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Ultra Low-Cost Vacuum Formed Shell and Tube Heat Exchanger Learning Module*

NEGAR BEHESHTI POUR, DAVID B. THIESSEN, ROBERT F. RICHARDS and BERNARD J. VAN WIE
Washington State University, 1605 Stadium Way, Pullman WA, 99164-6515, USA.
E-mail: negar.beheshtipour@wsu.edu, thiessen@wsu.edu, heatran@wsu.edu, bvanwie@wsu.edu

Hands-on experimentation with engineering equipment is one form of active learning which is often not experienced until a senior lab course. A major hindrance to this kind of experiential learning is the cost of equipment. Our group has developed a manufacturing method to bridge the price barrier by employing 3D printing and vacuum forming. In this paper, methods are described for the development and testing of a new low-cost (overall $115), miniaturized, lightweight, see-through, easy and safe to use shell and tube heat exchanger (STHX) learning module, and corresponding results for engineering classroom implementations are highlighted. The implementation was done in one section of a two-section sophomore level material and energy balance course with 31 students and pre- and post assessment were compared to the other section with 43 students which had a standard lecture. Statistical analysis results show significant improvements for the intervention group, and no significant improvements on any questions for the control group. We think that the STHX can help students understand the practical definition of the system and system boundary and conservation of energy as long as they experience a physical system that represents the energy conservation concepts in action. Student results and feedback presented in this paper provide evidence that students can take reasonable data with this low-cost apparatus in a 50-minute class period and they will have a positive attitude toward the STHX module that will provide further motivation to learn.

Keywords: active learning; hands-on learning; collaborative learning; thermal/fluids processes; low-cost desktop learning module; transparent miniaturized shell and tube heat exchanger; vacuum forming and 3D printing; energy conservation; system boundary

1. Introduction

Many studies in engineering education have demonstrated benefits of active learning in the classroom [1–4]. Active learning is broadly defined as any instructional method that can actively engage students with course material in the learning process [3]. One form of active learning, hands-on experimentation with engineering equipment, is often not experienced until a senior lab course. This is particularly true in the case of thermal/fluids process equipment that often requires a dedicated space with connection to utilities. Some institutions have spaces dedicated to collaborative, interdisciplinary, hands-on learning with engineering equipment to supplement both introductory engineering and engineering science courses that might not otherwise have a lab component. The University of Colorado's Integrated Teaching and Learning Laboratory [5] has many modular experiments available in a dedicated space that can serve courses at different levels across the engineering disciplines. The available experiments in the area of thermal/fluids processes include heat exchangers and fluid flow experiments. In the absence of a dedicated space it is helpful to have portable, stand-alone experimental modules that can be brought into a classroom with tables. There is a growing trend for universities to have collaborative learning spaces with tables to facilitate student collaboration on projects. Such spaces can be used for hands-on activities with portable equipment. Our group at Washington State University (WSU) has developed the Desktop Learning Module (DLM) system for thermal and fluids processes [6–11] that uses instrumented miniaturized versions of industrial processes such as heat exchangers, variable-area flow measurement devices, a fluidized bed, and a flow channel with bends. These units are now commercially available from Armfield Ltd. [12] with recommended best practices through use of a university level workbook with exercises that can easily be modified to meet instructor and student needs [13].

The cost of commercial engineering lab equipment can be a barrier for some institutions and may limit the number of units that can be deployed in a class. A number of works describe low-cost, portable, hands-on experiments to help students with engineering concepts. The "Engineering of Everyday Things" [14] includes simple experiments using everyday technology to teach thermal and fluids concepts. Classroom-friendly laboratory kits have been used for hands-on learning of process control [15]. Speich et al. [16] describe the development of an "Experiential Engineering Library" in which students can check out experiments for independent work outside of class. Garrison and Garrison [17]

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describe many simple home-made fluid mechanics demonstrations. Minerick and Schulz [18] developed low-cost hands-on experiments on electrophoresis and fermentation for a freshman chemical engineering course and Minerick [18] describes a desktop heat transfer experiment for a junior-level heat transfer course. These low-cost experiments are useful for conveying important concepts, but they do not attempt to reproduce a piece of miniaturized industrial process equipment.

More recently, our group has developed a manufacturing method to bridge the price barrier by employing 3D printing and vacuum forming [19]. In this paper methods are described for the development and testing of an ultra-low-cost, miniaturized, shell and tube heat exchanger (STHX) learning module and corresponding results for engineering classroom implementations are highlighted. For the final detailed system design, we used SolidWorks, the same CAD software that many undergraduate engineering students learn to use in freshman and sophomore level courses. We believe this may also encourage students to participate in the design process and propose their own modifications of the hardware, as is done at Drexel University where undergraduate students design, prototype and demonstrate hands-on micro-fluidic heat exchangers [20]. In this paper, we present an approach that is not limited to constructing heat exchanger modules, but can also be used for making different classroom instructional tools including fluidics modules [21].

Many articles discuss persistent student misconceptions related to thermodynamic concepts such as heat versus energy, temperature versus amount of energy, rate of energy exchange versus the amount of energy and the first law of thermodynamics or energy conservation [22–27]. It has been reported that students do not learn the thermodynamic concepts properly and they have difficulty relating the principles and concepts together to solve problems rather than just plugging numbers into formulas [28]. Regarding this aspect of the paper, our research questions focus on: (1) whether a miniaturized very low-cost heat exchanger provides data that is quantitative enough to illustrate the principle of conservation of energy, the linear dependence of heat flux on temperature driving force, and the fact that heat transfer resistance is reduced by increasing one or both flow rates; and (2) whether associated hands-on activities repair common misconceptions relative to open systems energy balances. In particular, we answer the question of whether hands-on activities, where students measure temperatures and flow rates and use an energy balance to compute the heat duty of the exchanger, can help them more generally with identifying the appropriate system boundary for finding the heat duty of a simplified heat exchanger.

2. Methods

2.1 Design, modeling, and manufacturing

The availability of modern digital tools such as finite element simulation, 3D CAD software, and 3D printing of CAD designs coupled with low-cost vacuum forming equipment allows for rapid prototyping of designs. The design of an instructional module should be fairly simple for pedagogical reasons. Our goal is to design a miniaturized and see-through shell and tube heat exchanger which weighs and costs less than a textbook and is suitable for student purchase. This heat exchanger module is simple and inexpensive to construct and is made of off the shelf materials. The design of the heat exchanger needs to meet two important goals, those of having measurable temperature changes for both shell and tube sides and having turbulent flow capability within the tubes when driven by modest head pressure.

Comsol Multiphysics was used to simulate the proposed design, and SolidWorks 3D CAD software for design details. One practical design consideration was that the mold could be 3D printed in one piece. Fig. 1(a) shows one-half of the mold designed in SolidWorks. Use of the fillet tool for rounding the corners and tapering the sides was necessary for designing the mold as it facilitates removing the vacuum formed plastic from the mold. Rapid prototyping allowed several design iterations mainly related to constructability.

