DEVELOPMENT AND IMPLEMENTATION OF A LOW-COST DESKTOP LEARNING MODULE FOR DOUBLE PIPE HEAT EXCHANGE

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INTRODUCTION

The use of active learning pedagogies continues to expand in engineering courses due to substantial evidence that their use can increase academic performance,[1,2] improve student attitudes towards learning,[2] and disproportionately benefit minority and disadvantaged student groups by reducing the academic performance gap.[3-6] Active learning is broadly defined as activities that promote student engagement with the material they are learning.[7] According to Chi, these methods can be further separated into distinct forms of engagement: interactive, constructive, active, and passive (ICAP).[8,9] Interactive engagement activities, which require students to construct new understanding through an exchange of ideas with peers, have been shown in several studies to promote greater conceptual understanding than other forms of engagement;[10-12] thus, these activities are valuable in the classroom.

The use of hands-on experimentation can promote interactive engagement. Experience with relevant equipment is critical for student education, but providing a quality laboratory experience can be challenging due to increasing equipment cost and limited faculty time.[13] Several universities have revised their engineering programs to feature positively received experimentation that increased student engagement throughout the curriculum;[14-16] however, these integrated approaches often require specially designed learning spaces and costly equipment. Lower cost, benchtop scale experiments are an excellent alternative. Recently, Kaminski developed desktop-scale experimental set ups for demonstration of steady and unsteady state conduction and convection phenomena within a price range of $50-600.[17] Flack and Volino developed a $3,000 set of fin and tube-type cross-flow heat exchangers that

was used to demonstrate heat transfer through one exchanger or exchangers in series or parallel.[18] Researchers at Bucknell University incorporated simple inquiry-based heat transfer activities using everyday materials to address common misconceptions such as (a) the difference between heat transfer rate and the amount of heat transferred, and (b) the difference between temperature and energy.[19] Minerick developed a versatile $65 Desktop Experiment Module demonstrating conduction and convection principles for various geometries.[20] These examples demonstrate significant progress towards lowering the cost and improving the accessibility of hands-on activities. However, the continued development of ultra-low-cost, small-scale, visual, and quantitatively accurate heat exchange equipment that incorporates industrially relevant principles is still necessary.

To address this challenge, our group has previously developed Low-cost Desktop Learning Modules (LCDLMs) that replicate industrial fluid mechanics and heat transfer equipment on a miniature scale.[21-23] These modules are effective for increasing student conceptual understanding and are positively received by students.[21-23] However, the fabrication technique employed to produce them, vacuum forming over 3D printed molds, was time-consuming and resulted in inconsistent units, making mass production unfeasible. Therefore, in the present study, we report on the fabrication, testing, and classroom implementation of a next-generation double-pipe heat exchanger LCDLM, manufactured via injection molding and robotic adhesive application, which has improved the ability to mass-produce LCDLMs without sacrificing their low cost and overall quality. In this paper we address three primary issues: first, whether the new double-pipe module can

mimic the industrial scale counterpart with respect to steady state flow and heat transfer; second, whether the module and associated classroom activities improve student conceptual understanding; and third, whether students endorse the use of the LCDLM as helpful for their conceptual understanding and engagement.

METHODS

Heat Exchanger Construction, Specifications, and Cost

The miniaturized double-pipe heat exchanger shown in Figure 1 (two-dimensional schematic in 1A and photograph in 1B) was used for all data collection. Unlike typical double pipe heat exchangers, the LCDLM has four tubes within an annulus constructed from two mirror-image halves of injection molded polycarbonate plastic, ensuring dimensional consistency (tolerance +/- 0.1 mm for the outer annulus diameter, for example). The transparent plastic annulus has an inner diameter of 9.53 mm, while inner tubes are cut from 304 stainless steel tubing (4.57 mm inner diameter, 6.35 mm outer diameter) with a length of 137 mm, giving an outside-tube heat transfer surface area of 109 cm². The two polycarbonate halves and steel tubes are assembled via robotically-assisted application of UV-curable adhesive, further ensuring consistency between units. The experimental setup for measurement of temperatures and flow rates consisted of the elements shown in Figure 1C. Pump assemblies consisting of a battery-operated centrifugal pump, silicone tubing, and a quarter-turn valve were placed in 1 L inlet beakers and connected to the module inlets via 8.9 mm inner diameter Tygon® tubing and elbow fittings. U-fittings were connected to module outlets to direct flow into 1 L outlet beakers.

All the heat exchanger kit components — with the exception of the module, stand, U-fittings, and fully-assembled pump units — are off-the-shelf items, ensuring easy replacement by instructors should components be broken or misplaced during classroom use. The total cost to produce the LCDLM cartridge and auxiliary kit components is approximately $120. At larger scale production — for example, 10,000 units instead of the 500 units used for the estimate above — the cost of
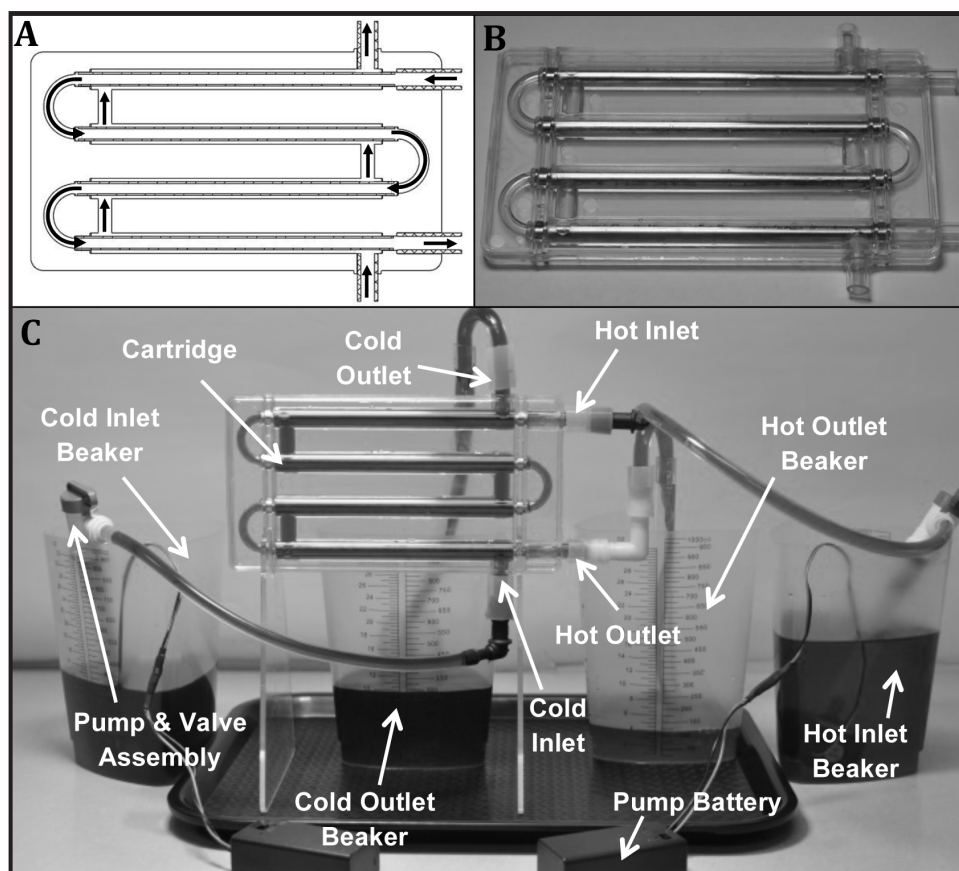

