PID CONTROLLER SETTINGS

Based on a Transient Response Experiment

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Process control and automatic control systems play an important role in the design and operation of modern industrial plants, resulting in economical and safe plant operation. Among other topics in the field, controller tuning is particularly important because controller settings severely affect the performance of the closed-loop system. In addition, accurate settings from experimental dynamic data are extremely useful when processes are too complex to be modeled from fundamental principles.[1] Chemical engineering instruction should emphasize these facts. The unit we propose to study has a nonadiabiatic plate-heat exchanger, complex internal geometry, and nonlinear dynamics coupled and reciprocally interacting with a heater tank without agitation. In this unit, a monitoring-control system using Labview[2] has been implemented. Multivariable control examples were proposed, but the emphasis in this work was toward showing the new, improved computer interface and the pedagogical potential of the experimental unit. The PCT23 unit has also been used as the main tool for developing advanced control tracking in the controller.[3] In that work, a solution strategy was developed based on a set of partial differential equations, reflecting the complexity of the system model. In our case, an experimental reaction curve combined with tested sintonization techniques is considered as a viable method for tuning up a PID controller. Similar laboratory pilot-scale experiments have appeared elsewhere in the literature.[4, 5] These include computer-controlled units with a standard shell and pipe heat exchanger and a steady external heat source.[4] The controlled temperature is the exit hot stream, and the manipulated vari-

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able is the cold stream flow rate with additional disturbance introduced in the hot stream flow. The system identification is carried out in the frequency domain by building an experimental Bode plot diagram. This method has two drawbacks. First, it's complex in that poor students lack understanding due to the frequency domain analysis requirements. Furthermore, frequency response analysis is not practical for systems with time constants—in the order of hours as in this laboratory unit—because it needs five to six experimental runs using a sinusoidal signal to obtain a complete Bode diagram. In this experiment, the manipulated variable is the power to a heater tank source and the disturbances are introduced in the cold flow stream. The open-loop identification is performed using the classic reaction curve with only a single experimental run, with a power step perturbation inside the heater tank. The resulting reaction curve is fitted directly in the time domain using readily available worksheet program tools.[6] Other experiments[5] focus on a theoretical homework profile, which is more appropriate for advanced courses without experimental requirements. Undergraduate students in the Department of Chemistry at the University of Aveiro receive lectures on fundamentals and applications of process dynamics, simulation, modeling, and control as part of four courses as follows: Instrumentation and Process Control, Laboratory EQ4, Chemical Process Modeling and Simulation, and Advanced Process Control. This paper focuses on the controller tuning experiment of Laboratory EQ4.

This is a weekly, six-hour laboratory where students are divided into groups of three. Each experiment lasts two weeks. In the first week, students carry out the lab exercise. In the second week, they do the numerical calculations and simulations that require computational support available in the PC computer laboratory near the wet laboratory. Assessment is based on an individual oral quiz and a report prepared by each group. At the end of semester, a selected group has the opportunity to present a longer report and an oral presentation. In this final report, the students can collect the experimental results from the other parties and prepare a review of the accumulated results.

In our opinion, there are two ways to train students to tune a PID controller: i) through the use of computer simulators with powerful numerical libraries embedded in commercial software such as Matlab/Simulink, Mathcad, and Hysys or other specifically tailored applications;[7-9] or ii) by direct experimentation[9]—as in this experiment. With this experiment, chemical engineering students have the opportunity to study a small process unit to determine the PID controller settings using the Process Reaction Curve Method combined with Internal Model Control or Ziegler-Nichols tuning relations. These theoretical parameters are tested via closed-loop experiments and the results are compared.

