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Development, dissemination and assessment of inexpensive miniature equipment for interactive learning of fluid mechanics, heat transfer and biomedical concepts

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Development, Dissemination and Assessment of Inexpensive Miniature Equipment for Interactive Learning of Fluid Mechanics, Heat Transfer and Biomedical Concepts

Introduction

When a connection is established between theoretical engineering knowledge and practical applications the concepts can be understood better to perform tasks more satisfactorily [1], [2]. Therefore, creating an interactive learning environment helps students to learn more efficiently [2], [3]. In undergraduate STEM education, hands-on tasks allow students to understand concepts better when integrated with lecture material in the areas of fluid mechanics, heat transfer, biomedical engineering, transport phenomena and reaction engineering [4].

Currently, Low-Cost Desktop Learning Modules (LCDLMs) are being used at over 30 universities by more than 1,000 students to enhance interactive undergraduate STEM education [5]. Where those LCDLMs have been introduced to university classrooms, results have shown that student interest and efficiency in learning have been increased [5]–[7]. To propagate the applications of LCDLMs, hubs throughout the US train the instructors. With the goal to improve interactive learning experiences for our students, our team has perfected four different LCDLMs comprised of miniaturized industrial-scale equipment—a venturi meter, a hydraulic loss system consisting of 1/4" diameter piping, double pipe heat exchanger, and shell-and-tube heat exchanger LCDLM. This paper provides an update on the shell-and-tube heat exchanger module and describes our development of two new LCDLMs, an evaporative cooler and a cell-settling LCDLM.

As this NSF LCDLM dissemination, development, and assessment project matures going into our fourth year of support we are moving forward in parallel on several fronts. We are developing and testing an injection-molded shell-and-tube heat exchanger for heat transfer concepts, an evaporative cooler to expand to another industrial-based heat exchange system, and a bead separation module to demonstrate principles of fluid mechanics in blood cell separations applications. We are also comparing experimental data for our miniaturized hydraulic loss and venturi meter LCDLMs to predicted values based on standard industrial correlations. As we develop these new learning components, we are assessing differential gains based on gender and ethnicity, as well as how students learn with existing LCDLMs in a virtual mode with online videos compared to an in-person hands-on mode of instruction.

Progress & Findings

New and Improved LCDLMs

To create more robust and uniform shell-and-tube cartridges for our existing shell-and-tube heat exchanger, our team used an injection-molded approach to manufacture the unit displayed in Figure 1. A CAD design for an aluminum clamping jig was completed and constructed by the college machine shop. A program is used to control the robotic applicator in applying adhesive to the injection-molded shell-and-tube heat exchanger parts during assembly. This program was finalized, and we went through initial successful tests and tuning. An initial set of parts from the new mold was received and used to construct over 30 shell-and-tube heat exchangers, most of which have been shipped to students and professors (Fig. 1). The worksheet for the shell-and-tube heat exchanger was updated in time for remote implementation in the Fall of 2021.

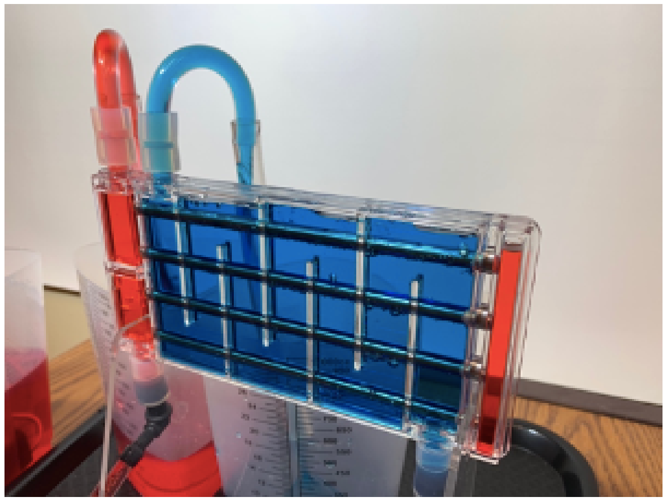

Figure 1: Injection-molded shell and tube heat exchanger with dyed water flowing through tubes and shell sides

Initial performance tests show that the heat exchanger is operating as expected in terms of transferring heat from a warmer to colder liquid. The new shell-and-tube heat exchangers were completed and tested in time to send to workshop participants for the Northeast Hub workshop on August 6, 2021. A video that explains the detailed flow patterns in the shell-and-tube heat exchanger has been produced and posted on the project website to aid students during implementation (Fig. 2).

