Educating High School Students in Process Simulation and Control with a Simulink-Based Controller Design for Microbial Fuel Cells

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Abstract

U.S. high school students are often weak in math and science, thus it is important to broaden the participation of high school students in these fields before they start to lose confidence and interest in them. One way to attract more high school students in math and science is through interesting research projects. This work presents an example for educating high school students to design a controller for a lab-scale microbial fuel cell (MFC) that can generate electricity from the organic compounds in the waste water. Upon the introduction of MFC, ODE models, PID controllers and MATLAB Simulink, the student, during a part-time summer internship, successfully developed a Simulink model for a MFC and used it to evaluate the performance of various PID controllers. The strategies for teaching high school students with modeling and programing skills, along with the evaluation of the teaching effectiveness, are also introduced in this work.

Keywords

Microbial fuel cells, Simulink, Process Simulation and Control, PID controller.

Introduction

High school students from the U.S. lag behind other high school students in STEM fields around the world. According to the National Math and Science Initiative, 56% of US high school graduates in 2013 were not ready for college-level math, and 64% were not ready for college-level science. In a study by the Organization for Economic Co-operation and Development (OECD), the U.S. is ranked 25th in math performance and 21st in science performance compared to other countries, with Finland, South Korea, and the Netherlands in the top 3. A country once known for being at the vanguard of technology and industry, such as during the World War II era or in the space race, is now being beaten. The implications are tremendous: a weak education during the early stages of development will only lead to a weaker professional labor force later. In fact, a study by the President's Council of Advisers on Science and Technology states that "economic forecasts point to a need for producing, over the next decade, approximately 1 million more college graduates in STEM fields than expected under current assumptions". If the USA is to remain at the forefront of innovation, the quality of education at the high school stage must rise. Whether it is a substandard STEM teaching force or a general disinterest in the STEM fields, it is unclear, but a way to attract more students' attention to these topics is through early research experience and projects. Such experiences should boost the interest and confidence of students in STEM related areas, and encourage them to pursue higher education and degrees in them, while giving them an introduction to such topics. The goal of this work is to demonstrate that education in engineering, such as process simulation and control, at a high-school level can be effective in garnering interest and knowledge, with a project in which a high school student was educated to design a controller for a lab-scale microbial fuel cell during the summer of 2014.

High school students must be interested in the modeling topics. Modeling techniques can be applied to such a wide variety of topics that a high school student is sure to find a subject that attracts their attention. Microbial fuel cells (MFCs) are selected in this work, which generate electricity from wastewater by means of bacterial functions on the surface of the anode electrode, and thus could potentially resolve the issues of energy production and waste treatment simultaneously[1]. Instead of introducing numerical methods to solve ODE, MATLAB Simulink was selected as the platform for ODE simulation. While other software for mathematical modeling often requires knowledge of programming languages, Simulink contains a set of modules to represent different mathematical operations, such as addition, subtraction, derivatives, and integrals. Much like building with LEGO, the user connects the modules together in Simulink to create systems that visually represent the equations. The friendly user-interface and intuitive applications of Simulink make representing high-level mathematical equations doable and even easy for high school students. After an interesting project and a user-friendly simulation platform were determined, which was essential to retain high school students in the project, interactive teaching strategies were applied to educate the students with the processes in the microbial fuel cells, and the relevant concepts for ODE development and simulation, and PID controller design. Since the rational design of PID controllers is based up a systemic training on Laplace transform, the commonly used tuning methods of PID controllers were not introduced in this project. Instead, the Simulink model was used as a platform for the student to evaluate the influence of the proportional (P) and integral (I) components on the controller performance so that the student can obtain a quick intuition and understanding of PID control. In addition, Simulink provides a PID controller module that can be easy to use by the student after he understands the physical meaning of each component of the PID controller.

After introductions to ordinary differential equations and Simulink simulation, the high school student was able to develop the Simulink ODE model for a MFC containing five equations and 25 parameters within one month by working as a part-time internship student and meeting the instructor once a week. The student then spent another month to integrate Simulink model for the MFC with the built-in PID controller module to evaluate the performance of PID controllers with different values in the proportional and integral components. The teaching strategies were also evaluated in this work. The student successfully created a Simulink simulation module, and the improvement of the student's skills in Simulink-based process simulation and control was assessed by a poster symposium for senior college students to present their summer research projects at Villanova University. Thus, we show an education project in which a high school student learned MATLAB Simulink, simulated an ODE model of a MFC, and developed PID controllers for a lab-scale MFC. It can be concluded from these assessments that these teaching methods effectively enhance the student's skill and interest in STEM topics.