EXPERIMENTAL SET-UP

Experiments are carried out on PCT23 Process Plant Trainer equipment shipped by Armfield.[10] It is a very flexible apparatus that integrates a small pasteurization unit, and offers a wide range of operating possibilities such as manual operation, data logging with PC, direct digital control, and industrial PID and PLC.[2] This equipment, schematically shown in Figure 1, consists of a cold water feed tank, heater tank, plate-heat

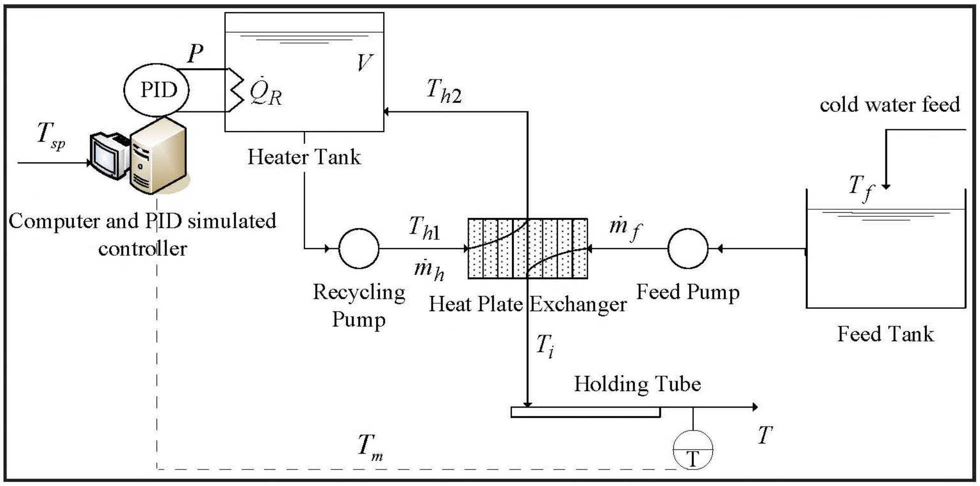

Figure 1. *Schematic of the experimental equipment.*

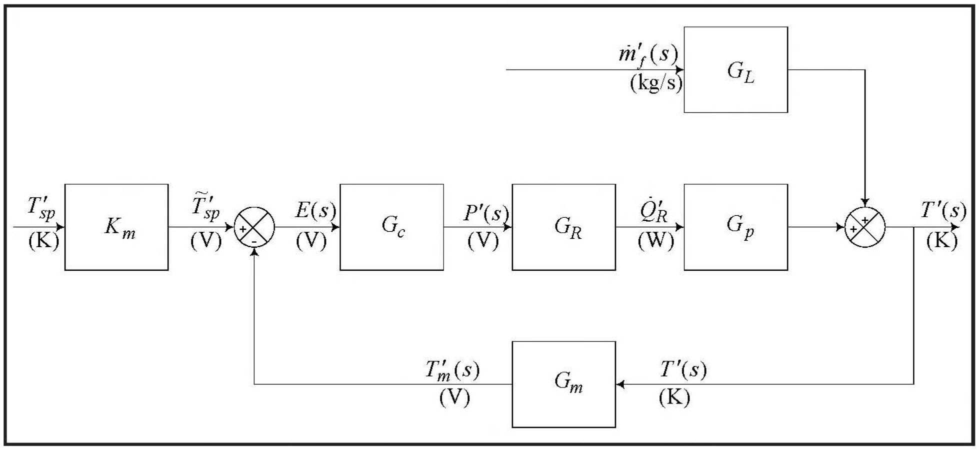

Figure 2. *Block diagram of the feedback control system.*

exchanger, holding tube with insulation, recycling pump, and feed pump. A PC-based system logs all signals and uses the Genesis software package where the PID control algorithm is implemented.[10]

The objective of this set-up is to heat the feed water from temperature T_f to an exit temperature, $T = T_{sp}$, using the plate-heat exchanger and a hot stream from the heater tank at T_{h1}. Therefore, the control strategy consists of measuring T and adjusting the power to the electric heater, $\dot{Q}_R$, so that, regardless of disturbances, the exit temperature returns to T_{sp}. The holding tube is insulated so a pure time delay results; $\dot{m}_f$ and $\dot{m}_h$ denote the water mass flows of the feed and the heating circuits, and V is the liquid volume inside the heater tank.