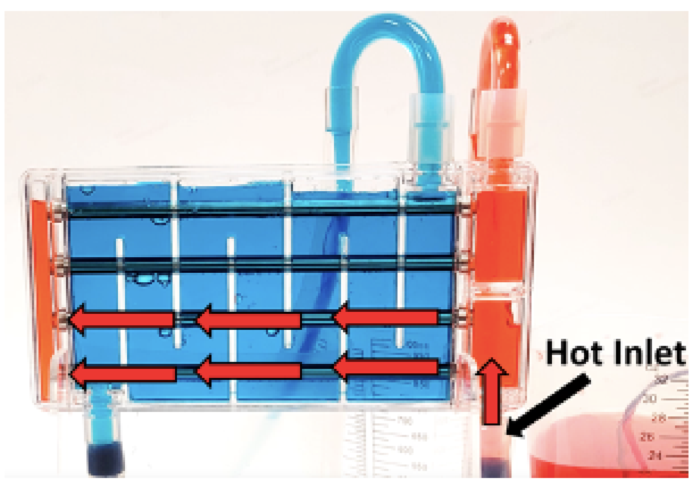

Figure 2: Screenshot of video illustrating the detailed flow pattern in the shell-and-tube heat exchanger

A newly developed LCDLM evaporative cooling module allows students to explore concepts such as latent and sensible heat transfer, mass transfer, energy balances, and non-steady-state temperature profiles. Our team is implementing the module in a fluid mechanics and heat transfer course for the first time this semester. The team has focused on expanding options for the heat exchange module to include a simple, low-cost, evaporative cooler. The evaporative cooler, which can be operated in water-cooling or air-cooling mode, contains simple, low-cost, components. Air flow is provided by a 12 V computer fan, water flow is provided by a 9 V battery-operated centrifugal pump with adjustable flow rate, and gravity-driven water flow occurs over porous, commercially available, expanded aluminum media. The total cost of the evaporative cooler LCDLM is less than $100 (Fig. 3).

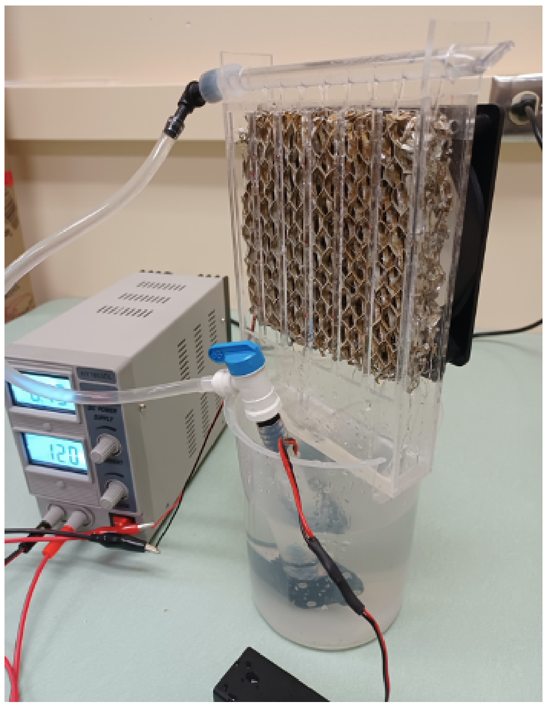

Figure 3: The evaporative cooler LCDLM

In another new module, a cell settling LCDLM has been developed to demonstrate fluid mechanics in biomedical applications, specifically to understand blood cell separation. This LCDLM portrays cell separation principles through separation of smaller, but higher density red microbeads from larger, but less dense white beads and white microbeads to represent red blood cells and white blood cell separations (Fig. 4). This new module was introduced in Fall 2022 in a Biomedical Engineering class and will be used in a Spring 2022 separations course.

Figure 5 shows settling velocity as a function of the increasing concentration of red beads while holding the concentration of white beads constant. At low red bead concentrations, the larger diameter white beads have a higher settling velocity because the surface area to volume ratio is low and therefore there is less drag relative to the smaller red beads. In an environment of higher red bead concentration, the larger white beads encounter more collisions which causes them to experience a higher effective viscosity and the two types of beads settle more closely to the same settling rate.

