Board 295: Five Year Assessment for Educating Diverse Undergraduate Communities with Affordable Transport Equipment

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Five Year Assessment for Educating Diverse Undergraduate Communities with Affordable Transport Equipment (ATE)

Abstract

Over the past five years, our group has worked on the development of desktop-sized learning tools to demonstrate fluid mechanics and heat transfer concepts. We use a hub-based approach, breaking the US into sections with faculty coordinators within each region who interact with other faculty at institutions in their areas. In this paper we present a review covering five years of implementing through this distribution model for use of affordable transport equipment (ATE) for fluid mechanics and heat transfer classes. A review of ATE construction, testing and distribution is also assessed. We summarize lessons learned in working with hub-coordinators and workshops participants, getting attendee participation, and motivating them to prepare for the training, and follow-up through use of pre- and post-implementation forms required for obtaining stipends and support. The cumulative results of pre- to posttest concept inventories are presented for a base set of two fluid mechanics and two heat transfer ATE as well as motivational surveys and information related to demographic findings. We present construction strategies, production and implementation findings for our latest modules, an Evaporative Cooler and Fluidized Bed, and how strong technical components are integrated into the process to assist chemical engineering graduate students in obtaining robust results suitable for extending PhD thesis work to include fundamental and applied modeling along with experimental results. We present up-to-date results on our latest module concept in creating a microfluidics glucose monitoring system consisting of a flow chamber and a cell phone-based spectrophotometer. Finally, we conclude next steps for sustainability and continuation of the project, and lessons learned on strategies for mass production for prospective large-scale distribution.

Introduction

Introducing active learning techniques into classrooms has evidential proof that it has positive impact on student learning [1]–[4]. Promoting active learning in undergraduate STEM education keeps students engaged and results in improved retention of knowledge on topics taught [2], [4]. While traditional lectures are still the most common way of teaching, many universities are focusing more attention on more student-centered activities.

Engineering education highly relies on practical applications. Laboratories are the most common way of practicing engineering theory. Knowledge gained from engineering laboratories is being used for applying engineering applications to real life design of processes and development of products [5]. Building bridges to transfer theoretical skills to industry applications is important in terms of improving future employee quality for [6]. However, the most common pedagogical method is to use laboratory practice though this expensive and requires large spaces.

Over the past five years, our group has worked on the development of learning tools that are able to promote better student learning in a classroom setting. These tools include small equipment that can be used on top of a classroom desk. Each learning tool designed by our group is less on the order of $100 which provides an opportunity to institutions that have financial challenges, limited space, or where faculty find it difficult to overcome the design and preparation time barriers required to include an active learning environment. We call these learning tools Low-Cost Desktop Learning Modules (LCDLMs) and are finding efficacy in promoting active student engagement. Previously our group developed six LCDLMs; a Venturi, a Hydraulic loss, an Evaporative Cooler, a Shell-and-Tube Heat Exchanger, a Double Pipe Heat Exchanger and a Cell Settling module. These tools can be used to demonstrate important concepts in fluid mechanics, heat transfer and biomedical theories while keeping students engaged in the learning process.

We disseminate our pedagogy through workshops and propagate our LCDLMs through regional hubs at institutions throughout the country. Until now, 1,762 students from different universities gave their consent to publish de-identified learning and motivational data but total number of students that used our LCDLMs is higher than this. Herein we present semesterly breakdowns for five years of data assessment for our fluid mechanics and heat transfer LCDLMs, posttest averages for two groups and, motivational aspects for all LCDLMs. We also present our newly developed Evaporative Cooler unit to demonstrate heat transfer, mass transfer and energy balances, as well as our most recent LCDLM, a Fluidized Bed to demonstrate packed bed and fluidized bed concepts. Lastly, we introduce the development of a microfluidic Glucose Analyzer based on a cell phone-based spectrometric analysis. Finally, we present our future directions and sustainability goals for this project for upcoming years.

New Modules

Evaporative Cooler, Fluidized Bed and Glucose Analyzer LCDLMs

Evaporative cooling is a commonly used unit operation to reject heat in industrial applications. The complex phenomenon for this process is not well understood by students [7]. Our group worked on the design of this simple learning tool to demonstrate the evaporative cooling process shown in Figure 1a to help students understand the underlying theory as well as work with industrial systems with more confidence when they graduate. This Evaporative Cooler LCDLM may be operated in water-cooling or air-cooling mode efficiently. Preliminary results obtained from pilot testing of the cartridge in the laboratory show this tool works well experimentally and agrees with the modeling analyses for the system. So, we expect this module to find use in classroom applications in the following semesters with accompanying data assessment strategies.

The fluidized bed LCDLM was constructed using all hardware store supplies for under $100 and is shown in Figure 2a. This tool may be used to demonstrate the most important concepts such as pressure drop in packed bed and fluidized beds, the minimum fluidization point, and pressure drop when the bed is repacked at the top of the column above a certain superficial velocity. We are planning implementation strategies for the classroom for the first time in the Spring 2023 semester. Data assessment will be performed in a similar fashion as to what we have done for other LCDLMs, i.e., the use of a student consent form, a pre-test prior to LCDLM use, a posttest after the implementation, a classroom worksheet to be sued during implementation and a motivational survey to understand student the impact on engagement. We will report our results in the following years as we move forward with the implementations.

A module that is still in development is a microfluidic Glucose Analyzer shown with a columnated flashlight below a well plate and use of a cell phone above the plate to assess absorbance readings using a widely available spectrometer smartphone app. This is shown in Figure 1c.

