PROBLEM-BASED LEARNING (PBL) AND PROJECT-BASED LEARNING (PJBL) IN A CONTINUOUSLY IMPROVING CHEMICAL ENGINEERING LABORATORY EXPERIENCE

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INTRODUCTION

Laboratory courses in the chemical engineering curriculum serve a central role in facilitating the development of students as engineering professionals, and are a key component of chemical engineering programs as they prepare students for the modern work environment.[1-4] Multiple studies discuss how the technical competencies required from engineering graduates are changing at a fast rate as modern work ecosystems increasingly demand engineers who are quick to adapt to change, eager to innovate, active at proposing solutions, and flexible to adapt to fluid work structures.[5-7] Chemical engineering programs are responsible for preparing new graduates for diverse career paths and for establishing educational conditions towards graduates with a commitment to lifelong learning, who thrive in collaborations, and who have developed self-efficacy.[8-11]

Chemical engineering laboratories are courses in which students solidify their knowledge and put theory into application by working in teams to solve challenging problems.[1,12-13] Their experiential learning with a hands-on focus makes them ideal spaces for the promotion of skills that facilitate the transition of students to the engineering practice [14] and for the emphasis of elements that are essential to professional development.[14-15] Within this framework, two educational approaches that facilitate the promotion of these elements in laboratory courses are Problem-Based Learning (PBL) [11,16-17] and Project-Based Learning (PjBL).[18-19]

PBL is an educational approach that enables students to learn by solving complex open-ended problems.[11, 16-17] PjBL is defined as an instructional method that engages students in the learning process through meaningful projects and the development of products created from these projects.[18-20] PjBL shares some similarities with PBL. The key difference between PBL and PjBL is the way in which students process knowledge; PBL focuses on knowledge application while PjBL centers the learning process on knowledge construction.[19] PjBL centers on the solution of complex problems by emphasizing the creation and development of research products or artifacts.[19-20] PBL has been previously applied as an effective method to enhance the benefits of experiential learning in laboratory courses;[12-17] nonetheless, few authors have reported on the application of the PjBL framework in engineering laboratory courses.[19] To the best of our knowledge, no studies have previously reported on the adaptation of a PjBL framework to chemical engineering laboratory courses, in particular.

Both PBL and PjBL frameworks aim to reinforce professional skills such as critical thinking, lifelong learning, time management, communication, teamwork, and problem solving.[12, 11, 18] However, PjBL can create further value in the learning experience by helping students become more engaged in the development of key engineering skills and in the analysis, application, and construction of knowledge and products.[18,19,21] Therefore, PjBL can be effectively incorporated into laboratory courses to offer new learning opportunities for students as they conduct research, integrate theory, formulate solutions to complex problems, develop projects, and create research products in a collaborative setting.

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The Department of Chemical Engineering at the University of Texas at Austin has renovated the two required chemical engineering undergraduate laboratories to create a sequence that incorporates elements of PBL and PjBL to accomplish the goals of the courses more effectively. The main purpose of this renovation has been to update and improve the content, teaching effectiveness, and general learning experience offered by the laboratory sequence. To accomplish this purpose, we redesigned the structure, objectives, experiments, and assignments of the courses to create enabling conditions that allow students to progressively become independent, confident, and self-directed learners who can solve engineering problems collaboratively.[1, 4, 11]

Our course enhancements to this date have been informed by engineering education research that highlights the importance of practical experiences,[1-4, 13] open-ended problems,[11, 17] and independent learning [12] directed at helping critical thinking and promoting lifelong learning skills. To ensure our course updates are dynamic, constantly improving, and student-centered, we have implemented a continuous improvement model in the development of our laboratory experience.[22] Continuous improvement is typically defined as an incremental and ongoing effort to improve all elements of a process.[23] In our context, this commitment requires us to promote constant progress towards each educational goal, a high degree of information sharing, and an invitation to involve all program stakeholders in the enhancement of the educational experience.[22, 23]

The overarching objective of this manuscript is to provide an overview of our laboratory sequence and describe the changes that have been implemented with aims to continuously improve the practical learning experience of chemical engineering students in our program.

LABORATORY RENOVATION OBJECTIVES

The chemical engineering degree program at the University of Texas at Austin requires all degree seeking students to complete two chemical engineering laboratory courses before graduation: the Measurement, Control, and Data Analysis Laboratory in the junior year (CHE253M, 2 credit hour, referred as the "junior year laboratory") and the Chemical Engineering Process and Projects Laboratory in the senior year (CHE264, 2 credit hour, referred as the "senior year laboratory.") Registration in each of the courses can fluctuate slightly every term; nonetheless, it is approximately 60 to 90 students per course every semester. The courses are offered twice a year. Our renovation process had four main objectives that pursued the optimization and enhancement of the student learning experience by:

1. Transforming the laboratory courses into an effective and complementary sequence
2. Introducing elements of problem-based learning into both laboratories
3. Incorporating project-based learning into the senior year laboratory
4. Creating a culture and commitment to continuous laboratory improvement and collaboration

IMPLEMENTATION

Below, we describe our approach to accomplish each of the four renovation objectives. Changes are described individually as a way to delimitate the activities associated with each update; nevertheless, all changes are intertwined and occurred simultaneously to create synergy between the different elements of the courses.