Background Materials

Microbial fuel cells

MFCs are bio-electrochemical systems that drive currents through bacteria and their natural processes. As shown by Fig. 1, MFCs have a layer of biofilm comprised of anodophilic bacteria on the surface of the anode electrode. These bacteria convert the substrate, in this case acetate, and water into carbon dioxide, electrons, and protons in the anode compartment. The produced protons diffuse through the cation exchange membrane into the cathode compartment. The oxidized form of the intracellular mediator protein M_{ox}, such as cytochrome proteins[2], accepts the electron and carries it in the reduced form M_{red}, which releases the electron on the surface of the anode electrode and returns back to its oxidized form. Through external electrical circuit, the electrons move to the cathode electrode on which the oxygen acts as the electron acceptor and reacts with the protons into the water. In addition to the anodophilic bacteria, methanogenic bacteria may consume acetate and produce methane and carbon dioxide. The MFC configuration shown in Fig.1 is presented by Pinto et al., 2010[3]. Although other MFC configurations exist, the bio-electrochemical principle remains the same.

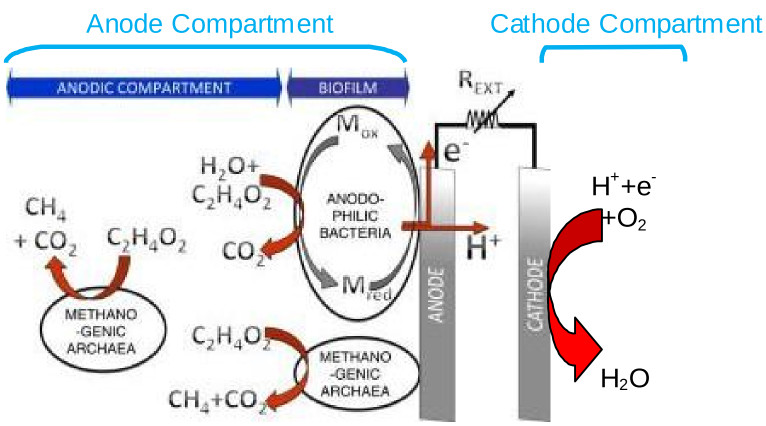


Figure 1. Schematic diagram of bio-chemical processes in a microbial fuel cell. This figure is adapted from Pinto et al., 2010[3]

Chiefly, MFCs are a source of renewable energy, as the anodophilic bacteria can produce electricity from organic compounds in the wastewater. In particular, the anodophilic bacteria used to drive the reaction grow by natural processes, and as long as they have the necessary nourishment, they continue to create electricity. Secondly, MFCs can assist wastewater treatment. In the wastewater treatment process, aeration, which is the pumping of air into waste to fuel the degradation of organic matter by bacteria, comprises between 45% and 75% of the plant energy costs. Additionally, sludge treatment accounts for about 20% of treatment plant costs[4]. Microbial fuel cells can remove the organic compounds from wastewater and use the acetate found in sludge as the substrate in the reaction. MFCs thus benefit the wastewater treatment by eliminating the energy costs of aeration entirely and with some electricity left over, and at the same time cutting sludge treatment costs significantly.

The ODE MFC model

The ODE MFC model presented by Pinto et al., 2010[3] was used in this work to quantify the time profiles of substrate concentration (i.e., S given by Equation (1)), microbial populations (i.e., x_a for the anodophilic bacteria given by Equation (2) and x_m for the methanogenic bacteria given by

Equation (3)), the oxidized mediator fraction per anodophilic bacteria (i.e., M_{ox} given by Equation (4)), and the current (i.e., I_{MFC} given by Equation (5)).

