Online Unit Operations Lab, a Difficult Balance

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Abstract

As a result of COVID-19, teaching Unit Operations Laboratory in an online format became necessary in Spring 2020. Implementing experiments, which could be easily conducted from home, or at least away from the standard lab environment, but were challenging in nature, proved difficult. In particular, the labs needed to be amenable to theoretical treatment and significant uncertainty analysis. In addition, the topics studied had to cover the usual range of material: fluid mechanics, heat transfer, thermodynamics, separations and chemical reactions. The lab has now been taught twice during May-term in a completely online format, with mixed results. Many of the usual class features can be incorporated easily, such as student presentations in Zoom, or the number and types of reports, or lecture coverage through Canvas and Kaltura. However, while student satisfaction, as measured by their evaluations, is generally good, some concern about a lack of rigor has been expressed. Moreover, while flexibility is excellent and allows students to work outside school, communication in the online format is not as good as in a laboratory setting on campus. Some potential improvements include using Arduinos in a heat exchanger experiment, using more synchronous contact to improve communication, and implementing a chemical reaction lab with glowsticks or other materials.

Keywords

Online, Laboratory, At-home Experiments, Faculty Paper

Introduction

To accommodate the teaching changes necessitated by the global pandemic, a variety of approaches have been taken to laboratory instruction, particularly for the upper division unit operations course in chemical engineering. For example, one method is the ‘lab-in-a-box’ technique [1], [2], in which the required materials to conduct an experiment are sent out to the students. This approach allows for a high level of sophisticated equipment, such as 3D printers [2]; however, it requires that multiple units of potentially expensive devices or chemicals be available. Another method is to design experiments which require only easily obtainable materials and permit construction of the apparatus in a non-laboratory setting. While this technique does not demand acquiring, packaging and mailing out hardware and components, questions arise as to whether such experiments can satisfy the intellectual obligations for the course. Moreover, because part of the purpose of unit operations lab is to introduce students to modern processes in chemical engineering, the features involving technical advancements seem to be lost. Nonetheless, the latter teaching strategy has been adopted at the University of Minnesota Duluth for the past two summers. In this paper, I will discuss the details of the at-home experiments, student assessment of them and my own analysis of the results. Finally, recommendations for improvement will be presented.

The Experiments

The experiments that have been used the last two May-mesters are listed in Table I. In the four weeks of the term, one experiment is conducted each week, with a Technical Report, two Memo Reports and a Presentation. The labs are performed in groups of three to four students. While the lectures are asynchronous, the office hours are conducted face-to-face through Zoom. The experiments are meant to be a semi-independent, guided learning experience. All of the details for the labs are not provided to the students. Rather, they are expected to draw from previous coursework in obtaining and analyzing their results.

Table I. Experiments for May-term Lab

Title	Topics Covered
Experiment 1: Tank Draining	Bernoulli's Eqn, Losses, Discharge Coefficients
Experiment 2: Osmosis (May 2020)	Osmosis, Work, Power
Experiment 2: Heat Exchanger Analysis and Design (May 2021)	Nusselt number, Overall Heat Transfer Coefficient
Experiment 3: Oil/Water Separation	Drag Force, Terminal Velocity, Non-linear Fit
Experiment 4: Crystallization	Design of Experiments, Digital Data Analysis

To give a better idea of the labs, more details will be provided, particularly for Experiment 1. In the first lab exercise, the goal is for the students to quantitatively investigate the effects of relative orifice size, pipe length and frictional losses on the draining of a tank. When losses are negligible, Torricelli's Law suffices to model the experimental data. However, viscous effects can be accounted for by a discharge coefficient C_D and frictional losses through the pipe. Made from a two-liter bottle, a straw, duct tape and a ruler, a sample apparatus is shown in Figure 1. The Tank Draining Lab is used in a more formal setting at the University of Louisiana at Lafayette [3]. As motivation, a counter-intuitive example from CACHE is provided, in which a longer tube extending from the tank results in a shorter drainage time [4]. Suggestions for experiments include 1) at least two different hole sizes for Torricelli's Law, 2) at least two different pipe (straw) lengths with the same diameter, 3) at least two different diameters with the same pipe length, and 4) two different liquids, such as oil and water.