Fig. 1(b) shows one half of the 3D printed mold manufactured with a uPrint SE Plus3D printer (Stratasys, Eden Prairie, MN) using ABSplus polymer. For vacuum forming, we used a Centroform EZFORM® SV 1217 Tabletop Vacuum Forming Machine and a shop vacuum. Fig. 1(c) represents one half of the vacuum formed shell (0.02-inch thick PETG plastic, WidgetWorks, NY). Baffles were cut out of 1/8-inch thick PETG sheets (McMaster-Carr) with a water jet. The tubes were 304 stainless steel (McMaster-Carr) which were cut to length by hand with a tubing cutter. Fig. 1(d) shows the six baffles passed through the four tubes and set inside the shell. A two-part Acrylic adhesive (SCIGRIP 40) was used for assembling. It is very critical to seal around the tubes at the ends because any mixing between shell fluid and tube fluid leads to system inefficiency. For connecting the silicone tubing to the heat exchanger module, we cemented 1.5-inch pieces of 3/8-inch OD PETG tubing at the inlets and outlets. Table 1 gives the specifications of the heat exchanger. The dimensions were selected in such a way that allows us to make optimal use of materials

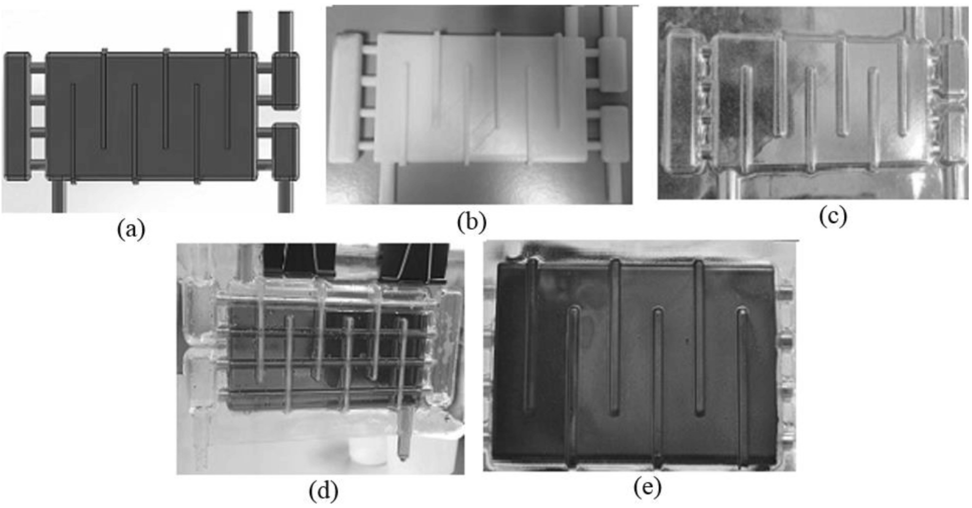


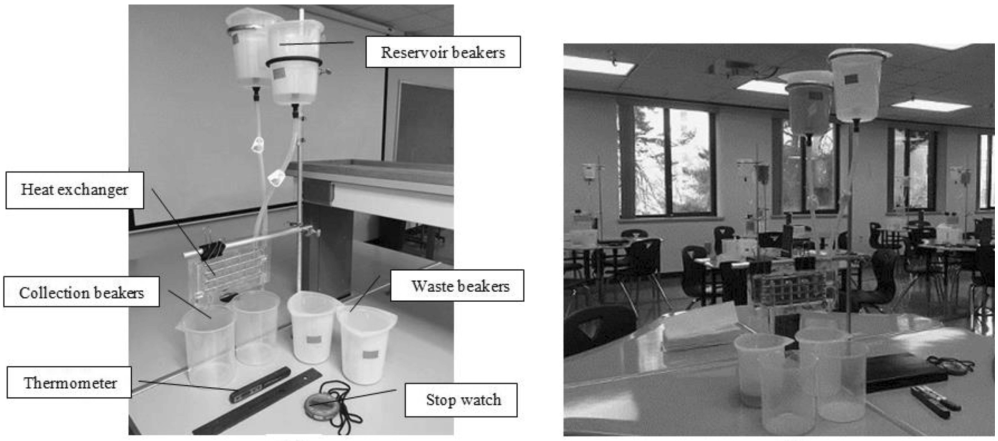
Fig. 1. Manufacturing steps for the shell and tube heat exchanger. (a) SolidWorks CAD design, (b) 3D printed mold. (c) Vacuum formed half-shell. (d) Close-up of the module in use after assembling the baffles and tubes. We made the shell side water green using food color to make it more intuitive. (e) The back side of the STHX was painted black and then TLC applied; as the temperature of the fluid in the shell side rises, the TLC changes its color; no color appears (black) at cooler inlet temperatures below 25°C which transitions to red at 25°C, then green and blue at higher respective temperatures up to 30°C.

while providing measurable temperature changes and flow rates in the transition or turbulent regime on the tube side for obtaining an adequate heat transfer coefficient.

Many factors can reduce a student's attention during an experiment including the complexity of the apparatus. For the classroom set up, to reduce cost and complexity, we exploit hydrostatic head to drive flow in the experiment. Two low-cost reservoirs per setup were made from disposable 1-liter beakers by drilling a hole in the bottom and installing a hose barb fitting. Flexible silicone tubing is used to connect these reservoirs to the heat exchanger inlets and allows for raising or lowering of the beakers to change the hydrostatic head and flow rates. Flow can be turned on or off by a pinch clamp on each tube. Two ring supports mounted on a ring stand are used for holding the beakers, and the STHX is mounted to an extension bar with Skilcraft binder clips. Four graduated effluent beakers and a stopwatch are needed for measuring flow rates. A handheld digital thermometer (COMARK, Beaverton, OR), which equilibrates within 5 seconds, is used for reading the inlet and outlet temperatures. Hot and cold water from the faucet may be used and are added to the respective feed reservoirs. Food coloring may be added to one or both reservoir beakers for students to better visualize the flow pattern on the shell or tube sides. Fig. 2 shows the final set up prepared in a studio-type lab for student use.

Table 1. Specifications for STHX

Tube Side Characteristics	**Shell Side Characteristics**
Number of tubes, $N_t = 4$	*Number of baffles,* $n_b = 6$
Tube passes, $n_p = 2$	*Shell passes,* $n_s = 1$
Tubes per pass, $n_t = 2$	*Number of tubes in baffle window = 1*
Tube type, $\frac{1}{4}$*'' BWG No. 20*	*Shell width,* $W_s = 12.7$ *mm (0.5 in)*
Tube length, $L = 160$ *mm (6.3 in)*	*Shell height,* $h_s = 80$ *mm (3.15 in)*
Tube wall thickness, $t_w = 0.899$ *mm (0.0354 in)*	*Baffle window height,* $h_{bw} = 20$ *mm (0.787 in)*
Tube dia., $D_o = 6.35$ *mm (0.25 in)* $D_i = 4.572$ *mm (0.18 in)*	*Baffle spacing,* $B = 18$ *mm (0.709 in)* *Baffle pitch,* $P_b = 21$ *mm (0.827 in)*
Vertical tube spacing, $c' = 20$ *mm (0.787 in)* *No horizontal tube pitch*	*Baffle window fraction,* $f_B = 0.25$
Tube material: stainless steel 304 $k_{Steel} = 16$ *W/mK (9.4 Btu/ft·h·°F)*	*Baffle thickness = 3.55 mm (1/8 in)*



(a) (b)

Fig. 2. (a) One heat exchanger setup with reservoirs, collection and waste beakers, hand-held thermometer and a stop watch. (b) Multiple heat exchanger units set up in a studio-learning environment.

The more intuitive a learning module is, the easier students can grasp what is going on. Transparent PETG plastic sheets used in vacuum forming for the shell of the heat exchanger allow students to visualize how the process works. Enhancements to the basic low-cost heat exchanger can further improve the visual experience and allow for more advanced studies. To demonstrate these possibilities, one heat exchanger was prepared with embedded thermocouples at the inlets and outlets and one side of the shell was coated with a thermochromic liquid crystal (TLC) layer to visually show the temperature gradient throughout the shell of the exchanger. This instrumented heat exchanger also allows us to check the speed of steady-state attainment and to check how well temperature measurements in the inlet reservoir beakers and outlet collection beakers correspond to the actual inlet and outlet temperatures at steady state. Small-diameter (30-gauge), fast-responding, type-K thermocouples (Omega Engineering) were sealed into holes in the sides of the inlet and outlet tubes so that the thermocouple bead is approximately centered in the tubing. These four thermocouples in addition to four others inserted in the inlet and outlet beakers were connected to a computer with a USB data acquisition interface (Measurement Computing). To apply the TLC coating, a black spray paint base was followed by the air brush application of several coats of a liquid crystal solution, SPN100 Chiral Nematic Sprayable Thermochromic Liquid Crystal (Hallcrest). The TLC is a temperature indicator that changes its color as the temperature varies, in this case in the 25–30°C range with three main reflection colors: red, green, and blue. As the temperature rises, the TLC changes its color from red to green and blue with mixed shades to show a smooth gradient in temperature. Below 25°C or above 30°C only the black base paint can be seen so for students to see the temperature profile the stream temperatures needed to be in the 25–30°C range for these types of experiments. Fig. 1(e) shows the temperature increase for the shell side fluid. The water enters the shell from the top-left corner and the TLC first shows black as the water temperature is less than 25°C but as it passes the hot tubes it gets warmer, so the TLC changes its color to red, green, and blue, respectively.

