AC 2011-1640: UNIT OPERATIONS LAB BAZAAR

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Mike Prudich is a professor in the Department of Chemical and Biomolecular Engineering at Ohio University were he has been for 27 years. Prior to joining the faculty at Ohio University, he was a senior research engineering at Gulf Research and Development Company in Pittsburgh, PA primarily working in the area of synthetic fuels.

Daina Briedis, Michigan State University

DAINA BRIEDIS is a faculty member in the Department of Chemical Engineering and Materials Science at Michigan State University. Dr. Briedis has been involved in several areas of education research including student retention, curriculum redesign, and the use of technology in the classroom. She is a co-PI on two NSF grants in the areas of integration of computation in engineering curricula and in developing comprehensive strategies to retain early engineering students. She is active nationally and internationally in engineering accreditation and is a Fellow of ABET.

Robert Y. Ofoli, Michigan State University

ROBERT Y. OFOLI is an associate professor in the Department of Chemical Engineering and Materials Science at Michigan State University. He has had a long interest in teaching innovations, and has used a variety of active learning protocols in his courses. His research interests include biosensors for biomedical applications, optical and electrochemical characterization of active nanostructured interfaces, nanocatalytic conversion of biorenewables to commodity chemicals and fuels, and nanoscale production of hydrogen on demand.

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Robert Barat is a Professor of Chemical Engineering at NJIT, where he has been a faculty member for over 20 years. He earned his PhD in Chemical Engineering from the Massachusetts Institute of Technology in 1990. His current research involves reaction catalysis by fluorinated phthalocyanines.

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Norman W. Loney is Professor and Chair of the Otto H. York Department of Chemical, Biological and Pharmaceutical Engineering at New Jersey Institute of Technology. He has served as Associate Chair for Undergraduate Studies at New Jersey Institute of Technology (NJIT) and Associate Editor of Chemical Product and Process Modeling. He has authored or coauthored more than 60 publications and presentations relating to the use of applied mathematics in chemical engineering since joining the Chemical Engineering department in 1991. His most outstanding publication is the textbook: "Applied Mathematical Methods for Chemical Engineers" 2nd Ed. published by Taylor & Francis. His book is adopted by nine schools and is sold in 25 countries. Dr. Loney has been awarded several certificates of recognition from the National Aeronautics and Space Administration and the American Society for Engineering Education for research contributions. He was awarded the Excellence in Teaching by the Newark College of Engineering. Prior to joining NJIT, Dr. Loney, a licensed professional engineer, practiced engineering at Foster Wheeler, M.W. Kellogg Company, Oxirane Chemical Company, and Exxon Chemical Company.

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Robert J. Wilkens, University of Dayton

Bob Wilkens is Associate Professor and Director of Chemical Engineering at the University of Dayton. He received his B.Ch.E. and M.S. in chemical engineering from the University of Dayton and his Ph.D. in chemical engineering from Ohio University. Following a post-doc research engineering position at Shell Westhollow Technology Center he returned to the University of Dayton to pursue an academic career. His research interests are in fluid flow and heat transfer and he has taught the Unit Operations Laboratory for 11 years.

Danilo Pozzo, University of Washington

Prof. Pozzo's research interests are in the area of soft materials and nanotechnology. His group focuses on developing structure-function relationships for a variety of nano-structured materials having applications in materials, alternative energy and separations. Prof. Pozzo obtained his B.S. from the University of Puerto Rico at Mayagez and his PhD in Chemical Engineering from Carnegie Mellon University in Pittsburgh PA. He also worked in the NIST Center for Neutron Research and is currently an Assistant Professor of Chemical Engineering at the University of Washington where he has served since 2007.

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Prof. Pfaendtner's research group focuses on multiscale modeling of biophysical systems. His group develops and applies new computational methodologies for a wide range of problems of chemical engineering interest including biomaterials and biocatalysis. Prof. Pfaendtner earned his B.S. from the Georgia Institute of Technology and his Ph.D. from Northwestern University. After serving a two year post-doc at ETH Zurich in Switzerland, he joined the faculty of Chemical Engineering at the University of Washington in 2009.

William B. Baratuci, University of Washington

William B. Baratuci is an independent contractor working in the Chemical Engineering Department at the University of Washington. He currently focuses his energies on revamping the unit operations laboratory and on the development of new experiments. Prior to becoming a contractor, he was a Senior Lecturer at the University of Washington. Before joining the faculty at the University of Washington, he was an Associate Professor in the Chemical Engineering Department at Rose-Hulman Institute of Technology. Baratuci@gmail.com

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John Sandell is an Associate Professor of Chemical Engineering at Michigan Technological University. He received his B.S. in Chemical Engineering (1986), M.S. in Environmental Engineering (1992), and Ph.D. in Environmental Engineering (1995) from Michigan Tech. He is the recipient of the Outstanding Faculty Teacher Award in Civil and Environmental Engineering (1995), an inductee in the Academy of Teaching Excellence (2001), and Michigan Tech's Distinguished Teaching Award (2006). His research interests include particle characterization, fire protection, and engineering education.

Adrienne R. Minerick, Michigan Technological University

Adrienne Minerick is an Associate Professor of Chemical Engineering at Michigan Tech having moved from Mississippi State University in Jan 2010, where she was a tenured Associate Professor. She received her M.S. and Ph.D. from the University of Notre Dame in 2003 and B.S. from Michigan Technological University in 1998. Adrienne's research interests include electrokinetics and the development of biomedical microdevices. She earned a 2007 NSF CAREER award; her group has published in the Proceedings of the National Academy of Science, Lab on a Chip, and had an AIChE Journal cover. She is an active mentor of undergraduate researchers and served as co-PI on an NSF REU site. Research within her Medical micro-Device Engineering Research Laboratory (M.D. ERL) also inspires the development of Desktop Experiment Modules (DEMos) for use in chemical engineering classrooms or as outreach activities in area schools. Adrienne has been an active member of ASEE's WIED, ChED, and NEE leadership teams since 2003.

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Jason Keith is an Associate Professor of Chemical Engineering at Michigan Technological University. He received his B.S.ChE from the University of Akron in 1995, and his Ph.D from the University of Notre Dame in 2001. He is the 2008 recipient of the Raymond W. Fahien Award for Outstanding Teaching Effectiveness and Educational Scholarship as well as a 2010 inductee into the Michigan Technological University Academy of Teaching Excellence. His current research interests include reactor stability, alternative energy, and engineering education. He is active within ASEE.

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David W. Caspary, Michigan Technological University

David Caspary is the Manager of Laboratory Facilities and Instructor in the Chemical Engineering Department at Michigan Technological University. He received a B.S.Engineering degree from Michigan Tech in 1982 and has also worked as a Training Specialist, Project Engineer, and Project Manager. He has over 25 years experience instructing and coordinating Unit Operations and Plant Operations Laboratory, implementing distributed control and data acquisition systems, and designing pilot-scale processing equipment.

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Instructor, Department of Chemical and Biological Engineering

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Sergio Mendez is an assistant professor of chemical engineering at CSULB. He has taught a variety of courses which include thermodynamics, separation processes, transport phenomena, numerical methods and the undergraduate ChE labs. His research is also diverse: polymer physics, computational modeling, nanomaterials, microfluidics and, more recently, alternative energy.

Arne Biermans, Chemical Engineering Department, University of Washington

Unit Operations Lab Bazaar

Session Coordinator: Michael E. Prudich
Department of Chemical and Biomolecular Engineering
Ohio University

The *Unit Operations Lab Bazaar* is a special topics session that will be part of the poster session sponsored by the Chemical Engineering Division of ASEE. It is envisioned that the *Unit Operations Lab Bazaar* will be a sharing of information regarding novel chemical engineering laboratory experiments and/or experiences as well as innovations related to more traditional unit operations laboratory and chemical engineering laboratory topics. Innovations and experiences in terms of overall chemical engineering lab course design and course assessment would also be legitimate topics for a poster presentation. Ideally, all participants and attendees will be able to go home with a number of ideas that might be applied to the improvement of the unit operations and other chemical engineering laboratories at their home institutions.

Extended abstracts describing the poster submissions are included below:

Integration of Statistics into Lab Practice and Analysis
Daina Briedis, Tim Bender, and Robert Ofoli
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We have recently re-designed our unit operations laboratory course to directly support the hands-on component, experiment design, and data analysis with instruction in statistics and probability. This paper describes the process by which this course was developed and also offers evidence that the regular assessment of the student learning outcomes coupled with attention to constituency feedback can provide motivation for meaningful curricular improvement.

Background

A few years ago, our faculty received contradictory student and industry feedback on the utility of a required course in our program, a calculus-based course in probability and statistics specifically offered for engineers. Students who had taken this course found it to be irrelevant to what they were learning in the chemical engineering curriculum. Our industrial advisory board, however, was emphatic about the need for statistics in the curriculum. In addition, the assessment of the ABET outcome on experimentation and data analysis showed some evidence of sub-threshold student performance.

Further interrogation of the issues by our curriculum committee indicated that the course offered by the campus statistics department rarely included examples relevant to chemical engineering. In addition, the students took the required statistics course at various points in their curricular

progression—as it fit their schedules—and then were rarely asked to apply the concepts in chemical engineering in any meaningful way. Thus, the concept of "use it or lose it" prevailed. The faculty responded to this situation by re-designing our undergraduate unit operations course to include both statistics content and its direct application in the planning of laboratory experiments and analysis of data.

The original junior-level three-credit course was comprised of two hours of lab (two 2 ½-hour sessions per week) and one hour of lecture. The course included a good blend of traditional and modern experiments and lecture topics on lab safety, writing skills, professionalism and ethics, and a token discussion of statistics and experimental design. When a one-credit junior seminar course, "Chemical Engineering as a Profession," was introduced in our curriculum, students learned about many of the professional topics (including safety issues) in that course. This eventually opened up the lab course to include material significantly more focused on statistics and probability and how those topics related to the laboratory experiments. Since the seminar course and the unit operations course are taught in a fall-spring sequence, with proper coordination, the topics presented in the fall seminar course could also serve as preparation for the spring lab course. The most significant transfer of content from the lab to the seminar course was communication skills with particular emphasis on writing.

The New Course

The new unit operations course, first offered in the spring of 2006 as "Lab Practice and Statistics," was expanded to four credits—a two-hour lecture and a two-hour lab. The main purpose of the lecture was to introduce key statistics concepts appropriate to the laboratory experiments. Initially, the coordination between lecture material and laboratory experiments was weak due to the sequence by which student teams rotated through the experiments. Inevitably, some teams would conduct the experiments most suited for statistical applications before the appropriate material was covered in lecture. In addition, as is frequently the case in many typical unit operations laboratories, obtaining a meaningful number of data points for statistical analysis was and continues to be a problem. However, a few years of experience, input from students, and adjustment of the statistics topic sequence in the course syllabus has led to good integration of "just-in-time" statistics with the cycle of laboratory work. Students also have a theoretically supported, heightened sense of awareness of the need to use lab time wisely and gather as much good data as possible.

At its current "steady state," some level of meaningful statistical analysis, often using Minitab, is included in every lab report. The statistical application culminates in a "stats report" that is given as a team poster presentation at the end of the semester. Teams are encouraged to select their most fruitful experiment of the semester on which to conduct and report their best shot at statistical analysis.

It is clear that a two-credit course cannot offer comprehensive instruction in statistics and probability. Therefore, topics have been selected and sequenced such that students are able to apply their learning to data analysis as soon as possible. The general sequence of topics is as follows:

- Basic descriptive statistics; Introduction to Minitab
- Error analysis
- Regression
- Design of experiments
- Distributions (mainly Gaussian)
- Central limit theorem
- Statistical inference and point estimation
- Hypothesis testing
- Inference on two samples; extended to multiple samples
- ANOVA
- Linear models; Model adequacy
- Probability
- Statistical process control
- Six Sigma

Resources

At least two excellent textbooks are available for the two-credit format. These are "Principles of Statistics for Engineers and Scientists" by William Navidi, and "Engineering Statistics" by D. Montgomery, G. Runger, and N. Faris Hubele. In the former example, the text represents a shortened format of a more comprehensive text. The latter text is used by the authors for a course of a similar format to our ChE 316 lab-lecture. Extensive web-based instructor resources are available for both.