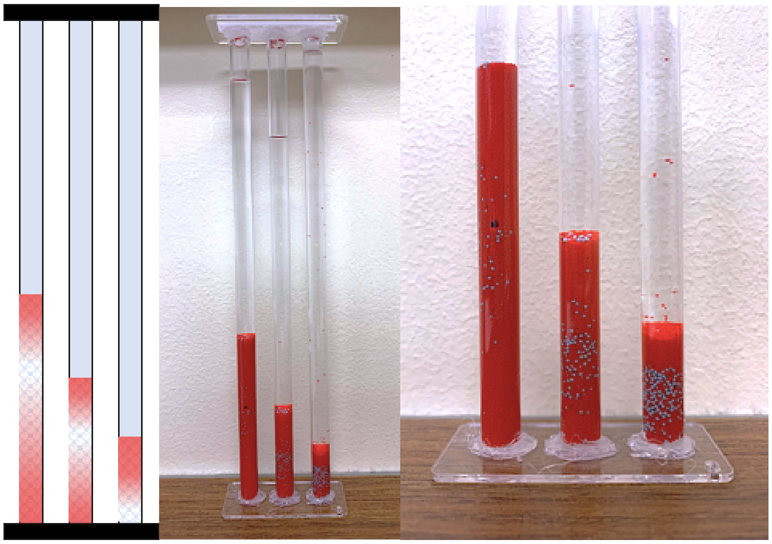

Figure 4: Cell settling LCDLM

At very high red bead particle suspension densities the smaller red beads have still fewer relative collisions and a larger effective porosity than the white beads and the white beads settle much slower and can actually settle more toward the top of the column. The white beads become more dispersed throughout the column (Fig. 4). The dispersion pattern indicates a hindrance effect, despite the white beads being larger in diameter and less dense than the red beads (Fig. 5).

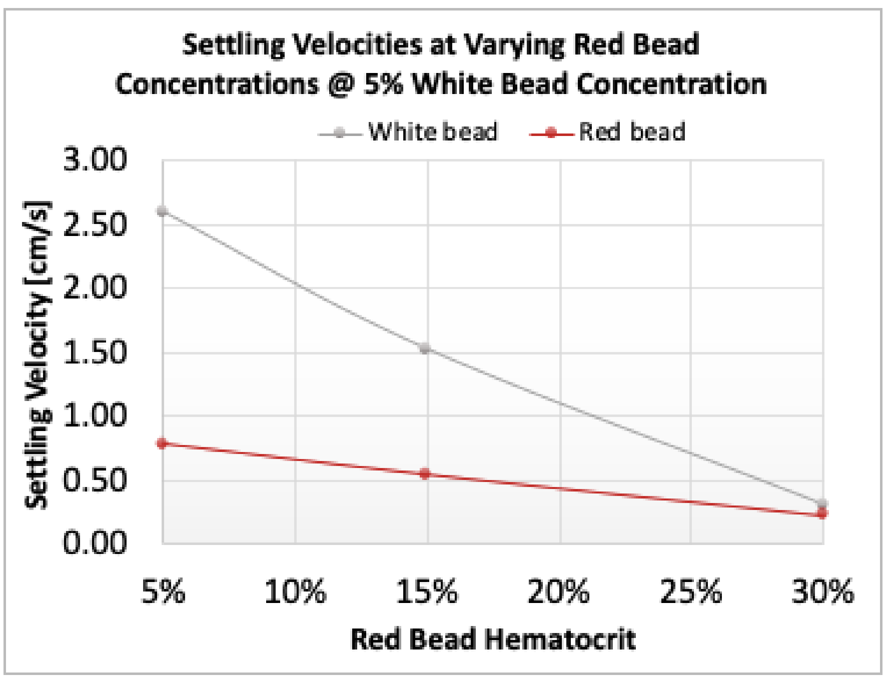

Figure 5: Cell settling velocities calculated at various hematocrits for the hand-on learning device

The Human Factor: Using LCDLMs

In order to assess the efficacy of the hydraulic loss, venturi meter, and heat exchanger modules, the dependent variable of student performance is being analyzed with reference to the two independent variables of gender and ethnicity. Table 1 shows the average pre-test scores, post-test scores, and performance gains for students identifying as women, men, and other.

Table 1: Pre/post-test averages, performance gain and percentage errors according to gender

Performance by Gender							
N	**Gender**	**Pre-test Average**	**Post-test Average**	**Performance Gain**	**Pre-Error**	**Post-Error**	**Diff-Error**
116	Woman	45%	66%	21%	2.5%	2.6%	3.1%
173	Man	57%	71%	14%	14%	1.6%	2.0%
3	Other	41%	68%	27%	27%	17.3%	17.0%

These data show that women and persons identifying as "other" showed better performance gains than those of men.