Figure 1. *A) Simple schematic of a double-pipe heat exchanger LCDLM cartridge with arrows showing counter-current flow pattern, B) photograph of cartridge, and C) experimental setup for flow rate and temperature measurement with pumps in beakers connected to module via tubing and fittings.*

cartridge manufacture could be reduced by approximately 50%. Using typical hot and cold water from the tap, this heat exchanger is capable of transferring heat at a rate on the order of 700 W.

Heat Exchanger Performance

The heat exchanger was configured for counter-current flow with cold tap water in the annulus and hot tap water on the tube-side to minimize the heat loss from the heat exchanger to the surroundings. The ambient temperature was approximately 20 °C for all experiments. Fresh tap water with an initial temperature of 48.6-59.2 °C for the hot fluid and 20.2-26.6 °C for the cold fluid was placed in the uninsulated inlet beakers approximately one minute before starting flow for each experiment with no additional heating or cooling. The fluid flow rate was controlled by adjusting quarter-turn valves attached to the supply pumps. First, the annular (cold water) flow rate was held between 17.9-21.6 mL/s while the tube-side (hot water) flow rate was varied from 3.5-19.5 mL/s in 14 experiments; then the annular flow rate was varied from 5.4-20.4 mL/s in 9 experiments at a tube-side flow rate of 16.3-18.4 mL/s. Flow rates were determined by measuring the water volume in the exit beakers and the time of flow. Four calibrated Type K thermocouples were placed in the LCDLM inlets and outlets and another four were placed in the inlet and outlet beakers. Temperatures were recorded simultaneously every second using LabVIEW™ to determine whether the module and beaker temperatures stabilize within the typical experimental timeframe (30 s) and whether temperatures measured in the beakers and module are comparable. Similar experiments with a vacuum-formed shell and tube heat exchanger LCDLM showed these modules reach steady state within 10 s and that beaker and module temperatures are consistent within 1 °C.[21] This is important for classroom use as beaker temperatures are measured with a handheld thermometer before and after operation.

Classroom Implementation Procedure

Experimental and assessment data were collected during a one-hour implementation in a fourth-year chemical engineering fluid flow and heat transfer course with 19 students. Students worked in teams of 3-4 to complete a worksheet, publicly available on our website,[24] consisting of an experimental and a conceptual discussion section. For the experimental section, students were asked to 1) measure the temperature of the hot and cold fluids in the inlet beakers using a handheld digital thermometer immediately before starting flow; 2) start the flow and simultaneously start a cell phone timer; 3) run the exchanger in counter-current mode until the inlet beakers were nearly empty; 4) stop the flow and the timer, immediately measure the temperatures of the water in the hot and cold outlet beakers; and 5) record the water volume in the exit beakers. Students used tap water dyed with one 400 mg dissolvable, non-staining fizzing dye tablet per liter, red for the hot fluid and blue for the cold fluid, to increase the visibility of flow patterns. Because there were only five student groups, we asked four untrained undergraduate engineering students, guided by the same worksheet instructions given to classroom groups, to individually operate the module and collect additional experimental temperature and flow rate data to allow a more rigorous comparison to the laboratory collected data.

Measures

To assess changes in conceptual understanding, short multiple-choice assessments were administered via the Qualtrics XM Platform™ before and after the LCDLM activity. The assessment completed before module implementation had four questions, and the post-activity assessment had the same four questions with three additional questions. These were added to increase the number of concepts tested and, because they are different questions, to ensure that the effects are not solely due to re-exposure to test items.[25] The conceptual foci for all questions related to concepts on the worksheet are shown in Table 1. Changes in conceptual understanding were examined using paired sample Student's t-tests and Hedges' g effect sizes.

Students also completed an assessment focused on self-reported engagement and the usefulness of various physical features of the LCDLM for enhanced learning. All assessment data were collected in the classroom on the same day as the module implementation from students who consented to participate in this study via an IRB-approved digital consent form.

RESULTS AND DISCUSSION

Approach to Steady-State Temperatures

The double-pipe heat exchanger cartridge reaches steady-state temperatures within 10 s for flow rates used in classroom experiments, allowing confidence in further calculations. Figure 2A shows hot-side temperature profiles with both flow control valves fully open. Temperatures reached 95% of the final, steady-state values in 4 and 7 s at the LCDLM outlet and outlet beaker, respectively, and within 2 s at the LCDLM inlet and inlet beaker after the pumps were turned on. Remarkable to note is that the module outlet and outlet beaker temperatures stabilize within 2 and 4 s, respectively, after water reaches the outlets and heat exchange begins, indicating a near-negligible period of non-steady-state operation for flow rates typically used during classroom experiments. A similar trend was observed for fully-open flow on the cold-side, with outlet temperatures stabilizing within 7 s (not shown).

