INDUSTRIAL PROCESS CONTROL EDUCATION WITH A WASTEWATER TREATMENT PLANT

Emiliano Pérez[1], Inés Tejado[1], Francisco Duque-Gruart[1], Alejandro Gómez-Garrido[1], Marina Rangel-Zambrano[1], Fabio Tirabassi[2]

[1]University of Extremadura, Industrial Engineering School (SPAIN)
[2]Università Politecnica delle Marche (ITALY)

Abstract

This paper deals with the use of the DELTALAB-COSIMI wastewater treatment (WWT) plant SP244 to support laboratory teaching of industrial process control in engineering degrees at the University of Extremadura. With this equipment, automation technician students can learn in a practical way a variety of fundamentals concepts of process control. A set of examples of control problems, ranging from modelling to closed-loop experiments, are given to illustrate possible practices that can be carried out within this laboratory.

Keywords: Control, process, engineering, education, wastewater treatment, plant, laboratory.

1 INTRODUCTION

The main goal of educators in engineering is to prepare students for the real world outside university, where they will have to apply their knowledge, experience, and practical skills to improve the progress in a particular field, especially if they end up in industry. That is the reason why the acquisition of practical skills and experimentation play an important role in engineering education [1, 2].

Among current trends in engineering education, several methodologies have become very popular to interconnect theory and practice in a balanced way [3], which can be mainly grouped in those based on hands-on, remote and virtual laboratories. Although many aspects of the educational framework have to be taken into account to decide which of them is the most adequate, it has been demonstrated that hands-on experiences with real equipment are necessary in control courses to help students to the understanding of theoretical fundamentals. Many laboratories have been developed to teach process control engineering (see e.g. [4–7]); current reviews can be found in [8, 9].

Given this scenario, and within the initiative of lecturers in the area of systems engineering and automation of the University of Extremadura to disseminate teaching experiences, this paper presents the preliminary experience of the course “Industrial process control” for undergraduate students with a laboratory based on the DELTALAB-COSIMI wastewater treatment (WWT) plant SP244. A set of control problems to be solved by students with this equipment to learn fundamentals of process control is proposed. Some experiments are given to illustrate how such problems can be handled to support learning of practical skills in process control.

The remainder of this paper is organized as follows. Section 2 describes the DELTALAB-COSIMI WWT plant. Section 3 proposes a set of control problems that can be tested with the plant. Section 4 contains the results of the experiments proposed in the previous section. Finally, concluding remarks are drawn in Section 5.

2 LABORATORY DESCRIPTION

Figure 1 shows a picture of the WWT pilot plant SP244 of DELTALAB-COSIMI. It allows the treatment procedure of wastewater produced by activated sludge, supervising the main variables of the whole process, such as the level of dissolved oxygen, level of water, pH, temperature, and Red-Ox potential.

The equipment is essentially composed by seven different tanks, two of them with agitators, three peristaltic pumps, sensors to measure the process variables, and five electrovalves. The control of the whole process is carried out by means of a National Instruments CompactRIO-9014, which is inside the control panel (on the right in Figure 1) and where all sensors and actuators are connected to.

From left to right, water flows as follows. The feeding tank (# 1), which is the biggest of the plant, contains the substrate solution to be cleaned. This tank is connected to an anoxic tank (# 2) by a

peristaltic pump (P1), where the substrate is mixed with the mother liquor that comes from the base tank (# 3) thanks to another peristaltic pump (P2). An agitator (A1) in the anoxic tank is in charge of obtaining the mixture. The excess of mixture in the anoxic tank goes, by gravity, to the reactor tank (# 4). That is an oxidation-ventilation tank where wastewater is degraded by the action of microorganisms or activated sludge under the effect of oxygen. It has another agitator (A2) for the homogenization of the mixture, and four probes to measure pH, Red-ox potential, temperature, and dissolved oxygen. Electrovalves EV1/EV2 allow to feed tank # 2 or # 4 from tank # 1, respectively. The excess of water plus sludge flows into the decanting tank (# 5), also by gravity. It is possible to fill tank # 4 directly from tank # 1 by selecting appropriately electrovalves EV3/EV4. In the decanting tank, the mixture is separated into sludge and other solid particles, which are deposited at the bottom of the cone, whereas clear water flows into the clarification tank (# 6). The sludge and particles are conducted to the sludge tank (# 7), or again to the anoxic tank by means of a peristaltic pump (P3).

