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Introduction of a Carbon Dioxide Capture Experiment in a Senior Chemical Engineering Laboratory Course

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Abstract

With the severity of climate change impacts increasing, it is imperative to educate students about climate change and potential technologies that may be used to mitigate it. To teach students about climate change and an emerging industry in carbon dioxide removal (CDR), a carbon dioxide capture experiment was included in a senior chemical engineering laboratory course. The experiment was iteratively scaled-up and student-designed in one rotation of a single-semester course. This paper includes experimental designs and associated data and outcomes from different iterations of the carbon dioxide capture module. The prototypes and experiments were designed and made by successive laboratory groups, with initial groups starting from small-scale chemistry experiments and subsequent groups progressively scaling up to a carbon dioxide absorption column. By the end of the semester, students had constructed a benchtop direct air capture (DAC) absorption column, using KOH to remove carbon dioxide from air. In addition to teaching important context, this curriculum modification also aimed to have students apply the fundamentals of reactor design and to have students collaborate with their peers to scale up chemical processes and create a final, usable product for future courses. Assignments were created to encourage student collaboration, creativity, hands-on design, and construction. The curriculum modification was evaluated by means of quantitative and qualitative survey, assessing aspects like the value of a student-led design module, of a climate change-relevant experiment, and of communicating with other groups to scale up a chemical process. A secondary outcome of this pedagogical experiment is a cheap and simple design of a chemical engineering laboratory experiment that can be easily replicated. This work demonstrates the value of supplementing traditional experiments with inquiry-based learning (IBL) and of including climate change content into the primary chemical engineering curriculum.

Introduction

The impacts of climate change are global and unprecedented. According to the UN Human Rights Office, “Human-induced Climate Change is the largest, most pervasive threat to the natural environment and societies the world has ever experienced, and the poorest countries are paying the heaviest price” [1]. Nearly all nations have committed to limiting global warming to less than 2°C above pre-industrial levels [2]. Integrated assessment models that connect emissions, economy, and climate demonstrate that the path to remaining below this limit will be exceedingly challenging, and that following the current trajectory, the threshold will be exceeded between 2034 and 2052 [2]. Students will need to solve problems in an environment of unprecedented change, so their curriculum needs to prepare them for these social, cultural, and technical challenges.

In a 2017 review of the academic literature on climate change education strategies by Monroe et al., the authors identified increases in curricular guidelines that address climate change, coinciding with increased interest in and funding for climate education [3]. ABET incorporates sustainability and ethics in criterion 3, in student outcome 2: “an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors” and outcome 4: “an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgements, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts [4].” Thus, it is not only important to integrate the climate crisis into our teaching from a moral perspective, but increasingly it is becoming required by governing and accrediting organizations.

Chemical engineering technologies have significantly contributed to climate change, but the discipline is necessary for developing solutions to it [5]. A recent report from the National Academies of Science Engineering and Medicine said chemical engineering would likely be the “enabling discipline” for decarbonization of energy and materials [5]. The report further points out that, despite rapid evolution of technology and thought, “the core chemical engineering curriculum has evolved more slowly over the preceding decades, even as the challenges facing engineers have expanded and become more difficult [5].” Traditional chemical engineering curricula may cover sustainability at a surface level, but the literature suggests it is often only in senior design courses [6], electives [7], or outreach programs [8], and few published papers discuss new climate change or sustainability topics integrated into core classes in chemical engineering.

In this paper, we present results from a semester-long inquiry-based learning (IBL) climate change related experiment that was added to the fourth-year chemical engineering laboratory course. For laboratory classes, an IBL approach moves away from prescribed tasks defined by an instructor or lab manual to open-ended curricula where students determine their own procedures and analyses [9, 10]. In a laboratory course, the IBL approach more closely mirrors that of independent research [10], which has been shown to improve confidence and retention of students within STEM fields [11]. Although the IBL approach is well documented for design courses [12], there are fewer papers on IBL in science or engineering laboratory courses [10].

For the IBL laboratory experiment, successive student groups scaled up a carbon dioxide removal (CDR) experiment and created their own experimental design and methods for data collection and analyses. In addition to adding climate change relevant material to the curriculum, the goal of this change was also to incorporate an IBL module in the course, to develop skills not previously focused on in the course like machining and prototyping, and to have students collaborate between groups to scale up an experiment over a semester.