Figure 6 below shows the overall engagement responses of males and females on a 5-point Likert scale (1 = Strongly disagree, 5 = Strongly agree) with respect to the use of LCDLMs. Engagement behaviors are categorized based on Chi's ICAP construct, which splits engagement into four distinct categories: passive, active, constructive, and interactive, each theorized to promote deeper levels of understanding than the previous engagement mode [8]. The use of LCDLMs promoted similar responses to engagement between males and females in engineering classrooms.

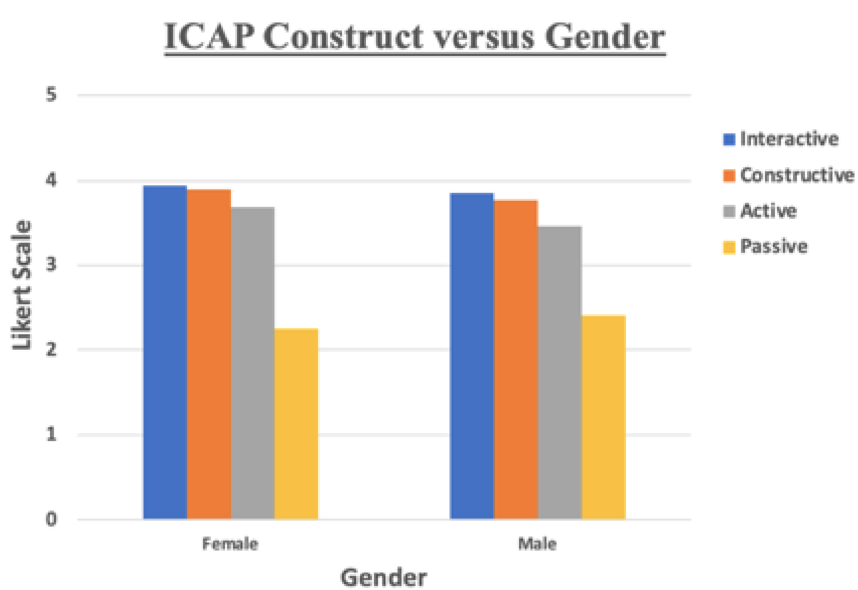

Figure 6: Gender differences in engagement on the LCDLMs analyzed in the ICAP framework

In Table 2, we present the collective data for all four of our base LCDLMs for fluid mechanics and our double pipe and shell and tube heat exchanger, for pre-test and post-test scores, and performance gains for various racial and ethnic groups. Because of the low number of entries across all demographics, no statistical significance can be found; however, significance will be re-assessed as the project matures.

Table 2: Pre/post-test averages, performance gain and percentage errors according to race and ethnicity

Performance by Race and Ethnicity							
N	**Race and Ethnicity**	**Pre-test Average**	**Post-test Average**	**Performance Gain**	**Pre-Error**	**Post-Error**	**Diff-Error**
1	American Indian or Alaska Native	85%	85%	0%	0.0%	0.0%	0.0%
22	Asian or Asian American	53%	59%	6%	7.0%	6.7%	6.3%
39	Black or African American	59%	71%	12%	4.6%	4.5%	5.0%
12	Hispanic or Latino	49%	77%	28%	6.9%	5.6%	7.7%
1	Native Hawaiian or other Pacific Islander	17%	52%	35%	0.0%	0.0%	0.0%
196	White or Caucasian	51%	69%	18%	1.9%	1.6%	2.1%
21	Multiethnic or other	49%	75%	25%	6.2%	5.8%	6.8%

Another aspect of the LCDLM implementation was to further explore the effect of the professor on student performance. Figure 7 shows that fifteen professors from five different hubs implemented the previously constructed venturi, hydraulic loss, or double pipe modules in their classrooms. One-way analysis of difference between pre- and post-test scores by professor was done. The fractional difference in pre/post-test is plotted against the individual professors. The black dots are the individual student scores while the green diamond centerlines represent the mean. The top and bottom points are the standard deviation.

The variance of scores is represented by the maximum and minimum data points, which range from -0.7 for professor 13 to as high as 1 for professor 3. A score of 1 indicates the student received a zero on the pre-test and a 100 on the post-test, so the fractional difference is one. Similarly, the student with a -0.7 decreased by 70% on the conceptual knowledge test after the implementation. Overall, nine of the fifteen professors showed positive fractional differences, differences which indicate students performed better on average on the posttest than the pre-test. Six of the fifteen professors saw a negative mean, which indicates students performed worse on the posttest than the pre-test.

