The Effectiveness of In-Class, Hands-On Learning vs. Lecture for Teaching About Shell and Tube Heat Exchangers

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New technologies, such as the Armfield DLMX, are in the market, which allow hands-on learning to occur in standard classrooms. While the benefits of hands-on learning, such as increased student attention, are widely acclaimed [1-5], there are also benefits to more traditional teaching styles, such as the ability transmit more information [6], and the instructor is left trying to determine which pedagogy will be best suited for each topic in a course. As part of an effort to develop and promulgate hands-on, active learning pedagogies, the authors have undertaken a study to develop guidelines for lecture versus hands-on, active learning in fluid mechanics and heat transfer.

Students in a junior level Chemical Engineering Fluid Mechanics and Heat Transfer course were taught in a split manner with two sections and one instructor. The sections were taught in an alternating manner. For any given course topic, one section of the class received instruction in a traditional manner, while the second section was taught in a hands-on, active manner, utilizing the Armfield DLMX, a system that uses plug-and-play cartridges in the form of miniaturized fluid mechanics and heat transfer equipment. For example, Section 1 may have received lectures on applying the Bernoulli Equation to orifice and venturi meters, while Section 2 performed hands-on learning activities. Later in the course Section 1 may have had hands-on learning for shell and tube heat exchangers, while Section 2 received lectures. To determine conceptual learning gains, a conceptually based test, containing short answer questions, was given at the beginning of the heat transfer portion of the course and at the end of the course. The students’ reasoning, as shown in their test answers, were rated using a rubric. This paper reports on student learning gains in the topics of shell and tube and extended area heat exchangers.

Introduction

As part of an ongoing effort [1, 4, 7-20] to develop more effective teaching tools and methods, the authors have undertaken to study how students learning and attitudes are affected by varied teaching methods on a topic-by-topic basis. This will allow us to be more intentional about balancing hands-on and active learning opportunities with more passive classroom experiences. To this end we utilized pre and post testing, surveys, and interviews with a subset of students to gain insight into student learning. This information will allow us to develop guidelines for hands-on learning implementation.

Specifically we are working with chemical engineering students in a required two credit fluid mechanics and heat transfer course. This is taken during the second semester of the junior year. This course is the second in our transport series, and focuses on practical applications of transport theory such as sizing heat exchangers or pumps. While many of the topics presented in this course are well suited for a hands-on learning environment, not all are. A part of our overall goal is determining topics for which learning is not enhanced by hands-on activities.
Methods

With enrollments up, we now have enough students to split courses into two sections and retain enough students in each to have meaningful numbers. At our institution, a two-credit course needs only to meet twice a week. This allows a unique course set-up wherein one section meets Monday and Wednesday, while the second meets Wednesday and Friday. Both sections share the Wednesday class. In this manner we can offer, for a given topic, one section a hands-on experience and the other a lecture-based experience, while holding other topics in a shared manner. As a control, extended area heat exchangers were taught in a hands-on manner for both sections.

For the heat transfer portion of the course, both sections where given identical lengthy, 38 question, pre and post tests, taken near the midpoint and end of the semester. In this test students were asked conceptual questions regarding the three types of heat exchangers for which we have desktop scale hands-on equipment. At no point in the semester were the students given solutions for this test. The questions were developed by the instructor, based on his experience teaching this course for 11 years.

Student responses were rated for quality of reasoning as well as correctness, using a rubric, found in the Appendix. This rubric is a framework for assigning a score, on a scale of 0 to 9, that reflects both the correctness and depth of reasoning presented in the student’s answer. For example if a question asks that a student include their reasoning and the student only provides a correct answer, that answer rates a 1.

For this paper, only the results of the shell and tube, 16 questions, and extended area, seven questions, heat exchanger portions of the test were analyzed. The score for each student was then used to calculate an individual learning gain according to the formula:

\[ \% \text{ gain} = \frac{\text{post} - \text{pre}}{\text{maximum} - \text{pre}} \]

This learning gain represents the maximum observed change as a percentage of the maximum possible change.