$$\frac{dS}{dt} = -q_a x_a - q_m x_m + D(S_0 - S) \tag{1}$$

$$\frac{dx_a}{dt} = -\mu_a x_a - K_{d,a} x_a - \alpha_a D x_a \tag{2}$$

$$\frac{dx_m}{dt} = -\mu_m x_m - K_{d,m} x_m - \alpha_m D x_m \tag{3}$$

$$\frac{dM_{ox}}{dt} = -Y q_a + \gamma \frac{I_{MFC}}{mF} \frac{1}{V x_a} \tag{4}$$

$$I_{MFC} = \frac{E_{ocv}}{R_{Ext} + R_{Int}} \frac{M_{red}}{\varepsilon + M_{red}} \tag{5}$$

where q_a and q_m are the substrate consumption rates by anodophilic and methanogenic bacteria, respectively; D is the dilution rate; S_0 is the influent substrate concentration; μ_a and μ_m are the growth rates of the bacteria; $K_{d,a}$ and $K_{d,m}$ are the decay rates of the bacteria; Y is the mediator yield; γ is the mediator molar mass; m is the number of electrons transferred per mol of mediator; F is Faraday's constant; V is the volume of the anodic compartment; E_{OCV} is the open circuit voltage; R_{Ext} and R_{Int} are the external and internal resistances, respectively; M_{red} is the reduced mediator fraction per anodophilic bacteria; and ε is a constant. There are 25 parameters in this ODE model. Due to the space limitation, the values of these parameters along with the equations to quantify q_a, q_m, μ_a, and μ_m are not shown here. The MATLAB program for the ODE model will be provided upon the request by interested readers.

PID controller

PID controllers are commonly used in chemical plants. PID controllers can be generally represented by Equation (6) [5]:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \tag{6}$$

where $u(t)$ is the controller output; e is the error value representing the difference between the measured output and the set point value of the output; K_p is the proportional gain that determines the controller response to the present error; K_i is the integral gain that determines the controller response to the accumulation of historical error; and K_d is the derivative gain that determines the controller response to future error. K_p, K_i, and K_d are tuning parameters for PID controllers.

The PID control system is based on a negative feedback loop, which minimizes the measured output with its set point value. Good PID controllers can maintain the system performance regardless of disturbances from the surrounding environment. In this work, the current output from MFCs is selected as the system output, while the inlet substrate flow-rate is the system input that can be manipulated overtime to maintain the current to the desired value. The control system implemented in this work is shown in Fig. 2. Generally, the change of inlet acetate flow-rate leads to the change of the population of anodophilic bacteria on the anode electrode, which in turn results a change in the electron production. The error value is processed by the PID controller, which contains a set of values to determine how much to shift the valve, which controls the substrate flow-rate. The PID keeps changing the substrate flow-rate until the measured current is equal to the set point value.

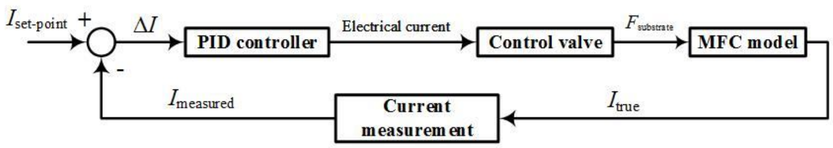


Figure 2. Representation of a control system based on a feedback loop

PID controller design theory is a topic typically introduced only to junior or senior college students, dealing with Laplace transform and other mathematical knowledge not expected of high school students. In this work, we only deal with the basic knowledge of PID controller design, and use the built-in Simulink PID controller module to study the impact of the P, I, and D components on the controller performance. We aim to teach the concept of control systems and the negative feedback loop and provide a platform for the high school student to learn the more intricate mechanics of controller design.

Results

Development of the Simulink MFC model

The MFC model consists of Equations (1)-(5) that represent the various populations (substrate, anodophilic microorganisms, methanogenic organisms, mediator) and the current (I_{MFC}) of the fuel cell. Much like LEGO, the various parameters were connected to create the equations, which were simulated to determine the current based on the substrate flow rate (Fig. 3). The simulation results from the Simulink model were the same to the results produced from a script-based model that was built by the instructor in the command line. Compared to the script-based model, which is complicated due to the highly coupled reactions and the large amount of model parameters, the Simulink platform allows a MATLAB layman to simulate ODE models. The Simulink model was further validated by making sure the results were logical: for instance, if the population of anodophilic microorganisms was increased, then the current should increase because of the higher number of bacteria.