Course Description

Chemical engineering laboratory I is a two credit, four contact hour per week course offered each fall semester to seniors at our institution. It is part of a two-course laboratory sequence taken by fourth year students. The goal of the two courses is to have students apply engineering fundamentals they have learned in their other courses in a laboratory setting. In each semester, four experiments are performed in three-week rotations. Course sections are capped at 15 students. The course descriptions and goals are generally similar for both semesters, but they cover different types of unit operations. The learning objectives for the fall semester are that by the end of the course, students can:

1. Design chemical engineering experiments and create hypotheses
2. Operate chemical engineering tools, equipment, and instrumentation
3. Analyze and interpret data, and use engineering judgement to draw conclusions
4. Write and present scientific information clearly to a range of audiences
5. Collaborate with peers and instructors and function as a part of a healthy, creative, and cohesive team
6. Identify safety hazards and preventative measures for scientific experiments

The experiments in the fall have traditionally been filtration, pipe flow, flooding point, and heat exchange. The experiments were designed to have students apply their skills from heat and mass transfer, separations, fluid dynamics, and thermodynamics to the operation of lab-scale operations. The full list of experiments for the two semesters is shown below in Table 1.

Table 1: List of experiments for fall and spring semesters

Fall semester		
Experiment	Equipment	Application from course:
Filtration	Hydraulic ram, pneumatic pump, valves, filters	Fluid dynamics, Separations
Pipe flow	Piping, flow meters, manometer, valves	Fluid dynamics
Flooding point	Flow meter, valves, packed bed column, gas pressure regulation, manometer	Separations
Heat exchange	Temperature controllers, heat exchangers (tubular, plate, shell and tube)	Heat and mass transfer, Thermodynamics
Spring semester		
Experiment	Equipment	Application from Course:
Gas permeation	Gas permeation membrane, O_2 sensor	Heat and mass transfer, Separations
Reverse osmosis	Reverse osmosis membrane, Pump, Conductivity monitor	Heat and mass transfer, Separations
Distillation	Closed loop trayed distillation column, Refractometer	Thermodynamics, Separations
Drying	Tray dryer, Humidity sensor	Heat and mass transfer, Separations

Past implementations of these experiments have followed an expository style of lab instruction, where procedures are well-defined, and students have a predetermined outcome to compare to a theoretical value or relationship [9]. These labs have been designed to minimize hazards and be performed simultaneously by many students without significant involvement of the instructor or laboratory technician. Since the experiments in the fall semester did not have significant safety hazards (nor chemical use), a safety module was added to the first two weeks of instruction. Each lab has a rotating assessment (laboratory report, memo, poster presentation, or oral presentation) with a rubric that includes assessment of the quality of the students' data and its correct interpretation. Students completing the DAC experiment completed the same assessment method as the other labs during that rotation.

The applications of unit operations like heat exchangers to industry are intentionally broad; chemical engineers work in a variety of industries and therefore learn in the context of equipment rather than product. We believe that student work has typically been limited by lack of understanding of the potential applications of various unit operations to specific and important processes. To address this, we wanted to include a contextual problem in the course that was meaningful to the students and had a specific technical solution it was investigating. We also wanted to add design and prototype training to the curriculum and to add inquiry-based instruction to one of the rotating experiments.

Curricular Changes

The primary curricular change in the fall of 2022 was a redesign of the traditional flooding point experiment to an inquiry-based, collaborative experiment removing carbon dioxide from air, a technology known as direct air capture (DAC). One reason this experiment was reconceived was because it was appropriate to use the flooding point experiment's packed bed design for DAC reactions. In the past, the set-up used only air and water and none of the other experiments (Table 1) included chemical reactions. Thus, incorporating the DAC reactions was also an opportunity to integrate content from reaction engineering. We decided to have the students design the DAC experiment themselves, progressively scaling up their ideas throughout the semester. Our primary instructional goals were to:

1. Incorporate contextual learning about climate change.
2. Incorporate inquiry-based instruction.
3. Have students learn and apply new skills in design, machining, and prototyping.
4. Have students apply fundamentals from courses not previously covered in the laboratory (reaction engineering).
5. Have students learn from each other and collaborate by contributing to a final usable product.

The redesign of the flooding point lab to a DAC lab was introduced as one of four rotating experiments, giving student teams three weeks to work on it. A DAC experiment was chosen instead of a more traditional carbon dioxide capture separation to keep costs low, minimize safety risks, and to reduce design changes from the traditional flooding point laboratory.

Results from Student Experiments

During the fall 2022 semester, groups of three to four students rotated between the four experiments in Table 1. For the pipe flow, filtration, and heat exchanger experiment, students worked from the traditional lab manual. For the flooding point experiment, reconceived as a DAC experiment, students had to create their own experimental design, including test set-ups. A general pedagogical change from previous years was that, for all experiments, students were encouraged to share data and ideas between groups. For the DAC experiment specifically, students passed on their results, prototypes, and suggestions to the next rotating group. This section describes the results from each of the four rotations, for both course sections, from the fall 2022 semester.

Rotation 1

Groups in the first rotation completed the traditional flooding point laboratory with a supplemental assignment to determine whether it could safely and easily be transitioned to a DAC system. At the end of their three-week rotation, they presented their findings, including a PFD design for the DAC unit (Figure 1a) and an analysis of possible liquid absorbents to replace the water in the traditional set-up, categorizing each using metrics of performance, safety, and cost. They recommended NaOH and KOH as the absorbent for subsequent groups. They were also tasked with teaching the class about motivations and ethical complications for DAC technologies. In the second section, the group completed these tasks and tried to measure the carbon dioxide capture capacity of NaOH via titration. The group bubbled pure CO_2 in samples of 0.5M and 1M NaOH. A diagram of the experimental setup is depicted below in Figure 1b.