THEORY

Using the described control strategy, the controlled variable is T, whose set-point is $T = T_{sp}$, and the manipulated variable is $\dot{Q}_R$. In this experiment, a disturbance is introduced by changing the cold water feed flow rate, $\dot{m}_f$, using a peristaltic pump. Figure 2 (previous page) is the resulting block diagram of the feedback control system, where: G_c, G_R, G_p, G_m, and G_L are the transfer functions for controller, electrical resistance heater, process, thermocouple-transmitter combination, and load, respectively; K_m is the gain that converts the set-point, T'_{sp}, to a voltage signal, $\tilde{T}'_{sp}$, that is used internally by the controller; E is the error signal; P' is the controller output; and T'_m is the measured temperature. Apostrophes identify deviation variables calculated from the original steady state values, for instance: $T'_m \equiv T_m - T_m^o, \dot{Q}'_R \equiv \dot{Q}_R - \dot{Q}_R^o$, etc.

In this experiment two different controller tuning techniques are tested: i) Process Reaction Curve Method combined with an Internal Model Control Method (IMC) tuning rule; and ii) Process Reaction Curve Method combined with Ziegler-Nichols (ZN) tuning relations.[1, 11]

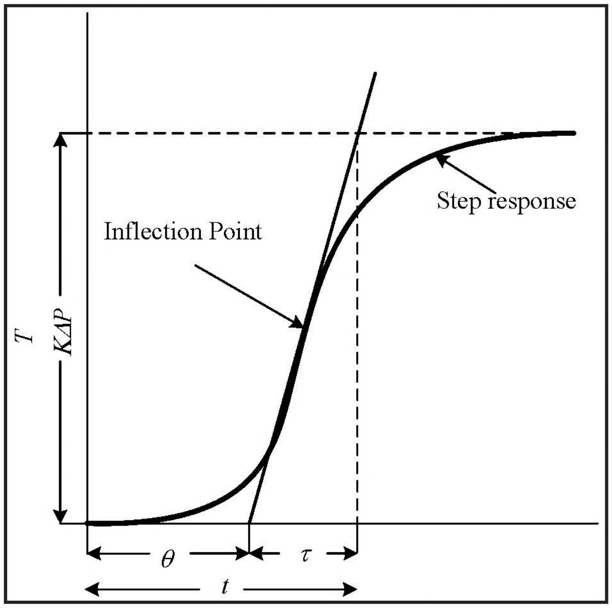

Figure 3. Step response of a first-order system with time delay, and the graphical analysis[1, 11] required to obtain the parameters for the Ziegler-Nichols tuning rules.

The Process Reaction Curve Method is an established procedure for determining the parameters of an open-loop transfer function with a single experimental test carried out with the controller in manual. A step change in the controller output (ΔP) is introduced and the measured process response, reaction curve T(t), is recorded. In this experiment, a first-order plus time delay model is selected and can be written in the Laplace or frequency domain as:

$$\frac{T'(s)}{P'(s)} = G_R G_p G_m = \frac{Ke^{-\theta s}}{\tau s + 1} \tag{1}$$

Eq. (1) includes the transfer functions for the electrical resistance heater, the process, the thermocouple, and the temperature transmitter, for a step input of magnitude ΔP:

$$P'(s) = \Delta P / s \Rightarrow T'(s) = \frac{K\Delta P e^{-\theta s}}{s(\tau s + 1)}. \tag{2}$$

Taking the inverse Laplace transform, the time domain response is:

$$\Delta T(t) = K\Delta P(1 - e^{-(t-\theta)/\tau}) \tag{3}$$

Note the system gain K, the time delay θ, and the time constant τ are the model parameters. Process gain is the ratio of the change in the steady state value of ΔT to the size of the step change ΔP [from Eq. (3): $\Delta T^{\infty} = \Delta T\ (t = \infty) = K\Delta P$], and τ may be found using several graphical methods.[1, 11] Alternatively, the three parameters may be estimated by nonlinear regression.

