

Freshman Chemical Engineering Experiment: Charged up on Electrophoresis & Brewing with Bioreactors

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Abstract

A freshman Introduction to Chemical Engineering seminar course can be a useful part of the undergraduate curriculum. Goals for such a course range from gaining an appreciation for chemical engineering manufacturing processes and safety, to an overview of the subject areas students will become proficient in by the time they graduate. This article discusses two experiments, Charged Up on Electrophoresis and Brewing with Bioreactors, which are used to enhance the introductory chemical engineering experience. Electrophoresis and bioreactor processes are brought to life via an introductory lecture, assignments, and a simple desktop experiment that utilizes inexpensive supplies to demonstrate electrophoretic separations and bioprocessing. Advantages of these hands-on experiences include that they are not dependent on the availability of lab space, and students have a unique experience to link into their evolving understanding of chemical engineering concepts. Complete supply lists, pre-assignment exercises, experimental procedures, and lab mats are discussed for both experiments and available for instructor use.

Keywords: Freshman course, Electrophoresis, Bioreactor, Experiment, Inexpensive equipment

Introduction

At Mississippi State University, our 1-credit hour freshman seminar course has been designed to introduce students to the Chemical Engineering field. The class meets once a week for 50 minutes with about 15 contact sessions in the fall semester. The objectives of the course are multifaceted and include having the students

- Gain an appreciation and knowledge of chemical engineering as a career,
- Perform laboratory activities that illustrate key chemical engineering concepts,
- Gain experience in oral and written communication skills,
- Gain an appreciation for chemical manufacturing processes,
- Be introduced to MSU chemical engineering faculty and the curriculum.

Laboratory activities are valuable instrumental tools that tie these objectives together. This paper discusses two such laboratory experiments, Charged up on Electrophoresis and Brewing with Bioreactors. For clarity, all of the activities associated with Charged up on Electrophoresis are discussed first in section 1. Section 2 follows a similar format with discussions of the lectures, supplies & setting up, experimental procedure, and student work & assignments.

The concept of including a freshman seminar in the curriculum is not novel¹⁻⁴, and has been integral to facilitating contact with and retaining freshman chemical engineering students who traditionally do not take classes in their area until their sophomore year. Within these freshman seminars, a number of experimental approaches have been discussed in the literature including the fascinating ideas of freshman design in chemical engineering⁵, or reverse engineering a brewing process⁶. Other creative approaches are organism level experiments such as energy balances and respiration in the human body^{7,8} or modules that closely integrate biology into the curriculum⁹. Biochemical engineering experiments have become more prevalent mainly in upper level courses¹⁰⁻¹². However, many of these experiments require special facilities, limit class size, and may even require costly equipment.

Both experiments, Charged up on Electrophoresis and Brewing with Bioreactors, have also been conducted in conjunction with programs such as the Ameritech Precollege Minority Engineering Program at the University of Notre Dame (APMEP)^{13,14}, and the University Familiarization Program for Minorities in Engineering (UFPME) at Mississippi State University¹⁵. APMEP was particularly notable because Minerick facilitated the activities via teleconferencing with high school students performing experiments on their classroom desk. UFPME experiments were conducted on folding tables and chairs in a large loading dock. The authors recommend that when conducting these experiments with greater than 25 students, a few Laboratory Assistants be recruited to help set up and facilitate the 30 to 40-minute experiments.

1. Charged up on Electrophoresis

Activities associated with the Charged Up On Electrophoresis experiment span four contact sessions, but only two need to be dedicated solely to this topic. The first is an introductory lecture that reviews basic knowledge, industrial applications, and teaches the students important equations and procedures. At this first contact meeting, a preassignment and experimental procedure is handed out; the preassignment is due the following week, just prior to the experiment. The experiment is conducted in teams of two during the second contact session. Each team is assigned to one of four salt solution concentrations. The procedure can be completed within about 30 minutes leaving plenty of time for explanations, corrections, and clean up. The students leave the lab with the data they have collected and are asked to work with their lab mate to calculate mobility of the ions in solution. They turn these results in at the beginning of the third contact session. The instructor compiles the ion mobility results, organizes it by the four salt concentrations, and distributes this to the entire class. The teams then write a two-page report complete with tables and graphs discussing their results and how they compared to the

class mobility trend as a function of salt concentration. These reports are turned in during the fourth contact session. The experiment and each stage of the learning experience are discussed in the following sections.