Transformation of the Laboratories into an Effective Sequence

The first step in our renovation efforts focused on converting the laboratory courses into a sequence that pursued complementary objectives and that targeted a more structured learning experience. In the past, the laboratories were taught as two different entities with similar objectives that were not complementary. Consequently, there were redundant elements in the courses.

We targeted a structure that facilitated a transition towards self-directed learning. This transition was achieved by delimiting the scope of both courses: the junior year laboratory is mostly instruction-driven, and the senior year laboratory promotes teamwork in the solution of open-ended problems and independent projects. In particular, we took three actions to update the course structure:

1. All experiments were renovated, improved, or newly built to ensure different areas of chemical engineering were covered in the laboratories. Experiments in areas such as bioengineering, pressure swing adsorption, extraction, fluidization, material characterization, and polymer processing were added as a result of these renovations. The number of experiments available in both laboratories was doubled, and the experiments in the junior year laboratory complemented the experiments in the senior laboratory. For example, students are introduced to qualitative process control in the junior laboratory, and then they have an opportunity to perform a class project on process control in the senior laboratory. A list of the experiments available in both laboratories is presented in Table 1.

TABLE 1
Experiments in the Junior Year and Senior Year Laboratories - Some Areas Have Multiple Units; Students May Use These Units During Standard Experiments, Class Projects, or Both

Junior Year Laboratory	Senior Year Laboratory	
Statistical Process Control and Mixing	Reaction (Batch, CSTR, or PFR)	Process Control Units
Temperature and Pressure Measurement	Distillation (Batch and Continuous)	Absorption and Stripping
Material Balances in an Extraction Column	Reverse Osmosis	Pressure Swing Absorption (PSA)
Heat Transfer	Gas Separation Membranes	Polymer Processing Units
Fluid Flow	Bioengineering and Fermentation	Liquid Extraction

2. All assignments and activities were updated and revamped to pursue course synergy. One goal of the laboratories is to help students improve their data analysis and technical communication skills. To accomplish this more effectively, we redesigned all lectures and assignments to create a structured sequence. For example, in the junior year we focus on introducing students to collaboration through their individual efforts, and in the senior year, all work is completed in groups and the focus is on teamwork. Students complete individual laboratory reports in the junior year, while in the senior year, we focus on group memorandums, technical presentations, proposals, and posters.
3. We updated and redefined the role of the teaching assistants (TAs). We focused on optimizing the use of the resources assigned to the laboratories; we realized the primary and most limited resource we have to serve our students better is our people. The teaching team (TAs and instructors) is what makes a successful laboratory possible. In response, we revamped teaching assistant training, redefined their roles, and implemented biweekly sessions to understand their challenges and progress. We also included TAs in the enhancement of laboratory manuals and grading rubrics. We believe that if properly trained and assigned, TAs are fundamental to an improved and successful laboratory experience.

As a consequence of these updates, the course structure, objectives, experiments, assignments, and manuals have been crafted to promote the accomplishment of this sequence. We divided the laboratory sequence into four steps:

1. Instruction-driven experiments (first half of junior year laboratory)
2. Introduction to PBL experiments (second half of junior year laboratory)
3. PBL experiments (first half of senior year laboratory)
4. PjBL research project (senior year laboratory)

The resultant sequence gradually introduces students to self-directed learning [10] and provides them with the experimental tools required by the engineering work environment.[1]

Instruction-Driven Experiments: First Half of Junior Year Laboratory. The junior year laboratory is the first required chemical engineering laboratory course offered in the program. The laboratory introduces students to measurements, analysis, and reports typical to the junior year. The students are organized in teams of 3 or 4 assigned randomly by the instructors; the random team assignment tries to best simulate the typical team formation conditions in postgraduation experiences.[9] We follow the same approach to team formation in the senior year laboratory.

To incorporate an instruction-driven approach in the first half of the junior year laboratory, students complete experiments that focus on data analysis and the development of laboratory skills. An online pre-laboratory quiz and a written pre-laboratory report help them understand the experiments in detail as they research information necessary to describe each system. All experiments have laboratory manuals that provide step-by-step guidance and a grading rubric that details the type of data analysis and discussions required to complete each report. This is the first time students are introduced to hands-on learning in engineering; therefore, this type of highly supervised instruction is necessary. By this approach, students are able to conduct experiments safely under the supervision of the teaching team. Students complete two experiments in eight weeks.

Each experiment requires three to four hours, and the experiments are completed over a four-week cycle. The first week of the cycle is used as a time to work on the completion of the pre-laboratory work. Students perform all experimental work in the second week. Subsequently, they are required to work individually (i.e., without their teams) in the completion of research-type laboratory reports in weeks three and four. The individual report requirement helps us ensure all students can individually and effectively understand calculations, research information, and complete the data analysis.

Introduction to PBL Experiments: Second Half of Junior Year Laboratory. The second half of the junior year laboratory introduces students purposely to problem-based learning. Instead of an individual pre-laboratory quiz, students develop a team pre-laboratory presentation which is discussed with the teaching team. As part of this presentation, they are required to create an experimental plan and decide on the experiments necessary to obtain experimental data. Student teams must create their safety rules, experiment assignments, data collection methods, and define their overall approach to complete experiments. Furthermore, in this part of the class, students complete individual technical memoranda instead of full laboratory reports. By changing the type of report, students are forced to decide on the data to include (e.g., which plot or figure) and on the final scope of the memo. During this part of the course, students complete two experiments following the same eight-week cycle previously described.

