Integrating Virtual Laboratory Exercises into Chemical Engineering Curricula

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Abstract

Recent changes in accreditation criteria has led to structural changes in the undergraduate curriculum. There is increasing emphasis on design throughout the curriculum, along with team oriented, industrially relevant project experience. There is also a need to expose students to state of the art engineering software. In this paper, we discuss the use of virtual laboratories to supplement engineering courses as a means for meeting some of the needs stated above. We describe how such exercises were integrated into two chemical engineering undergraduate courses to reinforce concepts and to show application to real world design problems. Some preliminary assessment results are also presented.

1. INTRODUCTION

Students adopt one of the two different approaches when they start working on a subject: deep and surface level processing [1]. Deep level processing is necessary to get a good grasp of the material and to promote retention for later use. The student's motivation to learn is a determining factor on the approach taken. If the student gets interested in the topic, deep level processing

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begins. Problem based learning is used in engineering education to mimic the learning process in real life, where we learn naturally while solving problems. When the problems to be solved in class have resemblance to real life situations rather than abstract exercises that addresses solely analytical skills, students are more likely to get motivated to work on them and learn [2].

The undergraduate laboratory experience can be a great motivating experience for students. Laboratory experiments are used to reinforce concepts learned in the classroom and to expose the students to the equipment, instrumentation and experimental design and data analysis techniques. One essential distinguishing feature of the laboratory course experience is that it requires more active participation than lecture based courses. Students find it rewarding to see concepts in action. Care must be taken to avoid tedious and repetitive experiments for this to happen.

There are a number of difficulties in fully integrating the laboratory experience with the rest of the curriculum. Usually, laboratory courses are offered as independent stand alone courses. This makes it difficult to synchronize the material covered in lecture courses with the laboratory experience. Laboratories require more resource commitment than lecture based courses, so it becomes difficult to expand the experience beyond what is minimally required for accreditation purposes. Laboratory courses are generally more demanding on the instructor's time than lecture courses and hence many faculty tend to shy away from getting involved. Finally, the constraints imposed by safety, time and economic considerations tend to limit the type of experiments that can be performed in the laboratory. Experiments are often rigidly formatted and scheduled laboratory hours limit the number of experiments than can be carried out. To give students a wide variety of experience, they are rotated through many experiments in a course which makes it difficult to synchronize theory courses with the laboratory experience.

In this article we focus on the development and integration of virtual laboratory exercises into two required chemical engineering undergraduate courses at the University of South Florida. Our emphasis has been on the using the virtual laboratories as

a means of reinforcing concepts learned in the class room. Because the laboratory is handled as part of the regular course, it is possible to achieve a high level of integration between the laboratory experience and the theory covered in lectures. The virtual nature of the laboratory frees one from the constraints of time, space and money while enabling closer ties with industrial scale application studies. It also allows greater freedom for students since the experiment is no longer set in hardware. The students can design, configure and run new experiments with minimal effort. We want to emphasize that these virtual laboratories are not suggested as a replacement for actual laboratory experience, but rather as a way of enhancing the curriculum.

The objectives of this paper are (i) to show how tight the integration of virtual laboratories with core courses can be achieved and (ii) how the design experience can be made an integral part of the curriculum. We show how we achieved this in two core classes (Process Engineering III, which is concerned primarily with principles of chemical reaction engineering and Auto Controls I, which is concerned with principles of process dynamics and control) through structural change in the course offering and through virtual experiments that were designed by graduate student teaching assistants.   We have structured these core courses to have three-hours of lecture and three-hours of "virtual" laboratory experience. These laboratory sessions provide sufficient time to carry out one or more virtual experiements related to the concepts discussed in the lecture hours. These "virtual laboratory" exercises were meant to simulate the experience gained in a real laboratory. The virtual laboratories provide a setting quite similar to those encountered in the practical application of the concepts.

