AC 2010-1852: CONNECTING EXPERIMENT, THEORY, AND PHYSICAL INTUITION IN HEAT TRANSFER WITH A LOW-COST SOLAR WATER HEATER DESIGN PROJECT

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Abstract

Engineering students often struggle with developing physical, tangible understandings of the theories they learn in the classroom. Additionally, they often struggle when faced with messy, non-idealized, real-world systems as opposed to the idealized geometries and assemblies frequently encountered within classrooms and textbooks. As such, they also rarely have the opportunity to learn how experimental design and theoretical modeling work together to understand practical systems. To address these shortcomings, a low-cost solar water heater design project was developed and integrated concurrently between a mechanical engineering heat transfer course and a thermal systems laboratory course. The low-cost constraint reinforced physical understanding of heat transfer concepts and ensured messy, non-ideal designs to which theoretical modeling could not be neatly applied. A heat transfer concept inventory to assess student learning showed minimal gains in student understanding while a self-report attitude survey administered to the students demonstrated that they perceived the design project to be a valuable and enjoyable learning experience. Students failed, however, to understand the complementary nature of experimentation and theoretical modeling. Improved coordination between the two classes was needed to fully realize this benefit, and will be implemented in the future.

1.0 Introduction

1.1 Background

Pedagogical research carried out in many science and engineering courses have shown that students can develop the ability to correctly solve mathematical problems without having a physical, conceptual understanding of the topics involved. Concept inventories developed to test students' conceptual understanding before and after taking a class on a topic have shown that students frequently exhibit no gain or even regress in their conceptual understanding, regardless of their academic performance within the class.[1] Students frequently fail to understand how to apply mathematical concepts to real problems.

Within mechanical engineering curriculum, heat transfer is considered a notoriously difficult course for students.[2,3] Concept inventories have been developed to assess students' level of conceptual understanding; reported student scores on these inventories have been quite low, with average performance in the range of 50%.[2,4] The incorporation of active learning approaches within classes and programs have been shown to increase conceptual understanding of core content,[5] but are infrequently utilized in core content engineering courses such as those in the thermal sciences, due to time and financial constraints.

In addition to struggling with conceptual understanding of physical systems, students also struggle to understand how to model and analyze real systems. This is in part due to the fact that assigned homework problems can often be solved following a cook book type solution laid out in the textbook or outlined during lectures. However, approaching problems that depart from the familiar types of analysis often causes the students to fail to recognize the type of analysis to perform regardless of their capability to perform that analysis. For example, in heat transfer they may be able to correctly utilize convection analysis for internal flow but would fail to recognize that a pipe with water flowing through it requires internal flow analysis. Additionally, physical systems are rarely perfect matches for the available theoretical models. Geometries may differ, boundary conditions may not be perfectly replicable, assumptions may be necessary to neglect various considerations, etc. Students rarely have the opportunity or are required to adapt existing models to imperfect or complex real systems. Whenever a complex real system is offered for analysis, the theoretical analysis must be supplemented with experimentation; for example, some model parameters may need to be measured because the theory is unable to predict them. However, students rarely have the opportunity or are required to complete assignments that involve application of theory and experimentation to obtain required information about a system. This paper presents an approach taken to facilitate the students' exposure to both theoretical and experimental investigations on real complex heat transfer related problems/topics.

1.2 Course Structure

To improve students' ability to conceptually understand, model, and design experimentation for real-world, physical systems, a design project was implemented concurrently in two required mechanical engineering undergraduate courses in our program: Heat Transfer (ME350) and Experimental Methods in the Thermal Sciences (ME495). The learning outcomes associated with ME350 were for students to be able to 1) calculate temperature distributions and heat flows within materials and systems; 2) design components and systems to control the flow of heat; and 3) make appropriate assumptions to enable applying analytical heat transfer methods to real systems. These fed into the ABET Criterion 3 program outcomes a) an ability to apply knowledge of mathematics, science and engineering; c) an ability to design a system, component, or process to meet desired needs; e) an ability to identify, formulate and solve engineering problems, and k) an ability to use the techniques, skills and modern engineering tools necessary for engineering practice. The ABET outcomes targeted in ME495 are b) an ability to design and conduct experiments as well as to analyze and interpret data; c) an ability to design a system, component, or process to meet desired needs; d) an ability to function on design teams; g) an ability to communicate effectively; and k) an ability to use the techniques, skills and modern engineering tools necessary for engineering practice.

