Integration of Commercial Dynamic Simulators into the Undergraduate Process Control Curriculum

Michael A. Henson* and Yongchun Zhang
Department of Chemical Engineering
Louisiana State University
Baton Rouge, LA 70803-7303

Prepared for presentation at the 2000 AIChE Annual Meeting
Session on "Teaching Process Control and Dynamics Through Practical Examples"

November, 2000

Unpublished

Abstract

The integration of a commercial dynamic simulator into the undergraduate process control course at Louisiana State University is discussed. The HYSYS.Plant simulation package has been placed on the departmental network as well as supplied directly to students under a unique licensing agreement with the vendor Hyprotech. A flowsheet developed by Hyprotech has been modified to produce a representative reaction/separation simulation amenable to student use. The simulator serves as the basis for a series of open-loop and closed-loop simulation experiments that cover key concepts in process dynamics and control. Our initial experience has been favorable and demonstrates the power of incorporating commercial dynamic simulators into the undergraduate process control curriculum.

*To who correspondence should be addressed: Phone: 225-388-3690; Fax: 225-388-1476; E-mail: henson@che.lsu.edu

1 Introduction

The traditional approach to undergraduate process control education relies heavily on written homework problems to illustrate concepts covered in lectures. Such problems necessarily involve very simple processes that are amenable to rigorous analysis. An unfortunate consequence of this approach is that students fail to gain an adequate appreciation for the complexity of control problems encountered in industry. The result is a large gap between their academic training and industrial practice. One possible solution to this problem is the incorporation of experiments into the undergraduate process control course. However this approach several potential drawbacks including: (*i*) the requisite experimental facilities must be available; (*ii*) a separate process control laboratory course often must be established; and (*iii*) plant-wide control problems encountered in industry are difficult to replicate in a laboratory setting.

We have pursued an alternative approach based on the integration of a commercial dynamic simulator into the process control course. We believe such simulators are better suited for this purpose than are general purpose simulation tools such as MATLAB because complex flowsheets can be constructed without developing specialized code. Our department recently entered into a licensing agreement with Hyprotech for their dynamic simulation package HYSYS.Plant. The software is resident on our local area network, and qualified students can purchase a temporary home license for a small fee. Our long-term vision is that the steady-state and dynamic simulation features will be incorporated throughout the undergraduate curriculum starting with the mass and energy balance course and culminating with the senior level design courses. Currently the simulator has been fully integrated into the process design and control courses and partially incorporated into the unit operations course. We believe the utilization of commercial simulation software throughout the chemical engineering curriculum provides a key unifying theme and gives our students a competitive advantage in the job market.

In this paper the challenges and opportunities associated with the integration of a commercial dynamic simulator into a traditional undergraduate process control course are discussed. While the presentation focuses on the HYSYS.Plant software, similar experiences can be expected with other dynamic simulators. The remainder of the paper is organized as follows. In Section 2, the flowsheet of the reaction/separation process is described. Open-loop and closed-loop simulation experiments developed using the simulator are discussed in Section 3. Section 4 summarizes our experience with the simulation experiments and outlines our future plans for the development of additional simulation modules.

2 Process Description

The HYSYS flowsheet of the reaction/separation process is shown in Figure 1. The process consists of a continuous stirred tank reactor (CSTR) that produces the desired product and a distillation column that separates the product from the reactants. The top half of Figure 1 shows the overall flowsheet, while the bottom half shows the detailed flowsheet of the column. The feed stream to the CSTR consists of a mixture of ethylene oxide and water. The following irreversible reaction produces the ethylene glycol product: $C_2H_4O + H_2O \rightarrow C_2H_6O_2$. Because the reaction is exothermic, a coolant stream is required to manage the reactor temperature. The ethylene oxide feed contains a small amount of nitrogen that is removed from the reactor via the vent stream. The liquid stream sent forward to the column consists of a mixture of ethylene glycol,

