A Hands-on Activity to Assist Students in Making Connections between Topics in Heat Transfer

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Abstract

The preliminary work presented here consists of an educational module designed for a course in thermal fluid sciences focused on fundamental thermodynamic and heat transfer principles. The hands-on, project-based activity promotes entrepreneurially-minded learning by encouraging students to connect information across topics in both courses to solve a real-world problem. This was accomplished using a project-based approach where students conducted an experiment to investigate the cooling of pizza. Students had to apply the 1st Law of Thermodynamics and fundamental heat transfer principles, such as conduction and convection, to determine the optimal temperature to eat the pizza and an estimated delivery time. To do this students were required to go beyond basic problem-solving and forced to apply theory from multiple courses to solve an ill-defined problem. The author has delivered the course Thermal Fluid Sciences II five times and implemented the module in two of the five deliveries. After the most recent execution in fall 2019, a preliminary study was conducted via student surveys to determine if students considered the module a valuable addition to the course. These preliminary findings aimed at not only determining if the module should be continued in the future, but also at evaluating if the module resulted in: (1) increased student engagement and interest in thermal fluids, (2) increased learning effectiveness compared to traditional teaching methods, and (3) increased understanding of how topics within thermal fluids are connected. Exam scores between course sections that completed the module and those that did not were also compared to provide quantitative data regarding increased learning effectiveness. Preliminary findings conclude that students perceive this module to be a great tool for not only improving learning effectiveness and engagement, but also helping them connect information across topics. A comparison of exams scores and class averages between the two semesters the module was delivered and the three semesters the module was not, showed an improvement in scores in two of the three semesters. Future work will include improving the module to enhance the understanding of transient conduction and collecting more data to obtain a statistically significant data set.

Introduction

There are numerous articles in the literature describing the widespread poor learning of basic concepts and principles within thermal fluids courses, i.e. fluid mechanics, thermodynamics, and heat transfer[1, 2, 3]. These are concept heavy courses that students often struggle with due to their abstract nature[4]. Thus, students simply memorize equations and never truly understand what those equations mean or how to apply them[4]. In addition, when students are asked to provide explanations or reasoning while problem solving, they often struggle and fail. Finally, these courses usually require coverage of a wide breadth of topics in a short period of time, making them especially challenging to teach effectively[1,2,3].

In response, educators have developed real-life examples, hands-on experiments, and projects to tackle difficult concepts, helping students connect abstract ideas to actual hardware[1]. However, these activities tend to focus on a single concept in one course, for example head loss in fluid mechanics. They do not encourage students to connect information across topics or courses, an important component in graduating entrepreneurially minded engineers[4,5,6].

Realizing this student perception of, and difficulty with, thermal fluids courses, plus the shortfall of existing activities, a project-based learning module was designed at the Rochester Institute of Technology for Thermal Fluid Sciences II (MCET 530), a senior level mechanical engineering technology course. It was hypothesized that by implementing a module focused on how to integrate and apply knowledge across several topics within thermal fluids, students would gain a better understanding of fundamental concepts and know how to apply them, becoming better engineers.

The module is a project-based, hands-on activity designed to address student difficulty with fundamental heat transfer principles, such as conduction and convection. The module also requires students to not only make connections between multiple heat transfer concepts, but also back to thermodynamics. In the activity students connect abstract ideas within thermal fluids by analyzing the cooling of various types of pizza slices from delivery to consumption. The project provides students not only with the understanding of basic concepts and principles, but also how this information can be integrated to solve a problem. This takes students above basic problem solving and makes them think about how to approach a real-world solution.

This preliminary work was motivated by the questions: did students perceive this activity to help them connect information regarding the different types of heat transfer to solve a real-world problem? Did this hands-on activity improve knowledge retention and comprehension, as demonstrated by exam performance? A preliminary study was conducted to determine if the activity did help students connect information across topics and gain a better understanding of fundamental principles.

Heat Transfer Course Module

Overview

The work proposed here consists of an educational module designed for Thermal Fluid Sciences II, a core Mechanical Engineering Technology course at the Rochester Institute of Technology focused on Thermodynamics and Heat Transfer. The module promotes entrepreneurially-minded problem-solving by encouraging students to connect and apply principles across topics within thermal fluids to solve a real-world problem.

