AC 2011-1128: A FOLLOW UP STUDY ON BUILDING CONNECTIONS BETWEEN EXPERIMENT, THEORY, AND PHYSICAL INTUITION IN THERMAL SYSTEMS

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A Follow Up Study on Building Connections Between Experiment, Theory, and Physical Intuition in Thermal Systems

Abstract

This article describes a second implementation of a low-cost solar design project used for both a theory-based heat transfer class and an experimentation-based thermo-fluids lab class. The project was meant to reinforce conceptual understanding of heat transfer and also demonstrate the importance of experimental design for validating theoretical models. Based on lessons learned in the previous implementation, the current implementation included improved coordination between the two courses and increased communication of the project objectives to the students in both courses. Students displayed significant competence in their conceptual understanding of heat transfer, but they still struggled to perform thoughtful experimental design even though most students reported that they realized that experimentation and theoretical modeling were closely connected. In the next implementation of the project, we will make the connection between theoretical modeling and experimental design even more clear by having students turn in a proposed experimental design along with their theoretical model, coupling the experimental design to the theoretical model instead of coupling it to the data collection and analysis, as has been the case previously. Despite the challenges with experimental design, student feedback continued to indicate that the project was a valuable learning experience.

1.0 Introduction

1.1 Background & Motivation

In engineering education, students often encounter a disconnect between the theory they are taught in the classroom and textbook and the application of that theory to real processes and systems. One manifestation of this disconnect is in students exhibiting fundamental misconceptions regarding the theories they are learning, unable to make simple predictions regarding how physical processes will proceed, even despite satisfactory or good performance in the classroom or on exams. Students will demonstrate an ability to correctly solve numerical problems while maintaining physical misconceptions about the topics involved in the problems they solve.\(^1\) To evaluate and address this disconnect, many concept inventories have been developed to evaluate students’ conceptual understanding of various topics within science and engineering.\(^2\)\(^-\)\(^10\) Research using these inventories has shown that students in a class will frequently exhibit no gain, and even regress, in their conceptual understanding of the topics covered in the class, regardless of their academic performance in the course. Students frequently fail to understand how mathematical and physical concepts translate to real systems and vice versa.

Another manifestation of the disconnect between theory and real systems occurs when students encounter the non-idealized systems that exist in the real world instead of the idealized theoretical systems presented in textbooks and the classroom. Equations and models are often developed for perfectly symmetrical objects with uniform boundary conditions and orthogonal geometries, but rarely are such mathematically/physically ideal systems encountered in the real
world. As a result, modeling real systems typically requires assumptions to be made, which have to be validated through experimentation. Coursework rarely requires students to make significant assumptions in their analysis, and although engineering students generally have courses on experimentation, such courses are rarely combined with any significant theoretical modeling activities.

1.2 A Low-Cost Joint Design Project

1.2.1 Course Structure

In order to address the disconnect between theory and real systems that often occurs in engineering education, we developed a low-cost design project, administered jointly between a theory-focused course on heat transfer (ME450) and an experimental laboratory course in thermo-fluid systems (ME495). Note that the heat transfer course has been renumbered since the previous implementation of the design project, when the number was ME350. The ME450 course is focused on the physics of heat transfer, calculating and modeling heat flows and temperature distributions, and designing systems to control heat flows and temperature distributions. The ME495 course is focused on experimental design, measurement techniques, error analysis, and data analysis and interpretation. Due to the course sequence of our program, most students enroll in both courses concurrently.

The design project constituted 25% of the course grade in ME450 and 15% of the grade in ME495. In ME450, the design project grade was divided between progress reports (15%), design performance (20%), design approach and methodology (15%), and modeling and analysis (50%). In ME495, the project grade was made of experimental setup (30%), experimental procedure (20%), theoretical modeling (20%) and data analysis/interpretation (30%).

For ME495, the project fit naturally into the existing course structure. The lecture component of the course introduces students to concepts regarding experimental design, data acquisition, data uncertainty and analysis. The laboratory component consists of a total of eight laboratories and a project. Seven of the eight laboratories are fully structured, and out of these, three labs cover experiments associated with fluid mechanics, three labs cover experiments related to heat transfer, and one is an introduction to LabVIEW and data acquisition. The eighth laboratory assignment was an open-ended problem for which the students must provide an experimental solution backed by a theoretical analysis. As the topics for the open-ended assignments can vary every year, the students were given the option of using their design project for ME450 as the open-ended experimental design project for ME495.

1.2.2 Design Project Structure

The design project was first implemented during Fall 2009, and details regarding the initial implementation of the design project have been previously reported. In the first implementation of the design project students were required to build solar water heaters capable of achieving a 10 °C temperature rise, while in the current implementation students were required to build solar ovens capable of fully cooking a refrigerated egg within 45 minutes. Both projects had a $30 cost-limit.
In addition to being designed and built, the project had supplementary requirements for each of the two courses. For ME450, students were required to analytically model their system, making theoretical predictions of the temperature rise for the solar water heater and predicting cooking times and steady state temperature for the solar oven. For ME495, the students had to design an experimental system that would validate and inform their theoretical model developed for ME450. The experimental results acquired with the system were to be used to evaluate, interpret, and accordingly update their analytical heat transfer models for their design.

