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Application of Finite Element Software to Bridge the Gap between Hand Calculations and Experimental Results in Undergraduate Heat Transfer Education*

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A project involving the design, building, and testing of a hot liquid thermos was implemented in a junior level mechanical engineering heat transfer class. Finite element analysis (FEA) software was used to bridge the typical gap between hand calculations of heat transfer performance and experimental results. On average, student hand calculations over-predicted the thermos's thermal resistance by 124% as compared to experimental results. FEA, in the hand of undergraduate students, over-predicted the thermal resistance by only 33%. Student self-assessment survey results showed an overall positive feeling regarding the project. Despite the increased accuracy of FEA, 60% of students indicated that hand calculations were a more useful design tool, 65% indicated that they learned the most from hand calculations, and 75% indicated that hand calculations would be the future method of choice when heat transfer problems arise.

Keywords: finite element; heat transfer

INTRODUCTION

TYPICAL UNDERGRADUATE heat transfer education, as part of an engineering curriculum, includes design projects in addition to traditional homework assignments and exams. Due to time and resource issues, these projects typically do not involve more than a "design on paper". More recently, the effectiveness of transforming these projects from "paper designs" to actual building and testing of devices has been well established in engineering education literature. Although extremely beneficial to the student, this shift to a "design, build, test" strategy for engineering education can pose its own unique challenges. Specifically, as these projects become more complex, the assumptions typically used during the design process, which are thoroughly reinforced in the classroom and homework assignments, break down. With heat transfer projects, large discrepancies often exist between predicted temperatures from "paper design" engineering calculations and results obtained after the system is built and tested. In other words, components, which on paper should be strong enough, often fail during testing. While this is extremely educational for the student, it can be very confusing, and lead to a lack of confidence in the engineering fundamentals emphasized in textbooks.

To bridge this discrepancy gap between design and experiment, COMSOL Multiphysics finite element analysis (FEA) software was used in an undergraduate heat transfer project as an intermediary step. The use of various software packages in undergraduate heat transfer education is common today. Diverse applications such as the use of very specific design software for heat transfer unit operation analysis [1] as well and web-based software for heat transfer education [2] have been demonstrated. Specifically to FEA, its use throughout an entire curriculum, not just for a heat transfer course, has been proposed [3]. While finite element analysis has commonly been used in undergraduate heat transfer student projects for design purposes [4], as well as in other mechanical engineering fields in combination with experiments for enhanced undergraduate education and understanding [5], its application specifically as a bridge between hand calculations and experiment, and a student assessment of its value during the design process, is a unique aspect of this study.

For this specific project, teams of students were asked to design and build a liquid thermos, and do three things along the way: predict the heat loss rate using hand calculations, predict the heat loss rate using FEA, and measure the heat loss rate experimentally. All 26 mechanical engineering students undertaking the project were near the end of a semester-long course in undergraduate heat transfer. Course topics included: governing PDEs of heat conduction, 1D and 2D steady state conduction, transient conduction, fundamentals of convection, internal and external convection, radiation, and heat exchanger design. The course also covered finite difference methods for solution

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of 2D steady state conduction problems. All students taking the course were familiar with thermodynamics, fluid mechanics, solid mechanics, and CAD solid modeling.

IMPLEMENTATION

Beafore project implementation, students were given approximately an hour of instruction on the basics of finite element modeling, half an hour introduction to the project, and an hour tutorial on the software itself. It must be noted that while several students went on to take dedicated courses in FEA, background knowledge among the class was limited at the project's beginning. The one hour introduction to the finite element method built upon the students' knowledge of heat transfer and finite difference methods. Because of limited FEA background, during actual modeling, students relied heavily on their physical understanding of heat transfer to produce accurate models.

During the project introduction, students were asked to design a thermos to hold hot or cold liquids. The thermos had to hold at least 355 mL of fluid and had to be entirely manufactured from raw materials by the student team (except for a thermocouple and compression fitting). Due to corrosion and chemical leaching from plastics at elevated temperatures, all wetted surfaces had to be manufactured from non-corrosive metals. Non-wetted surfaces were free. In addition to these constraints, the devices had to be leak proof while inverted. To limit final design size, the user had to be able to drink from the thermos using only one hand. The thermoses were to be tested by measuring coffee temperature as a function of time, with air blowing over the thermos at 5 m/s via a box fan during testing. For the project, students worked in teams of three to four. At the project conclusion, each team had to submit a written report containing all calculations, experimental data, design drawings, the team's FEA model, and design methodology. The teams were given roughly two weeks to complete the entire project.

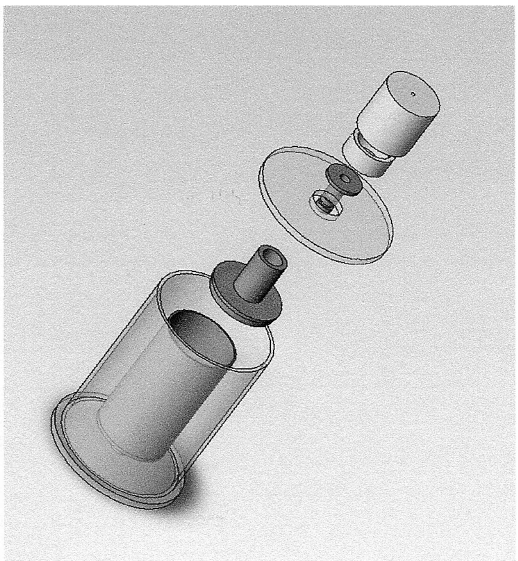

Fig. 1. Typical student team CAD design.