Before designing the PID controller, the steady state current value versus the substrate flow-rate was plotted to determine the maximum current value that can be obtained from the MFC system (Fig. 4). If the substrate flow is too small, the anodophilic bacteria do not have enough nutrients for bacteria to survive and produce the electron flow. However, if the substrate flow was too large, the microorganisms could not digest all the substrate and thus could not further improve the electron production rate. In addition, some anodophilic microorganisms would be pushed out of the fuel cell, which in turn reduced the current production. As shown by Fig. 4, the maximum steady state current that could be produced by the studied MFC was 11.4 mA, which occurred at a substrate flow rate of 1 mL/min. From this value, an obtainable objective of a steady state less than 11.4 mA could be used as a standard to study the performance of various PID controllers.

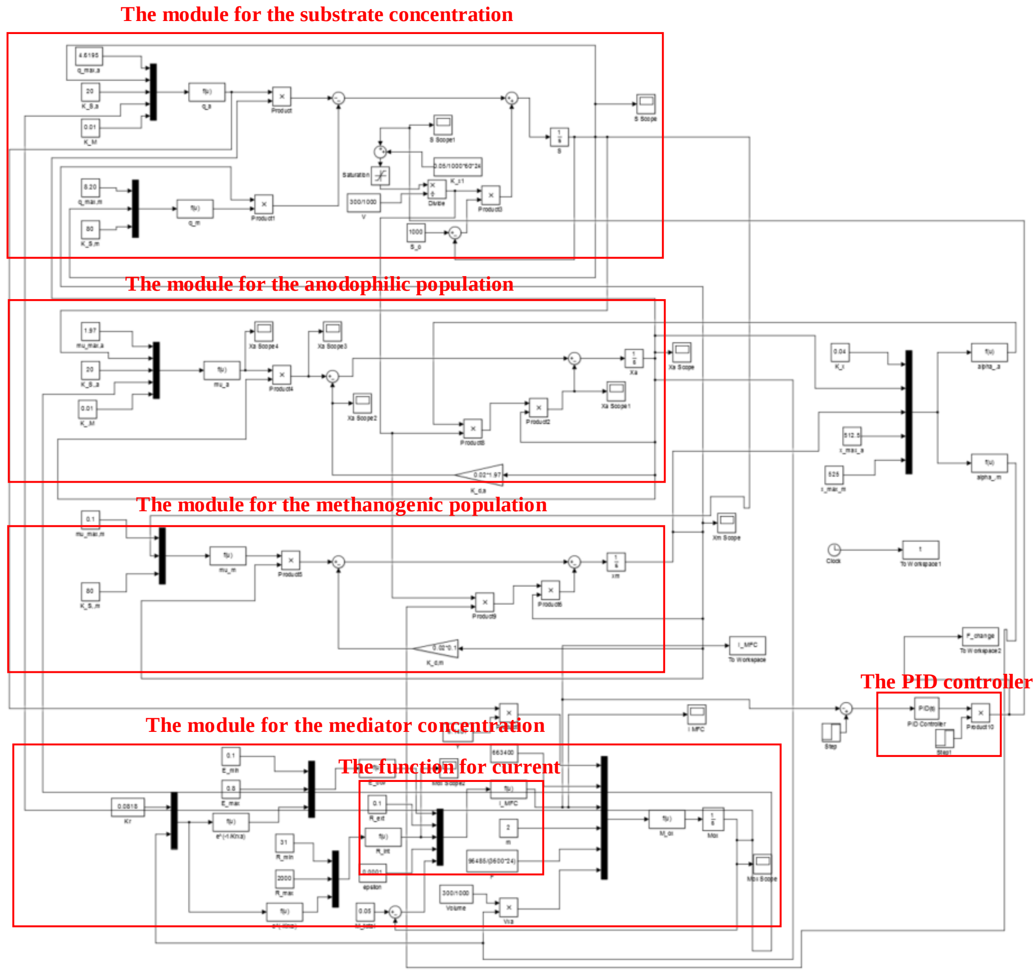


Figure 3. The Simulink model developed for the MFC

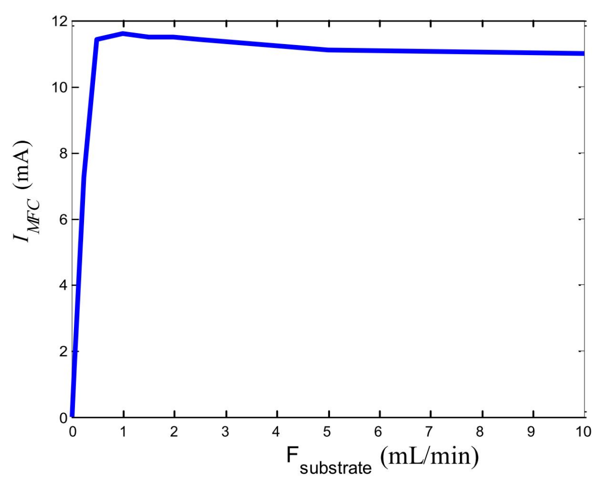
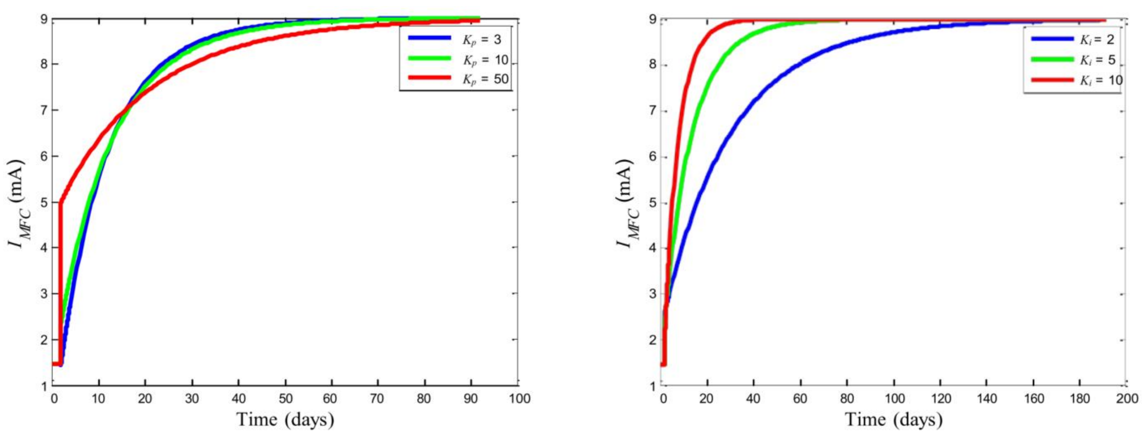


Figure 4. The current I_{MFC} versus various values of $F_{substrate}$ predicted by the Simulink MFC model

