

# EMBEDDING HANDS-ON MINI LABORATORY EXPERIENCES IN A CORE UNDERGRADUATE FLUID MECHANICS COURSE: *A Pilot Study*

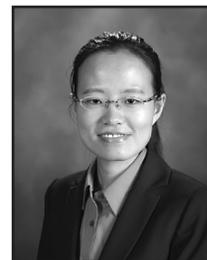
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The engineering profession involves applying fundamental scientific and mathematical concepts toward solving problems involving real systems. These fundamentals are typically introduced in a theoretical context, making instructional laboratories vitally important to bridge the gap between concept and application.<sup>[1]</sup> In addition to introducing real-world scenarios,<sup>[2]</sup> laboratory experiences enable students to develop self-identities as engineers with relevant and valuable problem-solving skills.<sup>[3]</sup> Achieving an optimal balance between theory and hands-on experience has been an important topic in engineering education since the 19th century, when both military academies and civilian schools heavily emphasized laboratory experience in the curricula by virtue of its focus on design and construction of machines and tools.<sup>[4]</sup> This practical focus continued until the mid-1950s when the Grinter report, issued by a committee formed under the American Society for Engineering Education (ASEE), advocated a shift from practice-oriented activities to basic science as part of an emphasis on solving problems by referring to fundamental principles.<sup>[5,6]</sup> In the 1980s, the former Engineer's Council for Professional Development (now ABET), issued new criteria to evaluate engineering programs that brought renewed emphasis to laboratory courses,<sup>[7]</sup> and ASEE further reaffirmed the irreplaceable role of laboratory experiences.<sup>[8]</sup> At present, ABET criteria for accrediting engineering programs prominently include availability of laboratory facilities to support achievement of learning outcomes.<sup>[9]</sup> It is now widely accepted that laboratory courses effectively promote active and cooperative learning,<sup>[6,10]</sup> both

of which are proven to enhance engineering education and accommodate students with different learning styles.<sup>[11]</sup>

In chemical engineering, unit operations laboratory courses play a critical role by allowing students to apply momentum, heat, and mass conservation principles.<sup>[12]</sup> These laboratories are generally scheduled during the senior year, after fundamental instruction associated with these subjects has taken

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place in previous theory courses. This structure inevitably leads to a multiple-semester delay between the time when topics are introduced in theory courses and the time when they are linked to applications, reducing the effectiveness of laboratories to reinforce fundamental learning objectives.<sup>[13]</sup> Integrating laboratory experiences into a theory course therefore offers an opportunity to link theory and application at the same stage of the curriculum.

Hands-on experiments, sometimes referred to as “learning by doing,” have been explored as a method to capture student interest and enhance achievement of learning outcomes.<sup>[14]</sup> These activities have been broadly implemented across academic levels ranging from high schools<sup>[15]</sup> to the undergraduate senior-level capstone design.<sup>[16]</sup> One embodiment involved a one-week summer camp for high school students offering hands-on projects intended to attract the students to the engineering field (*e.g.*, air pollutant measurement, water desalination). These activities were credited with contributing to the camp’s success, with 28 out of 30 students indicating an interest in pursuing an engineering major as a consequence of participation.<sup>[15]</sup> At the undergraduate freshman level, a hands-on experiment exploring the science of carbonated soft drinks was incorporated into an introductory engineering course.<sup>[17]</sup> This activity enabled students to apply fundamental chemical engineering principles (gas absorption) toward a practical application at an early stage of college study (*e.g.*, how to keep soft drinks carbonated after their containers were opened), with the goal of increasing retention in the chemical engineering major. Although generally successful, the project was found by some students to be challenging due to its open-ended nature. Another example, the Controlled Operation Mechanical Energy Transducer (COMETs) competition, was designed to expose sophomore chemical engineering students to a complete cycle of designing, building, and testing a product. This hands-on project was welcomed by students as learning “away from paper and theory,” but strengthening the connection with the course material (*i.e.*, energy balances) was cited as an area for improvement.<sup>[18]</sup> In the upper-level engineering curriculum, hands-on experiments have been implemented in junior-level core courses, including fluid mechanics, heat transfer, and mass transfer. Students have, for example, been assigned tasks associated with design and scale-up of heat exchangers,<sup>[19]</sup> and identifying leaks in a gas separation device.<sup>[20]</sup> Student feedback was generally positive, but the additional time commitment and operational costs involved imposed barriers against expanding implementation to other subjects.