These kinds of learning modules are also amenable to extend to student-led design and construction as many universities have a maker space facility. Students could propose their own modifications, trying different prototypes, experimenting with different baffle spacing, differing numbers of tube passes, etc.

2.2 Classroom experimental procedure

Classroom activities with the heat exchangers can involve both qualitative observations and quantitative measurements. For the qualitative section, as the shell side is made of transparent plastic, students can look through the heat exchanger, and see the structure of the heat exchanger, the tubes, the baffles, the lateral surface of the tubes and the area available for cross flow and parallel flow. Students usually have an abstract picture of the design of heat exchangers as detailed photos and cutaways to show the internal anatomy are sparsely used in textbooks, and 2D diagrams do not adequately convey the 3D geometry. However, by employing the transparent plastic vacuum formed STHX created in this work, students can be asked to draw flow patterns directly on the plastic shell of the heat exchanger for both the shell and tube sides using two different colors of dry erase markers before and after running an experiment. This allows them to actively engage in the learning process, especially as teams discuss hypothetical flow patterns and then correct any misconceptions. In order to correct a possible misconception that the hot and cold streams mix in a heat exchanger and to make the apparatus even more intuitive, we made the shell side water colored using a safe green food coloring, so students can see the flow pattern better, and as they see no color change for the tube side liquid at the end of the run, they will conclude that there is no mixing in the heat exchanger. Feeling the temperatures by hand before and after running is another qualitative observation that students can make with this module. For the quantitative observations, students can be asked to calculate the mass flow rates and heat duties from their in-class measurements as a homework assignment.

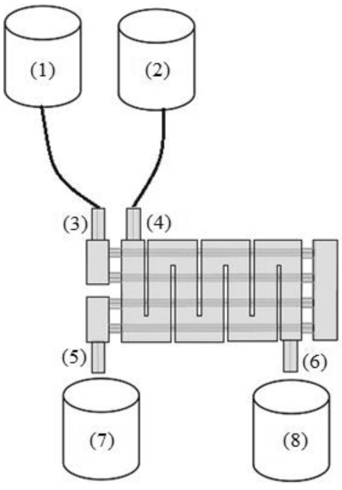
2.3 Method for testing heat exchanger performance and accuracy of classroom procedure

To verify the heat exchanger performance and the accuracy of the classroom procedure we collected data in two different approaches simultaneously, both in the way that students are supposed to run the experiment, with thermometers and volumetric readings from graduated collection beakers, and in a more accurate way with K-type thermocouples, at the 8 points indicated in Fig. 3, linked to a Measurement Computing USB interface reader and a scale to measure the collected liquid. The hose pinch clamps were closed and the tube-side and shell-side inlet reservoir beakers were filled with hot and cold tap water, respectively. Computer logging of the temperatures in the inlet reservoir beakers, the outlet collection beakers and at the heat exchanger inlets and outlets was started, then the temperatures in the inlet beakers were measured one at a time with the hand-held thermocouple and recorded. Next, both pinch clamps were opened simultaneously. For the first five seconds the water was allowed to flow into waste beakers after which the outlet collection beakers with thermocouples were slid into place and flow timing was started with a stopwatch. After approximately 20 seconds the waste beakers were slid back in place of the collection beakers (before the supply beakers ran empty). The temperatures in the collection beakers were immediately measured by the handheld thermocouple and recorded along with the volumes measured from the beaker graduations and the water masses determined by weighing and subtraction of dry beaker weights.

2.4 Implementation and assessment of learning

The DLM was implemented in one section of a two-section sophomore level material and energy balance course, during the fall 2015 semester. A control group with 43 students had a standard lecture while an experimental group with 31 students had a hands-on session with the low-cost heat exchanger module. On the day that the students were taught energy balance concepts, the control class was taught through lecture while the students in the experimental class were taught the same concepts through interactive exercises and discussion, working in teams of three or four and using the low-cost heat exchanger module as prescribed by a guided inquiry worksheet. We did the posttest two weeks after the pre-test and four days after the implementation to minimize the effect of other factors, such as doing homework and studying for quizzes, in the posttest results. The materials, homework, pre- and posttest, and exams for both classes were the same, and students had 15 minutes to do each of the pre- and posttests.

Measuring the effectiveness of active learning is not easy as active learning affects more than one learning outcome such as knowledge, relevant skills, student attitudes, etc., and many of these outcomes



Thermocouples

(1) hot supply beaker
(2) cold supply beaker
(3) hot inlet
(4) cold inlet
(5) hot outlet
(6) cold outlet
(7) hot collection beaker
(8) cold collection beaker

Fig. 3. Schematic of the simple heat exchanger with 8 mounted thermocouples.

Table 2. Descriptions of pre- and posttest questions

Question	Description
Question 1 pre- and posttest	Picking the right system and drawing the system boundary to calculate the rate of heat transfer from hot to cold side fluids.
Question 2 pre-test	Between hot and cold *water* with identical flow rates which will experience the largest temperature change in a cross-flow heat exchanger and why?
Question 2 posttest	Between hot water and cold *air* flow with identical mass flow rate, which experiences the larger temperature change in a cross-flow heat exchanger and why?
Question 3 pre-test	Justifying why a large bucket of boiling water poured over a deep layer of snow will melt more of the snow than a small bucket of boiling water.
Question 3 posttest	Between hot and cold water with different mass flow rates which experiences the larger temperature change in a counter-flow heat exchanger and why?
Question 4-1 pre-and posttest	Selecting which choice ultimately melts more ice: (1) using one metal block at 200°C or (2) using two metal blocks identical to the first option, but at 100°C.
Question 4-2 pre-and posttest	Justify the answer for part 4-1.

are difficult to measure [1]. Prince suggests looking at a broad range of learning outcomes and interpreting data carefully, considering the statistical measurements like effect sizes and learning gains. Taking the literature suggestions into account we designed a pre- and posttest, given to both the control and the experimental groups. The pre-test was given the week before the instructors taught about energy balance to measure students' performance on the questions based on their primary knowledge about energy balances.

We had four questions in each of the pre- and posttests as outlined in Table 2. The first and last questions were the same on the pre- and posttests, and the second and the third questions were slightly different, but focusing on the same concepts. We designed the first question to focus on the system boundary concept. This was presented to both groups, with the control group seeing the ideas in PowerPoint lecture slides and the intervention group learning the concepts by discussing the system with each other while guided by prompts from the worksheet (see Appendix). Students were asked to pick the right system in the schematic shown in Fig. 4 below and draw the system boundary considered when calculating the rate of heat transfer from hot to cold side fluids.

We took the remaining questions from the AIChE Concept Warehouse [29] which also has the Heat and Energy Concept Inventory (HECI) questions [23]. HECI includes assessment of four specific concept areas related to heat transfer. We took advantage of this inventory and selected two questions from concept area number three, "Rate vs. Amount", because students often confuse the total amount of thermal energy transferred with the rate at which it gets transferred. This also gives us the ability to compare our results with the data that have been collected through the inventory from ten different universities and colleges. On the posttest, Question 2 was a slightly modified version of the second question on the pre-test, formulated by changing "cold water" to "cold air" for which the heat capacity differs and therefore changes the answer to the question. This was done to test whether students understand the concepts rather than just remembering an answer from the pre-test. Question 3 on the pre-test was also from the HECI (ID: 2378). On the posttest, Question 2 (ID: 1656) and Question 3 (ID: 1657) were selected from the AIChE Warehouse. Question 4 (ID: 2366) on the pre-test was duplicated on the posttest and is a two-part question chosen from HECI.