Prior to this offering, ME350 operated as a mostly traditional lecture style course, discussing the transfer of heat through conduction, convection, and radiation processes. Students were evaluated based on 3 tests (30%); one comprehensive, qualitative final (10%); weekly homework assignments (15%); a finite difference computer simulation project (15%); and the aforementioned design project (30%). The design project grade was divided between design performance (20%); design approach (20%); and heat transfer analysis (60%). Additionally, bonuses were available for teams with the highest performance, resourcefulness, and innovativeness. Students in both courses were all seniors, in at least their fourth year.

The structure of ME495 remained unchanged for the purposes of this experiment. The course has a lecture component in which the students are introduced to concepts regarding experiments' design, data acquisition, data uncertainty and analysis, and a laboratory component in which students complete a total of nine fully structured laboratories. Out of these, three labs cover experiments associated with fluid mechanics, four labs cover experiments related to heat transfer, and two labs consist of open-ended problems for which the students must provide an experimental solution backed up by a theoretical analysis. The topics for these open-ended problems vary every year; this allowed us to combine the final projects for both the Heat Transfer and Experimental Methods courses during the 2009 Fall semester. The grading structure involved two exams (15% each), homework (5%), lab reports (50%), and the project (15%). The project grade was made out of experimental setup (30%), experimental procedure (20%), data and uncertainty analysis (30%), and theoretical modeling (20%).

1.3 Design Project

The assigned design project required students to design, build and model a low-cost solar water heater capable of producing a 10°C temperature rise from inlet to outlet. The emphasis for the project in the heat transfer course was on the theoretical predictions of the performance of the designed heater, while in the laboratory course the emphasis was on the instrumentation, development of the experimental setup, and data analysis to assess the actual performance of the heater. For the heat transfer course, the analysis needed to predict the water outlet temperature, which required some intermediate calculations depending on the design chosen by the students. The integration of the project in both courses created a bridge between theory and experimentation, giving the students the opportunity to observe firsthand the limitations of theoretical modeling as well as recognize how experimentation can supplement theoretical limitations. The majority of the students (35/39) were enrolled in both courses concurrently.

The choice of a solar water heater as the design project served several purposes. First, the project incorporated all three main subjects of heat transfer: conduction, convection, and radiation. Second, the direct application towards reducing energy usage and moving towards sustainable engineering were attractive to the students and consistent with the goals of our institution. Third, a solar water heater holds relevance to the daily life of the students since it is something that they could potentially implement in their own homes. Finally, the project lends itself naturally to competition between design teams, giving students additional incentive to innovate.

One of the primary innovative aspects of the assigned design project was the implementation of a low-cost constraint. Students were given a $30 limit for the construction of their design, but were allowed to scavenge any materials that were freely available to all students. Such a constraint served several purposes. First, it minimized the financial burden on students who already have significant living expenses, tuition, and fees. Moreover, it equalized the resource base among all the students, preventing some students from utilizing personal and family resources to which other students might not have access. The low-cost requirement also prevented students from being able to buy specific products targeted for the design application. Instead, students were forced to determine and understand their required functional needs and identify affordable, free, and everyday resources that could meet those needs. The ingenuity and resourcefulness required for the project necessarily reinforced physical understanding of heat transfer mechanisms and concepts. The low-cost constraint also promoted creative, divergent thinking as students had to consider the vast array of potential resources to implement into their project. Finally, it was highly unlikely that a completed design would be easily described by available theoretical heat transfer models since the designed systems would have been scrapped together from available materials. The use of theoretical models for the system analysis required students to make assumptions with respect to material properties and encouraged them to use experimental measurements to verify the validity of their theoretical predictions.