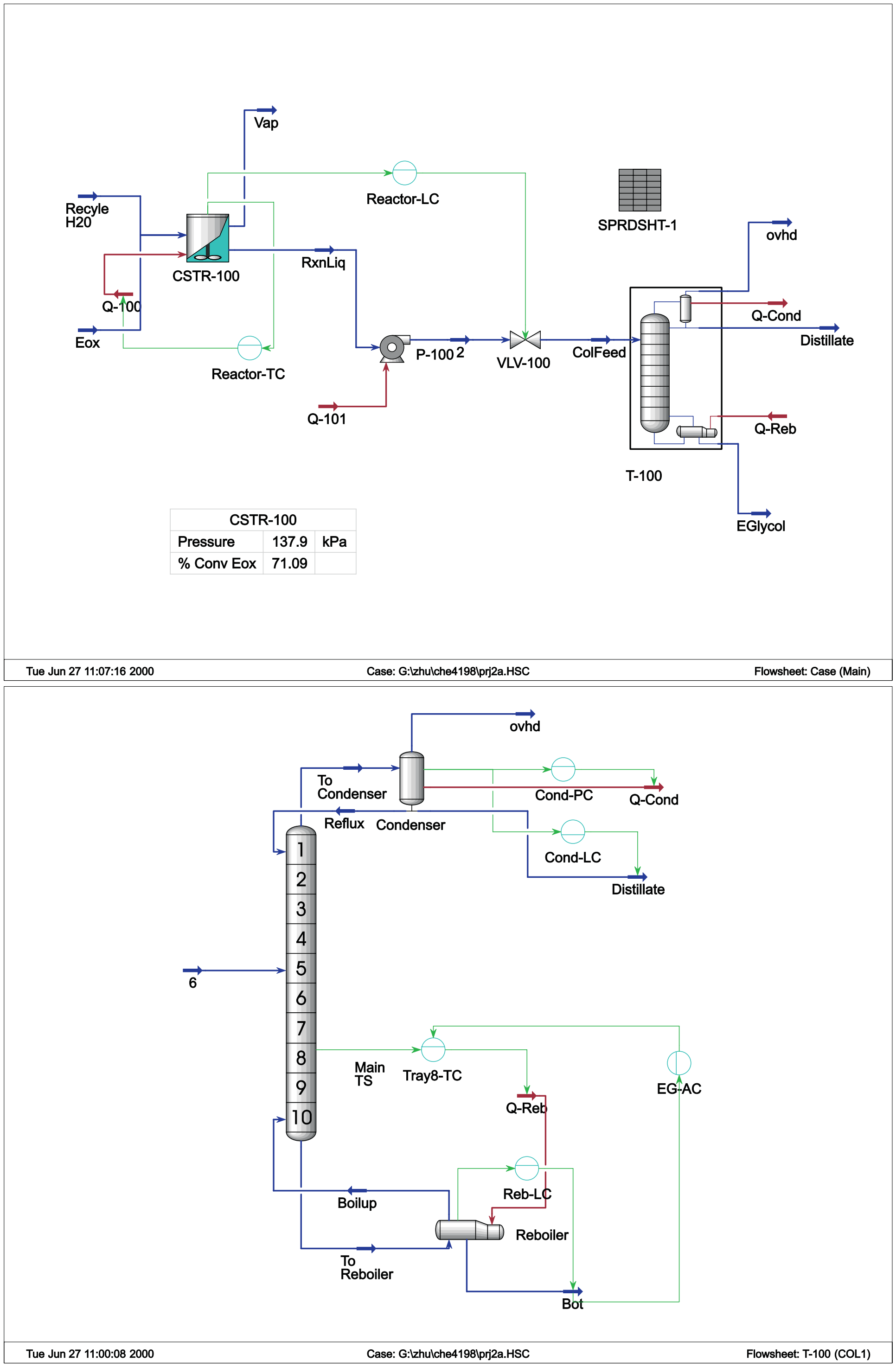

Figure 1: Process flowsheet.

ethylene oxide, water and trace amounts of nitrogen. The column is modeled as ten equilibrium stages, a reboiler and a partial condenser using the standard distillation column unit operation in HYSYS.Plant. The reactor effluent is fed as liquid to the fifth stage of the column. The distillate stream enriched in ethylene oxide and water is treated as a waste stream. The overhead circuit also contains a small vent stream that is used to remove any remaining nitrogen. The ethylene glycol is recovered as the bottom product. The simulation does not include control valve dynamics, but the controlled flow rates can be constrained within limits to mimic valve saturation. The process includes unstable reactor dynamics and integrating dynamics associated with liquid inventories in the reactor and the column.

In the original flowsheet downloaded from the Hyprotech website (`www.hyprotech.com`), the distillate stream is recycled to the reactor to conserve raw materials. This recycle stream introduces slow dynamics that result in prohibitively long simulation times on the 133 MHz computers in our undergraduate laboratory. Consequently, the recycle stream was removed and the distillate is treated as a waste stream. The simulation files are provided to students via the course webpage. This was deemed necessary given the limited time available to cover HYSYS flowsheet development.