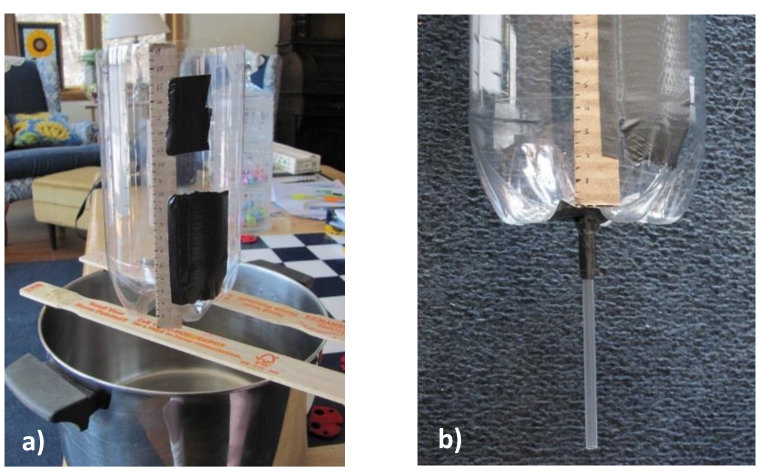

Figure 1. Sample apparatus for tank draining a) without pipe extension and b) with pipe extension.

The theoretical analysis requires applying a transient mass balance and Torricelli's Law in the absence of a pipe extension. Simplification yields a differential equation with an analytical solution for the liquid height *h* as a function of time *t*:

$$\frac{dh}{dt} = -\frac{a}{A}\sqrt{2gh}, \quad (1)$$

where *a* and *A* are the cross-sectional area of the orifice and the tank, respectively. In Eqn.(1), g is the acceleration due to gravity. Students are left to integrate (1) for themselves. Since the orifice leaving the tank has sharp edges, a discharge coefficient C_D may be required to obtain a good fit for the experimental data. Some sample results are provided in Figure 2a.

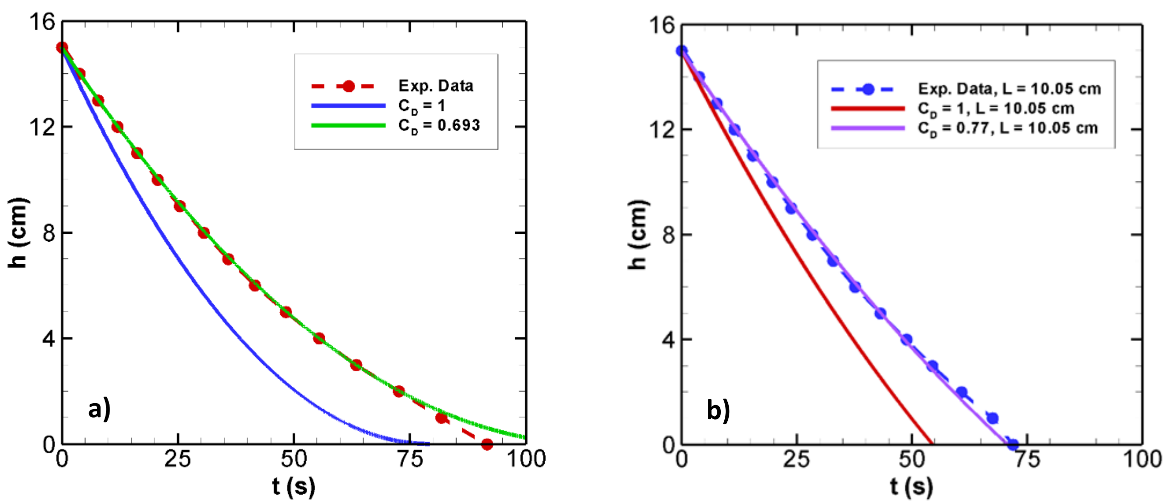

Figure 2. a) Height *h* of liquid in tank as a function of time *t* without pipe extension. b) Height *h* of liquid in tank as a function of time *t* with a pipe extension of length *L* = 10.05 cm.