Evaluation of the performance of PID controllers

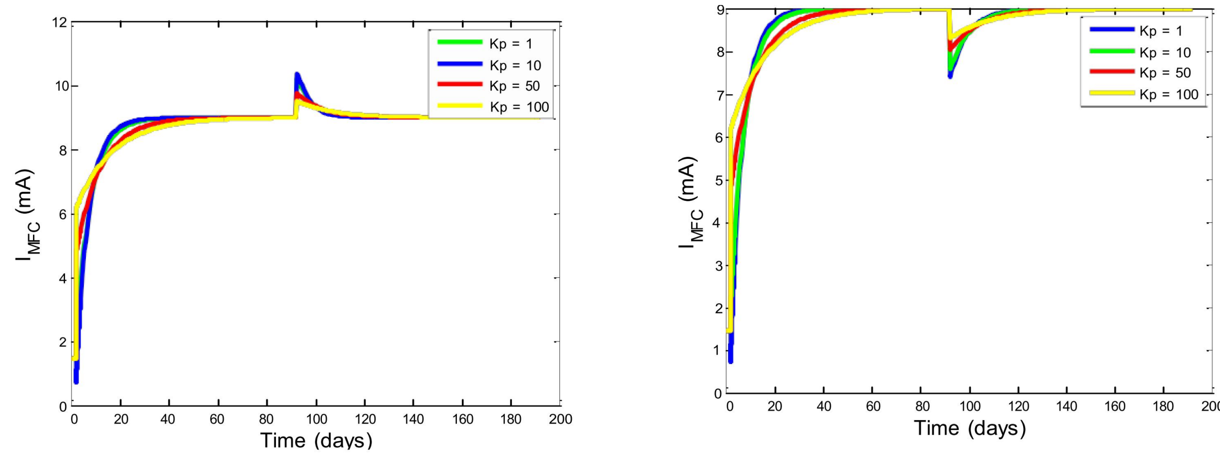
The Simulink model allowed the high school student to try different combinations of K_p and K_i. In this work, we only analyzed the effect of the proportional and integral gains on the controller performance, as PI controllers are the most commonly used controllers. We studied the controller performance first for the set-point change and then for the load change. To determine the effectiveness of the controller, the time profiles of current production for PID controllers with different K_p and K_i values were plotted together in the same figure for a direct comparison. In the set-point change, the output current was improved from 1.5 to 9 mA. Various values were assigned to only one of the two parameters (i.e., K_p and K_i) while the other parameter was kept constant. The current profiles for the MFC regulated by PID controllers with various K_p were shown in Fig. 5A, while the corresponding profiles for different K_i values were plotted in Fig. 5B. According to Fig. 5A, a PID controller with a larger K_p value can accelerate the change of current initially but reach the new steady state value more slowly. No overshoot was observed here as the time constant for this MFC is large due to the slow growth of anodophilic bacteria. Without a K_i term, the P controller could not completely eliminate the residual error (results not shown). According to Fig. 5B, a controller with a larger K_i (e.g., K_i = 10) could accelerate process towards the set-point value, while a controller with a smaller K_i (e.g., K_i = 2) responded much more slowly. Therefore, a high K_i value is necessary to eliminate the steady-state offset produced by a controller with only a K_p term.



(A) (B)

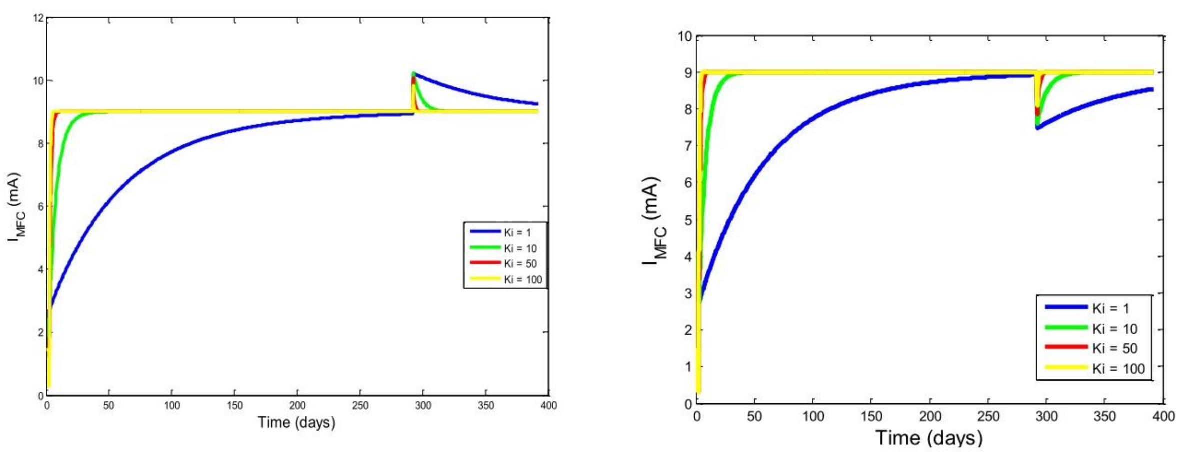
Figure 5. Effect of parameters K_p and K_i on controlling the current dynamics: (A) K_p was changed with K_i = 5; (B) K_i was changed with K_p = 10

In the load change, a pulse disturbance was introduced to the MFC system by increasing or decreasing of the inlet substrate concentration by 5% during Day 91. The pulse disturbance only lasted for one day. For each disturbance stimulation, multiple K_p values (Fig. 6) and K_i values (Fig. 7) were tested using the same approach as the one for the set point change. As shown by Fig. 6, a higher K_p value had a smaller overshoot/undershoot during the disturbance. As shown in Fig 5A, a higher K_p resulted in a longer time for the system to reach the new steady state. This may explain the smaller overshoot/undershoot for a higher K_p value. This indicates that a PID controller of the best performance for the set-point change may not be of the best performance for the load change control (i.e., disturbance rejection). It is nontrivial to determine the K_p value for the PID controllers designed for both the set-point and load changes. On the other hand, Fig.7 showed that a higher K_i value was able to minimize the impact from the disturbance. Combining Fig 5B and Fig. 7, we conclude that a higher K_i value may be a better option for both the set-point and load changes.