Details

In mechanical engineering technology at the Rochester Institute of Technology, undergraduate students, typically in their fourth or fifth year, are required to take the course Thermal Fluid Sciences II. This course covers topics in both Thermodynamics II and Heat Transfer. For the Heat Transfer content, students learn how thermal energy moves by conduction, convection, and radiation in real-world systems. Each key concept consists of several related topics, such as Thermal Circuits, Heat Diffusion Equation, and Transient Conduction, which were presented via lectures in class. The goal of this module was to encourage students to not only connect information across these heat transfer topics, but also back to what was learned in Thermodynamics.

The project starts by each student selecting two slices of pizza. In this course since students are only taught one-dimensional heat transfer, they analyze the heat transfer leaving the sides of one slice and the top of the other. A comparison of the heat transfer analysis of each slice is done throughout the project.

To start, students create schematics of the initial temperature distribution in each slice of pizza. They use a combination of bulb and infrared thermometers to measure the initial temperature from the center of the slice of pizza to the outside. For each slice, several data points are taken from the center to the edge of the slice (side for once slice, top for the other).

The ambient temperature is recorded, along with the time of delivery and time of initial temperature measurement. Figure 1 shows a student and author example of the initial temperature distribution for each slice of pizza.

The overall length, width, and thickness of each slice is measured using calipers. The thickness of each layer, i.e. crust, sauce, cheese, and pepperoni, is also measured and recorded.

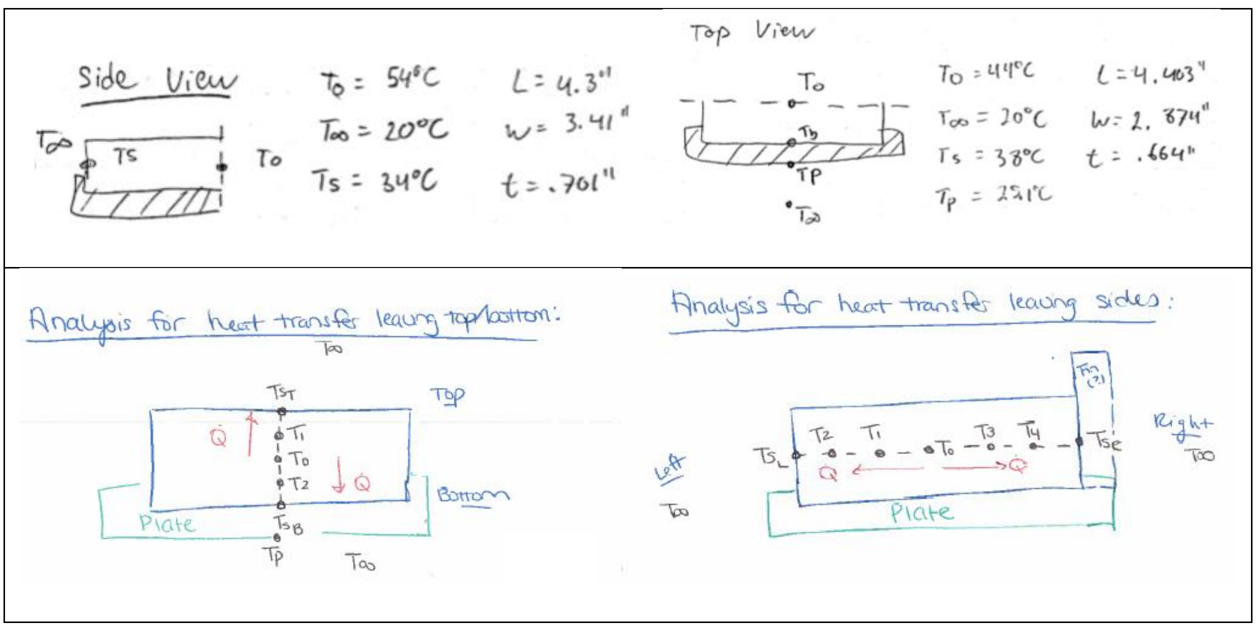

Figure 1: Examples of initial temperature distribution schematics by student (top) and author (bottom)

After establishing an initial temperature distribution, students then draw the resistance network for each slice of pizza. The resulting resistance network will depend on what type of pizza slice was chosen, and therefore vary among students. For example, did the student choose a slice with just cheese, or cheese and pepperoni? Is the thickness of the cheese consistent between slices?