Experiments challenge students with a design problem in which they use their experimental knowledge to propose solutions about the feasibility of the scale-up of a process. Hence, once students have gained experimental knowledge and experience in the practice of engineering in the laboratory, they are granted more freedom in the learning experience. Figure 1 shows an example of a design problem that introduces students to PBL in the heat transfer experiment.

By the end of the junior year laboratory, students can create experimental plans, perform work safely inside the laboratory, analyze data, work in teams, create reports, and propose courses of action. Additionally, by this structure we introduce students more effectively to technical communications in engineering.

PBL Experiments: First Half of the Senior Year Laboratory. The senior year laboratory is also divided into two interdependent sections: (a) students complete four pilot-plant-type laboratory experiments, and (b) they simultaneously develop a research project that is self-directed to promote PjBL.

The first half of the senior year laboratory is focused on open-ended problems, and it is structured using elements that gradually contribute to the development of independent learning towards PjBL.[10] During the first half of the semester, students complete four experiments for which they prepare different types of technical communications. Each experiment requires students to solve a challenging design problem utilizing data they have gathered in the assigned experimental unit. The four standard experiments are completed in an overlapping four-week cycle over eight weeks. Additionally, we utilize the lecture component of the laboratory (one hour per week) to discuss topics relevant to the professional development of senior students (e.g., teamwork, leadership, diversity, etc.) We use a portion of these lectures to initiate a conversation on the importance of diversity in chemical engineering and the advantages of creating an inclusive environment within engineering teams and organizations. A detailed description of these lecture topics can be found elsewhere.[24]

The first week of the cycle is used for preparing a pre-laboratory report and a pre-laboratory presentation as described in the second half of the junior year laboratory. Unlike the junior year laboratory, the experiment manual and grading rubric do not include very detailed information on the expected analysis and discussions to include in the final report; teams must decide this on their own. The laboratory manual guides students on the overall objectives and the use of the equipment, but students decide their experimental plans to solve the problems, the experiments to perform, safety rules, internal group assignments, and the tools necessary for the evaluation of results (e.g., software). Teams collect data in a four-hour experiment during which the teaching team is available to supervise safety and guide them in case of

Heat Exchanger Design Question

Let's assume that we are tasked with designing a heat exchange system to cool a hot water stream with a volumetric flowrate of 2 L/s from a temperature of 80 °C to 15 °C. You have cooling water available at 4 °C with a maximum flowrate of 5 L/s. Unfortunately, space is an issue, as we will have to add this system to a confined area that is not very large in terms of length/width, so the largest area a ***single*** heat exchanger will be able to occupy is 28.75 m^2 (let's assume that the maximum heat transfer area is 80% of that). Furthermore, you have been told that the system cannot cost more than \$60,000. To simplify things, let's also assume that heat transfer occurs perfectly (that is, no heat is lost during travel through pipes, and you can assume a geometry factor of 1), and management has limited your options to two types of heat exchangers: U-tube shell and tube OR floating head shell and tube. Finally, you can assume that a normal valve range for the overall heat transfer coefficient is 800 - 1200 $\frac{W}{m^2 K}$. Use the above information and equation $Ce = a + bS^n$ for equipment costs to propose a heat exchange system for this process (Ce = equipment cost in US dollars, S = heat transfer area in m^2, cost constants for the U-tube shell and tube a = 28,000, b = 54, n = 1.2, cost constants for the floating head shell and tube HXT a = 32,000, b = 70, n = 1.2). Please report the total cost of the system and the pieces of the equipment that will be needed.

Figure 1. *Design problem example in the heat transfer experiment.*

questions; however, students are responsible for the operation of the equipment and the effective recording of the necessary data. After the laboratory is completed, teams use the next two weeks to develop a technical report and propose a solution to an open-ended design problem. This cycle is repeated for each of the four experiments.

This portion of the class is helpful in the improvement of some key aspects in engineering training: developing experimental plans, gathering data effectively, analyzing results, and solving challenging problems within a team.

PjBL Research Project: Senior Year Laboratory. Throughout the senior year laboratory, but mainly during the second part of the semester, we utilize PjBL as our main educational framework. We visualize PjBL as the last step in the introduction of our students to the practice of chemical engineering in a research laboratory.

To successfully incorporate PjBL in the implementation of the class projects, we developed class activities and assignments considering the six key features of the PjBL framework:[18–20]

1. Including a driving question
2. Focusing on learning goals
3. Engaging students in scientific practices
4. Centering in collaboration
5. Using technology tools to support learning
6. Allowing the creation of tangible products and artifacts

Below we explore the assignments and activities utilized to incorporate each of these key features. Figure 2 depicts an overview of the course structure during the class projects; the number in parentheses denotes the PjBL features accomplished by each of the activities listed.