Desktop-scale modules have been explored as a way to enable expanded implementation of hands-on activities owing to their low cost and ability to be operated during regularly scheduled class time. For example, inexpensive apparatuses (*e.g.*, coffee cup warmers, metal rods, CPU heat sinks) were used to assemble portable demonstration sets aligned with

fundamentals of heat transfer.<sup>[21]</sup> Working in teams, students were able to study the apparatuses at their own pace, and actively engage with peers displaying different learning styles. In another adaptation, a pre-assembled see-through shell and tube heat exchanger was analyzed by students in teams.<sup>[22]</sup>

Virtual “weblabs” have also been explored owing to their minimal space, staffing, scheduling, and safety requirements. In one example, students remotely operated a set of heat exchangers via a software interface.<sup>[23,24]</sup> Students valued the opportunity to learn through a “remotely hands-on experiment” while practicing data collection and analysis in a scenario similar to an industrial control room environment. But the lack of physical interaction with real equipment can make it challenging to replicate the first-hand experience of troubleshooting and dealing with uncertainty, leading some students to view the instruments as virtual elements that are not likely to malfunction or generate imperfect data. Live, remote, and virtual labs each offer their own unique benefits, and a balanced combination of each is therefore likely to deliver the most impactful student experiences.

In this paper, we describe an effort to address the challenges associated with delivery of hands-on experiences in large classes by embedding “mini-lab” experiments operated on pilot scale instruments directly into a junior-level core fluid mechanics course. We piloted an adaptation of mini-labs that consisted of three 50-min laboratory sessions designed for the undergraduate core fluid mechanics class in the Department of Chemical Engineering at Texas A&M University, part of a three-course sequence covering momentum, heat, and mass transport. The course (CHEN 304) uses the textbook *Fluid Mechanics for Chemical Engineers*, by J.O. Wilkes, and had a total enrollment of 155 students in Fall 2015 (across three sections, one of which participated in the mini-lab pilot) and 28 students in Spring 2016. Three mini-labs were developed focusing on fluid mechanics concepts including friction losses in pipes, flow measurement, and centrifugal pump analysis. These topics dovetail with the dedicated senior-level unit operations laboratory course, but are presented in a more focused and concise format (Table 1, next page). Students were assigned to complete the mini-labs in the same manner as a typical homework assignment, and were responsible for booking time on the experimental apparatus using an online scheduling tool. In addition to reinforcing fundamental concepts, the mini-labs were structured to help students gain confidence in problem solving, establish self-identities as engineers, and obtain experience working in teams.

## METHODS

### Organization and implementation

Mini-labs were scheduled approximately concurrently with presentations of corresponding fundamental material in the theory course. Each student was asked to book a single 50-minute session using the SignUpGenius service

