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Low-Cost Hands-on Shell-and-Tube Heat Exchanger: Design, Manufacture, Test, and In-class Implementation

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Low-Cost Hands-on Shell-and-Tube Heat Exchanger Learning Tools: Design, Manufacture, Test, and Implementation

Abstract: Hands-on learning improves students' cognitive understanding of the subject materials, fosters teamwork, and expands social skills. To introduce hands-on learning activities in the heat transfer and thermodynamics classroom, we have developed a low-cost shell-and-tube desktop learning module to provide effective heat exchange instruction. This module allows students to experiment with a shell-and-tube heat exchanger in the classroom or laboratory and learn the basic principles behind the heat flow between two non-contacting fluids. In this paper, we will present the design, manufacture, testing, and classroom implementation of this low-cost, reproducible, highly visual miniaturized shell-and-tube heat exchanger module. The highly visual nature of the developed desktop learning module helps students identify the key components of a shell-and-tube heat exchanger. In addition, the visualization of fluid flow assists students in understanding the different flow types occurring inside a shell-and-tube heat exchanger. A comparison of the measured overall heat transfer coefficient and associated parameters with the corresponding theory reveals its usefulness for demonstrating heat transfer mechanism in the undergraduate classroom. Pretest, posttest, and motivational survey results show its effectiveness in promoting students' conceptual understanding and engagement in the classroom. The developed module can be used in the undergraduate classroom to improve student's understanding of heat transfer from hot fluid to cold fluid in a shell-and-tube heat exchanger and improve their ability to apply theoretical concepts in practice.

1. Introduction

The use of hands-on learning devices is a well-accepted instruction method in the active learning domain [1-6]. It allows students to engage directly with the subject matter which enhances understanding, retention, knowledge, and skills. In addition, hands-on devices provide opportunities to apply theoretical concepts in real-world scenarios that help students bridge the gap between theory and practice, allowing learners to develop practical skills and gain valuable real-life experiences. Moreover, hands-on projects often involve tackling real-life problems that nurture critical thinking, problem-solving, and decision-making skills as learners navigate through obstacles and seek innovative solutions. Furthermore, hands-on devices are mostly used in a collaborative setting, fostering teamwork and interpersonal skills which encourage communication, cooperation, and the ability to work effectively in a group setting [7, 8]. Finally, hands-on devices encourage creativity and innovation as learners are given the freedom to explore and experiment. It provides an opportunity to think outside the box, develop new ideas, and find unique novel approaches to problem-solving.

However, the major drawbacks that hinder the use of hands-on learning devices in a classroom are time and cost, lack of guided structure, potential for mistakes, limited coverage of theory, assessment, and evaluation. Hands-on projects can be time-consuming and require resources such as materials, equipment, and tools which can pose challenges in terms of logistics, budget, and availability of resources. In addition, hands-on projects often require self-direction and independent learning which some students may find challenging to navigate through the project without clear guidance, leading to confusion or feeling overwhelmed. Moreover, hands-on projects sometime involve trial and error, and learners may make mistakes along the way. While mistakes can be valuable learning experiences, they can also cause disappointment if not addressed effectively. Furthermore, there may be a risk of focusing solely on practical aspects and neglecting theoretical foundations depending on the nature of the hands-on project. *Therefore, a balance between hands-on experience and a solid understanding of underlying principles is necessary.* Finally, assessing and evaluating learning outcomes from hands-on projects can be challenging because traditional assessment methods may not fully capture the skills, knowledge, and creativity demonstrated through project-based learning.

Therefore, to address the major cons of hands-on learning projects and foster the pros of hands-on learning projects, we have developed low-cost, highly visual, compact, and long-lasting hands-on learning devices for the heat transfer and fluid mechanics classroom [9-11]. These second-generation devices are built based on the success of first-generation desktop learning modules (DLMs) [12-15]. The second-generation DLMs are made with injection molding of polycarbonate plastics instead of vacuum forming around a mold. Although we have developed several modules [16] such as hydraulic loss DLM, venturi DLM [17], blood separator, evaporative cooling, double pipe heat exchanger [18], shell-and-tube heat exchanger, etc., focusing on different fluid mechanics and heat transfer concepts, this paper focuses exclusively on the shell-and-tube heat exchanger.