With a straw extension, losses in a smooth pipe and due to a sudden contraction should be taken into account, and a more complicated differential equation for *dh/dt* is needed:

$$\frac{dh}{dt} = -\frac{a}{A}\frac{\sqrt{2g(h+L)}}{\sqrt{1+0.45(1-\beta)+4f_F\frac{L}{D}}}, \quad (2)$$

where *L* is the pipe length, β is the contraction coefficient, f_F is the Fanning friction factor, and *D* is the pipe diameter. Eqn. (2) does not have an analytical solution, so the students must use Euler's method or a similar technique for numerical integration. Again, a discharge coefficient can be included in the analysis, with more sample results in Figure 2b. Although error bars are expected in the student results, they are not provided in the examples.

All of the other experiments require data acquisition and theoretical calculations, with comparison between the two. Students are expected to do thorough uncertainty analysis as part of their write-up. In the course of teaching lab, I found that Experiment 2 (see Table I) needed to be changed between May 2020 and May 2021. While my data for the osmosis experiment worked well, none of the students was able to replicate the results. Therefore, in May 2020, I gave the groups my data and asked them to analyze it. A necessary and satisfactory expedient at the time, I substituted a heat exchanger exercise for Experiment 2 in May 2021.

In a normal May-mester, with lab taught on campus, the students model and build their own shell-and-tube heat exchangers. They then compare their builds to their theoretical predictions. Historically, this experiment has been well received by the students, and they find it very satisfying. Thus, a similar lab was presented as Experiment 2 in May 2021. Unable to come up with an easy way to conduct the experimental temperature measurements, I asked the students to verify a simulation using Wolfram software [5], [6] and to use the techniques for Nusselt number calculations to perform a heat exchanger design for given specifications. Sample output from the simulation is shown in Figure 3. One group did not understand how the Wolfram simulation

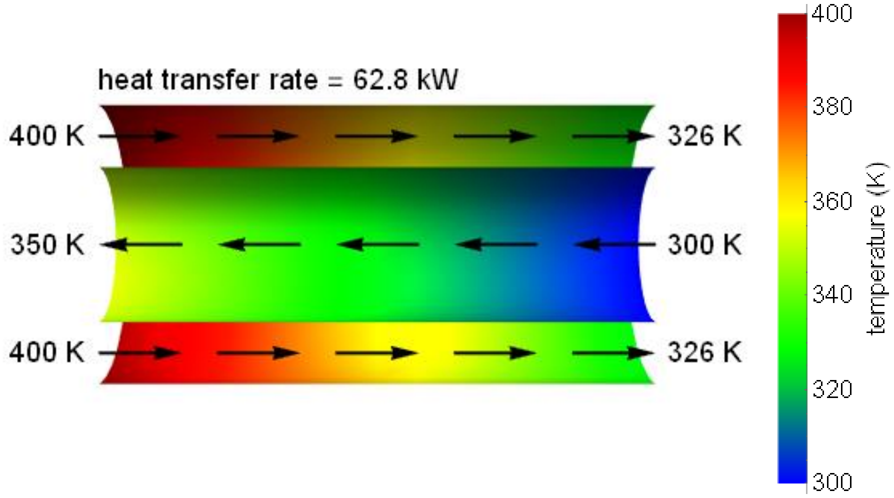

Figure 3. Sample output from the Wolfram module [6] in countercurrent flow.

fit into the heat exchanger design, so the response to this hybrid experiment was mixed. On the other hand, the remainder of the groups were all able to make the connection between the ideas.

Nusselt number correlations were necessary to find the values of the convective thin-film heat transfer coefficients h_i. Some examples, such as the Dittus-Boelter correlation for turbulent flow, are provided in the Wolfram module [6]:

$$Nu = 0.023 Re^{4/5} Pr^{1/3}, \tag{3}$$

where *Nu*, *Re* and *Pr* are the Nusselt, Reynolds and Prandtl numbers, respectively. In the design component of the lab, students needed to recognize that the flow is laminar, and different correlations have to be employed.