MODELING AND EXPERIMENTAL TECHNIQUES

Teams typically first came up with a rough design and used 1-D thermal resistance network calculations to model the thermos. They also

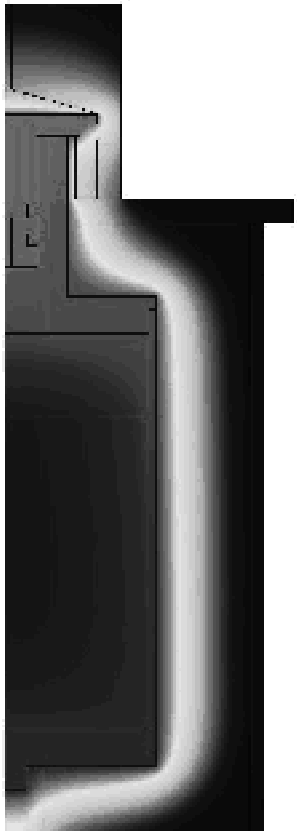

Fig. 2. Typical student team axi-symmetric FEA results.

Fig. 3. Thermos testing.

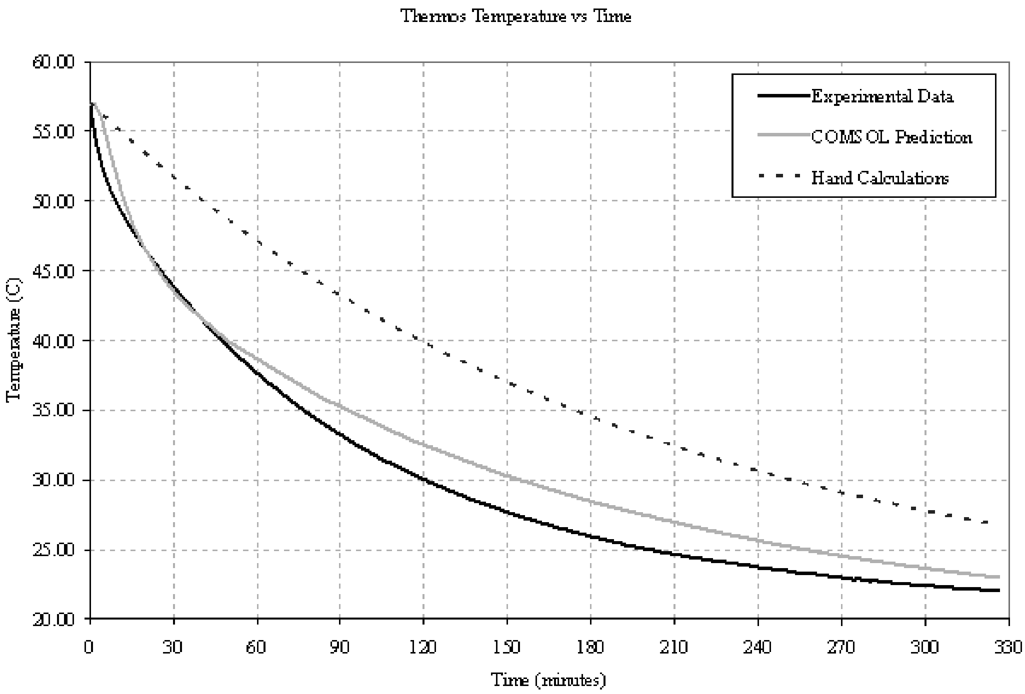

Fig. 4. Typical student comparison of hand calculations, FEA predictions, and experimental results.

typically used a lumped capacitance model for transient heat transfer to estimate liquid temperature as a function of time. After this, most teams produced CAD models for manufacturing purposes. In addition, student teams imported these CAD models into the FEA software for modeling purposes. To simplify the solutions, most teams took advantage of their thermos' axi-symmetric nature, and performed a 2-D simulation of transient heat transfer. For the student teams, modeling in the FEA software first involved defining material properties for their thermos. External surface boundary conditions involved a convection condition. Each team calculated average convection coefficients using cylinder cross flow correlations. After modeling, student teams constructed their thermoses. Experimental testing involved measuring hot coffee temperature, via a thermocouple, as a function of time. Figures 1–3 show a typical CAD design, FEA results, and experimental testing respectively.