A heat exchanger is a device in which two fluid streams at different temperatures exchange heat across a wall under the influence of a temperature potential [19]. Among all different types of heat exchangers [20], the shell-and-tube heat exchanger offers the most extensive rating, i.e., the ability to operate in a variety of process conditions. Shell-and-tube heat exchangers can have many tubes supported by baffles placed inside a large cylindrical shell such that the tube-axis is parallel to that of the shell. In a shell-and-tube heat exchanger, one fluid flows inside the tubes while the other fluid flows through the shell guided by baffles which creates a complex fluid flow scenario. Shell-and-tube heat exchangers are commonly used in industrial applications such as the oil and gas industry, power generation, refrigeration, electronics cooling, air-conditioning, automotive applications, etc. to cool down or warm up a fluid and/or to carry out liquid–vapor phase transformation. Because of its widespread use in industry, a thorough understanding of the principles and operation of shell-and-tube heat exchangers is important for engineering students. Therefore, we hope that the developed DLM will help to understand the complex structures and operating principles of a shell-and-tube heat exchanger.

2. Methods

2.1 Heat Exchanger Construction, Specifications, and Cost

SolidWorks^{TM}, a computer aided design (CAD) software, was used to design an injection mold for the shell-and-tube heat exchanger. To speed up the manufacturing process, the CAD files were sent to a company that produced the injection molded parts from polycarbonate plastic. The shell-and-tube cartridge was constructed from two mirror-image halves with insertion of stainless-steel tubes as shown in Fig. 1a. The tubes are made of stainless steel 304 with an inner and outer diameter of 4.752 mm and 6.35 mm, respectively. The tubes have a length of 138 mm. As shown in the schematic, the shell-and-tube heat exchanger has one shell pass and two tube passes with two tubes per pass. Six baffles are used with a spacing of 18 mm. Those baffles have a thickness of 2 mm and height of 60 mm. The shell has a width of 10 mm and height of 80 mm, leaving a baffle window height of 20 mm. To ensure dimensional consistency and make the heat exchanger leakproof, the two polycarbonate halves were assembled via robotically assisted application of UV-curable adhesive.

The complete shell-and-tube heat exchanger experiment is shown in Fig. 1b. Besides the shell-and-tube cartridge, the complete setup requires several auxiliary elements as identified in Fig. 1b. The complete setup of shell-and-tube heat exchanger includes universal stands (two legs), two pump assemblies, two rechargeable NiMH 9V (280 mAh) batteries, four 1-liter beakers, two 90° adapters, two 3/8-inch u-bend connectors, two Tygon outlet tubes, one digital thermometer, 1 tray).

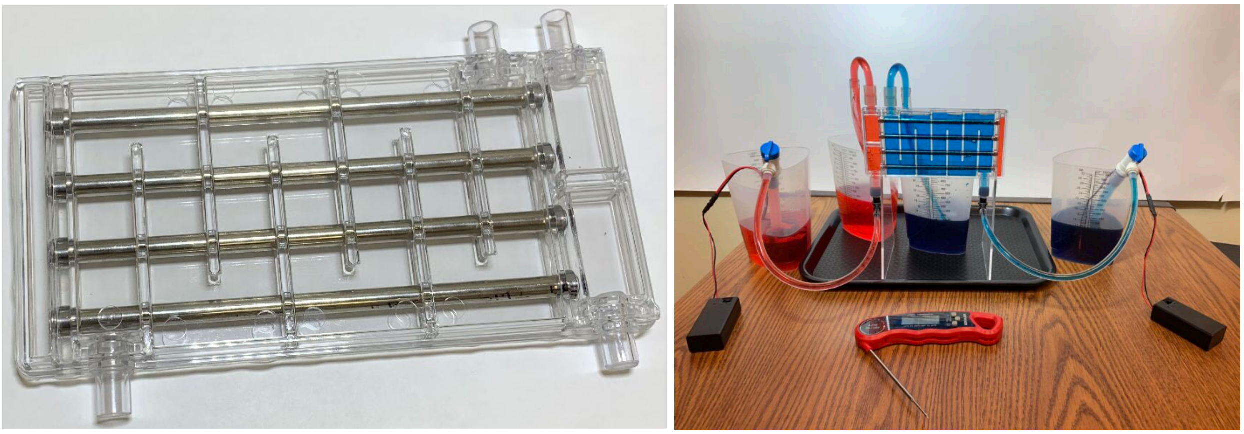

Fig. 1. (a) Photograph of shell and tube heat exchanger cartridge. (b) The complete experimental setup for the shell and tube heat exchanger.