There are many methods to select the PID controller settings. The ideal PID controller equation illustrates the three required parameters (gain K_c, integral time τ_I, and derivative time τ_D):

$$P = P^o + K_c \left[E(t) + \frac{1}{\tau_I} \int_0^t E(t)dt + \tau_D \frac{dE(t)}{dt} \right] \tag{4}$$

For a first-order plus dead time model, the IMC provides the following tuning relations:[11]

$$K_c = \frac{1}{K} \frac{\tau + \frac{\theta}{2}}{\tau_c + \frac{\theta}{2}}, \tau_I = \tau + \frac{\theta}{2}; \tau_D = \frac{\tau\theta}{2\tau + \theta}, \tag{5}$$

where τ_c is a design controller parameter normally chosen as $\theta \le \tau_c < \tau$.

Alternatively, controller settings may be determined using the ZN tuning rules,

$$K_c = \frac{1.2}{\theta S^*}, \tau_I = 2\theta, \tau_D = 0.5\theta, \tag{6}$$

where θ and $S^* = S/\Delta P = K/\tau$ are determined by graphical analysis of the process reaction curve shown in Figure 3.

Accordingly: i) process gain K is the ratio of the change in the steady state value of T divided by the step change ΔP; ii) the root of tangent line drawn at inflection point S is the time delay θ; iii) S is the slope of tangent line; and iv) extending the tangent at inflection point to the steady state line $T = K\Delta P$, the intersection point corresponds to $t = \theta + \tau$.

The performance of the resultant feedback control system has to be tested and evaluated prior to start-up of an industrial plant, by studying the dynamic and steady state characteristics of its response to some perturbations. This task is accomplished using two laboratory experiments, one for each set of suggested controller settings [Eq. (5) or Eq. (6)].

EXPERIMENTAL PROCEDURE

Table 1 shows the operating conditions, useful notes, and necessary data as part of the laboratory controller tuning experiment in steady state conditions. Superscripts 'o' and '∞' stand for original and final steady state conditions, respectively [*e.g.*, $P^o = P(t = 0)$ and $P^\infty = P(t = \infty)$]. The computer interface of the PCT23 Process Plant Trainer shows the controller output as a percentage. Experimental procedure is as follows:

a) Initialize experimental set-up and let system reach a steady state.

b) Carry out an open-loop experiment (controller in manual) to measure the process reaction curve by introducing a step change

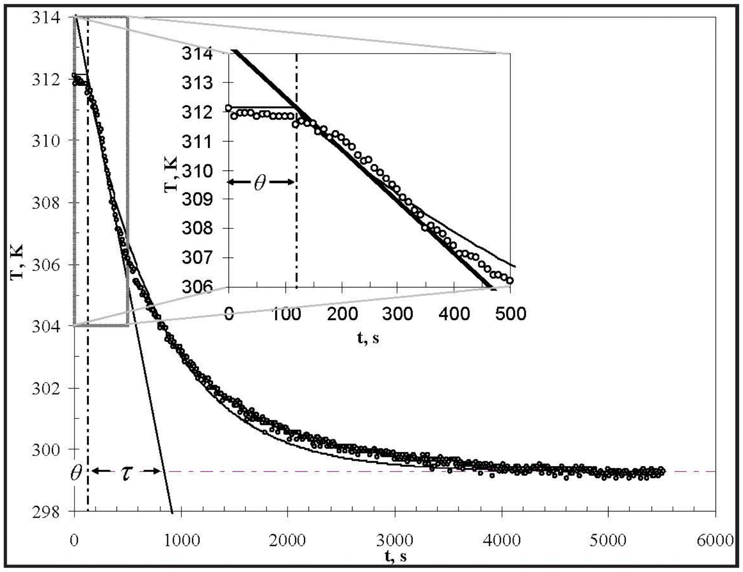

Figure 4. *Process reaction curve for operating conditions shown in Table 2, and first-order plus time delay model fitted to experimental data. The expanded area of the first 500s is given in the inset.*