Did the student choose a center piece or a crust piece? All of these factors will change their resistance networks. For example, the student with the crust piece will need to consider fin resistance in the analysis of the heat transfer in the direction of the crust. Based on their type of pizza slice, the students then calculate the total resistance for each of their slices. An example of a student and author resistance networks are shown in Figure 2.

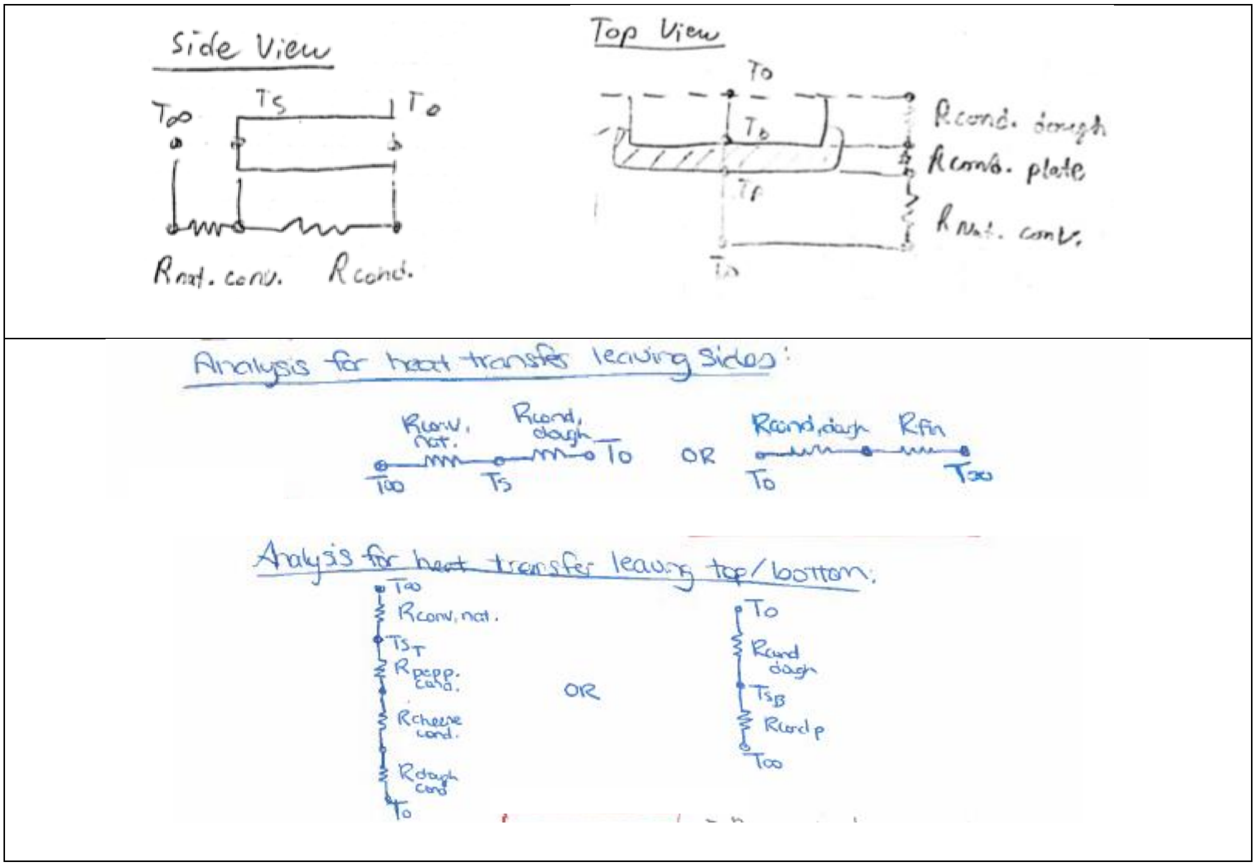

Figure 2: Examples of resistance networks by student (top) and author (bottom)

During this process students will need to apply the resistance equations for conduction, Equation 1, and convection, Equation 2. As mentioned, students may also need to apply the fin resistance equation, Equation 3.

$$R_{conduction} = \frac{L}{kA} \quad \text{Eq. (1)}$$

$$R_{convection} = \frac{1}{hA} \quad \text{Eq. (2)}$$

$$R_{fin} = \frac{1}{h(A_{base} + \eta_{fin} A_{fin})} \quad \text{Eq. (3)}$$

Where L is the length of the pizza [m], k is the thermal conductivity of the material [W/m-K], h is the convection heat transfer coefficient [W/m^2-K], A is the surface area of the pizza [m^2], A_{base} is the area with no fin [m^2], η_{fin} is the fin efficiency, and A_{fin} is the area of the fin [m^2].