**TABLE 1**  
**Comparison between mini-labs and dedicated unit operations laboratory courses.**

	Mini-labs	Dedicated unit operations laboratory course
Curriculum schedule	Junior year, part of fluid mechanics course, lab completed within two weeks after concepts covered in lecture	Senior year, lab completed one or two semesters after concepts covered in lecture
Content scope	Fluid mechanics	Fluid mechanics
Prerequisite	Differential equations, material balances	Fluid mechanics course
Scheduling approach	Online scheduling tool deployed after the concepts are covered in lecture	Students register for a dedicated course
Attendance	Optional during Fall 2015 pilot, mandatory as part of Spring 2016 pilot: students unable to attend were given an alternate assignment	Mandatory
Level of participation	Groups of 1 to 4 students run lab and submit individual assignments	Groups of four students run lab and submit a single group report
Length of meeting time	Three 50-min sessions	Weekly 3-h sessions
Level of in-lab instruction related to theory	Review of fundamental concepts and step-by-step demonstration of experiment procedures	Minimal
Lab report format	Assignment involving data analysis and answers to discussion questions, primarily evaluated for technical content	Formal written lab report including background, materials/methods, results/discussion, and conclusion sections, oral presentation
Lab report workload	1 to 2 h, comparable to typical homework assignment questions	Writing intensive, 4 to 5 h per student
Lab report focus	Basic data analysis and short-answer questions to describe key phenomena	Thorough data analysis, technical writing emphasized
Learning objectives	Apply mass and momentum transport principles, analyze experiment data	Apply mass and momentum transport principles, acquire accurate data, analyze experimental results, prepare formal written reports, give oral presentations

([www.signupgenius.com](http://www.signupgenius.com)), an online signup tool. Time slots were assigned on a first-come, first-served basis, and the signup tool remained open throughout the entire 1- to 2-week period during which mini-labs were scheduled. Students were able to change their signup choices at any time prior to the start of their session. Preparatory materials—as well as a guide to each experiment, assignments, and safety information—were provided through the course website.

The lab instructor provided an introduction to the experiment apparatus (a single Armfield C6-MKII-10 station), the associated theory concepts, and the operation procedure. Students were asked to work in groups of up to four students to operate the apparatus and collect data. Instructions regarding the accompanying data analysis assignment were provided upon completion of the experiment. Students completed the assignments individually, and the instructor was available by appointment to answer questions. Anonymous assessment surveys were conducted using the online platform Qualtrics to gather student feedback about their pre-, in-, and post-lab experiences.

Student participation in the mini-lab pilot is detailed in Table 2. For lab 1 during the Fall 2015 semester, the mini-lab and the alternate assignment were both optional. For lab 2 during the Fall 2015 semester, the mini-labs were optional but the alternate assignment was mandatory. During the Spring

2016 semester, mini-labs were mandatory and the alternate assignment was mandatory for students who could not attend under circumstances governed by institutional excused class absence policies. The alternate assignment included a video screencast describing the apparatus, theory background, operation procedure, and acquisition of a sample data set. Students were then asked to complete the same lab assignment as students who attended the mini-lab sessions using the provided sample data set. Examples of the screencasts are available online (friction loss in pipes - <https://youtu.be/m3RuDhHLkt8>; flow measurement - <https://youtu.be/3KsgeiJHI10>; we did not prepare a screencast for the centrifugal pump mini-lab).

### Course development cycle

A standard course development cycle framework was used in the instructional design process, as described below.

- **Analysis:** *The purpose of the mini-labs is to embed fluid mechanics unit operations experiences into a lecture-based theory course to provide early exposure to hands-on activities, reinforce theory-oriented fundamental concepts, and offer opportunities to apply fluid mechanics principles to solve real-system problems.*
- **Design:** *Each mini-lab focuses on one concept and invites students to participate in a short lab session scheduled outside the regular class meeting time, after*

**TABLE 2**  
Student participation in mini-lab pilot.

Semester	No. of students registered for fluid mechanics course	Mini-lab content	No. of students who participated in mini-labs	No. of students who completed post-lab surveys
Fall 2015	47 Mini-lab not mandatory	Lab 1: flow measurement	26 attended  20 submitted lab assignment  4 submitted alternate assignment	Survey 1: 19 Survey given after completion of lab 1
	47 Either mini-lab or alternate assignment mandatory	Lab 2: friction losses in pipes	35 attended  33 submitted lab assignment  10 submitted alternate assignment	No survey
Spring 2016	28 Mini-lab mandatory	Lab 1: friction losses in pipes	28 attended  28 submitted lab assignment	Survey 2: 19 Survey given after completion of all 3 mini-labs
	28 Mini-lab mandatory	Lab 2: flow measurement	27 attended  26 submitted lab assignment  1 submitted alternate assignment	
	28 Mini-lab mandatory	Lab 3: centrifugal pump analysis	27 submitted lab assignment	

which students complete a data analysis assignment.