TABLE 1
Outline of the Experiment

Step	Task	Experimental Conditions	Register	Notes
a	Reach steady-state	$P = 30\%$ $\dot{m}_f = 4\text{x}10^{-3}\,\text{kg/s}$ $\dot{m}_h = 6.2\text{x}10^{-3}\,\text{kg/s}$	T^∞	• $T^\infty = T(t = \infty)$, etc. • Computer interface shows P in percentage
b	Open-loop experiment to measure process reaction curve	$T^o = T^\infty$ (step a) Input step in P: $\Delta P = -15\% \Rightarrow P = 15\%$	T(t)	• Put controller in manual mode • Initial steady-state is the final condition of step a
c	Wait for steady-state (*e.g.*, same as step a)	$P = 30\%$ $\dot{m}_f = 4\text{x}10^{-3}\,\text{kg/s}$ $\dot{m}_h = 6.2\text{x}10^{-3}\,\text{kg/s}$	T^∞	• There is enough time to optimize model parameters [Eq.(3)], carry out graphical analysis (Fig.3), and calculate controller settings using Eqs. (5) and (6)
d	Closed-loop experiment (controller settings obtained by Internal Model Control in step c)	$T_{sp} = T^\infty$ (step c) $P^o = 30\%$ K_c, τ_I, τ_D Input step in $\dot{m}_f$: $\Delta\dot{m}_f = (4 \rightarrow 2)\text{x}10^{-3}\,\text{kg/s}$	T(t)	• Initial steady state is final condition of step c • Set-point is T^∞ from step c • P varies with time
e	Reach same steady-state of step c	$P = 30\%$ $\dot{m}_f = 4\text{x}10^{-3}\,\text{kg/s}$ $\dot{m}_h = 6.2\text{x}10^{-3}\,\text{kg/s}$	T^∞	—
f	Closed-loop experiment (controller settings obtained from Ziegler - Nichols equations in step c)	$T_{sp} = T^\infty$ (step e) $P^o = 30\%$ K_c, τ_I, τ_D Input step in $\dot{m}_f$: $\Delta\dot{m}_f = (4 \rightarrow 2)\text{x}10^{-3}\,\text{kg/s}$	T(t)	• Initial steady state is final condition of step e • Set-point is T^∞ from step e (or step c) • P varies with time

in the controller output (ΔP). Plot temperature T vs. time.

c) Operate system to attain a steady state. During this time period, optimize the parameters of the first-order plus time delay model [Eq. (3)] using a spreadsheet program and least-squares method. Plot the resultant correlation on the same plot as the experimental data. Next, calculate the PID controller settings using Eq. (5) (IMC). Using the required graphical analysis of Figure 3, compute the controller settings using the ZN tuning rules [Eq. (6)].

TABLE 2
Experimental Conditions, Observations, and Calculated Results

Open-loop identification experiment (Table 3, step b)
Experimental conditions: $\dot{m}_f = 4\times10^{-3}\,\mathrm{kg/s},\ \dot{m}_h = 6.2\times10^{-3}\,\mathrm{kg/s}, T^\circ = 39^\circ\mathrm{C}$
Input step in P: $\Delta P^\circ : 30\% \rightarrow 15\%$
Experimental observations: T= T(t) shown in Figure 4.
Calculated results from process reaction curve
Model parameters [Eq.(3)]: $K = 0.8476$ K/%, $\theta = 120$ s, $\tau = 717.3$ s (from nonlinear fitting AAD =0.073%)
PID controller settings from Internal Model Control Method [Eq.(5)]: $K_c = 5.10$ %/K, $\tau_I = 777.3$ s, $\tau_D = 55.4$ s
Experimental parameters (from Figure 4): $\left\|S^*\right\| = 0.0014\,\mathrm{K/s}; \theta = 120\,\mathrm{s}, \tau = 730\,\mathrm{s}$
PID controller settings from Ziegler-Nichols relations [Eq.(6)]: $K_c = 7.14$ %/K, $\tau_I = 240.0$ s, $\tau_D = 60.0$ s
Closed-loop experiments (Table 3, steps d and f)
Experimental conditions: $\dot{m}_h = 6.2\times10^{-3}\,\mathrm{kg/s}, P^\circ = 30\%, T_{sp} = T^\circ = 39^\circ\mathrm{C}$
Input step in $\dot{m}_f$: $\Delta\dot{m}_f : (4 \rightarrow 2)\mathrm{x}10^{-3}\,\mathrm{kg/s}$
Experimental observations for each set of PID parameters T = T(t) shown in Figure 5.