Most of the heat exchanger kit components, apart from the module, stand, and fully assembled pump units, are off-the-shelf items. This offers the flexibility to replace any components that are broken or misplaced during implementation. The total cost to produce the heat exchanger DLMs including shell-and-tube cartridge and auxiliary kit components, is ~ \$150, which could be further reduced with large-scale production.

2.2 Heat Exchanger Performance

To measure the performance, the shell-and-tube heat exchanger was supplied with cold (20-30 ºC) and hot water (50-60ºC) from the tap. Hot water was placed inside the tube while cold water was placed in the shell to minimize the heat loss from the heat exchanger to the surroundings during the operation. The room temperature was approximately 23 °C for all experiments. Both cold and hot water were placed in the uninsulated inlet beakers approximately one minute before starting flow for each experiment; then both pumps were turned on simultaneously. The water flow rate was controlled by adjusting quarter-turn valves attached to the supply pumps. Flow rates were measured by dividing the water volume in the exit beakers with the time of flow. Four calibrated Type K thermocouples were placed in the inlet and outlet beakers to measure the hot and cold fluid inlet and outlet temperatures. The time of the flow is recorded with a stopwatch, and temperatures were recorded for four positions with HUATO data logger (model No. S220-T8) during the heat exchanger operation.

The heat transfer rates are calculated for the hot and cold water using the energy balances,

$$\dot{Q}_h = \dot{m}_h C_{p,h} \Delta T_h \qquad \dot{Q}_c = \dot{m}_c C_{p,c} \Delta T_c \tag{1}$$

where $\dot{Q}_h$ and $\dot{Q}_c$ are heat transfer rates, $\dot{m}_h$ and $\dot{m}_c$ are mass flow rates, $C_{p,h}$ and $C_{p,c}$ are heat capacities, and ΔT_h and ΔT_c are the temperature differences between the inlet and outlet for hot and cold water, respectively. The mass flow rates are determined from volume flow rates by

$$\dot{m}_h = \rho_h \dot{V}_h \qquad \dot{m}_c = \rho_c \dot{V}_c \tag{2}$$

where ρ_h and ρ_c are densities, $\dot{V}_h$ and $\dot{V}_c$ are volume flow rates of hot and cold water, respectively. Usually, the tube side has a turbulent flow (Re > 4000). Therefore, the tube-side heat transfer coefficient (h_i) is calculated using the Colburn equation as,

$$\frac{h_i D_i}{k} = Nu_i = 0.023\, Re^{4/5} Pr^{1/3} \tag{3}$$

where D_i is the tube inner diameter, k is the thermal conductivity of hot water, Nu_i, Re and Pr are the tube-side Nusselt, Reynolds, and Prandtl numbers, respectively. The shell-side heat transfer coefficient (h_o) is calculated using the Donohue equation,

$$\frac{h_o D_o}{k} = Nu_o = 0.2\, Re^{0.6} Pr^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{4}$$

where D_o is the tube outer diameter, k is the thermal conductivity of cold water, Nu_o, Re, and Pr are the shell-side Nusselt, Reynolds, and Prandtl numbers, respectively. The factor $(\mu/\mu_w)^{0.14}$ involves the ratio of the bulk fluid viscosity to the viscosity of the fluid at the wall temperature. This factor is often near 1 for water and will be ignored in the current analysis. The shell-side Reynolds number in the Donohue equation is defined as

$$Re = \frac{G_{avg} . D_o}{\mu} \tag{5}$$

where μ is the viscosity, G_{avg} is the average mass flow rate per unit area which can be calculated from mass flow rate per unit cross flow area (G_c) and mass flow rate per unit parallel flow area (G_p) as follows,

$$G_{avg} = \sqrt{G_c G_p} \tag{6}$$

where $G_p = \dot{m}_s/A_p$ and $G_c = \dot{m}_s/A_c$. Here, $\dot{m}_s$ is the shell-side mass flow rate, and A_p and A_c are parallel and cross flow area. Once the tube-side and shell-side heat transfer rates are known, the $(UA)_{th}$ can be calculated as

