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A Design-and-Build Project for Heat Transfer Course

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A Design and Build Project for Heat Transfer Course

Abstract

Design and build type projects could constitute a part of experiential learning. This paper presents a design and build type project that was implemented in a senior level Heat Transfer course in mechanical engineering. The project was about designing and building of an insulation device that would keep a specified amount of hot water in a standard 250 ml beaker for extended period of time as warm as possible as well as the mathematical modeling and numerical simulation of the behavior of the insulation device. The project was first implemented in winter 2014 semester with considerable success and was assigned again for the second time in winter 2015 with improved specifications of the requirements and deliverable product and analyses. This paper will present the design project, which was run as a performance competition project among the students that were enrolled in the aforementioned course. The lessons learned and the feedback from the students are presented in the paper.

Introduction

There are three engineering majors in the School of Engineering at Grand Valley State University; Mechanical Engineering, Electrical and Computer Engineering, and Product Design and Manufacturing Engineering. Students in all majors have three semesters of mandatory cooperative education requirement as part of the curricula. In addition, the two-semester capstone design course normally involves industry sponsored design and build type projects, most of which are sponsored by the companies that also employ our students as coop students. Many of the engineering courses involve some kind of hands on experience either through laboratory work and or various types of projects. Some of the courses involve design and build type projects whereas others involve mostly conceptual design and analysis type projects. The senior level heat transfer course in mechanical engineering has, in the past, implemented various design projects. Some of the analysis type projects included modeling the thermal envelope of one of the engineering buildings and predicting the fuel usage for space heating during a typical winter day or for an extended period during the winter months and comparing with the actual usage obtained from the natural gas meter. Such analysis started from the information in the blueprints of the building to model the thermal envelope by modeling the various type of walls, fenestration, roof and ceiling and determining an overall heat transfer coefficient. A design and build type project dealing with the design of a shelter mostly from recycled materials has been assigned at different times in the past as described by Fleischmann et al[1]. Others have reported various implementations of design projects and project based learning into thermo-fluid courses[2-5].

For the past two years the author has used one mini-project/case study and one semester project, which was a design and build type project. The mini-project dealt with solving a two-dimensional steady state conduction problem with convective boundary conditions by numerical methods. The problem assigned is actually an example of a simplified gas-cooled turbine blade problem that is presented in the textbook by Bergman et al[6]. The students were required to solve the problem by both finite difference method as well as finite element method. In the first method, they were to derive the finite difference equations for each node and develop forms to implement into Gauss-Seidel iteration method. Here they were provided a solution algorithm but required to write their own code in their choice of C, C++, MATLAB, Visual BASIC, etc. The second part of the case study was to set up the same problem in FEHT (Finite Element Heat Transfer) package[7] and solve it for a mesh that results in comparable nodal positions as in the case of finite element nodal network they used for comparison. They were to subsequently refine the mesh and observe the differences in results if any. This case study has been successfully utilized by the author in reinforcing the understanding of numerical methods in heat transfer problems as well as enforcing the programming skills of the students to be put into use in addition to utilizing analysis tools such as FEHT.

Complementing the mini-project in which students had to work on and submit individual reports, a second design and build type project has been assigned to the students of the heat transfer course for the past two winter semesters. This project required the students to work in teams of two. Each team submitted a built product and a report describing their design. For mathematical modeling and numerical simulation the students were allowed to use any of the simulation packages they were familiar with both from the Heat Transfer course as well as other required or technical elective courses, such as Finite Element Analysis and Computer Aided Design. In the next section the details of this project are presented.

Project description and timing

The project titled “Keep it Warm” dealt with designing and building an insulation device that would keep a prescribed amount of hot water in a beaker as hot as possible for as long as possible. Some of the major requirements included the use of post-consumer materials or pre-consumer waste materials. Although this project was originally inspired by a similar project in the Science Olympiad for middle school students, the depth of analysis and modeling for numerical simulations and prediction of the expected performance of the designed device made it sufficiently challenging for the college students. The information provided to the students on the requirements and constraints of the design project were summarized in the handout, a copy of which is presented as attachment in Appendix A.