The hands-on exercises consisted of worksheets found in the DLMX workbook \[12\]. The shell and tube worksheet may be found in the appendix as an example of the types of activities involved. For the shell and tube heat exchanger, Section 1 had two 50 minute sessions with Armfield DLMX apparatuses and the worksheet. In this time the instructor and a number of TAs were present to respond to questions, ask guiding questions, and coach the students through the learning process. Meanwhile Section 2 received two lectures on the same material. As the instructor has previously and successfully taught the course with very minimal lecture\[1, 10, 18, 19\] this was expected to be an equivalent coverage of material between the two sections. For the extended area heat exchanger, both sections had two sessions with the equipment.
Results

It should be noted that shell and tube heat exchangers were the first section on the test and the control, extended area heat exchangers, was the last topic. There were two results in the pre-test in which the students didn’t write anything in the control topic, and a small number of post-tests in which students only answered a few of the extended area questions, leaving the remainder blank. Students may not have had enough time to complete the test, because of this seven tests, essentially evenly distributed between the two sections, are not usable for analysis of the control topic. Anecdotally, one student has admitted that he made a point of attending the lecture course as well. We do not know how prevalent this behavior was, but it is a potential confound for the study.

Analysis of the test results, Table 1, gives a modest apparent difference between the two groups for both the intervention and control portions of the test, with Section 1 showing a higher learning gain than Section 2. Performing a two-tailed Student’s t-test shows that these differences are not significant at the 90% confidence level (p values of 0.145 and 0.307 for the shell and tube and extended area sections, respectively). While these differences are not significant, they do provide an indication that the intervention might be effective overall.

Table 1: Descriptive statistics for the overall learning gain results.

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>Mean Learning Gain</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S &amp; T</td>
<td>Ext’d Area</td>
</tr>
<tr>
<td>Section 1</td>
<td>32 (DLMX)</td>
<td>28 (DLMX)</td>
</tr>
<tr>
<td>Section 2</td>
<td>27 (Lecture)</td>
<td>24 (DLMX)</td>
</tr>
</tbody>
</table>

Each topic being examined consists of a collection of subtopics. There is the possibility that different subtopics are more suited to one or the other of the teaching methods being used. Examining this requires evaluating learning gains for the individual questions on the test. This will be discussed next.

Shell and Tube Heat Exchanger: This section contains three broad questions consisting of multiple sub-questions. Question 1 focused on students’ understanding of the physical system, such as where the flows are going and to what terms such as baffle window refer. Question 2 asks about correlated vs. experimental heat fluxes and the temperature differences associated with each. Question 3 deals with a student’s understanding of heat transfer coefficients. Descriptive statistics for the learning gains on these questions may be found in Table 2.

Again there is an apparent trend of Section 1 outperforming Section 2. Again, however, the statistics do not support this. A two-tailed heteroscedastic Student’s t-test returns p values of 0.154, 0.188, and 0.464 respectively for Questions 1-3. A brief analysis of the raw pre and post scores shows that Section 1, the intervention group, significantly (at the 90% confidence level) outperformed Section 2 on the pre-test (p=0.0948).

It is notable that the p-values for the different questions show a trend that corresponds to the difference in mean learning gain. Both Questions 1 and 2 show a larger difference in mean learning gain than Question 3. At the same time, this difference would be significant at a fairly low 80% confidence. This may be indicative that these topics, a physical understanding of what
is happening in the heat exchanger and the differences between experimental and correlated heat fluxes, might be more influenced by hands-on learning sessions. These are also the topics for which we would expect to see more impact from hands-on learning.

Table 2: Descriptive statistics for the shell and tube heat exchanger learning gain results.