- **Develop:** The experiment procedure was developed by the instructor and tested with the help of an undergraduate honors program student.
- **Implement:** Students were asked to participate in mini-lab sessions and complete lab assignments.
- **Evaluate:** Student performance on lab assignments was assessed. Student feedback was collected and used to modify course design.

## RESULTS AND DISCUSSION

### Teamwork

To foster teamwork, each mini-lab session was structured to allow up to four students to participate as a group. Groups of three to four students participated in 60% of the sessions. Students were prompted to take turns performing different tasks (e.g., changing pressure sensor positions and flow rates, recording data, operating the control software) and discuss their observations in the group setting. Communication among students was observed by the lab instructor. For example, in the flow measurement lab, one student who changed the pressure sensor position announced loudly the sensor positions, and the student in charge of acquiring data also read the

number aloud to confirm the measurement and ensure that all participants could record the data. One student in a medical situation with restricted mobility was also able to perform data recording tasks with the aid of other students in the group.

### Assessment of learning objectives

The mini-lab learning objectives were structured to lead students toward the dedicated senior-level unit operations laboratory course, which emphasizes equipment operation, data recording and analysis, and communication of technical results via written and oral formats.<sup>[25]</sup> Assessment methods and results for the three mini-labs piloted are summarized in Tables 3-5 (next page). An additional evaluative assessment question included in each mini-lab asked students to list at least two possible sources of error in the experiment.

Multiple students expressed positive impressions of mini-labs as a tool to reinforce the theory course learning objectives, with visualization of real equipment a recurring theme. Representative positive responses to the question “are mini labs an effective use of your time to help reinforce the lecture material?” included the following.

- “It helped me relate the lecture to the real world.”
- “Being able to visualize the meters we were talking about was really helpful.”

<b>TABLE 3</b> <b>Learning objectives linked to mini-lab #1 (friction losses in pipes).</b>			
<b>Learning objective</b>	<b>Level of learning</b>	<b>Assessment method</b>	<b>Assessment result</b>
Measure pressure drops in pipe segments of different diameters and roughness at different flow rates	Remembering	Method: instructor's observation Level of assessment: group Purpose of assessment: formative Object of assessment: behavior	Students were able to finish the tasks, either in group or individually, without difficulties. This operation required changing pressure sensor positions. Students communicated effectively among each other about the parameters being measured.
Calculate friction factor with pressure drop data	Applying	Method: lab assignment Level of assessment: individual Purpose of assessment: formative Object of assessment: skill	91% of students answered the question correctly.
Compare friction factor with correlations (Moody chart)	Evaluating	Method: lab assignment Level of assessment: individual Purpose of assessment: formative Object of assessment: skill	68% of students answered the question correctly. Some students have difficulties working with logarithmic-scales and consequently plotted their data incorrectly.

<b>TABLE 4</b> <b>Learning objectives linked to mini-lab #2 (flow measurement).</b>			
<b>Learning objective</b>	<b>Level of learning</b>	<b>Assessment method</b>	<b>Assessment result</b>
Measure pressure at different positions across flow meters at different flow rates	Remembering	Method: instructor's observation Level of assessment: group Purpose of assessment: formative Object of assessment: behavior	Students were able to finish the tasks, either in group or individually, without difficulties. This operation required changing pressure sensor positions. Students communicated effectively among each other about the parameters being measured.
Calculate the flow velocity at different positions	Understanding	Method: lab assignment Level of assessment: individual Purpose of assessment: formative Object of assessment: skill	88% of students answered the question correctly. Tables provided for students to record their data were revised in Spring 2016 based on feedback from the previous semester.
Calculate the flow rate using the Venturi equation	Applying	Method: lab assignment Level of assessment: individual Purpose of assessment: formative Object of assessment: skill	88% of students answered the question correctly. This question could be self-checked by comparing with the apparatus' electronic flowmeter reading.
Calculate discharge coefficient and flow rate using the orifice plate equation	Applying	Method: lab assignment Level of assessment: individual Purpose of assessment: formative Object of assessment: skill	70% of students answered the question correctly. This question could be self-checked by comparing with the apparatus' electronic flowmeter reading.