The need for experimentation led to the joint implementation of the project in the Heat Transfer and Experimental Methods courses, simultaneously. This approach moved towards an integrated curriculum, reduced the overall workload for the students, provided greater accountability in ensuring student progress over the course of the project, and bridged naturally theoretical and experimental approaches to understanding physical systems. Furthermore, the open-ended problem/experiment associated with the project required students to apply heat transfer concepts in imperfect environments, to design an experiment and the corresponding experimental procedure, as well as to deal with inherent uncertainties, which is seldom done in a regular course. The uniqueness of each system, corroborated with the abundance of assumptions that were made in modeling the system's performance, required experimental validation of the results. This gave students the opportunity to apply the material learned in Experimental Methods with respect to design of experiments, use of appropriate instrumentation for measuring the parameters of interest, the data acquisition process, and analysis of the acquired data. A thorough uncertainty analysis was required for the experimental data.

The implemented approach facilitated students' understanding of the limitations of the theoretical modeling and emphasized the importance of acquiring both analytical and experimental skills for engineering students. Furthermore, requiring the students to develop their own experimental and data acquisition procedures facilitated the first hand identification of the uncertainties that affected the accuracy of their results.

2.0 Methods

Conceptual tests have been developed and validated in several fields to determine students' conceptual understanding of various topics and identify persistence of misconceptions. Originally developed for physics,[6] such 'concept inventories' have also been developed for various fields within other science and engineering disciplines, including concept inventories for biology,[7] chemistry,[8] statics,[9] dynamics,[10] electronics,[11] and also for the thermal sciences, including heat transfer specifically.[2]

To evaluate the gain in physical understanding of heat transfer among students, a heat transfer concept inventory was given to the students at the beginning and at the end of the semester. Completing the inventory was assigned as part of completing the first and last homework assignments of the semester. Students were only graded on their completion of the inventory, not on their performance. Ideally, results would be compared between a heat transfer class with and without the design project incorporated within it. However, our institution only offers a single section of heat transfer per year, making comparisons between courses difficult. Therefore, concept inventory results were compared with those from other institutions utilizing the inventory.

In addition to evaluating student conceptual understanding with the concept inventory, a survey instrument was given to the heat transfer students at the end of the semester to allow them to self-report on their reaction to the project and their perceptions of how it impacted their understanding of heat transfer from both the conceptual and experimental perspectives. Like the concept inventory, the survey was included as part of the final homework assignment for the class. The survey was adapted from the Student Assessment of their Learning Gains survey, which has previously been validated.[12] In the survey utilized in this article, students were asked to respond, using a Likert scale, the degree to which different aspects of the class (attending lectures, completing homework assignments, studying for examinations, and completing the design project) impacted their learning of concepts, application of concepts, and physical understanding. One question asked the students to select which of the described aspects of the class had the most impact on their overall learning, and questions were also written to determine what effect, if any, the design project had on the students' interest in the course materials and motivation for the class. The survey also included questions that asked the students whether the integration of the project between the theoretical and experimental classes had any influence on their physical understanding of heat transfer and their ability to model real systems. The entire survey instrument is included in the appendix.

3.0 Results

3.1 Project Results

Students generated a wide array of designs for their solar water heaters, several of which are shown in Figure **1**. A number of designs were some variant of an insulated cavity with a window on one side and a black tube snaking through the interior. One such design utilized scavenged evaporator coils from several refrigerators and housed them inside another refrigerator with its doors replaced with plexiglass, as shown in Figure **1**a. Three of these cavity/tube designs also used a reflective collector to draw more sunlight into the cavity, one of which is shown in Figure **1**b. Two teams utilized scavenged satellite dishes covered with a reflective material to concentrate sunlight onto a small surface through which water was flowing, one of which is shown in Figure **1**c. One team formed a parabolic trough to concentrate sunlight onto a long pipe, as shown in Figure **1**d. All twelve design teams met the minimum requirement of a 10 °C temperature rise in the water, with most teams achieving a temperature rise of at least 30-40 °C. Two teams were able to produce steam at the output, one of which produced continuous steam, while the other could only initially produce steam immediately after the water flow was turned on. The systems were tested during a sunny morning, over a total of about three hours.