$$\frac{1}{(UA)_{th}} = \frac{1}{h_o A_o} + \frac{ln(D_o/D_i)}{2\pi k_{wall} L N_t N_p} + \frac{1}{h_i A_i} \tag{7}$$

where A_i and A_o are inner and outer heat transfer areas, respectively, k_{wall} is the thermal conductivity of the tube material, L is the length of the tube, N_t is the number of tubes per pass, and N_p is the number of tube passes. The theoretical (predicted) heat transfer rate can be calculated as

$$\dot{Q}_{th} = (UA)_{th} \Delta T_{LM} F \tag{8}$$

where ΔT_{LM} is the log mean temperature difference (LMTD) and F is the LMTD correction factor. We compare this theoretically predicted heat transfer rate with measured heat transfer rate for cold fluid to evaluate the performance of the developed shell-and-tube heat exchanger.

2.3 Classroom Implementation and Assessment Procedure

All the students who are interested in participating in the DLM implementation signed a consent form and completed the pretest focusing on concepts related to the shell-and-tube heat exchanger. After completion of the consent form and pretest, random groups of 3-4 students were formed to complete the experiment, guided by a worksheet available on our project (Educating Diverse Undergraduate Communities with Affordable Transport Equipment) website. Then, each group was asked to complete the experimental setup by assembling all required components following the tutorial video. Once the setup was complete, each group collected the cold and hot water from the tap, which were then dyed with blue and red food color, respectively. Dyed water was used to increase the visibility of the water inside the shell-and-tube heat exchanger. After measuring the temperature at inlet beakers, students quickly started the flow for both fluids by starting the pumps simultaneously. One student recorded the flow time with a stopwatch, while others shut down the pumps simultaneously once the inlet beakers were almost empty. After that, students quickly recorded the temperature and water volumes at the outlet beakers for both fluids. Students repeated the experiments for different valve positions and various temperature differences between hot and cold fluids to observe the effect of temperature potentials and flow rates on the heat transfer rate. After data collection, students completed the in-class part of the guided worksheet which includes (i) identification of heat transfer area and flow area, (ii) identification of different types of flow inside the shell-and-tube heat exchanger, (iii) development of mathematical expression of cross flow and parallel/counter flow areas, (iv) determination of heat transfer rates, and (v) an exercise to compare the theoretical heat transfer coefficient and the measured heat transfer coefficient using theoretical correlations. After the completion of DLM experiment and the in-class part of the worksheet, the posttest was introduced focusing on similar concepts as pretest. In Fall 2023, we implemented the shell-and-tube heat exchanger in three universities, namely, the University of Central Oklahoma, Miami University, and Washington State University following the aforementioned implementation method. There was a total of 75 students from these three universities who gave their consent and completed pretest, implementation and posttest. Students also completed an assessment focused on self-reported engagement and the usefulness of various physical features of the DLM in learning heat transfer concepts. The conceptual focus of each of the pretest and posttest questions is listed in Table 1.

Table 1. 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-and-tube heat exchanger
Q2	Deduce the mathematical expression for the 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 the heat transfer rate
Q5	Quantify the shell side fluid velocity from the volume flow rate
Q6	Understand the influence of cold-water flow rate on hot water outlet temperature
Q6R	Identify the correct reason for Q6 choices

The paired sample t-test on the means is carried out to check for statistically significant differences between pretest and posttest scores. The effect size is calculated using the following formula [21]

$$ES = \frac{(M_{post} - M_{pre})}{\sqrt{\frac{SD_{post}^2 + SD_{pre}^2}{2}}} \tag{9}$$

where M_{post} and M_{pre} are average score for posttest and pretest, respectively, SD_{post} and SD_{pre} are standard deviation of posttest and pretest scores, respectively.

3. Results and Discussions

3.1 Attainment of Steady State

The method of measuring the heat transfer rate in the classroom assumes that the heat exchanger reaches steady state almost immediately. To check this assumption, temperature versus time data was collected from the instrumented shell-and-tube heat exchanger, which is shown in Fig. 2. The start of the system is marked with the pink dashed line while the attainment of steady state is marked with dotted blue line. Therefore, temperature results obtained from heat transfer experiments show that heat exchanger DLM only takes six seconds to reach a steady state. These readings confirm the accuracy of the classroom procedure for temperature measurement.