1.2.3 Design Project Rationale

The solar design projects were chosen because they encompass all three phases of heat transfer: conduction, convection, and radiation. Also, the cost-limit for the project was imposed for several reasons. First, it minimizes the expense to students and is set sufficiently low that all students are essentially on an even playing field, regardless of their available financial resources. Second, such a low cost-limit forces students to understand the physical principles needed for their design, as they will not be able to simply purchase equipment or materials designed specifically for their application. This is expected to reinforce their conceptual and functional understanding of heat transfer processes since students must understand the required functionality for their design, and then identify and procure available resources that fulfill those functions. Also, since most materials are scavenged from junkyards and dumpsters, the design geometries are often unpredictable and rarely match the idealized geometries of textbooks. Furthermore, thermal properties of the material properties may not match those tabulated in the textbooks, as most materials are scavenged and their thermal properties may have altered during their lifecycle. These constraints require students to make assumptions in order to properly model their systems, and these often must be validated through proper experimentation. Thus, students experience firsthand the connection between theoretical modeling and experimental design for analyzing real systems. Moreover, by coordinating the project between the two classes, the overall burden to the students is minimized by allowing them to use a single project for multiple classes.

1.3 Results from Previous Implementation

1.3.1 Findings

A full description of the results of the previous implementation of the low-cost solar design project has been previously reported,[11] but the results are summarized here. In the previous implementation, student designs demonstrated good conceptual understanding of heat transfer, with a wide array of designs being built and all of them achieving the required water temperature rise. A validated concept inventory test was also used to evaluate student conceptual understanding, the results of which demonstrated no significant conceptual gains over the course of the semester. Student performance on the concept inventory at the end of the semester was primarily correlated to their performance on the initial test at the beginning of the semester. Students however failed to grasp the concept of experimental design, with very few students designing effective experiments for evaluating their theoretical models or using their experimental data to interpret their models. The connection between the two courses and the two sides of the design project was not clear to the students.
A survey was also given to the students to allow them to self-report on how various aspects of the classes impacted their learning. The results indicated that students rated the design project by far as the component of the class most impactful on their learning. Comments from the students were generally very positive, as the students enjoyed the project and saw it as an effective learning experience. However, students also commented on the lack of integration between the two courses and the challenges associated with sequencing the deadlines for the two classes within the constraints of the semester schedule.

1.3.2 Recommendations

As a result of the previous study, we made several changes for this implementation. The concept inventory was no longer used, as students’ motivation and effort on the inventory was unclear, and the inventory also did not test the concepts that were being emphasized in the class or reinforced by the design project. Also, since the biggest weakness in the previous results regarded the integration of the project between the two classes, our primary recommendations were in regard to this issue. To improve coordination between the two classes, we made several changes to how we ran the project in this iteration. First, when the project was introduced in ME450, the professors for both classes were present and made a joint presentation regarding the project goals and how it would be implemented jointly in the two classes. Second, scaffolding for the project with preliminary assignments was increased to ensure that students were making progress in thinking about their theoretical models well before the final due date. Third, deadlines were adjusted to ensure an appropriate sequence of assignments for the two classes. In particular, the theoretical model was due for ME450 well before the experimental analysis was due for ME495, and re-evaluating the theoretical model for ME450 in consideration of the data obtained for ME495 was a requirement for the project report in ME495.

2.0 Methods

Several aspects of the project and its impact on student learning were evaluated. In particular, the project was evaluated for its impact on students’ understanding of heat transfer, students’ ability to perform experimental design, and students’ understanding of the interaction between theoretical modeling and experimental validation. Data used in the evaluation came from surveys administered in each of the two classes and from student grades. In an ideal situation, two groups would be used for the study: one group of students who were assigned the project, and a control group without the project. However, our institution only offers a single section of the ME450 and ME495 courses each year, and we wanted to ensure uniform assignments and grading within a single course. Moreover, the instructor for ME450 has included this design project every team he has taught the course, so he has no previous classes with which to compare. Additionally, the emphasis of this article is on the coordination and joint implementation of the project, and thus our primary goal is to make comparisons with results from the previous implementation.