Finally, we did a question-by-question statistical analysis of covariance (ANCOVA) of the scores for the pre- and posttests contrasting improvements for the two groups. Our goals were to see if there were any differences between the two groups initially, and to determine if improvements were significant for either group on each particular question by control-

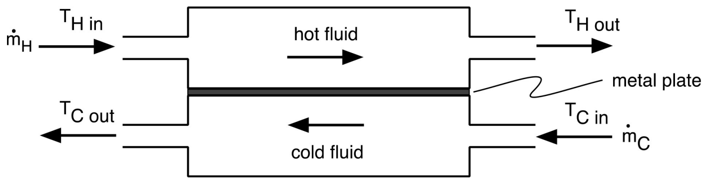


Fig. 4. The schematic of a simple heat exchanger used in the first question.

ling for different initial starting points for each group. Two effect sizes were calculated, Cohen's d which is the difference between the means divided by the pooled standard deviation, and the odds ratio which is the fraction of students answering a question correctly divided by the fraction failing to answer correctly. An analysis of significant and non-significant findings was done first to determine if our hypothesis, learning with a miniaturized very visual working heat exchanger system will assist with conceptual understanding of system boundaries, is supported by the study. Second, we assessed the impact on learning and elimination of misconceptions surrounding the "Rate versus Amount" issue in heat transfer.

3. Results

3.1 *Accuracy of basic classroom procedure*

The instrumented heat exchanger was used to test the speed of attaining steady-state temperatures and to confirm the accuracy of the classroom procedure for temperature measurement. In the classroom procedure, the heat exchanger inlet and outlet temperatures are estimated by measuring temperatures in the inlet reservoir beakers just prior to starting the flow and subsequently measuring temperatures in the outlet collection beakers. Figs. 6 and 7 present thermocouple data for the hot and cold side respectively. It can be seen that the hot reservoir and the inlet are nearly the same but there

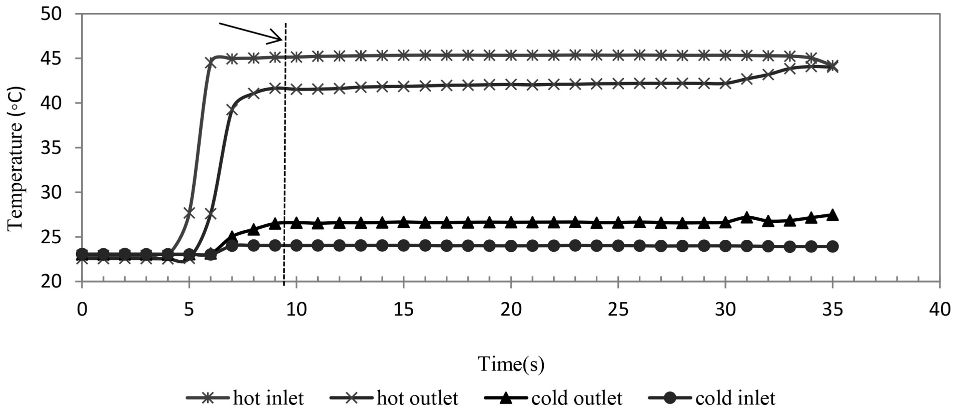


Fig. 5. Thermocouple data plotted for inlet and outlet temperatures of both hot and cold streams. The flow was started after four seconds and before that, all the thermocouples showed the room temperature. The arrow shows that after about five seconds the miniaturized module reaches steady-state. The cold and hot reservoirs run out of water after about 25 and 30 seconds, respectively. Because the cold side runs out of water sooner than the hot side, the temperature of the hot outlet rises to the hot inlet temperature.

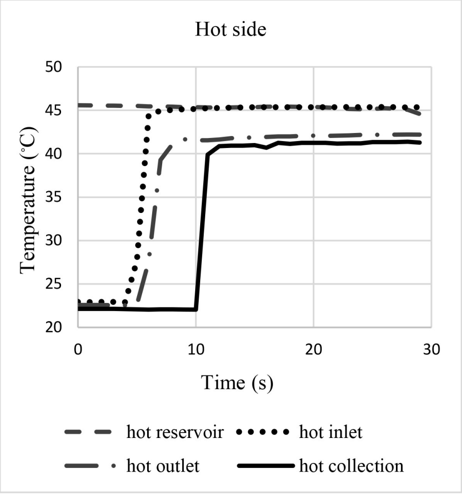


Fig. 6. Thermocouple data for the hot side. Data show that the hot reservoir and the inlet are nearly the same, but there is a temperature difference of about 1°C between the outlet and collection beaker which is due to rapid evaporative heat loss from the stream flowing into the beaker.

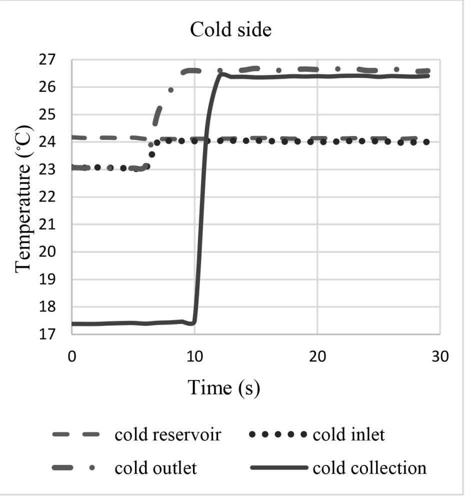


Fig. 7. Thermocouple data for the cold side. As the figure shows for the cold side there is a very little temperature difference between the cold reservoir and cold inlet or between the cold outlet and cold collection beaker so that cold-side beaker temperatures will give more accurate heat duties than hot side temperatures.

Table 3. Comparing the heat duties and mass flow rates calculated for both hot and cold streams comparing an accurate thermocouple and scale instrumented method to a less accurate thermometer and graduated beaker measurement method

Accurate Measurements‡			**Hand Measurements†**		
time = 19.8 s	*Hot side*	*Cold side*	*time = 19.8 s*	*Hot side*	*Cold side*
m	525.4 g	722.3 g	V	530 ml	737 ml
$\dot{m}$	$0.026\,\frac{kg}{s}$	$0.036\,\frac{kg}{s}$	$\dot{m}$	$0.027\,\frac{kg}{s}$	$0.037\,\frac{kg}{s}$
ΔT	3.59 °C	2.42 °C	ΔT	4.4 °C	2.4 °C
$\dot{Q}$	398 W	368 W	$\dot{Q}$	492 W	373 W

‡ based on masses measured on a scale and thermocouple readings.
† based on volumes in graduated beakers and thermometer readings.

is a temperature difference of about 1 °C between the outlet and collection beaker which is due to rapid evaporative heat loss from the stream flowing into the beaker while for the cold side there is very little temperature difference between the cold reservoir and cold inlet or between the cold outlet and cold collection beaker. So, for the classroom procedure, it is more accurate to measure the heat duty based on cold side data. Fig. 5 shows that the module attains steady-state temperatures in about five seconds after flow is started (at the 4-second mark). The classroom procedure for measuring flow rate by volume measurement with a low-cost plastic beaker is also checked against a more accurate technique that involves weighing the collected liquid. Table 3 compares the heat duties and mass flow rates calculated in both ways. The mass flow rates and the ΔT of the cold side are in good agreement. Hence, the heat duties measured in the more accurate way and by the classroom procedure are close to each other for the cold side while for the hot side the classroom procedure overestimates the heat duty by about 100 W which is attributed to heat loss from the hot stream flowing into the collection beaker.