Our course is taught by two faculty members, one for the lecture and one for the laboratory. Course administration and scheduling is coordinated closely between the two. Additional staffing includes teaching assistants for the lecture and for the lab, and a grader for the lecture.

Results

Our approach of shrinking a three-credit curricular requirement in statistics to only two credits may be questioned. The fact that the course is taught by chemical engineering faculty rather than statistics faculty may also be suspect. However, we believe that the pedagogical advantages of introducing core concepts that students immediately apply in a hands-on setting provides significant enough added value to overcome these criticisms. Our assessment of the ABET outcome in the design of experiments and analysis of data has also shown improvement and stabilization over the past several years. Most encouraging, however, is the feedback we have received from our students and alumni about their experiences with statistics in the workplace. One example is cited below from a 2009 graduate:

"I just started at Kimberly-Clark in Neenah, WI . . . and statistical analysis seems to be as important as ever. More and more, I find myself thankful for having taken this class and at least knowing what people are talking about when they say, "statistically similar/different" or "setting up a DOE;" it's nice knowing that there's one less thing I need to learn on-the-fly. My position does not require me to do the calculations myself, but it is expected that I know how to interpret the data. Sometimes, it's hard as a student to realize how a subject like statistics will actually tie into your future career, but it has probably been the one course that has been applicable across all positions I've considered."

A Senior-Level Biological Engineering Laboratory at the University of Colorado
Charles R. Nuttelman
University of Colorado

Introduction

The Chemical and Biological Engineering degree in the Department of Chemical and Biological Engineering at the University of Colorado at Boulder was initiated in the fall of 2005. The required senior-level Biological Engineering Lab course was taught for the first time in the fall of 2008. As the popularity of the degree has skyrocketed over the last three years, the size of the class has gone from nine students in the first year to two sections of 20 students each in the fall of 2010. Consequently, the course has evolved to accommodate the increase in enrollment and experiments have been modified and adjusted to address technical and practical shortcomings and difficulties. Lab modules that have been used with varying degrees of success throughout the last three years include yeast and *E. coli* growth in sophisticated bioreactors, *E. coli* bacterial growth and transfection, lysozyme enzyme stability assays, protein gel electrophoresis and Western blotting, computer modeling of biological engineering processes, "virtual" on-line simulations of bioreactors, and ion-exchange chromatography. These experiments have been used to address various course-related learning goals and ABET outcomes.

Course Format and Deliverables

Biological Engineering Laboratory (CHEN 4810) is a senior-level laboratory course that is a part of the Chemical and Biological Engineering B.S. degree. The semester-long course meets once a week for 4 hours during the 15-week semester. Students are required to do either 3 or 4 experiments (this has varied during the past years) as a group; there are 3 weeks of class devoted to each experiment. Advance preparation is expected and required of students prior to performing the experiments and instructor interaction is strongly encouraged during the process. Course deliverables include an Individual Written Report (Experiment #1), an Oral Presentation (Experiment #2), and a Poster Presentation (Experiment #3). In addition, a Team Assessment is required, in which students evaluate their team members, and is an integral part of the final course grade. During the fall of 2010, the first three weeks were devoted to teaching important laboratory skills to the students. These skills include exercises and tutorials related to making solutions from stock solutions, serial dilutions, and pipetting correctly and accurately. Past experience has indicated that students struggle with these areas.

Lab Modules

E. Coli Growth and Transfection: Students have access to two types of *E. coli* bacteria – a strain with the pGLO plasmid and one without. The pGLO plasmid contains a green fluorescent protein (GFP)-producing gene under the control of an arabinose-inducible promoter. When induced with the sugar arabinose, pGLO-containing cells will produce GFP and this can easily be quantified using a fluorometer. Cells without pGLO will not fluoresce. In this experimental module, students first investigate growth parameters important to cell growth and secondly modulate arabinose concentrations and temporal profiles with the goal of maximizing GFP production. Students are responsible for designing their experiments and analyzing their data. This has perhaps been one of the most valuable experiments primarily since important controls are required and this experiment works well while allowing students to design their experiments with minimal input from the instructor.

Yeast Growth in a Bioreactor: During the first week of this experiment, students investigate the relationship between gas sparging and agitation on mass transfer rates of oxygen in a benchtop fermentor (bioreactor). On weeks two and three, students select two different growth conditions (pH and temperature can be manipulated) and investigate the growth rate of cells. This particular experiment also has a design component – students must scale up their benchtop bioreactor to a 100-L scale vessel using common scaling laws and equations. While the in-class lab is quite simple, the analysis and design component are challenging.

Lysozyme Enzyme Stability: This experiment demonstrates protein stability. Students denature the protein lysozyme using a variety of techniques (freeze-thaw cycles, urea, and guanidine) with or without cryoprotectants (trehalose, sucrose). Activity of lysozyme after these treatments is assessed using a lysozyme activity assay in which a cloudy solution of bacteria is hydrolyzed by the active lysozyme and relative enzyme stability can be assessed according to the rate of bacteria hydrolysis. Students are responsible for creating serial dilutions, diluting stock solutions, and pipetting small amounts and substantial calculations and experimental design is required. While the experiment works very well for those trained well in laboratory techniques (i.e., pipetting and diluting), students have a hard time pipetting very small solutions. This experiment has been eliminated from the current curriculum due to these problems and issues.

Protein Gel Electrophoresis and Western Blotting: During the first week of this lab module, students set up and run a standard protein gel using several known proteins. The second week is spent doing the same but finishing with a Western blot, in which the electrophoresed proteins are transferred to a membrane and stained with an antibody. Both the gel and membrane are imaged. Finally, on week 3 the students are given several unknown solutions and, using the techniques acquired during the first 2 weeks, determine which proteins are in each unknown solution. This experiment was found to be quite simple and lacked any sound engineering principles or fundamentals. In addition, protein gel electrophoresis is an art that is only learned after repeating the process many times. Students' gels did not turn out well and the utility of this experiment was small. Furthermore, the electrophoresis process is a long one with lots of down time and students were not finishing in the four-hour weekly time slot allotted to this course.

Computer Simulations/Modeling of Biological Processes: Using a relatively easy finite element analysis software package (COMSOL), students would set up a biological engineering problem and attempt to solve it using a computer simulation. There were two problems. One involved drug delivery from microparticles and the other involved microbial growth in a milk carton left out on the kitchen counter. This module had mixed reviews. While students could generate a lot of information and investigate the effect of changing a particular parameter (e.g., the diameter or diffusivity of drug microparticles) on the response (drug delivery rate), it was quite difficult to learn the software and set up the constraints and physical system in COMSOL. This experiment was eliminated during the fall of 2010 but the instructor will resurrect it for the fall of 2011 with some modifications.

Virtual Online Simulations: During the fall of 2010 the student groups participated in a virtual, online experiment module hosted by Oregon State University (School of Chemical, Biological and Environmental Engineering). The simulation is very "real world" in that students start with little information about their yeast strain and must maximize productivity in a bioreactor by changing parameters such as temperature, batch time, fed batch time, fed batch flow rate, etc. Moreover, students are provided a fixed budget and each of the yeast optical density measurements, product concentration, and other measurements cost money. Consequently, there is much thought that must be put into how the budget should be utilized and what steps the students should take to improve productivity. This experiment has been very successful.

Ion Exchange Chromatography: The final experiment involves ion exchange chromatography. Students use bovine serum albumin (BSA) in an anion exchange column. While ranges of pertinent parameters (flow rate, loading concentration, buffer pH, NaCl concentration, others) are provided to the students, the groups must design experiments themselves since they don't have time to do everything. This experiment is a worthwhile experiment despite some of the frustrations that are encountered. Students seem to learn a lot about chromatography since nothing is automated except for the simple pump that is used to perfuse the column.

Conclusions

The Biological Engineering Lab has been designed with primarily three considerations in mind. The first goal is to teach the students the necessary skills to carry out biological experiments. This includes things like serial dilutions, creating solutions from stock solutions, and pipetting correctly, skills that have not been developed elsewhere in the curriculum. The second goal of the course is to have several lab experiments that provide good data (i.e., are "easy" experiments) yet have a more complex design or statistical analysis component. The third goal of the course is to have at least one experiment that requires quite a bit of thought and troubleshooting as well as some frustration, aspects that will be encountered in their future. The experiments designed in this course touch on these aspects and have been designed to give the students experience in a variety of areas that will be representative of their eventual working environment.

New Experiments on a Limited Budget for ChE Unit Operations Laboratory

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New Jersey Institute of Technology

Current budgetary constraints facing all universities, especially state-supported institutions, particularly impact teaching laboratories, both from capital and operating perspectives. Accommodating larger class sizes with limited funding has dictated an increasing dependence on available laboratory components assembled in new ways. Converting obsolete equipment into new experiments requires imagination, though can often be done at a modest cost. During the last two years, we have introduced four new experiments into the second course of our two-course capstone Chemical Engineering Laboratory. The first course emphasizes heat and momentum transfer, while the second course considers separations, reactor engineering, and process control.

Three of the new experiments emphasize chemical reaction, while one is based in process dynamics and control. While many of our ChE experiments are at the preferred pilot scale, chemical reactions on this scale often require large amounts of expensive reagents. In addition, there can be costly waste disposal issues. Therefore, in order to utilize existing equipment as well as keep operating costs low, the new experiments can all be classified as bench scale. The reaction experiments use inexpensive reagents available in commercial or consumer form. All four experiments have active data collection via PC.

Semi-Batch Reactor

The first new experiment uses a semi-batch reactor. The reaction is $H_2O_{2(aq)} + NaOCl_{(aq)} \rightarrow H_2O_{(l)} + NaCl_{(aq)} + O_{2(g)}$. The reagents used are consumer hydrogen peroxide (3 wt.%) and laundry bleach (e.g. Clorox$^{®}$ 6 wt.% NaOCl). The reaction is rapid, exothermic, and evolves oxygen gas. Besides the usual safety measures (e.g. goggles), chemically resistant gloves (e.g. nitrile) are worn in handling both the peroxide and bleach solutions.

We are unaware of any convenient and inexpensive means for in-situ monitoring of H_2O_2 or NaOCl. However, evolved O_2 is easily monitored with a calibrated rotameter. Product NaCl can be monitored with a chloride ion specific electrode. However, these probes – similar to pH probes – are not as robust as simple, stainless steel conductivity probes. The system is pictured in Figure 1. A surplus bench fermentation vessel is used, though any agitated vessel that can accommodate ports, probes, and can be sealed will suffice. The peroxide, cold from a refrigerator, is charged to the vessel. Bleach is pumped in at a fixed rate. Any small pump will do, though it should be corrosion-resistant. Solution conductivity, temperature, and evolved oxygen rate are all monitored as functions of time for a fixed bleach feed rate. The conductivity and temperature probes were purchased from Vernier$^{®}$, and feature a very convenient USB-based interface and accompanying data collection program. The probes are stainless steel, and have proven to be rugged. With the vessel sealed, O_2 evolving as the bleach is pumped in flows through a calibrated rotameter. Inexpensive air and water rotameters are available from Dwyer$^{®}$.