2.1 Survey Instrument

In ME450, a survey instrument identical to that used previously was used again in this iteration of the design project. The survey was adapted from the validated Student Assessment of their Learning Gains (SALG) instrument. The survey allowed the students to self-report on the
aspects of the class that most impacted their learning, as well as on how they viewed the integration between theoretical modeling and experimental design. Students were asked to use a likert scale to respond to the degree to which various aspects of the class affected their conceptual understanding, application of concepts, and physical understanding of heat transfer, and were also asked to identify which aspect of the class impacted them the most. The survey also had questions to evaluate how the design project impacted the students’ motivation and interest in the subject. Finally, the survey included questions regarding how the students perceived the integration of the project and their perception of the degree to which experimentation and theoretical modeling work together. The portion of the survey regarding integration issues between ME495 and ME450 and the connection between theoretical modeling and experimental design was given in ME495, while the portion of the survey dealing with conceptual understanding, application, and physical understanding of heat transfer was delivered in ME450 after the final exam. The survey instrument is included in the appendix.

2.2 Conceptual Understanding of Heat Transfer

To evaluate impacts of the design project on student conceptual understanding of heat transfer, data was taken both from the described survey as well as from student grades on the analysis portion of the design project and grades on exams. The exams for ME450 had both conceptual and analytical questions, allowing comparison to be made between design project analysis grades and various aspects of the exam grades. Four exams were given: midterm one focused on steady state conduction, midterm two focused on convection and transient conduction, midterm three focused on radiation, and the final exam was fully conceptual. In addition to several conceptual questions about heat transfer, the final exam also included a design problem in which students were presented with a physical system (a turkey fryer) and asked to identify relevant modes of heat transfer and then suggest design modifications to increase the effectiveness of the system, addressing each of the identified heat transfer modes. Correlations were determined between the design project analysis grades and each of the following: exam grades, conceptual exam grades, final exam grades, and final exam design problem grades. The first midterm was excluded from the analysis because it was given before students had made any significant progress on their design projects.

2.3 Understanding of Experimental Design

Students’ ability to design an experiment that could be used to validate a theoretical model for a system was assessed in ME495. They were required to do this both for the solar design project as well as for another experiment utilizing a strain gage based force transducer. For both assignments, students were expected to apply an experimental procedure to calibrate and validate theoretical models of the system behavior. For the solar oven project, particular attention was given to the depth at which students related the data (i.e. temperature measurements at various points in the system) to the theoretical model developed to predict the system behavior. Students were expected to take multiple temperature measurements throughout the oven and compare them with model predictions. When significant discrepancies were observed, students were to further investigate the reasons for those discrepancies and carry out more experimental measurements to interpret them. For example, since design materials were scavenged from various sources, assumptions often had to be made regarding their thermal properties as they were typically not listed in property tables in the textbooks; experiments were needed to verify
these assumptions. In addition, students were expected to perform an uncertainty analysis for both the theoretical analysis as well as the experimental design. Students were evaluated on several tasks, including: the ability to properly instrument the physical system with transducers (i.e. thermocouples) in order to calibrate and validate the analytical model of the system; the ability to develop and implement an experimental procedure that will lead to repeatable/reliable acquired data; the ability to use experimental data to inform and evaluate their analytical model of the system; the ability to perform an uncertainty analysis of the experimental and theoretical data; and the ability to analyze, interpret and report data. The assessment was based on the grades assigned to the project report and presentation. Grades on these tasks are reported and also compared to grades on the other, fully-structured, laboratory exercises also assigned in the class.

3.0 Results

3.1 Design Project Results

The overall quality of the students’ design projects was more than satisfactory. Students showed significant innovation and built a wide variety of designs, ranging from parabolic dishes, a converted projection television utilizing the television’s large Fresnel lens, a parabolic trough complete with rotisserie, and several simpler ovens built from various materials, including cardboard boxes, mini-refrigerators, streetlights, toolboxes, and various other scavenged items. A wide variety of insulation materials were utilized, including shredded newspaper, carpeting, plastic bottles, Styrofoam, commercial spray foams, commercial fiberglass insulation, and scavenged clothes and blankets. In addition to the basic egg, many students made more creative dishes, including French toast, steak and eggs, eggs and biscuits, eggs and sausage, omelets, and one team made a Persian egg dish.

Out of the 17 design teams in ME450 (16 teams in ME495), four did not achieve the objective of cooking the egg within 45 minutes. Of those four unsuccessful teams, three had significant issues with group members not completing their work, and the fourth encountered an unanticipated challenge related to condensation on the window through which sunlight was entering their oven.

3.2 Heat Transfer Analysis Results

Modeling the solar ovens was fairly complex, as it required determining the transient cooking time for the egg while the egg was in an environment that also was changing in temperature. Moreover, correlations for buoyancy-driven convection are temperature-dependent, resulting in time-varying heat transfer rates from the cooking surfaces to the surroundings. Given these complexities, significant help was available for the students and the grading was somewhat lenient as long as the students made and justified reasonable assumptions in their analysis. The average analysis grade was 81%, with 73% of the class receiving scores above the mean, indicating that the grade distribution was significantly skewed towards higher scores. Thus the students did reasonably well, and the mean would have been higher were it not for a small number of particularly poor teams pulling the average down.
3.3 Conceptual Understanding Results