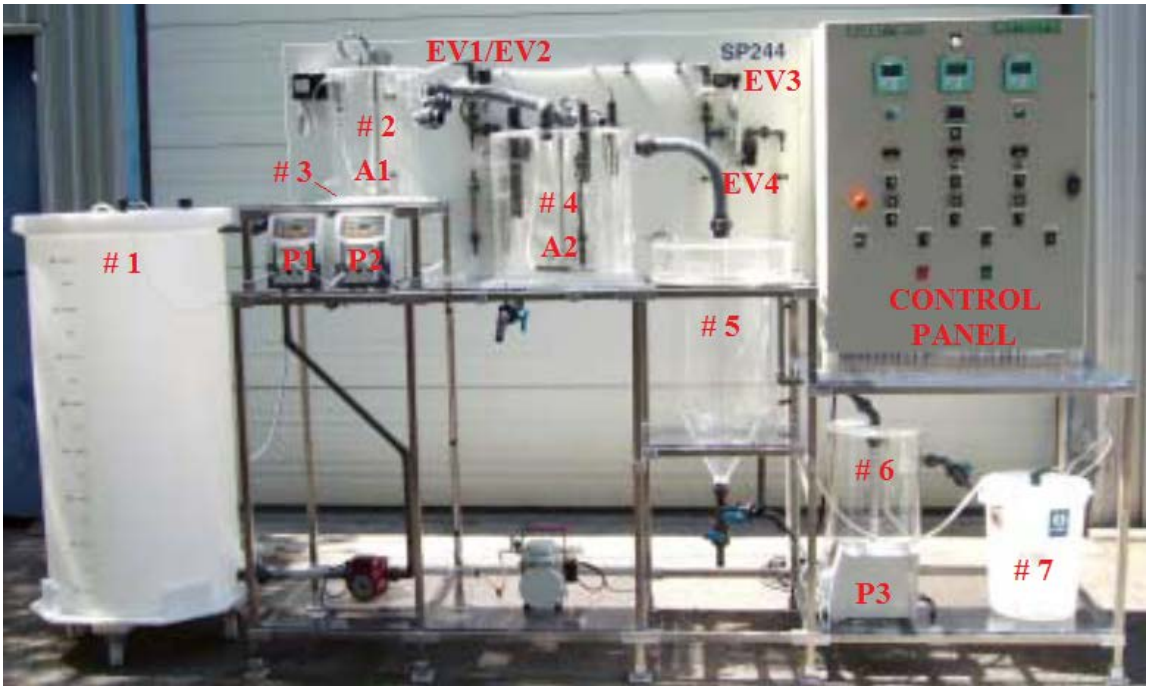


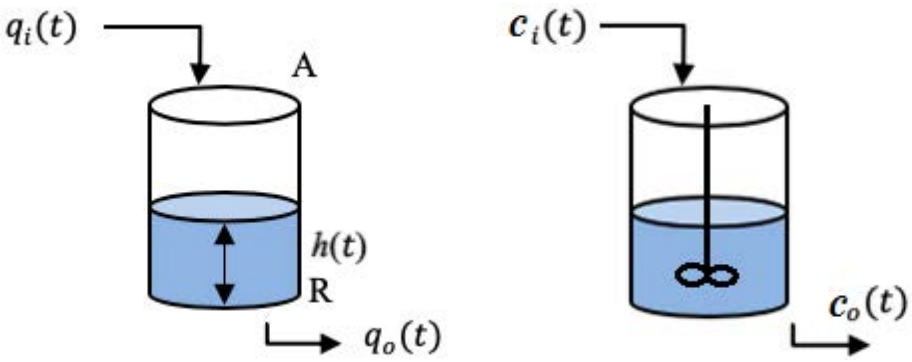
Figure 1. Picture of the DELTALAB-COSIMI wastewater treatment plant SP244.