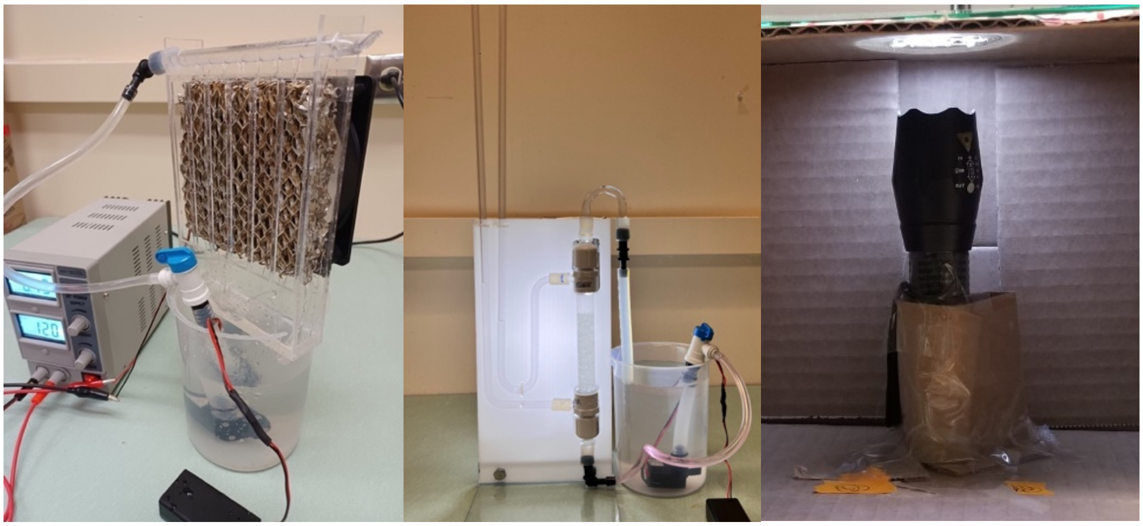

Figure 1. *Newly developed modules a) Evaporative Cooler LCDLM b) Fluidized Bed LCDLM c) Glucose Analyzer LCDLM showing a columnated flashlight source below a well plate.*

The solution within the well plate will react to form varying shades of red dependent on glucose concentration through the well-known Trinder reaction. This module will be used to teach students concepts such as spectrometry and kinetics superimposed on a microfluidic flow profile. A large-scale prototype of the analysis section of the module has been built and tested to prove that the smartphone app allows the capability of accurate analyses of glucose concentrations within a minute sample size. Further development is necessary to miniaturize and create the reaction segment of the module.

Fluid Mechanics LCDLMs Implementation Results

Hydraulic Loss & Venturi

We have successfully implemented the Hydraulic Loss LCDLM in 29 courses across 17 institutions and 20 instructors since the beginning of the project, Fall 2019. Data usable for publications and reports came from 617 students, who consent for use of their data. As seen in Figure 2, the average growth from pre- to posttest across all data collected is 31% ± 2%, i.e., three letter grades worth of growth, with statistical significance $p < 0.001$ and a large Cohen's d effect size of 1.05.

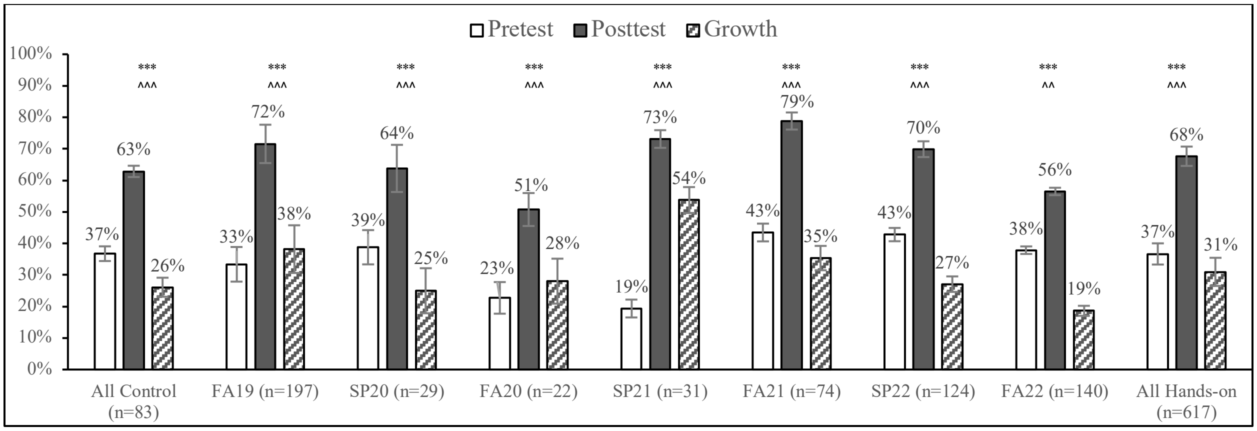

Figure 2. *Semesterly breakdown of average scores across all students who used the Hydraulic Loss LCDLM. Statistical significance and Cohen's d effect sizes were calculated between pre- and posttest scores (* = p<0.05, ** = p<0.01, *** = p<0.005; ^ = d>0.2, ^^ = d>0.5, ^^^ = d>0.8).*

The Venturi LCDLM was successfully implemented in 24 courses across 15 institutions and 17 instructors since the Fall 2019 semester. Usable data came from 521 students, who consented for use of their data. Figure 3 shows the average growth from pre- to posttest across all data collected is 9% ± 1%, i.e., nearly one letter grade worth of growth, with statistical significance $p < 0.001$ and near medium Cohen's d effect size of 0.45.