3.2 Demonstration of transport measurements

To illustrate the use of this low-cost heat exchanger to make heat transfer coefficient measurements as a function of flow rate we made a set of careful measurements with a handheld thermometer and varying tube-side flow rate by changing the height of the tube-side reservoir beaker. We compared the experimentally measured overall heat transfer coefficient to that predicted from standard correlations. For the experimental measurement, we calculated the overall heat transfer coefficient using Equation 1 based on a shell side energy balance and outlet and inlet temperature data as with the cold side we have less heat lost as the fluid exits and is collected and the data are more accurate as illustrated in the previous section.

$$U_o = \frac{\dot{Q}}{A_o \Delta T_{LM} F} = \frac{\dot{m}_c C_p (T_{c_{out}} - T_{c_{in}})}{A_o \Delta T_{LM} F} \tag{1}$$

Where:

U_o = overall heat transfer coefficient $\left[\frac{W}{m^2 K}\right]$
$\dot{Q}$ = heat duty $[W]$
A_o = outer heat transfer area $[m^2]$
$\dot{m}_c$= cold side mass flow rate $\left[\frac{kg}{s}\right]$
C_p= specific heat capacity $\left[\frac{J}{kg\ K}\right]$
ΔT_{LM}= Log mean temperature difference $[K]$ $(LMTD)$
F= $LMTD$ correction factor
T_c= cold side temperature $[K]$

To compare with theoretical predictions the tube-side heat-transfer coefficient, h_i was calculated using the Nusselt correlation for the transition regime [30], since Reynold's numbers (Re) were in the 4,000–7,500 range, the coefficient for the shell-side h_o was predicted using the Donohue equation, and the overall heat transfer coefficient calculated by taking the inverse of the sum of the inside, outside and wall resistances using the following relationship where D_i and D_o are the inner and outer diameter and h_i and h_o are the inner and outer heat transfer coefficients, respectively.

$$U_o = \frac{1}{\frac{D_o}{D_i}\frac{1}{h_i} + \frac{1}{h_o} + \frac{D_o}{2K_w}\ln\left(\frac{D_o}{D_i}\right)} \tag{2}$$

Results show close quantitative agreement with the correlation as illustrated in Fig. 8 with an average agreement of 10% between experimental and predicted values. This suggests that the units can be used in more advanced heat transfer courses. In ongoing studies, the low-cost heat exchangers are being used in a junior-level chemical engineering

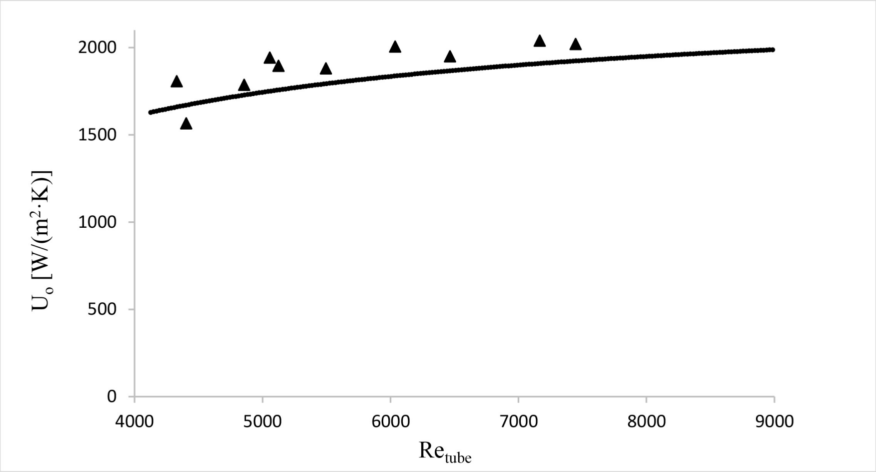


Fig. 8. The overall heat transfer coefficient versus Reynolds number of the tube side based on experimental measurements (symbols) and the Nusselt number correlation (line).

fluid mechanics and heat transfer course and a senior mechanical engineering thermal systems design course.

3.3 *Student results*

In this section, we present student data taken from the low-cost shell and tube heat exchanger during the classroom implementation. Fig. 9 represents the data taken by nine groups of students (teams of three or four). Each data series in this figure belongs to one group. Each group was asked to do four runs, reusing the water. Therefore, they can see how the heat duty decreases as the temperature difference decreases. One group refreshed water for each run mistakenly so their data has not been shown in Figs. 9 and 10.

For an ideal insulated system, the heat transferring from the hot side is equal to the heat transferred to the cold side, so the heat loss to the surroundings would be zero. If we plot the rate of heat transferring to the cold side versus the rate of heat transferring from the hot side one expects to see a slope of 1, while in reality we work with non-ideal systems which have imperfections, and the slope of 0.75 indicates 25% of the heat lost from the hot stream is unaccounted for. This is due to two systematic phenomena: (1) unaccounted heat loss takes place as the system is not perfectly insulated from the environment and heat losses occur through the plastic tubing, inlet/outlet manifold and 180° turn manifold for the hot side fluid through natural convection and then there is the heating required

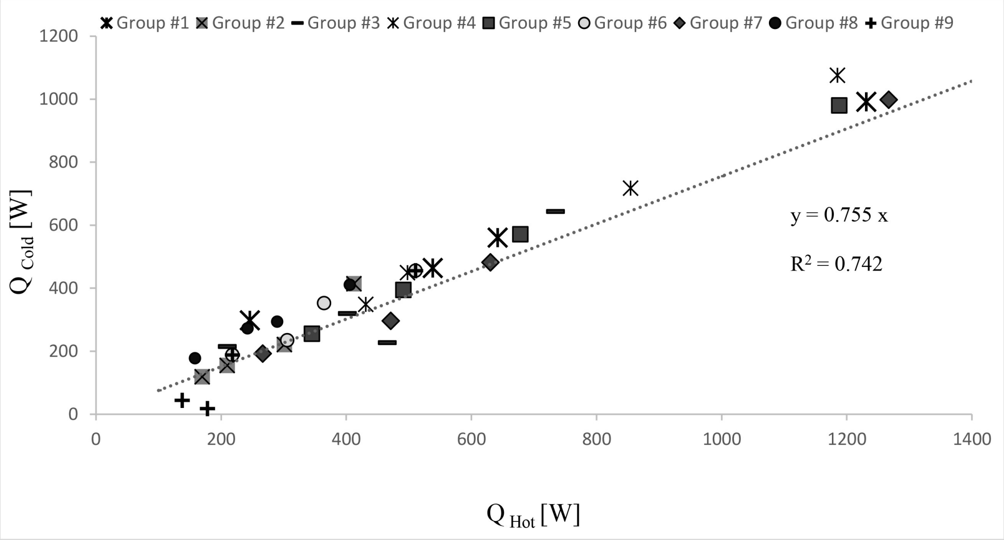


Fig. 9. Heat rate of cold side vs. heat rate of hot side. The heat rates are not equal as the system is not insulated and there are heat losses due to evaporation especially for the hot fluid as it exits the STHX.

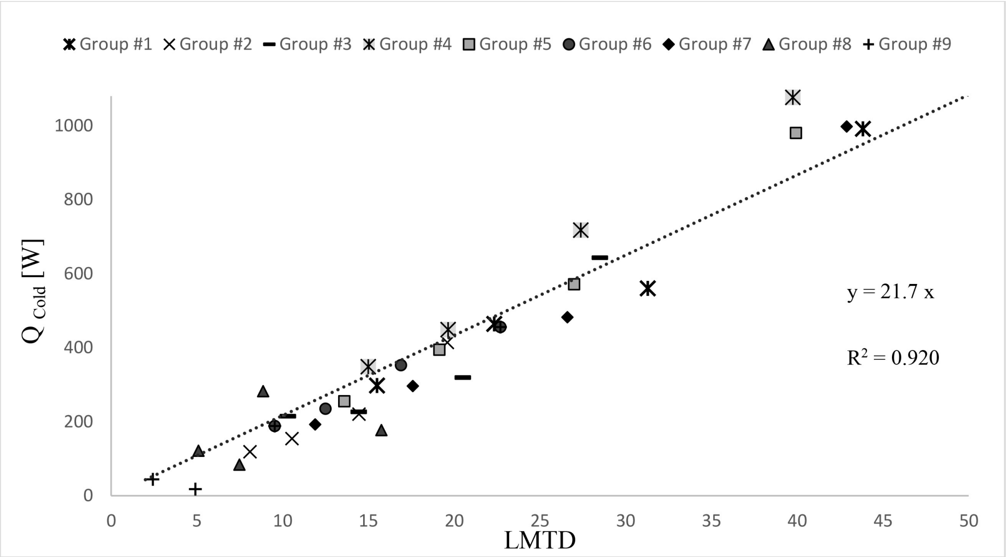


Fig. 10. Measured heat duty versus logarithmic mean temperature difference based on student group data for four trials reusing the water. The linear relationship between heat duty and log mean temperature difference shows that students can take reasonable data using the STHX apparatus.