Due to an approximately 10% higher specific gravity of bleach as compared to water, a calibrated-for-water rotameter should be recalibrated for bleach.
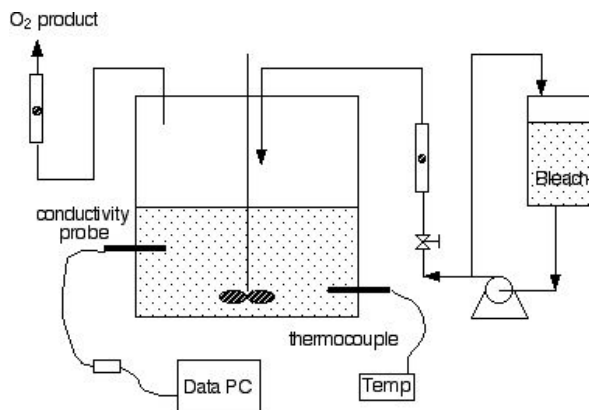

Figure 1: Schematic of the semi-batch reactor experiment

This experiment is not difficult to execute, but the modeling is challenging. A transient model of species and energy balances, and conductivity, simulates the runs. The model is run on a math solver (e.g. Polymath®). All measured quantities are directly compared to the predictions (conductivity, temperature, O_2 rate). Sample data and predictions of O_2 rate and temperature are shown in Figure 2. Better fits to the temperature data are obtained if heat losses are accounted for in the energy balance model. This is accomplished by inserting any simple electrical resistance heater of known output into a known volume of water in the vessel, and then comparing the actual and ideal temperature profiles. A paper (Derevjanik, Badri, and Barat) detailing this experiment was accepted in October 2010 for publication in *Chemical Engineering Education*.
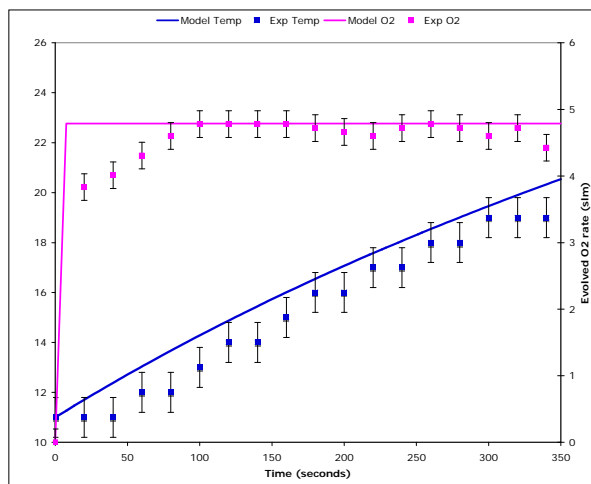

Figure 2: Observed and predicted temperature and O_2 rates in the semi-batch reactor.

CSTR with Optical Diagnostic

The second experiment features a CSTR processing the oxidation of an organic dye; specifically, a 0.33 grams/liter solution of erioglaucine (blue food color) in water is reacted with household bleach (6 wt. % NaOCl active ingredient). The powdered dye is available from Sigma-Aldrich[®]. The blue dye has a broad-banded absorption spectrum peaking in the red. Any collimated red light will be absorbed (e.g. helium-neon laser, laser pointer). The transmission of a laser beam through the dye solution is governed by the Beer-Lambert law. The absorbance is directly proportional to the dye concentration, and serves as the basis for experimental determination of reaction conversion. Absorbance measurements are made using an optical flow cell located after the reactor. The flow cell can accept either the reactor effluent directly or an inlet bypass stream. A schematic of the experiment is shown in Figure 3. The temperature of the reactor is measured with a thermocouple.
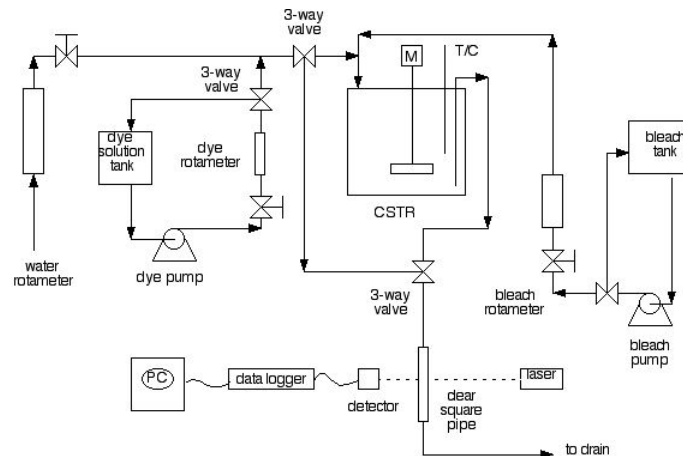
Figure 3: Schematic of CSTR with Optical Diagnostic experiment

The reactor is a surplus agitated bench fermentation vessel. The feed can be introduced either above the liquid level in the vessel, or below the surface near the bottom. The effluent can be withdrawn from either the top or bottom. A typical experiment involves observation of dye conversion as a function of space-time, feed/effluent configuration, or even agitation rate. Students compare their experimental conversions to those predicted by a CSTR model using independently determined kinetics.

Protein Oxidation

While the first two reaction experiments are fairly well defined, the third is quite exploratory. A solution of powdered egg whites (10 wt.% in water) – consisting almost entirely of proteins, and available from a food ingredients supplier (e.g. Honeyville[®]) – is fed with household bleach at known rates through a long glass tube equipped with thermocouples at each end. A schematic is shown in Figure 4. The setup is currently being fitted for rugged pH probes at either end.
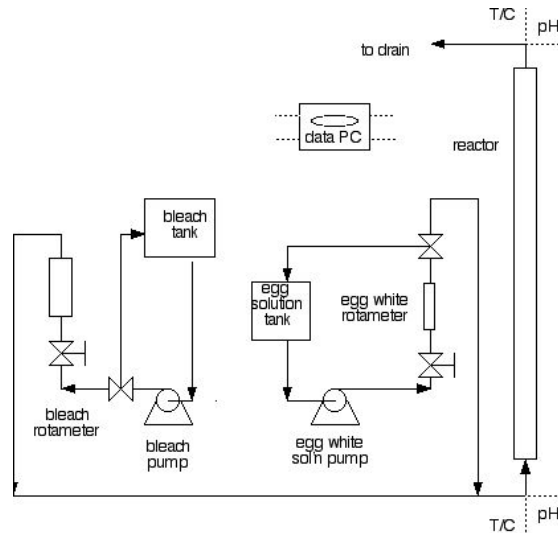
Figure 4: Schematic of protein oxidation experiment

The oxidation is exothermic, but little other information is available. The students are challenged to make engineering assumptions about the reactor and the reaction. Simultaneous species and energy balances are solved with parameter values "optimized" to yield the observed temperatures.

Temperature Control

The final new experiment is a simulated CSTR with feedback temperature control, as shown in Figure 5. A surplus agitated fermentation vessel contains an immersed coil for flowing coolant water controlled by a surplus proportional solenoid valve. An electrical immersion heater provides simulated reaction exothermicity. After open-loop dynamic characterization of the key components of the system, feedback control experiments are performed with a relatively inexpensive digital temperature controller. Proportional and proportional-integral control are tested with servo and regulator problems, respectively.
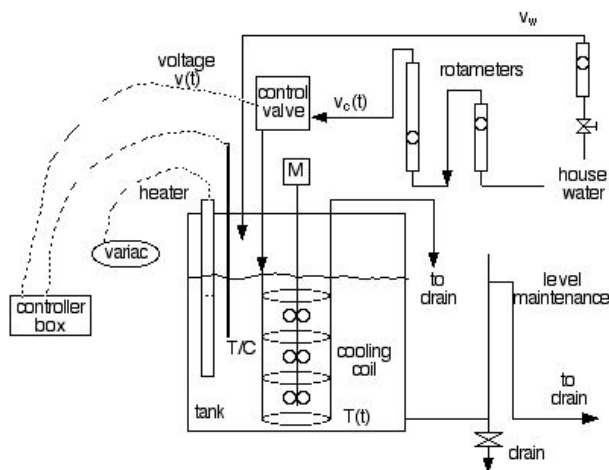

Figure 5: Schematic of temperature control experiment

Experiences at the Unit Operations Laboratory at Texas A&M University-Kingsville
Horacio A. Duarte and Ali A. Pilehvari
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Texas A&M University-Kingsville

This poster discusses the advantages and disadvantages of manual operation versus fully automated operation of the Unit Operations laboratory experiments. Ten out of the twelve experiments in our laboratory involve typical chemical engineering units such as distillation and liquid-liquid extraction columns that are pilot plant size. The construction material of most of these pieces of equipment is glass so the students can see the inner workings of the experiment. While there are some digital transducers in these units, most of the measurements are done manually. Most flow rates are measured with rotameters. Pressure drops are measured with glass manometers. Compositions are measured indirectly by measuring other properties such as density or electrical conductivity.

It has been recommended that these laboratory experiments should be modified to allow computer data acquisition of all pertinent parameters. This will involve replacing all the old measuring devices with digital ones that can be connected to a computer. While there are advantages to this approach, we believe that some learning experiences may be lost if all the experiments are fully automated. The advantages and disadvantages of these two modes of operation are discussed in this poster using specific examples related to our Unit Operations Laboratory experiments.

Three laboratory experiments are discussed. The first experiment involves complete manual operation and data acquisition. The second experiment involves automatic operation and manual data acquisition. The third experiment involves automated operation and data acquisition.

The first experiment is a liquid-liquid extraction experiment. Acetic acid is extracted from a dilute solution of acetic acid and kerosene using water as a solvent. The experiment is conducted at ambient temperature and pressure. The extraction column is a glass column (York Rotating Disk Contactor), four inches in diameter and six feet tall. The students have to bring the column to steady state by manually adjusting the flow rates of water and acetic acid-kerosene solution to keep the liquid-liquid interface at the midpoint of the column. The students can usually bring the extractor to steady state in less than 90 minutes. Flow rates are measured with rotameters and compositions are measured by drawing samples and measuring thermal conductivity. The students can run experiments at different rotating disk speeds to determine the effect of rotating disk speed on the HETP (Height of Equivalent Theoretical Plate). This experiment is extremely labor intensive but the students seem to enjoy it.

The second experiment involves a continuous distillation column. The stream to be separated is a binary mixture of water and isopropanol. This is a column made out of glass (bubble-cap trays). It has a diameter of 12 inches, a height of about 20 feet (eight actual trays), a reboiler heated by steam and a condenser cooled by water. The column operation is controlled by controlling the liquid level in the reboiler pot and the condenser vessel. These liquid levels are controlled using PI controllers. The final control elements are two control valves, one

controls the distillate flow rate and the other controls the bottoms flow rate. The rest of the column operation, such as changing the reflux ratio, is manual and so is all of the data acquisition. The temperature measurement devices have digital readouts but are not connected to a computer. The compositions are measured by sampling. Compositions are determined indirectly by measuring liquid densities of the binary mixtures at 25˚C. The flow rates of the feed stream and the reflux stream are measured with rotameters. Flow rates of the distillate and the bottoms are measured with a graduated cylinder and a timer. The flow rate of the cooling water (condenser) is measured with a bucket and a timer. The steam flow rate (reboiler) is measured by measuring the flow rate of the condensate (bucket and timer method). The steam pressure is measured with a Bourdon pressure gauge. The main objective of this experiment is to determine the overall efficiency of the column. Even though there is some computer control for the operation of the column, students do not really learn about process control in this experiment. The liquid level controller's main purpose is to facilitate getting the distillation column to steady state. Students learn about process control in a separate laboratory that is an integral part of the process control course. One advantage of this experiment is that students get a more hands on experience on how process variables can be measured in different ways. A disadvantage of this experiment is that the students get less exposure to computer data acquisition tools and techniques.

The third experiment involves a miniature power plant (Rankine cycle experiment). This is a recently acquired piece of equipment. This apparatus is almost completely automated. A distinct characteristic of this piece of equipment, as compared with the previous two, is its size. It is fairly small. Also, its fabrication material is steel, so students cannot see the inner workings of its different components. The data acquisition on this piece of equipment is completely automated. All temperatures and pressures, as well as the current and voltage generated by the miniature plant, are automatically recorded and stored in a computer file. The fuel flow rate is controlled and automatically recorded in the data file. The only variable that needs to be recorded manually is the steam flow rate. The equipment is very well instrumented. It measures the turbine's inlet and outlet temperature and pressure, the boiler's temperature and pressure, the current and voltage generated by the electric generator coupled to the turbine, as well as the speed of rotation of the turbine and the fuel flow rate. With this information, the students determine the efficiency of the turbine, the boiler, the electric generator and the entire cycle. One could argue that this experiment exposes our students to modern data acquisition techniques. Unfortunately, this is not correct. The students are only exposed to a black box that does all the data acquisition for them, but they do not know the inner workings of this black box.

