statements on a Likert scale ranging 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 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. Easy comprehension and use of the interface and downloading of experimental data are listed by Bencomo[4] as some of the most important features of a remote experiment. Various suggestions for minor improvements of the interface were received.

❑ ***Working in a Group***
*(Contribution to group and actual and preferred group size)*

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

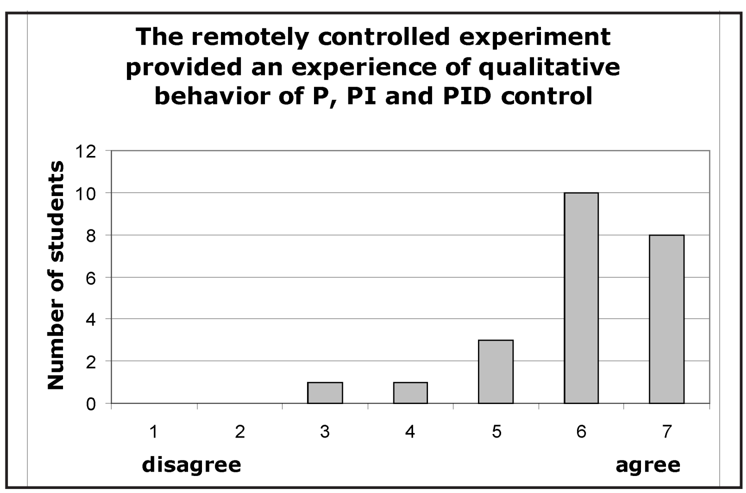


***Figure 4.*** *Students ranked the remotely controlled experiment.*

students said they very much liked working in groups and felt 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.) From a teaching point of view, we would prefer smaller groups. This is a matter of resources available, however, since smaller groups require more experimental sessions and increase the associated workload for technicians and tutors. When this exercise was repeated during 2005, the group size was set to three students, which was also the group size used at Rensselaer.[6]

❑ ***Meeting Educational Objectives***
*(Measurement and analysis of real data and qualitative behavior)*

Even though some students commented on the lack of a sense of reality when performing the experiment, most agreed that it provided an experience of measurements and analysis of both real data *and* the qualitative behavior of P, PI, and PID control (see Figure 4). A Webcam, not yet in place at the time we used the experiment, has since been added to enhance the experience with video and sound from the laboratory equipment.

❑ ***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. It was very positively received by most students (see Figure 5).

## CONCLUSION

We have developed, used, and evaluated a new exercise in process dynamics and control incorporating a Web-based experiment physically located at MIT. We described the experimental equipment, the interface used, and the new exercise, and reported on 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 shown by positive responses to the course-evaluation questionnaire.

***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.***

The authors at the 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.

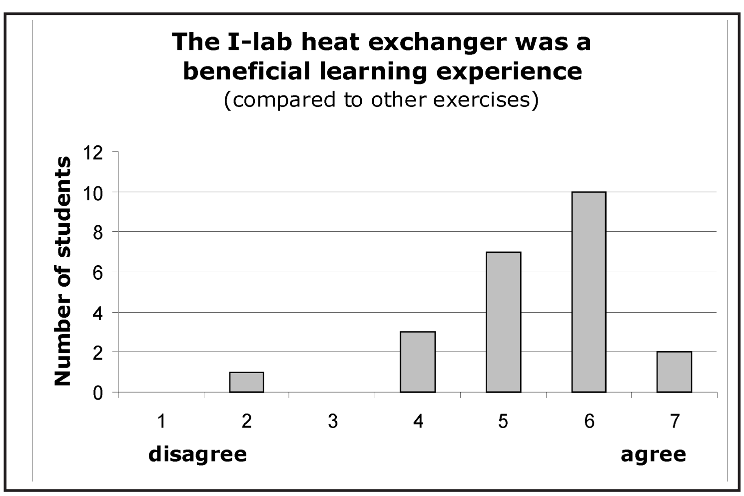


***Figure 5.*** *Students ranked the remote-learning experience.*

## ACKNOWLEDGMENT

This new teaching activity was funded in part by The Cambridge-MIT Institute, <http://www.cambridge-mit.org>, a cooperation between the University of Cambridge (U.K.) and MIT (U.S.), and by the iLabs project of iCampus <http://icampus.mit.edu>, an educational research grant to MIT from Microsoft Corporation (U.S.).

## REFERENCES

1. <http://icampus.mit.edu>, <http://icampus.mit.edu/ilabs>, <http://heatex.mit.edu>
2. Colton, C.K., M. Knight, R.A. Khan, S. Ibrahim, and R. West, "A Web-Accessible Heat Exchanger Experiment," in *Innovations 2004. World Innovations in Engineering Education and Research*, W. Aung, R. Altenkirch, R. Cermak, R.W. King, and L.M.S. Ruiz, eds. Begell House Publishing, New York, NY, 93 (2004)
3. Ang, S., and R.D. Braatz, "Experimental Projects for the Process Control Laboratory," *Chem. Eng. Ed.*, **36**(3), 182 (2002)
4. Bencomo, S.D., "Control Learning: Present and Future," *Annual Reviews in Control,* **28**, 115 (2004)
5. Deddis, C., Lecture Notes PD&C *Department of Chemical Engineering, University of Cambridge* (2004-2005).
6. Bequette, B.W., K.D. Schott, V. Prasad, V. Natarajan, and R.R. Rao, "Case Study Projects in an Undergraduate Process Control Course," *Chem. Eng. Ed.*, **32**(3) 214 (1998)
7. Skliar, M., J.W. Price, and C.A. Tyler, "Experimental Projects in Teaching Process Control," *Chem. Eng. Ed.*, **32**(4) 254 (1998)
8. Cohen, G.H., and G.A. Coon, "Theoretical Consideration of Related Control," *Trans. ASME*, **75**, 827 (1953) ❐