The use of virtual laboratories in engineering courses is not new. Li et al. [3] built a web-based environmental engineering mass transfer processes laboratory emphasizing the processes occurring at the particle scale. They used FORTRAN and C++ as the numerical engines and presented system development and implementation in detail. Shin et al [4] describe the use of virtual laboratory for unit operations. Yarborough et al. [5] developed virtual laboratory modules with LabVIEW for undergraduate civil

engineering probability and statistics course. They appended virtual laboratory modules to lectures to improve students' understanding of the concepts through real world applications. The assessment data showed that the students liked the virtual laboratory modules because they included real world civil engineering applications and they helped reinforce the concepts learned in class. Forbes et al [6] describe a virtual laboratory module called Cyclepad, a software to teach engineering thermodynamics through designing cycles such as refrigerators, engines, power plants, cryogenic systems. Virtual laboratories for chemical engineering unit operations and process system engineering courses have also been developed. Fleming and Paulatis built a batch distillation column simulation model to cover design, scale up, start up problems, normal and unusual operating conditions and safety issues [7]. Ko et al. [8] worked on the development of a virtual laboratory for control experiments on a coupled tank apparatus to test various control algorithms such as fuzzy logic and state space control. They used LabVIEW for implementation. Squires et al [9] describe the Purdue laboratory computer simulation modules available through CACHE. These modules provide the capability to conduct virtual experiments on simulations of industrial scale processes as a way to supplement the laboratory scale experiments.

3.1. Virtual Laboratory Exercises in the Process Control Course

A large number of software modules have been reported for enhancing process control education, primarily because computers have become ubiquitous in process control applications (see for example [10] and [11]). In fact, today, operators are routinely trained using process simulators interfaced to the computer control systems that they will use in running the real plant.

Our guiding principles in selecting the software platform for deployment of these modules were that,

(i)   it should provide students with a platform of sufficient flexibility to synthesize, implement and test simple and advanced control strategies on a realistic process simulator,

(ii)   it should be easy to use with a Graphic User Interface (GUI),

(iii)   learning should be incremental from simple to more complex issues, and

(iv)   it should provide challenge and open-endedness with a view to motivating students with varying levels of background preparation.

We chose Matlab/Simulink as the software platform because it was already introduced in the curriculum and students were familiar with the software.

A simulation of a naphtha cracker (used in petroleum refineries to break up high molecular weight hydrocarbons into smaller molecules) was built on the Matlab/Simulink platform to achieve the pedagogical objectives listed above. Figure 1 shows a schematic of the cracker interface. As shown, the students have access to 7 measurements, 2 control valves, a PID feedback controller block, and a feed forward controller block. In addition we have shown two virtual sensors, one indicating the instantaneous profit made by the process and another showing the cumulative profit. The latter two are provided to make the students aware of the economic consequence of the control actions. This also provides the students with a game playing competitive option to try and do better with each additional concept / tool that they learn in class. The student is asked to synthesize, design, implement, and, test simple and advanced control strategies as they are introduced in the class. The typical virtual laboratory schedule is shown in Table 1.

Table 1. Typical schedule of virtual laboratory exercises in process control course

Week	Virtual Laboratory Exercise

1	An introductory tutorial on Simulink
2	Getting familiar with the naphtha cracking process and the simulation.
3	Manual control of the process. Process identification exercise. Developing transfer functions from empirical testing
4	Tuning a PID controller to control the reactor temperature using fuel flow input
5	Feedforward control (using the ambient temperature sensor to compensate)
6	Cascade control (using furnace temperature controller in an inner loop)
7	Ratio Control (to tie the flow of air and fuel to achieve safety objectives)
8	Multivariable control (control of the oxygen content in the stack and the reactor temperature)
9-12	Open-ended exercises

The simulation adds realism by incorporating diurnal ambient temperature variations and effect of passing thunderstorms that affect the furnace operations. Additive random noise on the measurements combined with these external disturbances provide a realistic setting for making students aware of practical issues in relation to process identification testing and control system performance evaluation. Such a setting is hard to achieve even with well-designed laboratory exercises because of the inherent limitations of a bench scale apparatus.