3 CONTROL PROBLEMS

This section contains a set of experiments that can be carried out with the DELTALAB-COSIMI plant to support learning of practical skills in process control:

- Modeling of filling process of the anoxic tank. This experiment consists of identifying the transfer function that corresponds to filling process of the anoxic tank offline. Firstly, students are required to record the evolution of the liquid level ($h(t)$) in the tank for constant input and output flows ($q_i(t)$ and $q_o(t)$, respectively), fixed by pump P1 and an electrovalve placed at the bottom of the tank, respectively, as illustrated in Figure 2(a). Tank area (A) and resistance to the output flow (R) have to be estimated. (The tank is not empty at the beginning of the experiment to reduce the time needed to reach the equilibrium level.) For validation purposes, two experiments, namely for two different input flows, are required: one of them will be used to identify the model, and the other to validate it. Once the filling curves are recorded, students have to apply identification methods to obtain the transfer function that describes the process.
- Level control of the anoxic tank. In this experiment, students are required to design a proportional-integral (PI) controller to fulfill a set of specifications. The digital implementation of the PI controller has to be programmed and tested on the plant to validate the control.
- Control of the amount of reagent produced after the reaction inside the oxidation tank (see Figure 2(b)): for a fixed concentration of reagent A ($c_i(t)$), a certain amount of a second

compound B ($c_o(t)$) is obtained. The evolution of the amount of both reagent A and compound B of the reaction have to be recorded in order to, firstly, identify the reaction dynamics; then, an appropriate controller has to be designed to regulate the amount of compound B. For this experiment, students need to be familiarized with control strategies to compensate large time-delays, such as, the Smith predictor. Similarly to the previous experiment, the digital implementation of the controller has to be programmed and tested.



(a) (b)

Figure 2. Illustrations of different experiments to be controlled: (a) filling process of anoxic tank (b) reaction inside oxidation tank.

4 RESULTS

This section provides the simulation and experimental results corresponding to the control problems described in the previous section. It is worth mentioning that simulation results were obtained in the MATLAB/Simulink environment.

4.1 Identification of anoxic tank filling process

Firstly, two experiments of filling were carried out, recording the water level of the tank for two constant input flows, namely, 24 and 10 l/h (see Figure 3(a) for one of the experiments). Water level is given in mm. It must be said that, due to the fact that filling process is slow, these experiments took more than one hour.

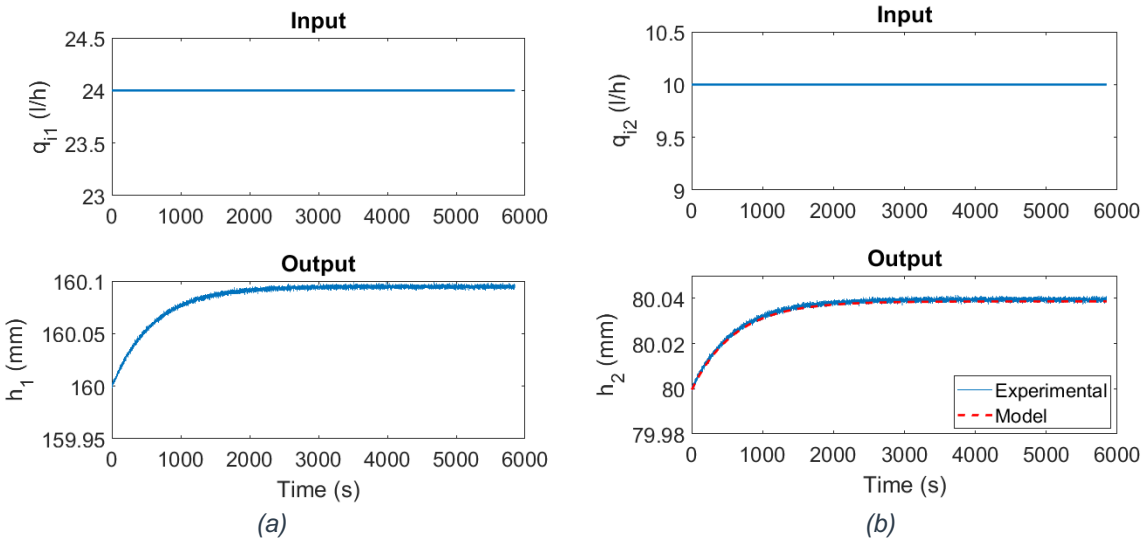
Although from Figure 3(a) it can be stated that the filling process can be described by a first order transfer function, the following expressions can be written that relate input and output flow with the variation of the level of water in the tank and the resistance to output flow:

$$q_i - q_o = A\dot{h} \tag{1}$$

$$R = \frac{h}{q_o} \tag{2}$$

Applying the Laplace transform for zero initial conditions and doing some manipulations, relations (1) and (2) result in the following transfer function:

$$G(s) = \frac{H(s)}{Q_i(s)} = \frac{R}{ARs + 1} \tag{3}$$



(a) *(b)*

Figure 3. Identification of filling process dynamics of anoxic tank: (a) Data for identification (data of experiment #1) (b) Model validation (data of experiment #2).

To determine the transfer function that describes the filling process, the units of input and output variable have to be converted to the International System ones. Considering one of the experiments and doing units conversion, the following transfer function can be obtained:

$$G(s) = \frac{14.09}{605.9s + 1} \tag{4}$$

The validation of the model is done considering the data from the second experiment, after converting units. Figure 3(b) shows the comparison between experimental (second data) and simulated data

(step response of the system for the value of the input flow corresponding to the second experiment). As can be observed, model (4) is validated because only slight differences can be found between experimental and simulated data.

Comparing transfer functions (3) and (4), it is possible to estimate the values of the tank area and resistance as: $R = 14.09$, and $A = 43$.

4.2 Level control of anoxic tank

A PI controller is going to be designed to regulate the level of the anoxic tank guarantying the following design specifications in closed-loop: settling time (t_s) of the response has to be less or equal to 800 s with an overshoot (M_p) less or equal to 10%. For simplicity, lambda tuning [10] will be used to design the controller. Once the controller is validated in simulation, it will be implemented in the CompacRio for its experimental validation.

Let consider the characteristic equation of the closed-loop system as:

$$1 + \frac{K_p(T_i s + 1)}{T_i s} \frac{K}{Ts + 1} = 0, \tag{5}$$

where K and T are the gain and time constant of the system ($K = 14.09$ and $T = 605.9$ s), and K_p and T_i, the proportional gain and the integral time constant, i.e., the controller parameters to be tuned.

Taking $T_i = T = 605.9$, equation (5) reduces to:

$$Ts + K_p K = 0, \tag{6}$$

$$\frac{T}{K_p K} s + 1 = 0 \tag{7}$$

Comparing (7) with the characteristic equation corresponding to lambda tuning method, i.e., $\lambda s + 1 = 0$, proportional gain can be obtained as

$$\frac{T}{K_p K} = \lambda \Rightarrow K_p = \frac{T}{\lambda K} \tag{8}$$

In order to guarantee the design specifications, parameter λ has to be taken accordingly. In this case, it is considered as $\lambda = 120$ (the greater the value of λ, the faster the response, i.e., the smaller t_s), but the higher the overshoot. Hence, $K_p = 0.36$.