<table>
<thead>
<tr>
<th></th>
<th>Questions 1 a-d</th>
<th>Questions 2 a-d</th>
<th>Questions 3 a-f</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Learning</td>
<td>Variance</td>
<td>Mean Learning</td>
</tr>
<tr>
<td>Section 1</td>
<td>49%</td>
<td>11%</td>
<td>72%</td>
</tr>
<tr>
<td>(DLMX)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Section 2</td>
<td>30%</td>
<td>36%</td>
<td>63%</td>
</tr>
<tr>
<td>(Lecture)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Extended Area Heat Exchanger: The questions in this section dealt with two main sub-topics: first, where, physically, is heat transfer occurring (i.e. where are the ‘phoney’ boundary layer films [21] and where are the channels through which fluids are passing?); and how do fins affect the calculation (i.e. what does fin efficiency mean?). Questions 8 a-c fit into the first category, while 9 a-d fit into the second. Analyzing learning gains using these categories yields the descriptive results found in Table 3.

Table 3: Descriptive statistics for the extended area heat exchanger learning gain results.

<table>
<thead>
<tr>
<th></th>
<th>Questions 8 a-c</th>
<th>Questions 9 a-d</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Learning</td>
<td>Variance</td>
</tr>
<tr>
<td>Section 1</td>
<td>43%</td>
<td>40%</td>
</tr>
<tr>
<td>(DLMX)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Section 2</td>
<td>39%</td>
<td>39%</td>
</tr>
<tr>
<td>(DLMX)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A simple analysis using Student’s t-test assuming unequal variance at the 90% confidence level yields the following results. There is no significant difference between the total score for the two groups (p = 0.31). Nor is the difference between the groups significant for questions 8 a-c (p = 0.82). However, the difference between the groups on the remaining questions, 9 a-d, is indeed significant (p = 0.00011). As both groups received the same treatment for this portion of the course and took the pre and post tests at the same time, this result is unexpected. Given the prior underlying difference between the two sections, as seen in the pre-test results, and that this discrepancy arises in the final portion of the test, perhaps this is an indication that the students in Section 2 were less able to complete this test in the time given.

Conclusion

While the majority of the results were inconclusive, there are indications, based on the scale of the difference between mean learning gains of the two sections, that hands-on learning exercises may have enhanced learning, in comparison to lectures, for understanding what is physically happening with a shell and tube heat exchanger and the difference between theoretical and experimental heat fluxes. Given that the section which received a hands-on treatment for shell and tube heat exchangers maintained the trends present in the pre-test data, namely out
performing the other section, we can say that hands-on learning has not negatively impacted student understanding in any of the topics addressed.

Unfortunately this study has suffered from confounds that affect most classroom based studies. Since students self-select their section, we have no control over the composition of the sections. There is an apparent difference in the underlying make-up of the two sections, with Section 1 consistently outperforming Section 2. One might speculate that more ambitious students sign up before others and select the Monday/Wednesday section so they will have Friday’s off. One way to assess this would be to normalize gains to student GPA, university entrance exams, or some combination of indicators. This work and analysis will need to be done in order to develop further insights from this data. In addition the remaining section of the test will be examined and combined both with this data and affective domain data from a survey asking students for feedback on a topic-by-topic basis to build a more complete picture of what impacted student learning. A similar study is being undertaken this year, with pre and post quizzes being given closely before and after each activity. This is expected to help isolate the effect of the hands-on activities from homework and other course activities.

Acknowledgements

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References


Appendix

Rubric used to rate tests.

<table>
<thead>
<tr>
<th>0 Points</th>
<th>1 (Low)</th>
<th>3</th>
<th>5 (Medium)</th>
<th>7</th>
<th>9 (High)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Answer</td>
<td>Correct with no explanation</td>
<td>Explanation is strongly flawed</td>
<td>Explanation relates to fundamentals strongly</td>
<td>Explanation relates to fundamentals</td>
<td>Provides clear explanation</td>
</tr>
<tr>
<td>OR</td>
<td>OR</td>
<td>OR</td>
<td>OR</td>
<td>OR</td>
<td></td>
</tr>
<tr>
<td>No Reasoning</td>
<td>Correct/Incorrect w/incorrect logic</td>
<td>50-75% critical mistakes/incorrect</td>
<td>25-50% critical mistakes/incorrect</td>
<td>25% critical mistakes/incorrect</td>
<td>1 simple mistake</td>
</tr>
</tbody>
</table>