In Experiment 3, on oil/water separation, a simple apparatus is again required, as shown in Figure 4a. The students had to perform a non-linear fit of the data to an empirical expression [7], given in Eqn. (4):

$$R\% = \frac{R_{max}t}{k_t + t}\ , \tag{4}$$

where $R\%$ is the percentage recovery of the oil phase, R_{max} is the maximum achievable separation, and k_t is a constant defined as the time required to achieve 50% separation. The time constant k_t is the adjustable fitting parameter. If the cross-sectional area of the container is approximately constant, the height of the water phase is proportional to the percent recovery. Some sample results are shown in Figure 4b. A characteristic drop size for the dispersion can also be found using the appropriate flow regime for drag on a sphere.

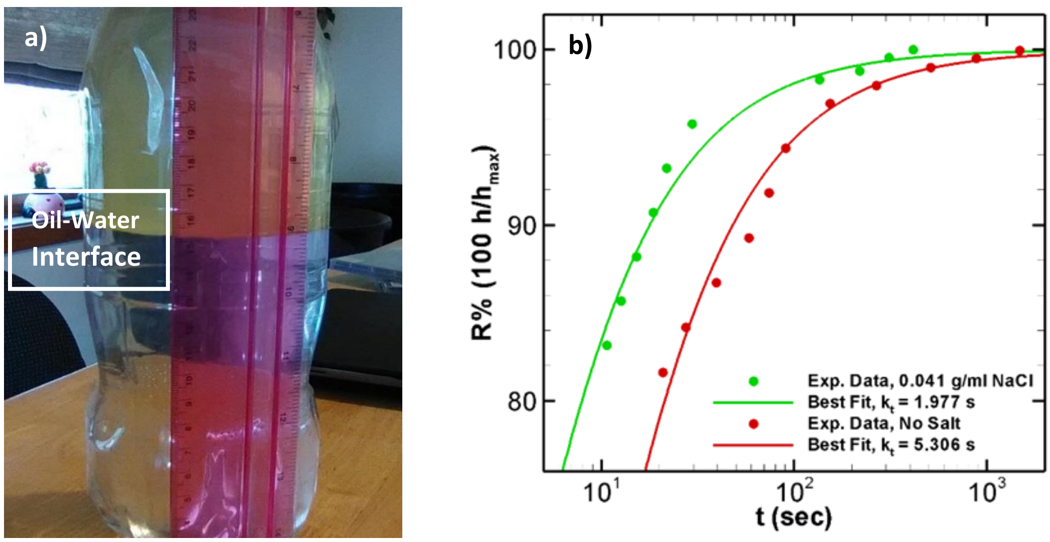

Figure 4. a) Apparatus for oil-water separation. b) Recovery of oil from water with and without NaCl at room temperature.

The fourth and final experiment was intended to be an open-ended investigation into crystallization of salt (NaCl) with a goal to quantitatively investigate the factors that affect crystal size distributions and try to obtain nearly uniform crystal sizes. The students obtained crystal samples similar to those in Figure 5a and then used image analysis software [8] to find size distributions, number-averaged sizes $\bar{a}$, volume averaged sizes $\langle a \rangle$ and standard deviations, where

$$\bar{a} = \frac{\sum_i n_i a_i}{\sum_i n_i}, \tag{5}$$

$$\langle a \rangle = \frac{\sum_i n_i a_i^4}{\sum_i n_i a_i^3}, \tag{6}$$

n_i is the number of crystals in the i^{th} crystal size category, and a_i is the length or size of the crystals in the i^{th} category A sample distribution is provided in Figure 5b.