Each team was provided with a 250 ml beaker and a liquid in glass thermometer 5 weeks in advance of the due date of the project so that as they built their devices they could test the performance of their design and if necessary make any modifications to improve their design. Early on, on a couple of occasions the students’ attention was drawn to the fact that building a good insulating device was only part of the task. A good mathematical model to simulate the predicted behavior was equally important. This was done in the hope of avoiding any complex design for which building a model in the simulation software would be too challenging or outright impossible – for example in FEHT it is possible to solve a problem which can be easily built using Cartesian coordinate system or axi-symmetric geometry in cylindrical coordinate system. However, a mixture of two, for example, a rectangular prism envelope with cylindrical object inside would not be easily modeled as the software package is not versatile enough like commercial CAD or FEA packages. The laboratory facilities of the course were made available to the students so that they could test their projects at their convenience. Likewise, it is attractive to consider shredded paper or wood shavings as insulation materials but in mathematical modeling of the effective thermal conductivity and other thermophysical properties of such media can be rather complicated. A report was required to be submitted before the testing of the devices. Appendix B depicts the document that provided some guidelines in the report preparation.

The mini-project/case study on numerical methods in solving heat transfer problems, which involves the introduction of the FEHT software, is completed, submitted and graded by the seventh week of the semester. The design and build project was assigned during the seventh or eighth week of the semester and the project reports were due in approximately five weeks, which included the week of the spring break. The testing of the devices occurred immediately afterwards. The material covered in the lecture section of the course during this period included the introductory chapter on convection, chapters on forced convection in external flows, internal flows and free convection. This means that as the students worked on designing and building their projects and developing their simulation models they were going through the detailed discussion of convection for external and internal flows with forced convection and eventually one of the most important topic to their design: free convection.

Student projects

Two major geometries stood out in most of the insulating devices built by the students. One was a rectangular box with a cavity in the form of a cylinder to accommodate the beaker with hot water to be placed inside. Some of these designs used plywood or other kind of wood or polyurethane foam or polystyrene board of different types for the outer walls. A number of projects that used latter type of materials in board layer form just cut those, stack them together in layers without a need for an additional outer envelope. The second commonly used geometry was cylindrical. Different teams came up with different ideas, ranging from a used ground coffee container to an empty paint can to a simply rolled cardboard in cylinder shape with circular discs providing support at the top and bottom, to no special outer wall in the case of stacked layers of polystyrene cut in circular disc shape. The filling materials also ranged from shredded paper to wood shavings to cotton lint and straw simply stacked in cavities. Figures 1-4 depict some of the devices built by the students.

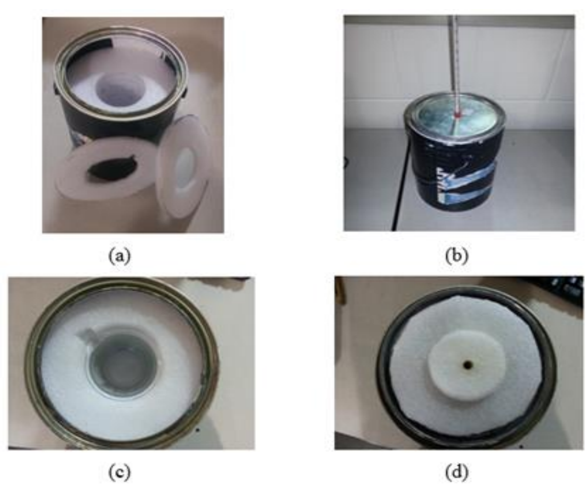

Figure 1. Project Example #1

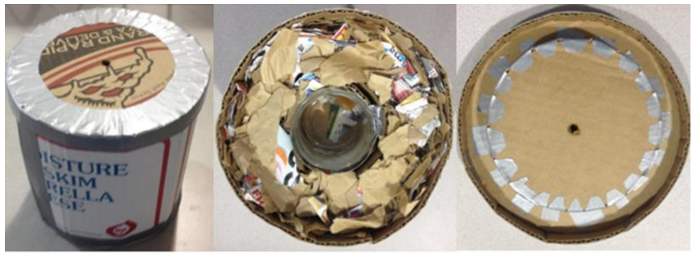

Figure 2. Project Example #2

Figure 3. Project Example #3

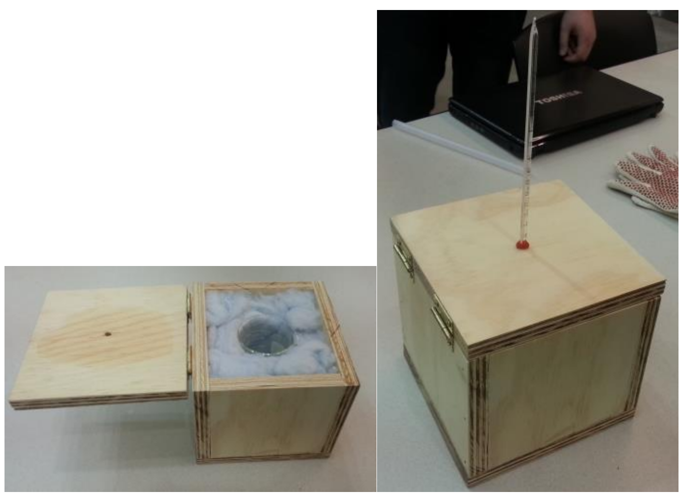

Figure 4. Project Example #4

As may be seen there was a good variety of design concepts and post-consumer materials utilized in the projects built by the students.