In conclusion, we think it is desirable to have some process automation in our unit operations laboratory experiments. However, we think that manual operation of some of these experiments should be kept because it serves as a useful teaching tool.

Simulating heat exchanger fouling for unit operations laboratory experiments

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One challenge when instructing a unit operations laboratory is developing a variety of experiments for a limited number of apparatuses. While it is possible for each laboratory group to perform the same experiment on a given apparatus, there is a potential for groups to collaborate across experiments thus reducing the level of knowledge gained. A good experimental design will have the students calculate a set of operational parameters from experimental measurements as well as developing some type of mathematical model for the apparatus. Each different experiment performed on an apparatus should retain the basic set of calculations and modeling to ensure sufficient complexity for data analysis. For instance, several experiments can be performed on a continuous distillation column including a feed tray location study, a tray efficiency study, and a reflux ratio study. Each of these experiments require the students to operate the column but the variables altered for each run will differ based on the experimental specifications. For each experiment, the students will use material and energy balances as well as vapor-liquid equilibrium relations to evaluate column performance, and will compare this data to a model such as McCabe-Thiele. Therefore, there is a variety of experiments that students can perform and still retain the conceptual complexity that underlies the apparatus operation while lessening the potential for collaboration amongst groups working on the column during the semester.

The shell and tube heat exchanger is a common unit operations laboratory experiment. It introduces the students to industrial heat transfer equipment operation as well as providing them a means to apply heat transfer theory to a real apparatus. A downside of the heat exchanger is the limited number of experiments that can be performed. Typical experiments involve calculating an experimental overall heat transfer coefficient and comparing it to a correlated value. Comparative studies of the overall heat transfer coefficient for countercurrent versus concurrent operation can also be performed if the apparatus is appropriately piped. Comparing the effectiveness of different fluids is another possibility but water is usually used as both the hot and cold fluid due to cost and safety considerations. Another potential experiment is to evaluate fouling in the heat exchanger. This experiment can be difficult because the level of fouling in laboratory heat exchangers is very low due to the fluids used and the short time period the heat exchangers are in use. However, a heat exchanger can be configured to simulate fouling.

Heat exchanger fouling is defined as the scales or deposits that build up on the shell and tube and is caused by the fluids flowing through the exchanger. Fouling increases the resistance to heat transfer within the exchanger, which causes the performance to decrease[1,2]. Fouling is measured as a part of the overall heat transfer coefficient (U). The overall heat transfer coefficient (U) is the sum the resistances to heat transfer and provides a measure of heat exchanger performance.

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{D_i ln(D_o/D_i)}{2k} + \frac{A_i}{h_o A_o} + R_F = R_s + R_w + R_t + R_F$$

In the above equation, R_s is the shell side fluid resistance, R_w is the tube wall resistance, R_t is the tube side fluid resistance, and R_F is the fouling[1,2]. For a clean exchanger, there is no fouling resistance and $R_F = 0$. Heat exchanger fouling can then be calculated by comparing the heat transfer coefficients calculated when the exchanger is clean to that of when it is fouled.

The University of Dayton has designed and assembled a 1-2 pass shell and tube heat exchanger for the unit operations laboratory which is piped in a manner that does not allow for different flow configurations. This exchanger consists of 32 copper tubes inside a glass shell. Water is heated in a hot water tank and pumped through the tubes while cold city water flows through the shell. Both flow rates are measured and adjusted with rotameters and the inlet and outlet temperatures of both the shell and tube flows are measured with thermocouples. Tube side flow can be reliably operated at a range of zero to three gallons per minute and shell side flow at a range of zero to nine gallons per minute. Due to safety concerns, the hot water tank temperature is limited to a maximum of 55°C. Cooling water inlet temperatures are a function of the seasonal temperature.

During the course of the semester, the heat exchanger is modified to simulate fouling. The students operating the heat exchanger for the first experimental session are tasked with finding the overall heat transfer coefficient both experimentally and by correlation at a range of different shell and tube flows. Once the report is complete, the data for experimental heat transfer coefficient is saved for the next session as "clean" data. For the next experiment, six tubes in the heat exchanger are plugged to simulate fouling but students are not told of the modification. Students operating the heat exchanger for this experimental session are tasked with calculating the resistance due to fouling. They are provided with the experimental data from the previous session and told that this data was obtained when the heat exchanger was clean. The students operate the heat exchanger at the same flow rates and as close to the same inlet temperatures as possible as the clean data and record the flows and temperatures. With this data, the students calculate the heat flow from the tube flow to the shell flow for both the clean and fouled data with

$$Q = \dot{m}C_p(T_{inlet} - T_{outlet})$$

Heat flow is calculated for both the tube and shell, and due to the conservation of energy, these values should be similar. Students can use this energy balance closure as a means to reject data. The heat flow is used to calculate the overall heat transfer coefficients as shown below[3].

$$U_i = \frac{Q}{F_g A_i \Delta T_{LM}}$$

The fouling resistance is then calculated by the following equation[3,4].

$$R_F = \left(\frac{1}{U_i}\right)_{fouled} - \left(\frac{1}{U_i}\right)_{clean}$$

Another metric to evaluate performance is heat exchanger effectiveness. The effectiveness is the ratio of the heat flow from the hot to the cold fluid to the maximum heat flow possible for the given inlet conditions. Effectiveness relations are shown below[4].

$$\varepsilon \equiv \frac{Q}{Q_{max}}$$

where

$$Q_{max} = C_{min}(T_{h,i} - T_{c,i})$$

For this experiment, the decrease is effectiveness is due to the simulated fouling and is measured as the difference between the clean and fouled effectiveness values. Once the calculations are complete, students compare their calculated values with literature.

With six of 32 tubes plugged, or three tubes of sixteen when factoring in two tube passes, the fouling factors ranged from 0.00018 to 0.00059 $m^2 \cdot K/W$ which corresponds to a decrease in U from 10% to 40%. These values compare well with literature for water which lists fouling factors as 0.0002 $m^2 \cdot K/W$ [4,5], 0.0004 $m^2 \cdot K/W$ [6]. Similarly, the heat exchanger effectiveness decreased in the range of 1% to 4% as the tube and shell flow rates increased.

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Integration of the Chemical Engineering Laboratory with a Focus on Bio-Fuel Production

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The production of renewable energy is one of the most important technological problems that we face today. This challenge also offers us an opportunity to motivate and shape the early careers of chemical engineering undergraduate students. With this goal in mind, we have designed an innovative pedagogical model for the Chemical Engineering Laboratory that is based on the central theme of producing fuels from biomass. The most innovative component of the new laboratory is the complete integration of new and existing experimental stations. The second part of the unit operations laboratory course at the University of Washington was integrated to model a bio-fuel production plant where student groups work on individual operations that make up a complete process. This full-plant view of the laboratory allows students, for the first time, to evaluate the effects of their decision on upstream and downstream plant operations. Furthermore, it also provides a common framework to promote active discussion and engagement amongst student groups. The transformation of the course included the development of completely new modules for fermentation of biomass and the modification of existing equipment and modules for the treatment, separation and extraction of product and waste streams. The new fermentation modules utilize internet-based remote monitoring technologies to track the development of fermentations while students are outside of the laboratory. Fully interconnected units now define a common goal of reducing costs and improving productivity and replace the original independent design concepts, such as cost analysis and environmental compliance, into the laboratory. The objective of the re-designed course is to provide a realistic structure that is congruent with what students will experience after graduation. The new laboratory structure is also designed to foster leadership, creative thinking, composure under uncertainty and the critical review of information. Furthermore, with the new structure, we also continue to meet the original learning objectives of instructing students on the basics of experimental planning and reporting.

Jimmy Crack Corn and I DO Care: Fluidized-Bed Drying of Cracked Corn

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Fluidized-bed fundamentals and technologies are often only briefly covered in undergraduate chemical engineering curricula, if at all. However, fluidized-bed reactors, fluidized-bed coating systems, and fluidized-bed driers play important parts in the chemical process industry. This abstract describes a laboratory experiment used in the senior unit operations laboratory at Ohio University. Students who complete this laboratory assignment are introduced to the basic concepts of fluidized-bed behavior.

The unit operations laboratory course at Ohio University consists of a two quarter sequence in which teams of students perform eight laboratory experiments, four each quarter. The course is team taught, with each experiment being motivated by a design problem. The course is writing intensive with each student team producing two reports for each experiment - a prelab planning report and a postlab analysis report. Each report is evaluated on a number of criteria. Failure to satisfactorily pass on even one of the criteria results in the requirement of a rewrite of the report. The unit operations laboratory is also used as a point for end-of-program assessment of the ability of students to apply statistical methods. The details of the operation of this course are reported elsewhere [1-3].

This extended abstract deals with a specific laboratory experiment that focuses on determining the fluidization characteristics and drying behavior of a bed of cracked corn. The equipment used is a batch fluidized bed which consists of a 4-inch ID section of plexiglas tubing. Air is supplied to the bed as the fluidizing gas. The volumetric flow rate of the air is controlled with a hand valve and measured using a rotometer. There is an electronic heater in the inlet air line which allows the students to control the temperature of the air entering the fluidized bed. The bed is instrumented with temperature, relative humidity and differential pressure sensors. Temperature and relative humidity can be measured both at the bed inlet and outlet. Differential pressures can be measured both across the bed and across the distributor plate. Cracked corn is the solid to be fluidized, and is purchased directly from a local feed store. Students separate the corn, using standard screens, into "large" and "small" fractions (typically with nominal diameters in the order of 0.1 to 0.2 inches). The screening of the corn is always an adventure since the students are not familiar with the concept of screen sizes and/or screening techniques and have to be instructed as to how they can be effectively used.

For each experiment, the lab meets for two sessions of five hours each. Some independent prelab work is required (determination of corn particle density and fixed-bed voidage) prior to the first lab meeting as the students learn that the physical characteristics of cracked corn and fixed beds of cracked corn are not easily found using Google. During the first lab session, the students characterize the fluidization behavior of their two size fractions of cracked corn (minimum fluidization velocity, pressure drop versus superficial air velocity for both fixed and fluidized beds, and bed expansion versus superficial air velocity). Their assignment is to take this experimental data and compare it (using statistical techniques) to data predicted using appropriate correlations found in the literature. Figure 1 illustrates typical data collected by the

students for the first day's experimentation. During the second lab session, the students dry their cracked corn. So that a significant amount of drying can occur, water is pre-added to the cracked corn in a ratio of 4 masses of water to 10 masses of 'as delivered' cracked corn. Since the fluidized bed operates in a batch mode, unsteady state behavior is observed. Upon adding the dampened corn to the fluidized bed, the exit gas temperature quickly decreases to a minimum and then slowly increases to a constant value, while the exit gas relative humidity quickly increases and then slowly decreases