Contemplating the diversity of the heaters that were built led to the conclusion that the students had a good conceptual understanding of the heat transfer principles governing solar water heater operation and that they also had good manufacturing skills. However, analysis of the lab reports submitted for this experiment indicates that a large percentage of the students did not seem to understand the purpose of the experiment and the experimental results in the whole project. Specifically, 24/39 students didn't compare the measured water temperature difference with the predicted one, they only reported the experimental values for it; 6/39 students attempted to compare the experimental and theoretical results, and only 9/39 students provided an in depth comparison of the results. Moreover, a small percentage of the students provided a thorough uncertainty analysis of the experimental results; 21/39 students only stated their opinions relative to what may have affected the accuracy of the experimental results, without providing an analytical support for their statements; 15/39 students attempted a rigorous uncertainty analysis, and only 3/39 students delivered an almost complete uncertainty analysis.

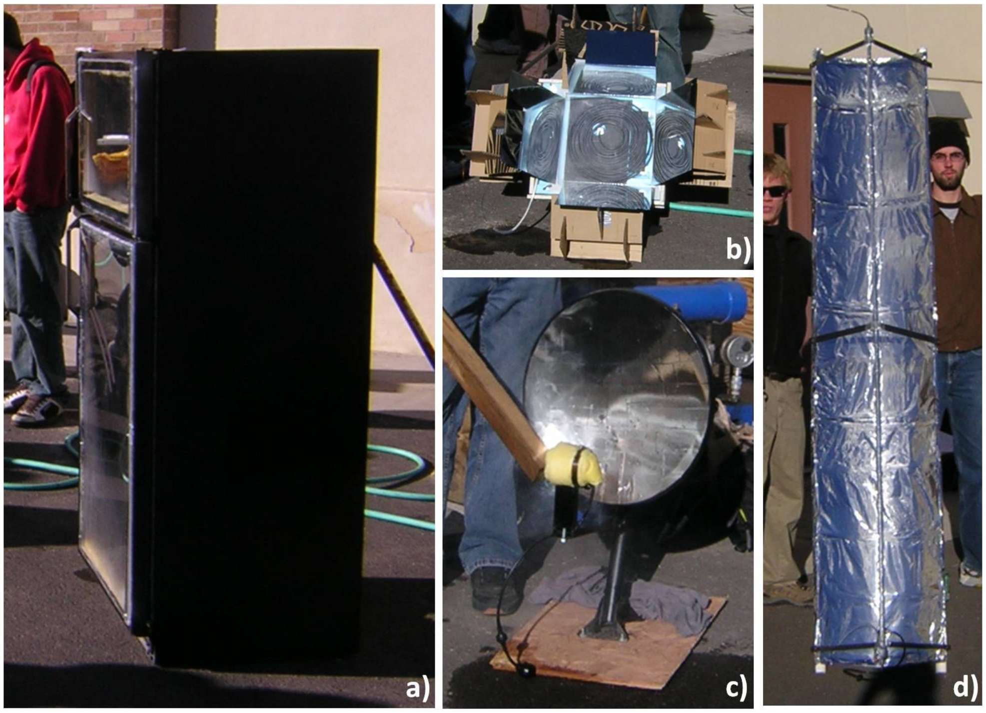

Figure 1. Solar water heater designs. a) scavenged refrigerator; b) mirrored collector; c) parabolic dish; d) parabolic trough.