Testing procedure

On the day of the testing of the devices built by the students each team was provided with a second beaker of the same capacity and a pair of gloves. Each team was seated at a table with ample space to have their devices and a laptop computers to run the test and simulation program concurrently. A large kettle was used to bring water close to boiling. The instructor went around and disbursed close to 250 ml of hot water at each station. The students were instructed ahead of time that they had one minute to fill the second beaker up to 200 ml of hot water and insert the beaker into their insulating device and the thermometer into the water and take the first measurement of the water temperature. That would be the starting point of the testing of the device performance. From there onwards the temperature of the water was to be recorded at one minute intervals on a data sheet provided by the instructor. At the same time the simulation program was to be started with the initial condition of the water temperature coming from the first measurement. The duration of testing as set at 50 minutes. The students did not know a priori what this duration was going to be. They were told that they could expect the duration to be at least 40 minutes. At the conclusion of the testing the students were asked to submit their raw data sheet for experimental temperature readings and the corresponding temperature time history from their simulation models.

Observations

Our engineering students have ample hand-on experience on simple manufacturing processes in a workshop and the woodshop of the School by the time they reach senior standing and take this course. Therefore, the students have had no difficulty in working on the building part of a project. It was expected that they would have some challenges in the modeling and simulation part of the project. This was partly due to the limitation of the capabilities of the software package that might have been used and partly due to limited knowledge of how to define and implement the proper boundary conditions in numerical simulation. Moreover we covered the topic of natural convection at about the same time as the project due date was set. So for instance, although most students recognized the convective boundary conditions on the top and side walls of their devices, only a few of them realized that there are empirical correlations for vertical and horizontal surfaces in their textbook that could be utilized for the Nusselt number to yield the convective heat transfer coefficients. Instead some used “typical values” that they had used in tutorial problems in their Finite Element Analysis course. It was common to model the body of hot water as a stagnant pure conductive medium. Modeling the body of air above the water surface was the most challenging part. Since this is an inherently transient problem there is a continuously varying air temperature in the cavity. Trying to model heat transfer between the surfaces bounding the cavity and the air inside was rather difficult. It is interesting to note that although we formally covered using FEHT software in the mini-project before this project few students opted to use FEHT in their simulation analyses. In winter 2014 only about one sixth of the teams used FEHT. The rest used SolidWorks[8] FEA analysis modules. In winter 2015 out of 11 teams, only two teams attempted to use FEHT at first only to switch to SolidWorks afterwards. Even though SolidWorks FEA analysis is introduced and used in an elective intermediate CAD course that roughly half of the mechanical engineering majors take, they recognize the additional capabilities of the software and its user friendliness. On the positive side, some of the more curious students took initiative to model the air cavity in the device using a CFD approach with natural convection. One team even used this approach on the exterior walls of the device by extending the computational domain appropriately. It was not difficult to tell that those happened to take a CFD course as an elective course.

In summary the main challenges encountered by the students included the following: (1) Difficulty in finding the thermophysical properties of some of the post-consumer materials, (2) Difficulty in modeling the average/effective thermophysical properties of materials they manufactured from post-consumer materials, e.g., shredded packed paper, (3) Modeling the hot water and any air cavities within the insulating device - most common approach was to model the fluids as stagnant bodies, (4) Difficulties with external boundary conditions especially natural convective boundary conditions - some students oversimplified using typical range values for the convective heat transfer coefficient instead of recognizing the available correlations for horizontal and vertical flat surfaces and vertical cylindrical surfaces.

The student success in predicting the experimental results showed some variation but overall could be considered good. More than 60% of the students predicted the water temperature after 45 minutes of testing time to be within less than 2^oC difference with experimental values. Only a few cases were observed with a difference of 8^oC or more between experimental and predicted temperatures in the two offerings of the course.