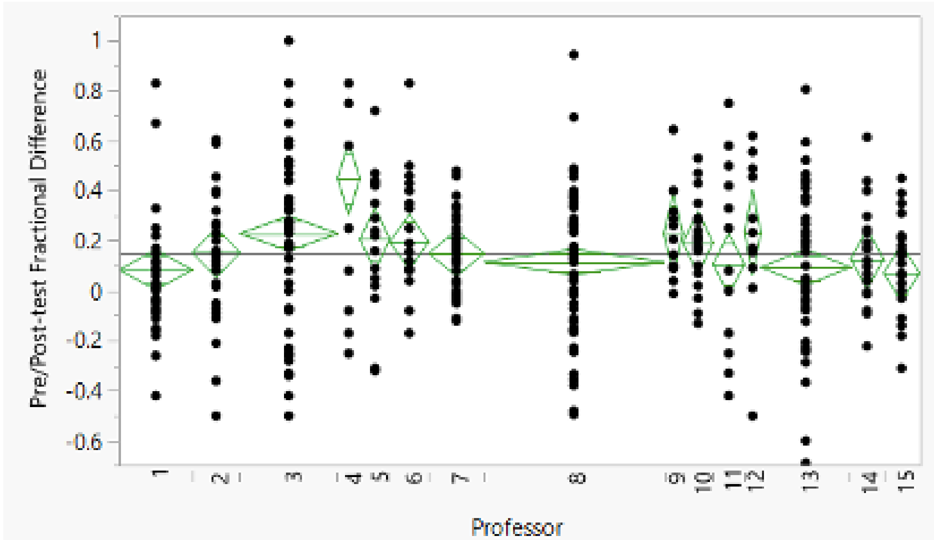

Figure 7: Implementing professor plotted against the difference in pre/post-test with respect to their students

To assess how well experimental results obtained with the LCDLMs align with traditional fluid mechanics theory, experimental data were collected and evaluated by two groups of students: graduate students working in this IUSE project (research group) and third--year chemical engineering undergraduate students (in-class students) who used a venturi meter LCDLM in their coursework to learn working principles. Figure 8 shows the measured and predicted head loss in the hydraulic loss LCDLM for these two groups.

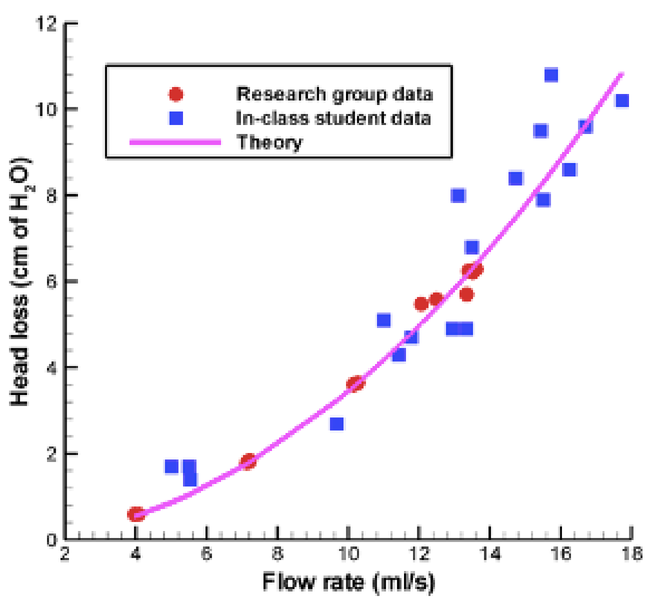

Figure 8: Comparison of experimental head loss and theoretical prediction of head loss (water column height difference between inlet and throat) with respect to flow rate for injection molded venturi meter

The theoretical prediction was calculated using the following formula:

$$\Delta h = h_i - h_{th} = \frac{8\dot{V}^2\left[1-\left(\frac{d_{th}}{d}\right)^4\right]}{g\pi^2 d_{th}^4 C_d^2}$$

where h_i and h_{th} are the water column height at the venturi inlet (diameter: $d = 12.7\ mm$) and throat (diameter: $d_{th} = 4.06\ mm$), respectively. V is the volumetric flow rate; g is the gravitational acceleration and c_d is the discharge coefficient. For our system, the discharge coefficient has been estimated as 0.935.

The research group data are perfectly in-line with the theoretical prediction but the in-class student data are more scattered than the research group data. Since undergraduate students were working with the venturi meter LCDLM for the first time, with a tight 50-minute time frame, a dispersion was expected. In conclusion, the developed injection molded venturi meter can be used for flow measurements in a classroom setting.