for the mass in the tubes and plastic to bring them up to temperatures midway between that of the hot and cold fluids; and (2) evaporative heat loss from the hot fluid as it exits the tube side of the exchanger and enters the waste reservoir. Taking these phenomena into account will provide excellent opportunities for upper division students in heat transfer courses who are learning about these phenomena in their coursework. Fig. 10 shows the expected linear trend for the heat duty calculated from an energy balance relationship, $\dot{m}_c C_p (T_{c_{out}} - T_{c_{in}})$, as a function of the log mean temperature driving force between the hot and cold fluids. These data offer support for use of the low cost shell and tube heat exchanger in the classroom. An instructor can display collective student data to the class after an in-class implementation. In upper division courses add an exercise for students to compare the data to correlated heat exchange values based on the LMTD, the LMTD correction factor, and an overall heat transfer coefficient based on the sum of the resistances to heat transfer from individual heat transfer coefficient correlations and a calculation for the resistance through the metal.

3.4 Assessment results

Before discussing results from the pre- and posttests, part of our study was to design a question to meet a persisting misconception related to the system boundary. In an early test implementation in a previous offering of the same course (summer 2015), it was noticed that students often are confused about selecting the correct system for analyzing the heat duty. We therefore developed the simplified system schematic shown in Fig. 4 and asked students to draw the system boundary around the system needed to analyze the rate of heat transfer. Interestingly, we saw the same misconceptions on the pre-test for both sections as were seen in the summer course. Fig. 11 shows incorrect system boundaries selected by students. Many chose the whole system as the system boundary, some the separating plate between the cold and hot side, and a number selected the hot inlet/cold outlet combination while others the hot outlet/cold inlet combination. The remainder correctly chose the cold or the hot side fluid as the system for analysis. This clearly shows that students have difficulty appreciating system definition and system boundary concepts. What is interesting, however, and the subject of ensuing discussion, is whether one form of learning about the system has advantages over the other in terms of repairing these misconceptions.

An overview of the pre- and posttests, graded anonymously by the first author, give results shown in the bar charts in Figs. 12 and 13 allowing a quick visual comparison of the percentage of students answering correctly, while statistical analyses for the ANCOVA comparison between groups are presented in Table 4. Statistical analysis between pre- and posttests show significant improvements for the intervention group only on Questions 1 and 4-1; and no significant improvements on any questions for the control group. Specifically, student performance for the intervention group shows significant improvement on Question 1 from an average score of 0.35, out of 1 maximum, to 0.65 ($p = 0.008$) and for Question 4-1 from 0.26 to 0.55 ($p = 0.044$). By contrast for the control group, there is an

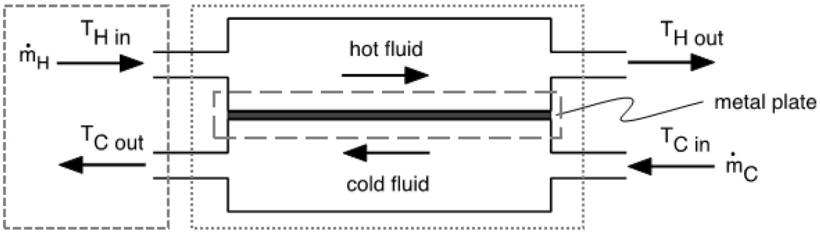


Fig. 11. Schematic of a simple heat exchanger used in the first question asking students to draw a system boundary needed to analyze the rate of heat transfer from the hot to cold fluids and the incorrect system boundaries with each category of answer indicated by a different dashed line type.

increase from 0.33 to 0.35 for both questions, but neither increase is statistically significant. The control section result for Question 4 is interesting because it is consistent with results from Prince's study [23] where use of the very same HECI question in a standard lecture class shows that students had difficulty analyzing the system in this question with only 14.2% and 23.1% of them getting it right before and after instruction, respectively. On Question 2 both groups' performances appear to decline, though not with statistical significance. This apparent decline, and more importantly lack of improvement, may be because the question is very similar between the pre- and posttest except that the cold stream was changed from air on the pre-test to water on the posttest. One explanation is that students did not pay enough attention to the question and thought this question was the same as the pre-test question remembering which answer was correct on the pre-test and transferring that answer to the posttest. This cannot be known for certain without asking students to justify their answer, something that should be considered for future implementations. While there was an apparent increase in the correct responses for Question 3 in both sections, after controlling for pre-test scores, there is no significant difference in the improvement between the sections.

Of further interest is the effect size and odds ratio for the questions as these put into perspective the gains resulting from the intervention. The odds ratio used here is the ratio of number of students with the correct response to number with the incorrect response. For example, for Question 1 in the control section, the odds ratio goes from 0.48 to 0.54 while for the experimental group it went from 0.55 to 1.82. The net change from pre- to posttest for the control section on this question was only one additional student getting the correct answer out of 43 while for the experimental section it was 9 out of 31 that answered correctly. We see a similar situation on Question 4-1 where the net change from pre- to posttest in the control section was only one student while nine students corrected their wrong pre-test answers in the experimental section. Table 5 summarizes the odds ratio for the control and experimental groups for each question.

The collective data for Questions 1 and 4 suggest that, as hypothesized, the learning module and associated activities guided by a worksheet have advantages. For Question 1 the use of a guided inquiry that directly correlates to the module offers significant benefit over a multi-media PowerPoint lecture even when the instructor specifically pointed out the solution in the lecture. In essence, we think that the DLM can help students understand

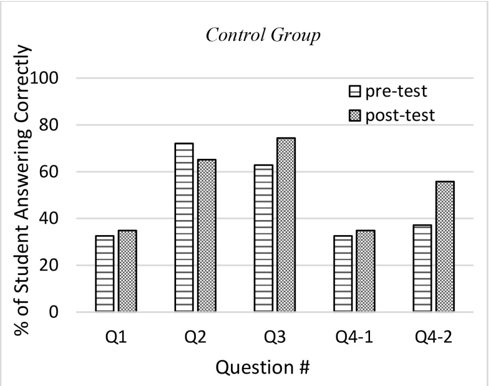


Fig. 12. Pre- and posttest results for the control group.

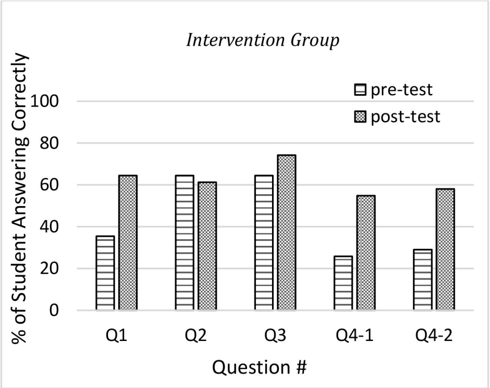


Fig. 13. Pre- and posttest results for the intervention group.