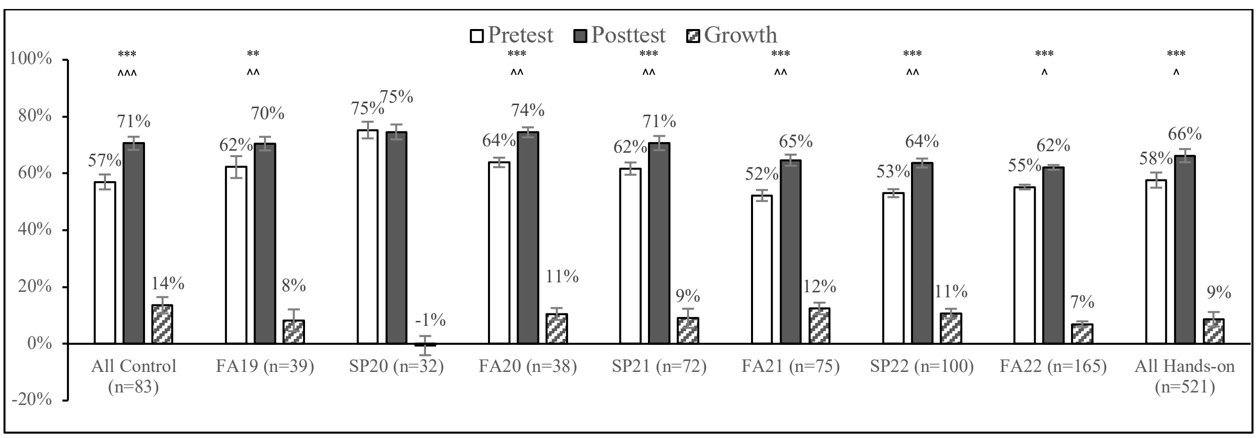

Figure 3. *Semesterly breakdown of average scores across all students who used the Venturi LCDLM. Statistical significance and Cohen's d effect sizes were calculated between pre- and posttest scores (* = p<0.05, ** = p<0.01, *** = p<0.005; ^ = d>0.2, ^^ = d>0.5, ^^^ = d>0.8).*

When comparing gains between the Hydraulic Loss and Venturi LCDLMs, we see higher growth from pre- to posttest for the Hydraulic Loss LCDLM. This may be attributed to the order in which the students are exposed to the LCDLMs. Typically, students use the Hydraulic Loss before the Venturi LCDLM; therefore, there is more potential for growth, which can also be seen from the overall average pretest scores for the Hydraulic Loss and Venturi LCDLMs.

Heat Transfer LCDLMs Implementation Results

Double Pipe Heat Exchanger & Shell-and-Tube Heat Exchanger

Our previously developed Double Pipe Heat Exchanger learning tool was constructed by using injection molding and usage is focused on the concepts shown in Table 1.

Table 1. *The conceptual focus of Double Pipe Heat Exchanger pre- and posttest questions*

Question No.	Conceptual Focus
Q1	Understanding system boundaries when heat flows from hot to cold fluids
Q2	Quantifying the areas for fluid flow and heat transfer
Q3	Double pipe tube length for heat transfer rate
Q4	Rate of heat transfer for a tube in a duct
Q5	Temperature driving force for the countercurrent heat exchanger

We have implemented our Double Pipe Heat Exchanger module among 476 students starting from Fall 2019. Our module was used in 11 different courses across 9 institutions and 11 instructors until Fall 2022. In the Figure 4 we present Double Pipe Heat Exchanger pretest, posttest, and performance gains for each semester with significant difference is the $p < 0.005$ range. Fall 2022 data has a large 0.6 Cohen's d effect size and compared to previous semesters has the highest performance gain of 13% compared to other semesters.

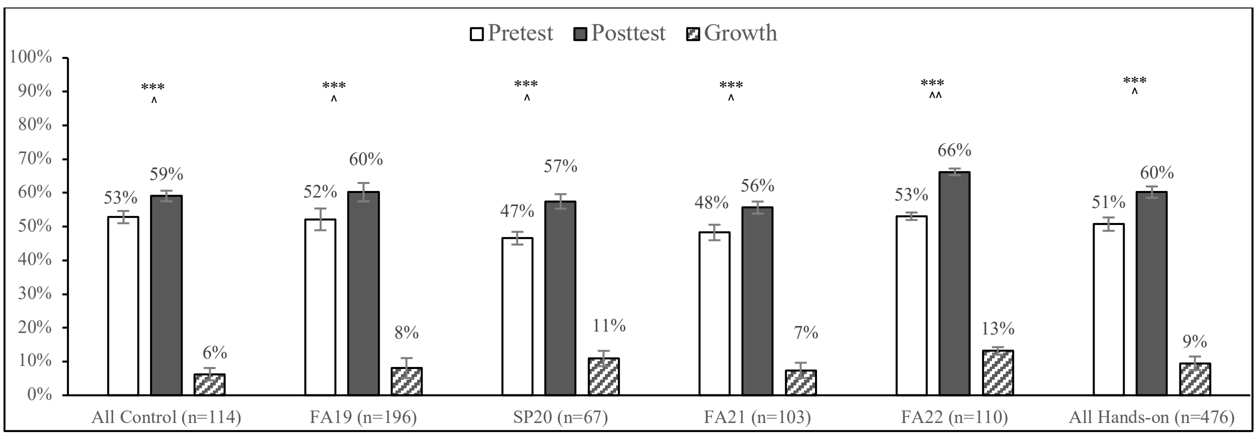

Figure 4. *Semesterly breakdown of average scores across all students who used the Double Pipe Heat Exchanger LCDLM. Statistical significance and Cohen's d effect sizes were calculated between pre- and posttest scores (* = p<0.05, ** = p<0.01, *** = p<0.005; ^ = d>0.2, ^^ = d>0.5, ^^^ = d>0.8).*