<b>TABLE 5</b> <b>Learning objectives linked to mini-lab #3 (centrifugal pump analysis).</b>			
<b>Learning objective</b>	<b>Level of learning</b>	<b>Assessment method</b>	<b>Assessment result</b>
Measure discharge head at a fixed impeller speed at different flow rates.	Remembering	Method: instructor's observation Level of assessment: group Purpose of assessment: formative Object of assessment: behavior.	Students were able to finish the tasks, either in groups or individually, without difficulties. This was the third mini-lab performed, so students had developed deep familiarity with the procedures.
Plot a pump performance curve	Understanding	Method: lab assignment Level of assessment: individual Purpose of assessment: formative Object of assessment: skill	All 27 students answered this question correctly.
Identify how discharge head changes with flow rate	Analyzing	Method: lab assignment Level of assessment: individual Purpose of assessment: formative Object of assessment: skill	All 27 students answered this question correctly.

**TABLE 6**  
**Comparison between mini-lab schedule and regular course schedule.**

Regular course schedule (Monday, Wednesday, and Friday)	Mini-lab schedule (Monday, Wednesday, and Friday)	Regular course schedule (Tuesday and Thursday)	Mini-lab schedule (Tuesday and Thursday)
9:10 – 10:00 a.m.	9:10 – 10:00 a.m.	8:00 – 9:15 a.m.	8:25 – 9:15 a.m. *
10:20 – 11:10 a.m.	10:20 – 11:10 a.m.	9:35 – 10:50 a.m.	9:35 – 10:25 a.m.
11:30 – 12:20 a.m.	11:30 – 12:20 a.m.	11:10 – 12:25 p.m.	11:10 – 12:00 p.m.

\*This session is postponed to match the end time of the first regularly scheduled course.

- *“Seeing the actual equipment helps understanding material conceptually.”*
- *“Definitely effective to help reinforce the material for me, since I am a pretty visual learner.”*
- *“I believe the mini-labs were useful in the fact that they gave me more ‘face time’ with the material as well as that they allowed me to practice more problems with the different types of scenarios pertaining to fluids.”*

Some negative comments were also expressed as follows.

- *“It was too long and repetitive to fill out the whole table.”*
- *“Let us get a little more involve in the experiment. We just moved sensors to where we were suppose. While I was fine doing them, I didn’t feel like they added additional insight from what we were already discussing in lecture. Make us think a little more during the lab.”*
- *“I think mini-lab 3 needs to have more to it. Simply plotting 5 points did not have much meaning to me. Otherwise mini-lab 1&2 need to somehow have less work. It would also help to do the labs earlier in the semester so they are not all back-to-back right before finals/projects.”*

The mini-labs also helped students tie their visual impressions back to fundamental principles and link their experiences with real equipment back to theory. As one student said, “worked with orifice plates in internship this summer, and it was very interesting to actually be able to do the calculations that accompany them.” The assessment survey also indicated that 73% of students reported feeling new confidence in their ability to solve real-world problems, demonstrating self-recognition as future engineers.

### Scheduling

Some challenges were encountered in coordinating between the students’ schedules and the availability of the lab apparatus. Standard class periods are scheduled for either 50 minutes (Monday, Wednesday, and Friday) or 75 minutes (Tuesday and Thursday). To avoid overlap with multiple course periods and keep the lab material consistent, each lab session was structured so that it could be completed in 50 minutes. The time slots were arranged to begin at the same time as regularly scheduled courses. Since the mini-labs share apparatuses with the senior-level unit operations laboratory course, only limited four-hour periods in the mornings were available,

allowing three time slots to be made available (Table 6). With groups of up to four per session, mini-labs scheduled during four consecutive weekdays (12 total sessions with capacity for 48 students) successfully accommodated all the enrolled students. Additional sessions were scheduled for individual students who could not attend during these time slots.

