AC 2010-1056: APPLYING MASS BALANCES TO ALCOHOL METABOLISM: A TEAM PROJECT THAT APPLIES FUNDAMENTAL CHEMICAL ENGINEERING SKILLS TO BIOTECHNOLOGY

Allen Yang, Cornell University

Kathryn Dimiduk, Cornell University

Susan Daniel, Cornell University

Applying mass balances to alcohol metabolism: a team project that applies fundamental chemical engineering skills to biotechnology

Abstract

In the last decade, chemical engineering has evolved to meet the growing challenges of the 21st century, particularly in the areas of biotechnology and sustainable development. However, the chemical engineering curriculum has somewhat lagged in integrating and reflecting these modern topics. Approximately 30% of students entering our *Mass and Energy Balances* class list interests in biologically-related topics (pharmaceutical, biomedical, medical, environmental) versus about 10% each for industry, energy, research, and other, with 20 % undecided, and about 10% non-respondents (mostly non-chemical engineering undergrads). This traditional gateway course needs to continually evolve to develop student awareness of the current issues, excite their interest in finding solutions to challenges that face their generation, and engage them in learning the required fundamental skills to find those solutions. Topics on biotechnology were absent in the course initially, and as we investigated ways to integrate these topics into the class we found that there was a paucity of published biochemical-themed projects for a sophomore-level mass balance curriculum. This challenged us to develop a new team project that incorporates biotechnology. We chose to apply mass balances to human alcohol metabolism.

Student teams create a mass balance model of the breakdown of ethanol within the human body using computer spreadsheets to calculate mass flow rates to and from key organs. Process units model the organs handling biological functions such as oxygen and liquid intake, chemical breakdown, and waste removal. The project requires only knowledge of multi-unit mass balances and chemical reactions in the steady state; parameters are designed to create reasonable physiological results from their model. Students test their model using an established basis and monitor variables such as blood alcohol concentration and blood acetaldehyde concentration. Students investigate "Asian blush", a physiological syndrome resulting from different enzymatic degradation of ethanol in some Asian populations compared to those of European descent, thus introducing the students to human health issues. Students then scale their model from human proportions down to a microscale lab-on-a-chip device, a so-called "body-on-a-chip", which is an in vitro platform that is used for testing metabolic effects of various chemicals. With the premise of working as consultants for a pharmaceutical company, students study a fictional drug which is supposed to suppress alcoholism by artificially increasing alcohol sensitivity. Student groups are assigned different formulations, each altering different parameters in their mass balance model, and are asked to analyze the effects of their drug to determine its efficacy. Formulations can vary from detrimental to beneficial, requiring students to develop analytical skills and engineering judgment as they assess the drug performance.

By combining computer technology and biochemical principles, we created a self-contained, group, project module which introduces students to a number of different biotechnological and human health issues, and develops critical thinking, team work, and communication skills. This project addresses students' professional interests, engages them in active learning, and reinforces the mass balance fundamentals that are building blocks for subsequent courses in the chemical engineering curriculum.

Introduction

The fundamental concepts and problem solving approaches of chemical engineering are well-suited to meet the growing challenges of the 21st century, particularly in the areas of biotechnology and sustainable energy. However, the chemical engineering curriculum somewhat lags in integrating and reflecting these modern topics. For example, the traditional gateway course, *Mass and Energy Balances,* needs to continuously evolve to develop student awareness of current issues, excite student interest in finding solutions to challenges that face their generation, and engage students in learning the required skills to solve these problems.

Never has it been more important to engage more students in science and engineering than in today's society where the demand for engineers is expected to significantly exceed the supply in the near future[1]. Concurrent to this growing deficit in technically-trained workers is the rapid diversification of our population. In order to fill the gap, people from diverse backgrounds will need to be motivated to choose engineering as a career choice[2]. Extensive research shows that one way to engage students is to connect problems to societal impact by integrating the "human element" into the course material[3]. This motivation was also reflected in student responses to a survey given on the first day of class, that queried their attraction to chemical engineering, which will be presented in a later section.