Table 4. Data analysis of pre-test and posttest

Question	Pre-test Means (Std. Deviation)		Posttest Means (Std. Deviation)		F	P-value
	Control	Intervention	Control	Intervention		
1	0.33 (0.474)	0.36 (0.486)	0.35 (0.482)	0.65 (0.486)	7.42	0.008*
2	0.72 (0.454)	0.65 (0.486)	0.65 (0.482)	0.61 (0.495)	0.028	0.867
3	0.63 (0.489)	0.65 (0.486)	0.74 (0.441)	0.74 (0.445)	0.003	0.959
4-1	0.33 (0.474)	0.26 (0.445)	0.35 (0.482)	0.55 (0.506)	4.20	0.044*
4-2	0.37 (0.489)	0.29 (0.461)	0.56 (0.502)	0.58 (0.502)	0.419	0.519

Table 5. Changes in odds ratio (odds of passing/odds of failing) in pre- and posttests and the effect size comparing the two sections. † indicates large increases in intervention section odds ratios compared to the control section; * indicates medium effect sizes with the intervention section outpacing the control section

Question	Pre-test odds ratio		Posttest odds ratio		Effect size
	Control	Intervention	Control	Intervention	
1	0.48	0.55	0.54	1.82†	0.56*
2	2.58	1.82	1.87	1.58	0.06
3	1.69	1.82	2.91	2.88	–0.04
4-1	0.49	0.35	0.54	1.21†	0.57*
4-2	0.59	0.41	1.26	1.38	0.21

the practical definition of the system and system boundary, targeted in Question 1, and the conservation of energy targeted in Question 4 as long as they have experience with a physical system that represents the energy conservation concepts in action. This is likely a result of the fact that the STHX allows students to observe the interplay of varied mass flow rate and the energy balance ΔT. The philosophy used in developing the hands-on activities and corresponding worksheets could extend to the rate versus amount issues captured in Questions 2 and 3 by simply developing a heat transfer DLM exercise that uses the water for one stream and variable liquids for the other with the option of varying flow rates. Such reconfigurations are expected to support our hypothesis.

3.5 Student feedback

We used the Minute Paper technique [31] to assess what students found interesting in the implementation and where the weak points were. In the worksheet, we had two questions about the most interesting and the muddiest point of the experiment. One of the most interesting points of this instructional module based on student feedback is the design of the heat exchanger, its simplicity and intuitive design. Using dye in the shell side flow is another positive point from the student viewpoint. Most of them mention that they like hands-on activities, and they benefited from the implementation.

Some comments on the most interesting point are:

- *"Actually having a physical system to experiment with and doing hands-on learning rather than classroom learning was more engaging."*
- *"The way that the different streams stayed separated was cool."*
- *"It was interesting how quickly the heat was transferred through the system."*
- *"Watching the exchange of heat physically occur in front of us."*
- *"The design of the process to maximize the transfer of heat."*
- *". . . the relation between the* ΔT *and* $\dot{m}$*."*

And some comments regarding the muddiest point were:

- *"The muddiest point of the experiment was moving the beakers."*
- *"Moving beakers back and forth."*
- *"Attempting to make flow rates for the two streams close to equal. . ."*

The limited time that students have to run the experiments might be viewed as a primary disadvantage of this approach. However, it lets students do the experiment several times in a 50-minute class period. Needing only five seconds to reach steady state is advantageous. However, after ~30 seconds, depending on the inlet reservoir height or liquid head, one side runs out of water and the temperature change for the other side is eliminated because heat transfer no longer takes place. To avoid transient effects associated with startup and shut down of flow, as mentioned earlier, the timer should be started at the instant the beakers are switched, and students should allow the flows to continue until one of the beakers is about to run out of water, at which time they should quickly pull the measurement beakers out of the streams replacing them with the waste beakers to collect the rest of the flow. This procedure was mentioned by the students as one of the drawbacks of the experiment because switching the beakers at the same time is tricky, besides that one side runs empty sooner due to having less path resistance and therefore lesser head loss.

4. Discussion

Evidence from the current implementation of the STHX DLM shows significant improvement in student conceptual understanding with enhanced ability in correctly identifying the system boundary to use for the purpose of computing a heat duty. This is consistent with prior work by members of our group [6] in open channel flow DLMs implemented in a team-based interactive mode as students show not only conceptual gains, but also correct their explanations of the phenomena at hand demonstrating effectiveness in utilizing DLMs in the classroom in contrast to passive learning. The hands-on learning sessions used in this implementation where students work in groups offer many opportunities for collaborative team interactive learning as groups work their way through a series of conceptual questions on the worksheet. This is a similar dynamic to the method of peer instruction that has been shown to significantly improve scores on ConcepTests in physics courses [32]. Other work by our team provides rationale for greater gains at the higher levels of Bloom's taxonomy when using DLMs and the improvements can be explained in light of the ICAP (Interactive, Constructive, Active, Passive) hypothesis, Anderson's Information Processing and cognitive load theories [33]. The analysis aspect in determining the system boundary would be at level 4 in Bloom's taxonomy showing consistency with this previous study.

It is also of benefit to discuss another persisting misconception around which we can develop future learning modules and associated activities. The misconception involves the meaning of the ΔT term in the energy balance or more specifically the $\dot{Q} = \dot{m}C_p\Delta T$ expression. Students tend to search for any ΔT that can be substituted into the energy balance equation, e.g., rather than choosing the temperature difference between either the cold outlet and inlet or hot inlet and outlet, students choose the temperature difference between the hot and cold fluid which is the thermal driving force ΔT. When calculating the log mean temperature difference they often make the opposite mistake using an energy balance ΔT between inlet and outlet streams rather than a driving force ΔT as represented in the $\dot{Q} = U_oA_o\Delta T_{LM}$ expression. To address these misconceptions a simple module like that in Fig. 11 may be used where students can properly identify the system boundary and mark the fluid plus an example point from which thermal energy originates, i.e., the hot fluid before crossing the system boundary which separates the hot and cold fluid. Next, they can mark the fluid and an example point to which thermal energy is transferred when it arrives in the cold fluid. This serves to clarify the meaning of the driving force ΔT. By like manner, they can identify a temperature point for entering and exiting hot fluids and describe how they would model the thermal energy lost between those two temperature points which will clarify the meaning behind the energy balance ΔT. One can think of a host of other examples for eliminating persisting misconceptions.

Other modes of implementation can be of benefit as well. Students can be asked to predict heat transfer coefficients that require geometric parameters for determining system Reynolds numbers for this heat exchanger. An advantage is that the vacuum formed heat exchanger is not built in the standard way, but has a simplified geometry making it easy to determine the cross and parallel flow areas. needed to calculate the mean mass velocity for cross flow and parallel flow. This forces them to truly understand the meaning behind the more complex formulas used to determine velocities in industrial shell and tube heat exchangers. Fig. 14 shows a close-up view of the simplified geometry in the current STHX where distance (a) represents the baffle spacing, (b) the shell width and (c) the baffle window height. Each of these parameters are easily measured by the student or can be given, and readily understood given the see through nature of the low cost STHX. We can simplify future implementations by eliminating the beaker switching procedure and provide a correction factor to account for transient effects associated with initiation or termi-

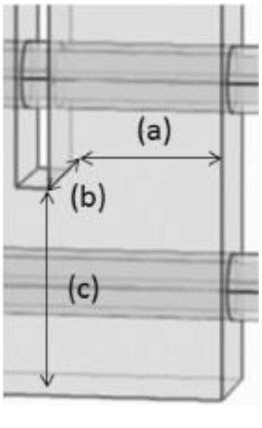


Fig. 14. Close-up schematic of the free parallel and cross-sectional area.

nation of flow. Or if we just want to demonstrate how the heat exchanger works in introductory level classes we can have students observe how fluid temperatures change in the process. For more advanced classes we can have students actually design their own low-cost DLMs to demonstrate learning objectives and account for non-idealities introduced because of imperfections in their systems. Given the breadth of concepts that can be covered in fluids and thermal systems classes the opportunities for creative use of the DLM concept are quite broad.

5. Conclusions

Commercially available engineering lab equipment in the area of thermal-fluids can be expensive and generally requires a dedicated lab space. For this reason, hands-on experimentation is often restricted to specific lab courses. Many of the concepts we teach in engineering science courses would benefit from a timely experiential component that could be brought into the classroom. To overcome the cost barrier to providing such experiences, low-cost, vacuum formed heat exchangers have been developed and tested in the classroom. The heat exchanger provides quality data that are in excellent agreement with correlations developed for industrial scale heat exchangers. The system reaches steady state within five seconds thereby reducing the time typically necessary for use of pilot scale equipment in standard upper division laboratories even if such systems were available at a low enough cost for widespread use. Results presented provide evidence that students can take reasonable data with this low-cost apparatus in a 50-minute class period that illustrate the linear relationship between heat duty and the log mean temperature difference. Energy conservation principles can readily be learned as well and one can expect corresponding conceptual gains related to identifying appropriate system boundaries for energy balances in sophomore-level courses. Student feedback shows generally good receptivity for use of the STHX learning module with constructive feedback on how to improve the implementation. Further work needs to be done with other implementations to identify other areas where similar systems may be used to assist in accomplishing learning objectives through hands-on sessions.