### Student feedback survey results

#### Pre-lab experience

- *Sign-up: All students who participated in the survey responded that the sign-up system was easy to use.*
- *Lab preparation material: 92% of students agreed that the material posted on course website were helpful.*

#### In-lab experience

- *Time arrangement: All students who participated in the survey responded that they had enough time to complete the experiments, either participated alone or in group. The lab instructor’s observation was the same.*
- *Worksheet for data recording: 92% of students agreed that the worksheets provided were easy to use.*
- *Introduction from the lab instructor: All students agreed that the lab instructor was effective in giving theory background introduction and operation demonstration. The lab instructor was “to the point on introduction; also tied everything to what we were learning in class.”*

#### Post-lab experience

##### • Homework load

- Survey 1 (Fall 2015, lab 1: flow measurements)
  - *Students spent an average of 2 – 3 hours on the lab assignment and 50% agreed that the workload was higher than a typical homework assignment.*
  - *Student feedback toward the lab assignment calculations was mixed. Some reflected that “the repetitive calculations also helped reinforce the course material,” whereas others responded that “the write-up was very iterative and took a lot of time, about 50% of the time I spent learning and the other 50% was just changing numbers in my calculator and pressing enter,” and “I should have done it all in excel.”*
  - *We reduced the workload significantly in Fall 2015, lab 2 (friction losses in pipes) to 1 – 1.5 hours, by decreasing the number of parameters tested.*

- B. Survey 2 (Spring 2016: all labs):
- Most students agreed that Lab 1 (friction losses in pipes) and Lab 2 (flow measurement) have similar workload as a typical homework assignment and Lab 3 (centrifugal pump analysis) has less workload, and spent 1.45, 1.57, and 0.72 hours on the lab assignment, respectively.

• **Lab assignment format, instructions, and scheduling**

- A. Some students indicated that headers of data tables were confusing in survey 1. For example, students were confused about “which flow rate is chosen to calculate the Reynolds number.”
- B. To improve this, data tables were revised (for example, to clearly state that the electronic flow meter readings are used to calculate Reynolds number)
- C. More instructions were also provided upon completion of the experiment, and students were encouraged to contact the lab instructor with any questions.
- D. The lab instructor noted several students plotted their data incorrectly while grading the lab assignments in the 2015 fall semester. Then in the 2016 spring semester, the lab instructor gave additional instructions on reading logarithmic scale and notified the students that it was a common mistake in previous classes.
- E. Some students also expressed concern of scheduling labs during weeks close to final exams, with comments including “do the lab earlier in the semester” and “have them consistently” along the course rather than “all back-to-back right before finals and projects.”

**Connection to theory course**

We examined course grades of the Spring 2016 cohort, for whom participation in the mini-labs was mandatory. This class of 28 students earned an average course grade of 3.233, which was more than one standard deviation greater than the five-year average grade for the course in previous sections taught by the same instructor where no mini-labs were included ( $3.107 \pm 0.058$ ). Although these data from our limited pilot-scale implementation are preliminary, they nevertheless provide encouraging evidence that the mini-labs enhance student mastery of the course learning objectives.

Student perspectives toward the fundamental concepts and their applications to real-world examples were quantified in terms of their level of confidence in solving problems associated with the mini-lab experiments at three different time points: after attending the lecture, after attending the mini-lab session, and after completing the data analysis assignment. Student responses were classified according to four different levels of problem-solving skills. Each successive level includes the skills described in the preceding levels.

- **Level 1:** *I am unfamiliar with friction losses and unable to solve problems involving them.*

- **Level 2:** *I have a basic knowledge of the subject. I know enough to prepare for homework and exam problems.*
- **Level 3:** *I am able to apply textbook principles in a controlled laboratory environment.*
- **Level 4:** *I am able to solve real-world problems that I may encounter as an engineer.*

After classifying the student responses, their perceptions of mastery were interpreted in the context of the goals listed below.