One place to connect the course material to the human element, and resulting societal impact, is through integration of real-world biotechnology problems. The paucity of published biochemical-themed projects for a mass balance curriculum challenged us to develop a new project that incorporates biotechnology. A straightforward example is applying mass balances to human alcohol metabolism. During the development of this project we decided that it was also important to integrate the following pedagogical elements. First, we wanted to clearly illustrate *why* chemical engineering is particularly suited to these kinds of problems and what our skill set offers to biotechnological problem-solving that no other engineering discipline is wholly equipped to do. These skills include defining systems with multiple unit operations and complex interconnections, writing and solving systems of equations based on chemical reaction stoichiometry and kinetics, and scale-down of a system from human-scale to "lab-on-a-chip" micro-scale using dimensionless numbers. Additionally, we wanted to create a project that would encourage teamwork and cooperation in developing problem-solving strategies and in the analysis and evaluation of the results. Here students would learn about dividing responsibility among their fellow students and developing an appreciation of synergies that come from learning in an interactive team environment, while also learning about how to manage the dynamics of multi-person projects. These skills are important to cultivate in college since the professional environment often relies on group problem-solving and assessment, especially in pharmaceutical and biomedical research. Finally, we wanted to make the project tunable to student ability so that student groups that wanted to delve deeper into the analysis could do so, while students with less experience could still perform the analysis and learn skills from this project that would prepare them for more sophisticated analyses in future classes. Thus, all students would be able to gain skills and understanding from this project that educates them on a real-world application of chemical engineering and that challenges their abilities in various ways.

Class interest statistics

From previous informal discussions with students about their interests and motivation for pursuing chemical engineering, it appeared that an interest in biotechnology and the possibility of having societal impact were major driving factors for why students were selecting chemical engineering as a major. To determine whether this anecdotal observation applied to the whole class, this year more complete data was collected through a survey given on the first day of class. The survey had a 90% response rate with most of the non-respondents being either late adds to the class who missed the survey or students who were not chemical engineering undergraduates. The information collected from this survey became part of the motivation and direction for the new projects added to the course. Data and discussion for several questions from the survey is included below.

Free response question: What attracts you to the field of chemical engineering?

About one-third of the class gave answers that indicated that they were attracted to chemical engineering because of the potential for real-world problem solving and impact on society. Another 14% indicated that versatility of the degree was attractive to them. The remaining students indicated that they were attracted to this profession because of a specific interest in chemistry and mathematics, or other specialized interests.

Free response question: What career path(s) are you interested in?

Table 1 summarizes the student responses to this second question. Unlike the numbers in the abstract, which were rounded off percentages for the entire class, these numbers are percentages of the respondents whose answer included a career in the category.

Table 1. Student Career Interests
(Totals exceed 100% as some students listed more than one career choice)

Career Interests	Percent of Respondents
Biology related (pharmaceutical, biomedical, medical, environmental)	30
Research or academic	13
Industry or industrial research	21
Energy or petroleum	12
Other	17
Undecided	25

Free response question: What do you think are three important real-world challenges that society faces that could be important for chemical engineers to address?

Students identified a variety of challenges that could be addressed with the skills one is equipped with after obtaining a chemical engineering degree, as summarized in Table 2.

Table 2. Societal Issues Chemical Engineers Could Help Solve
(Total exceeds 100% as many students listed more than one issue.)

Societal Issue	Percent of survey respondents that listed the issue
Energy sources	88
Environment (pollution, global warming, green, etc)	66
Drugs, vaccines, medicine (new, cheap, delivery, etc.)	48
Clean water	12
Allocation of resources	9
Food (products, supply)	8
New technology	7
Efficiency	7
Other	11

Overall, the responses to the survey and our conversations with students indicated student awareness of the overlap of chemical engineering with biology and the unique opportunities to positively advance human health that result from this overlap. With this information, it became clear to us that a project addressing human health and biotechnology from the chemical engineering perspective was a key topic to be included in this class this year. Overlap was also observed with energy and environmental issues, topics included in other class projects.

Introduction to the biotechnology project

To develop our biotechnology-based project, we took inspiration from current research on the development of an alternative drug testing device called an "body-on-a-chip"[4-6]. In the project, students are asked to build a simple mass balance model of the human body and use it to monitor the metabolism of alcohol and pharmaceuticals and then scale down their model to microchip size to simulate the "body-on-a-chip" platform that can be used for further testing and analysis using the scaled model (figure 1). This project meets our pedagogical goals of connecting to societal impact by illustrating how medicines can impact human health, providing students interested in pharmaceuticals and medicine an opportunity to see chemical engineering impact in these fields, and directly addressing a grand challenge facing the world today of the rapid development of safe and effective medicines.