Table 1 shows the average exam scores and standard deviations for each of the exams given in ME450, during or after the design project was in process. The scores are shown separately for both the conceptual portion of the exams and the problem-solving analytical portion of the exams. Table 1 also shows the percentage of students scoring above 80%, which both gives an indication of the skewness of the grade distribution since the means are close to 80% and also indicates the percentage of students demonstrating proficiency at the ‘B’ level or higher in the subject. Finally, Table 1 also shows p-values for t-tests comparing student performance on various parts of the exams. For midterms one and two, a two-tailed t-test was used to determine whether student performance on the conceptual portion of the exam was significantly different from their performance on the analytical portion. For the final exam, a two-tailed t-test was used to determine whether student performance on the conceptual questions was significantly different than the student performance on the design problem.

<table>
<thead>
<tr>
<th></th>
<th>Midterm 2</th>
<th>Midterm 3</th>
<th>Final Exam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>conceptual</td>
<td>problems</td>
<td>conceptual</td>
</tr>
<tr>
<td>Averages</td>
<td>0.78</td>
<td>0.47</td>
<td>0.73</td>
</tr>
<tr>
<td>Standard Dev.</td>
<td>0.15</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>% Above 80</td>
<td>50%</td>
<td>6%</td>
<td>60%</td>
</tr>
<tr>
<td>p-value</td>
<td>5.1E-15</td>
<td></td>
<td>0.018</td>
</tr>
</tbody>
</table>

Average scores on the conceptual portions of the exams were between 73-78%, with 50-63% of the class demonstrating proficiency in the subject. At a 98% confidence level, students demonstrated significantly higher conceptual understanding than problem-solving ability for midterms two and three, with the problem-solving ability for midterm two (convection and transient conduction) being particularly low. Student performance on the design problem portion of the final exam (described previously) was particularly encouraging, with an average score of 81% and with 79% of the class scoring above 80%.

3.4 Correlations between Design Project Analysis and Exam Performance

Table 2 shows correlations between student grades on the analysis portion of their design project and their performance on exams. Correlations are calculated for the combined overall exam grades, the combined grade on the conceptual portions of the exams, the conceptual questions portion of the final exam, and the design problem on the final exam. A one-tailed t-test testing for positive correlation showed correlation with project analysis grades to be statistically-significant at a 95% confidence level for overall exam grades and the design problem on the final exam. Correlation with the project analysis grade was significant at a 90% confidence level for the combined conceptual grade on the exams as well as for the conceptual question portion of the final exam. Correlation was stronger between the project analysis and overall exam grade than it was for just the conceptual portion of the exams.
Table 2. Design project analysis correlation with exam performance

<table>
<thead>
<tr>
<th></th>
<th>Exams (overall)</th>
<th>Exams (conceptual)</th>
<th>Final Exam (conceptual)</th>
<th>Final Exam (design problem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation with project analysis grade</td>
<td>0.2894</td>
<td>0.2135</td>
<td>0.2166</td>
<td>0.2687</td>
</tr>
<tr>
<td>p-value</td>
<td>0.023</td>
<td>0.073</td>
<td>0.070</td>
<td>0.032</td>
</tr>
</tbody>
</table>

3.5 Experimental Design Results

From the 16 lab groups in ME495, 15 groups instrumented their physical system (i.e. the solar oven) with more than one thermocouple and out of these 15, only 10 groups compared more than one temperature measurement with theoretically predicted temperatures. Also, only one of the 16 groups attempted to refine their theoretical analysis based on experimental data input. This was surprising for both faculty, as throughout the semester, they reminded the students several times about the importance of such an approach in the whole analysis process. Furthermore, despite the fact that most groups measured more than one temperature inside the system, 6 of the 16 groups compared only the temperature of the “the hottest point” inside the oven with the theoretically predicted value. The majority of the groups failed to perform an uncertainty analysis, with zero groups performing uncertainty analysis for both the model and their experimental results, and only three groups attempting an uncertainty analysis for either of the two.

The ME495 project data was also used to assess students’ ability to design experiments, conduct experiments, and analyze and interpret data. The ANOVA test performed with this data is summarized in Figure 1, which indicates that students demonstrate a greater ability to conduct experiments and analyze and interpret experimental data than to properly design the experiments. These grades reflect how grading was done on the project. If the students failed to develop a comprehensive experimental program for the project, the design portion of the grade was heavily impacted while the experimental procedure and data analysis and interpretation were not impacted.
Grades for the open-ended solar design project were also compared to the grades assigned to the fully structured/step-by-step laboratories assigned as part of the course. A paired-samples $t$-test was conducted to evaluate whether the mean for the final project was statistically different from the mean of each of the structured lab reports. The correlations between these grades are shown in Table 3. The results indicate that performance on the design project was largely uncorrelated to performance on the fully-structured labs, with the exception of the lab on temperature measurement.