- **Goal 1:** *reach skill level 2 after attending the theory course.*
- **Goal 2:** *reach skill level 3 after attending the mini-lab.*
- **Goal 3:** *reach skill level 4 after completing the data analysis assignment.*

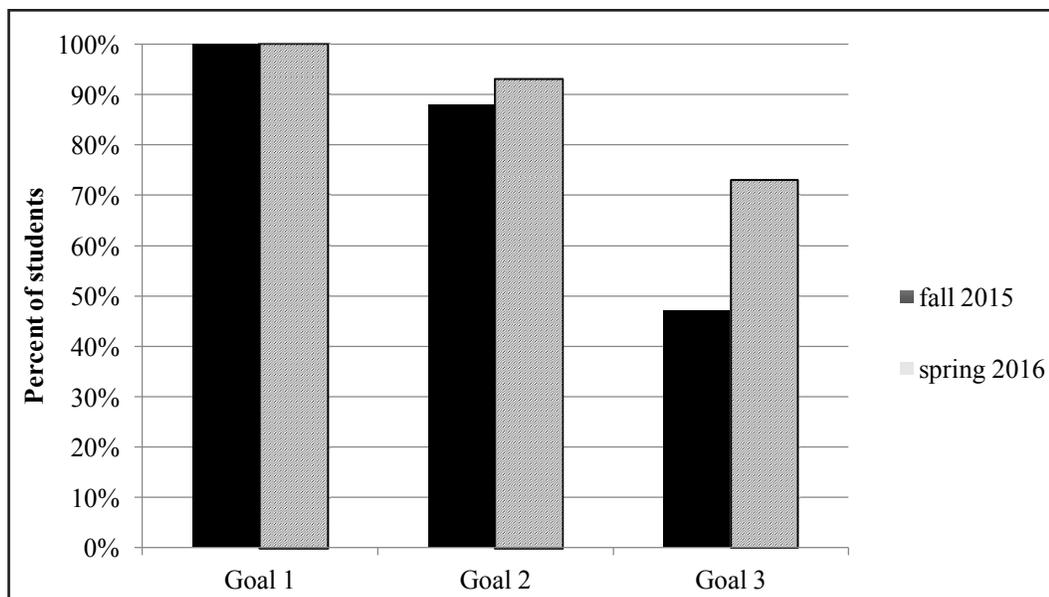
Goal 1 reflects a minimum level of mastery upon completion of classroom instruction and is included to confirm that students are equipped with fundamental knowledge needed to perform the mini-lab experiment. Goal 2 reflects the primary objective of the mini-labs, focusing on hands-on experience acquired simultaneously with the theory course instruction. Goal 3 reflects an additional level of mastery, as mini-labs are executed in a controlled environment that is less complicated than real systems. This goal captures the design of mini-labs as a vehicle to help students begin to develop self-identities as engineers.

Survey 1 (Fall 2015, lab 1: flow measurement)

Overall, 50% of students responded that they “learn more in a mini-lab than a typical homework assignment.” Exposure to the physical equipment and involvement in data collection and analysis are experiences available in mini-labs that do not occur in a conventional theory course. These unique experiences therefore likely contributed to impressions of “learning more.” As to the level of confidence in solving problems involving flow meters (Figure 1), 100% of students felt prepared for the mini-lab after attending the theory course (reached goal 1). With respect to higher-level goals, 88% of students perceived that they met the primary goal of the mini-lab (goal 2) and 47% perceived that they attained the additional level of goal 3. It should be noted, however, that self-assessments of mastery by students are often biased toward higher ratings than objective assessments.