To determine the total resistance students must be able to differentiate between a conduction and convection process. They need to be able to determine the thermal conductivity of the material, k, for all conduction processes (i.e. heat transfer through the dough, cheese, or pepperoni layers). This requires them to conduct independent research to determine average values. This research was done during class time and resources shared via a class discussion on the course page. The instructor also contributed a resource a few days prior to the project being due[7].

Students also need to determine the convection heat transfer coefficient, h. The author has observed that students typically take different approaches for this parameter. Some conduct independent research to determine an average cooling convection coefficient. Others calculate the variable using natural convection principles – determine a Rayleigh number to calculate the average Nusselt number, which can be used to calculate the convection coefficient, h. The relation between Nusselt number and the convection coefficient is provided in Equation 4, where L_c is the characteristic length.

$$Nusselt\ Number, Nu = \frac{hL_c}{k} \qquad \text{Eq. (4)}$$

Students quickly learn that they need to identify all of the processes occurring in their cooling scenario first to be able to determine the equations needed to reach a solution. They also learn it is beneficial to identify known and unknown variables at the start. This helps determine which assumptions might need to be made about the real problem to reach a logical solution.

The next step is for students to discuss how the total resistance for each slice would change if the cooling process was sped up with a standard tabletop fan. Students need to identify that this change in scenario only changes the convection coefficient, h, and therefore need to only recalculate this parameter and the convection resistance. Students start by determining the average speed of a household fan so that they can calculate Reynolds number, which is used to calculate the Nusselt number. The convection coefficient can be determined using Nusselt number and Equation 4.

Often times when students arrive to this step they will realize they need to go back to their total resistance calculation and account for natural convection. This step serves as another "check point" for students as they compare their natural and forced convection coefficient values. If their forced convection coefficient value is less than the natural convection value they should realize a mistake has been made. This is a great discussion point between the instructor and students. The instructor can use the two different pizza slices as a tangible object to discuss (1) the difference between natural and forced convection principles, and (2) why the different slices of pizza (heat transfer from the sides versus top) have vastly different convection coefficients for both the natural and forced processes.

Finally students determine the total rate of heat transfer for both slices of pizza using Equation 5, where ΔT is the temperature difference and R_{total} is the total resistance.

$$Q_{total} = \frac{\Delta T}{R_{total}} \qquad \text{Eq. (5)}$$

Students repeat this process first for natural convection and then forced convection. They must make a comparison not only between the side and top heat transfer analyses, but the different convection methods. Students can then repeat this calculation using their knowledge of thermodynamics and the 1st Law to make a comparison with their heat transfer analysis.

Finally students need to combine their knowledge of steady and transient conduction with the multi-modes of convection. They are asked to determine the optimal time and temperature to eat the pizza starting from delivery. They have to describe all assumptions they would make and the approach they would take analytically. Typical solutions use a transient plane wall conduction analysis, shown in Equation 6. Where T(x,t) is the temperature at a specific time and location [K], T_∞ is the ambient temperature [K], T_i is the initial temperature [K], A_1 and λ_1 are coefficients based on the Biot number when using a one-term approximation for a transient solution, τ is the Fourier number, x is the distance at the temperature of interest [m], and L is the overall length [m].

Students are then asked to back calculate what the estimated delivery time is. They can estimate how accurate their answer is by assuming a route and calculating a delivery time with Google Maps.

$$\frac{T(x,t)-T_\infty}{T_i-T_\infty} = A_1 e^{-\lambda_1^2\tau}\cos\left(\frac{\lambda_1 x}{L}\right) \qquad \text{Eq. (6)}$$

Some students take this analysis a step further by continuing their temperature measurements for the duration of the class. They create a temperature distribution as a function of time, which can be compared with a calculated distribution using Equation 6.