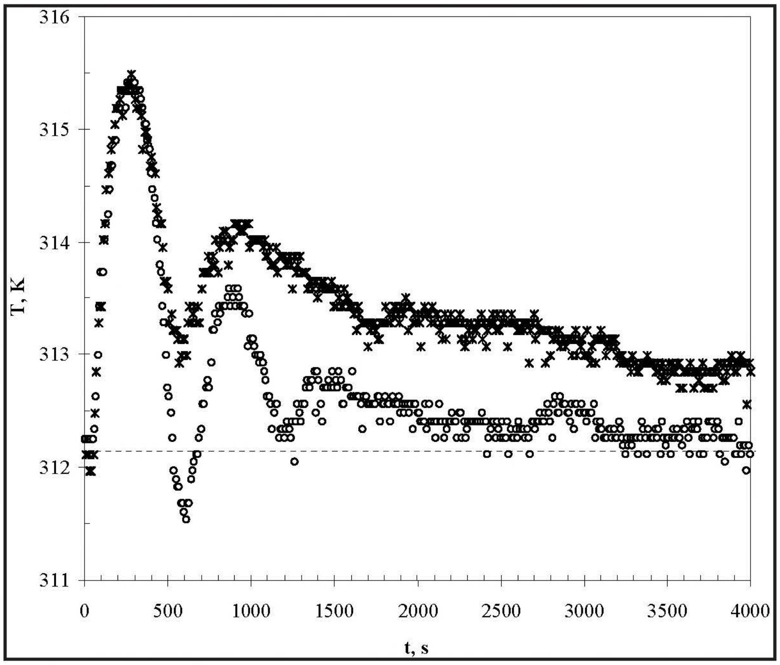

Figure 5. *Closed-loop responses obtained for the PID controller settings determined by Internal Model Control tuning relations [Eq. (5)], (xxx); Ziegler-Nichols relations [Eq. (6)], (ooo). Experimental conditions and parameters are shown in Table 2.*

d) Perform a closed-loop experiment with the PID controller settings obtained in step c) using IMC, introducing a step perturbation in the feed mass flow. Plot the temperature T vs. time.

e) Return the system to attain the same initial steady state (*i.e.*, final condition of step c).

f) Perform a closed-loop experiment with the PID controller settings obtained from the c) ZN approach. Again introduce the same step perturbation in the feed mass flow and plot the temperature T vs. time on the same graph of step d).

NOTE: In order to reduce experimental time duration, the reaction curve can be given to students before the laboratory session. For a reduced two-week laboratory session, students can perform the reaction curve and PID tuning calculation in the first week, and the closed-loop experiments in the second week.

TYPICAL RESULTS AND DISCUSSION

After the experimental work proposed, the students collected one reaction curve and two closed-loop experiments with IMC and ZN tuning settings. Table 2 summarizes the experimental conditions, observations, and calculated results. The obtained process reaction curve is presented in Figure 4 (previous page), as well as the results from a first-order plus dead time model [Eq. (3)]. The results of using the ZN rules are also shown in Figure 4. The small deviation (AAD = 0.073%) does show the excellent fit of the data. Furthermore, students can also conclude that the process is self-regulating since its reaction curve is bounded and reaches a new steady state after a step change at t = 0. It should be noted that the student must realize the reaction curve can be inverted, resulting in the standard diagram (Figure 3).

Figure 5 shows the typical underdampened-load responses of the closed-loop PID controlled system.