### Table 3. Correlation between ME495 design project grade and grades on highly structured lab reports

<table>
<thead>
<tr>
<th></th>
<th>p-value</th>
<th>Correlation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended fin – Final project</td>
<td>0.663</td>
<td>0.446</td>
</tr>
<tr>
<td>Tank blowdown - Final project</td>
<td>0.916</td>
<td>0.710</td>
</tr>
<tr>
<td>Pipe flow - Final project</td>
<td>0.241</td>
<td>0.448</td>
</tr>
<tr>
<td>Temperature - Final project</td>
<td>0.006</td>
<td>0.444</td>
</tr>
<tr>
<td>Wind Tunnel - Final project</td>
<td>0.032</td>
<td>0.615</td>
</tr>
</tbody>
</table>
3.6 Survey Results

Results of the survey are shown in Tables 4 through 6. Table 4 shows the results of the survey for the question regarding the component of the ME450 class that most impacted learning (question 13). Results are shown both for this implementation and that of the previous year. Most students identified either the design project, the lectures, or the combination of all class components as being most impactful on their learning. Compared with the previous implementation, fewer students identified the project as the most valuable, and there was a significant rise in the number of students identifying the lecture and combination of assignments as being the most impactful on their learning.

Table 4. Component of the class that most impacted learning (survey question 13)

<table>
<thead>
<tr>
<th></th>
<th>Project (% of Respondents (2010))</th>
<th>Homework (% of Respondents (2010))</th>
<th>Exams (% of Respondents (2010))</th>
<th>Lectures (% of Respondents (2010))</th>
<th>Combination (% of Respondents (2010))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>23%</td>
<td>9.1%</td>
<td>8.5%</td>
<td>27%</td>
<td>32%</td>
</tr>
<tr>
<td></td>
<td>62%</td>
<td>15%</td>
<td>5.1%</td>
<td>2.5%</td>
<td>15%</td>
</tr>
</tbody>
</table>

Table 5 shows the results for the portion of the survey that asked about the impact that each individual component of the class had on learning, and the impact that the design project had on student motivation. Numerical values were determined by assigning a numerical value of 5 to statements indicating the greatest help or impact and a numerical value of 1 to statements indicating no help or impact. Using this scheme, results were averaged for the 45 students who completed the survey and the data are shown in Table 5, which also indicates the associated question number from the survey. In brackets are the data from the previous year, showing that students reported a 5-10% increase in the perceived impact of each of the various aspects of the class on their learning. A two-tailed t-test showed that the increase was statistically significant at a 95% confidence level for each aspect of the course. As in the previous implementation, the lectures and the design project had similar scores and were perceived to be more impactful than the other aspects of the class. The impact of the design project on student interest and motivation similarly showed a 5-10% increase, but was not statistically significant at a 95% confidence level.

Table 5. ME450 survey average responses.

<table>
<thead>
<tr>
<th></th>
<th>OVERALL GROUP</th>
<th>2009-2010 P-value</th>
<th>Average Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lectures: Concepts (1)</td>
<td>4.21 [3.97]</td>
<td>.005</td>
<td>4.42</td>
</tr>
<tr>
<td>Lectures: Applications (2)</td>
<td></td>
<td></td>
<td>3.84</td>
</tr>
<tr>
<td>Lectures: Physical (3)</td>
<td></td>
<td></td>
<td>4.36</td>
</tr>
<tr>
<td>Homework: Concepts (4)</td>
<td>3.78 [3.60]</td>
<td>.05</td>
<td>3.80</td>
</tr>
<tr>
<td>Homework: Applications (5)</td>
<td></td>
<td></td>
<td>3.95</td>
</tr>
<tr>
<td>Homework: Physical (6)</td>
<td></td>
<td></td>
<td>3.60</td>
</tr>
<tr>
<td>Exams: Concepts (7)</td>
<td>3.69 [3.39]</td>
<td>.005</td>
<td>3.73</td>
</tr>
<tr>
<td>Exams: Applications (8)</td>
<td></td>
<td></td>
<td>3.80</td>
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</tbody>
</table>
The answers to the eight question survey administered in ME495 (included in the appendix) focusing on the integration between the two classes are summarized in Table 6 and in the subsequent paragraphs (the answers to questions six and seven were qualitative). The questions inquired about the project coordination between the two courses (Q1), about the students’ perception on the level of dependency between theoretical and experimental investigations (Q2), about how the integration of the project in the two courses enhanced students’ physical understanding (Q3), and about how the theoretical analysis facilitated the development of the experimental program (Q5). The values listed in Table 6 represent the percent of students who provided a certain answer to the posed questions. The number of students participating in the survey was 38 out of 42 in the course.