Class projects are developed throughout the semester to maximize the learning experience. Students are first introduced to class projects during the first week of classes; during this week, students learn about possible experimental equipment, variables to study, and other important aspects of the projects. By the second week of classes, students are required to meet with their teams and decide on a project topic using any of the experiment stations in the laboratories. Students submit their top equipment and topic preferences, and the teaching team makes project assignments. As soon as teams are assigned to an experiment, students complete an individual project pre-proposal; this is the only individual assignment during the class projects. This individual proposal requires each student to research the project topic and create a problem statement with details of possible objectives. This assignment helps ensure that all students receive feedback and can participate in the following discussions to complete the team project. We also ensure that every student has effectively developed a **driving question**. Thereafter, individuals review feedback from the teaching team and meet with their group to decide on a final project idea to pursue.

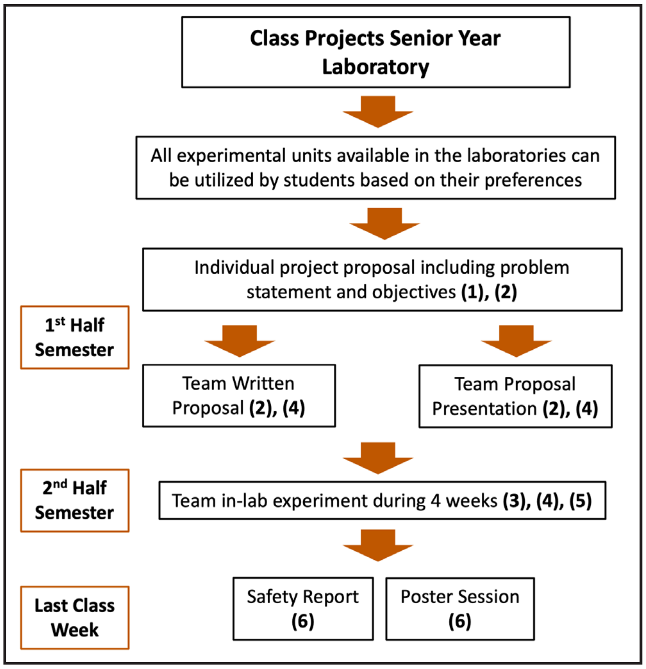

Figure 2. *Course structure overview in class projects of the Senior Year Chemical Engineering Laboratory. Parentheses indicates a key feature of PjBL accomplished by each activity: (1) driving question, (2) learning goals, (3) scientific practices, (4) collaboration, (5) use of technology, and (6) creation of products.*

The next step in the completion of the class project is the submission of a group written proposal in which each team defines the problem to be solved, the relevance of the problem, their proposed solution and approach, a summary of relevant theory and methods, their management plan, a detail of supplies and equipment needed, and a draft of the calculations needed to complete the problem solution. Teams receive feedback on this written work, and in addition, they complete a 10-minute oral presentation of the written proposal a week later. This presentation is the final opportunity to discuss experimental plans and the feasibility of the proposed research with the teaching team before they start experimentation. By completing all project work in teams, we center the project efforts in **collaboration**; furthermore, students develop their own **learning goals** in consultation with the teaching team as they finalize and present their project proposal.

Teams complete the experimental section of the class projects over a four-week period. During this time, teams complete their experiments following their own experimental procedures, and as a consequence, they **engage in scientific practices**. Teams also decide the supplies and analytical equipment needed to complete the experimental research, the type of measurements, the data to gather, and the software packages necessary for data recording and analysis. This degree of independence helps students engage in the **use of learning technologies** to perform experiments and support their own learning. As teams complete experiments, the teaching team promotes discussions and guides students in the accomplishment of their research goals adding elements of review and feedback to the project experiments.

The self-directed project culminates in a poster session for which teams also prepare a summary of their approach to safety. The poster summarizes all of the steps in the completion of their experiments: the main experimental results, a discussion of the main findings, recommendations for future work, and an understanding of the contribution of their research to chemical engineering knowledge. The research results, the poster, and the safety report are the final **products** developed from the class projects. Additionally, as required by the PjBL framework, knowledge is created by the students through the development of a proposal, the completion of the experimental research, and the data analysis and discussion of results.

The addition of PjBL in the class projects helps students practice key skills in engineering: how to design a problem, propose solutions, experiment and utilize internal and external resources to solve problems, and collaborate in teams to contribute to the construction of engineering knowledge. Moreover, we believe this project experience promotes critical thinking, self-directed learning, and the utilization of the scientific method.

Continuous Laboratory Improvement and Laboratory Collaborations

In the foregoing discussion, we described how we have restructured the laboratory courses to incorporate PBL and PjBL to accomplish the laboratories objectives more effectively. A second goal in our revamping efforts has been a commitment to continuous improvement. We have defined continuous improvement as a constant revision of the course content, a focus on collaboration, and an openness to feedback as a driver for change.

Our department has always been characterized by a strong commitment to collaboration within the university, with our alumni, and with our industry partners. However, this commitment was not translated into an improved laboratory experience for our students. By our new efforts, we wanted to ensure we could create effective collaborations that help us continuously improve our courses and recognize the elements of chemical engineering most relevant to professional success.