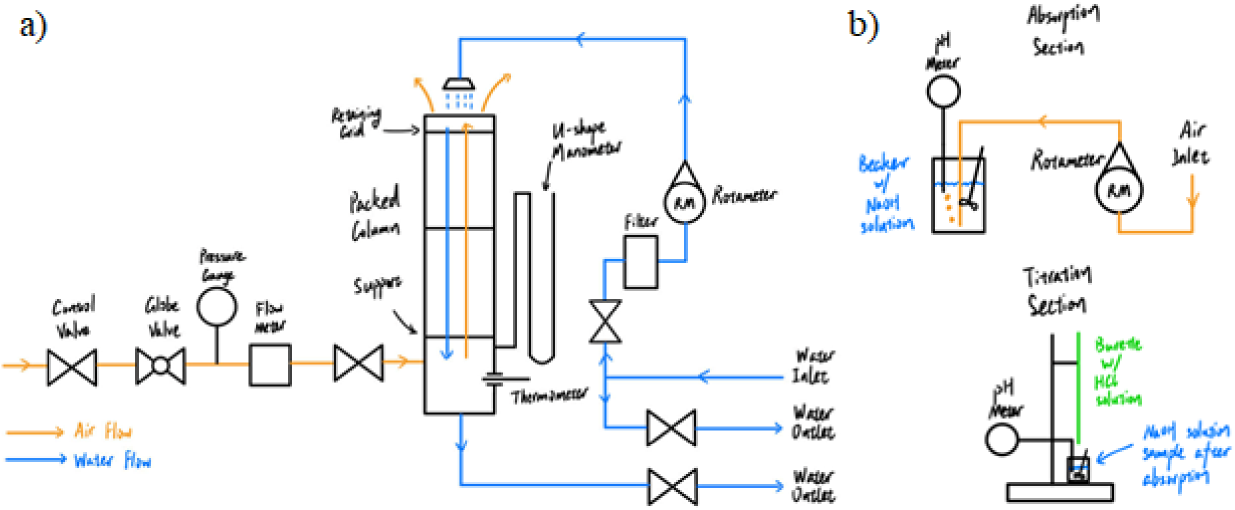

Figure 1: a) PFD of original flooding point experiment and b) Initial experimental set-up for DAC using NaOH

Rotation 2

The first group in rotation two built a small semi-batch reactor using a Vernier carbon dioxide monitor, parts available in the laboratory, and supplemental parts from the local hardware store. They were able to measure and present the first set of carbon dioxide removal data to the class and passed on a prototype reactor as well as suggested improvements to the next group. They also ordered additional parts for the next group, including a second gas sensor. The group in the second section also created a small prototype semi-batch reactor but using liquid analysis rather than gas analysis. This group learned that mass transfer limitations, and low partial pressures of CO_2 in the air made measurement of the reaction via titration difficult. They recommended that subsequent groups use gas analysis and in-situ pH measurement of the sorbent instead of titration.

Rotation 3

The first group in rotation three carried out suggested improvements to the reactor, suggested by the previous group. Figure 2a is a student diagram for the prototype packed bed using two gas sensors. They focused on measuring breakthrough curves for different molarities of KOH and were able to identify breakthrough time for several different concentrations. They made recommendations for the fourth group, including some reactor changes to avoid issues of channeling. The second group in this rotation was interested in regenerating the NaOH or KOH sorbent using a method published on by Carbon Engineering [13]. They used $Ca(OH)_2$ to convert sodium carbonate into calcium carbonate, which they were able to precipitate for a mass balance.

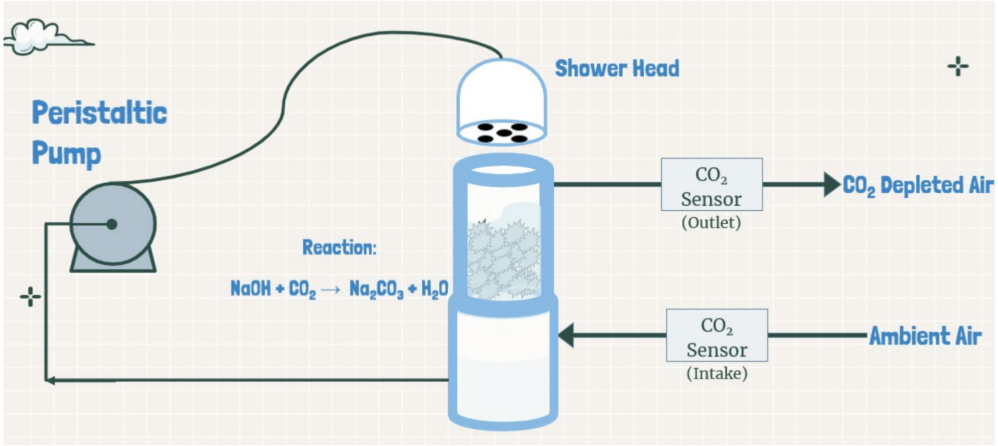

Figure 2: Diagram from Rotation 3 in Section A for continuous small-scale DAC reactor