TABLE 1		
Pre-and Post-Activity Assessment Questions		
Question	**Conceptual Focus**	
1	Identification of system boundary for energy balance on the hot fluid in a flat plate exchanger	
2	Identification of measured temperature differences that drive heat transfer	
3 (A/B)	Understanding the relationship between heat exchanger length and heat duty with justification	
4	Understanding the relationship between annular diameter, fluid velocity, and heat duty	
5	Understanding influence of flow rate and cold water temperature on hot water temperature	
6 (A/B/C)	Identification of areas for cold water flow, hot water flow, and heat transfer	
7 (A/B)	Understanding non-constant driving force in heat exchanger and the need to account for this	

In fact, steady-state operation was demonstrated to occur at all thermocouple locations within 10 s for all but the slowest tested flow rates of 3.5-6 mL/s, with a 6 mL/s example for the cold-side fluid shown in Figure 2B. During these experiments, the outlet beaker temperature gradually increased for 13-20 s after flow began, while the temperature at the module outlet stabilized within 5-13 s. This demonstrates that steady state conditions are achievable within the 30 s timeframe in a typical classroom experiment for all flow rates, and that students and faculty are safe to assume that the system can be treated as operating at steady state by the conclusion of each experiment. We can use pre-steady-state information to help account for the small deviations of hot- and cold-side heat duty and between predicted and experimental heat transfer coefficients.

Also important to note is the agreement between module temperatures and temperatures in the corresponding inlet or collection beaker once the exchanger reaches steady state. Temperature differences between the module and the corresponding beaker at the hot- and cold-side inlet and at the cold outlet were below 0.6 °C for 81% of experiments with differences of less than 0.3 °C in 46% of cases. The largest temperature differences between the module inlets and inlet beakers occurred at the slowest water flow rates on both the hot and cold-side. This is demonstrated in Figure 2B where the module cold inlet temperature is 0.95 °C higher than the cold inlet beaker temperature. This is presumably due to poor mixing in the beaker or heat exchange through the 8.9 mm plastic inlet tubing that has a high surface area for heat transfer with higher temperature ambient air. As demonstrated in Figure 2A, inlet temperature differences were negligible at higher flow rates typically used in a classroom setting. A larger average difference of 1.2 °C occurred between the hot-side outlet and outlet beaker, with only 26% of experiments showing less than a 1 °C difference. Hot fluid exits the module at a temperature of 30-52 °C and is directly exposed to ambient air before entering the uninsulated beaker, resulting in heat loss due to evaporative cooling. As seen in Figure 2B, this effect occurs, but is less pronounced, at the cold-side exit with beaker temperatures only 0.3 °C degrees lower, on average, than module outlet temperatures, as the cold fluid exit temperature of 24-40 °C is within 20 °C of the surrounding air. Collectively, the comparison of the module and beaker temperatures shows that beaker temperatures collected during classroom experiments are a reasonable estimation of module temperatures. Students may be asked to consider how accurate the beaker temperatures are, why they may be slightly different from what is measured at module inlets and outlets, and how this affects further calculations.

Heat Duty

Thermal energy transport between streams is consistent with expectations. Hot- and cold-side heat duties calculated using the steady-state temperature data collected with thermocouples at the LCDLM inlets/outlets and in the inlet/outlet beakers for 23 individual experiments with varying hot and cold inlet temperatures and flow rates are shown in Figure 3. Figure 3 also shows the heat duties calculated using beaker temperatures measured by five student groups and four individual undergraduate students with handheld thermometers. In all cases, the hot- and cold-side heat duties were calculated by multiplying the fluid mass flow rate, the heat capacity at the average hot or cold fluid temperature, and the difference between the hot or cold inlet and outlet temperatures. In an insulated heat exchanger, the hot and cold-side heat duties are expected to be nearly equal due to energy conservation. However, the LCDLM is not insulated and the metal piping and plastic casing initially at room temperature, with a total mass of 200 g, must equilibrate with the fluids they contain. As a result, a 6.1% lower cold-side heat duty on average across all 23 experiments is observed when thermocouple readings directly at the entrance and exit of the module are used in calculations. Even with these small differences, a highly linear relationship between calculated heat duties with a slope of 0.95 ($R^2 = 0.97$) is observed.