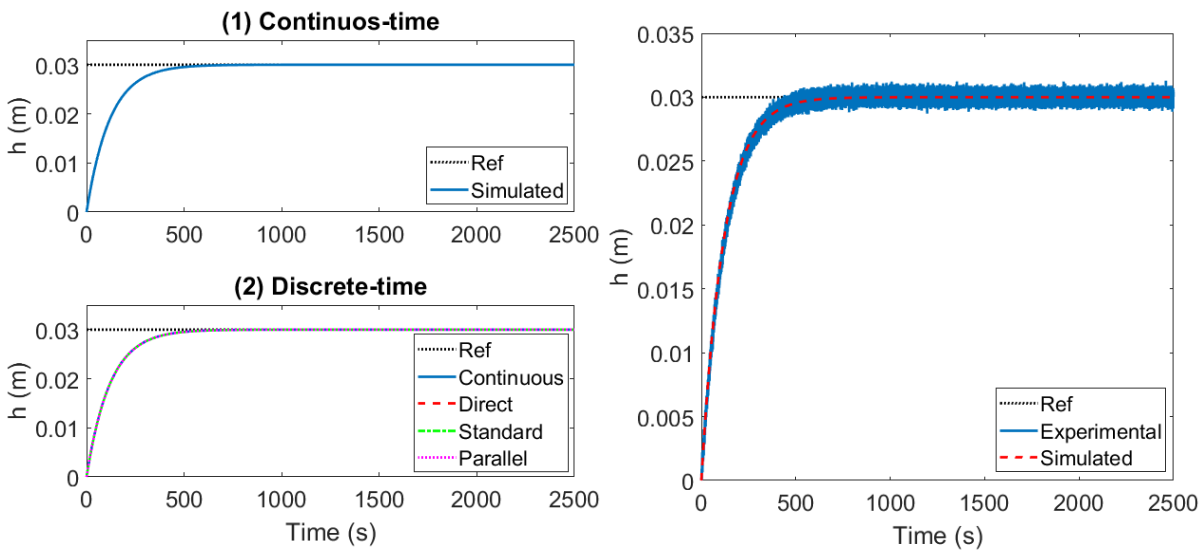
Figure 4(a) shows simulated results of the anoxic tank level when applying the designed PI controller. As can be seen in the plot at the top, the response of the system is stable and with no overshoot; the settling time is 469.44 s. Then, design specifications are fulfilled.

With the objective of validating the controller experimentally, different digital implementations of the controller have been obtained and tested in simulations. The first implementation can be obtained directly from the difference equation as follows. Using the Tustin rule for a sampling time (T_s) of 10 ms, the controller can be written in discrete form as

$$C(z) = \frac{U(z)}{E(z)} = \frac{K_1 + K_2 z^{-1}}{1 - z^{-1}}, \tag{9}$$

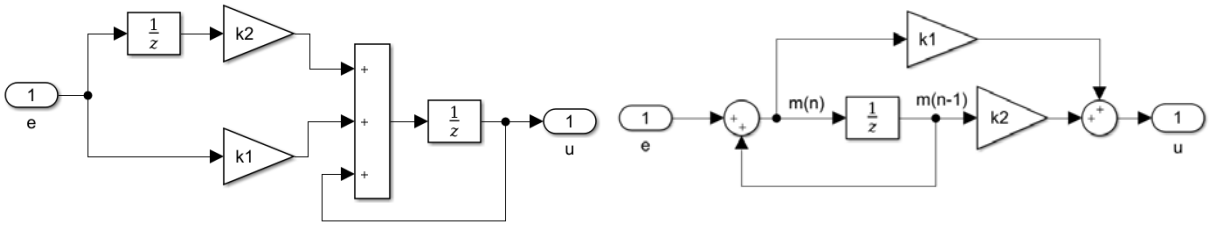
where $U(z)$ and $E(z)$ are the transforms of the control signal and error, respectively, and with $K_1 = K_p\left(1 + \frac{T_s}{2T_i}\right) = 0.3584$ and $K_2 = K_p\left(\frac{T_s}{2T_i} - 1\right) = -0.3583$. Thus, multiplying in cross in (9), the following expression can be obtained:

$$U(z)(1 - z^{-1}) = (K_1 + K_2 z^{-1})E(z), \tag{10}$$

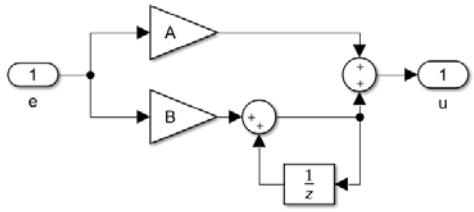


(a) (b)

Figure 4. Level control of anoxic tank: (a) Simulation results for continuous- and discrete-time controlleres (b) Experimental validation.



(a) (b)



(c)

Figure 5. Digital implementations of PI controller for anoxic tank: (a) Direct (b) Standard (c) Parallel.