Lecture

During the first contact session, we conduct a traditional introductory lecture that reviews basic knowledge and teaches the students important equations and procedures. The specific topics covered in the introductory lecture include:

- Highlight on Dr. Meredith C. Gourdine, an athlete, physicist, and engineer who pioneered research on electrogasdynamics (EGD)¹⁶
- Industrial electroseparations
- Ions, cations, anions¹⁷
- The formation of ionic compounds
 - Example / Class Activity
- Ionic Radii
 - Example
- Ionic Strength¹⁸
 - Coulomb's Law
 - Lewis & Randall
 - Example / Class Activity
- Electrolysis Reactions
 - Balance an equation
- pH changes and indicators¹⁷
 - Additional handout
- Electrophoretic mobility
 - Example / Class Activity

The biographical highlight of Meredith Gourdine is an effective way to draw attention to a renowned and accomplished minority in an area related to the experiment¹⁶. It also serves as a transition into talking about the many possible paths one takes to success in life. Some of the industrial applications described in Farrell's "Exploring The Potential of Electrodialysis" are discussed in lecture and explored by students in the preassignment¹⁹. In addition, the authors hope to continue to integrate such electrical separations modules throughout the MSU curriculum. Next, the lecture reviews some fundamental chemistry and we talk about applying this knowledge to the electroseparation tools used in the experiment and by chemical engineers.

Over the past two years, Minerick has been unable to finish the lecture up to calculating the electrophoretic mobility. However, this works out just fine because the pre-assignment and the experimental procedure reading assignment reinforce these ideas. These assignments are handed out in class and due at the start of the experiment the following period. The conclusion of this first contact session is also a good time to remind students about proper dress in the

"laboratory." Frequently students come up with questions at the end of class. They enjoy being engaged in a topic that relates to their chemistry classes, but has an entirely different twist.

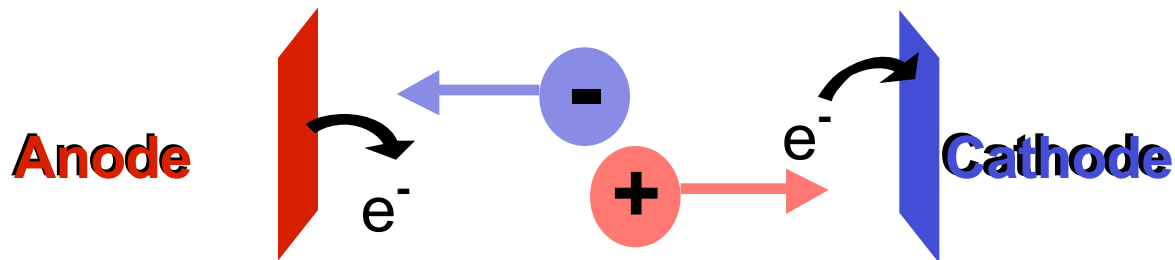
PreAssignment & Readings

The prelaboratory assignment includes a review of ionic charges, ionic bonding rules, and a short exercise where the students are asked to look up definitions and describe the following concepts in their own words. This activity prompts them to begin using terminology necessary for their experiment and lab report.

- | | |
|--------------------|-------------------------|
| 1. electricity | 5. anode |
| 2. ionic solutions | 6. electrical potential |
| 3. electrophoresis | 7. electrical field |
| 4. cathode | 8. mobility |

Lastly, the students are asked to write a brief summary of electroseparations in industry building upon the list discussed in class¹⁹.