What is more important is how well heat duties calculated using beaker thermocouple readings and using student-measured temperatures agree. When inlet and outlet beaker
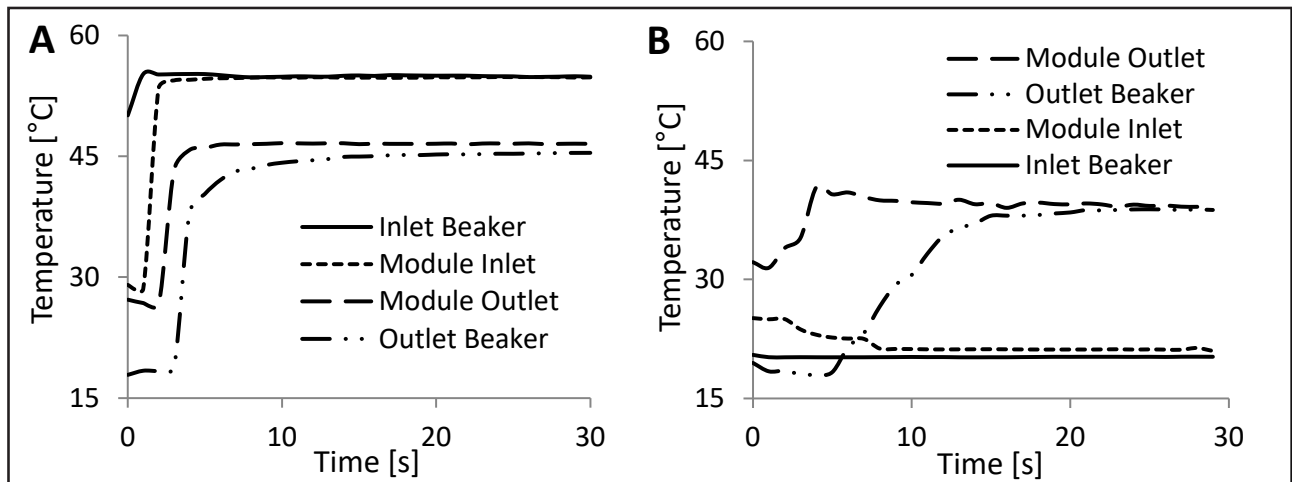
Figure 2. *A) Hot-side temperature profiles for the inlet and outlet streams for fully open valve settings, and B) cold-side temperature profiles for inlet and outlet streams for a cold-water flow rate reduced to 6 mL/s.*
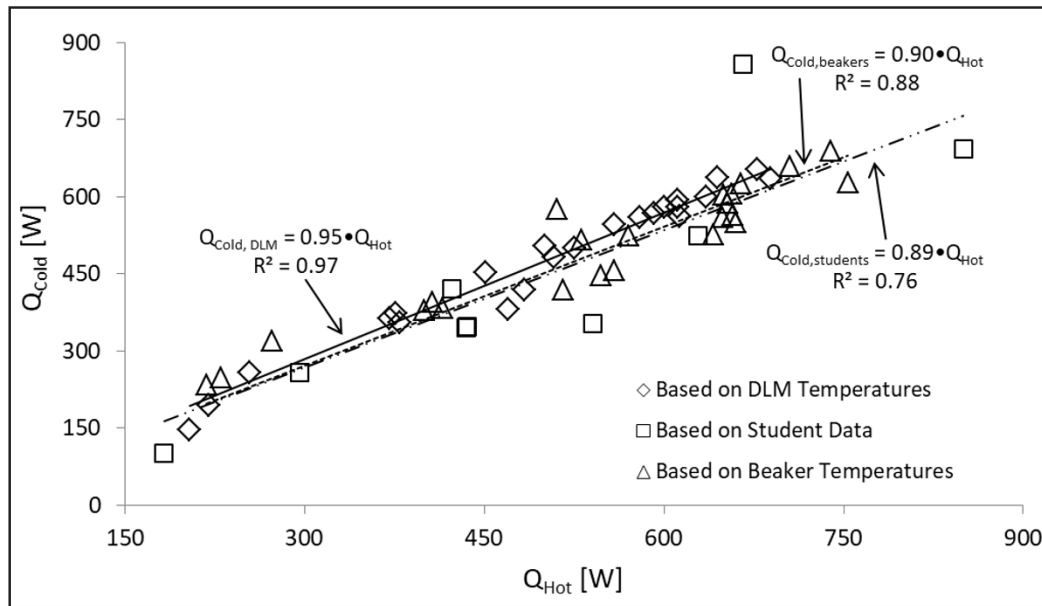

Figure 3. *Hot- and cold-side heat duties calculated using temperatures collected via thermocouples at module inlets and outlets and in beakers, and by student groups or individual students using handheld thermometers.*

thermocouple readings are used, a 10.9% lower cold-side heat duty and a linear relationship with a slope of 0.90 ($R^2 = 0.88$) are observed. A greater than 10% difference was observed in 46% of experiments when beaker temperatures were used in our analysis. These differences are due to the evaporative cooling of the hot exit stream, which is exposed to cooler air, and to a lesser extent, due to the fact that tubing and fittings begin at ambient temperature and must equilibrate. The average predicted heat loss between the hot-side outlet and outlet beaker, calculated using measured temperature differences be-

tween the LCDLM outlet and outlet beaker, is 61.3 W, which is ~11.4% of the total hot-side heat duty. Subtracting the heat loss from the total measured hot-side heat duty reduces the average error between the hot- and cold-side heat duty calculated using beaker temperatures to 7.9%. The error is closer to that for heat duties calculated with module temperatures, with only 4 experiments (17%) showing greater than a 10% difference. To minimize the impact of evaporative cooling and other heat losses, instructors may consider adding insulating material to the beakers, exit fittings, and tubing. When

student flow rate and thermometer temperature data are used, a 22.0% average difference between the hot and cold-side duty is found with a slope of 0.89 ($R^2 = 0.76$). The larger variation between the heat duties for the student data can be explained by the classroom procedure and inaccuracy of data collection when students operate the module. Students may incorrectly measure flow rates, they collect only a single thermometer temperature measurement in each beaker, and they may not measure temperatures immediately before and after operation, resulting in several opportunities for measurement error. Instructors should inform students of the importance of accurate and prompt data collection prior to beginning experimentation and can instruct students to collect temperature data directly at the module outlets rather than in beakers. As a powerful example of the importance of accurate temperature and flow rate measurement, students may compare their data with that carefully collected at module inlets and outlets. In summary, the simple classroom procedure for LCDLM operation, while non-ideal, still gives a reasonable correlation between heat transferred from the hot to the cold fluid.

Overall Heat Transfer Coefficient

An analysis of the overall heat transfer coefficient, U_o, strongly supports the utility of the double pipe LCDLM for the demonstration of convective heat transfer theory. Experimental values for U_o were calculated using Eq. 1, where $\dot{Q}_{av}$ is the average of the hot- and cold- heat duties, A_o is the outer surface area for heat transfer, and ΔT_{LM} is the log mean temperature difference

$$U_{o,expt} = \frac{\dot{Q}_{av}}{A_o \Delta T_{LM}} \qquad (1)$$

This was compared to the coefficient predicted using the sum of the individual thermal resistances based on correlations for industrial-scale equipment for the annular and tube side resistances and the resistance through the metal tube as shown in Eq. 2. Here A_i is the inner surface area for heat transfer, h_i and h_o are the individual tube- and annular-side heat transfer coefficients, $D_{t,i}$ and $D_{t,o}$ are the inside and outside tube diameters, L_t is the tube length, N_t is the number of tubes, and k_{wall} is the conductivity of the tube wall.

$$U_{o,predicted} = \frac{1}{\frac{A_o}{h_i A_i} + \frac{A_o \ln\left(\frac{D_{t,o}}{D_{t,i}}\right)}{2\pi L_t N_t k_{wall}} + \frac{1}{h_o}} \qquad (2)$$