Rotation 4

The student groups in Rotation 4 made reactor design changes proposed by the previous group to create a continuous reactor using a liquid flow pump (Figure 2), like the design of the proposed DAC-converted flooding point column. By the end of the rotation, students were able to compare the final cost for a scaled-up DAC column with a quote for a fully assembled setup available for purchase, to close the mass balance between the measured pH change of the sorbent and the measured gas composition change (within 9%), and to close the mass balance by regeneration of the sorbent to capture the carbon in calcium carbonate (recovering 85% of carbon captured). The parts list for the final reactor is included in Appendix B.

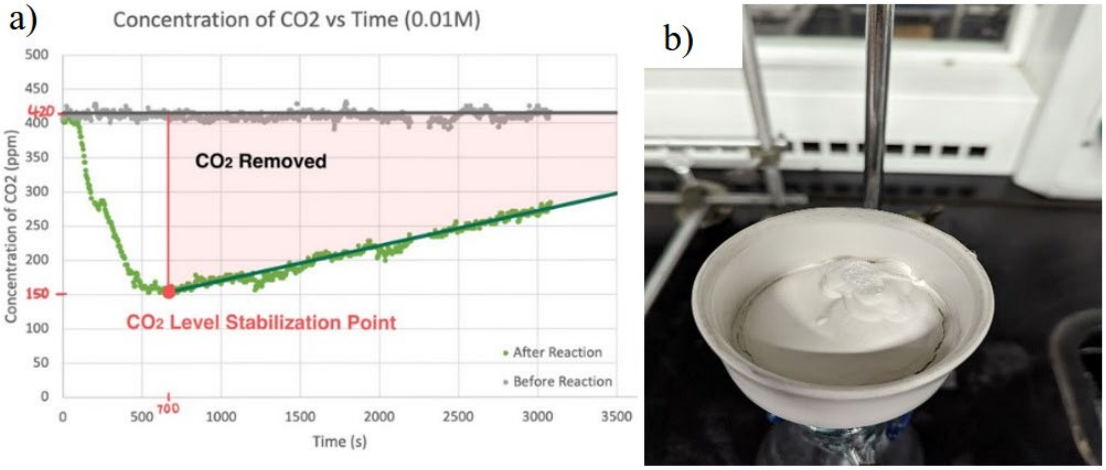

Figure 3: a) Breakthrough curves used for mass balances of carbon removal b) Calcium carbonate used for regeneration mass balance.

Curricular Assessment

At the end of the semester, a 14-question survey was given to students on a voluntary basis to understand how they felt about the new experiment. There were 14 survey respondents (64% of the class). The primary goals were to understand whether students felt that the changes were useful for their learning, what skills it contributed to compared to traditional laboratory experiments, and how it impacted students' interest level and knowledge of climate change and carbon removal technologies. Students did not indicate which rotation they completed the DAC experiment in and thus Likert values in the following figures are averaged across the four rotations in each of the two sections.

The first set of questions asked students whether the curriculum changes contributed to their knowledge and skill development. Students were asked how aspects like "Discussing and transferring information between groups" contributed to their learning on a five-point Likert scale; from "Contributed significantly (value = 5) to "Detracted significantly" (value = 0) with neutral as "Did not contribute" (value = 3). As shown in Figure 1, students felt that each of the five surveyed aspects contributed to their learning with average values ranging from 4.1 to 4.9. Students particularly valued building and designing their own experiments, as the two highest rated aspects were "Building new experimental set-ups" with an average rating of 4.9 and "Designing a new aspect of an existing experiment" with an average rating of 4.8. This finding was supported in several short answer responses at the end of the survey. One student responded "As for past semesters, most of the experiments were focused on repeating or following the guidelines and lab manuals. However, the experiments conducted this semester focused on designing new experimental set-ups and even making our own design. This is the essence of engineering, and I am very grateful for this experience." Students also valued the intergroup communication necessary to scale up the DAC experiment, with 71% of students reporting that "Discussing and transferring information between groups" contributed significantly to their learning. Interestingly, the lowest-rated aspect: "Scaling up the DAC experiment" (with an average rating of 4.1), was, from the faculty perspective, perceived to be one of the most valuable additions to the curriculum.