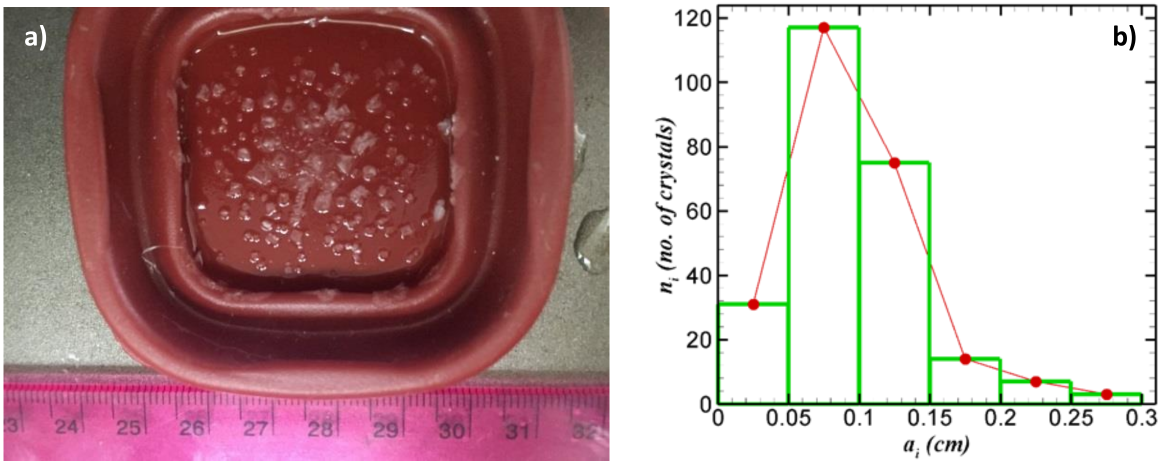

Figure 5. a) NaCl sample used for analysis in part b. b) Histogram of crystal sizes for a 2.5 mL sample of 1.03 mol/L NaCl solution after 23 hours at room temperature.

The students found this experiment interesting and enjoyed the open-ended nature of the investigation. Several groups either found software of their own choosing for the data analysis or were able to adapt certain features, of which I was unaware, for their own purposes.

Student Feedback

Student feedback is often difficult to obtain. Two forms of course evaluation have been employed: 1) Students Ratings of Teaching (SRT's) and 2) peer group assessment. The latter is an indirect measure of student opinions but sometimes yields interesting information. A summary of the SRT's is provided in Table II with student comments following.

Table II. SRT (Student Rating of Teaching) Individual Reports for Online Lab (All questions are scored out of 6. In each column, the first value is the average μ, and the second is standard deviation σ.)

	May 2020	May 2021
Number of Students	11	14
Responses	2	2
<u>Question</u>	<u>μ, σ</u>	<u>μ, σ</u>
Appropriate and Effective Methods	4.5, 0.71	5, 0
Clear Instructions and Help Available	5.5, 0.71	6, 0
Clearly Articulated Expectations	5, 0	5, 1.41
Assignments – Good Measure of Learning	4, 0	4.5, 0.71
Instructor was available	6, 0	6, 0
Overall, I learned a lot in this course	5, 1.41	6, 0

Comments:

The labs were mostly appropriate and were able to be done at home. Under the circumstances I think they were good labs and well done.

When I compare the in person lab 1 I just took in the spring term to this may term semester I almost feel like I learned more in the at home version. Partly because the spring semester got cut short and also because a lot of the labs we did in person had pieces or equipment that were broken or were inaccurate enough that our data was pretty much unusable.

The at home lab at least produced data that we could use to reinforce our knowledge though, it was slightly too easy I think for us.

Lab 1 and 3 were both interesting and related to process engineering. I also liked lab 4 because it was more open ended. I thought using the digital size analyzer was kind of relaxing actually and not too tedious. I also appreciated that we wrote different kinds of papers, with the technical report, memos and a presentation, so that I could have more practice with each.

Being able to work in a group was a godsend. With multiple of us working full time it really allowed us to tackle the lab each week when we were available with select times to meet up and finalize things/work out problems.

Even though the write ups were not the most fun things to do, I did learn alot from them. And, the only way I was going to learn this type of stuff (propagating uncertainty, technical writing, listing figures tables and graphs, etc.) is to do it many times. It was a good class. My ability to write a technical document has undoubtedly gotten better. Also, Thanks professor for always hosting office hours. This made a world of difference. Really motivates us kids to work hard, knowing our professors are right there, willing to help us out when we get stuck.