The Shell-and-Tube Heat Exchanger is one of our newly developed desktop learning modules. It is designed to teach several key concepts of heat transfer including identification of flow type, understanding of the difference between cross-sectional flow and heat transfer areas, quantification of heat transfer rates, theoretical calculation of overall heat transfer coefficients and comparison with the experimental values. Conceptual foci for pre- and posttest questions are listed in Table 2.

Table 2. *The conceptual focus of Shell-and-Tube Heat Exchanger pre- and posttest questions*

Question No.	Conceptual Focus
Q1	Understand the types of flow occurring in a Shell & Tube Heat Exchanger
Q2	Deduce the mathematical expression for heat transfer area
Q3	Evaluate the effect of baffles on the heat transfer rate
Q4	Judge the effect of cold and hot fluid inlet temperatures on heat transfer rate

Q5	Quantify the shell side fluid velocity from the volumetric flow rate
Q6	Understand the influence of cold-water flow rate on hot water outlet temperature
Q7	Identify the reasoning for Q6

During Fall 2022, we have implemented the Shell-and-Tube Heat Exchanger module in 3 courses across 3 institutions with 61 students giving consent for use of their pre- and posttest . As seen in Figure 5, the average scores for each question are increased after the implementation. However, the growth in scores from pre- to posttest are statistically significant for only two questions Q2 and Q5 with a p-values of 0.002 and 0.0003, respectively. These two significant results are also associated with a medium Cohen's d effect size. Overall, for Fall 2022 semester, the assessment shows a significant improvement with a p-value of 0.0007 and a medium Cohen's d effect size of 0.52. These results support the premise that the Shell-and-Tube Heat Exchanger can be used to teach complex heat exchange phenomena occurring in a widely used heat exchanger.

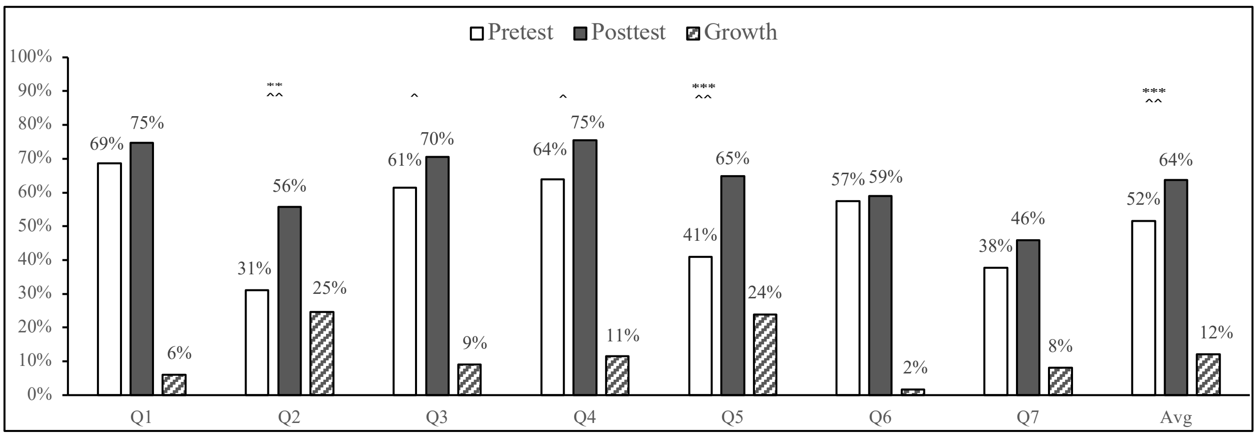

Figure 5. *Question breakdown of average scores and assessment for the Shell-and-Tube Heat Exchanger module in Fall 2022 (n=61). Statistical significance and Cohen's d effect sizes were calculated between pre- and posttest scores (* = p<0.05, ** = p<0.01, *** = p<0.005; ^ = d>0.2, ^^ = d>0.5, ^^^ = d>0.8).*

The Shell-and-Tube Heat Exchanger was implemented for the first time in Fall 2021. Since then this LCDLM was implemented in 12 classes, at 9 institutions and with 11 instructors. Out of these implementations, 148 students gave their consent for publishing their data. Control data was collected in Spring 2022 only for one semester showed negative gain in learning and only 3 students gave their consents for usable data. Control data was collected from a very small group of students, but we will expand the number of students in control group in the following years. Semesterly breakdown for pre- and posttest results are shown in Figure 6. Overall hands-on data showed a significant difference p=0.000 and small effect size of 0.4.