<table>
<thead>
<tr>
<th></th>
<th>Very good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Coordination [1]</td>
<td>15.8%</td>
<td>42.1%</td>
<td>31.6%</td>
<td>7.9%</td>
<td>2.6%</td>
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<tr>
<td>Connection between experiment &amp; modeling [2]</td>
<td>84.2%</td>
<td>15.8%</td>
<td>0%</td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Integrated effect on physical understanding [3]</td>
<td>18.4%</td>
<td>44.7%</td>
<td>23.7%</td>
<td>10.5%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modeling effect on experimental design [5]</td>
<td>21.1%</td>
<td>52.6%</td>
<td>18.4%</td>
<td>5.3%</td>
<td>0%</td>
</tr>
</tbody>
</table>

These results indicate that a still higher level of coordination has to be achieved between the two courses if this approach is going to be implemented again in upcoming semesters. The majority of the students acknowledged that the project integration between the two courses helped their physical understanding of the heat transfer concepts introduced in ME450. While the majority of the students stated that developing the theoretical models helped them develop their experimental design, this does not seem to be supported by the quality of the experimental designs developed...
for the ME495 course (see Figure 1). However, it is encouraging to see that the majority of the students at least recognize a dependence between theoretical and experimental investigations, at least for heat transfer related problems. This may be due to the fact that the students were constantly reminded throughout the semester about the relationship between the two.

3.7 Survey Free-response Comments from Survey

As with the previous implementation of the design project, student comments were generally positive. Some such comments were:

“The project was just a really fun thing that helped conceptualize the theories learned in class”

“I learned more in here than I have in most classes about real-world application”

“[The design project] was awesome and helped motivate me to learn”

“Overall good experience [with] combined project”

As with last year, there were also continued comments concerning the sequence and coordination of the courses, such as the following:

“I would have preferred a little more info about radiation before committing to a design…”

“[In ME450] the expectations were clearly stated but did not match up with [ME495]”

“Would have been helpful if both classes coordinated and had one page of deadlines and requirements.”

Comments regarding the integration between experimentation and theoretical modeling varied. Some examples include:

“The theoretical investigation is directly related to the theoretical. The theoretical model tells you what you need to test, rather than guessing”

“There are many unknowns that there is no way to measure, i.e. irradiation, reflectivity, etc”

Some student comments also pertained to a general resistance to open-ended problems, including the following:

“I think there should have been a little more direction from the instructors (ME495) to guide us through the experiment”

“More of a(n) outline of what needed to be presented [was needed]”
4.0 Analysis

4.1 Heat Transfer Conceptual Understanding

Students demonstrated a respectable level of conceptual understanding of heat transfer, with reasonably high conceptual scores across both midterm two and the final exam. Student understanding of heat transfer was particularly evidenced by nearly 80% of the class demonstrating a ‘B’-level or higher understanding of the design problem on the final exam. The problem was designed specifically to evaluate students’ ability to evaluate a physical situation, recognize the applicable modes of heat transfer, understand how to control those modes of heat transfer, and make design modifications accordingly. That 80% of the class was able to do this with a ‘B’-level proficiency is encouraging and could be a result of the concepts reinforced through completion of the design project. This possibility is reinforced by the results of the survey shown in Tables 4 and 5, in which students indicated that the design project had significantly impacted their learning.

The low conceptual score on midterm three may be due to several factors. First, radiation is a notoriously difficult subject within heat transfer. Second, the design project likely would have had only a minimal impact on students’ understanding of radiation. The only radiation concepts fully necessary for the design project were that shiny objects reflect radiation, clear ones transmit radiation, and black ones absorb radiation. Midterm three covered radiation at a level of detail significantly deeper than that which was needed for the solar oven design project, as detailed radiation analysis was not covered in the ME450 until after the design project was due.

The low problem-solving ability demonstrated on midterm two was surprising given that some of the analysis for the design project was focused on transient conduction and convection analysis, the same topics as those covered on the second midterm. However, the poor performance on the problem-solving portion of the second midterm could be due to several causes. First, despite encouragement to the contrary, many students may not have yet begun their analysis for their projects in earnest as it was not due until 1.5 weeks after the exam. Second, the midterm came during a particularly busy period in the semester, and this may have impacted student preparation. Moreover, since the students performed reasonably well on the conceptual portion of the exam, their functional understanding of convection and transient conduction may have been aided by the design project.

4.2 Grade Correlations

Table 2 shows that project analysis grades were significantly correlated to exam grades. This is not particularly surprising as good students generally will perform well across various components of a given class. What was somewhat surprising, however, was that the analysis grades were more closely correlated with overall exam grades than they were with just the conceptual portion of the exam grades, despite the overall exam grade and conceptual portion of the exam grade being tightly correlated to each other (\( \rho = .94, p=3\times10^{-23} \)). There are multiple possibilities as to why this would be the case. One possibility is that since students were working on teams, the better students on the team were doing the analysis. However, this should result in a weaker correlation between project analysis grades and overall exam grades. The students who did not contribute to their teams’ analysis should have lower problem-solving
scores on exams while still receiving a high analysis grade. Thus the more likely explanation for the weaker correlation between conceptual exam grade and project analysis grade is that students were doing better on the conceptual portions of their exams than on their project analysis. This implies that even the students who did not perform well on their project analysis were still building their conceptual understanding of heat transfer.