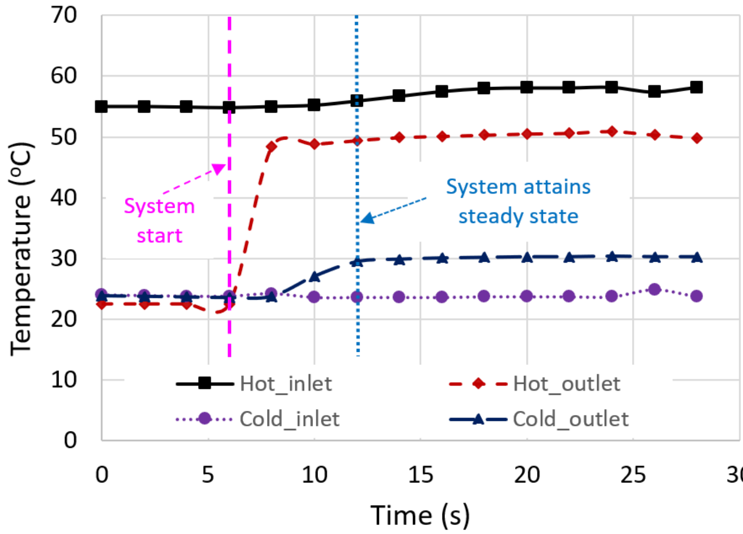

Fig. 2. Transient temperature data of hot and cold fluids obtained through thermocouples at inlet and exit beakers.

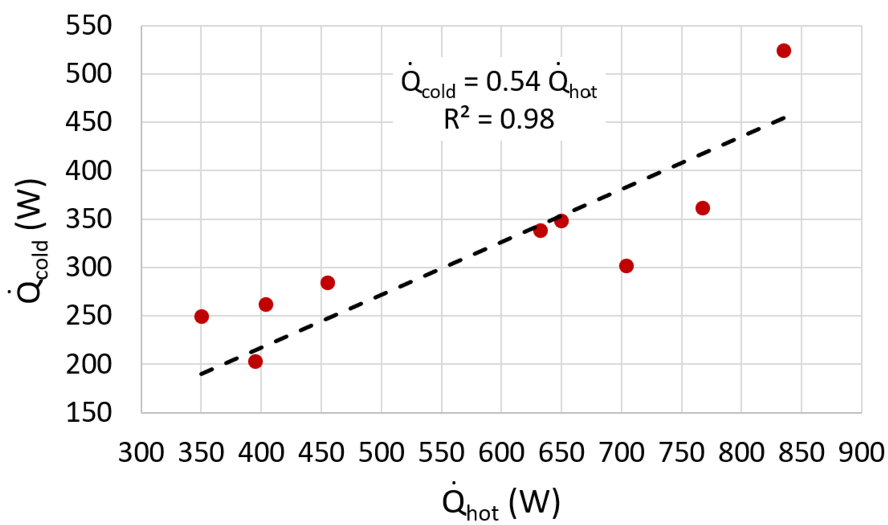

Fig. 3. Heat transfer rate of hot and cold fluids based on temperature measured at inlet and exit beakers.

Fig. 3 shows the comparison of heat transfer rates for cold and hot fluids. Theoretically, these two parameters should be equal for an insulated heat exchanger. As shown in Fig. 3, the heat transfer rates of cold and hot fluid show a linear trend, but they are not equal. Based on the experimental data, the heat transfer rate of cold fluid is only 54% of the heat transfer rate of hot fluid showing a significant amount of heat loss to the surrounding. This result is expected as the heat exchanger is not insulated, and the hot and cold reservoir beakers are open to the atmosphere. Since the cold fluid is less sensitive to heat loss/gain because of its temperature, we asked students to use heat transfer rate of cold fluid as the net heat exchange between cold and hot fluids.