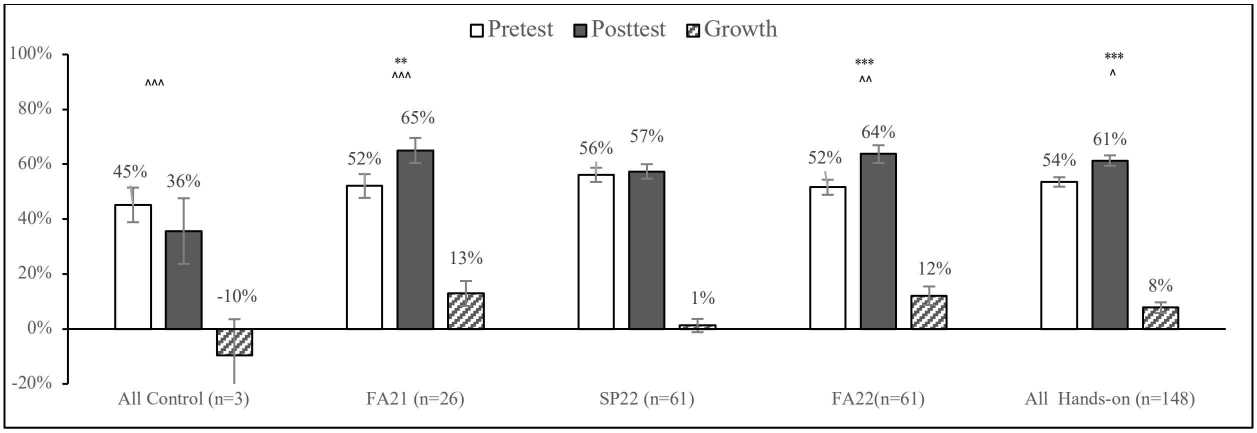

Figure 6. *Semesterly breakdown of average scores across all students who used the Shell-and-Tube Heat Exchanger LCDLM. Statistical significance and Cohen's d effect sizes were calculated between pre- and posttest scores (* = p<0.05, ** = p<0.01, *** = p<0.005; ^ = d>0.2, ^^ = d>0.5, ^^^ = d>0.8).*

When comparing the two heat exchange units, the Shell-and-Tube Heat Exchanger data (n=146) is almost 3-fold less than the amount of students who took pre- and posttest for Double Pipe Heat Exchanger (n=476). Except for the Shell-and-Tube Spring 2022, both heat exchanger pre- and posttest results were significantly different with $p < 0.001$ for each semester and for the overall hands-on data. We will expand the use of our Shell-and Tube LCDLM in subsequent years and will be analyzing the data for the Shell-and-Tube with a larger volume of students.

Combined LCDLMs Posttest Analysis

All four LCDLM data from Fall 2020 and Spring 2021 were analyzed excluding control groups. The data was first divided into two groups: those who scored 50% or above, and those below 50% on the pretest. An ANOVA was performed on the posttest scores for each group of students for all LCDLMs to compare posttest scores for high and low prior knowledge. Figure 7 shows the results. When comparing the two groups, there was a p-value of <0.0001 indicating there was a significant difference between the two groups. The mean posttest score for the high prior knowledge group was 71.4% and the mean for the low prior knowledge group was 59.4% indicating that the students with high prior knowledge score higher on the posttest than the low prior knowledge group after using the LCDLMs.

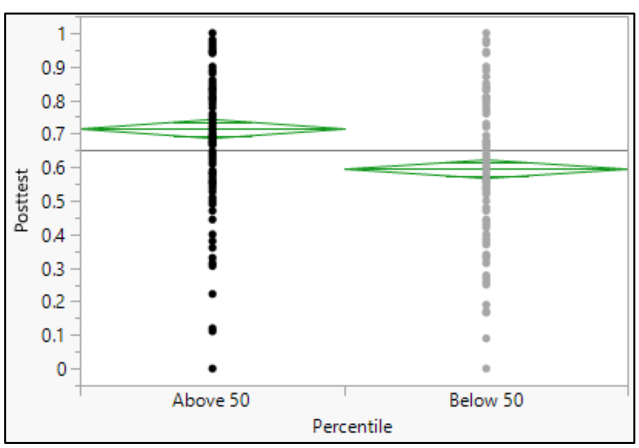

Figure 7. *Posttest means for two groups.*

Motivational Survey Analysis

We studied motivation surveys to understand what drives student behavior and how they perceive their own abilities towards learning after the LCDLM work. This analysis helps us design and deliver more effective interventions to increase student involvement and learning. The engagement behaviors are grouped according to Chi's ICAP construct, which divides results into four categories: interactive, constructive, active, and passive [8]. According to ICAP theory, responses further to the left in the ICAP acronym indicate engagements that promote deeper learning levels than those further to the right. The engagement responses are shown on a 5-point Likert scale, where 1 represents "Strongly Disagree" and 5 represents "Strongly Agree." Figure 8 shows the visual representation of the average engagement responses (from highest level of engagement to low levels of engagement) for all participants regarding the use of all four LCDLMs over the past five years. When using LCDLMs data suggest students experience higher engagement levels in the Interactive, then Constructive, then Active realms and that very few students believe they the activity is in the Passive realm. Figure 9 shows a visual representation of the frequency of participant responses to the use of LCDLMs with the overall percentage of participants who responded in each engagement category defined by Chi's ICAP construct. Approximately 65% of the participants indicated the LCDLMs promoted the superior Interactive, Constructive, and Active modes of engagement.