Implementation challenges and recommendations

One of the significant challenges of assigning this project was with time limitation and the other was the timing of the project. The first numerical mini project/case study that forms a prelude to this project cannot be assigned very early in the semester; steady state multi-dimensional conduction has to be covered before that. It is also desired that course projects other than the senior capstone project be completed before the final week of classes. This leaves a relatively short period of approximately five weeks for this project. Meanwhile some of the material that might be needed for successful completion of the mathematical modeling and numerical simulation will still be going on during this period. This puts a lot of pressure on the students even though our students are in general used to these conditions from a number of courses in the curriculum. Ideally it would be best to assign this kind of project early in the semester and stretch it throughout the semester to cover more relevant material in the lectures and give students more time to complete the project. If the first numerical project is mandatory the timing of the two projects could possibly overlap with one another. Another possibility is to cut back on the finite difference program implementation and concentrate on the finite element solution using FEHT.

Results of student survey

A student exit survey was conducted to evaluate the student feedback on this design and build type project. A copy of the survey is presented in Appendix C. The responses to the questions that could be compiled in the form of a bar chart or table are presented in Figures 5-7 and Table 1. The majority of the students liked the idea of having a design and build type project. They, therefore, thought that this type of project should be assigned in this course in the future. The question of whether the requirement for modeling and simulation in this project was a valuable learning experience that should be incorporated in more of the engineering course received a 78% positive response while the rest of the students were split equally as either indifferent or having negative response. A significant majority of the students (approximately. 90%) thought the timeline of the project was reasonable/ appropriate. The remaining questions required that the students answer the question in the form of a short statement or comment.

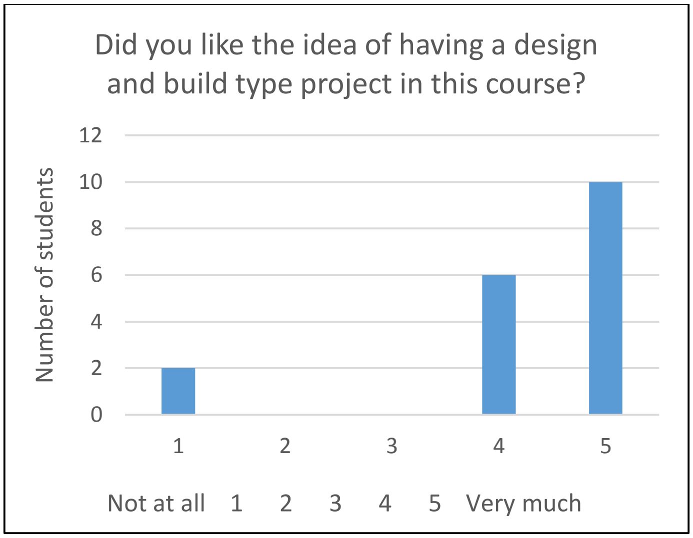

Figure 5. Responses to Question 1

Table 1: Responses to Question 2

Answer	Number of students	% of students
Yes	16	88.89
No	0	0
Maybe	2	11.11

The students overwhelmingly responded by saying the most challenging part of the project was (modeling and) simulation including deciding on material properties. Part of the reason for this might be that some of the topics needed for proper modeling were still being covered in the class as the students worked on their models. One student stated that finding post-consumer products was the most challenging part.