We first focused on the creation of new communication channels to effectively listen and act based on the feedback received from different stakeholders in our program. We created mid-semester surveys targeting feedback from our students on key aspects of the laboratories. We also welcomed feedback from TAs participating in the classes through biweekly meetings used to share feedback on manuals, assignments, and class projects. Externally, we opened channels of communication with industry partners and alumni as they are important in helping us understand how to better prepare our students for their postgraduate careers. Industry collaborators helped us with guest lectures, one-on-one meetings with our students, and occasional funding; in addition, they were key in the conception and design of new experiments and in the enhancement of the safety experience in our laboratories.

We believe our newly added fluidized bed experiment highlights this approach and our commitment to improvement through external (industry) and internal (intradepartmental) collaborations. The fluidized bed experiment was created through a collaboration in which we pursued the creation of a pilot-plant-type experiment that introduces students to fluidization and mass transfer. The experiment was developed to provide students with an enhanced experiential learning that offers a way to study fluidized systems through design experiences. The purpose of this experiment is to increase the exposure of students to mass transfer processes, separation operations, process design, and as with other elements of the class, introduce them to lifelong learning skills.

The experiment was funded by and designed in collaboration with industry partners of our department. The experiment was fully built by departmental staff, and the laboratory manual was created by doctoral chemical engineering students in consultation with the faculty associated with the courses and industry experts in the subject matter. The experiment provides a high degree of flexibility to study various process parameters of interest: minimum fluidization velocity, fluidization regimes, changes in density and pressure across fluidized systems, effects of particle size and bed height, and the design and use of cyclone separators.

Within our laboratory renovation and our continuous improvement process, we visualize the process to create an effective new experiment as a six-step process:

1. Sponsorship and Design: During this stage we met with industry partners, staff, and other collaborators to determine possible experimental updates to enhance the student experience. After funding was secured to build an experiment, we developed multiple partnerships to design the experiment and ensured experimental and safety design were up to industry standards.
2. Construction and Development of the Experience: Once the design phase is finalized, we worked with companies to secure parts and obtain software platforms. At this stage, we built the experiment to target the most effective approach to include elements of practical learning.

3. Creation of the Laboratory Manual: We worked on the creation of the laboratory manual after the experiment was finalized. We integrated the input and best practices received in the previous steps to allow us to design an effective experience. The manual was created with a design problem in mind that will conclude the practical experience. This step was developed, revised, and tested with departmental doctoral students associated with the laboratories in consultation with industry partners and faculty.
4. Testing and Improvement: The laboratory manual was tested and sample data were obtained. Units were enhanced and modified until the experiments adhere to our expectations.
5. Utilization in Courses: The experiment was first implemented for use in the class projects in the senior year laboratory. This allowed us to understand how students interact with the newly created units and how to utilize them to solve open-ended problems. We also used this test run to understand the feasibility in applying the experiment within a guided laboratory.
6. Feedback and Improvement: We constantly revise the laboratory manual and improve experiments based on observations from students, teaching assistants, and laboratory staff. We also value and welcome recommendations from industry partners visiting our laboratories. This step is most important to ensure an enhanced and updated laboratory experience for our students.

The aforementioned process was utilized to incorporate the fluidized bed unit depicted in Figure 3 to the senior year laboratory. The full process took approximately 18 months, including designing, building, testing, and integrating the experiment within the course.

The column pictured in Figure 3 is constructed of clear acrylic tubing. Building air enters the column from the bottom and exits through the top. The media inside the column is usually glass beads, and the media can be changed to study different flow regimes and applications. The column is equipped with two cyclone separators that introduce students to engineering concepts beyond our chemical engineering topics as a way to promote the development of lifelong learning skills.

The laboratory manual provides an overview of the basic theory of fluidization, the applications of fluidization in chemical engineering, and the design of separation processes and cyclone separators. In the experiment, students calculate a theoretical minimum fluidization velocity, and then they perform experiments to find this value experimentally. Figure 4 depicts an example plot of gas velocity (in *cm/s*) as a function of column pressure drop (ΔP, in *kPa*) obtained using a Geldart Group B particle in the column.