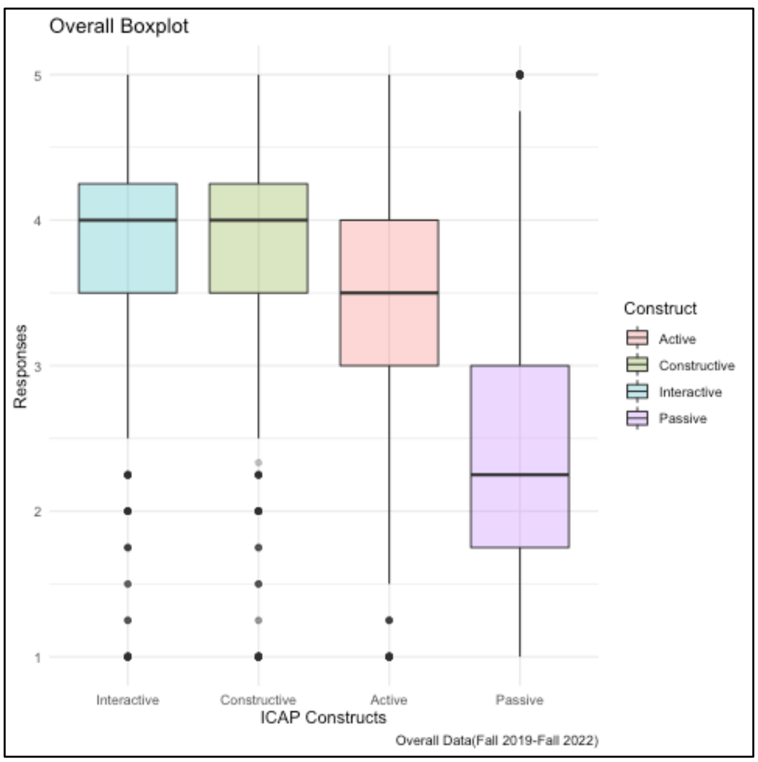

Figure 8. *Summary of the motivational data collected over the past five years for all LCDLMs.*

On the other hand, only a small percentage of the participants reported that LCDLMs made them passive, suggesting most of the participants found the LCDLMs to be engaging and stimulating. This information provides valuable insight about the effectiveness of LCDLMs in promoting student engagement and learning. These results suggest LCDLMs are promising tools for enhanced student engagement and deeper learning in the classroom.

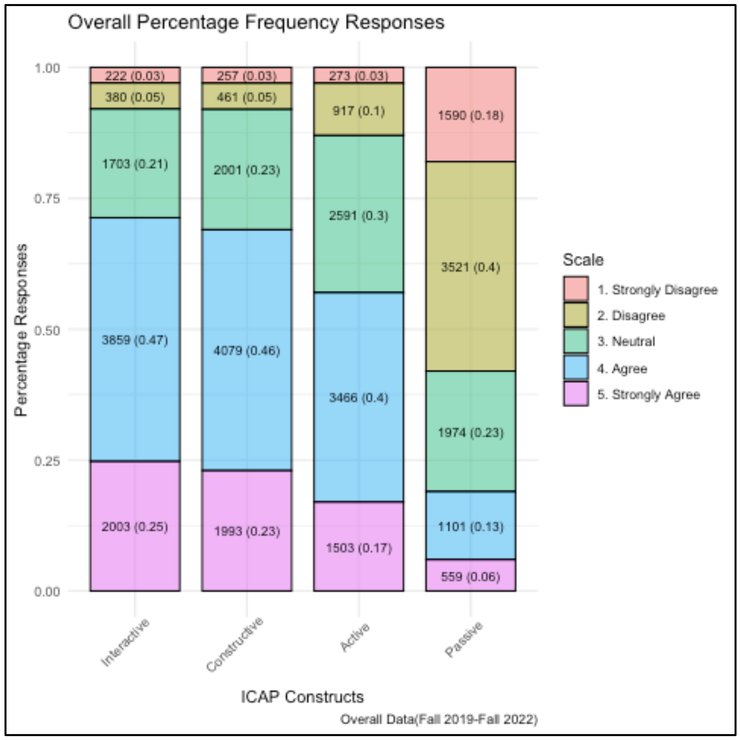

Figure 9. *Overall frequency responses grouped into four the ICAP engagement modes.*

Figure 10 findings suggest that the use of LCDLMs promotes similar engagement among different genders identified as male, female and, other in engineering classrooms. The data of gender grouped as “other” is not shown in this plot because compared to male (n=958) and female (n=495) students, the number of students grouped as “other” (n=16) was not significant to show on the plot. However, we will present gender data identified as “other” as we collect more data in the upcoming years. Results show that both genders generally agree with the statement that LCDLMs improve their classroom engagement. This finding is important because it supports the idea that LCDLMs can be effective instructional tools for promoting engagement and motivating all students in their learning, regardless of gender.

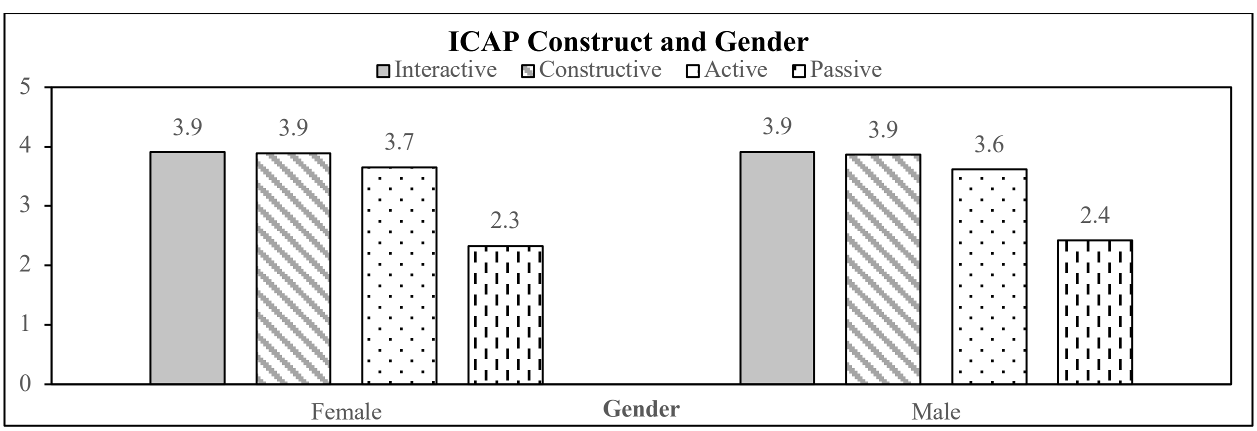

Figure 10. *Gender differences in engagement with the LCDLMs analyzed using the ICAP framework*