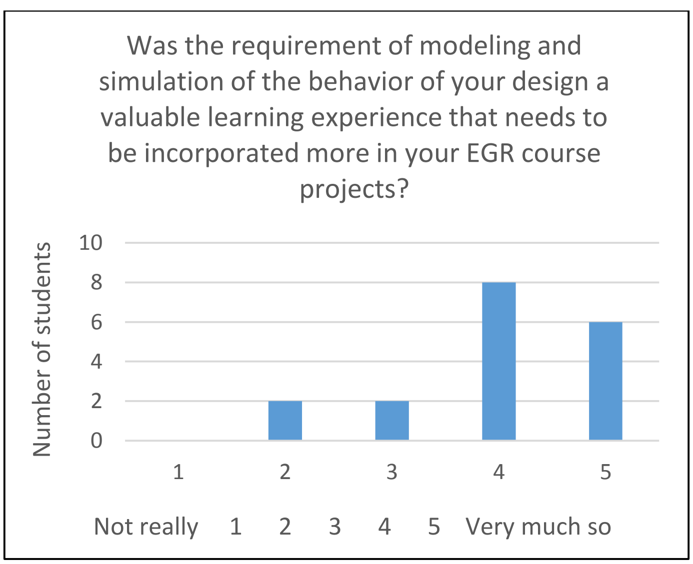

Figure 6. Responses to Question 4

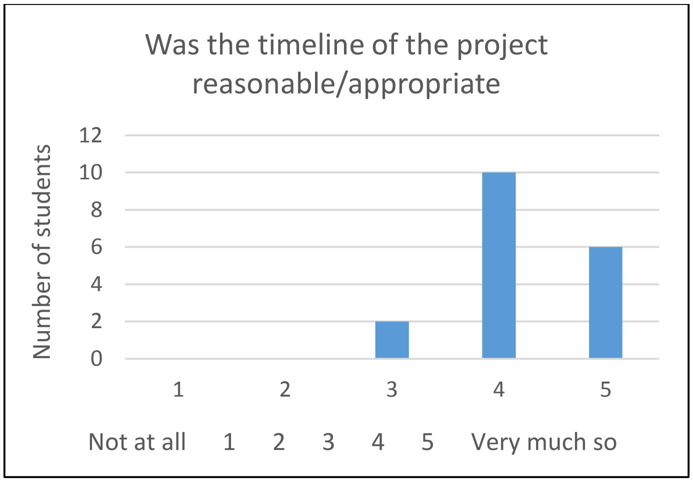

Figure 7. Responses to Question 5

For the most enjoyable part of the project, two thirds of the students directly responded as building (constructing) the device. A couple of students stated building and testing while another couple of students enjoyed "realization of the results and comparing to predictions" and "seeing similar results between simulation and experiment".

The largest variation in the responses came from Question 8, in which the students commented on what part of the project they found least enjoyable. The responses varied from material handling to simulation/modeling, looking for thermal properties of materials (research) to testing the device, being quizzed on the simulation to writing the report. Whereas the students' responses showed small deviation about what they found most challenging or most enjoyable, they seemed to differ widely on what aspects of the work they found least enjoyable.

Assessment

Quantitative assessment of the benefits of the design and build project to the students has not been attempted in this work. This issue requires a careful design of questions in the form of a quiz or as part of the final exam of the course to gauge whether the understanding of the material has improved as a result of implementing this project. The author plans to take that into consideration in the future. It is, however, the opinion of the author that this kind of project has some significant contribution to the students' understanding of some key issues in heat transfer applications. First, the students are forced to do research or even come up with a model of evaluating the thermophysical properties of materials that are not readily available in textbooks or even on-line sources. Secondly, many design problems require the use of modern computational tools such as commercial or other software programs. Having been introduced to the use of these particularly for solving heat transfer problems prepares them better for their future career as practicing engineers. The modeling and simulation part of the project instills a better understanding of how one implements the boundary conditions to the numerical solution of a heat transfer problem as opposed to how boundary conditions are applied in the theoretical/ analytical solution of the governing equation for simple problems that can be solved that way. This particular project also forced students to consider contemporary issues such as using recycled materials or post-consumer materials and the effect of such practice on the environment, society and economy. Likewise being forced to learn or improve their knowledge and skills of a simulation software is a valuable practice of life-long learning process. Both of the latter two are emphasized in ABET criteria.

Conclusions

A design and build type project was introduced into a senior level Heat Transfer course. The project was planned as a complement to the earlier mini project/case study that introduced the students to the numerical solution methods to heat transfer problems; namely finite difference method and finite element method. It was observed that majority of the students opted to use the more sophisticated simulation software with better capabilities but requiring more time to build and simulate a model rather than a simple to use software with less capabilities.

Challenges in implementation of this kind of project were identified and recommendations were provided for improvement and implementation. A qualitative assessment of the value of implementation of this kind of project into a Heat Transfer course was also provided.

A survey was conducted on the student feedback on this design and build type project. In general there was a wide agreement that such a project was beneficial and should be continued to be assigned in the future. The students generally found the modeling and simulation part most challenging while majority of the students found the building of the device most enjoyable.

The assigned design and build type project covers aspects that can be used for assessment for ABET's criteria i (a recognition of the need for, and an ability to engage in life-long learning) and j (a knowledge of contemporary issues) and the author has been working on evaluating the students' work for submitting the necessary assessment documentation.

References

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6. Bergman, T., Lavine, A., Incropera, F. and Dewitt, D., 2011, *Introduction to Heat Transfer, 6th Ed.*, John Wiley & Sons, Inc., Hoboken, NJ, pp. 251-256.
7. FEHT Finite Element Heat Transfer© 2015 by F-Chart Software, LLC., Madison, WI.
8. SolidWorks© 2002-2015 Dassault Systèmes.