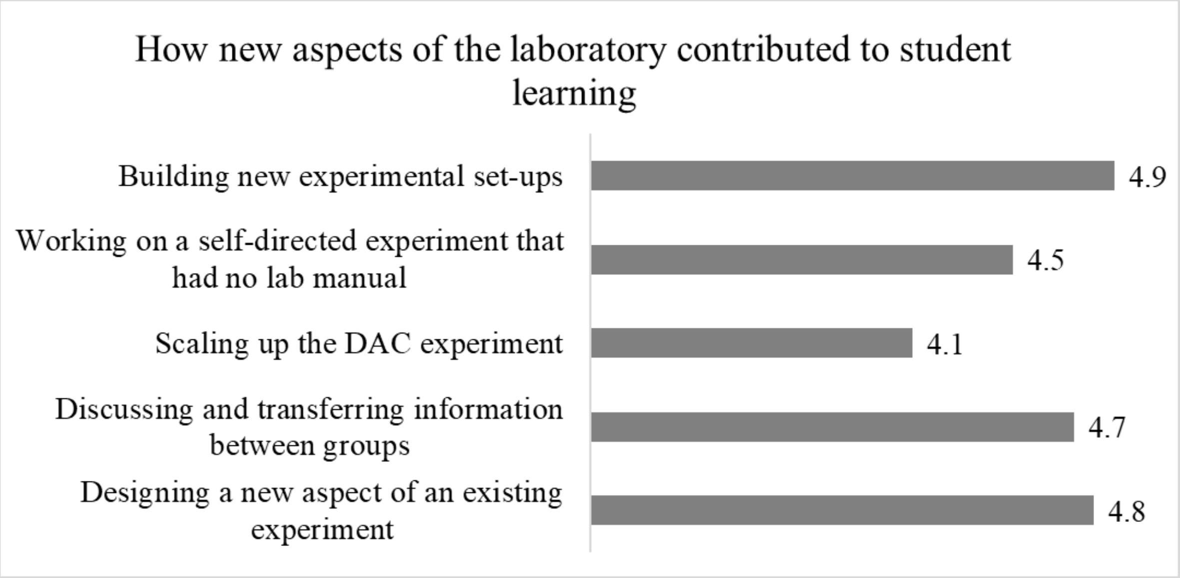

Figure 5: Contributions of various aspects of curriculum changes, measured on five-point Likert scale (1= Detracted significantly, 3=Did not contribute, 5=Contributed significantly), and plotted on a scale from 3 to 5.

In the class survey, students were asked how the DAC experiment compared to the other laboratory experiments for skill development. Students were asked whether each of the experiments "Did contribute" or "Did not contribute" to the development of a set of eight skills, shown in Table 2. In Figure 6, the percentage of students that thought a lab contributed to their learning of a particular skill is shown with the three traditional labs (pipe flow, filtration, and heat exchange) averaged to a single percentage. As shown, the traditional labs develop different skillsets: 55% of students rated that the traditional experiments developed the skill "Comparing experimental to theoretical data" whereas 43% of students said this was true for the DAC lab. In contrast, 86% of students said that the DAC lab developed the skill "Designing chemical engineering experiments and hypotheses" compared to 38% for the traditional experiments (29% for pipe flow, 43% for filtration, and 43% for heat transfer). Students felt that the DAC experiment supported skill development more than the traditional experiments for 7 out of 8 of the listed skills. However, due to the IBL approach, it is difficult to identify specific outcomes that can be compared to predetermined fundamental content from other courses. These results show the importance of a portfolio of laboratory experiments designed to target different outcomes and associated skills.