Shell & Tube Heat Exchanger Pre/Post Questions

1. Consider the shell & tube heat exchanger below.
   a. What kind of shell & tube exchanger is it? Tell why.
   b. Label the best place for: \( T_{\text{hot,in}} \), \( T_{\text{hot,out}} \), \( T_{\text{cold,in}} \), \( T_{\text{cold,out}} \). Why did you choose the given place for \( T_{\text{hot,in}} \)?
   c. Shell side: add flow direction arrows between all baffles with flow reversals (e.g., \( \mathcal{U} \) or \( \mathcal{D} \)); label the baffle window; label the baffle pitch \( P_B \) adding a line with arrows (\( \rightarrow \)) showing the baffle pitch length.
   d. Tube side: add flow direction arrows (e.g., \( \rightarrow \)) for 3 bottom tubes, 3 top tubes, and flow reversals (e.g., \( \mathcal{D} \)).

2. Given the data below:

<table>
<thead>
<tr>
<th>Cold in (Shell inlet) ( T_{\text{cold,in}} ) (°C)</th>
<th>Cold out (Shell outlet) ( T_{\text{cold, out}} ) (°C)</th>
<th>Hot in (Tube inlet) ( T_{\text{hot,in}} ) (°C)</th>
<th>Hot out (Tube outlet) ( T_{\text{hot, out}} ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36°C</td>
<td>40°C</td>
<td>53°C</td>
<td>48°C</td>
</tr>
</tbody>
</table>

   a. Write the most general defining equation for the correlated \( \dot{Q} \) that depends on \( U \) and the \( \Delta T \) driving force.
   b. Show how to calculate the \( \Delta T \) driving force needed if we consider counter current flow. Show the equation and insert temperature numbers, but don’t punch your calculator.
c. Explain with the help of the shell & tube figure above why you need a correction factor, $F_T$, for $\Delta T_{LM}$.

d. Write the equation for $\dot{Q}$ for the energy balance for the hot side and calculate the $\Delta T$ needed.

3. Heat transfer coefficient:
   a. Given the cross section on the right and a baffle pitch of 0.75" (inches) write a formula for the shell side mass velocity, $G_\text{shell}$ if $V_{shell} = 35$ GPH. Show formula, sub in all numbers, but don’t punch your calculator.
   b. If the tubes are 6 inches long show how to calculate $A_o$ (sub in all numbers/no calcs!).
   c. The shell side Nusselt No. is:

$$Nu = \frac{h_o D}{\mu} = 0.2(\frac{\rho v D}{\mu})^{0.6}Sc^{0.33}$$

- Why does the correlation apply from low Re of 400 up to very high Re?
- What is the characteristic length, in inches, that’s used in Re and Nu. Tell why?
- Calculate the best shell side temperature to find $\rho$ and $\mu$.

d. If you double the number of baffles what will happened to $h_o$ and why?

e. Explain the effect of tube diameter on heat transfer.

f. In a shell & tube heat exchanger the tube side flow rate decreases from 35 GPH to 10 GPH, and $\dot{Q}$ decreases from 1900 Btu/hr to 1400 Btu/hr. Tell what happens based on fundamental changes in tube side flow patterns, and with the aid of the $U_o$ equation below explain how this affects the value of $U_o$.

$$U_o = \frac{1}{A_o} \left( \frac{1}{A_i} \frac{1}{h_i} + \frac{A_o \ln \left( \frac{D_o}{D_i} \right)}{2\pi L k_{wall}} + \frac{1}{h_o} \right)$$

Extended Area Heat Exchanger Pre/Post Questions

8. Resistances to heat transfer.
   a. On the photograph (right) of a section of the radiator sketch the paths for heat flow from the hot liquid inside the tube to cool air blowing past the fin.
   b. Label the tube wall and the inner and outer films through which heat is transferred. Use $k_m$, $h_i$, and $h_o$ to correspond to the thin films through which energy is transferred.
   c. For the air-side individual heat transfer coefficient $h_o$ found from a correlation what would you use for $D_{eq}$?