The operational objectives are to maintain the following seven output variables at their setpoints: reactor temperature, reactor liquid level, condenser pressure, condenser liquid level, reboiler liquid level and ethylene oxide mole fraction in the bottoms stream. These objectives are achieved by seven feedback controllers that manipulate the following input variables: reactor cooling duty, valve position on the reactor liquid stream, condenser duty, distillate flow rate, bottom flow rate and reboiler duty. Note that a cascade controller is used to regulate the bottom ethylene oxide mole fraction. The inner loop consists of a temperature controller that manipulates the reboiler duty to achieve a specified temperature on the eighth stage. The setpoint for the temperature controller is the manipulated input of a composition controller that is designed to achieve the desired bottom ethylene oxide mole fraction. Although it is not essential in this simulation, the cascade configuration might be required in practice to compensate for variations in the reboiler utility stream.

3 Simulation Experiments

The dynamic simulation of the reaction/separation process has been used to develop a series of open-loop and closed-loop simulation assignments. Because our undergraduate curriculum does not include a separate control laboratory course, the simulation experiments had to be incorporated into the existing three-hour process control course along with traditional written homework assignments. We determined that four simulation experiments could be added without loss of continuity. The simulation experiments were developed in the spring of 1999 and further refined in the spring of 2000. The four assignments cover the following topics:

1. The reaction/separation process and motivation for feedback control.

2. Open-loop dynamics and empirical process modeling.

3. PID controller tuning.

4. Control loop interactions and variable pairing.

Each simulation includes a process flow diagram (see Figure 1), seven controller face plates that are used to configure and manage the control loops, two strip charts that automatically plot the dynamic responses of the most important reactor and column variables, and a databook that provides numeric values of these variables. Students are required to work in two-person groups and to prepare a written report for each assignment. For the sake of brevity, only the first three simulation experiments are described below.

Background and Motivation

The objectives of the first assignment are to become familiar with the reaction/separation simulation and to gain an appreciation for the benefits of automatic feedback control. Students are asked to justify the selection of the eighth stage temperature for cascade control of the bottoms ethylene glycol composition by examining the composition profile in the column. In the first set of simulation tests, students investigate the open-loop process dynamics for step changes in the reactor cooling duty, reactor outlet flow rate, condenser duty and reboiler duty. These tests introduce several important concepts including integrating dynamics (reactor outlet flow rate changes), unstable dynamics (reactor cooling duty changes) and process nonlinearities (condenser and reboiler duty changes). In the next set of tests, students compare manual and automatic control of the reactor temperature and level via manipulation of the reactor cooling duty and outlet flow rate, respectively. Students quickly learn that manual control of reactor temperature is near impossible due to the highly nonlinear ignition/extinction behavior. While manual control of the reactor level is feasible, students realize that effective control would require frequent intervention by the operator. The associated automatic control loops provide far superior regulation and provide considerable motivation for a more detailed study of feedback control. Students are asked to explain the action (direct or reverse) of each controller based on their physical understanding of the process.

Empirical Process Modeling

The objectives of the second assignment are to perform step testing to generate open-loop dynamic data and to use these data for the development of empirical transfer function models between key input and output variables. It is important to note that the temperature controller must be placed in automatic to stabilize the reactor. As a result, the plant behavior modeled consists of the intrinsic process dynamics as well as the dynamics of the temperature control loop. In the first set of tests, open-loop dynamic data are generated by implementing step changes in the reactor outlet stream valve position, condenser cooling duty, distillate flow rate, reboiler heat duty and bottom flow rate. For each input/output pair in Table 1, students are asked to provide a physical explanation for the dynamic response and to propose a candidate transfer function model form. Students quickly learn that several of the responses are not easily described with the low-order transfer function models covered in lecture.