Figure 11 shows there for average scores on ICAP hypothesis modes of engagement there is no significant difference in average scores between different ethnic groups, implying that the implementation uniformly promotes the more reliable forms of learning engagement regardless of ethnicity. Out of 1423 individuals who gave consent the categorical breakdown is as follows: 11 American Indian or Alaska Native; 129 Asian; 97 Black or African American; 91 Hispanic or Latino; 18 Middle Eastern or North African and; 1077 White. This suggests that the LCDLMs provide equal opportunities and benefits to all ethnic groups and the learning outcomes are not biased towards a particular ethnic group.

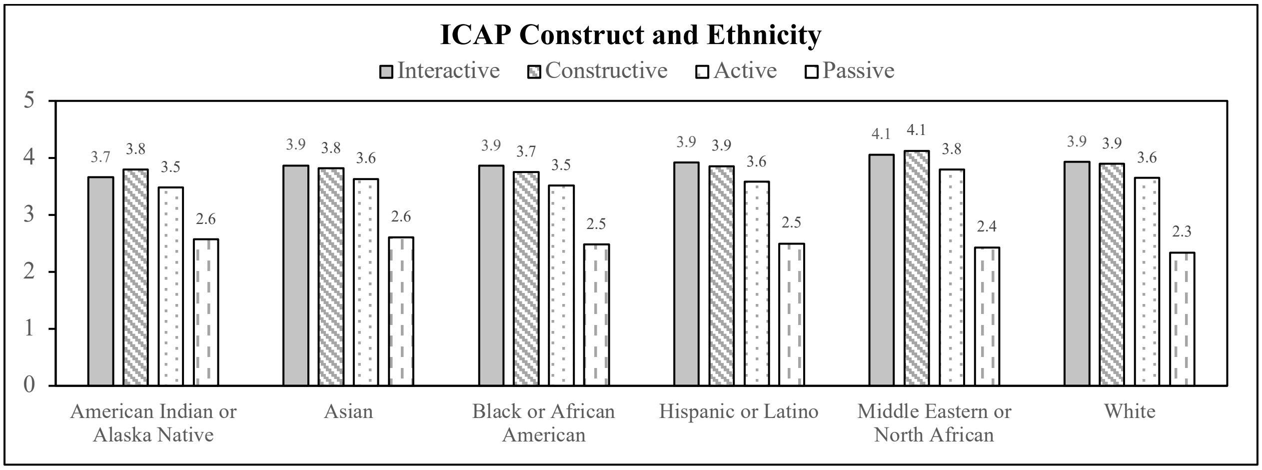

Figure 11. *Ethnicity differences in engagement with LCDLMs analyzed using the ICAP framework.*

These results emphasize the importance of creating inclusive learning environments that provide equal opportunities for all students regardless of ethnic background. The work also highlights the potential for use of LCDLMs as an effective tool for promoting equity and diversity in education.

Lessons Learned from Faculty Implementers

Starting from Fall 2021, our group started to collect instructor feedback after the LCDLM implementation. We have collected responses from 33 different instructors from different universities in fluid mechanics and heat transfer related courses for three years in until 2023. With each LCDLM, we provided additional supplements on our website (https://labs.wsu.edu/educ-ate/) such as worksheets, setup tutorials, virtual demo videos and, concept videos. We asked instructors to rate the usefulness of these additional supplies (0: Did not use, 1: Not helpful, 2: Neutral, 3: Helpful, 4: Very helpful). Instructor averages per response is shown in Table 3. According to the average of responses on additional supplies, instructors find these supplies helpful.

Table 3. *Additional material rating averages*

Additional Material	Average
LCDLM worksheet	3.6
LCDLM setup tutorial	3.6
LCDLM virtual demo videos	3.2
LCDLM concept videos	3.4

We also asked to the instructors about their suggestion to improve implementation processes. While some of them are leaving the survey question blank, some individuals provided positive and some provided suggestions for improvement. Suggestion coming from instructors to improve LCDLM implementations are grouped into three categories are gathered in the Table 4. To address the equipment related issues: we send out replacements or suggest links for implementers to purchase a new one; for precisely controlled flow, we suggest connecting a rotameter to the pump; for hot water supply, we suggest using big jugs to carry water to class before the implementation and we address assembly issues through our instructional videos provided on our website.

Table 4. *LCDLM improvement suggestions in categories*

Suggestions to improve LCDLM implementations		
Equipment related	**Learning material related**	**Hub coordination related**
-Pump and battery malfunctions / failure	-Worksheet too long to cover	-Sharing links / hub coordination
-Broken additional equipment (beakers, stands)	-Videos provided on our website not uploading / have not seen	
-Flow control issue due to stiff pump valves	-After class activities (homework)	
-Hot water supply		
-LCDLM assembly issues		

Learning material-related issues are constantly being evaluated by our group to shape and refine our activities for instructor and student use. We aim to fit these implementations into a 50-min class time with the support of videos provided on our website without any issues. We modify and update our worksheets and homework questions to instructor needs up to date. We suggest instructors who struggle with the time limit the classroom activity with a worksheet provided and let the students work on their own by assigning them homework for completion of the full LCDLM activity.