In our LCDLM experiments, tube-side Reynolds numbers (Re) were primarily in the transitional region with values between 3,500 and 10,200 with the exception of the lowest flow rates tested where Re values were in the laminar region between 1,580 and 1,960. Annular-side Reynolds numbers were always in the laminar regime ($Re < 2,000$). For laminar

flow on the tube-side, the Nusselt number correlation developed by Sieder and Tate[26] with a correction factor for natural convection effects[27] was used to calculate individual heat transfer coefficients, as shown in Eq. 3, where k is the thermal conductivity determined at the average bulk temperature, Re and Pr are the Reynolds and Prandtl numbers, respectively, and Gr is the Grashof number.

$$Nu_{laminar} = \frac{h_i D_{t,i}}{k} = 1.86 \left[Re \cdot Pr \left(\frac{D_{t,i}}{L_t}\right) \right]^{1/3} \left[0.87(1 + 0.015 Gr^{1/3}) \right] \quad (3)$$

For laminar flow in the annulus, the Nusselt number was determined using a correlation developed by Chen, Hawkins, and Solberg,[28] shown in Eq. 4, where D_h is the hydraulic diameter and D_a is the diameter of the annulus.

$$Nu_{laminar} = \frac{h_o D_h}{k} = 1.02 \cdot Re^{0.45} Pr^{1/3} \cdot \left(\frac{D_h}{L_t}\right)^{0.4} \left(\frac{D_a}{D_{t,o}}\right)^{0.8} Gr^{0.05} \quad (4)$$

For transitional flow on the tube-side, Gnielinski's correlation with a correction for entrance effects due to the low length-to-diameter ratio in the LCDLM,[29] shown in Eq. 5a, was used, where f is a friction factor defined in Eq. 5b.

$$Nu_{transitional} = \frac{\left(\frac{f}{2}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{2}\right)^{0.5}(Pr^{\frac{2}{3}} - 1)} \left[1 + \left(\frac{D_{t,i}}{L_t}\right)^{2/3} \right] \quad (5a)$$

$$f = (1.58 \ln(Re) - 3.28)^{-2} \qquad (5b)$$

The wall viscosity correction factor was neglected due to a maximum difference between bulk hot and cold temperatures of 27 °C resulting in a correction of at most 7% in the Nusselt number. This worst-case correction would occur if the resistance to heat transfer on one side of the wall dominates, giving the full 27°C temperature change between bulk and wall on the high-resistance side of the exchanger. Resistances due to tube fouling were also neglected as tubes were free from dirt and scale. Figure 4A shows the predicted and experimental values for the overall heat transfer coefficient and 4B shows the experimental overall resistance, the inverse of $U_{o,expt}$, versus the Reynolds number.

Predicted overall heat transfer coefficient values agree quite well with the measured values within 7.2% on average when module thermocouple temperatures were used and within 17.4% when temperatures collected by students with handheld thermometers in beakers were used in the analysis. When measured with thermocouples in our laboratory, coefficients were similarly within 18.8% of the experimental values. The larger deviation between the predicted and experimental values for beaker measurements can be explained by the overestimation of the hot-side heat duty due to heat loss from the exiting hot fluid as previously discussed. Figure 4B shows an

asymptotic decrease of the overall resistance as the tube-side Reynolds number increases, closely approaching the predicted sum of the wall and annular resistances. It is important to note that even when students use beaker temperature readings that differ slightly from actual module temperatures, U_o can be predicted within 20% of the experimental values. If desired, an instructor can provide the approximate temperature differences due to evaporative cooling and the students could account for this and show the impact on the calculations. Collectively, the technical data show that the LCDLM, despite its small size and low cost of under $120, is appropriate for the demonstration of basic principles such as flow patterns in a heat exchanger and agrees remarkably well with steady state heat transfer theory. Due to the flexibility of the LCDLM, we expect to see extended applications in heat transfer courses beyond the activities previously discussed. With the existing module students may compare heat transfer for co-current and counter-current flow configurations, investigate the optimum experimental conditions to maximize the heat duty, and observe the impact of heat transfer area by connecting modules in series. Analysis of time-dependent temperature profiles and non-steady state behavior is also possible in the classroom using thermocouples. With a modified module, students could investigate location-dependent heat transfer with thermocouples inserted along the length of the annular or tube-side as an advanced exercise. Finally, students could compare experimental results to results obtained with numerical simulation to further their understanding of complex heat transfer phenomena.

Effectiveness in Enhancing Conceptual Understanding

Effective hands-on activities should promote both engaging experimentation and meaningful conceptual understanding. Figure 5 shows the average percentage score for each individual assessment question, the average overall percentage score for the questions repeated on both the pretest and posttest, and the average overall percentage score on the posttest for all questions for the 19 student class.