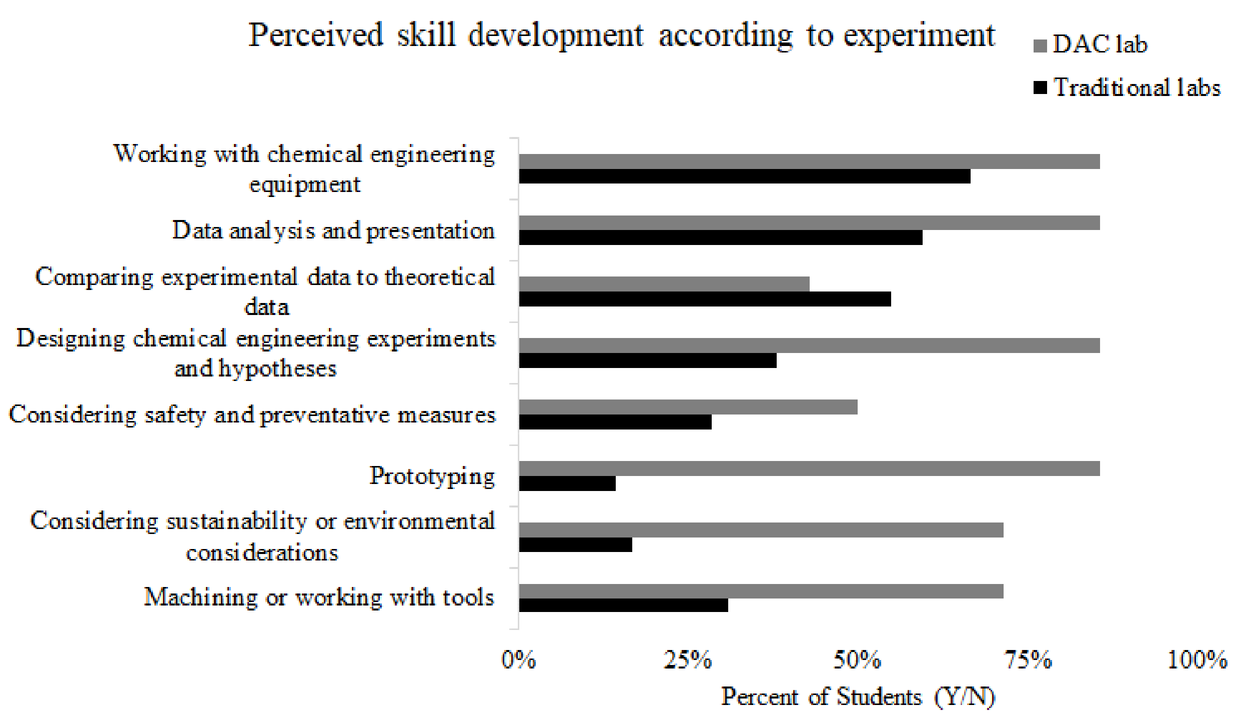

Figure 6: Student perception on skill development according to traditional labs (pipe flow, filtration, and heat exchange) compared to the new DAC lab, measured as a percentage of the 14 participants that felt experiments contributed to the skills presented in Table 2.

In addition to surveying students about the skills directly pertaining to the syllabus learning outcomes, we surveyed students about three new skills: 6. “Prototyping” 7. “Considering sustainability” and 8. “Machining or working with tools.” Students reported that the DAC experiment contributed to these skills more than traditional experiments. Specifically, 83% of students said the DAC experiment contributed to learning “Prototyping”, 67% to “Considering sustainability”, and 75% to “Machining or working with tools” (compared to 14%, 17%, and 31% of students for the traditional experiments). Although the experiment contributed more to the development of these skills, the (IBL) approach meant that students were not guaranteed to develop specific skills. But this flexibility also meant that students might learn unexpected skills as well; as one student mentioned in a short answer, one of the most valuable things they learned was how to purchase equipment.

For the DAC experiment, students had to develop or modify test set-ups and design their own experiments. However, for one rotation of all experiments, students were asked to develop their own experimental design, using data from previous lab groups. Students were asked how this IBL approach impacted different aspects of their course experience including Collaboration, Workload, and Interest and investment. Each of the responses was averaged on a five-point Likert scale using “Very good” as a 5, and “Very poor” as a 0. As shown in Figure 7, students felt positive about all aspects, but most positive about “Collaboration” and “Interest and investment”, with average ratings of 4.8 each. Students also reported that it did not significantly affect the workload for the experiment. Students were asked whether they would recommend “self-guided” labs, traditional labs (with lab manuals), or a mix of the two types of labs for future iterations of the course. Most of the class, 58% of students, said they would recommend only self-guided labs and 42% recommended a mix of traditional and self-guided labs. No students recommended only traditional experiments that followed a lab manual. Thus, students felt that the IBL experiments contributed both to skill development as well as to their classroom experience.

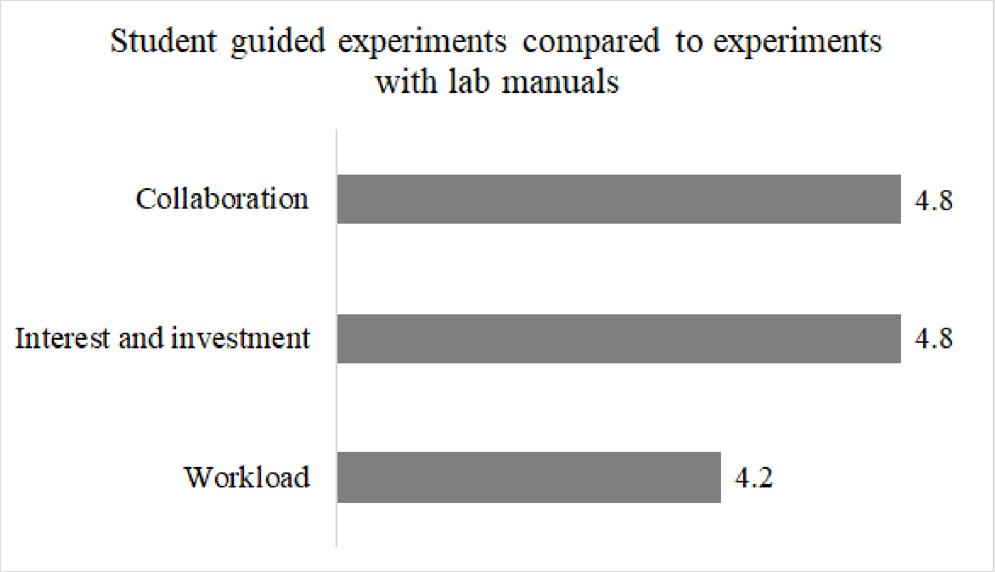

Figure 7: Student perceptions comparing different aspects of the DAC experiment to traditional experiments, measured on 5-point Likert scale (1= Very poor, 3=Did not contribute, 5=Very good), and plotted on a scale from 3 to 5.