In the next set of tests, students use the open-loop data to develop empirical transfer function models that will be used for PID controller design in the third assignment. Table 1 shows the variables pairings as well as the type of transfer function used to model each dynamic response. With the exception of the fifth control loop, the parameters of the transfer function models can be found by standard graphical methods [2]. A second-order overdamped model with a right-half plane zero is required to model the large inverse response between the reboiler duty and the

Table 1. Input/Output Pairings			
Loop	Input	Output	Transfer Function Model
1	Outlet valve position	Reactor liquid level	Second-order underdamped
2	Condenser duty	Condenser pressure	First-order
3	Distillate flow rate	Condenser liquid level	Integrating
4	Bottoms flow rate	Reboiler liquid level	First-order
5	Reboiler duty	Tray 8 temperature	Second-order overdamped with right-half plane zero

tray 8 temperature. These model parameters are found by Euler discretization of the associated differential equation model followed by least-squares estimation. For each input/output pair, the quality of the empirical model is evaluated by comparing the model prediction and the open-loop response.

PID Controller Tuning

The objectives of the third assignment are to use the transfer function models derived in the second assignment to design PID controllers and to fine tune the controllers to obtain satisfactory closed-loop performance. The internal model control tuning rules [2] are used to design PID controllers for the five control loops in Table 1. Although not discussed here, in the fourth assignment the relative gain array [2] is used to investigate alternative pairings of the input-output variables. Note that the reactor temperature controller cannot be retuned because it was placed in automatic to stabilize the reactor during open-loop data collection. In addition, the bottom ethylene oxide controller must be tuned by trial-and-error because a model between the tray 8 temperature controller setpoint and the bottom ethylene oxide model fraction is not developed as part of the empirical modeling assignment. The closed-loop performance is evaluated for setpoint changes in the reactor temperature, reactor liquid level, condenser pressure, condenser liquid level, reboiler liquid level, tray 8 temperature, and bottoms ethylene oxide mole fraction and an unmeasured disturbance in the ethylene oxide feed flow rate. Students are asked to fine tune each controller to obtain an acceptable closed-loop response. The trial-and-error tuning of the bottom ethylene oxide controller clearly demonstrates the advantage of using a model-based tuning method to obtain good initial values of the controller parameters.

4 Student Feedback and Future Plans

The HYSYS simulation experiments have been a key component of the undergraduate process control course the last two semesters the class has been offered (Spring 1999, Spring 2000). Student response to the simulation assignments has been very favorable. Many students note that the simulations allow concepts covered in class to be illustrated in a more realistic setting than is possible with conventional written homeworks. Although there is some initial reluctance, students rapidly gain an appreciation for the small group environment as they attempt to interpret their simulation results. The dynamic simulation experiments have proven to have a synergistic effect with the capstone process design course where HYSYS is used for steady-state simulation. We believe that additional benefits will be realized as HYSYS is integrated into our other undergraduate courses.

The only major problem encountered has been lack of high speed computers in our undergraduate computing laboratories. Many students have complained that the existing 133 MHz computers lead to unreasonably long simulations times. We have learned that a 450 MHz processor is the minimum requirement for effective use of the HYSYS software. An extensive upgrade of our computing facilities to surpass these requirements is being performed, and continuous upgrades will be required to support future versions of the software. Despite this drawback, we believe that the integration of commercial simulation software throughout the chemical engineering curriculum offers students a unique opportunity to utilize the computational tools they will encounter in their professional careers.

We have plans to develop other dynamic simulation modules using more complex flowsheets. As part of our undergraduate research course we intend to develop a detailed simulation of the production of styrene via the dehydrogenation of ethylbenzene [3], which in turn is produced by the exothermic reaction of ethylene and benzene [1]. This flowsheet consists of two reactor trains, ten distillation columns and various other unit operations. Due to the large number of unit operations and the extensive use of recycle, this simulation will require significantly more computational resources than the simple reaction/separation flowsheet described above. We anticipate incorporating the styrene simulation (or perhaps just the ethylbenzene production subsystem) into the process control course in the spring of 2001 after the current upgrade of our undergraduate computing facilities is completed. The emphasis on traditional written homeworks will be decreased further by offering a total of six simulation experiments.

Acknowledgements

Financial support from the National Science Foundation (CTS-9501368) and technical support from Hyprotech are gratefully acknowledged.

References

[1] H. K. Hummel, G. B. C. de Wit, and A. Maarleveld. Optimization of EB plant by constraint control. *Hydrocarbon Processing*, pages 67–71, March 1991.

[2] D. E. Seborg, T. F. Edgar, and D. A. Mellichamp. *Process Dynamics and Control*. Wiley, New York, NY, 1989.

[3] K. M. Sundaram, H. Sardina, J. M. Fernandez-Baujin, and J. M. Hildreth. Styrene plant simulation and optimization. *Hydrocarbon Processing*, pages 93–97, January 1991.