The following is an excerpt from the discussion the students read prior to session two, the experiment. **Electrophoresis** is the migration of charged particles or molecules through a solution under the influence of an applied electric field usually provided by immersed electrodes. Particles with a positive charge go to the cathode (negatively charged electrode) and negative charges go to the anode (positively charged electrode). Electrophoresis is widely known in its role in determining the human genome. This method can separate proteins or nucleic acid chains; analysis of the rate of movement (mobility) of each component in a gel, the molecular structure can be deduced.



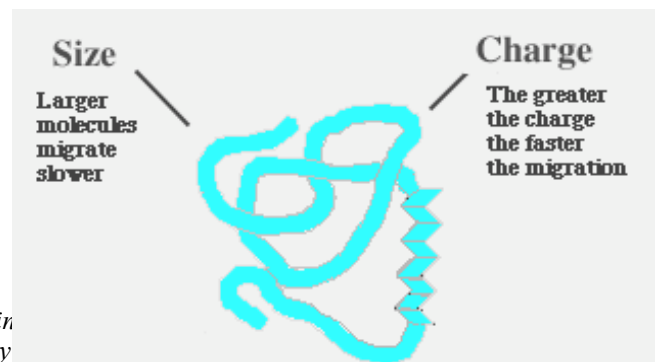
We are going to measure the **mobility, or rate of migration**, of NaCl ions in a water filled tray.

Mobility, μ , of a charged ion is described by

$$\mu = \frac{q}{6 \cdot \pi \cdot \eta \cdot r} \quad \left(\text{mobility} = \frac{\text{charge}}{6 \cdot \pi \cdot \text{viscosity} \cdot \text{radius}} \right)$$

Where q is the charge of the ion, η is the viscosity of the solution (water in our case = 1 cp), and r is the ionic radius of the ion.

The electrophoretic mobility, μ , of ions in solution can be obtained from experimental



data by taking the **velocity of the ion, v , divided by the electric field, E .**

$$\mu = \frac{v}{E} \quad \left(\text{mobility} = \frac{\text{velocity}}{\text{Electric Field}} \right)$$

The electric field is the **voltage divided by the length** between the anode and the cathode.

$$E = \frac{V}{l} \quad \left(\text{Electric Field} = \frac{\text{Voltage}}{\text{length}} \right)$$

The students then use these equations to calculate mobility, μ , from the ion velocity data they collect during the experiment.

Supplies & Setting Up

These supplies will need to be ordered some time in advance.

For each team of students (~2 students per team):

Clear sample tray (Heathrow Scientific® Multi-Channel Solution Basin: obtained from Daigger Cat # RX205808AX)
9V battery
9V battery adaptor (RadioShack)
stopwatch timer

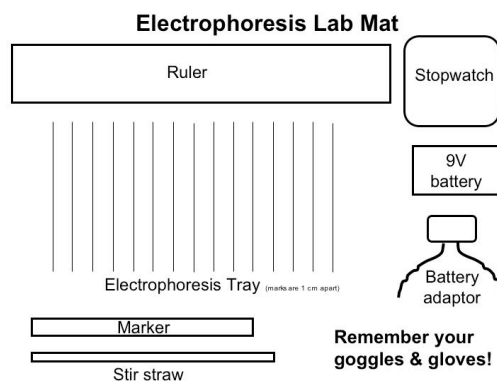
ruler
1 stir straw
2 pairs of goggles
2 pairs of gloves
10 mL graduated cylinder

For the laboratory:

25 mM Bromothymol Blue Solution (CAS # 76-59-5)
1 M Sodium Chloride Solution
DI water
Waste containers

pH paper
electrical tape
scissors
paper towels

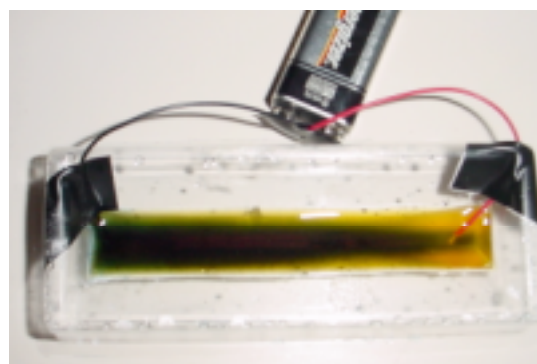
Typically, it takes less than an hour before the class to set up experiment stations for 40 to 50 students. Placing all of the equipment on lab mats helps facilitate this process. A sample Electrophoresis Lab Mat, which can simply be photocopied on letter paper is shown at right. The authors recommend recruiting Laboratory Assistants (approximately 1 per 25 students) to help set up and facilitate. At MSU, AICHE student chapter members help as a component of their departmental service.



Charged Up On Electrophoresis Experimental Procedure

The following is an excerpt from the experimental procedure the students are given. Lay out your materials for your electrophoresis apparatus. **You should put on your goggles and gloves now.**

- Step 1. Using the electrical tape, attach your wire adaptor to your electrophoresis tray. Refer to the example setup in the photograph. Make sure the exposed wire is close to the bottom of the trough. Do not connect your 9V battery yet.
- Step 2. Place the electrophoresis tray on the 1 cm lines on your electrophoresis lab mat. Number the lines starting at 0 on up to 15 cm. This will be



used to measure ion movement. **Record the total length of your tray on the Results Page.**

Step 3. Measure out 10 mL of Bromothymol Blue pH indicator using your graduated cylinder. Carefully pour this into your electrophoresis tray. **Record this amount on your Results Page.**

Step 4. Using your graduated cylinder, measure out the amount of NaCl solution and E-pure H₂O that corresponds to your group. Carefully pour this into your electrophoresis tray. **Record these amounts on your Results Page.**

Group A	10 mL NaCl	0 mL E-pure H ₂ O
Group B	7 mL NaCl	3 mL E-pure H ₂ O
Group C	5 mL NaCl	5 mL E-pure H ₂ O
Group D	3 mL NaCl	7 mL E-pure H ₂ O

Step 5. Stir with your stir straw until everything in the tray is well mixed. Connect the 9V battery to the wire adapter. **Start your timer now.**

Step 6. **Record** the time that the blue color reaches each 1 cm mark on the electrophoresis lab mat.

Step 7. At various times during the experiment, use the pH paper to test the pH along the length of the tray. Just dip one end of the paper into the liquid and compare the color to the scale on the container.

Example Results Page

Step 1. The voltage that will be applied is _____ Volts

Step 2. The total length of the tray is _____ cm
The electric field is _____ Volts/cm

Step 3. Amount of Bromothymol blue indicator _____ mL

Step 4. Amount of NaCl solution _____ mL
Amount of E-pure H₂O _____ mL

Step 5. Total liquid in the electrophoresis tray _____ mL

Step 6.

Hash mark (cm)	Time (min: sec)	pH (optional)
1 cm		

Final Lab Report

With freshman, we have found it is extremely important to clearly communicate what is meant by a lab report and what it should contain. In Fall 2004, we provided the following set of instructions:

Please write the 2-page lab report with your partner and turn in only one copy with both of your names on it. Use your data to develop Excel plots of blue color position versus time and pH versus time (optional). Specifically, the lab report should contain 1) a brief description of electrophoresis, 2) a summary (in your own words) of the experimental

procedure and data collection methods, 3) a step-by-step narrative of your calculations to obtain mobility, 4) a summary of results obtained (include plots here), 5) a comparison of your results with class results (table format is good), 6) a paragraph or two discussing what you think the results mean, and 7) draw conclusions from this discussion.

Reports are turned in, graded by the instructor, and returned prior to the second experiment.

2. Brewing with Bioreactors

Activities associated with the Brewing with Bioreactors experiment span four contact sessions, but only one needs to be dedicated solely to this topic. The first contact session need only be 10 to 15 minutes at the end of another class and serves as a brief introduction to bioremediation / bioreactors. We find it useful to tie this discussion back to the research lab tour the students went on at the beginning of the semester (we have an extremely active bioremediation research team in the department). Also during this introduction, a preassignment and experimental procedure is handed out; the preassignment is due the following week, just prior to the experiment.