One of the primary goals of adding the DAC experiment was to have students learn about the role of CDR technology as a tool for limiting global temperature rise. We wanted to understand how the experiment impacted students' interest and knowledge of climate change and carbon removal. Students were asked to rate their level of interest and knowledge before and after the class. Each of the responses was averaged on a five-point Likert Scale using "Very interested" and "Very familiar" as a 5, and "Very uninterested" and "Very unfamiliar" as a 0 with "Somewhat interested" and "Somewhat familiar" as a 3. A significant increase in interest in climate change and carbon removal technology was reported by students during the semester. Before the course, 29% of students said they were "Very interested" in climate change and carbon removal technology whereas after the course this rating was 64%. Figure 8 shows the average Likert values for interest and knowledge on the topics. As shown, the interest level increased from 3.8 to 4.6 over the semester, showing that the average student came in with some interest in the topic. Figure 8 also shows that the experiment was successful in teaching general knowledge about climate change and carbon removal technology. The reported level of knowledge increased from an average rating of 3.4 to 4.3. According to the survey data, an IBL experiment in laboratory was successful in educating students on skills and also increased interest and knowledge of the contextual problem.

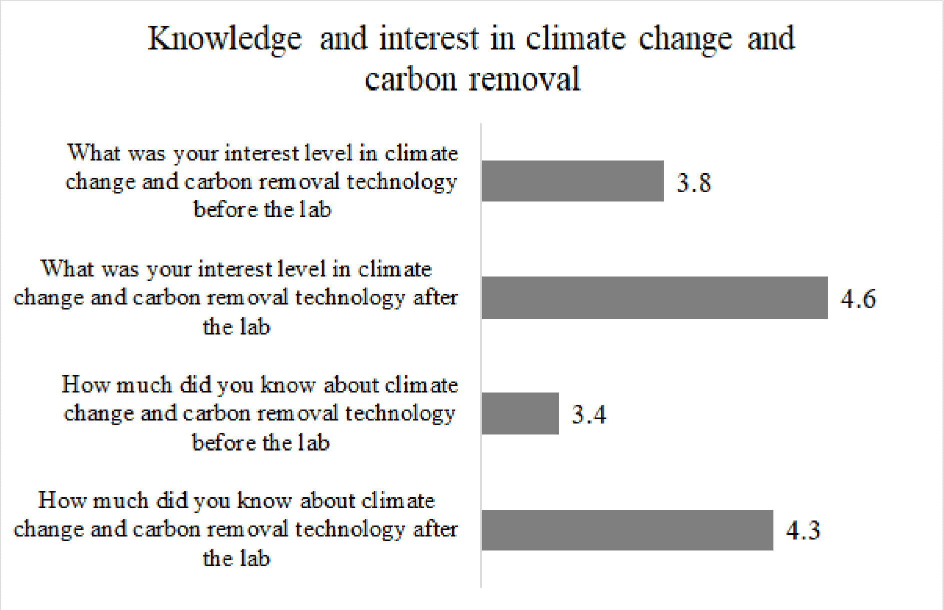

Figure 8: Student reflections on their level of knowledge and interest in climate change and carbon removal before and after experiment, measured on 5-point Likert scale (1= Very unfamiliar, 3=Somewhat familiar, 5=Very familiar), and plotted on a scale from 3 to 5.

Students responded whether it is important to have climate change content in the chemical engineering curriculum. Every student believed that it was important to have this topic covered: 86% of students believed it was “Very important” and 14% believed it was “Important” to cover. A student-led and contextual experiment in chemical engineering laboratory can be a tool for educators to keep up with a rapidly evolving field and foster creative problem solving, one in which students are interested in participating.

Conclusion

Student perceptions of various aspects of laboratory learning were captured for a new inquiry-based learning (IBL) experiment focused on carbon dioxide removal (CDR) and compared to results for the traditional experiments. Students designed a technical solution to a specific contextual problem: current carbon dioxide concentrations in the atmosphere. Subsequent laboratory groups scaled up previous prototypes and collaborated between groups to develop several experimental setups. Survey results show that students find value in both the traditional laboratory experiment structure and the new inquiry-based direct air capture (DAC) experiment structure. Students reported better skill development for the DAC lab than for traditional labs, showing that incorporating student-led design and experimentation can achieve course learning objectives. This year, students approached the prompt by scaling up a packed bed absorber using KOH and NaOH. We believe that future sections could continue to use this same prompt with different outcomes and results for comparison. Students reported that they thought it was important to incorporate climate change related content into their curriculum, and that this laboratory increased both their interest in and general knowledge of climate change and carbon removal technologies.