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Appendix

Heat Exchanger Lab – Turn in one handout per team at the end of session.

A. Learning Objectives/Outcomes. Students will be able to:

1. Trace shell side and tube side flows and label inlet & outlet flows and temperatures.
2. Perform an energy balance on a shell & tube heat exchanger.
3. Define the meaning of $\dot{m}C_p\Delta T$.
4. Explain why ΔT on the shell side may differ from ΔT on the tube side.

B. Select team roles:

C. Experimental Procedures

a. Timer & temperature monitor: Takes water temperatures in cups before and after experiments; Uses stop watch (20 sec). **Name:** ________________________________	b. Valve controller; beaker assistant: opens & closes flow valves. Helps push beakers back. **Name:** ________________________________
c. Beaker controller: pushes beakers into flow stream; pulls them back after 20 sec. **Name:** ________________________________	d. Moderator: reads questions & leads discussions. (if a 4th person) **Name:** ________________________________

Qualitative Observations

1. Close both pinch clamps
2. Fill tube-side beaker with *hot* water
3. Fill shell-side beaker with *cold* water
4. Feel water temperatures
5. Place one drop of food coloring in *cold* beaker (shell side).

6. Draw the expected flow patterns for both the shell side and tube side flows directly on the cartridge using different colored pens.
7. Label inlet and outlet flows and temperatures.
8. Open both pinch clamps & observe flow patterns
9. Update your knowledge of the flow patterns
10. Note the difference in how the water feels in the two outflow beakers.

D. Discussion Questions

1. Do you feel a difference in the water temperatures from before they flowed through the heat exchanger? Describe the change.
2. Was there any mixing of the hot and cold water streams in the exchanger? How can you tell?

Quantitative Measurements

1. Close both pinch clamps
2. Fill tube-side beaker with *hot* water
3. Fill shell-side beaker with *cold* water
4. *Starting with cold shell side measure & record inlet water temperatures* in table below
5. Stop! *Review roles:* (a) temperature monitor/timer; (b) valve turner/beaker assistant; (c) beaker controller
6. *Open both pinch clamps* & count to 5 (1–1000, 2-1-000, . . . , 5–1000); collect water into 3-cornered waste beakers
7. At 5 *quickly push graduated beakers* into place; *start stopwatch for 20 sec*.
8. At 20 sec pull graduated beakers back while replacing with waste beakers
9. Close valves
10. *Immediately, starting with hot tube side record temperatures, volumes, and time*
11. Repeat three more times using the same water recording the data as trials 2, 3 & 4.

Data Table

Trial #	Shell Side			Tube Side			time (s)
	T in	T out	V (mL)	T in	T out	V (mL)	
1							
2							
3							
4							

Notes on specific heat capacity

In performing energy balances on systems involving liquids it is convenient to make the approximation that the change in specific enthalpy of the liquid is directly proportional to the change in temperature.

$$\Delta \hat{H} = C_p \Delta T$$

The proportionality constant here, C_p, is termed the specific heat capacity, and is a property of the particular liquid. For water the specific heat capacity is

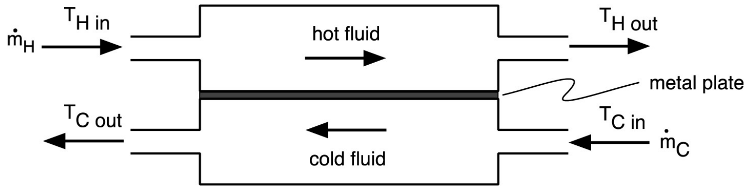
$$C_p = 4180 \frac{J}{kg\ K}$$

Note: In chapter 8 of Felder and Rousseau you will learn that specific enthalpy cannot always be assumed to be a linear function of temperature and in those cases the enthalpy change must be found by an integration procedure.

Conceptual Questions

Please work with your group members to answer the following questions.

1. Below you see a schematic of a simple heat exchanger. If you want to determine the rate of the heat transfer from the hot fluid to the cold fluid, what would you pick as the system to analyze? Please draw the system boundary on the diagram.



2. If we use $\dot{Q} = \dot{m}C_p\Delta T = \dot{m}\Delta\hat{H}$ for calculating the heat duty of the heat exchanger, what does ΔT refer to?
   a. $T_{H\ avg} - T_{C\ avg}$
   b. $T_{H\ in} - T_{H\ out}$
   c. $T_{H\ out} - T_{C\ out}$
   d. $T_{H\ in} - T_{C\ in}$
3. If the reduction in the hot water temperature is not the same as the increase in cold water temperature this means
   a. $\dot{m}_h \neq \dot{m}_c$
   b. Loss of heat to surroundings
   c. One fluid was not inside as long
   d. a and/or b
4. What does the equation $\dot{Q} = \dot{m}C_p\Delta T$ represent?

Most Interesting & Muddiest Point

What was the most interesting point of this laboratory session?
How interesting was it?
1 2 3 4 5 Very Interesting
What was the muddiest point of this laboratory today?
How muddy was it?
1 2 3 4 5 Very Muddy

Individual Assignment:

Using the data collected from trials 1 to 4 determine the rate of heat transfer for each trial by separate energy balances on the tube side and shell side of the exchanger and record in the table below. First determine the mass flow rate for each side using the volume and time data that you recorded. Then determine the temperature change (outlet minus inlet) for each side of the exchanger. Finally determine the rate of heat transfer to or from the water passing through the tube side and shell side respectively.

Heat Duty Analysis

Trial #	Shell Side			Tube Side		
	$\dot{m}$ (kg/s)	ΔT	$\dot{Q}$ (W)	$\dot{m}$ (kg/s)	ΔT	$\dot{Q}$ (W)
1						
2						
3						
4						

1. When you reuse the same water for several trials do you see a change in the rate of heat transfer for the different trials? What do you propose causes these changes if any?
2. Is the rate of heat leaving the hot water equal to the rate of heat gain by the cold water? Do you expect it to be? Why or why not?

Negar Beheshti Pour received her B.S. in Polymer Engineering at Tehran University and her M.S. in Chemical Engineering at Washington State University (WSU) where she also served as a teacher assistant. She is currently working towards a PhD in Chemical Engineering at WSU. In addition to her chemical engineering research in phase separation in microgravity, Negar is interested in engineering education and new pedagogies. Now she is working on a low-cost versions of desktop learning modules.

David Thiessen teaches and conducts research in the Voiland School of Chemical Engineering and Bioengineering at WSU. He received his PhD in Chemical Engineering from the University of Colorado. He is active in research in the areas of fluid mechanics (drops, bubbles, and capillary channels under microgravity or microscale conditions) and physical acoustics.

Robert Richards received the Ph.D. from UC Irvine, did post-doctoral research at the NIST, and then joined the WSU Mechanical and Materials Engineering faculty where his research is in thermodynamics and heat and mass transfer. Recently he participated in the NSF Virtual Communities of Practice (VCP) focusing on developing and disseminating research-based learning methods in thermodynamics. He introduced the concept of fabricating very low-cost thermal fluid experiments using 3-D printing and vacuum forming at the National Academy of Engineering's Frontiers of Engineering Education and is a co-PI on an NSF IUSE for developing associated manufacturing techniques.

Bernard Van Wie received all three degrees, his B.S., M.S. and Ph.D., did postdoctoral work and was a visiting lecturer at Oklahoma University. He has taught in WSU's Voiland School of Chemical Engineering and Bioengineering for 33 years and for the last 19 years has developed and assessed "Desktop Learning Modules" alongside his technical research in biotechnology. A 2007-2008 Fulbright to Nigeria led to receiving WSU's 2009 Marian Smith Award for innovative instruction. In 2016 he was awarded WSU's Teaching Academy, Office of Undergraduate Education, and Provost Office inaugural Innovation in Teaching Award for sustained efforts to develop novel instructional tools.