Secondary project objectives are to promote teamwork, cooperation and improved interpersonal skills among the students which should aid them in navigating group work in future courses and in their career. Careful consideration of many criteria was used in creating effective teams, leading to team assignments based on the following constraints: groups of 4 students with only a few groups of 3, at least one strong performer on test 1 in each group, weak performers on test 1 placed only in groups of 4 and only 1 weak performer per group, two middle performers in each group, no group has only one student of either gender, and as far as possible each group has a student who self identified as a writer, a student who self identified as an organizer, and one who

self identified as a strong problem solver, calculator, or spreadsheet developer on the self-evaluations from the first project.

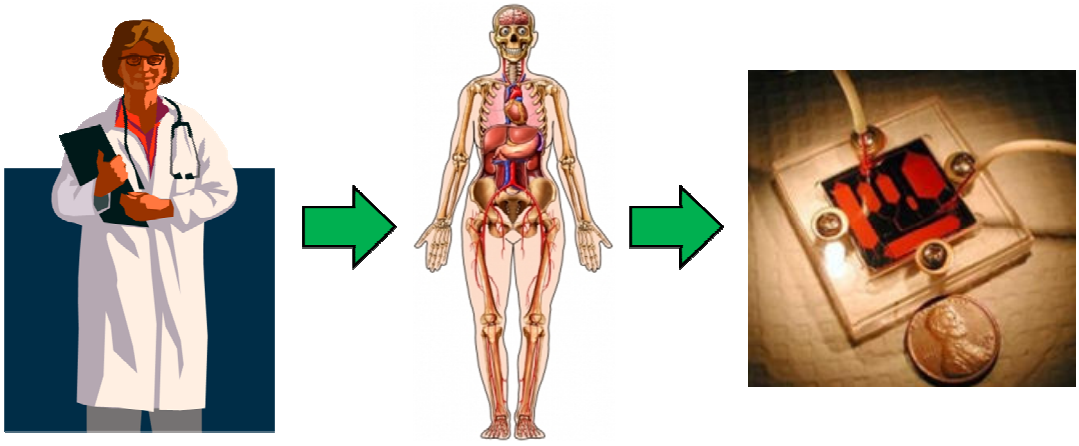

Figure 1: Scaling down the essential features of the human body to create an in-vitro model for drug testing that accurately mimics the metabolism of chemicals ingested in the body. The small chip on the right contains chambers (red) that mimic the organs in the body. Microfluidic channels connect the chambers on the chip like blood flow connects organs in the body. *Image credit: Michael Shuler, Cornell University, used with permission, also see ref*[6].

Biotechnology project technical background

Human metabolism of alcohol was chosen as the core topic for the project because it is a well-studied metabolic system which also has a variety of biochemical and human health aspects related to modern chemical engineering. Alcoholic beverages, such as beer, wine, and distilled spirits, are a significant component of traditions in human culture around the globe and comprise a considerable portion of the global economy. For example, the average person in the United States consumes 8.5 liters of alcohol a year, according to a recent report by the World Health Organization[7]. While the majority of people maintain healthy drinking practices, irresponsible drinking has implications in vehicle safety, personal health, and medical costs. Over time, sustained drinking at alcoholic levels for more than a decade can lead to irreparable liver damage, known as cirrhosis, and eventually result in liver failure and death. Within the human body, the liver is the organ primarily responsible for alcohol metabolism. The main pathway of ethanol (CH_3CH_2OH) degradation is oxidation of the alcohol into acetaldehyde (CH_3CHO), which is then further degraded into acetic acid (CH_3COOH). Acetaldehyde buildup in the body is partially responsible for the physiological reaction to alcohol consumption known as a hangover. Recent efforts to treat alcoholism use a negative reinforcement method through drugs such as Disulfiram, known commercially as Antabuse, which inhibits the degradation of acetaldehyde and increases hangover symptoms as a deterrent to alcoholic behavior[8].