The experiment is conducted in teams of two with each team assigned to one of four sugar concentrations. The procedure can be completed within about 40 minutes leaving time for questions, discussions, and clean up. The students leave the lab with the data they have collected and are asked to work with their lab mate to calculate lag time, maximum and minimum bubble rates, temperature cooling curves, and biomass height in the bioreactor. They turn in their results on lag time and maximum bubble rate in at the beginning of the third contact session. The instructor compiles the data, organizes it by the four sugar concentrations, and emails the summary to the entire class. The lab mates once again work in teams to write a two-page report complete with tables and graphs discussing their results and how they compared to the trend in the class. These reports are turned in during the fourth contact session. The experiment and each stage of the learning experience are discussed in the following sections.

Lecture

During the first contact session, we conduct a short (<15 minute) introductory lecture that draws student's attention to basic principles and important concepts. The specific topics covered include:

- Highlight on Dr. Mae C. Jemison, a physician, astronaut, and chemical engineer who become the first female African-American astronaut to blast off into space²⁰.
- Mass balances
- Raw materials, products and by-products
 - Example / Class Activity
- Population life cycles of single celled organisms²¹
- Reactions within a batch reactor through the metabolization of sugar to CO₂ and ethanol²¹

- Antifoaming agents or other necessary additives in bioprocessing²¹
- Value of finished product leaving the process

The biographical highlight of Mae Jemison²⁰ compliments the discussion in the handouts about NASA developing bioreactors to metabolize human waste (solid, liquid, and gas) on spaceships into breathable air, water, and fertilizer for plants²². The brief lecture discusses that students will monitor the phases of growth of a bread yeast population in a tiny bioreactor. A sample growth curve can be obtained from "Biochemical Engineering" by Blanch and Clark²¹. From the discussions in class, the students have been introduced to the idea that mass is conserved in every process. We discuss the two processes occurring in a bioreactor: the cellular process and the bioreactor itself. For the cellular process, the students learn that cells eat food and excrete waste. Food in our system is sugar, which the cells take in and metabolize to CO₂, ethanol, and hydrocarbons (waste). The instructor explains that they are going to monitor CO₂ production by watching how much gas is produced from their desktop bioreactors. The pre-assignment and the experimental procedure handouts reinforce these ideas and include short activities for the students to work on. These assignments are handed out in class and due at the start of the experiment the following period. Once again, the students are reminded about proper dress in the "laboratory" and the floor is opened to any questions they may have.

PreAssignment & Readings

The preassignment includes discussions on batch versus continuous processes, conservation of mass, terminology for raw materials and products, etc. There are two main problems the students are asked to work. The first is an applesauce facility where apples enter, are peeled and cored, then added to a large cooker with sugar and water. The students are asked to calculate weight of raw materials, and figure out how much product is produced. The most common mistake is to not disregard the peels and cores. This problem also encourages the students to think about maximizing efficiency (cores used as feedstock), utilizing steam, etc. The second problem posed to the students is to extend the theme of full utilization of resources to examine recycling within the community. They usually enjoy discussing mass in / mass out when they realize the large amounts that go into the landfills. For the past two years, Minerick has also asked the students to write a brief discussion of bioproducts that chemical engineers are involved in making and ethical / environmental responsibilities of dealing with mass leaving the process. The reading contains considerable discussions on the different stages of population growth dynamics²¹. The following is an excerpt from the handout the students are given. The students are asked to match each stage of growth with its definition.

- | | |
|----------------------|---------------------------|
| _____ 1) Lag | _____ 3) Declining growth |
| _____ 2) Exponential | _____ 4) Stationary |
| | _____ 5) Death |

- a) Cell number and weight increases rapidly.
- b) Number of forming cells is equal to number dying cells. Existing cells live off of dwindling food supply and by metabolizing dying cells. Toxins build up and interfere with cell function.
- c) Time for cells to adjust to their environment before beginning to metabolize the food.
- d) Cells run out of food and population crashes. Toxins are at a lethal level and cells die rapidly.
- e) Cell growth slows down due to the crowded environment and cells competing for food.