Appendix A: Survey

Chemical Engineering Lab Survey, Fall 2022
Content and Pedagogy Assessment for the Fall 2022 Chemical Engineering Senior Laboratory Course

1.How much do you think each of the following aspects of the laboratory course contributed to your learning?

	Detracted Significantly	Detracted Somewhat	Did Not Contribute	Contributed Somewhat	Contributed Significantly	n/a
Designing a new aspect of an existing experiment. (new type of experiment for heat exchange, filtration, etc)						
Discussing labs and transferring information between groups (having continuous experiments)						
Scaling up the adsorption experiment (either from beaker to column, or from small column to larger column)						
Evaluating previous educational goals of the labs. (in presentation 1 or the lab manual edits)						
Working on a self-directed experiment that had no lab manual (the adsorption experiment)						
Building new experimental set-ups						

2. Are there any other aspects of the class this semester that you feel strongly contributed or detracted to your learning, or your preparation for being an engineer?

3. What skills did the Pipe Flow Lab Contribute to?

	Comparing experimental data to theoretical data Prototyping
	Considering Sustainability or Environmental Considerations
	Machining or working with tools
	Working with chemical engineering equipment (i.e. pumps, valves, etc)
	Data Analysis and Presentation

	Designing Chemical Engineering experiments and hypotheses
	Considering safety and preventative measures
	None

4. What skills did the Filtration Lab Contribute to?

	Comparing experimental data to theoretical data Prototyping
	Considering Sustainability or Environmental Considerations
	Machining or working with tools
	Working with chemical engineering equipment (i.e. pumps, valves, etc)
	Data Analysis and Presentation
	Designing Chemical Engineering experiments and hypotheses
	Considering safety and preventative measures
	None

5. What skills did the Heat Exchange Lab Contribute to?

	Comparing experimental data to theoretical data Prototyping
	Considering Sustainability or Environmental Considerations
	Machining or working with tools
	Working with chemical engineering equipment (i.e. pumps, valves, etc)
	Data Analysis and Presentation
	Designing Chemical Engineering experiments and hypotheses
	Considering safety and preventative measures
	None

6.What skills did the Absorption Lab Contribute to?

	Comparing experimental data to theoretical data Prototyping
	Considering Sustainability or Environmental Considerations
	Machining or working with tools
	Working with chemical engineering equipment (i.e. pumps, valves, etc)
	Data Analysis and Presentation
	Designing Chemical Engineering experiments and hypotheses
	Considering safety and preventative measures
	None

7.For several experiments this semester, you were asked to not use a lab manual. Instead, you were prompted to create a student-generated procedure. Compare the quality of each of the following outcomes to the outcomes from performing labs with set lab manuals.

	Very Poor	Poor	Acceptable	Good	Very Good	n/a
Workload						
Quantitative Analysis						

Interest and Involvement						
Problem Solving						
Application of Theory						
Collaboration						

8. Would you recommend self-designed laboratories for future classes? Check all that apply

	Recommend to have self guided labs
	Do not recommend to have self guided labs
	Recommend a mix of both self guided and traditionally guided labs

9. Were there any other skills you learned in lab?

10. Were there any other skills you would have like to have learned in lab?

11. What was your interest and knowledge in Climate Change and Carbon Removal Technology before and after working on the Carbon Capture Absorption Experiment?

	Very Unfamiliar	Unfamiliar	Somewhat Familiar	Familiar	Very Familiar	n/a
What was your interest level in Climate Change and Carbon Removal Technology before the lab						
What was your interest level in Climate Change and Carbon Removal Technology after the lab						
How much did you know about Climate Change and Carbon Removal Technology before the lab						
How much did you know about Climate Change and Carbon Removal Technology after the lab						

12. How important do you think it is to have a Climate-related experiment in a Chemical Engineering Laboratory Course (1 Not at all important, 5 Very important)

13. Are there other fields or technologies that you think should be added as topics for experiments in either semester of the Chemical Engineering Laboratory course?

14. Do you have any additional feedback about the course, or how to improve it for future years?

Appendix B: Parts list

Pro-Pak Distillation Packing 0.16” 316SS

5-500mL HDPE bottles

Thermo Scientific Manostat Kate peristaltic pump [0-0.6 LPM]

Air flowmeter ¼” NPT female [0-5 LPM]

Vernier LabQuest 2

2-Vernier CO2 gas sensors

1-Vernier pH sensor

10’ Tygon tubing 1/8” ID

6-Brass barbed tube fittings 1/8” tube to ¼” NPT male

Commercial showerhead ¼” NPT female

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