The reaction sequence that occurs in the liver is two metabolic pathways that decompose ethanol to acetaldehyde and then acetic acid. The primary pathway degrades ethanol through the enzyme Alcohol Dehydrogenase (ADH)[7, 9-13]:

$$C_2H_5OH + NAD^+ \rightarrow CH_3CHO + NADH + H^+ \qquad \text{(catalyzed by ADH)} \qquad (1)$$

In addition to the main reaction catalyzed by ADH, there is a second parallel reaction for converting ethanol to acetaldehyde in the liver. This process is known as the microsomal ethanol-oxidizing system (MEOS)[13]:

$$C_2H_5OH + NADP^+ \rightarrow CH_3CHO + NADPH + H^+ \quad \text{(MEOS process)} \qquad (2)$$

The MEOS process represents the main non-ADH pathway for ethanol degradation. This is due to the activity of the cytochrome P450 oxygenase enzymes. The last reaction in the process degrades the acetaldehyde formed in Eq. 1 and Eq. 2 into acetic acid:

$$CH_3CHO + H_2O + NAD^+ \rightarrow CH_3COOH + NADH + H^+ \quad \text{(ALDH process)} \qquad (3)$$

Similar to the ADH process, the acetaldehyde degradation process is catalyzed by the enzyme acetaldehyde dehydrogenase (ALDH). Acetic acid is removed from the body via the urinary tract and also metabolized in the body.

The analysis of alcohol metabolic rates in the liver is typically done computationally or through measuring the concentration of aliquots of blood over a period of time. Experimental measurements are not practical for constant monitoring of a person, while computational methods generally require estimations of kinetic parameters. One can merge the best aspects of computational and experimental metabolic studies by creating an in vitro model that mimics the metabolism of a human within a microfluidic chip. Each "organ" (represented by a small chamber in the microfluidic device filled with cells cultured from that organ) acts as a unit operation connected by channels filled with a fluid that mimics blood flow and allows metabolites to flow around the chip, just like they would in an actual person. This model allows for constant in vitro monitoring of metabolic processes which would not be possible to do with a human, while also preserving the integrity of the biochemical reactions in the tissue[4-6]. This "body-on-a-chip" fuses the best aspects of current research in biomimetic materials with the flexibility of microfabrication to produce a biochemical system that functions similarly to chemical plant flowsheets in mass and energy balances classes. Using this biomimetic chip as a basis for the project exposes the students to these cutting-edge aspects of modern chemical engineering. This unique mix of biotechnology and chemical engineering fundamentals provides an excellent opportunity for introducing students immediately to realistic applications of the course material, gives them an example of the unique skill set that chemical engineering brings to these types of problems, and promotes "buy in" to the learning process because it directly links to human health and societal impact.

Modeling the human body as a chemical plant

As with any chemical process which involves reagent input, reaction, and product separation, the students are asked to create a multi-unit mass balance, in this case involving the organs for alcohol intake, degradation, and waste removal. The simplified model we employ focuses on basic features of lungs, stomach, liver, and kidney function in alcohol metabolism as seen in Figure 2.