The cut/paste capability of Simulink, along with its large library of simulator blocks makes control system implementation as easy as drawing a process instrumentation diagram on paper. At the same time, the simulation requires students to pay attention to practical details such as the bias setting in a controller, the proper units of the controller gain, choosing the correct action (direct vs.

reverse) of the controller, the initial setting for the set points. More complex issues such as reset windup, come up later as they progress towards more advanced control strategies.

The importance of providing the students the ability to synthesize and test their own control strategies cannot be overemphasized. This makes them at once aware of the ownership of their work and the need to be precise with their decisions and actions. The abstract equations they use in the homework exercises become a real component in the control system implementation. The deep learning associated with mastering a concept becomes a necessity to carry out these exercises.

We hold these exercises in a three-hour laboratory session (as opposed to a homework assignment) because it is important to provide help in overcoming simple obstacles such as manipulating the GUI and graphing the data. Without this immediate help, students will become frustrated and give up rather than persist. Not all students are able to complete the exercise in the allocated time. These students complete the exercise after-hours in the lab or at home.

The virtual laboratories have allowed instructors to focus the student's attention on deep learning of the course material while covering a broad range of topics. Students' perceptions have been positive as indicated by the end of the term survey (see Table 2).

3.2. CHEMICAL REACTION ENGINEERING

The virtual laboratory module prepared for Chemical Reaction Engineering class is on the kinetics of the preferential oxidation (PROX) of carbon monoxide in a plug flow reactor (see Figure 2a). This catalytic process has become of interest with the development of fuel cell technology. PROX reactor is required to reduce carbon monoxide content of a hydrogen rich stream to avoid poisoning of the fuel cell catalyst [12,13].

The module was developed to teach students general characteristics of a tubular catalytic reactor and how to model its steady state behavior. Carbon monoxide is fed to the reactor in a hydrogen rich stream. Both hydrogen and carbon monoxide react with oxygen in the reactor; the concept of selectivity is also of interest. The inlet and outlet streams are quantitatively analyzed using a gas chromatograph (see Figure 2b). The basics of gas chromatography and the methods used for quantitative analysis are introduced in addition to the safety aspects as part of this virtual laboratory exercise.

The students are first asked to determine the rate expression of the reaction by collecting data at different carbon monoxide, oxygen concentrations and temperatures. They are free to select any catalyst load and inlet total flowrate within the given range (see Figure 2c). The output is in terms of the ratio of peak areas of the reactants, which is obtained from a gas chromatograph. From this information, students calculate the conversion of carbon monoxide and use nonlinear regression to determine the reaction orders with respect to the reactants. This part of the module was developed using JavaScript with a web interface to Matlab for numerical computations. The student connects to the web server via a browser to view the virtual laboratory module. To run the experiment, the student input (the properties of the inlet stream to the reactor) needs to be transmitted to the numerical engine. JavaScript embedded HTML is used to create interactive pages and communication with the numerical engine is done using CGI.

The second part of the exercise to troubleshoot an existing PROX reactor designed for a fuel cell vehicle by conducting tests on its operational characteristics. The students are asked to determine the changes that need to be made in the operation of the existing reactor and optimize the reactor with respect to a given objective function. ChemCAD simulation software is used as the platform, since it had realistic reactor simulation models along with the thermodynamic data bank and property models. Students download the ChemCAD input files that are executed locally on their individual personal computers. By providing the students with a working model

of the process to begin with, we minimize the time spent on setup and debugging of the simulation. The students are able to concentrate on the concept at hand. No prior knowledge of the ChemCAD software is necessary to use this module.

We divided the virtual laboratory exercise into two workshops, one for the kinetics of the PROX reaction and one for the design application. In the first workshop, the students were introduced to the module. Students are asked to determine the rate constant at different temperatures and to estimate the prexponential factor and the activation energy of the reaction.   In the second workshop, they determined the effect of temperature on conversion and catalyst loading and did the cost analysis for the best option. There were thirty students each in these workshops. Student perceptions of the workshop experience are summarized in Table 3. Their responses are positive, indicating that the students believed that they improved their knowledge. Some students followed this two short exercises with an extended project based on the virtual laboratory in which they investigated various issues in depth.