Survey 2 (Spring 2016, all labs)

In lab 1 (friction losses in pipes) and lab 2 (flow measurement), most students responded that they learned more in this lab than a typical homework assignment. In lab 3 (centrifugal pump analysis), most students responded that they learned less in this lab than a typical homework assignment. Lab 3 appeared to be slightly less effective regarding homework problem solving (goal 1), part of which might be attributed to the lack of homework problems focused on the same concepts to



**Figure 1.** Student feedback expressed perceptions toward reaching the three goals set for mini-labs for Fall 2015 and Spring 2016.

serve as a prior reference. Students also suggested adding more content to lab 3 regarding pump curve construction and/or merging lab 3 with other labs. The fact that all three labs share the same apparatus possibly contributed to a feeling that lab 3 “seemed too simple and could go up another level” as students were familiar with the apparatus after the first two sessions. We interpreted this reaction positively as students gaining confidence in working with real equipment and solving engineering problems through mini-labs exercises.

As to the level of confidence in solving problems, students expressed similar responses regarding all three mini-labs with 100%, 93%, and 73% indicating perceptions that they met goals 1, 2, and 3, respectively. Achievement of goals 1 and 2 remained the same as in Fall 2015, while goal 3 experienced a higher level of perceived attainment due to two factors. First, the mini-lab procedure was refined according to student feedback from the Fall 2015 lab sessions and surveys. Secondly, many Spring 2016 students have completed more junior-level engineering courses and/or industry internships than the Fall 2015 students, thereby building more confidence and more clearly picturing their future engineering careers.

### Using mini-labs to accommodate different learning styles

Felder and Silverman have expressed that there is a need to reach students of different learning styles when selecting teaching approaches.<sup>[11]</sup> Mini-labs can help achieve this goal by mixing multiple teaching approaches. The group experiment and individual responsibilities of completing lab reports are tailored toward active and reflective learners. The physical data gathering and data analysis through calculation

suit the needs of sensors and intuitors. The pilot-scale instrument experience with clearly defined steps to obtain a final result suit global learners and sequential learners.

## LIMITATIONS

### Mini-labs

The limited time available for scheduling the lab sessions is an issue as each session must be 50 min or less in order to accommodate the students’ regular course schedule. Operation instructions were given in detail by the lab instructor and data

recording sheets were provided with all parameters listed to save time. These approaches effectively accelerate the lab session but limit students’ development of practical laboratory skills such as troubleshooting of the apparatus and experiment planning that are covered in dedicated laboratory courses of longer duration.<sup>[26]</sup>

### Study approach

The number of students enrolled in this study was limited, and their willingness to voluntarily participate in the mini-labs and surveys was impacted by their regular semester schedule. For example, the survey for all three labs in the Spring 2016 semester was distributed after the final exam and the response rate was only 68% (19 of 28). Scheduling constraints also made it difficult for us to designate a direct control group for our study. While a cohort of students in the pilot section of the course during Fall 2015 did not participate in the mini-labs, participation was not required. Thus, the fact that the students who participated had already demonstrated initiative by seeking out the experience may introduce bias. We are working to design future studies to include pertinent controls.

## DISCUSSION AND CONCLUSIONS

Like many public universities, Texas A&M is facing increasing enrollment trends, ultimately expected to double the total number of engineering students over the next decade. This expansion makes it challenging to integrate active-learning experiences across large class sizes. Mini-labs offer an avenue to address these challenges by enabling hands-on activities to be easily inserted into traditional theory courses owing to their flexibility in scheduling and relatively short

time commitment. Regarding broader implementation of mini-labs throughout the curriculum, 60% of students indicated that they would like to see more mini-labs in fluid mechanics and other courses. Most concerns expressed centered on the extra workload added by mini-labs, as expressed by sentiments such as “it would be helpful to have mini-labs to replace homework assignments instead of at the same time.”

Early exposure to these sustainable high-impact learning practices expose students to real and non-ideal situations at the same time that fundamental concepts are introduced. The lab instructor experience also creates new opportunities for graduate students to gain teaching experience beyond traditional homework-focused grading roles by participating in a complete course-development cycle.

## SUPPLEMENTARY INFORMATION

Laboratory materials, assignments, and survey questions are provided as supplementary information.

## ACKNOWLEDGMENT

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