Score increases were observed for three of the four repeated questions, with a statistically significant difference and a medium effect size for question 1, which required students to identify the system boundary used to calculate the hot-side heat duty in a flat plate exchanger. Question 2, related to identifying which temperature differences drive heat transfer, also showed a small effect size. The overall score for repeated questions significantly increased from an average of 59±24% to 72±22% with a medium effect size, indicating that the LCDLM was indeed beneficial for improving conceptual understanding. For questions asked only on the posttest, students also demonstrated a high level of understanding, with an average score of 68% or above on all questions and an overall posttest score of 76±17%. A lack of improvement and low overall score was observed on question 4, which required students to correctly relate diameter to fluid velocity and fluid velocity to heat transfer rate. Though the latter concept was directly addressed during the activity, the relationship between diameter and velocity was not covered; poor understanding of this underlying fluid mechanics
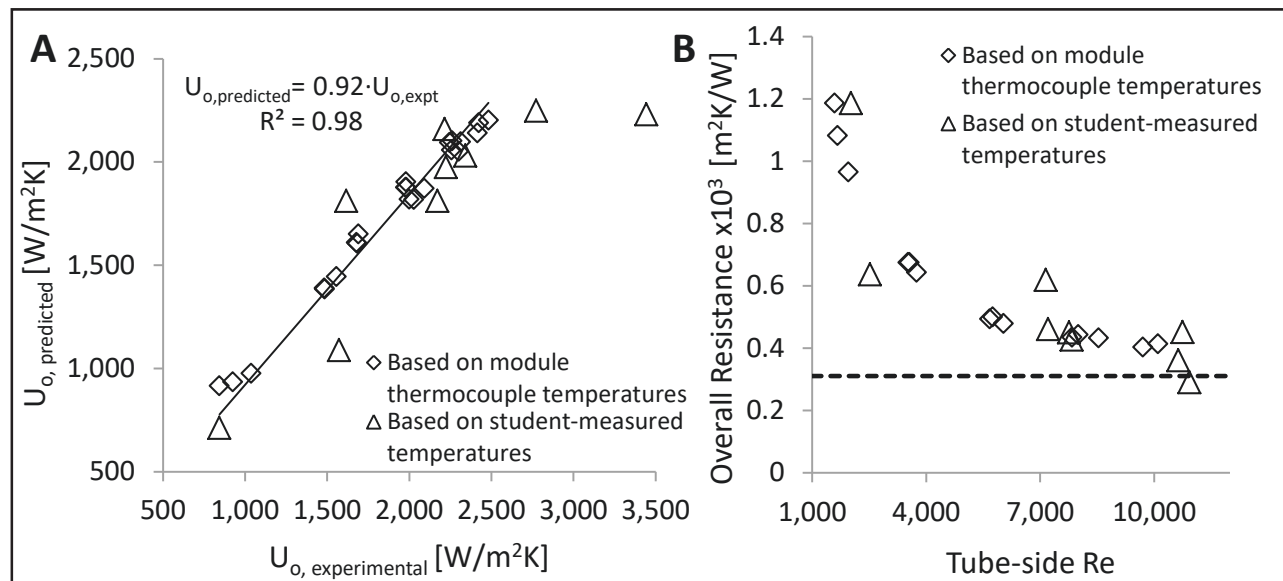

Figure 4. *A) Predicted versus experimental overall heat transfer coefficient using thermocouple temperatures collected at module inlets and outlets or student-measured beaker temperatures, and B) experimental overall resistance versus the tube-side Reynolds number. The dashed line on (B) indicates the predicted sum of the annular and wall resistance, an asymptote reached at very high Re numbers.*
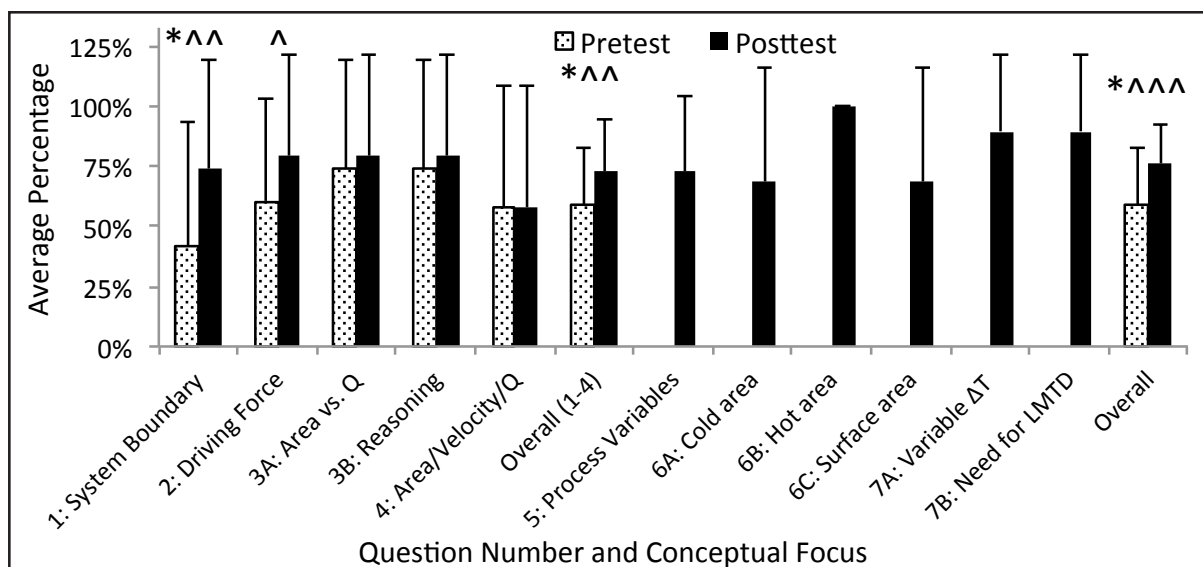
*Figure 5. Student performance on the pre- and post-implementation conceptual assessments (N=19). * indicates p<0.05, ^, ^^, ^^^ indicate small (0.2<g<0.5), medium (0.5<g<0.8), and large (g>0.8) effect sizes.*

concept would result in an inability to correctly answer question 4. Overall assessment results are consistent with Chi's ICAP framework[9] that suggests interactive activities such as LCDLM use, where students generate new knowledge through an exchange of ideas with peers, effectively increase conceptual understanding. To examine the robustness of these findings, we are conducting studies with a larger number of participants and collecting assessment data after traditional lectures. These results will be reported in future publications

Gender and LCDLM Effectiveness

There is strong evidence that interactive learning activities disproportionality benefit women by decreasing the gender gap in achievement. For example, Lorenzo et al. showed that when traditional physics instruction was replaced with interactive peer discussion and problem-solving, the difference between male and female scores on a concept inventory assessment was reduced from 10 to 2.4%.[3] Similarly, Lape et al. showed that the historic gender difference in final course grades in an introductory engineering course was eliminated through incorporation of team-based learning activities.[4] To examine whether the LCDLM activity was equally beneficial for female and male students, assessment scores for repeated questions were compared. Females ($N = 8$) showed a larger score improvement, 18.8% ($p = 0.055$, g = 0.84), compared to the 10.2% improvement ($p = 0.32$, g = 0.42) for males ($N = 11$). The average score for male students on the pretest was 14.7% higher than that for female students, but only 6.2% higher on the posttest, offering evidence for a reduced gender gap. Though the differences in male and female score changes are not statistically significant

($p = 0.53$), there is a small effect ($g = 0.28$) of gender on score change, indicating that with larger sample sizes, LCDLMs may disproportionately improve female understanding, suggesting usefulness for improving female performance and presumably retention in engineering, therefore increasing gender diversity. Further study with larger sample sizes on whether LCDLMs can aid in improving the performance of females and of low-achieving, disadvantaged students, as shown for other interactive activities,[5,6] is recommended.