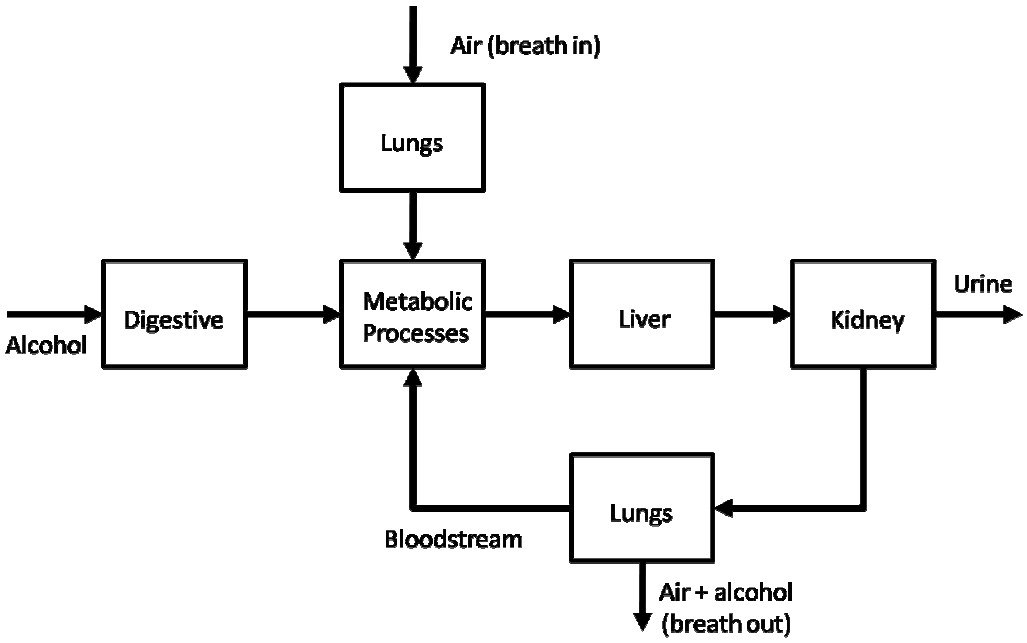

Figure 2: Schematic diagram of the simplified human alcohol metabolism model used in the project. The diagram illustrates the flow of alcohol and air through the body into the liver (where reactions take place), with the resulting products and remaining reactants migrating to the kidneys and lungs, and getting removed in the urine and breath. The metabolic processes box lumps the other metabolic processes occurring in the human body.

The project specifications give the key reactions and process parameters and the students are asked to determine the steady state alcohol and acetaldehyde concentrations in the blood for a given alcohol input. By this point in the course, students are familiar with chemical reaction balances using multiple units and conducting mass balances in Excel spreadsheets.

Each team developed a spreadsheet model of the mass balances for the human body and conducted an analysis for a unique alcoholic drink and a theoretical drug formulation intended to thwart alcoholism. The students were challenged to apply concepts to redox biochemical reactions in biological processes rather than traditional synthesis or combustion reactions. The correct steady state flow rates for their system required iterative calculations. This portion of the project reinforces the course material and allows students to apply their skills with mass balances to an analogous but unfamiliar system.

Student analysis of the system

In addition to developing the mass balance for alcohol metabolism, student teams were asked to use their model to analyze the effects of several scenarios presented in the form of tasks from their hypothetical pharmaceutical industry employer. These tasks were divided into three phases: controls, testing, and evaluation. As part of the controls phase, the student teams determined the baseline alcohol and acetaldehyde concentrations in the bloodstream given a low quantity alcohol input for a healthy average male. Then the students were asked to compare those results to results obtained from a subject who had a physiological condition that altered his

individual alcohol metabolism. Students were then introduced to studies of the effect of alcohol on East Asian populations having a genetic mutation that decreases the rate at which acetaldehyde is degraded, leading to the condition known as "Asian blush". Because of increased blood acetaldehyde, a person affected by this condition will experience stronger hangover symptoms with less alcohol consumption compared to the average human male [7, 9, 10]. For the purposes of this project, this effect is simulated by decreasing the reaction rate of acetaldehyde degradation, leading to a high level in the blood at steady state. Since the drug Disulfiram also raises blood acetaldehyde, this study provides a benchmark for the testing and evaluation phase of the project where students determine the efficacy of their particular hypothetical drug "Vaxachug".

In working through the project, the students scale down their human-sized alcohol metabolism model to one of microscale proportions for a "body-on-a-chip" experiment and determine the feed rates of water and alcohol needed to achieve the same performance as the larger macroscale "human" model. Similar to the traditional scale-up of chemical processes, students determine the dimensionless ratio of flow rates in the human blood stream and those in a hypothetical poly-dimethylsiloxane (PDMS) microfluidic chip and use that value as a scaling factor. Students also learn how scaling down processes can help with reagent consumption and practice a technique for process scaling that will be used in later design courses.

Scaling was an important aspect of this project because traditionally, the chemical engineering curriculum stresses the scaling up of laboratory chemical reactions to larger chemical processing unit operations and often students enter the class with the bias that chemical engineering means "scaling up". Particularly as studies of biochemical reactions in microbiological systems, such as proteomics or in microfabricated devices as in the body-on-a-chip described here, are so prevalent in the chemical engineering research literature, it is important that students are exposed to the possibilities and advantages for scaling down chemical processes and the related career choices.