4. CONCLUSION

Virtual laboratory exercises provide a powerful medium to reinforce concepts and to promote deep learning while motivating the students with realistic, open-ended design problems. Versatility, power and flexibility of computer simulations allow realistic simulation of systems, thus, allowing the instructor to break out of the limitations imposed by safety, resource-constraints and equipment availability.

Incorporating these exercises into the curriculum will require restructuring the course to include a virtual laboratory in addition to the more formal lectures. These virtual laboratory sessions provide an interactive component necessary to overcome students' initial inertia and trivial roadblocks not related to the actual subject matter at hand.   Group assignments promote teamwork and also

allow students to learn from each other. Design can be made an integral part of the laboratory exercise as illustrated in the virtual laboratories described herein.

The challenge often lies in the development and deployment of these laboratory exercises. In our case we have depended on graduate teaching assistants to develop these simulation exercises in close cooperation with the instructor. It took about a hundred man-hours (from a graduate student) to prepare the virtual laboratory module on the kinetics of the PROX reaction including the time spent for learning the necessary tools, JavaScript and CGI. The naphtha cracker also required similar effort to develop. Another concern is the valid shelf life of these modules. Some maintenance will be required to update these modules as new releases of the software platform become available.

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Table 2. Results obtained from the questionnaire prepared for the virtual laboratories on process control

Question	Average	Std. Dev.
Virtual laboratory exercises helped learn the concepts better	4.1	1.1
I understood the concepts better from the virtual laboratory exercises than from reading the text	3.7	1.2
Virtual laboratory exercises forced me to really grasp the material	3.4	1.3
I liked the virtual laboratory exercises because it gave immediate feedback on whether I applied the concepts correctly	4.0	1.0
I think I did better in the course because of the virtual laboratory exercises	3.4	1.1
In the future I would recommend replacing the virtual laboratories with more problem solving by students in class	2.4	1.1
My performance in the course improved because of the virtual laboratory exercises	3.3	1.1
Convention: 5. Strongly Agree 4. Agree 3. Neutral 2. Disagree 1. Strongly Disagree		

Table 3. Results obtained from the questionnaire prepared for the virtual laboratory exercise on the kinetics of PROX reactor

| Question	Average	Std. Dev.
The virtual laboratory module was suitable to my academic background	4.1	0.8
The virtual laboratory module was easy to use	4.0	1.1
The sections in the virtual laboratory module were easy to understand	3.9	0.8
By working on the virtual laboratory module, I improved my knowledge on		
Ideal Tubular Flow Reactors	3.9	0.7
Selectivity on Parallel Reactions	3.7	1.0
Gas Chromatography	3.9	0.8
Overall, I liked the virtual laboratory module	3.6	1.1
Convention: 5. Strongly Agree 4. Agree 3. Neutral 2. Disagree 1. Strongly Disagree		
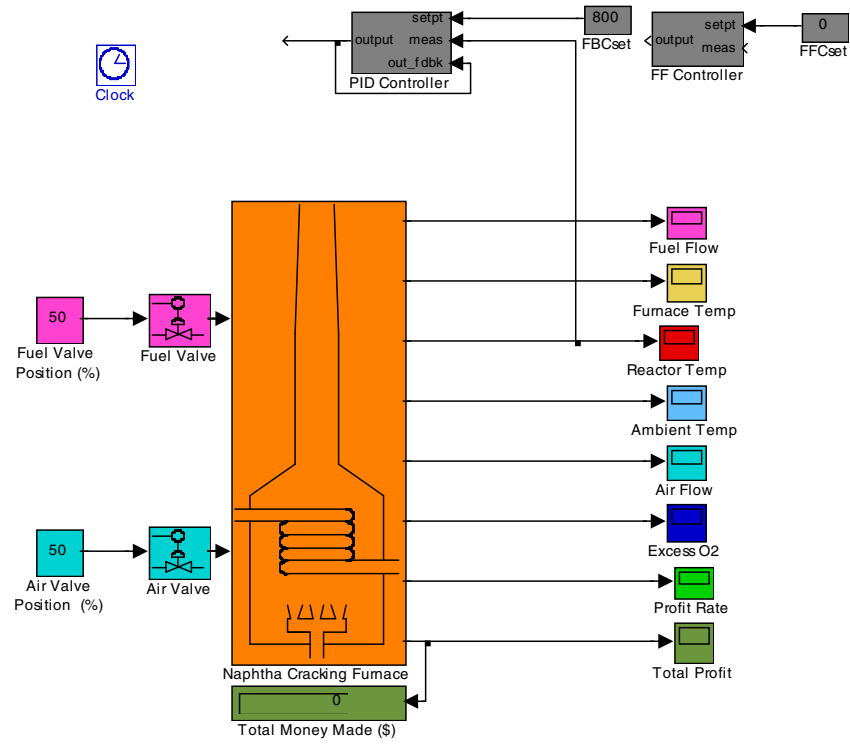
Figure 1. Virtual Laboratory for Simulating the Operation of a Naphtha Cracker in a Petroleum Refinery