Figure 1. Fluidization characteristics for the 'small'corn sample. u_{mf} = minimum fluidization velocity. [4]

to a constant value. The drying is said to be over when the absolute humidity of the exit gas stream is equal (within some predetermined specification) to the absolute humidity of the inlet gas stream. The unsteady-state behavior of the batch fluidized-bed drying system is often initially confusing to the students as most of their previous experiences, both in laboratories and in class problems, have been with steady-state systems. Figure 2 illustrates typical data collected by the student for the second day's experimentation.
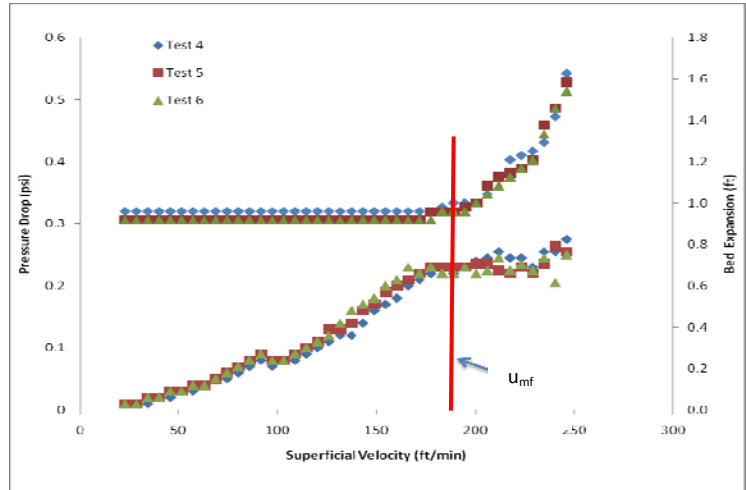
Statistical skills are reinforced as students are required to define the reproducibility of their data and to make statistically-justified judgments as to whether or not the data that they generate is effectively described by models found in the literature. The drying portion of the experiment requires the application of an unsteady-state mass balance to determine the percentage of the water removed from the dry corn product.
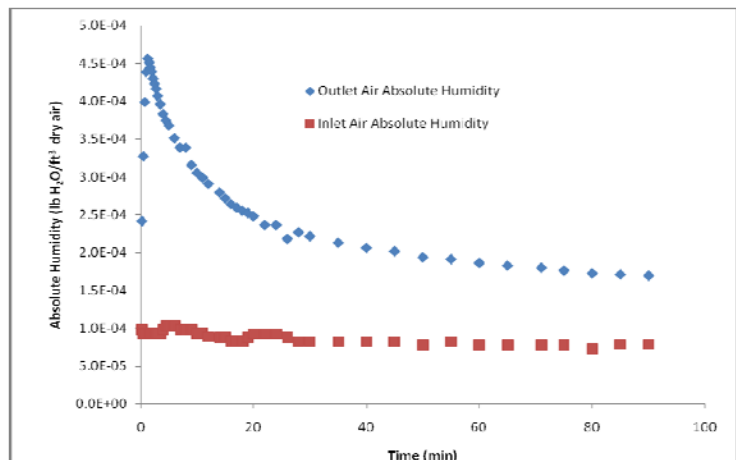

Figure 2. Drying characteristics for the 'small' corn sample. [4]

This experiment introduces a number of new concepts to our senior students as well as reinforcing several concepts already learned in our chemical engineering undergraduate curriculum.

New concepts introduced with the experiment include:

(1)   Pressure drop for fluid flow through a fixed bed (superficial velocities below the minimum fluidization velocity - Ergun's equation).

(2)   Minimum fluidization velocity (superficial velocity at the minimum fluidization velocity - the minimum fluidization velocity being predicted by a force balance).

(3)   Fluidized bed expansion as a function of superficial velocity (superficial velocities above the minimum fluidization velocity - the bed expansion behavior being described by one of a number of relationships, for example, the Richardson-Zaki equation).

(4)   Bed voidage (how it is measured for both fixed and fluidized beds).

(5)   Sphericity (how to determine the "diameter" of particles that are not spheres) .

Familiar concepts reinforced include:

(1)   Drag coefficients and force balances (related to both the minimum fluidization velocity and fluidized-bed expansion behavior).

(2)   Relative and absolute humidity (needed to complete an unsteady-state water balance on the batch system).

(3)   Unsteady-state mass balance (calculation of the drying rate and percentage water removal based on the knowledge of gas flow rate, relative humidity, and temperature).

As stated earlier, our students encounter many conceptual challenges while completing work on this experiment. Among the most common challenges are:

(1)   Accounting for and dealing with unsteady-state behavior.

(2)   Performing calculations with relative and absolute humidities and distinguishing between the two.

(3)   Dealing with uncertainties in the particle diameter and accepting that, while sphericity has a specific theoretical definition, it can be successfully used as a fitting factor for the cracked corn. [Cracked corn is neither spherical nor monodisperse.]

(4)   Understanding the relationship between fluidized-bed expansion and terminal velocity.

Additional details regarding the apparatus, experimental procedures, desired learning outcomes, and the mini-design project associated with this experiment will be described as part of the poster presentation.

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The Use of COMSOL Multiphysics Simulations to Enhance the Learning of Basic Concepts of Heat and Momentum Transfer

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Abstract

In the chemical engineering curriculum, students are taught about the fundamentals of heat and momentum transfer. The teaching process involves classroom lectures and often corresponding undergraduate laboratory experiments. Another tool that can be used to reinforce the concepts introduced in the classroom and practiced in the lab is computer simulation. The benefits of using COMSOL are many: 1) it is designed to model heat, momentum, mass, etc. transfer; 2) ease of learning the software; 3) the ability to have either simple or complicated models; 4) quick simulation time; 5) and relative low cost. We have developed two systems that incorporate COMSOL simulations. For the heat transfer lab, students perform a simple transient heat conduction experiment. First the density and thermal conductivity, k, are determined. Then a material in the shape of slab that is originally at room temperature is put in contact with a hot surface. The rise in temperature of the material is measured. To estimate the heat capacity, a COMSOL model is implemented with density, k, and C_p as the input parameters. The students can make a direct comparison between their experimental findings and the COMSOL simulation. In another application, the students can use the Navier-Stokes equations to derive the parabolic velocity profile of liquid flowing through a narrow slit. The students can compare the derived analytical expression and a COMSOL simulation. We hope that introducing students to COMSOL will intrigue them to explore the power of the software, especially the built-in "Chemical Engineering" module.
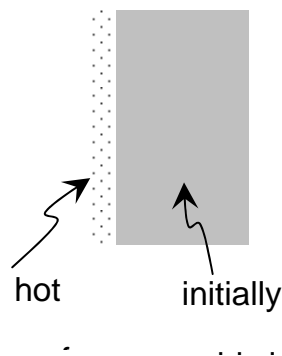
I. Introduction

Figure 1. 1-D heat transport.

The three modes of heat transfer are conduction, convection and radiation. In this lab, students can learn how to estimate the thermal properties of a material by performing heat conduction experiments. The two properties of interest are the thermal conductivity and the heat capacity.

To illustrate the concept of heat capacity, suppose that a cold slab of a material is suddenly put in contact with a hot medium. In Figure 1 is shown a cold slab of material exposed to a hot surface. From the second law of thermodynamics we know that heat flows in the direction of high to low temperature. Thus the left side of the slab will always be hotter than the right. A plot of the temperature at the right edge versus time would show an initial gradual rise, then a rapid increase, and finally a plateau, or an "S" shaped T-vs-t curve. Intuitively, we know that the temperature rise of the slab should be proportional to the amount of heat transferred to it. Actually, the constant of proportionality is the heat capacity, C_p, which is a thermal property of the slab material.

Once the slab temperature is equilibrated, a plot of the temperature as function of distance away from the hot surface might be a straight line with a negative slope. The magnitude of this slope will be determined by another property of the material, the thermal conductivity, k. For a given heat flux, a material with a high k will exhibit a smaller magnitude slope than a material with a low k.

For the case of 1-dimensional, transient heat conduction through a slab, the governing partial differential equation (PDE) is

$$\frac{\partial T}{\partial t} = \frac{k}{\rho\, C_p} \frac{\partial^2 T}{\partial x^2} \qquad \text{or} \qquad \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad\qquad \text{Equation 1}$$

where ρ is the density and α is the thermal diffusivity of the material. The solution to this PDE depends on the boundary conditions, and to solve it analytically one must use advanced math techniques.(Bird 1960)

For the case of 1-dimensional, steady-state heat conduction through a slab, the governing differential equation is

$$\frac{q}{A} = -k \frac{dT}{dx} \qquad\qquad \text{Equation 2}$$

where q/A is the heat flux. If the heat flux, slab thickness and temperature gradient can be measured, Equation 2 can be used to calculate the thermal conductivity.

II. Experimental Method

Prior to beginning the heat conduction data collection, a slab of red oak wood was weighed and its volume was measured to determine the density. Briefly, the thermal conductivity was determined by a simple method that had a stack composed of an upper steam block, an upper slab of wood, a water-cooled block at the center, a lower slab of wood, and a lower steam block. Since the focus of this paper is in the COMSOL modeling to find the heat capacity, the details of the procedure to measure k are not included.
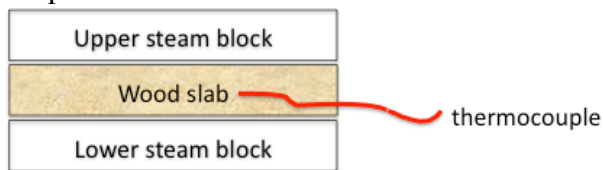

Figure 2. Experimental set-up.

The experimental set-up is shown in Figure 2. The wood block was sandwiched between two steam blocks with a constant temperature of 400 K. At the beginning of the transient heat conduction data collection, the three components were clamped tightly to ensure adequate thermal contact. The temperature at the center of the slab was collected with a digital thermocouple for a period of ten minutes.

III. Computational Method

In this lab, students performed heat conduction experiments to determine the thermal properties of a slab of material. The easiest way to model the unsteady state portion of the experiment with COMSOL is to treat the system as an infinite one-dimensional slab as shown below.
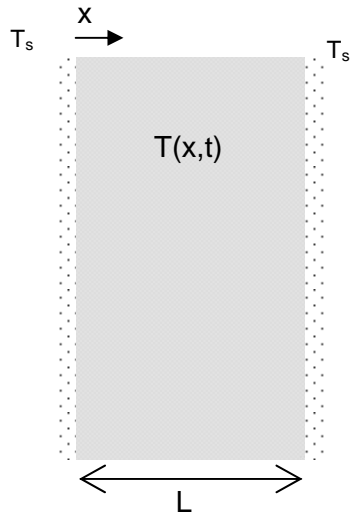
Initial condition: at t=0, T(x,0)=300 K

Boundary conditions: at x=0, T(0,t)=T_s=400K
                              at x=L, T(L,t)=T_s=400K
   where L = 0.02 m

To make the transient analysis even simpler, we can take advantage of the symmetry and model the heat transport for only half of the slab. Now the 2nd boundary condition becomes: at x=L/2, heat flux = 0. With these initial and two boundary conditions, COMSOL can solve the transient heat transfer behavior. The simulation can provide curves of the temperature-versus-position (along the x-direction) at a given time, and temperature-versus-time at a given position.

IV. Results

All of the experimental data was collected at the University of New Mexico chemical engineering undergraduate unit operations laboratory.(Johns 2008) The material used was a slab of red oak. The density was measured to be 707 kg/m^3 and the thermal conductivity was 0.189 W/(m K). According to the literature, the value *k* for a given type of wood will depend on the moisture content.(Anton 1999) According to the Wood Handbook, for lumber with 12% moisture content, *k* is in the range of 0.1 to 1.4 W/(m K).(Anton 1999) Because we had no way to determine the moisture content of our oak wood slab, in the future we will perform similar experiments with material with well known thermal properties such as a slab of pure aluminum.

A one-dimensional model was constructed with the COMSOL software. With the initial and boundary conditions noted above, temperature-vs-position (T-vs-x) profiles were generated at various times. In Figure 3, are the COMSOL results. The x=0 m position represents the location where the slab of wood is in contact with the hot steam block, and the x=0.01 m is the center of the wood slab. At t=0 s, there is an obvious discrepancy with the computer results since the temperature away from x=0 is non-zero and because the temperature of the slab drops below the initial temperature of 300 K. At longer times, all of the curves exhibit zero slope at x=0.01 m as expected because the heat flux must be zero at the center of the wood block. The curves indicate that after a long time (600 s), the temperature of the wood approaches that of the steam block. Unfortunately, we could not obtain such curves with our experimental set-up so a comparison could not be made. However, since the thermocouple was placed at the center of the wood block, we could compare the time-dependent temperature at this position (x=0.01 m).
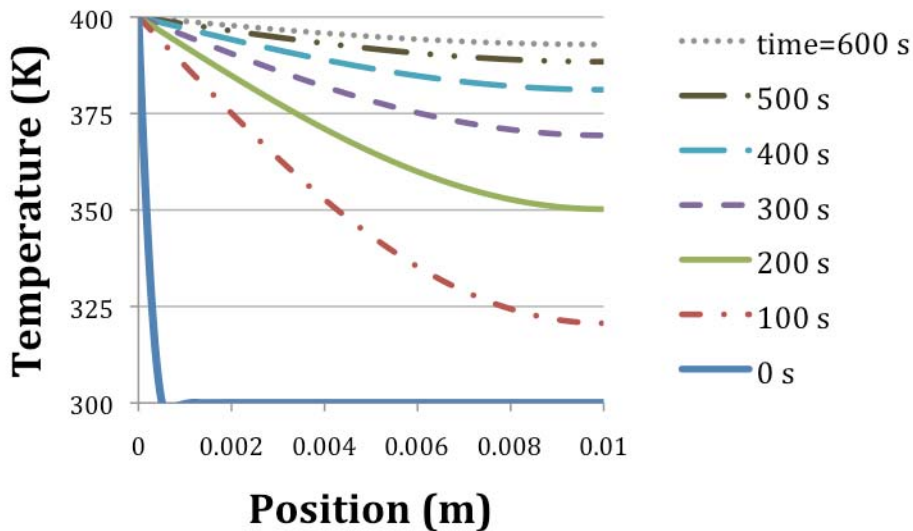
Figure 3. COMSOL T-vs-x results at varous times.