(A) (B)

Figure 6. Effect of K_p values on the response speed to a disturbance stimulation in which the substrate concentration was increased (A) and decreased (B) by 5% during Day 91. K_i was equal to 5.



(A) (B)

Figure 7. Effect of K_i values on the response speed to a disturbance stimulation in which the substrate concentration was increased (A) and decreased (B) by 5% during Day 91. K_p was equal to 10.

Teaching strategies

Teaching strategies for educating high school students with Simulink-based modeling skills

Selecting an interesting project is the first step to attract high school students in the education of process simulation and control. MFC is selected in this work, because it can generate electricity from the organic compounds from waste water on the surface of the anode and because it may resolve the challenges to handle energy crisis and waste water treatment at the same time. A detailed introduction of MFC and several Youtube videos of MFC were given to the high school student in the first week of the project.

The largest hurdle for educating high school students with modeling skills is that they subconsciously resist the math and they are not confident whether they are able to handle the math operations. In this work, we used Simulink as the platform to make process simulation and control doable to high school students. Here is the strategy for training the student with Simulink. The student was first taught the basics of Simulink: how to create a simulation, how to access the modules, and how to create and connect the modules. Simple examples for developing ODE model in Simulink were given to build the student's confidence. An assignment was then given where the student had to successfully reproduce a diagram representing a single simple ODE and run the program. If the student's results matched with the assignment, then the program was successful. The objective of this assignment was to teach the student how to access the modules and connect them to create a diagram. Next, the student had to create a program representing ODEs for the typical enzymatic reactions (i.e., E + S <—> ES —> P). In this training, no diagram was given. This assignment not only entailed creating the diagrams for the individual equations, but also connecting the equations together. The goal of this assignment was for the student to learn how to recreate mathematical functions without the assistance of a diagram, and figure out how the equations relate to each other. This training lasted for two weeks. The student was confident with building ODE models in Simulink after this training.

The ODE model given by Equations (1) – (5) was introduced to the student with the detailed physical meaning for each term and parameter in the model. This was essential for the success of the project, as the student might be scared away by the equations. This took for one week. The student was then asked to input one equation into Simulink for one week. The instructor helped the student to check his Simulink model and offered advice to further improve his model. After the student finished the first three equations, he gained enough experience to finish Simulink model one week earlier than the schedule. Therefore, the development of Simulink model only took four weeks with the student working for only two days per week.

Finally, the basic skills of PID controller design were introduced to the student along with a Simulink-based controller design module, which allowed the student to evaluate the impact of the proportional (P), integral (I), and derivative (D) components on the controller performance. This training lasted for one week. The student picked up the PID controller design skill fast and implemented it to the MFC system within one week.

Interactive training and effective learning are essential for educating high school students with complicated skills in engineering such as process simulation and control. The student was required to redo all the examples introduced in the training, and the instructor checked the student's programs in detail and offered timely suggestions for the student to improve his programs. Homework assignments were designed to be similar to the instruction examples but more difficult (e.g., an ODE with a large number of equations). Beginning the training with simple problems helped the student to build confidence. Breaking a complicated model/project into small steps which can be finished by the student within one week also helped the student to see the progress he made.

Evaluation of teaching effectiveness

The effectiveness of teaching and training was assessed by the student's performance to independently develop a Simulink simulation module for a MFC ODE model that consists of five ODE equations and 25 parameters, and a controller design module that can be used to evaluate a controller's performance. The Simulink model developed by the student was validated by a comparison between it and the script-based model developed by the instructor. The simulation results for PID controllers offered the student a quick intuition and understanding of PID control. In addition, the improvement of the student's skills in Simulink-based process simulation and control was assessed by a poster that was presented in a symposium for senior college students to present their summer research projects at Villanova University. In the presentation, the student showed his clear understanding of the key processes for MFC operation and the influence of proportional and integral components on the PID performance. For example, he knew that the integral component helps to eliminate the steady-state offset and that a good value of K_p for set-point change control may not be good for the disturbance rejection. Since the high school student worked two days per week and met the instructor once a week, his performance was far above the expectation of the instructor. It can be concluded from these assessments that the teaching modules effectively enhance the student's skill and interest in process modeling and control.