3.2 Concept Inventory Results

Data for the pre-test, taken during the first week of the semester, and the post-test, taken during the final week of the semester are summarized in Table 1. A total of 35 students completed both the pre- and post-tests. Average scores are reported both for the entire inventory, as well as each of the three subtopics to which the questions pertain. The questions were designed to evaluate student misconceptions surrounding heat vs. energy, energy vs. temperature, and steady-state vs. equilibrium. At a 95% confidence level, statistically significant increases occurred for overall student performance and for performance on steady-state vs. equilibrium questions. A statistically significant increase also occurred for questions regarding heat vs. energy at a confidence level of 90%. No significant change occurred for student performance on questions regarding energy vs. temperature misconceptions. P-values were calculated using a one-tailed t-test, testing for an increase in performance.

Table 1. Average concept inventory results for all students

	Overall	**Heat vs. E**	**E vs. T**	**SS vs. Equilibrium**
Pre	45.6%	63.8%	41.3%	43.6%
Post	51.6%	71.4%	42.1%	62.9%
Difference (p-value)	**6.0%** *(0.04)*	**7.6%** *(0.06)*	**0.8%** *(0.43)*	**19.3%** *(0.005)*

Individual performance on the post-test was also examined and correlated with performance on the pre-test as well as the course grade. The data in Figure 2 and Table 2 both indicate significant correlation between the pre- and post-test at a 1% confidence interval; a weak correlation between course grade and post-test performance that is significant at a 10% confidence interval; and no correlation between course grade and the difference between pre- and post-test scores. P-values were calculated using a one-tailed distribution, testing for a positive correlation.

Table 2. Concept inventory and course grade correlations.

	Pre- vs. Post-Test	**Grade vs. Post-Test**	**Grade vs. Pre/Post Diff**
Correlation (p-value)	**0.512** *(0.0008)*	**0.232** *(0.09)*	**-0.058** *(0.6)*

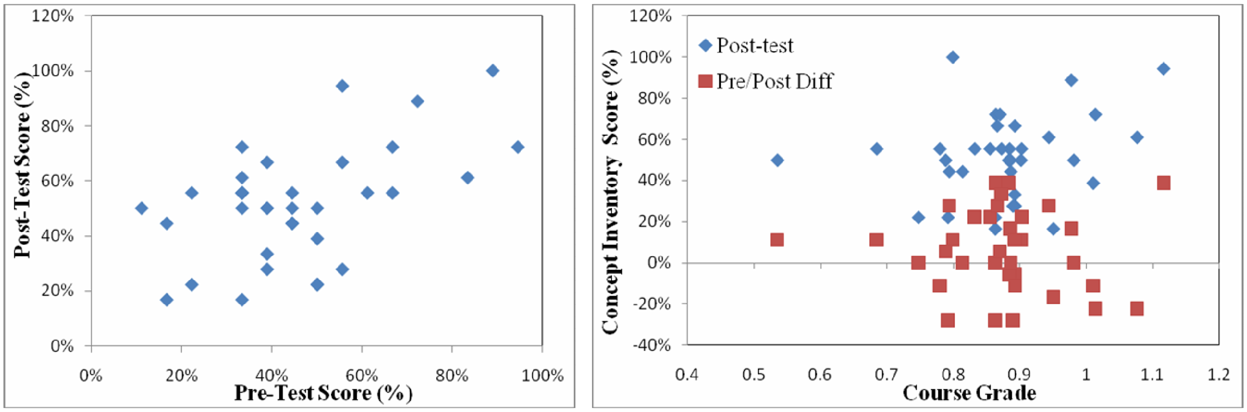

Figure 2. Left: pre-test score vs. post-test score, showing significant correlation. Right: concept inventory post-test and pre/post difference scores plotted against course grade. Weak correlation occurs for post-test with course grade, but no correlation exists for pre/post difference.