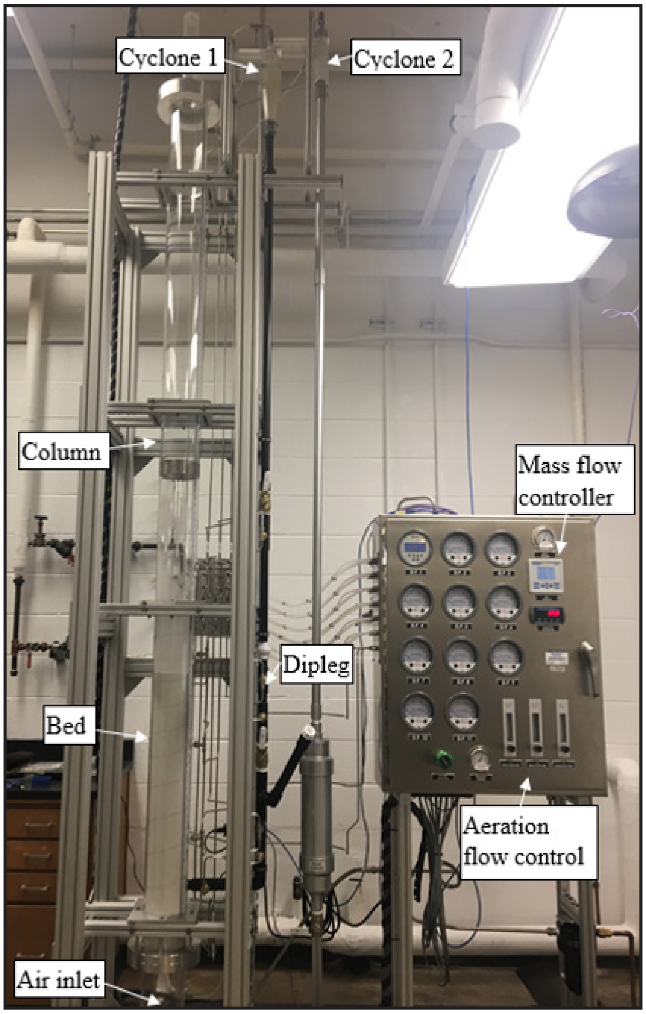

Figure 3. *Fluidized bed experimental equipment.*

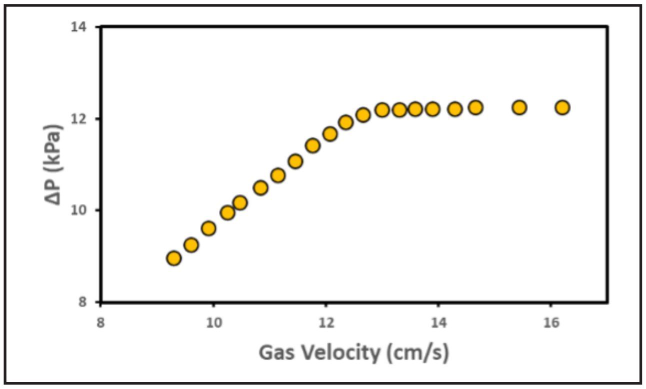

Figure 4. *Plot to determine the minimum fluidization velocity experimentally obtained in the fluidized bed experimental equipment using a Geldart Group B particle. The Y-axis represents the pressure drop (ΔP) across the column in kPa, while the X-axis represents the superficial velocity of the gas flowing through the column in cm/s.*

The experiment also requires students to explore bed height and bed density as determining factors in the optimization of a fluidized system;[25] moreover, the concept of entrainment and its effects over fluidization is also introduced and experimentally studied. The experiment has been designed to show different types of fluidization regimes; students use this information to explain how fluidization regimes affect mass transport inside the column and make conclusions about their effects on engineering applications. As part of the experimental experience, students also observe the operation of the cyclone separators through an independent screen showing a live stream of their operation. These cyclone separators are the focus of the design problem in which students are asked to utilize their experimental data to design a cyclone separator which will be used with a different particle size and a higher or lower minimum fluidization velocity.

This experiment has also been incorporated in the class projects portion of the senior year laboratory. In previous years, students assigned to the experiment have tried to understand the effects of bed height and density over the operation of a fluidized system and to study the optimization of bed material in a particular engineering application.

Collaborations have been at the center of our approach to enhance the courses. In the last year, we have updated the experiment and laboratory manual based on feedback received from different stakeholders in our program as part of our efforts to continually improve the laboratory experience:

- Our students and TAs suggested that information was lacking on the design of cyclone separators; we added a short write-up describing some design principles.
- We updated bed material types following a recommendation from an industry partner that suggested a different particle could improve the visualization of fluidization regimes.
- We added extra safety features (e.g., one more rupture disk) in response to a discussion with department alumni visiting our laboratories to discuss safety.

STUDENT PERCEPTION

We collected feedback from students in the senior year laboratory during the academic year after the laboratory updates were fully implemented in both courses. By the time of the survey, all students registered in the course had also been exposed to the updated version of the junior year laboratory. We surveyed students in the senior year laboratory as these students have experienced the fully updated courses (i.e., as opposed to students in the junior year laboratory who have only experienced one of the courses.) Our goal with this survey was to understand how our efforts have affected the student perception of the learning experience, and if, regardless of the extra work added and the newly implemented updates, students would still have a positive perception of the courses.

To gather this information, we used a mid-semester survey administered in Qualtrics® during class time. The survey contained four Likert-scale questions and two open-ended questions relevant to the laboratory. All survey data was collected electronically, and students were asked to provide consent for the data to be used for education research purposes. The use of survey data was approved by the Institutional Review Board at the University of Texas at Austin. Participation in the survey was voluntary.

Likert-scale questions surveyed students on their overall perception of the course experience using a 5-point scale as follows: “1=Strongly Disagree,” “2=Somewhat Disagree,” “3=Neither Agree nor Disagree,” “4=Somewhat Agree,” and “5=Strongly Agree.” We explored four areas through these questions:

- Q1 Contribution to Knowledge Solidification: We asked students their perception of the opportunities to practice their knowledge and solidify concepts learned.
- Q2 Connection to Chemical Engineering Coursework: We inquired about the connection of the laboratory to their previous courses.
- Q3 Contribution to the Development of Lifelong Learning Skills: We asked students if the course is helping them engage in lifelong learning skills (lifelong learning is discussed during lecture) and if they consider the course material will be applicable to future professional situations.
- Q4 Practicability and Applicability of Content: We explored perception on the laboratory content being hands-on, practical, and applicable to chemical engineering practice.