APPENDIX A

PROJECT REQUIREMENTS AND CONSTRAINTS

EGR 468 Heat Transfer
Winter 2015
Keep it Warm
Design Project

Description: Teams of two members must construct an insulated device to retain the thermal energy of an initially hot quantity of water in a beaker of specified size. A simulation program that can predict the temperature of the water in the beaker as a function of time must also be developed and submitted.

Construction: The device may be of any geometric shape but must fit within a $20 \text{ cm} \times 20 \text{ cm} \times 20 \text{ cm}$ cube.

(a) Material: You may use any post-consumer (as defined by Merriam-Webster dictionary: (1) discarded by an end consumer, (2) having been used and recycled for reuse in another consumer product) waste material or pre-consumer waste material such as manufacturing scrap, e.g., trimmings from paper production, etc.
(b) A well-defined envelope such as plywood enclosure is needed for your device.
(c) Within the device you must be able to easily insert and remove the 250 mL standard, beaker provided to you.
(d) The device must easily accommodate the insertion and removal of a liquid-in-glass type thermometer into the beaker via a hole that is at least 8 mm in diameter all the way through directly above the beaker. The top surface of the hole must be less than 2.5 cm above the top lip of the beaker. The hole must remain open and unobstructed during the competition.
(e) Devices cannot contain any energy sources (e.g., no electrical components, small battery powered heaters, chemically reacting material, etc.). You may be asked to disassemble the device at the end of the testing period in order to verify the materials used in construction.
(f) No part of the device should be significantly different from room temperature at impound.

Simulation program: For developing a model and running the simulation of the behavior of the system designed and built you may use any of the standard analysis packages such as FEHT, ANSYS, SolidWorks FEA, Star CCM, etc., or write your own simulation program. The simulation program will be run on-site at the beginning of the competition for predicting the behavior of the device for a specified period of time. The predicted results must be presented to the instructor at the end of the testing period.

APPENDIX B

PROJECT REPORT GUIDELINES

EGR 468 Heat Transfer
Project Report Guidelines

Format requirements: The report must be word-processed using Times New Roman font, font size 12, and 1.5 line spacing throughout the report.
The following must be specifically addressed:

- Description of the general approach in designing and building your insulation device. Your choice of materials and the reasons for your choices should be clearly stated. Keep in mind the project requirements/constraints provided previously.
- A clear listing of all the materials used and their source(s). The thermophysical properties of the materials (all of ρ, c, k are critical for a transient problem) and their sources should be stated. If you formed your own material from post-consumer materials (such as shredded paper filling a space) you need to discuss how you modeled or experimentally determined the necessary thermophysical properties.
- A discussion of the physical structure and the mathematical model. Present screenshots from the software about the solid model, if necessary sectional views for clarity. The mathematical model should clearly state the initial and boundary conditions for your system. If you include any contact resistance between touching surfaces you need to state so.
- Discussion of preliminary results. How well did your system work and how well did your experimental runs match with your predicted results? What improvements did you consider/apply in the physical structure and mathematical model?
- Considering the constraint of having to use post-consumer materials, provide a discussion on the global, economic, environmental and societal impact of such designs in general (not just limited to this particular design).

Please submit a hard copy of your report as well as an electronic copy. The electronic copy should have the filename of **lastname1lastname2.xxx** where xxx can be doc, docx, pdf, etc.

Due: 5:00 PM, Friday, April 10, 2015

APPENDIX C

STUDENT EXIT SURVEY

Survey on the Keep it Warm Project, EGR 468 Winter 2015

This survey is conducted in order to obtain feedback from the students that worked on a design and build type project titled “Keep it Warm”.
The scale used in the answers to some of the questions below is a 1-5 scale explained as appropriate

1. Did you like the idea of having a design and build type project in this course?

   Not at all 1 2 3 4 5 Very much

2. Do you think such projects should be assigned in this course in the future?

   Yes No Maybe

3. Did you find this project to be challenging in one or more aspects? If yes, which aspect(s)?

4. Was the requirement of modeling and simulation of the behavior of your design a valuable learning experience that needs to be incorporated more in your EGR course projects?

   Not really 1 2 3 4 5 Very much so

5. Was the timeline of the project reasonable/appropriate?

   Not at all 1 2 3 4 5 Very much so

6. What was the most challenging part of the project?

7. What was the most enjoyable part of the project?

8. What was the least enjoyable part of the project?

9. Do you have any suggestions for improvement of this type of project? Any other comments?