For the same experimental conditions (Table 2), these results emphasize the effect that different controller settings have on system response. The ZN tuning rules result in a faster response (more aggressive). This response is due to a combination of higher K_c and lower τ_I values:[11] 7.14 %/K and 200.0 s (ZN), respectively, compared to 5.10 %/K and 777.3 s (IMC). Students need to be aware of this fact. The feedback control system with IMC parameters exhibits a remarkably sluggish response, that of the set-point intersected at 7600 s, compared to ZN at 535 s.

Students should conclude there is no perfect controller tuning method. The goal is to have good preliminary education that can provide a starting point for additional field tuning, especially when available process information is incomplete or inaccurate.[1,11]

FURTHER REMARKS

The proposed experiment is mainly oriented toward system dynamics and controller tuning. Other useful tasks may be considered by instructors, such as carrying out a thermal analysis of the system to allow the estimation of heat losses and global heat transfer coefficients. The same experiment may be implemented using the industrial PID and console available in the PCT23 unit. This set-up allows us to change control strategy to a cascade control scheme.

At the end of this work students answer a survey, allowing instructors to figure out the benefits and difficulties found during its execution. Following a procedure suggested by other authors,[12] the set of questions listed in Table 3 was assessed from 1 (strongly disagree) to 5 (strongly agree). The results suggest that this experimental work accomplishes the main objectives in general and does contribute to students' understanding and interest in the field of process control.

TABLE 3

A Proposed Survey for Assessing the Usefulness of This Experimental Work

The answers for all questions were classified as:
strongly disagree (1 point); disagree (2 points);
somewhat agree (3 points); agree (4 points); strongly agree (5 points).
Results refer to 32 students in 2005-2006.

Question	Mean	Standard Deviation
1. Were the concepts previously acquired on process control sufficient to allow you to carry out this work?	3.29	0.61
2. Is this experimental work connected with the theory taught in other control courses?	3.29	0.61
3. Is the available bibliography sufficient?	4.00	0.68
4. Were you able to do the experimental work without difficulty?	2.29	0.91
5. Were you able to do the calculations without difficulty?	2.00	0.78
6. Were you able to interpret and discuss the results without difficulty?	2.50	0.65
7. Do you think you improved your skills in controller tuning?	3.43	0.51
8. Did the practical work motivate or increase your enthusiasm about process control?	3.36	0.50
9. Did you find the experimental work important for the understanding of chemical process control?	3.71	0.83
10. Do you feel stimulated to take future new challenges in the field of control?	3.43	0.65

CONCLUSIONS

PCT23 Process Plant Trainer equipment provided by Armfield[10] is used to teach PID controller tuning. The experiments introduce and solidify theoretical concepts by obtaining approximate transfer functions or time domain models from a process output response to some step input, and by calculating the PID controller settings from typical industry-developed tuning rules. They also provide the means for experimental validation of controller performance. Students do recognize that there are no unique methods to estimate satisfactory controller settings and that additional field tuning may be required.

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NOMENCLATURE

AAD	Absolute Average Deviation
IMC	Internal Model Control
E	$= T_{sp} - T$, Error signal
G_c, G_R, G_p, G_m, G_L	Transfer functions for controller, electrical resistance heater, process, thermocouple-transmitter, and load
K	Process gain
K_c	Controller gain
K_m	$= T'_{sp} / \tilde{T}'_{sp}$, gain to express set-point (K) as voltage signal (V)
$\dot{m}$	Mass flow, kg/s
P	Controller output
PID	Proportional-Integral-Derivative

$\dot{Q}_R$	Power of electrical heater, W
t	Time, s
T	Temperature, K
V	Liquid volume inside heater tank, m^3
ZN	Ziegler-Nichols

Greek letters

Δ	Deviation relative to initial steady state value; Step change
τ	System time constant, s
τ_I, τ_D	Integral and derivative time, s
θ	Time delay, s

Superscripts

$^\circ$,∞	Initial and final steady state conditions.
~	Variable expressed as voltage
´	Deviation variable

Subscripts

F	Feed
H	Heating circuit
M	Measured value
Sp	Set-point

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