More lectures throughout the week going in depth on the exact requirements on the lab would be incredibly helpful. Especially with uncertainty analysis, that was consistently what tripped us up and where we had to cut corners.

The lowest scores are for ‘Appropriate and Effective Methods’ and ‘Assignments – a Good Measure of Learning.’ In conjunction with the comment that the material ‘… was slightly too easy … for us,’ these responses seem to indicate that students felt the in-person lab was more rigorous. This perception is interesting to me, because I felt that the students often did not do a good job comparing experiment to theory for at-home labs specifically designed for such a purpose. One explanation for the perceived simplicity of the experiments is that the apparatus requirements were intentionally minimal and lacked the sophistication and size of many pieces of equipment in a standard unit operations laboratory.

The last comment, requesting more lectures, is tricky to address. As mentioned above, the course is meant to be a semi-independent learning experience. Moreover, an entire Zoom lecture, with PDF notes and examples, was dedicated to uncertainty analysis. Part of the nature of the comment on ‘exact requirements’ may be reflected in students’ natural desire to be told precisely what to do. Once again, however, the course is designed to be open-ended, so that students work out an experimental strategy on their own.

From the weekly peer assessments, the most common comments dealt with student dissatisfaction concerning having to work in groups. These make an interesting contrast to the remark above that, “Being able to work in a group was a godsend.” Such a disparity of opinion is to be expected in group work, where interpersonal interactions can vary so widely.

Instructor Observations

I have now taught May-term lab eight times, six times in person in the Unit Ops Lab and twice on-line. In comparing the two teaching platforms, I note that communication is vastly easier in person. This face-to-face advantage may be an artefact of the asynchronous nature of the on-line version. However, in a remote learning environment, some students steadfastly refuse to contact me, particularly by Zoom. In an offhand remark, one student informed me his group members did not want to contact me, because they were 'afraid' of me. This is an issue I may need to think about. Some of the advantages of each instructional environment are presented in Table III.

Table III. Advantages of each teaching platform.

In-person, Onsite	On-line, Remote
Easy Communication	Flexible
Better lab equipment	Better presentations
More professional	More independent

One characteristic I found is that the ease of group work seemed to be the same, regardless of the format. Moreover, students tend to be more adept than instructors at online technology, such as Zoom. Often, the result was that student presentations were better in an on-line format. Transitions were better between speakers, and the students were less nervous. Perhaps because they did not have to actually make eye contact and could refer to their notes, this feature may be a good one, since on-line presentations are frequent in today's work world.

The most significant advantage of in-person instruction in the Unit Operations Laboratory is that the experiments are technically superior and lead to a more professional experience. However, I would point out that students generally become better at working on their own in the remote environment, which is a good result, as well.

Recommendations

It seems likely enough that lab will continue to be offered as an online option, perhaps in conjunction with the in-person version, if for no other reason than to increase enrollment. As such, a few improvements should be made in remote instruction. Adding more synchronous features, such as lectures, would help with communication. Maybe giving extra credit for participating in office hours would help students engage, as well. To improve the technical side of the course, using Arduinos in a heat transfer experiment might be an option. Such a version is employed during the academic year. Finally, designing a chemical reaction experiment that fits the needs of the department should be a primary concern, since no satisfactory experiment has yet been developed in this area.

Conclusions

Because of the recent pandemic, instructors have been forced to become proficient in online teaching methodology. This trend applies to laboratory courses, as well. After two May-term offerings of Unit Operations Lab, both positive and negative outcomes have been observed. Students in the remote environment have benefited in terms of flexibility, aptitude in remote communication technology, presentation ability and an independent work ethic. However, a certain loss in sophistication has occurred in the experiments offered at the University of Minnesota Duluth. Moreover, communication is not as good as in face-to-face instruction. To remedy some of these shortcomings, more synchronous content, Arduino experiments in heat transfer and a satisfactory chemical reaction experiment have been recommended.

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