Using the heat transfer rate of cold fluid as net heat flow between hot and cold fluids, next we compare our heat exchanger performance with available theory to analyze the shell-and-tube heat exchanger. The predicted heat transfer rate, $\dot{Q}_{th}$ is calculated based on Eq. 8 with data recorded at steady state from our heat exchanger. The comparison of this predicted heat transfer rate with the measured heat transfer rate, $\dot{Q}_c$ is shown in Fig 4. As expected, the predicted heat transfer rate is linearly correlated with the measured heat transfer rate. Mathematically, the predicted heat transfer rate is 92% of the measured heat transfer rate. Thus, for a small-scale device like this, we can say that the measured heat transfer rate is in very good agreement with the predicted heat transfer rate calculated based on the theory. Therefore, we can confidently use these devices in undergraduate classrooms to teach heat transfer phenomena between two fluids occurring in a shell-and-tube heat exchanger in an industrial setting.

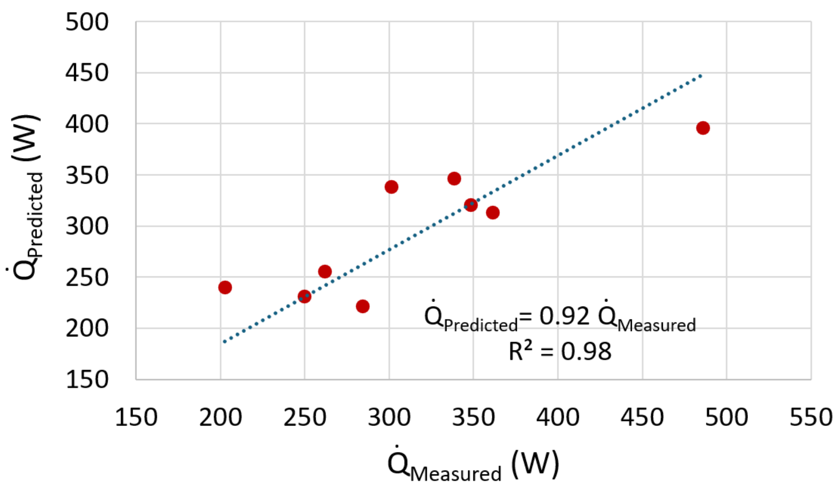

Fig. 4. Comparison of measured and predicted heat transfer rates.

As mentioned in the classroom implementation procedure section, in Fall 2023, we implemented shell and tube heat exchangers in three universities with 75 students in total. The combined average scores from the three implementations for each question are presented in Fig. 5. Different levels of statistical significance from the t-test are indicated in addition to the effect sizes.

Due to the complex structure of a shell-and-tube heat exchanger, different types of flow such as parallel, counter, and cross flow can take place in a shell-and-tube heat exchanger at different locations. Q1 measures students' understanding level of these flow types. As shown by the pre- and posttest scores, students' understanding level for this question has increased by greater than 5% with a small effect size. This indicates that the see-through nature of the DLM helps students visualize the flow pattern occurring inside the shell-and-tube heat exchanger. In Q2, students were asked to find the mathematical expression for the heat transfer area to calculate the heat transfer rate using Eq. 8. Again, the see-through nature of the DLM helps to realize the heat transfer areas for shell and tube sides which eventually leads to better comprehension of the heat transfer area as indicated by the comparison of pretest and posttest scores. In Q3, students were asked to evaluate the effect of a larger number of baffles on the heat transfer rate. As indicated by the pretest and posttest scores for Q3 in Fig. 5, there is significant improvement (p-value < 0.01) with moderate effect size (ES > 0.5) in understanding level after the implementation of shell-and-tube DLM. The understanding of the effect of a higher number of baffles on heat transfer rate requires making the connection between several ideas. By observing the DLM, the student gathers the idea that if flow rate remains constant, an increased number of baffles would increase the shell-side fluid velocity, which would increase the shell side Reynolds number, leading to a higher heat transfer rate. In Q4, students were asked about the effect of the inlet temperatures of the cold and hot fluids on the heat transfer rate. This concept was addressed by experimenting with three different inlet conditions; therefore, we should expect an improvement in performance after the DLM activity. The assessment result is in line with our expectation as it shows a significant improvement (p-value = 0.065) from pre- to posttest by ~13% with a small effect size.