A total of 135 students participated in the survey: 58 in Fall 2022 (89.2%, 65 students registered) and 77 in Spring 2023 (85.6%, 90 students registered). No other identifying characteristics were recorded; the goal of the survey was to understand the overall perception of the learning experience of all students rather than that of a particular group of students. To further simplify data visualization, we grouped answers to these questions in three categories:

1. Positive perception if students strongly agree (5) or somewhat agree (4)
2. Neutral perception if students neither agree nor disagree (3)
3. Negative perception if students somewhat disagree (2) or strongly disagree (1)

Figure 5 summarizes the results obtained in the survey. Most students had an overall positive perception of the effectiveness of the courses in helping their professional development after the changes were implemented. Data show a majority of students agree that the current format of the course contributes to the solidification of their chemical engineering knowledge (> 80%) and that the laboratory creates a good connection to concepts previously learned (> 70%). These are two fundamental aspects to evaluate the effectiveness of the sequence, as we have pursued opportunities where students practice and reinforce their knowledge while being introduced to practical engineering problems. Laboratory courses in engineering must create experiences where students can practice and apply their engineering knowledge.[1] From Figure 5 we can also infer that students perceive the utilization of projects and open-ended problems as a way to develop lifelong learning skills (> 70%). Students are constantly required to engage with external resources, participate in discussions, and solve challenging design problems.

The practicality and applicability of the laboratory resulted in lower positive outcomes during Fall 2022, with 27% of students having a negative perception; nonetheless, we see a sharp increase in Spring 2023 with only 5.2% of students disagreeing on this contribution. Unfortunately, due to a problem with data collection in Qualtrics in Fall 2022, only the responses of 18 students (27.7%) were recorded for this question. While we revised the course based on the feedback received and incorporated reflections to explore applications of the laboratory experiences to real situations, it was unclear if the changes in perception were rather due to the low percentage of responses recorded in Fall 2022 for this question. Nevertheless, we observe the overall data set for the question suggests students perceive the laboratory as applicable and as a contribution to their professional development. To investigate the data sets further, perception question results were analyzed using a Mann-Whitney U test.[26-27] In all cases, the test determined a statistically significant difference between the data sets for the Fall and Spring semester student groups (Q1: $n_{Fall} = 58$, $n_{Spring} = 77$, $U_1 = 1580.5$, $p_1 = 0.00155$; Q2: $n_{Fall} = 58$, $n_{Spring} = 77$, $U_2 = 1309.0$, $p_2 = 0.00001$; Q3: $n_{Fall} = 35$, $n_{Spring} = 77$, $U_3 = 1052.5$, $p_3 = 0.0477$; Q4: $n_{Fall} = 18$, $n_{Spring} = 77$, $U_4 = 407.0$, $p_4 = 0.00375$). From these results, we hypothesize changes in perception can be attributed to differences in the population of students (i.e., most students in the Spring were completing their degree that semester), the course updates made between semesters due to feedback received, and external factors such as teaching assistants participating in the laboratories and the student-to-instructor ratio each semester (i.e., the number of students increased considerably in the Spring, but the number of instructors and TAs was constant). Despite the calculated statistical differences in the data sets, the results depict a positive trend and an overall positive student perception in all aspects of the laboratory.