Perceived Usefulness and Engagement Potential

Results from the motivational assessment were used to examine whether students felt that the features of the LCDLM helped improve their conceptual understanding and whether they were more engaged during the LCDLM activity than during a typical lecture. Figure 6 shows Likert scale responses for a series of questions focused on the usefulness of the module for the understanding of six important concepts in heat transfer. The LCDLM was most often identified as helpful for improving the understanding of flow patterns within the heat exchanger, the area for heat transfer, and the influence of the temperature difference between the hot and cold streams on the heat duty. Fluid flow patterns and flow and heat transfer areas are easily visualized in the LCDLM due to the transparent plastic and dyed water used in the activity. Students highly valued these visual features; 78% identified the transparent plastic, colored water, or both in an open-ended question where they were asked to identify the most helpful features of the LCDLM. The visually focused LCDLM allows students to see as well as measure phenomena, increasing students' confidence in their knowledge of visual concepts.
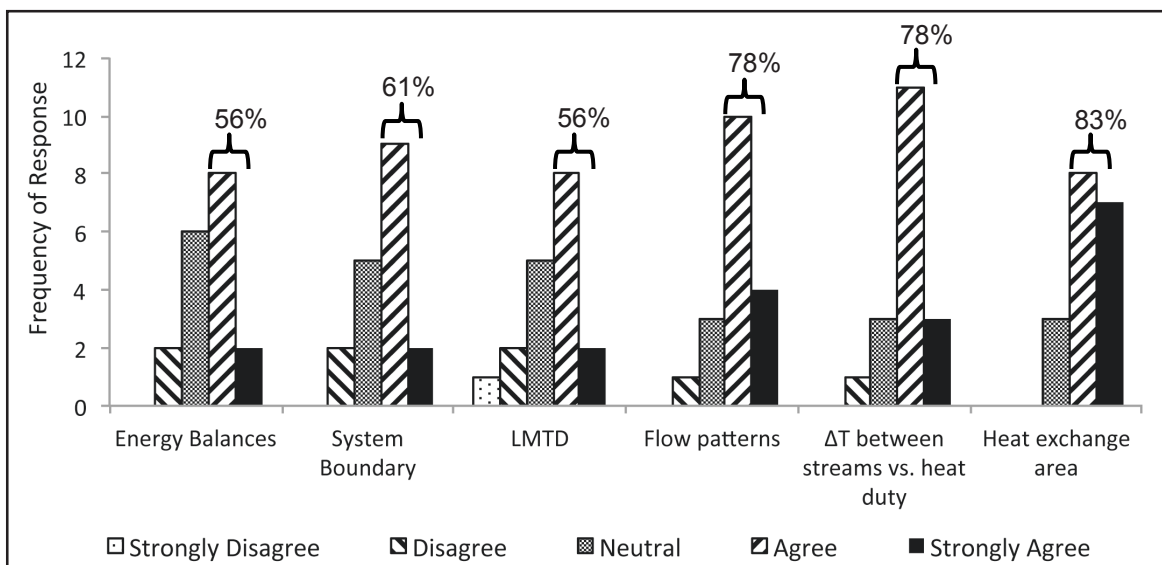
Figure 6. *Frequency of Likert scale responses for helpfulness of physical LCDLM features. Percentages indicate the total percentage of students who "agreed" and "strongly agreed" with the survey statement.*

TABLE 2 Engagement with the DLM Compared to Lecture			
Compared to lecture, the DLM…	Disagree (%)	Neutral (%)	Agree (%)
Gave me a deeper understanding of the HtX	0	32	68
Helped me see HtX concepts better	0	11	89
Only allowed me to be disengaged	68	21	11
Made me idle	79	21	0
Did not allow me to be engaged with concepts the same way	84	11	5

These results reveal that interactive activities in STEM courses can bolster student confidence in their conceptual knowledge and are in line with existing literature.[30,31] Table 2 shows that the majority of the students felt the LCDLM gave them a deeper understanding of the double-pipe heat exchanger (68%) and helped them see associated concepts better than lecture alone (89%). Students also agreed that, compared to lecture, they were not idle (79%), they could engage with concepts in the same way (84%), and that the LCDLM did not allow them to be disengaged (68%).

The results from the engagement and perceived usefulness questions indicate students believed that the activity with the LCDLM was both valuable for their conceptual understanding and for their engagement in the classroom.

CONCLUSION

The double-pipe heat exchanger LCDLM is useful for measurement of heat exchanger parameters including the heat duty and overall heat transfer coefficient, helps improve conceptual understanding of several key heat transfer concepts, and promotes a high-level of perceived usefulness for learning and engagement in the undergraduate classroom. The manufacturing techniques employed ensure excellent reproducibility and affordability, while the small-scale makes the LCDLM format highly flexible for a variety of interactive classroom applications. The double-pipe heat exchanger LCDLM is a promising candidate for unique hands-on learning experiences focused on heat transfer principles in undergraduate chemical and mechanical engineering classrooms.