Student appreciation of the significance of scale down on several levels (efficiency, safety, economics) is illustrated, for example, by this comment in a student team report: "The purpose of creating a simulation on a chip is significant. If we do not use the lab-on-a-chip, drug trials will have to be done on humans. This is costly, time consuming, and difficult. But a lab-on-a-chip is simple and involves no risk to human subjects. Therefore it allows for much quicker, safer, and cheaper trials on drugs."

Higher level thinking skills: student evaluation of drug efficacy

Finally, student teams use their model and 'data' acquired from testing the control cases to test one of eight potential drug formulations developed by their mock "pharmaceutical employer". Ideally, the clinical-phase drug is designed to work similarly to Disulfiram and thus should spike acetaldehyde levels in the blood with low amounts of alcohol consumed. However, to further motivate this exercise, students are informed that of the eight drug formulations only a few of the drug formulations would actually work as intended and therefore the students must test their formulation and determine, based on the resulting blood composition, whether their drug formulation meets the intended therapeutic goals of the drug. Several of the 'dud' formulations

were designed with specific side effects engineered for students to discover while conducting their analysis. An example is a formulation which increased acetaldehyde levels to ten times that of the concentration of someone afflicted with Asian blush syndrome. A project group with this formulation had the opportunity to recognize that with the physiological symptoms induced by increased acetaldehyde levels such as nausea, vomiting, and headaches that a drug that artificially spiked acetaldehyde levels to such proportions might prove to be a health hazard rather than a therapeutic drug. Ideally students would delve deeper into the analysis by discussing these ramifications.

The type of in-depth analysis of drug efficacy and potential dangers in the drug formulation aids in the development of the last teaching goal of the project, developing analytical analysis skills and engineering judgment. Rather than just reporting values and error, the students are asked to think about the significance of their results and evaluate their drug formulations within a set number of criteria, key amongst those being raised acetaldehyde levels similar to those of someone with Asian blush syndrome. The framing of the project provides the students with boundaries and a scope similar to what they would be asked to do as part of a professional engineering team rather than just finding a single numerical answer. One of the quotes below, shows an example of a team that got into the spirit of acting as a consulting company.

As a result of not knowing in advance how their drug will perform and including a range of results with assorted consequences, we can raise the student's level of learning in Bloom's taxonomy by encouraging students to conduct a thorough analysis and evaluation of their model and drug while at the same time reinforcing that mass balances are easily applicable to a realistic engineering scenario. Proof of student achievement of higher-level thinking skills such as analysis, evaluation, and creating new applications is provided below in excerpts from student reports.

Excerpts from student reports demonstrating higher-level thinking (Note, Vaxachug was the name given to the test drug in the project.)

"Although the drug does not produce the desired effects, it could still be commercialized if it were advertised as a drug that decreases the symptoms of alcohol ingestion and reduces hangovers. In addition it could be useful for people who want to drink in social gatherings but have to drive back home after. The drug Vaxachug would diminish the symptoms of intoxication while lowering BAC and the person would be able to drive normally. There are, however, side effects that would require further research to ensure the drug is safe and effective."

"Since Vaxachug increases the rate at which alcohol is converted to acetaldehyde (the single-pass conversion increases by 10%), it forces the cells to absorb more oxygen from the blood. As a consequence, the body might not have enough oxygen supply, causing fatigue and hypoxia of certain tissues of the body…."

"…the drug is at best a double-edge sword and should be used with caution. A person who has preexisting medical conditions in kidney, liver, and heart is at a greater risk under Vaxachug for even very moderate drinking."

"Vaxachug perhaps proves to be overly effective in its increase in the body's acetaldehyde levels. The rate at which a person taking Vaxachug while drinking feels the effects of alcohol is roughly 38 times greater than a person without the drug. Although Vaxachug does not affect the person's BAC level, it does alter the person's breath composition of acetaldehyde. A person taking the drug will appear to have a lower BAC when given a breathalyzer test than is accurate. Therefore, a new test would have to be implemented so that law enforcement officers would be able to tell whether or not the breathalyzer test is showing a skewed reading. Though Vaxachug proves to be an effective drug, the level at which it is effective may be too high and cause too many other negative implications for standard, commercial use."