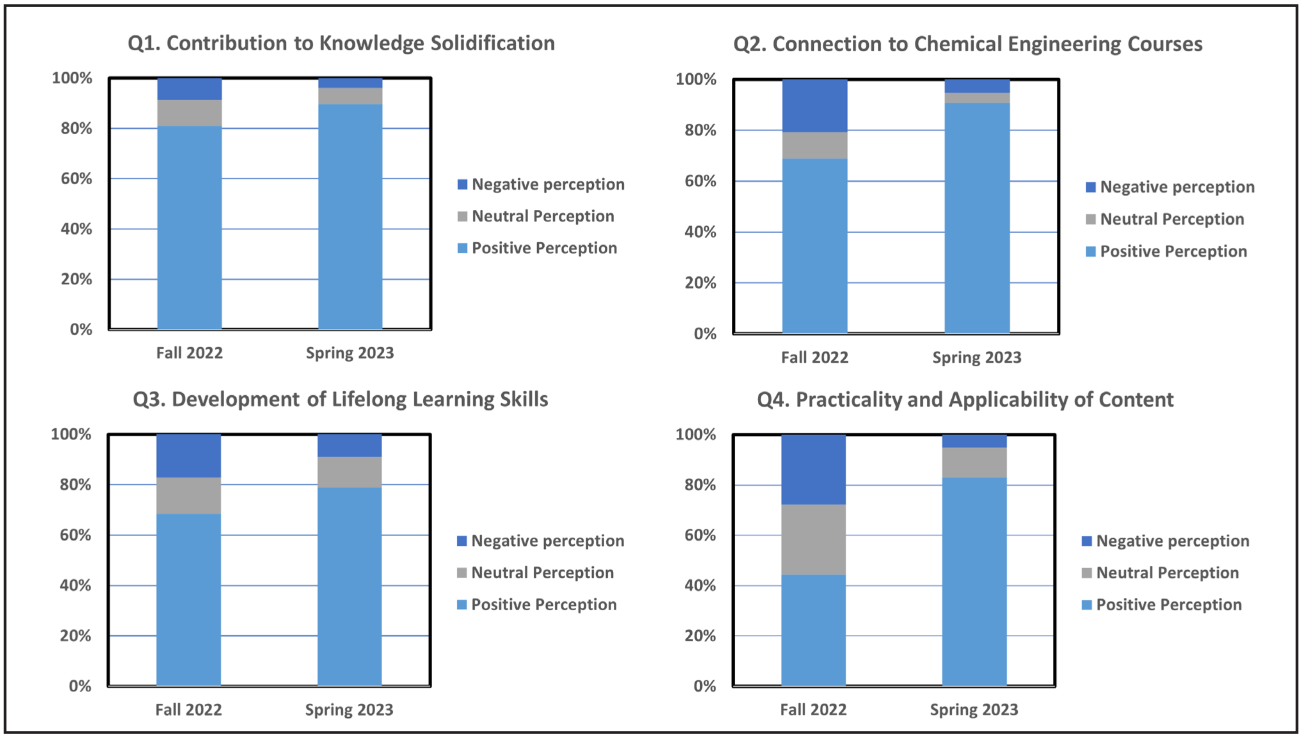

Figure 5. *Student survey results in targeted areas during Academic Year 2022-2023. Question 1: $n_{Fall} = 58$, $n_{Spring} = 77$; Question 2: $n_{Fall} = 58$, $n_{Spring} = 77$; Question 3: $n_{Fall} = 35$, $n_{Spring} = 77$; Question 4: $n_{Fall} = 18$, $n_{Spring} = 77$.*

Our survey also captured feedback through two open-text questions exploring aspects of the class that have been most helpful in student learning and aspects of the course that could be improved to enhance the learning experience. Student feedback was analyzed and divided into categories to clearly explore areas that need improvement and areas that were most effective at accomplishing our goals. We summarize these categories as follows:

- **Positive** - Laboratory experiments and applicability: 32% of students perceived the experiments, laboratory activities, and the overall practicality of the experience as positive:
    - *"It has been great working in the laboratory and experiencing what I've been studying on paper for 4 years in real life."*
    - *"Project based class and hands-on experiments to learn material in a different way. The design problems really made me think."*
- **Positive** - Teamwork: 27% of respondents considered working with others in teams improved their learning experience:
    - *"Being able to work as a team every step of the way has been a great way to learn how to communicate."*
- **Positive** - The updated role of teaching assistants: 21% of students perceived the role of TAs as direct participants in the teaching process as positive:
    - *"I really like how the TA will demonstrate and help students learn and practice theoretical procedures in real applications."*
    - *"The help of the TAs has been very valuable for learning and engagement"*.

Feedback on aspects for course improvement showed two repeated categories in both semesters:

- **Improvement** - Guidance in laboratory manuals and report rubrics: 45% of students considered that the laboratory manuals and grading rubrics are not as detailed as in other courses; however, results suggest they can still see the value of facing ill-structured problems and the extra degree of independence:
    - *"Sometimes the instructions can be broad, but it's important for us to ask questions and think about how to interpret it best."*
    - *"Sometimes the equations and theory build on previous chemical engineering concepts that students might be unfamiliar with and will need a review."*
- **Improvement** - Perceived laboratory workload: 25% of students considered the laboratory to have a relatively high workload for a two-credit hour course; in spite of this, results seem to indicate students see educational value in this challenge:
    - *"The schedule of the class is very fast-paced, to the point where it feels like two labs stuffed into one."*
    - *"I think having so many different deadlines for assignments coming up concurrently makes this class more difficult. However, this isn't a huge issue as it teaches time management."*

Some feedback on course improvement touched on the increased degree of independence and the workload associated with the collaborative aspects of the course. In response to this feedback, we introduced a teamwork training to facilitate collaboration within teams [24] and decrease the workload perception due to collaborative work; additionally, we have updated the assignment deadlines to reduce the number of assignments per week. In terms of the ill-structured problems and higher degree of independence, even when this is a typical issue of presenting students with PBL and PjBL strategies, [12, 17] our future plan is to dedicate additional time in lecture to explain the benefits of this approach as a way to alleviate some uncertainty in our students.

CONCLUSIONS

We have redesigned and updated our undergraduate laboratory experience to create a structured sequence that intends to continuously improve the learning experience of chemical engineering students. We have utilized a PBL and PjBL approach in which students are progressively introduced to challenging ill-structured open-ended problems, the development of projects, and the creation of research products. This approach promotes self-directed learning and contributes to the development of skills required by the modern engineering work environment. By completion of the courses, students increase their experimental experience, solidify their knowledge, solve open-ended challenges, and are exposed to design processes that facilitate their professional development and encourage the acquisition of lifelong learning skills. As part of these efforts, we have also benefited from the application of a continuous improvement model to dynamically evaluate the laboratory content and ensure the courses effectively serve the current needs of chemical engineering students, chemical engineering research, and the chemical engineering industry along with other stakeholders of our program.

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