In Figure 4 is shown both the experimental and COMSOL transient response (T-vs-t) at x=0.01 m. The experiment was run three times, and we plotted the average temperature at 60 second intervals. The error bars indicate a bigger standard deviation at low times as compared to long times. Once the COMSOL model was established, it was easy to vary the heat capacity. Although many others were calculated, in Figure 4 we only show T-vs-t curves calculated with C_p=400, 1400, and 2000 J/(kg K). Based on the comparison with the experimental data, our model indicates that the best fit is with C_p=1400 J/(kg K). According to the Wood Handbook, the heat capacity is a function of moisture content as well as temperature. For the sake of comparison, we choose a literature value for wood with 12% moisture content at 300K that is 1700 J/(kg K).(Anton 1999) Again, because we do not know the moisture content of our wood sample, a direct comparison cannot be made; however, there seems to be reasonable agreement.

V. Summary

In this paper, we demonstrate a simple method of using the commercially available COMSOL software to augment a chemical engineering heat conduction lab. The simple experimental set-up requires a heat source (e.g. steam blocks), a slab of solid material (e.g. wood), and a thermocouple. To ease the level of complexity, a one-dimensional model can be implemented with COMSOL. The partial differential equation can be presented along with the initial and boundary conditions. Once the model is established, it is easy to perform a parametric computer study of the effects of various material properties such as density, thermal conductivity and heat capacity on the thermal behavior. In this paper, we used red oak and found that the best fit of the heat capacity was in reasonable agreement with literature values.

In the future, we hope to repeat this study with a slab of a well-characterized material such as aluminum. Within COMSOL, we can input a function (from the literature) that captures the temperature dependence of the heat capacity. We could also increase the complexity by using 3-dimensional geometry, and by including heat loss from the edges of the slab due to heat conduction through insulation or heat convection to the surrounding air. Allowing the students

an opportunity to use this sophisticated modeling software will help them realize how such modern tools can be used to understand and optimize engineering systems.
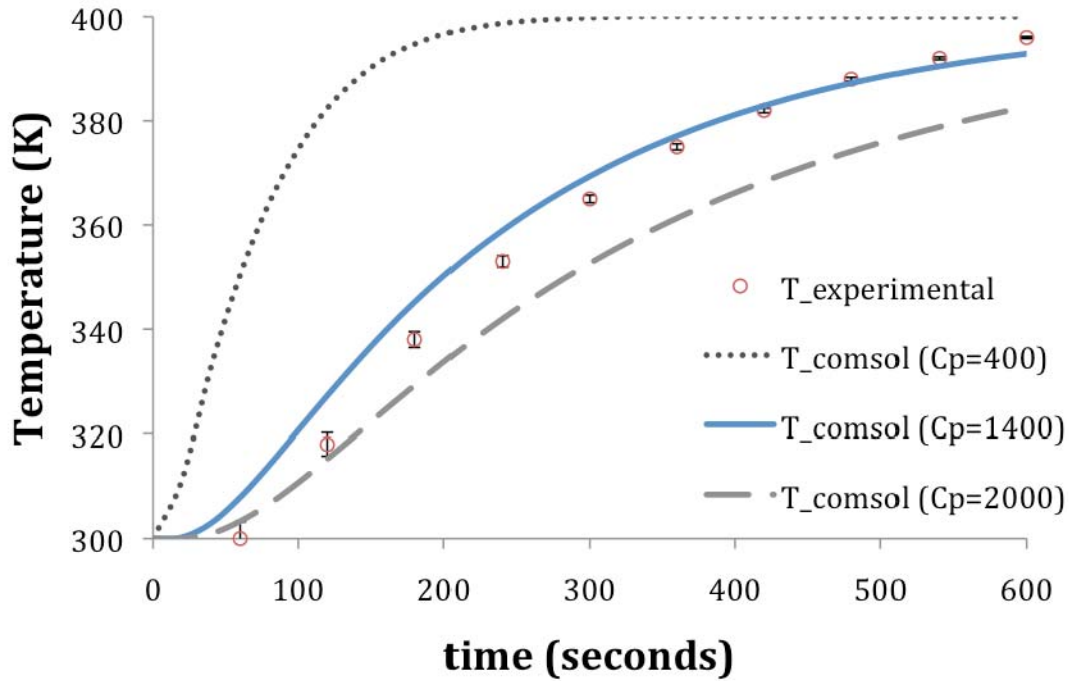
Figure 4. Experimental and COMSOL T-vs-t results.

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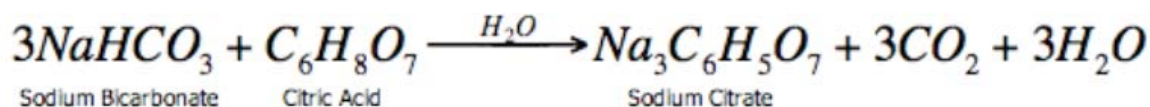
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Reaction Experiments: Low Cost, Safe, Hands-On Visually Observable
Reaction Experiments
Jim Henry
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Denture cleaning tablets (Efferdent, Polident and drugstore generic) are not only cheap but easily available and safe to handle. The tablets contain sodium bicarbonate and citric acid as solids. When immersed in water, they dissolve and react quite vigorously.

Reacting the tablets in water can illustrate several aspects of reactions and chemical engineering: Varying the temperature demonstrates different reaction rates. Different ratios of tablet mass to water can be explored (Efferdent and Polident tablets have different masses).

The experiment is intended to determine the order of the reaction, the rate constant at a given temperature, and the activation energy of the reaction. The denture cleaner works by the reaction between citric acid and sodium bicarbonate to produce sodium citrate, carbon dioxide, and water. Figure 1, below, shows the balanced reaction.

$$3NaHCO_3 + C_6H_8O_7 \xrightarrow{\ H_2O\ } Na_3C_6H_5O_7 + 3CO_2 + 3H_2O$$

Sodium Bicarbonate · · · · Citric Acid · · · · · · · · · · · · · Sodium Citrate

The experiment set-up involved using standard 150mL beakers filled to the 100mL mark with water. For reactions at greater than room temperature, a Fisher Scientific Isotemp stirring hot plate was used. Figure 2 shows a picture of the Isotemp loaded with a series of reactions.


The figure to the left shows the stirring hot plate with 9 different beakers with the reaction in progress. The reaction is observable as bubbles are released from the tablet-reaction system. The total reaction time is taken to be an estimate of the reciprocal of the reaction rate.

The procedure we used is as follows:

1. Measure into a 150mL beaker 100mL of water and record the temperature of the water.
2. Weigh to the nearest 0.1 g the individual denture cleaner tablets and record the weight.
3. Record the weight of the beaker with the 100ml of water.
4. Drop the tablet into the water and observe the effervescent reaction.
     a. Begin the timer to record the length of the reaction.
          i. The reaction is assumed to reach completion when the tablet has
               completely dissolved and any bubbling/foaming has stopped.
     b. Stop timer and record reaction time.
5. Repeat each experiment 2 more times to get sufficient data for statistical analysis.

The graph below shows the results from one set of experiments for reaction time as a function of temperature. "Brand A" had a larger mass of tablet: 2.8 g vs 2.1 g for the other two.

Temperature v. Reaction Time
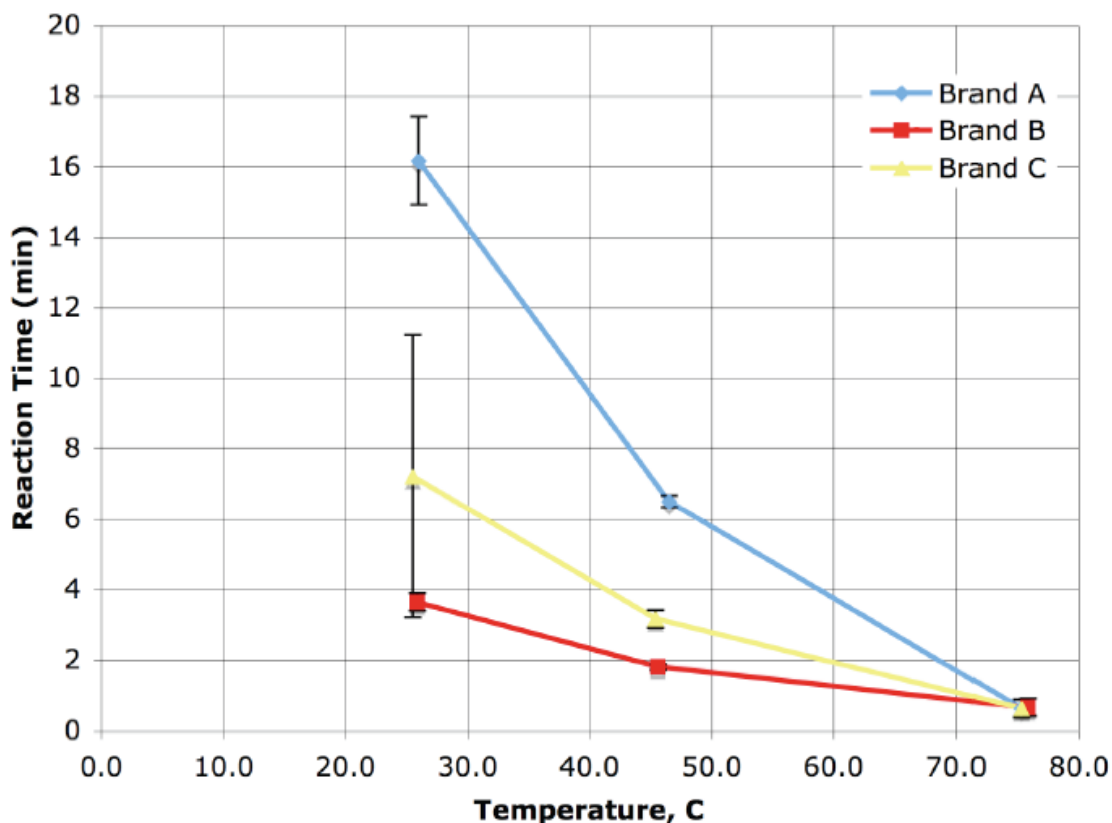
The activation energies were calculated using the data from 25°C to 45°C. They were found to vary from about 28 kJ/mol to 35 kJ/mol. The graph shows a halving of the reaction time (and thus a doubling of the reaction rate) for a change of temperature of 20°C.

One student suggested measuring the weight change as the CO_2 evolved. This experiment was attempted and less than 1 mg weight loss could be measured. In discussion between the instructor and the student, it was concluded that the foam above the reaction liquid was actually trapping the CO_2, so consequently it still contributed to the mass of the reaction system.

Safety issues: those conducting the experiments were to wear safety glasses and use protective gloves for handling the tablets.

Integrating Sustainability in Unit Operations Laboratory
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Abstract

More than ever, we need global citizens with the ingenuity to solve complex problems. We are faced with many urgent challenges: climate change, pollution, and the shortage of energy, food, and water. These problems require technical, social, ecological, economical, and political solutions. Engineering education sits at the core of this, as many industries and various engineering professional bodies have identified "sustainability" as a top priority (Hesketh et al. 2004). In the field of chemical engineering education, the evolution of green chemistry and pollution prevention have led to dedicated courses such as green engineering and industrial ecology in the senior levels. However, in order to bring the concepts of sustainability into the basis of all engineering design and practice, "full integration of the sustainability concept into engineering curricula" (Glavič 2006) is required and an Integrated framework of sustainability in chemical engineering connecting the pathway from individual to global levels has been described as the hierarchy in sustainability (Batterham 2006).