"Through the use of … Vaxachug an individual would be able to drink more and still become substantially intoxicated with the physical and mental affect through increase in BAC, while not being punished for the abuse of the liver and kidneys the next morning. Overall this drug would be a failure at curbing alcoholic behavior but would not harm the body in other ways; permitting it to be put to use for other functions (such as lessening "Asian blush" by lowering the amount of acetaldehyde in the blood) …By keeping these relationships in mind the test of the successfulness of curbing alcoholism through drug scenario #4 of Vaxachug was proven unsuccessful. …After the completion of this study we will retain all our data and our mass balance around the human body, permitting the test of any future drugs which hopefully have more fruitful results for your company."

Feedback from students after reflecting on what they learned during the biotechnology project

After the conclusion of the semester we asked individual students after having time to reflect on the biotechnology project, what they learned from it to determine if we had met our pedagogical and technical goals. Questions and selected responses from students are summarized below.

Free response question: What did you think of the application areas that we included with the alcohol project? (Human health - Asian blush, Drug delivery- Vaxachug, or scale-down-microchip question)

"I think the human health aspect was very important (like knowing how detrimental alcohol can be on the body)… I think it was important to have the drug delivery part of the project because it made it more realistic. And I liked learning about the microchip because that or something like that could show up in any future job."

"I thought it was a very creative way of combining many concepts into one project. Although it was very simplified, the project gave an overview of some biological aspects of human body that Chemical Engineers normally do not encounter unless they are very interested in biology. Also, investigating into Asian blush, the effects of drinking in human body, and drug delivery were interesting enough to get the students' attention…"

Free response question: Did you feel that the way the project was designed helped you to think more deeply about mass balances and the kinds of problems you could solve using them?

“The project certainly helped me to think more deeply about mass balances. I've already started to think about other systems as potential "mass balance systems" i.e. I no longer just think of mass balances as applying to chemical factories.”

“This project definitely helped me see that mass balances are actually something we use and that it won't be a useless tool when we graduate. At the very beginning of the project I couldn't envision how we would create a mass balance of the human body but by the end of it I felt like I completely understood how everything worked. I gained skills to take something as complicated as the body and size it down to use it on a spreadsheet.”

“I definitely felt that the project helped me think more deeply about mass balances and the kinds of problems I could solve using them. One particular problem that stands out in my memory is the one where we had to figure out what parts of our drug formulation caused the BAC or acetaldehyde concentration to change, and then explain why. We had to really think about how the recycle streams affected the concentrations in the streams.”

Free response question: Was there anything about the project you really liked, something that stood out or you thought was really cool?

“My favorite part of the project was learning about how drugs like disulfiram worked. I actually had fun changing the specifications of our spreadsheet model and watching what happened as a result.”

“I definitely liked this project the best. I felt like it was very straight-forward but challenging. I actually really liked learning about the body and seeing what alcohol does in the body.”

“We were surprised when some changes didn't affect the BAC or acetaldehyde, but then we realized we could reason it out. And, as with the other projects we had in this class, it's always fun to be able to reduce common, everyday phenomena to mass balances that college sophomores can simulate.”

Student evaluations responses regarding project goals

Anecdotal evidence suggested that students enjoyed the new biotechnology project and benefitted from working in projects teams on it. Preliminary results from student focus groups run by an independent evaluator also indicated that the students preferred this new biotechnology project to the first project in the course that was a more traditional industrial engineering application (sizing sulfur dioxide scrubbers in a coal fired power plant).

A second independent evaluator’s survey included questions on how students viewed teamwork on the projects. Of the 36 student-respondents, 92% agreed or strongly agreed they felt like productive members of their group and 80% felt that group members helped each other. Only 3% disagreed that their group was successful in meeting project goals. Most students did not agree that they would rather have done the project themselves.

To further evaluate whether we met project goals, two specific questions on the projects were added to the course evaluation. Students were asked to provide a numeric score (1 = not at all to 5 = very much so) and could include comments. Some students only provided comments and so are not included in the numerical tally. The questions, the goals being evaluated, and the results are summarized below.

Question 1: Did the projects help you relate the course material to real engineering applications and facilitate applying the course concepts and skills to a more complex problem?