Our team also assessed data on differential gains in understanding, first by comparing results from a COVID-motivated virtual option for teaching with LCDLMs with results from our "traditional" in-person hands on approach. Because of the restrictions caused by the COVID-19 pandemic, our team developed virtual implementation materials so that students could experience the LCDLM material outside of the traditional hands-on setting. Virtual materials included a ~10-minute demonstration video with a researcher demonstrating the module set-up; completing the LCDLM worksheet experiments; and explaining basic experimental trends. Additionally, 2-3-minute, narrated, animated videos were created to provide an in-depth conceptual discussion of each module worksheet learning objective. The virtual implementation materials were used from Spring 2020 through Spring 2021. Figure 9 shows the overall pre/post-activity conceptual assessment scores for hands-on and virtual implementations of the hydraulic loss module.

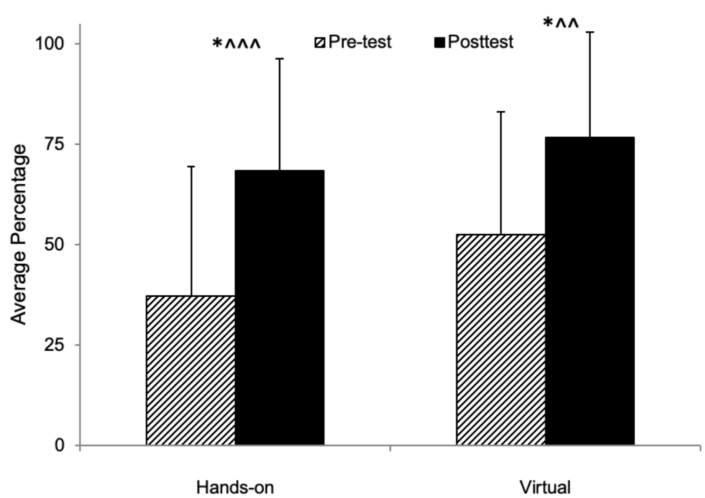

Figure 10: Average pre- and post-test scores for hands-on (N = 213) and virtual (N = 136) implementations from Fall 2019 to Fall 2020. * = $p < 0.05$ in paired samples t-test comparing pre- and posttest scores; ^^, ^^^ = small and medium Hedge's g effect size for pre- and post-test comparison

Results indicate that both implementation methods promoted statistically significant improvements in performance on the post-activity conceptual assessment and that there was no statistical difference between average score increases from pre-test to post-test for the hands-on and virtual methods.

Conclusion

This project has continued for four years with our development of low-cost hands-on learning modules with an aim of helping students understand important learning outcomes more efficiently. Previously, a venturi meter, hydraulic loss, and double pipe, and shell-and-tube heat exchangers were developed. Performance tests have been conducted to see the efficacy of those LCDLMs; the outcomes of those tests satisfied our team's expectations. However, due to COVID-19 restrictions, face to-face activities have been limited. To use those LCDLMs in classroom applications, our team worked on preparing explanatory videos.

Our team continued improving the previously developed shell-and-tube heat exchanger. The module has been constructed with an injection-mold approach. A new module, an evaporative cooler has been constructed and will be used in courses on fluid mechanics and heat transfer applications. This module is being introduced into classrooms for the first time this semester. A new cell settling module has also been developed to supply a better understanding of blood separation in biomedical applications and will also be used in Spring 2022. Results on the use of these latter two modules will be presented at the 2022 ASEE meeting.

Various tests have been applied to investigate the performance of people who use these modules. For the first test, gender and ethnicity and race have been investigated; most racial and ethnic groups showed performance gains, but more research is needed, as some groups were underrepresented. In addition, engagement responses have been collected from both males and females; similar engagement responses have been obtained. The effect of professors on student learning was investigated; results show that nine professors obtained positive and six negative fractional differences. More work needs to be done to determine why the students of some professors were more successful than those of others.

To test the accuracy of the venturi meter LCDLM, experimental data has been collected from two groups of students who used the LCDLMs in their classrooms. The results were compared with the theoretical data calculated from an equation in the textbook. Results show that experimental and theoretical values are well aligned. This indicates the LCDLM is accurate for use in the classroom. Finally, the hands-on learning and virtual learning gains were compared. Results show that switching to a virtual mode did not affect learning efficacy; in other words, similar gains were obtained. In a time of widespread virtual learning, this is good news.

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