This paper presents a case study of how sustainability was incorporated into our 3rd year unit operations laboratory course. There are two unit operations laboratory courses taken by 3rd year students where ten lab stations are available, including fluidized beds, fuel cell, heat exchanger, sedimentation, rotary viscometer, rotary filtration, air cyclone, pumps and valves, and thermocouple data logging. The class was split into four groups with 8-9 students per group to work on each project. This project was part of the University of British Columbia (UBC) SEEDS (Social Ecological, Economic, Development Studies program - http://www.sustain.ubc.ca/seeds) with projects pre-arranged to work on the UBC aquatic centre, UBC steam plant, UBC farm, and UBC composting facility. The UBC SEEDS program is "Western Canada's first academic program that combines the energy and enthusiasm of students, the intellectual capacity of faculty, and the commitment and expertise of staff to integrate sustainability on campus" (http://www.sustain.ubc.ca/campus-sustainability/getting-involved/faculty-staff). Each group was responsible for contacting their campus client to define the scope of the project, conducting research, proposing solutions, and reporting. The output of the group project was a report and a presentation where they stated the problem (as defined with the client) and proposed a solution. The clients were invited to the presentations to participate in questioning and providing feedback. A section on "Reflections on UBC and Sustainability" in the final report emphasized their learning and understanding of where the university stands, and how their project can contribute to sustainability on campus.

Introduction

The laboratory courses in the Chemical and Biological Engineering have traditionally had a strong component of hands-on learning. During the 3rd year curriculum, students conduct experiments on 10 different units. Additionally, there is a week-long field trip to the industry, data acquisition and analysis on the campus boiler unit, and a session on mechanical and electrical workshop. The project described here was conducted in place of the boiler trial for

2010. Thus, the second term of the 3rd year lab consisted of 4 experiments in the lab, and the project based on SEEDS, as shown in course evaluation scheme in Table 1. The four labs, which will not be covered here, were: heat exchanger; fuel cell; rotary viscometer; and rotary filtration.

SEEDS Projects

The four SEEDS project were predetermined and set up with the assistance of the SEEDS coordinator from the Campus Sustainability Office; UBC Farm; UBC Aquatic Centre; UBC Steam Plant; and UBC In-line Composting. An introductory lecture included the information on past SEEDS projects on campus (http://www.sustain.ubc.ca/seeds-library), and the overall UBC sustainability initiatives.

The overall learning objectives of the projects from engaging in one of the SEEDS projects were to:

Table 1. Mark distribution for the lab course (CHBE 344).

Item	Format	Mark
1st lab	Group formal report	10%
2nd lab	Individual short report	15%
3rd lab	Group presentation	15%
4th lab	Individual formal report	15%
SEEDS Project	Mid-term presentation	10%
SEEDS Project	Final presentation	10%
SEEDS Project	Final report	15%
Field trip	Report	10%

- gather relevant background information;
- define the scope of project;
- conduct the assessment;
- effectively communicate with staff and faculty;
- present results to peers; and
- prepare a final report to the staff.

Each SEEDS project had a loosely defined objective provided by the staff and redefined by the instructor, myself, as listed in Table 2. Students were given a short window to sign up for their project of interest through the course web site. From then on, the projects were run according to the timeline given in Table 3. Consulting hours were set up to allow students to share their challenges and progress with the instructor.

Table 2. SEEDS project and objectives.

SEEDS projects	Objectives
UBC Steam Plant	Looking into options for recovering residual heat from the flue gas
UBC Aquatic Centre	Possible ways to utilize the condensate of the steam used for heating the pool
UBC Composting	Measuring the flow rate and composition of the gas coming out of the composter
UBC Farm	Measuring the temperature and composition of the composter pile

Table 3. Timeline of SEEDS Project.

Dates	Tasks
January – April	• Duration of the course
Late January	• Meet with team and client: include Naoko in the initial meeting with the staff. Contact info is written in the SEEDS project form • Fill out SEEDS project form and Student Registration Form. Submit to Naoko
Early February	Mid-term Project Presentation • define scope of project • objectives and tasks
March	• work on project • read "UBC Climate Action" report when available
Mid April	Final Project Presentation
Late April	Final Report submission Online peer evaluation

Both mid-term and final presentations were marked by the instructor, teaching assistants, and the peers, according to the criteria shown in Table 4. Quick feedback was given after the mid-term presentation which encouraged the students to improve their final presentations.

Table 4. Presentation Evaluation Form.

The outcome of the projects consisted a final presentation and a report. Each client, i.e., staff member, was encouraged to attend the final presentation and raise questions and comments. The final report had a well-defined structure including: Introduction; Problem Definition; Methodology; Results and Discussion; Reflection (on UBC and sustainability); Recommendations for UBC Key Partners; Recommendations for Future CHBE 363 Groups; Conclusions; Acknowledgement; References; and Appendix.

> PRESENTAION EVALUATION FORM
>
> COMMENTS ABOUT CONTENT OF TALK:
> a) Introduction and Background Information:
> b) Definition of Problem:
> c) Scope of Project:
> d) Explanation of Experimental Apparatus and Procedures:
> e) Conclusions:
> f) Overall Organization:
>
> COMMENTS ABOUT PRESENTATION OF SEMINAR:
> a) Delivery (volume level, pronunciation, grammar, speech mannerisms, flow, etc.)
> b) Style (appearance, confidence, rapport with audience, etc.)
> c) Slides (legibility, neatness, impact, etc.)
>
> COMMENTS ABOUT SPEAKERS ABILITY TO ANSWER QUESTIONS:
>
> OTHER COMMENTS AND/OR QUESTIONS:
>
> Presentation Mark (OUT OF 10):
> MARKER:

Overall, the projects have collected and analyzed data, and come up with solutions and recommendations to the clients, who were very interested in the outcome. All the reports are available online. Some reflections from the reports are included below.

"This experience has taught us a lot about sustainable thinking. As the purpose for this project, our objectives and methods were developed with sustainability in mind. As a first exposure to its practices for all the group members, this project has taught us to think more about environmentally safe practices in our daily lives as well as to see areas that could be improved to be more efficient or less damaging. As student engineers, we believe this is an extremely useful lesson, as it will continue to be our responsibility to continually improve the area in which we live as well as pass on our knowledge to younger generations of engineers." (UBC Farm report)

"UBC is working strongly toward sustainability and it has high hopes for the way that the campus can be run. Using a somewhat closed loop system for compostable waste, UBC is working in the right direction toward being a fully sustainable entity. In order become fully sustainable in terms of organic matter UBC would have to grow all of its own food, process the waste through a compost facility, then use said compost as nutrients for more food to be grown. By starting with a compost facility that helps to keep some the organic matter on campus, while not emitting a significant amount of GHG emissions, UBC has taken the first step." (UBC composting)

In summary, the SEEDS project served as an excellent mode for students to engage in a part of the campus operation through dialogues with the staff, learning about the operation, collecting and analyzing data, testing the change or recommendation, and presenting the solutions. Students were enthusiastic about their projects and their solutions as they presented to their peers and the clients. It is hoped that a sense of belonging to the campus by engaging in such project has been cultivated. In fact, UBC has developed the Sustainability Academic Strategy in which the Campus as a Living Laboratory (http://www.sustain.ubc.ca/hubs/campus-living-laboratory) as a working model. Further engagement of students in this form is expected to continue.

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SEEDS Project Reports

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http://www.sustain.ubc.ca/sites/default/files/seedslibrary/CHBE%20363%20SEEDS%20Farm%20FINAL.pdf

Downsizing Space and Equipment, But Not the Experience: Reinvigorating the Unit Operations Laboratory at Vanderbilt University
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In August of 2010 the Chemical and Biomolecular Engineering Department at Vanderbilt University completed a major renovation of our teaching laboratory.   Our increasing undergraduate enrollment (up from 27 graduating seniors in 2007 to 59 graduating in the class of 2013, assuming no attrition between the sophomore and senior years) has increased the need for larger classrooms and teaching labs. Also, our growing graduate program (29 total students in 2007 increasing to 39 total students in 2010) lead to faculty hires and the need for more research space. These demands for increased space and/or better utilization of existing space drove the need for the renovation.

As seen in Figure 1, a photograph of the lab before renovation, our lab was a traditional high-bay lab with a large hole cut in the top floor to enable the installation of large-scale separation columns and their associated condensers, reboilers, and feed/product tanks. Smaller experiments, mostly used in our junior laboratory course, were set up around the perimeter of the upper floor. Additional work stations were located on the basement floor to facilitate characterization of the bottoms products from the large columns, chemical storage, and storage of many other research and teaching tools and instruments.

Figure 1. Photograph of the space before renovation

The renovation involved completely gutting the space on the top floor, filling in the hole in the top floor, and refitting the space with new utilities and furniture. Figure 2 is a photograph of the renovated space taken from approximately the same spot as the photograph in Figure 1. The solid doors leading out the loading dock were replaced with doors with windows and additional windows were added above the door. The added natural light and the new lighting design brightens up the space compared to the old space. We added a large support grid on the ceiling to enable full use of the space. Utilities are bundled in the ceiling. Ten utility panels, shown in Figure 3, each contain seven 110V, 20 A connections, each on its own circuit, and one 20 A, 208 connection. Each electrical receptacle connects to a twist-lock extension cord. In addition to the electrical connections each utility panel contains supply lines for filtered house water and a supply for house compressed air each with its own ball-valve shut-off.

Figure 2. Photograph of the renovated space taken from approximately the same spot as that in Figure 1.

Figure 3. Utility panel supplying seven 110 V and one 208 V circuits along with compressed air and filtered water.

The space was designed to hold ten groups, four students each, in each laboratory section. This will eliminate the need (in the foreseeable future) to add laboratory sections to meet our growing undergraduate enrollment. The space was also designed with flexibility in mind. All laboratory benches are height adjustable and on casters. This enables us to rearrange the space as needed for both the junior and senior lab set-ups. Additionally, several storage cabinets which also have casters are in the space to hold support equipment and lab consumables.

Students in our unit operations lab complete four laboratory exercises. For each exercise the students are challenged with a design problem which will require data collection using the laboratory equipment to solve. They work in groups of three or four students, with the same students working together for the entire semester. During the Fall 2010 semester we had one section of five groups and one section of seven groups. Figure 4 is a photograph taken during a Fall 2010 laboratory section..

Figure 4. Photograph taken during a Fall 201 laboratory section.

We currently have a distillation column, a liquid-liquid extraction column, batch and CSTR reactors for evaluation of kinetic parameters and reactor design, and a fermentation system. Figure 5 contains a photograph of the kinetics set up. Photographs of each of the distillation, fermentation, and liquid-liquid extraction set-ups are provided in Figure 6. Note that we have chosen to use mostly peristaltic pumps in these systems. Peristaltic pumps provide flow metering as well as flow, eliminating the need for flow sensors. They also provide flow rates in

the ranges needed for these smaller scale set-ups and can pump many types of chemicals without damaging the pump. The pumps we use also have the capability to be computer controlled, enabling us to build control systems for these experiments in the future.

Figure 5. Photograph of the kinetics laboratory set up

The renovation created a flexible, open-concept space for teaching. The light and airy space is much more esthetically pleasing to work in, especially during the long five-hour laboratory sessions. While the renovation removed the basement from the teaching space, it created more usable space than we had prior to the renovation. The basement space is currently being turned into two research laboratories to support new faculty hires.

Figure 6. Photographs of experimental set-ups. Top-left: distillation; Top-right: fermentation; Bottom-left: liquid-liquid extraction.

Intended Outcomes of a Unit Operations Laboratory Experience

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Graduates from an accredited ChE undergraduate program should enter the workforce with the ability to identify, understand, and solve the problems they encounter. Science, mathematics, design, and social sciences can be taught in a traditional classroom setting, while chemical process problem solving skills are best developed in a laboratory setting. For chemical engineers, the Unit Operations Laboratory is the ideal opportunity to develop this special skill set.