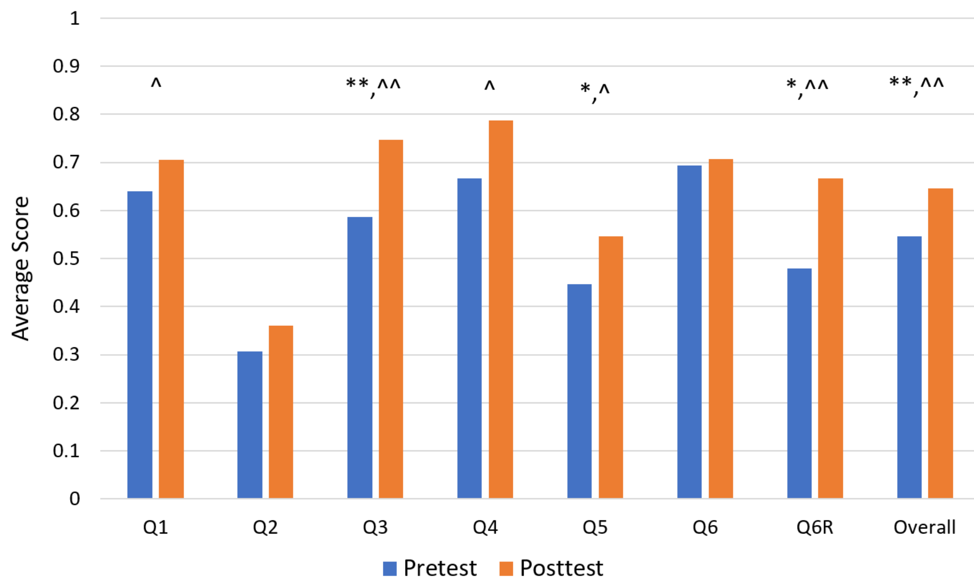

Fig. 5. Comparison of pretest and posttest scores with statistical analysis (N = 75). '*' means p values between 0.05 and 0.01, '**" means p-value < 0.01. '^' means effect size between 0.2 and 0.5, '^^' means effect size between 0.5 and 0.8.

In Q5, we asked students to identify the expression for the area required to quantify the shell-side fluid velocity from the volumetric flow rate. This concept was addressed by the DLM implementation exercise, the take-home part of the worksheet; however, most of the time, the take-home part was completed after the posttest. The result is favorable as it shows a significant increase (p-value = 0.05) in understanding level with a small effect size (ES = 0.44). In Q6, we asked students to analyze the influence of cold-water flow rate on hot-water outlet temperature. We demonstrated this concept during the DLM implementation by manipulating the cold-water flow rate. However, students were not able to grasp the concept as shown by the results (Q6). Further study is needed to identify the root cause. Although there is little improvement in score for Q6, the implementation of DLM helps students to understand the reasoning better as discussed next. In the pretest, 52 students correctly answered Q6, and among them, 22 students provided a wrong reason for Q6R; however, in the posttest, those numbers changed to 53 and 12, respectively, showing a better understanding of the influence of cold-water flow rate on hot-water outlet temperature. These results lead to a significant improvement (p-value = 0.034) for Q6R with a moderate effect size (ES = 0.54). With improvement in all questions, overall, the DLM implementation was beneficial for the students as there is > 10% improvement with a medium effect size.

4. Motivational Outcome

In addition to pre- and post-test, we also conducted motivational survey. Participant consists of 75 students from 3 different universities in the United States. The participant responses are shown in Fig. 6 from a survey assessing the Shell & Tube Heat Exchanger DLM features listed in table 2. The plot reflects a predominantly positive evaluation of the modules' features. Notably, features facilitating the hands-on measurement of temperatures and flow rates were highly endorsed, suggesting that interactive tools are instrumental in understanding thermal concepts. Most of the participants also acknowledged that these features not only enhanced their learning outcomes but also increased their engagement with the educational content. Specifically, over half of the participants agreed or strongly agreed that each module feature contributed to their understanding of the heat exchanger's operations, from energy balances and system boundaries to the effects of temperature differences and flow patterns.