9. Fin effectiveness
   a. Tell why an extended area $A_F$ is needed.
b. Discuss the meaning of the fin effectiveness factor, $\eta_f$, multiplying $A_F$ in the term for the air side resistance in the overall heat transfer coefficient, $U_i$. 

\[
U_i = \frac{1}{A_i} \frac{1}{[h_o(\eta_f A_F + A_R)]} + \frac{x_w}{k_m} + \frac{1}{h_i}
\]

c. The fin effectiveness factor $\eta_F$ can be found from the following plot. Explain the meaning of the x-axis value and how it explains the general nature of the curve.

d. Tell how you find the wetter perimeter, P, and the cross sectional area $A_x$. Use the diagram below to assist you in your explanation.
Shell and Tube Heat Exchanger Activity Worksheet

A. Learning Objectives/Outcomes

Students will be able to:
1. Describe construction geometry and flow patterns in a shell and tube heat exchanger and relate these to their impact on process operation.
2. Explain the impact of various design decisions on the performance of a shell and tube heat exchanger.
3. Calculate the heat duty of an operating shell and tube exchanger from flow rate and temperature measurements.
4. Discuss the various terms and mathematical models needed to predict the amount of heat transfer in the shell and the tube heat exchanger.

B. Experimental Procedure

1. Turn on power for both Base Units.
2. Install the DLM-4 cartridge (Shell & Tube Heat Exchanger) into a Base Unit filled with hot water (<60°C).
3. Plug the hoses from the cartridge into a second Base Unit filled with cold water. For a countercurrent flow setup, plug the hose from the top of the cartridge into the supply (left) port; plug the hose from the bottom of the cartridge into the return (right) port.
4. Scroll down to display the tube side flow rate and temperatures for the Base Unit to which the cartridge is attached; observe the shell side flow rate on the second Base Unit.
5. Increase the flow rates by rotating the flow adjustment knob clockwise and following the instructions in the Experimental DLMX Data Table.

Dimensions and constants: Fill in missing values in the table below by examining the shell and tube heat exchanger.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tubes, ( N_t )</td>
<td></td>
</tr>
<tr>
<td>Tube passes, ( n_p )</td>
<td></td>
</tr>
<tr>
<td>Tubes per pass, ( n_t )</td>
<td></td>
</tr>
<tr>
<td>Tube length, ( L )</td>
<td>231 mm</td>
</tr>
<tr>
<td>Tube type, ( \frac{1}{4} )&quot; BWG no. 22</td>
<td></td>
</tr>
<tr>
<td>Tube dia., ( D_o )</td>
<td>6.35 mm (0.25 in)</td>
</tr>
<tr>
<td>( D_i )</td>
<td>4.93 mm (0.194 in)</td>
</tr>
<tr>
<td>Tube wall thickness, ( t_w )</td>
<td>0.71 mm (0.028 in BWG no. 22)</td>
</tr>
<tr>
<td>Tube pitch, ( P_t )</td>
<td>15 mm</td>
</tr>
<tr>
<td>Tube Pitch, ( P_t )</td>
<td>15 mm</td>
</tr>
<tr>
<td>Number of baffles, ( n_b )</td>
<td></td>
</tr>
<tr>
<td>Shell passes, ( n_s )</td>
<td></td>
</tr>
<tr>
<td>Baffle pitch, ( P_b )</td>
<td>44.3 mm</td>
</tr>
<tr>
<td>Shell inside diameter, ( D_s )</td>
<td>47.0 mm</td>
</tr>
<tr>
<td>Baffle window fraction, ( f_p )</td>
<td>0.22</td>
</tr>
<tr>
<td>( k_{Steel} )</td>
<td>16 W/m·K (9.4 Btu/ft·h·°F)</td>
</tr>
<tr>
<td>Tubes material:</td>
<td>stainless steel 316</td>
</tr>
</tbody>
</table>

Page 26.1525.11
Experimental DLMX Data: Set flow rates and record temperature data after running for ~1 min.