Applying the inverse of Z-transform to (10), the first implementation of PI controller, referred to as direct implementation, is expressed as

$$u(n) = u(n-1) + K_1 e(n) + K_2 e(n-1), \tag{11}$$

which corresponds to the block diagram in Figure 5(a).

Likewise, controller transfer function (9) can be also written from an intermediate transfer function $M(z)$ as:

$$C(z) = \frac{K_1 + K_2 z^{-1}}{1 - z^{-1}} = \frac{U(z)}{M(z)} \frac{M(z)}{E(z)}, \tag{12}$$

where

$$\frac{U(z)}{M(z)} = K_1 + K_2 z^{-1}, \tag{13}$$

$$\frac{M(z)}{E(z)} = \frac{1}{1 - z^{-1}} \tag{14}$$

Again, applying the inverse of Z-transform to (13) and (14), the control signal can be written as:

$$u(n) = K_1 m(n) + K_2 m(n-1) \tag{15}$$

where $m(n) = e(n) + m(n-1)$. This second implementation, referred to as standard, is represented in Figure 5(b).

Finally, parallel digitalization of PI controller can be obtained applying Z-transform to the controller transfer function decomposed in simple fractions as

$$C(z) = \frac{U(z)}{E(z)} = A + \frac{B}{1 - z^{-1}} \tag{16}$$

with $A = -K_2 = 0.3853$ and $B = K_1 + K_2 = 1 \cdot 10^{-4}$. The control signal can be then written as

$$u(n) = u_1(n) + u_2(n) = \big(Ae(n)\big) + \big(u(n-1) + Be(n)\big) \tag{17}$$

The block diagram of this implementation is illustrated in Figure 5(c).

The parallel implementation was programmed in the CompacRio by means of a user function block. The experimental result is plotted in Figure 4(b). From this figure, only slight differences due to noise can be found between experimental and simulated results. Experimentally, design specifications are also fulfilled.

4.3 Control of amount of reagent inside the reactor tank

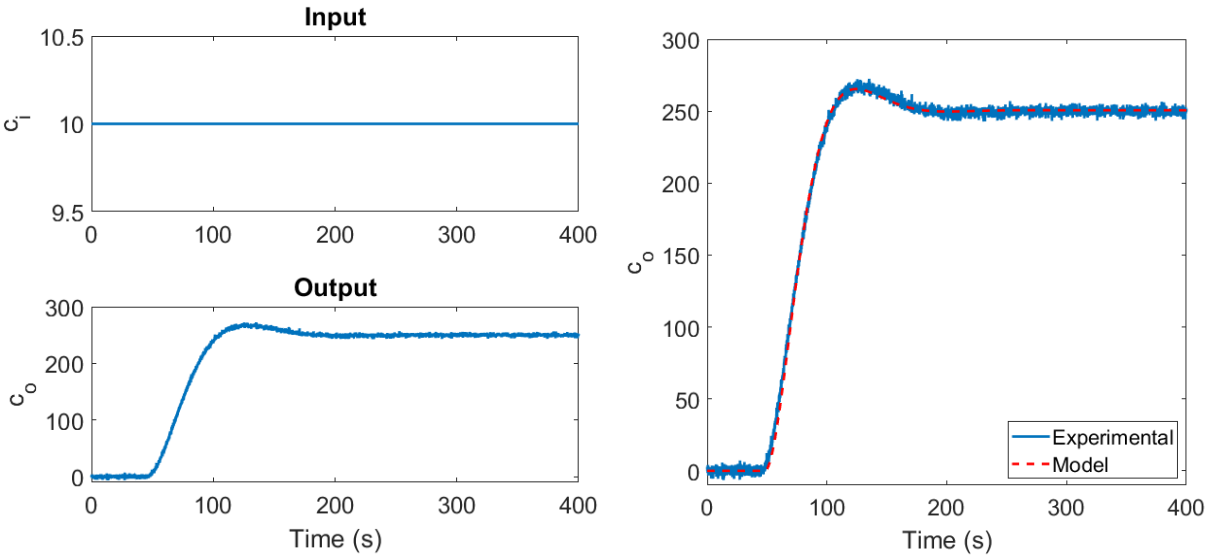
As commented, an irreversible second-order reaction happens inside the reactor tank so that, for a fixed concentration of reagent A, a certain amount of a second compound B is obtained. To ensure the correct treatment of water, the amount of compound B has to reach the equilibrium before 280 s

without exceeding the desired value; i.e., design specifications for the control are: $t_s \leq 280$ s and $M_p \approx 0$. For that end, before designing a proper controller, the dynamics of the chemical process that takes place in the tank has to be identified.