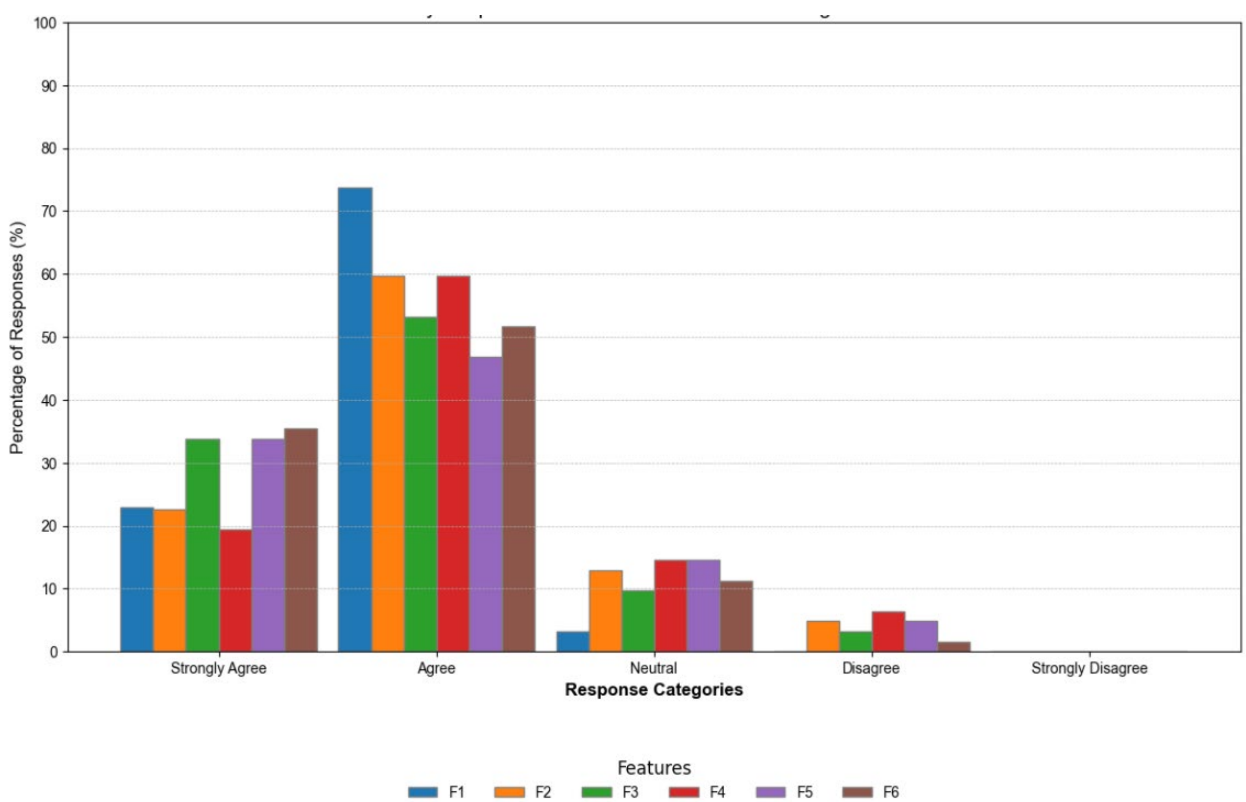

Fig. 6. Participant’s Responses to LC-DLM Features in Shell & Tube Heat Exchanger.

5. Conclusions

Hands-on learning devices are very beneficial for teaching undergraduate courses as they introduce active learning components. With that goal in mind, we developed a shell-and-tube DLM for fluid mechanics and heat transfer courses primarily aimed at mechanical and chemical engineering students. This DLM is very robust and rigid, low cost, and highly visual. Despite the small scale, the performance of the DLM can be predicted using industry-standard correlations. In addition to technical performance, the results of classroom implementations demonstrate its usefulness in teaching shell-and-tube-related concepts. The overall results suggest that the DLM can be confidently used in undergraduate classrooms in conjunction with lectures to teach heat exchange between fluids through shell-and-tube heat exchangers.

Table 2. Key features of the shell & tube DLM used during the motivational survey.

Feature of shell & tube desktop learning modules	
F1	The measuring of temperatures and flow rates helped me understand energy balances in the Shell & Tube Heat Exchanger.
F2	The measuring of temperatures and flow rates helped me understand system boundaries in the Shell & Tube Heat Exchanger.
F3	The LC-DLMs helped me to understand the effect of temperature difference of two fluid streams on heat transfer rate.
F4	Seeing the Shell & Tube geometry & baffles helped me understand the need for a temperature difference correction factor.
F5	The see-through plastic helped me understand the area for heat transfer in a shell & tube heat exchanger.
F6	The see-through plastic helped me understand the flow patterns for the two fluids in a shell & tube heat exchanger.

Acknowledgments

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