ACKNOWLEDGMENTS

REFERENCES

1. Freeman S, Eddy S, McDonough M, Smith, M, Okoroafor N, Jordt H, and Wenderoth M (2014) Active learning increases student performance in science, engineering, and mathematics. *Proc. of the National Academy of Sciences*. 111(2): 8410-8415. 10.1073/pnas.1319030111.
2. Prince M (2004) Does active learning work? A review of the research. *Journal of Eng. Ed*. 93(3): 223-231. 10.1002/j.2168-9830.2004.tb00809.x.
3. Lorenzo M, Crouch C, and Mazur E (2006) Reducing the gender gap in the physics classroom. *Am. Journal of of Physics*. 74(2): 118-122. 10.1119/1.2162549.
4. Lape N, Clark C, Bassman L, Spencer M, Lee A, Spjut R, Dato A, Blake L, and Tsai T (2018) Erasing a gender gap in performance in a multidisciplinary introductory engineering course. *Proceedings of the Collaborative Network for Engineering and Computing Diversity Conference*. https://peer.asee.org/29534.
5. Koles P, Stolfi A, Borges N, Nelson S, and Parmelee D (2010) The impact of team-based learning on medical students' academic performance. *Academic Medicine*. 85(11): 1739-1845. 10.1097/ACM.0b013e3181f52bed.
6. Haak D, HilleRisLambers J, Pitre E, and Freeman S (2011) Increased structure and active learning reduce the achievement gap in introductory biology. *Science*. 332(6034): 1213-1216. 10.1126/science.1204820.
7. Bonwell C and Eison J (1999) Active learning: Creating excitement in the classroom. *ASHE-ERIC Higher Ed. Report*. No. 1. https://eric.ed.gov/?id=ED336049.
8. Chi M (2009) Active-constructive-interactive: a conceptual framework for differentiating learning activties. *Topics in Cognitive Science*. 1(1): 75-105. 10.1111/j.1756-8765.2008.01005.x.
9. Chi M and Wylie R (2014) The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist*. 49(4): 219-243. 10.1080/00461520.2014.965823.
10. Meneske M, Stump G, Krause S, and Chi M (2013) Differentiated overt learning activities for effective instruction in engineering classrooms. *Journal of Eng. Ed*. 102(3): 346-374. 10.1002/jee.20021.
11. Wiggens B (2017) The ICAP learning framework predicts the learning gains observed in intensely active classroom experiences. *American Educational Research Association*. 3(2): 1-14. 10.1177/2332858417708567.
12. Linton D (2014) Identifying key features of effective active learning: the effects of writing and peer discussion. *CBE Life Sciences Ed*. 13(3): 469-477. 10.1187/cbe.13-12-0242.
13. Fiesel L and Rosa A (2013) The role of the laboratory in undergraduate engineering education. *Journal of Eng. Ed*. 94(1): 121-130. 10.1002/j.2168-9830.2005.tb00833.x.
14. Olinger D and Hermanson J (2013) Integrated thermal-fluids experiments in WPI's discovery classroom. *Journal of Eng. Ed*. 91(2): 239-243. 10.1002/j.2168-9830.2002.tb00697.x.
15. Carlson L and Sullivan J (1999) Hands-on engineering: Learning by doing in the integrated teaching and learning program. *Int. Journal of Eng. Ed*. 15(1): 20-31. https://www.ijee.ie/articles/Vol15-1/Ijee1041.pdf.
16. Chen W, Shah U, and Brechtelsbauer C (2019) A framework for hands-on learning in chemical engineering education—Training students with the end goal in mind. *Ed. for Chemical Engineers*. 28: 25-29. 10.1016/j.ece.2019.03.002.
17. Kaminski W (1998) A series of heat transfer experiments for the mechanical engineering technology student. *Proceedings of the ASEE Annual Conference*. 10.18260/1-2--7398.
18. Flack K and Volino R (1999) A series-parallel heat exchanger experiment. *Journal of Eng. Ed*. 88(1): 27-30. 10.1002/j.2168-9830.1999.tb00407.x.
19. Prince M, Vigeant M, and Nottis K (2016) Repairing student misconceptions in heat transfer using inquiry-based activities. *Chem. Eng. Ed*. 50(1): 52-61. https://journals.flvc.org/cee/article/view/87720
20. Minerick A (2010) Versatile desktop experiment module (DEMo) on heat transfer. *Chem. Eng. Ed*. 44(4): 274-279. https://journals.flvc.org/cee/article/view/122203.
21. Pour N, Thiessen D, Richards R, and Van Wie B (2017) Ultra low-cost vacuum formed shell and tube heat exchanger learning module. *Int. Journal of Eng. Ed*. 33(2A): 723-740. https://www.ijee.ie/contents/c330217A.html
22. Meng F, Van Wie B, Thiessen D, and Richards R (2018) Design and fabrication of very-low-cost engineering experiments via 3-D printing and vacuum forming. *Int. Journal of Mechanical Eng. Ed*. 47(3): 246-274. 10.1177/0306419018768091.
23. Richards C, Meng F, Van Wie B, Golter P, and Richards R (2015) Implementation of very low-cost fluids experiments to facilitate transformation in undergraduate engineering classes. *Proceedings of the ASEE Annual Conference*. 10.18260/p.24246.
24. Washington State University. LC-DLM Worksheets. https://labs.wsu.edu/educ-ate/worksheets-2/. Accessed 28 June 2021.
25. Adesope O, Trevisan, D, and Sundararajan N (2017) Rethinking the use of tests: A meta-analysis of practice testing. *Review of Educational Research*. 87(3): 659–701. 10.3102/0034654316689306.
26. Sieder E and Tate G (1936) Heat transfer and pressure drop of liquids in tubes. *Industrial and Eng. Chemistry*. 28(12): 1429-1435. 10.1021/ie50324a027.
27. Perry R and Green D (1984) *Perry's Chemical Engineers' Handbook*. 6th edition. McGraw Hill. London, United Kingdom.
28. Chen C, Hawkins G, and Solberg, H (1946) Heat transfer in annuli. *Transactions of the American Society of Mechanical Engineers*. 68: 99-106.
29. Tam L and Ghajar A (2006) Transitional heat transfer in plain horizontal tubes. Heat Transfer Eng. 27(5): 23-38. 10.1080/01457630600559538.
30. Ferri B, Ferri A, Majerich D, and Madden A (2016) Effects of in-class hands-on laboratories in a large enrollment, multiple section blended linear circuits course. *Advances in Eng. Ed*. 5(3). https://www.learntechlib.org/p/194900/.
31. Kolari S, Savander-Ranne C, and Tiili T (2005) Enhancing engineering students' confidence using interactive teaching methods, Part 2: Post-test results for the force concept inventory showing enhanced confidence. *World Trans. on Eng. and Technology Ed*. 4(1): 15-20. http://www.wiete.com.au/journals/WTE&TE/Pages/Vol.4,%20No.1%20(2005)/03-Kolari2.pdf. ❐