Table 3 shows the correlation between the grades given for the ME495 project and for the structured lab reports. The data indicate that there is not a strong correlation between the two types of assignments. This is not surprising as in the structured laboratories students are provided with step-by-step instructions on how to run the experiments during the lab time and with specific questions to be answered based on the experimental data acquired and the physical phenomenon experienced. This is exactly the opposite from the open-ended assignments in which students have to design the experiment, to formulate the proper questions for the experiment and to report only the relevant data for the experiment and the question to be answered by it. The expectation in the ME495 course was that students would develop the ability to learn from previous experiences. Specifically, it was expected that once students were exposed to six structured laboratories during the semester, they would have the ability toward the end of the semester to build on those experiences and apply, without extensive guidance, similar approaches to solving a completely new problem. As this did not happen to the extent expected, it is believed that due to the fast pace of the semester students do not have the opportunity to learn from previous experiences at the rate expected by the professors. Accordingly, it may be required that in future implementations, at the beginning of the open-ended assignments each group will discuss with the faculty their plan of action and where necessary, supplementary guidance will be provided.

4.3 Survey Results

Regarding learning in ME450, the survey results were largely consistent between the current iteration and the previous implementation of the design project, as shown in Tables 4 and 5. The increased number of students identifying the lecture as the most impactful on their learning may be due to increased experience of the instructor in the course, who was teaching it for the first time during the first implementation of the design project. Additionally, the improvement in all categories shown in Table 5 is likely due to the improved course coordination and communication that come with increased experience in the course. The relative values among the categories remained largely consistent from 2009-2010, with lectures and the design project rated as having the highest impact on student learning in both years.

For the current implementation, the significant drop in the number of students rating the design project as most impactful on their learning may be explained in several ways. The first explanation is that the increase in the number of students rating the lecture or the overall course assignments as being most impactful had to come from a corresponding decrease in the number identifying the project as most impactful. Table 5 indicates that the project still received the highest overall rating from the students in terms of its impact on learning, and actually increased over the previous year. So students still clearly view the project as impactful on their learning. Additionally, student enthusiasm for the project may have differed between the two control groups, as the project was novel in the 2009 implementation but may have been viewed as ‘just another assignment’ in the 2010 implementation. Third, the implementation was updated in
2010 leading to a slight increase in student deliverables, which may have caused an overload for the students, potentially resulting in them enjoying the project less while still recognizing its value, as indicated in Table 5.

Regarding the connection between theory and experiment, 84.2% of the students indicated a strong relationship while 15.8% of the students indicated barely any dependence. Provided that both faculty continually emphasized the importance of validating a theoretical model through experimental investigation, it was expected to see that an overwhelming majority of the students recognized the connection between two investigative approaches, although still disappointing that 15.8% still failed to fully see the connection.

Compared to last year’s results, when only approximately 15% of the students attempted to compare the measured and experimental results, this year’s outcome is significantly better. Regarding the uncertainty analysis of the data, almost 46% of the last year’s students attempted a rigorous uncertainty analysis compared to less than 19% this year.

4.4 Recommendations for Future Implementation

Based on responses from the students, the changes we made for the current implementation of the design project significantly improved the degree to which students saw the connection between theory and experiment. However, the students still have to develop the necessary skills to properly think through an appropriate experimental design. While the two sides of the project were better coordinated in this implementation, the students still seem to fail to understand the connection between the two sides despite significant discussion devoted to it from the instructors. One student comment suggested truly making the project into a single assignment with a single document detailing all expectations and deadlines for both classes. The challenge with such an approach, however, is that it would result in a long document with many instructions and details, and we have frequently observed students having a distinct inability to follow lengthy instructions. However, further increasing the coordination in assigned tasks could be beneficial. In particular, we plan to have the students propose their experimental design as part of their submission of their theoretical model for ME450 with the explicit understanding that their experimental design would be evaluated on the degree to which it validated their heat transfer model. The grade on this task would still be part of their ME495 grade, but it would help separate the ‘experimental design’ task from the ‘conduct experiments’ and ‘analyze and interpret data’ tasks. By coupling experimental design task to the submission of the theoretical model, we anticipate that students will recognize more clearly that their experimental design must be based explicitly on their heat transfer model.

5.0 Conclusions

The solar design project continues to be well-received by students. The feedback they have given, both formally and informally, attests to the project’s value as a learning experience and as a physical demonstration of the theory they learn in the classroom. While coordination between the experimental and theoretical sides of the project was improved in the current implementation of the project, students still failed to perform adequate experimental design, in particular. We hope to mitigate this by requiring students to submit a proposal for their experimental design in conjunction with their submission of their theoretical model, thereby making the connection
between their theoretical models and experimental designs even more explicit in the assignments
we give.