RESULTS AND DISCUSSION

Figure 4 shows typical student team results. The graph indicates coffee temperature in the thermos as a function of time. As shown, in general, hand calculations over-predicted performance, FEA to a lesser extent, as compared to actual experimental measurements. Table 1 shows the measured thermal resistance of each team's thermos (higher values are better). In addition, the percentage over-prediction is shown. On average, 1-D hand calculations over-predicted the thermal resistance by 124%, while FEA only by 33%. It is important to note here that the fundamental heat transfer equations solved via hand calculations and FEA are the same, but the hand calculations involve a great deal more assumptions than the FEA model. Furthermore, the hand calculations were all 1-D solutions to the heat conduction equation while the FEA simulation was an axi-symmetric 2-D simulation. As shown, this level of inconsistency was not

Table 1. FEA and hand calculations comparison

Team Name	**Experimental Value, K/Watt**	**FEA Over-Prediction**	**Hand Calculations Over-Prediction**
Duck2	4.00	45%	253%
Mug	9.08	28%	164%
Scooby Doo	7.08	92%	122%
Spiderman	6.73	16%	70%
Thermonator	9.80	0%	85%
Thrown From the Lathe	4.84	0%	0%
Vacuum	12.23	51%	176%
Average	7.68	33%	124%

universal among all teams. In particular, two of the seven teams' FEA model only over- predicted by less than 1%, and one team's hand calculations were accurate to within 1% of experimental results. With their hand calculations, these teams with higher accuracies typically used larger thermal resistance networks to account for the thermos's top and bottom surfaces, as well as more accurate material properties to achieve better results. With their FEA simulations, these teams typically had much more detailed and accurate CAD models of their thermos.

In addition to this, students were surveyed regarding the extent to which FEA software served as a bridge or barrier between hand calculations and experimental results, and whether it or traditional calculations were more helpful during the design process. For questions 1 through 6, responses were given on a 1–5 scale, with a score of unity corresponding to "Strongly Disagree", three corresponding to "Neutral", and five to "Strongly Agree". Questions 7 through 10 on the survey were multiple choice in format. The questions used, and student responses, are shown in Tables 2 and 3. As shown, most students disagreed with the statement that FEA software "should not have been included in the course". Students were neutral with respect to their PDE comfort before the project, and agreed that they were comfortable with PDEs after the project. Questions 4 through 6 show students strongly feel that future classes of mechanical engineering students should repeat the project, that FEA software provided a bridge between hand calculations and experimentation, and that finite element modeling should be taught in undergraduate heat transfer courses.

However, questions 7 through 10 were the most revealing. When asked which method, hand calculations or FEA modeling, was the more useful design tool (Question 7), 60% of students responded the hand calculations were superior. When asked about all three project phases (Question 8), 65% of students felt they learned the most about heat transfer from the project's hand calculation portion, with the experimental portion coming in second place with 19%, and FEA modeling coming in last with only 15%. In addition, 75% of students stated they would turn to hand calculations first next time they are faced with a heat transfer scenario (Question 10). Despite finding it not as useful nor as the best learning tool, 60% of students had the most faith in their FEA calculations (Question 9). These four questions seem to indicate that after an initial introduction to FEA modeling and a project involving its use, student comfort level, understanding of heat transfer, and future first analysis technique is still hand calculations. However, a majority of students seem to have quickly put trust in the results of their FEA modeling as opposed to hand calculations.

CONCLUSIONS

A project involving the design, analysis, building, and testing of thermoses was undertaken in an undergraduate heat transfer course. Project goals

Table 2. Survey questions 1–6 and results

Question	Average Response	Standard Deviation
1. Finite Element Analysis (FEA), like COMSOL, should not have been included in this project.	1.76	0.83
2. Prior to taking Heat Transfer, I felt comfortable with partial differential equations (i.e. equations like the steady state heat conduction equation).	3.08	1.04
3. After taking Heat Transfer, I feel comfortable with partial differential equations (i.e. equations like the steady state heat conduction equation).	4.12	0.78
4. Future classes of Mechanical Engineering students should do this project.	4.4	0.91
5. FEA software provided a bridge between hand calculations and experimental tests.	4.48	0.51
6. FEA software should be taught in Heat Transfer	4.52	0.59

1—Strongly Disagree; 2—Disagree; 3—Neutral; 4—Agree; 5—Strongly Agree.

Table 3. Survey questions 7–10 and results

Question	Hand Calculations	FEA Modeling	Experimental Results
7. Which analysis method was overall a more useful tool in helping you design your thermos?	60%	40%	N/A
8. In which part of the project did you learn the most about heat transfer?	65%	15%	19%
9. You trust and/or put the most faith in:	16%	60%	24%
10. Next time I am faced with a heat transfer situation, the first thing I will do is:	75%	17%	8%

were to use FEA software in an attempt to bridge the gap between hand calculations and experimental results. Analysis software was successful with this task. On average, 1-D thermal resistive network hand calculations over predicted thermal resistance by 124% compared to experimental results. Student finite element modeling over predicted the thermal resistance by only 33% on average.

Student self-assessment surveys were also used to quantify project effectiveness. Students were in strong agreement that FEA software should be taught in future heat transfer classes and that it provided a bridge between hand calculations and experimental results. Student perception seems to be that finite element modeling more accurately represents their experimental results, but hand calculations, despite their increased inaccuracy, are easier to use and will turn to when faced with a future heat transfer situation. Furthermore, students overwhelmingly reported that hand calculations were the more useful learning tool.

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