3.3 Self-Report Survey Results

The self-report survey consisted of 18 questions that asked the students to specify the degree to which the different aspects of the class (attending lectures, completing homework assignments, studying for examinations, and completing the design project) impacted their learning of concepts, application of concepts, and physical understanding. For the question regarding the component of the class which most impacted students' learning (see Appendix, question 13), the results are shown in Table 3. For all other questions, numerical values were assigned to the responses for each of the survey questions, with a value of 5 given to statements indicating the greatest help or impact and a value of 1 given to statements indicating no help or impact. Using this scheme, results were averaged for the 39 students who completed the survey and the data are shown in Table 4, which also indicates the associated question number from the survey. For the first twelve questions, which dealt with the degree to which different aspects of the class aided students in their understanding of concepts, application of concepts, and physical understanding, the data are further averaged to show average responses for each major component of the class: lectures, homework, exams, and the design project.

Table 3. Component of the class that most impacted learning (survey question 13)

	Project	**Homework**	**Exams**	**Lectures**	**Combination**
Number of Respondents	24	6	2	1	6

Table 4. Survey average responses.

	OVERALL GROUP	***Average Response***
Lectures: Concepts (1)	*3.97*	*4.18*
Lectures: Applications (2)		*3.82*
Lectures: Physical (3)		*3.90*
Homework: Concepts (4)	*3.60*	*3.77*
Homework: Applications (5)		*3.74*
Homework: Physical (6)		*3.28*
Exams: Concepts (7)	*3.39*	*3.51*
Exams: Applications (8)		*3.41*
Exams: Physical (9)		*3.26*
Project: Concepts (10)	*4.07*	*4.03*
Project: Applications (11)		*4.08*
Project: Physical (12)		*4.10*
Project: Motivation (14)		3.36
Project: Interest (15)		3.67
Integration: Physical (16)		3.28
Integration: Modeling (17)		2.88

3.4 Comments from free-response portion of survey

Comments from the free-response portion of the survey were generally positive, but also contained other pieces of interesting information. While there were many positive comments, some that were representative of the common theme include:

> "Hands on work and experience with the design project while working with the concepts learned from the book, greatly helped my understanding and interest in the class. Seeing how aspects of the book apply in real life helps my understanding of the class and the topics."

> "The design project allowed us to be creative in trying to find supplies with a $30 budget ($30 was perfect). The project pushed our understanding on how heat transfer really works. It was definitely one of the most fun projects we have done in the curriculum."

> "I thought the project was a great way to incorporate real life heat transfer problems into the class. I feel that alot of the times we take these classes and never see how it is actually applied in real life. I really enjoyed the project."

Comments regarding the integration of the two classes included the following:

> "We ran into a lot of troubles getting 350 done and then making it work for 495."
>
> "It would have been nice to have the 350 project due before the 495 project that way the analysis of the heater could have been used instead of just experimental for the lab report and presentation."
>
> "Nothing more to add besides emphasizing how useful and helpful it was being able to use the same project for ME495. The individual class requirements for the project on their own complimented the other class's really well as far as analysis goes."

Other comments regarded the difficulty, workload or complexity of the project. Representative examples include:

> "If we had an earlier understanding of analysis, then our design might have been better because we could have run preliminary numbers. I don't know how to offer a solution because there isn't enough time in the semester to learn the analysis first then do the project."
>
> "With that said our system was very complex along with most of the other projects in the class and essentially it was difficult to model the system using the learned heat transfer theories."