Supplies & Setting Up

These supplies will need to be ordered in advance. If you do not have a local microbrewery, beer brewing bubblers can be purchased online fairly inexpensively²³. Other varieties of yeast can also be purchased from this store.

For each team of students (~2 students per team):

125 mL Erlenmeyer flask

400 mL beaker

Beer brewing bubblers in rubber stoppers

stopwatch timer

Thermometer

stir straws / bars

2 pairs of goggles / safety glasses

Wax pencil – transparency pen

Small squirt bottle

For the laboratory:

4 to 6 scales (0.1 g accuracy)

weigh trays / paper

weigh sticks / spoons

paper towels

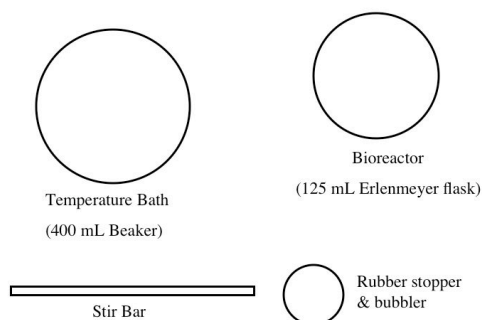
2 jars bakers yeast (grocery store)

1 lb sugar (grocery store)

2 to 3 hot plates

2 to 3 2-Liter beakers

Brewing -n- Bioreactors



The hot plates and 2-Liter beakers are to heat the water up to 120°F (shower temperature). We typically borrow this from research labs or alternatively kitchen pots and portable burners could be used. The weighing trays or paper can also be eliminated from the supply list if the students are instructed to tare the balance, then carefully add the desired weights of yeast and sugar directly to the bioreactor (Erlenmeyer flask). The drawback to this method is that students tend to weigh

out too much material and cannot correct it. Typically, it takes a half an hour before the class for the instructor and TAs to set up stations for 40 to 50 students. Placing all of the equipment on bioreactor lab mats shown above helps facilitate this process. The authors recommend recruiting Laboratory Assistants (approximately 1 per 25 students) to help set up, and facilitate the experiment. At MSU, AIChE student chapter members help as a component of their departmental service. We usually ask the freshman students to clean up their desk at the conclusion of the experiment.

Brewing with Bioreactors Experimental Procedure

The following is an excerpt from the experimental procedure the students are given. Lay out your materials for your bioreactor on your lab mat. **You should put on your goggles now.**

Step 1. Weigh out 2 grams of yeast (microorganism) using weighing paper on the scales and carefully pour this into your bioreactor (Erlenmeyer flask). Weigh out the amount of sugar (food source) that corresponds to your group assignment and add that to the bioreactor.

Group A (High Sugar)	4 grams sugar
Group B	3 grams sugar
Group C	2 grams sugar
Group D (Low Sugar)	1 gram sugar

Record these weights on the Results Page.

Step 2. Fill your bioreactor with 50°C (~120°F) water to the 75 mL line (milliliters are the same as cc's or cubic centimeters which are also written cm³). **Record this amount on your Results Page.**

Step 3. Stir rapidly with your stir bar until the yeast and sugar are completely dissolved. Push the stopper with the bubbler in it into the bioreactor flask until it is snug (IMPORTANT - THIS MUST BE SNUG SO THAT NO CO₂ ESCAPES).

Step 4. **Start your timer now.**

Step 5. Remove the cap from the bubbler apparatus on the top of the bioreactor. Using your squirt bottle, fill the bubbler with water up to the line marked with the arrow in the photograph.

Step 6. Place the entire bioreactor (flask and bubbler) inside the temperature bath (beaker). Fill the beaker to the 250 mL mark with warm 50°C (~120°F) water. Place the thermometer in the bath and record the temperature on your Results Page.