While these results demonstrate that it is possible for high school students to learn engineering concepts, with these methods, it is unlikely that more than a few high school students will have this chance. Such training requires an extremely small student to teacher ratio, as high school students need more attention than college or graduate students to apply the concepts to this extent. The STEM preparation of the student participating in the work was well supported by the advanced math and science courses he had taken, including AP Courses in Biology, Chemistry, and Physics (e.g., Newtonian Mechanics, Electricity, and Magnetism), as well as math courses up to Calculus (AP BC Calculus) and Computer Science. In addition, this student was ranked in the top 1-2% of his class. These factors contributed to the success of the implementation of the developed teaching module. It may take longer time for the high school students who haven't good STEM preparation in implementing the teaching module. However, the student participating in the work believed that there were a good amount of people in his school (e.g., top 25% ranked junior or senior students) who would be able to accomplish the same work if they had the same training opportunity. Since extra attention must be taken to make sure high school students understand the training materials, it may be challenging to teach more than a few students at a time. Having multiple students work on one project together is one way to get more high school students trained in this teaching module. All the students will have the benefit of learning the material, but also learning to work with peers. In addition, recording the teaching modules in videos and implementing the flipped-classroom teaching format may be helpful to improve the teaching efficiency, as the students can follow the videos to input their programs in MATLAB step by step. The recorded videos also allow the students to watch multiple times. This may help the students to understand the concepts and modeling processes. Nevertheless, it is possible for a larger number of high school students to learn concepts such as process control and simulations, possibly through a summer session or as a class offered during the school year.

Conclusion

High school students in USA fall behind the students of some other countries in Math and Science. This work presents an example project in which a high school student was educated with the skills in process simulation and control. Upon the training in Simulink and the introduction of basic concepts in ODE models and process control, the student was able to create a Simulink model representing the operations within a microbial fuel cell. The student also investigated the influence from the proportional and integral components on the performance of PID controllers that regulate the current production of the MFC by controlling the substrate inlet flow-rate. The developed Simulink model was validated by the instructor and the research results were presented at a poster session. Overall, this work demonstrates the possibility of introducing more advanced STEM topics to high school students by designing interesting projects, using software with friendly user interface, applying interactive teaching strategies such as breaking complex problems into small pieces to encourage the student's active participation and learning.

References

1 Logan, B., "Generating electricity from wastewater treatment," Water Environ Res, 2005, 77 (3), 211-211.
2 Ross, D. E., J. M. Flynn, D. B. Baron, J. A. Gralnick, D. R. Bond, "Towards electrosynthesis in Shewanella: energetics of reversing the Mtr pathway for reductive metabolism," PLoS One, 2011, 6 (2).
3 Pinto, R. P., B. Srinivasan, M. F. Manuel, B. Tartakovsky, "A two-population bio-electrochemical model of a microbial fuel cell," Bioresource Technol, 2010, 101 (14), 5256-5265.
4 Wang, H. M., Z. Y. J. Ren, "A comprehensive review of microbial electrochemical systems as a platform technology," Biotechnol Adv, 2013, 31 (8), 1796-1807.
5 Seborg, D. E. E., Edgar T.F., D.A. Mellichamp, F. Doyle, Process Dynamics and Control. 3 ed.; Wiley, John & Sons: 2010.

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Zuyi (Jacky) Huang

Zuyi (Jacky) Huang is an Assistant Professor in the Department of Chemical Engineering at Villanova University. He teaches Chemical Process Control (for senior students) and Systems Biology (for graduate students) at Villanova. His research is focused on developing advanced modeling and systems analysis techniques to manipulate microbial biological systems for generating biofuels from wastewater and for combating biofilm-associated pathogens. His group (the Biological & Environmental Systems Engineering lab (BESEL)) has developed the first model for microbial desalination cells and the first metabolic modeling approach for quantifying the biofilm formation of pathogens.