4.0 Discussion

4.1 Student Learning

Performance gains on the concept inventory were statistically significant, but overall they were minimal. More insight can be gained by looking more in detail at how concept inventory performance correlated with Heat Transfer course grade. There was a general positive correlation between course grade and concept inventory performance, and when grouped by course letter grade, average post-test scores increased with increasing letter grade. However, the only group of students for whom a statistically significant increase in performance occurred was those students who received a B in the class (p-value .04). The most significant gains for this group occurred on the steady-state vs. equilibrium questions, with an absolute increase in performance of 32.4% (a relative increase of 100%, p-value .003). That this should occur makes some intuitive sense. High performance on the concept inventory should depend primarily on two factors: mastery of the concepts being tested, and intrinsic motivation to do well on the test. The students receiving a C grade were those that lacked in one or both of these two areas, and a lack of significant improvement could be anticipated. On the other hand, the students who received an A grade ought to have some of both factors, but they also not surprisingly generally had better pre-test scores than the students who received lower grades in the class and thus had less room to improve. Also, it is possible that students with high grades in the class took the inventory less seriously, as their course grade was relatively assured already. In fact, several students who had displayed very high conceptual understanding on exams had significant decreases and very low post-test scores, which implies that motivation and effort may have been a significant factor. Alternatively, the B-students may have been the ones most likely to be struggling through the material and still trying to make sure they understood the concepts, while also still having room to improve from the pre-test. Increased incentive for the students to ensure maximum effort on the concept inventory would be beneficial and will be utilized in future iterations. It would have also been interesting to see how pre-test scores correlated with thermodynamics course grades, but those data were not available.

Post-test performance scores are consistent with other reported student performance data on heat transfer concept inventories.[2,4] That performance gains were minimal and post-test performance did not differ in any meaningful way from those reported from other classes imply that the design project may offer several benefits, but improving student conceptual understanding does not seem to be one of them. Moreover, no statistically significant correlation existed between design project grade and post-test score or pre/post difference. This lack of impact could be due to a lack of overlap between the concepts reinforced by the project and those tested on the concept inventory. The data in Table 3 showed that students overwhelmingly selected the project as the most impactful learning experience in the class, while the data in Table 4 showed that students on average rated the design project as the component that aided learning the most, while rating lecture attendance as slightly higher for understanding concepts. Comments such as those listed in section 3.4 reinforce that students found the design project helpful in deepening their conceptual understanding. It just seems that the concepts reinforced by the design project did not aid in the existing concept inventory.

4.2 Other Design Project Goals

In addition to improving conceptual understanding, other goals of the design project were to capture student interest and increase motivation, and also to connect experimentation and theoretical modeling. The survey results reported in Table 4 indicate that the project had somewhere between ‘moderate impact’ and ‘great impact’ on student experimentation and modeling. Positive reactions in the free reponse portion of the survey reinforce that the students found the design project to be an enjoyable and generally motivating experience.

In regards to the connection between experimentation and modeling, the project fell short. The low scores shown in Table 4 regarding how the integration of the project across both the Heat Transfer and Experimental Methods classes indicate that the students perceived relatively little value in the integrated aspect of the design project. The students reported some moderate gain in physical understanding due to the combination of experimental and theoretical approaches, but only saw little to moderate utility in the experimental aspect of the project aiding their model.

The degree to which students perceived the added value by integrating the design project across the two classes would be improved by increased coordination between the two course instructors. In this first iteration of the project, the instructors did not give significant discussion to how the project fit the other class. The instructors failed to communicate to the students how the experiments can be used to test, evaluate, and supplement theoretical modeling activities, and how developing the theoretical model guides the necessary experimentation. It was assumed that the laboratory assignments completed prior to the project would provide the students with the understanding of the theory-experiments relationship. Improved communication to the students of how both the experimental and design/modeling aspects of the project reinforce each other and work together should not only increase the degree to which students perceive the significance of the integration, but should also result in a better overall learning experience as students will better understand how to use the experimentation to inform the model and vice versa.

The expected in-depth comparison between the experimental and theoretical data, with identification of the causes for mismatch between the two, didn't occur primarily because of scheduling issues as a student explains this in one of the free-responses provided above. According to the student's comment, the project for the laboratory course was due before that for the heat transfer course, and the material needed to complete the theoretical analysis was covered in the Heat Transfer course after the Experimental Methods submission. Efforts will be made to correct such discrepancies in the future iterations.