(a)

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Back   Forward   Stop   Refresh   Home   Search   Favorites   Media   History   Mail   Print   Edit   Discuss   ICQ

Address   http://www.eng.usf.edu/~bunlusu/virtual/main2.html   Go   Links   Best of the Web

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VIRTUAL LABORATORY

BACKGROUND
THINGS TO DO
THEORY
EXPERIMENTAL SETUP
SAFETY
GAS CHROMATOGRAPHY
DESIGN OF EXPERIMENT
RUN EXPERIMENT
DATA ANALYSIS
DESIGN APPLICATION
REPORT
EQUIPMENT

EXPERIMENT #1

KINETICS of the SELECTIVE OXIDATION of CARBON MONOXIDE on Pt/Al_2O_3 CATALYST in a PLUG FLOW REACTOR

PROX (preferential oxidation) process has attracted significant attention with the development of the fuel cell technology. The objective of this experiment is to determine the rate expression of the PROX reaction to be carried out in a plug flow reactor as part of the ongoing research on fuel cells in your department.

Here are the learning objectives of this experiment:

- To learn the general characteristics of a Plug flow reactor and how to model the steady state behavior of it for catalytic and noncatalytic
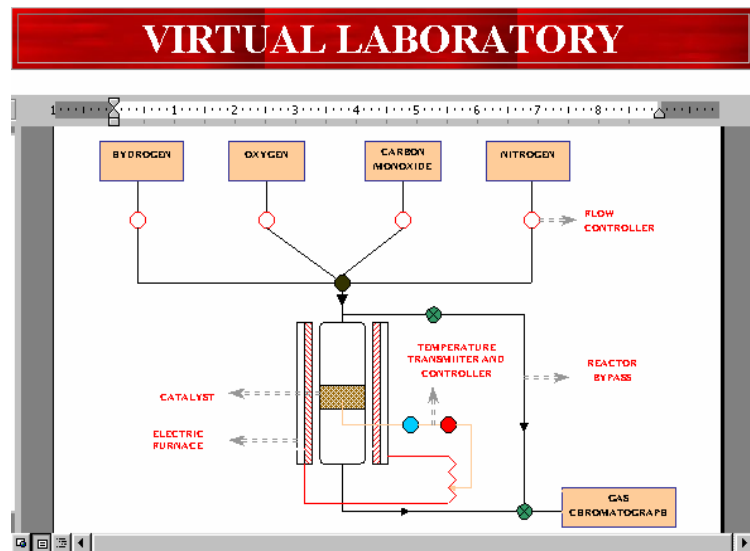
Done   Internet

Here, the student chooses the experimental cinditions

Here, the student is given pointers on data analysis

This page asks the student to apply the results of the experiment to a mini-design project

(b)

(c)

Figure 2. Virtual Lab Module prepared on the Selective Oxidation of Carbon Monoxide in a Hydrogen-Rich Stream