One of the objectives of adding the biotechnology to the curriculum was to connect fundamentals to real-world problems and give the students an opportunity to develop higher-level thinking and analysis skills. The average response was 3.86, indicating that this objective was met.

Question 2: Did the group project topics give you a sense of the variety of topics and range of scale of problems addressed by the chemical engineering discipline?

We added two more projects to the course this year to span the range of size scales that chemical engineers work on and to broaden and modernize the topics in the curriculum. Only the biotechnology project addressed process scale down. The average response was 4.13, indicating that the students recognized the value of scaling analysis as a part of chemical engineering and appreciated the exposure to the breadth of topics that could eventually be pursued as careers.

Feedback from student peer evaluations on the teamwork experience and interactive learning during the biotechnology project

98% of the students individually evaluated their group's function and their peer's efforts following the biotechnology project. Of these evaluations, only 5% were unhappy with their group's functioning and an additional 7% were fairly neutral about their groups function. The remaining 88% had positive and strongly positive things to say about their groups and the groups' dynamics. 16% of the students specifically commented on taking advantage of the diversity of skills in their group. Many students noted a synergy effect of cross-checking and discussing approaches and answers. Excerpts of student feedback illustrating these growth areas are given below.

Delegating work

"We were really good in terms of dividing work. However, instead of having one person completely in charge of some parts, we crosschecked our answers to make sure we were doing it correctly…. I would love to work with my group members again in the future, not only for this class but for other classes as well."

"The strengths of our team were that we were diligent. We all shared different abilities and delegated these jobs to each person. However, this does not mean we excluded each other from learning about how we did our parts. It was a team effort with each person spearheading a different part of the project."

Synergism in teamwork

"Where we really benefited in this project was in our combined abilities to problem solve…. At times we would split into pairs, each group using a different method to try to fix the problem and then compare results. Sometimes one group would be right, but at other times we found where both groups went wrong and were therefore able to recognize the correct approach… Overall, our group was extremely enthusiastic about this project and dedicated a significant amount of time to making sure we did the best we could, which really benefitted the group in the end."

"It was good that we worked together on most everything. This way we were able to finish more efficiently than if we had all worked independently. This also ensured that everyone participated."

"Our main strengths were our good problem solving skills in a group because we would discuss different approaches to solving a problem and together come up with the best solution."

Communication and Cooperation

"The group worked on each step together so that we all understood it and then divided the write up. That was a really good strategy because it allowed us to always be able to help each other because we all actually knew what was going on in each part. We also all discussed any assumptions we were making and we all double checked each other's work if work was done separately."

"Our team's biggest strength is everyone came to every meeting overly prepared. The more work we did as individuals to prepare, the smoother group meetings went and we were easily able to obtain the correct answer quickly. We had a challenge writing the final draft. We communicated with each other if we were stuck and gave ideas to one another."

"The members of my team were all very amiable and ready and willing to work with each other. The two guys and two girls ratio worked very nicely, as well as having members who fit specific roles (i.e. the number crunching math guy, the administrator and compiler, the editor and checker, the preparer and instigator of work)."

Responsibility and project success

"This group worked extremely well together. Everyone contributed, and so no one had to assume any disproportionate leadership or workload. We had a few key early meetings that got us off to a good start and kept us on an effective pace."

"This time, instead of doing things separately, our team adhered into one strong group and everyone participated in solving the problem. At any major team meeting, all members showed up and stayed through. I like this approach."

"Everyone in the group worked hard and simultaneously at different parts of the project so we were able to get the work done quickly and efficiently."

Summary

Development of a team-based biotechnology project on the metabolism of alcohol was an effective way to modernize the *Mass and Energy Balance* course. This project promoted teamwork, communication, and cooperation, while exposing students to modern biotechnology topics related to chemical engineering. The concepts of scaling down a process, creating in vitro models of biological processes for testing and design of pharmaceuticals, and development of engineering judgment and ethics in evaluating efficacy of drugs on human health was integrated into this project. Student response to the project was very positive and reinforced the pedagogical change to this type of interactive group learning experience as a way to reinforce fundamentals in chemical engineering in a contemporary real-world example.

Acknowledgments

Thanks to ____ for help with the independent evaluation of the course projects. We acknowledge _____ grant # 150 for funding some of the work including here.

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