Step 7. Your bioreactor is now together. **On your Results Page, record the time of each bubble and the temperature.** You may plot the results as you go on the chart provided, but you must also plot them later using Excel.

Step 8. Keep track of the height of the biomass in your bioreactor by using the wax pencil to mark liquid height on the outside of the flask. These volumes can be recorded and should be discussed in your lab report.



Example Results Page

Step 1: Exact weight of yeast, $W_y =$ _____ grams

Exact weight of sugar, $W_s =$ _____ grams

Step 2: Weight of 50°C water added, $W_w:$

Amount of water added = _____ mL

Density of water = 1 gram / mL

Total weight of water added, $W_w =$ _____ grams

What is the total mass entering the reactor? $W_T =$ _____ grams

Step 7:

<i>Bubble #</i>	<i>Timer</i>	<i>Temperature</i>
initial	0.00	
1		

The rate of bubble production can be determined from your raw data or from your graphs. This is the number of bubbles produced over a period of time. Locate the 2-minute period of time in which the number of bubbles produced was largest. Use this to calculate the maximum bubble production your biomass showed.

- Maximum bubble rate, $R_{\max} =$ _____ bubbles / sec
- What growth phase was this? _____
- Use the same strategy to determine the minimum bubble rate. $R_{\min} =$ _____ bubbles / sec
- What growth phase was this? _____

Graph your temperature results:

- What was the rate of cooling (calculate from temperature data)? $R_{\text{cool}} =$ _____ °C/sec

Final Lab Report

The final report for Brewing with Bioreactors followed the same format as was described in the Charged up on Electrophoresis experiment. However, for this report, students are asked to compare the effects of sugar concentration on lag time as well as maximum and minimum bubble rate. The student's reports improve dramatically with this second experiment. For them, having the experience of completing a second experiment provides the opportunity to improve and learn from the feedback. The students seem more comfortable comparing results now that they know each other better and have done it before.

Student Performance Evaluations

Students were evaluated based on a more traditional seminar class rubric. The syllabus outlined that class attendance was necessary for them to learn the material. Role was taken each class period and participation recorded by the second instructor. Each student was allowed one unexcused absence, and further absences resulted in a zero for the day. The overall semester breakdown was as follows:

- Class Attendance & Participation: 25%
- Homework & Lab Reports: 50%
- Final Project/Poster Presentation: 25%

Experimental PreAssignments (individual) were out of 50 points and lab reports (team effort) were graded out of 100 points. For the preassignments, 25 of the 50 points were allotted to working the problems while the second 25 points were distributed based on their essays discussing chemical engineers roles within industrial applications of electrophoresis and

bioreactors, respectively. The final lab reports were graded partially based on the student's ability to describe the project and their understanding of what physical mechanisms occurred during the experiment (50 points). The last 50 points of the lab report were earned based on the data the students had collected, the plots they developed from the data, and their comparison with class trends. In this last section, they were asked to draw conclusions. The students learned quickly from the feedback they received on the first set of reports and demonstrated significant improvement on the second lab report of the semester.

Student feedback on the course was positive. Many students commented that the experiments were the best part.

Conclusions

Two simple experiments for a freshman Introduction to Chemical Engineering seminar course can be useful tools to introduce young students to separations and bioreactors while highlighting expectations in the undergraduate curriculum. This article discussed two experiments, Charged Up on Electrophoresis and Brewing with Bioreactors, which are used to enhance the chemical engineering introductory experience. This article briefly discussed the introductory lecture, assignments, and simple desktop experiments, which utilized inexpensive supplies to demonstrate electrophoretic motion in an aqueous media and yeast population growth phases. Advantages of this hands-on experience include that it is not dependent on the availability of lab space, and students have a unique experience to link into their evolving understanding of chemical engineering concepts. A complete supply list, pre-assignment exercises, experimental procedure and lab mats were briefly discussed; full versions are available for instructor use upon request.

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