<table>
<thead>
<tr>
<th>Actual Tube Side Flow:</th>
<th>Actual Shell Side Flow:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubes In $T_{Hot,in}$ [°C]</td>
<td>Tubes Out $T_{Hot,out}$ [°C]</td>
</tr>
<tr>
<td></td>
<td>Shell 1 (inlet) $T_{Cold,in}$ [°C]</td>
</tr>
<tr>
<td></td>
<td>Shell 2 (outlet) $T_{Cold,out}$ [°C]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Actual Tube Side Flow:</th>
<th>Actual Shell Side Flow:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubes In $T_{Hot,in}$ [°C]</td>
<td>Tubes Out $T_{Hot,out}$ [°C]</td>
</tr>
<tr>
<td></td>
<td>Shell 1 (inlet) $T_{Cold,in}$ [°C]</td>
</tr>
<tr>
<td></td>
<td>Shell 2 (outlet) $T_{Cold,out}$ [°C]</td>
</tr>
</tbody>
</table>

C. Worksheet Exercises

1. Below is the DLMX tube layout and baffle window. Label the dimensions indicated by the arrows and the shaded region (bracket) with notation from the list of dimensions and constants.

2. Consider the various temperatures $T_{Hot,in}$, $T_{Hot,out}$, $T_{Cold,in}$, and $T_{Cold,out}$, and the baffle pitch, $P_b$. Label these in the diagram below. Note: the hot fluid goes into the tubes. Write an energy balance for the tube side of the shell and tube heat exchanger. When calculating the heat transferred from the tubes how well do you think it will compare to the heat received by the shell side? Why might they be different?
3. In the figure above draw in flow direction arrows for the shell fluid as it travels from entrance to exit. What is the purpose of putting baffles on the shell side? How do they affect the behavior of the shell fluid? How does having more baffles affect the velocity of the shell fluid? The flow rate? What about the total time the fluid spends in the shell (also referred to as residence time)? Explain your answers.

4. What are the two interfaces at which heat transfer occurs? Write formulas for their areas:

\[ A_o = \] \[ A_i = \]

5. \( U_o \), the overall heat transfer coefficient based on the outside area, can be expressed as shown in the formula below. If the tube side flow is reduced from turbulent to laminar flow, which resistance will be controlling? Why? Circle it.

\[
U_o = \frac{1}{\frac{A_o}{A_i} h_i + \frac{A_o \ln \left( \frac{D_o}{D_i} \right)}{2\pi Lk_{wall}} + \frac{1}{h_o}}
\]

\( h_o, h_i = \text{outer & inner heat transfer coefficients} \)

6. Examine the data acquired for the flow rate of \( \leq 2.0 \text{ L/min} \) on the tube side. What do you notice about the \( \Delta T \) across the entrance and exit streams? Why has this happened?

7. Write the correlation for the Nusselt number, the for the shell side. What is the name of this correlation? This correlation is valid for Reynolds numbers down to ~400. Why do you think this is the case? Note: consider the path the shell fluid experiences as it progresses through the heat exchanger in formulating your answer.

8. What do the terms parallel and cross flow mean, and at what points in the shell and tube exchanger would you find parallel flow and cross flow?
9. By visual inspection, determine a formula for the area available for cross flow, $A_{\text{cross}}$, at the center of the shell. Determine the area for parallel flow, $A_{\text{parallel}}$, in the baffle window. See if they agree with the derivations in your textbook. Why do you use the centermost row for the cross flow calculation? Explain how the areas are used in the correlation for the shell side heat transfer coefficient.

10. Write the formula for heat transfer on the tube side. Considering the shell side and tube side correlations explain the impact of various design decisions on the heat transfer, pressure drop, and cost of a shell and tube heat exchanger.

11. Show how the system temperatures are used to define the temperature driving force for a heat transfer correlation?

12. What is the purpose of the log mean temperature difference correction factor, $F_T$, in predicting heat transfer from correlations? Visually follow the flow of the shell fluid. Discuss at which points it is in contact with tubes containing the warmest and the coolest fluid. Briefly describe your conclusions and tell why you need the correction factor, $F_T$.