Firstly, two experiments were carried out, recording the amount of compound B inside the tank for two constant amounts of reagent A, namely, 10 and 25 mol/m^3 (see Figure 6(a) for one of the experiments). The amount of is also given in mol/m^3. As can be observed, the dynamics of the reaction is of second order, underdamped and time-delayed. Using the *System Identification Toolbox* of MATLAB, the following transfer function can be identified for the reaction dynamics:

$$P(s) = \frac{25.06}{327.9s^2 + 24.3s + 1} e^{-48s} \tag{18}$$

Due to time delay of (18) is considerably high, a Smith predictor is going to be designed to stabilize the process. The main controller will be a proportional-integral-derivative (PID). A scheme of the controller is shown in Figure 7(a), where $\widehat{P_0}(s)$ represents the model of the system with no delay. It must be remarked that, within a Smith predictor structure, main controllers have to be designed for the system with no delay; system delay is compensated with the given structure.



(a) (b)

Figure 6. Identification of chemical process dynamics in reaction tank: (a) Data for identification (data of experiment #1) (b) Model validation (data of experiment #2).

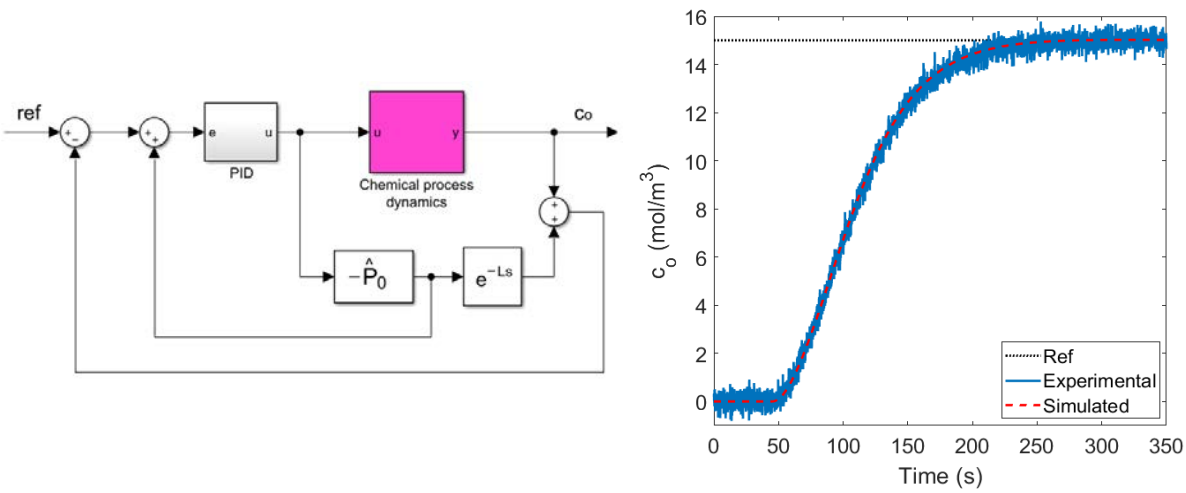


Figure 7. Control of amount of reagent inside the reactor tank: (a) Control scheme with Smith predictor (b) Experimental validation.