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6.0 Appendix

Self-Report Survey Given to ME450 Students

1. How much did ATTENDING LECTURES help your learning of heat transfer CONCEPTS?
   a. no help
   b. a little help
   c. moderate help
   d. much help
   e. great help

2. How much did ATTENDING LECTURES help your understanding of how to APPLY heat transfer concepts?
   a. no help
   b. a little help
   c. moderate help
   d. much help
   e. great help

3. How much did ATTENDING LECTURES help your PHYSICAL understanding of heat transfer?
   a. no help
   b. a little help
   c. moderate help
   d. much help
   e. great help

4. How much did HOMEWORK ASSIGNMENTS help your learning of heat transfer CONCEPTS?
   a. no help
   b. a little help
   c. moderate help
   d. much help
   e. great help

5. How much did HOMEWORK ASSIGNMENTS help your learning of how to APPLY heat transfer concepts?
   a. no help
   b. a little help
   c. moderate help
   d. much help
   e. great help

6. How much did the HOMEWORK help your PHYSICAL understanding of heat transfer?
a. no help  
b. a little help  
c. moderate help  
d. much help  
e. great help  

7. How much did studying for EXAMS help your learning of heat transfer CONCEPTS?  
a. no help  
b. a little help  
c. moderate help  
d. much help  
e. great help  

8. How much did studying for EXAMS help your understanding of how to APPLY heat transfer concepts?  
a. no help  
b. a little help  
c. moderate help  
d. much help  
e. great help  

9. How much did studying for EXAMS help your PHYSICAL understanding of heat transfer?  
a. no help  
b. a little help  
c. moderate help  
d. much help  
e. great help  

10. How much did the DESIGN PROJECT help your learning of heat transfer CONCEPTS?  
a. no help  
b. a little help  
c. moderate help  
d. much help  
e. great help  

11. How much did the DESIGN PROJECT help your understanding of how to APPLY heat transfer concepts?  
a. no help  
b. a little help  
c. moderate help  
d. much help  
e. great help  

12. How much did the DESIGN PROJECT help your PHYSICAL understanding of heat transfer?
a. no help  
b. a little help  
c. moderate help  
d. much help  
e. great help

13. Which of the following aspects of the class helped your overall learning the most?  
   a. Projects  
   b. Homeworks  
   c. Exams  
   d. Lectures  
   e. The combination of all

14. How did the design project increase your MOTIVATION for this class?  
   a. no impact  
   b. a little impact  
   c. moderate impact  
   d. good impact  
   e. great impact

15. How did the design project increase your INTEREST in the course material?  
   a. no impact  
   b. a little impact  
   c. moderate impact  
   d. good impact  
   e. great impact

16. Did having an integrated project between ME495 and ME350 that combined both experimental analysis and heat transfer analysis enhance your PHYSICAL understanding of heat transfer concepts?  
   (select n/a if you were NOT enrolled in ME495 concurrently with ME350 or did not use the same project for both classes)  
   a. no help  
   b. a little help  
   c. moderate help  
   d. much help  
   e. great help  
   f. n/a

17. Did the development of your experimental analysis for ME495 help you think through, understand, and develop your heat transfer model for the design project?  
   (select n/a if you were NOT enrolled in ME495 concurrently with ME350 or did not use the same project for both classes)  
   a. no help  
   b. a little help  
   c. moderate help
18. What other feedback do you have regarding the design project that was not asked in the previous questions?

*Self-Report Survey Given to ME495 Students*

1. How would you characterize the project coordination between the ME495 and ME350 courses?
   - a. poor
   - b. fair
   - c. good
   - d. very good

2. After completing the solar oven project, how would you characterize the relationship between experimental investigations and theoretical modeling?
   - a. independent
   - b. barely any dependence
   - c. strongly dependent

3. Did having an integrated project between ME495 and ME350 that combined both experimental analysis and heat transfer analysis enhance your PHYSICAL understanding of heat transfer concepts?
   - a. no help
   - b. a little help
   - c. moderate help
   - d. much help
   - e. great help

4. Did the development of your experimental analysis for ME495 help you think through, understand, and develop your heat transfer model for the design project? (select n/a if you were NOT enrolled in ME350 concurrently with ME495)
   - a. no help
   - b. a little help
   - c. moderate help
   - d. much help
   - e. great help
   - f. n/a

5. Did the development of your heat transfer model for the solar oven help you think through and properly develop your experimental program/analysis for ME495? (select n/a if you were NOT enrolled in ME350 concurrently with ME495)
   - a. no help
b. a little help
c. moderate help
d. much help
e. great help
f. n/a

6. If you answered a), b), or c) to the previous question, please support your answer with a brief explanation.

7. What other feedback do you have regarding the design project that was not asked in the previous questions?

8. How did the design project increase your MOTIVATION for this class?
   a. no impact
   b. a little impact
   c. moderate impact
   d. good impact
   e. great impact