Due to resource limitations, Unit Operations Laboratory courses are typically designed around available equipment. Experimental objectives are formulated based on equipment capabilities; students run an experiment following an accepted procedure; data are collected and analyzed; and a report is submitted for grading. An alternative to this "equipment-defined assignment" is to develop experimental objectives based on the program's ABET Outcomes.

An "Outcomes-based Assignment" encourages the students to explore the equipment's possible range of operation to a) determine applicable theory and appropriate empirical relationships, b)

develop an experimental strategy bounded by safe work practices and the equipment's operating range, and c) develop a plan to minimize the effects of experimental error. Materials provided to the students at the start of the planning stage should provide only enough information for the students to make these determinations. For example: piping, instrumentation and equipment specifications are provided along with a cover memorandum stating the specific experiment objectives. If the unit operation of interest is one not typically introduced in a prerequisite course, then suggested references might also be included. Equipment diagrams, operating procedures, MSDSs, and determination of parameter space are left to the teams of students to discover or develop. The Unit Operations Laboratory at Michigan Technological University has been designed and built to facilitate development of the ABET Outcomes-defined skill set. The year-long course sequence is split into a traditional Unit Operations Laboratory course where the students operate five different unit operations experiments during the 14 week semester. The second semester builds on the skill set from the first semester and requires the students to work in "teams of teams" to operate each of our two pilot plant processes in a course called Plant Operations Laboratory. The theme of the second semester course is Continuous Improvement in Chemical Manufacturing.

Michigan Tech's Unit Operations Laboratory (semester 1) includes 17 unit ops, most of which were designed and fabricated in-house. These units are of large enough scale that industrial instrumentation is used for measuring flow, level, temperature, and pressure, thus exposing the students to the types of instrumentation they will encounter professionally. The large-scale equipment also forces the students to work as a team to accomplish their experimental objectives. The laboratory safety program develops an awareness of safety in all actions within the lab environment and encourages the students to take ownership of the safety of others. The pre-laboratory work requires the team to divide the work into manageable tasks to explore a range of possibilities for problem definition, examination of the parameter space and development of a strategy for success. The laboratory proposal and final report helps prepare our students to write succinct, accurate, engineering reports. Finally, a requirement for two oral presentations in the first-semester Unit Operations Laboratory course develops professional oral presentation skills.

The mandatory unit operations used in this course include the heat exchanger (each lab group must complete this experiment) and centrifugal pumping (each lab group must complete one of two pumping experiments). The optional unit operations experiments offered in fall 2010 were: air cyclone, continuous stirred tank reactor, comminution, fixed bed reactor, membrane separation, cooling tower, fluidization, liquid-liquid extraction, non-Newtonian flow, and vacuum drying.

The laboratory facilities for the Plant Operations course (semester 2) are the two pilot plants included in the Process Simulation and Control Center. The Solvent Recovery Unit (SRU) is a continuous distillation pilot plant that is operated in shifts without shutting down between transfer of responsibility between teams of students. The Polymerization Reaction Unit (PRU) is a 30-gallon batch reactor, complete with all supporting equipment to batch process polydimethylsiloxane. The SRU is a continuous process while the PRU is a batch process, so control, operation, and analysis of these processes is very different. In both cases, the students are assigned to improve an imperfect process. In a seven week project, they research historical

data to determine assignable causes for variation that produced off-specification product, then develop a total solution to eliminate this type of event from occurring in the future.

These capstone laboratory courses prepare students for a career in chemical manufacturing and are unique to the Michigan Tech Chemical Engineering undergraduate experience. The outcomes-based approach allows students to practice ABET skills while functioning as a Chemical Engineering Professional team to solve real-world problems.

Integration of A Biodiesel Production Platform as A Teaching Tool in the Senior Unit Operation Laboratory at UM

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The mission of the Chemical Engineering (ChE) curriculum at The University of Michigan (UM) is to provide a solid technical education that prepares our students for a future career and leadership in chemical engineering or related fields. Among many technical and non-technical knowledge items that the students need to acquire during their study, we sincerely believe that the important life long skills of teamwork, open-ended problem solving, and critical thinking should also be included within the curriculum. The students must take two laboratory courses, ChE 360 and ChE 460 during their junior and senior years respectively. These courses are focused on educating our students in the fundamentals of experimental design, data gathering and analysis, uncertainty estimation and propagation, teamwork, and written and oral communication skills in a simulated laboratory/pilot plant environment. While all these skills are required for both courses, data gathering, uncertainty estimation and written communication skills are mainly emphasized in the junior lab and teamwork, process integration, and oral presentation skills are emphasized in the senior lab.

To meet the mission of our ChE curriculum, the Unit Operations Lab (ChE 460, senior lab) has been revamped recently to simulate several unit operations required in a sustainable biodiesel pilot plant production facility using soybean oil as the starting material. The goal is to generate an ASTM grade biodiesel product with an emphasis on process integration with product recovery and reprocessing. The main difference of this new approach is to integrate most of the existing but previously isolated unit operations in the laboratory into a "virtual" process where the inputs and outputs of each unit operation are intimately related with each other. This approach illustrates how decision-making in one operation may affect the other parts of the entire plant operation. During the entire semester, the students are encouraged to interact with student members of other teams and to understand the entire process and grasp the interconnectedness of all the processing streams in the proposed plant. Students address the need to meet the product quality and specifications, as well as byproducts recycling to minimize waste generation. We strongly encourage the students to identify various technical problems associated with the process, generate possible solutions, and evaluate the economic consequences of these solutions for the proposed plant.

In the beginning of the semester, a memo was sent out to the students to introduce them about a proposed biodiesel production scheme developed and published by the United States Department of Agriculture (USDA) (Haas et al).[1] and expect them to improve on this process using critical thinking and problem solving skills. The ultimate goal is to design a new process generating minimal amount of waste streams by proposing ways to recover, reuse, or recycle all the byproduct streams. Students use laboratory information obtained through experimentation and data analysis to evaluate each of the proposed improved processes and subsequently scale-up to meet the desired output of the plant. The semester is divided into three 4-week rotations. Teams of three students work for 3 weeks on an assigned unit operation and spend one week to present their results orally to the entire section. Each team produces a final report that will be used by the following student team as a starting point for follow-up assignments. The students are all assigned randomly to these project assignments so as not to work more than once in a project assignment or with the same partners.

Process Equipment and Assignment Flow in ChE 460 Laboratory

The ChE 460 Unit Operations Laboratory has the following small scale or pilot equipment to simulate the biodiesel production process: A. <u>Reaction Cell:</u> It is used for the transesterification of triglycerides (vegetable oils or waste fats) to produce Fatty Acids Methyl Esters (FAMES or Biodiesel). B. <u>Liquid-Liquid Extraction:</u> this Podbielniak centrifugal contactor is used for the removal of impurities from the FAME (biodiesel) phase produced in the transesterification reactor, using water as the solvent. C. <u>Fractional Distillation Column:</u> used to separate the components of aqueous methanol mixtures produced in the centrifugal contactor used to purify the biodiesel product. D. <u>Double Effect Evaporator:</u> used for the production of concentrated glycerol solutions from any dilute glycerol feed stream. It can be used to model the recovery of methanol from the glycerol-methanol-catalyst product stream from the transesterification reaction. E. <u>Process Control Simulator:</u> used to simulate the process step in which the washed biodiesel fuel from the centrifugal contactor is heated to a specified temperature prior to the de-watering of the fuel in a flash dryer. In addition to these major equipment to simulate different unit operations, the laboratory is also equipped with analytical instruments to analyze various effluent streams to determine their operation parameters. These include GC, uv-vis spectrophotometers, titration, balances, etc. Students are encouraged to analyze all sources of error, from initial sample preparations to the final interpretation of results from the instruments.

In the beginning of the semester, each designated student team is expected to define the overall goal and specific objectives of the specific assignment. They must always keep an eye in the "Bigger Picture" of the assignment so that they know what to achieve in each task and how this fits in with the overall improvement of the biodiesel process. During the first rotation, students use the laboratory to characterize the process or equipment for the assignment. For example, establishing reaction rates as function of catalyst concentration and reactor operating parameters; or measuring mass transfer characteristic of a proposed packing to be used in the plant distillation operation etc. In some cases, simple Design of Experiment (DOE) concept will be encouraged in the experimental plan. For the second rotation the students are usually asked to generate correlations using modeling techniques for the specific unit operation so they can be

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[1] A process model to estimate biodiesel production costs; Michael J. Haas *, Andrew J. McAloon, Winnie C. Yee, Thomas A. Foglia; US Department of Agriculture, Agricultural Research Service, (ERRC,1)

used in the prediction of various operation conditions encountered in the proposed plant. For this aspect of the project students are encouraged to use simulation packages such as "Aspen Plus" or simpler spreadsheet modeling. Concept of "sustainability" through recycling and waste minimization have been encouraged throughout the semester as the students start to evaluate the use of the process equipment and test various operating conditions to be used in the plant. During the final rotation, students are encouraged to interact with other student teams as they embark on the assignment to pull all the unit operations together and produce an overall process flow sheet for the entire process. This requires the students to focus not only on their particular unit operation and the best way to operate the specific equipment, but also to think of how the output of their specific processing step may affect the process downstream, and how the processing conditions of the upstream process step would affect their performance.

Skill development using this new approach of learning:

The new approach has helped the students to learn additional technical skills as well as teamwork beyond the usual technical training of focusing on a specific piece of equipment as in the Junior Laboratory (ChE 360) and UG research. The following are some examples that the student would have missed:

A.   The reactor group may think it better to operate with high catalyst concentration because it reduces residence time so they can propose smaller reactor units. However this will provide a larger problem for the groups trying to recover the glycerol byproduct, which now will contain a larger amount of catalyst waste that need to be neutralized or removed.

B.   The biodiesel washing process with water may operate better if higher water to biodiesel ratio is used, but that will require a larger distillation column and larger energy consumption to recover the methanol from a larger volume of a more dilute solution.

C.   The residual amount of water left in the recovered methanol to be recycled back to the reactor may affect the reaction yield, or the product purity

Figure 1 below shows the schematic drawing of the final outcome produced by a particular student team at the end of the third rotation.
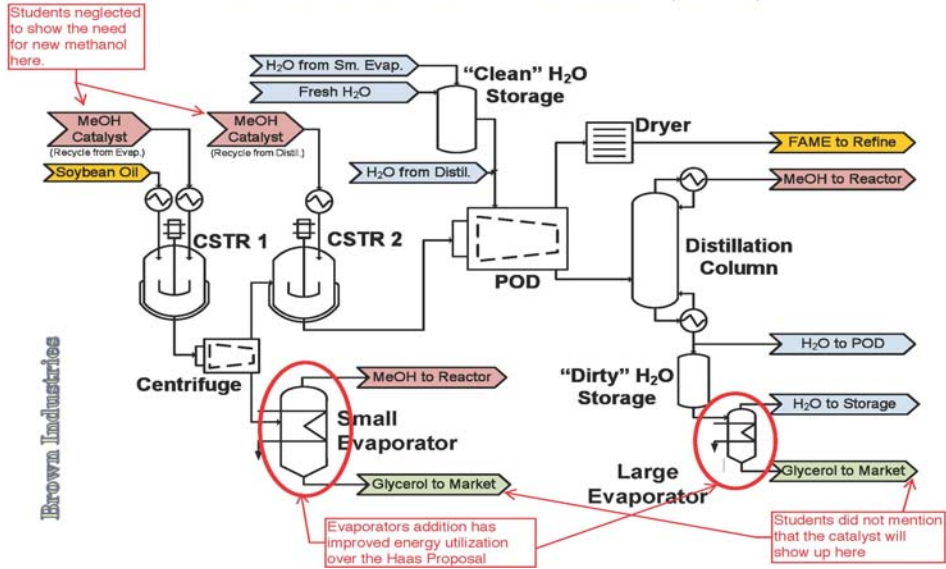
Figure 1:A Sample of the final proposed biodiesel plant by a student team during the Winter 2010 Semester