4.3 Future Iterations

One issue that is a challenge to resolve concerns the timeline of the project. As indicated in several student responses, it is difficult to give students time to build the project while also having time to give them the information they need to build the model, which they would need to properly design an experiment. One possibility to mitigate this is to assign a design project that only requires knowledge of the heat transfer concepts taught in, say, the first half of the semester. However, this does not seem to be a good solution since it will exclude key heat transfer concepts that are taught later in the semester. The approach that will be incorporated in the next iteration is to include more scaffolding and milestones for development of the theoretical model. Improved experimental design should occur through forcing students to think through the model at an earlier point in the semester, coupled with improved communication regarding the purpose of the integration of experimental and theoretical approaches.

Solar-based projects seem to be an effective and simple way to incorporate radiation into a design project, and will be continued. While the solar water heater proved an interesting project, a new solar project will be used in the next iteration to avoid repetition and design stagnancy.

5.0 Conclusions

The solar water heater design project was well-received by the students and proved to be a valuable learning experience. However, that learning experience did not translate to improved performance on the heat transfer concept inventory, perhaps due to a lack of overlap between the misconceptions addressed on the inventory and the concepts that were reinforced by the design project. Improved coordination from the instructors between the experimental and theoretical classes is required to ensure that the mutually reinforcing aspects of the projects yield meaningful benefits to student learning. Ultimately, this coordinated design project between Heat Transfer and Experimental Methods courses showed significant potential as a learning approach, and the coordinated delivery will be refined in future course offerings.

Bibliography

1. Richard Hake, "Interactive-engagement vs. traditional methods: a six-thousand-student survey of mechanics test data for introductory physics courses," American Journal of Physics **66**, 64-74 (1998).
2. R.A. Streveler, R.L. Miller, M.A. Nelson et al., "Use of Concept Inventories to Identify Misconceptions in Thermal Sciences," proceedings of the 2nd International Conference on Engineering Education & Training, Kuwait City, Kuwait, 2007.
3. Marilia F Thomaz, I. M. Malaquias, M.C. Valente et al., "An attempt to overcome alternative conceptions related to heat and temperature," Physics Education **30**, 19-26 (1995).
4. Michael Prince, Margot Vigeant, and Katharyn Nottis, "Development of a concept inventory in heat transfer," proceedings of the American Society for Engineering Education Annual Conference and Exposition, Austin, TX, 2009.
5. P. Laws, D. Sokoloff, and R. Thornton, "Promoting active learning using the results of physics education research," Uniserve Science News **13**, 14-19 (1999).
6. I. A. Halloun and D. Hestenes, "Common-sense concepts about motion," American Journal of Physics **53** (11), 1056-1065 (1985).
7. C. D'Avanzo, "Biology Concept Inventories: Overview, Status, and Next Steps," Bioscience **58** (11), 1079-1085 (2008).
8. B. E. Jenkins, J. P. Birk, R. C. Bauer et al., "Development and application of a chemistry concept inventory," Abstracts of Papers of the American Chemical Society **227**, 1119-CHED (2004).
9. P.S. Steif and J Dantzler, "A Statics Concept Inventory: Development And Psychometric Analysis," Journal of Engineering Education **33**, 363-371 (2005).
10. Gary Gray, Don Evans, Phillip Cornwell et al., "The Dynamics Concept Inventory Assessment Test: A Progress Report," proceedings of the 2005 American Society for Engineering Education Annual Conference, Portland, OR, 2005.
11. M.F. Simoni, M.E. Herniter, and B.A. Ferguson, "Concepts to Questions: Creating an Electronics Concept Inventory Exam," proceedings of the 2004 American Society for Engineering Education Annual Conference & Exposition, Salt Lake City, UT, 2004.
12. E. Seymour, D. Wiese, A. Hunger et al., "Creating a Better Mousetrap: On-line Student Assessment of their Learning Gains," proceedings of the National Meeting of the American Chemical Society, San Francisco, CA, 2000.

Appendix

Self-Report Survey Given to HEAT TRANSFER 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
    d. much help
    e. great help
    f. n/a
18. What other feedback do you have regarding the design project that was not asked in the previous questions?