Hub coordination-related issues involved sharing the consent, pre-, posttest and motivational survey links through email or on our website. Some instructors miss the emails sent or some of them are having issues sharing the links on their web-based learning management system. We resolve these issues by reminding them to be prepared a week prior to their implementations to prevent any malfunctions in data collection.

In addition to these suggestions, most of the instructor's feedback was positive and rewarding. Some responses regarding our LCDLM activities included: “Students enjoyed working with LCDLMs.”, “This is a great program!”, “These are great modules!”, “The videos were super clear and helpful!”, “Some students said they prefer this desktop-scale model instead of large units”, and “My students really seemed to like the hands-on”. These valuable comments which recognize our group’s efforts, motivate us to work hard and strive for success.

Conclusions

As we continued to mature in our efforts on this project over the past five years, we continued to work on design and development of new desktop scaled equipment for educational purposes. Our approach aims to enable students to experience hands-on learning by eliminating the costly installation of traditional active learning techniques and other preclusive reasons why students are hindered from participating in an active learning environment. Until now, our team has developed 6 LCDLMs: a Venturi Meter, a Hydraulic Loss cartridge, an Evaporative Cooler, Shell-and-Tube and Double Pipe Heat Exchangers and a Cell Settling module. These modules can be used to demonstrate governing concepts associated with them.

Recently our group worked on the development of three new modules: an Evaporative Cooler, a Fluidized Bed and a microfluidic Glucose Analyzer. Design approaches for each module have been articulated, along with implementation and dissemination strategies. We will work on design improvements, and plan new implementations as we design pre- and posttests for learning gain measurements as well as classroom activities to be used during implementations. We aim to use these modules in classrooms in the upcoming semesters.

In this paper, we presented a five-year assessment of the initial four LCDLM pre- and posttest scores. Regardless of LCDLM type, all modules show improved learning gains. We also analyzed the posttest scores in two groups: high prior knowledge and low prior knowledge. This analyses show students with high prior knowledge scored better in the posttest.

The motivational aspect of this project was studied for all LCDLMs. Students show motivation towards active engagement and deeper understanding in the implementation of LCDLMs. Gender and ethnicity analyses indicate LCDLMs are useful tools for every student regardless of gender and ethnic backgrounds. Hence, LCDLMs will promote a positive impact on diversity, inclusion and equity in classroom.

Our future work involves expanding our data base by collecting data from a larger number of students, different types of course implementations and reaching out to different institutions with more types of LCDLMs. We aim to manage our implementations in our hub-based system as we disseminate our pedagogy. We will work on design enhancements for our learning tools as needed and implement our new worksheet and testing/motivation assessment tools as we complete our steps towards implementations. We will work on a 3D printed version of the Fluidized Bed LCDLM to make our design more accessible and publicly available for more faculty and students to get involved. There is a new module still in its development stage, a microfluidic Glucose Analyzer. The steps going forward will be to develop a micromixer for a reaction segment and to miniaturize the module to be created using 3D printing. Pre- and posttests, motivation surveys, and classroom material will also be created based on this module for data collection for when the module is ready for implementation.

Finally, instructor feedback acknowledges our hard work and provides insight into our strengths and weaknesses. This recognition provides a sense of validation and instills a feeling of accomplishment, motivating us to keep up the good work.

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References

[1] O. Reynolds, “Development and Implementation of a Low-Cost Desktop Learning Module for Double Pipe Heat Exchange,” *Chem. Eng. Educ.*, vol. 56, no. 2, 2021, doi: 10.18260/2-1-370.660-128296.

[2] M. Prince, “Does Active Learning Work? A Review of the Research,” *J. Eng. Educ.*, vol. 93, no. 3, pp. 223–231, Jul. 2004, doi: 10.1002/j.2168-9830.2004.tb00809.x.

[3] R. M. Felder, “LEARNING AND TEACHING STYLES IN ENGINEERING EDUCATION”.

[4] S. Freeman *et al.*, “Active learning increases student performance in science, engineering, and mathematics,” *Proc. Natl. Acad. Sci.*, vol. 111, no. 23, pp. 8410–8415, Jun. 2014, doi: 10.1073/pnas.1319030111.

[5] N. Pramounma, “Improving Student Preparedness for Entering the Workforce: A Hands-On Experience in Project Management for a Graduate-Level Protein Engineering Class,” *Chem. Eng. Educ.*, vol. 54, no. 4, 2020, doi: 10.18260/2-1-370.660-119358.

[6] L. D. Feisel and A. J. Rosa, “The Role of the Laboratory in Undergraduate Engineering Education,” *J. Eng. Educ.*, vol. 94, no. 1, pp. 121–130, Jan. 2005, doi: 10.1002/j.2168-9830.2005.tb00833.x.

[7] “Misconceptions in engineering thermodynamics: A review - Sepehr Foroushani, 2019.” Accessed: Feb. 11, 2023. [Online]. Available: https://journals.sagepub.com/doi/abs/10.1177/0306419018754396

[8] M. T. H. Chi and R. Wylie, “The ICAP Framework: Linking Cognitive Engagement to Active Learning Outcomes,” *Educ. Psychol.*, vol. 49, no. 4, pp. 219–243, Oct. 2014, doi: 10.1080/00461520.2014.965823.