Again, lambda tuning is used to design the PID to fulfill design specifications. Considering a PID controller with standard form, the characteristic equation of the closed-loop system can be written as

$$1 + \frac{K_p(T_i s + 1 + T_i T_d s^2)}{T_i s} \frac{25.06}{327.9s^2 + 24.3s + 1} = 0, \tag{19}$$

where K_p, T_i, and T_d are the proportional gain, and the integral and derivative time constant to be tuned. To reduce (19) to first order, the term $(T_i s + 1 + T_i T_d s^2)$ must be designed to be simplified with the denominator of the process model. Thus, matching coefficients of both polynomials results in

$$T_i = 24.3;\ T_i T_d = 327.9 \quad \Longrightarrow\ T_d = 13.49$$

Taking those values, (19) can be reduced to

$$\frac{T_i}{25.06K_p} s + 1 = 0 \tag{20}$$

After comparing (20) with the first order equation corresponding to lambda tuning, parameter K_p can be obtained as

$$K_p = \frac{T_i}{25.06\lambda}$$

For $\lambda = 100$, $K_p = 9.69 \cdot 10^{-3}$.

Figure 7(b) shows a comparison between experimental and simulated results corresponding to the control of the amount of reagent B inside the reactor tank for a desired value of 15 mol/m^3. It can be seen that: 1) both responses are quite similar and with no overshoot, and 2) for both cases, $t_s \approx 220.4$ s, so design specifications are fulfilled. For this experiment, parallel form of PID controller was used.

5 CONCLUSIONS

This paper has dealt with the use of the DELTALAB-COSIMI wastewater treatment (WWT) plant SP244 to support laboratory teaching of industrial process control in engineering degrees at the University of Extremadura. With this equipment, automation technician students were able to learn in a practical way a variety of fundamental concepts of process control. A set of experiments, concerning processes modeling and closed-loop control designs, were given to illustrate possible practices that can be carried out within this laboratory.

Future work will go towards increasing the number of control problems to be solved with the plant, as well as incorporating external equipment that allows its remote control.

REFERENCES

[1] S. Nikolic, C. Ritz, P.J. Vial, M. Ros, D. Stirling, “Decoding Student Satisfaction: How to Manage and Improve the Laboratory Experience,” *IEEE Transactions on Education*, vol. 58, no. 3, pp. 151–158, 2015.

[2] S. Dormido Bencomo, “Control Learning: Present and Future,” *Annual Reviews in Control*, vol. 28, no. 1, pp. 115–136, 2004.

[3] I. Tejado, E. Pérez, I. González, P. Merchán, “Introducing Systems Theory With Virtual Laboratories at the University of Extremadura: How to Improve Learning in the Lab in Engineering Degrees,” *International Journal of Electrical Engineering Education*, 2019 (submitted).

[4] M. Rampazzo, A. Cervato, A. Beghi, “Remote Refrigeration System Experiments for Control Engineering Education,” *Computer Applications in Engineering Education*, vol. 25, pp. 430–440, 2017.

[5] S. Meenatchi Sundaram, “Design of Virtual Process Control Laboratory (VPCL) Using First Principle Method and Interactive PID Control Toolkit Using Labview,” *Proceedings of the 9th International Conference on Information Technology and Electrical Engineering (ICITEE)*, 2017.

[6] R.E. Vasquez, N.L. Posada, F. Castrillón, D. Giraldo, “Development of a Laboratory Equipment for Dynamic Systems and Process Control Education,” *Proceedings of the ASME 2014 International Mechanical Engineering Congress and Exposition*, 2014.

[7] P.L. Lee, R.M. Allen, G.R. Cole, S.S. Shastri, “A Modular Laboratory for Process Control and Process Engineering,” *Journal of Process Control*, vol. 13, no. 4, pp. 283–289, 2003.

[8] R. Heradio, L. de la Torre, S. Dormido, “Virtual and Remote Labs in Control Education: A survey,” *Annual Reviews in Control*, vol. 42, 1-10, 2016.

[9] V. Potkonjak, M. Gardner, V. Callaghan, P. Mattila, C. Guetl, V.M. Petrovic, K. Jovanovic, “Virtual Laboratories for Education in Science, Technology, and Engineering: A Review,” *Computers & Education*, vol. 95, pp. 309–327, 2016.

[10] A.A. Rovira, P.W. Murrill, C.L. Smith, “Tuning Controllers for Set Point Changes,” *Instruments and Control Systems*, vol. 42, no. 12, pp. 67–69, 1969.