Learning Outcomes

This module was designed around *four main learning outcomes*, outlined below. A preliminary qualitative assessment was done using an anonymous student survey and a preliminary quantitative assessment was done through a comparison of exam grades. Future work will look at assessing the learning outcomes in detail with a larger data set.

***Learning Outcome 1*: Students will be able to apply 1-D steady state conduction heat transfer.**

a. Students need to apply knowledge of resistance networks to determine the total resistance in different heat transfer situations, i.e. heat transfer from the side of a slice of pizza versus the top.

b. Students need to apply knowledge of fin conduction if analyzing a piece of pizza with crust.

c. Students need to apply knowledge of 1-D steady state conduction to calculate the total heat transfer through a slice of pizza.

Learning Outcome 2: **Students will be able to apply 1-D steady state natural and forced convection heat transfer.**

a. Students need to apply knowledge of a how to determine the convection heat transfer coefficient in a natural convection situation.

b. Students need to apply knowledge of a how to determine the convection heat transfer coefficient in a forced convection situation.

c. Students need to understand how the different methods of convection, natural and forced, change the total resistance and heat transfer values.

Learning Outcome 3: **Students will be able to evaluate systems under transient conduction heat transfer conditions to calculate temperature and energy transfer by position and time.**

a. Students need to apply knowledge of plane wall transient conduction to determine the temperature distribution throughout the pizza as a function of time.

Learning Outcome 4: **Students will be able to apply fundamental heat transfer and thermodynamic principles to a real-world application.**

a. Students must apply their knowledge of heat transfer and thermodynamics to make assumptions about, and successfully analyze, a real-world problem.

Assessment and Evaluation

The author delivered the course Thermal Fluid Sciences II (MCET 530) in Fall 2017 (35 students), Spring 2018 (72 students), and Spring 2019 (85 students) without the hands-on activity, and with the activity in Fall 2018 (38 students) and Fall 2019 (34 students). After execution of the activity in Fall 2019, the effectiveness of the developed activity in achieving the desired learning outcomes was investigated. Students were assessed at the end of the activity with an exam composed of two problems, one focused on conduction and one on convection. Performance on this problem was compared between students who participated in the activity and those who did not during semesters Fall 2017 to Fall 2019. Perception of the activity's impact on student learning was also assessed via anonymous surveys.

The preliminary study used a survey where questions were written in the form of statements or questions and students were asked their level of agreement on a 7 point Likert scale between 1 (strongly disagree) and 7 (strongly agree). It is noted that as this is a preliminary assessment the questions were not peer reviewed. However, they were based on other peer reviewed published papers[4]. Future work will include an expert review of survey questions. The survey was administered at the end of the fall 2019 semester, upon completion of the project. To date, the preliminary study consists of one administration of the survey to purely see if the project was (1) enjoyable to the students and (2) if students perceived it to increase their understanding.

Results

The goal of the survey was to determine if the students' learning experience benefited from the addition of a hands-on activity focused on fundamental heat transfer concepts and integrating these with fundamental thermodynamic concepts. The survey also sought to determine if students found this activity to be effective in enhancing their understanding of the material. Of the 34 students enrolled in the fall 2019 Thermal Fluid Sciences II course, 12 survey responses were obtained. The demographic of the students surveyed were those who opted to take the final, typically students with a class average below 85.

The first set of questions, shown in Figure 3, focused on the delivery of the activity in the course. Of the students surveyed, only less than 10% believed the activity was not as useful as a traditional homework or lecture in terms of being an effective means of understanding the material. In terms of having class time to work on the project, all students surveyed believed it was time well spent.

When asked if the activity helped students prepare for an exam on which similar concepts were tested, 60% of students strongly agreed it was helpful while less than 20% of students surveyed were indifferent.

When asked if the activity helped students understand and apply conduction and convection to a real problem, 90% of students were in agreement with over 80% responding with “agree” or “strongly agree.” Less than 10% of students were indifferent if the activity improved understanding.

When asked specifically about steady conduction and students’ understanding of conduction through different materials, 85% of students felt the activity improved their understanding. When asked specifically about convection and students’ understanding of natural versus forced convection, over 90% of students felt that the activity improved their understanding.

When asked if the activity helped students understand transient conduction, only 30% of students responded with “agree” or “strongly agree” with the majority of students only “partly agreeing.” This indicates that the transient conduction component of the module could be improved.

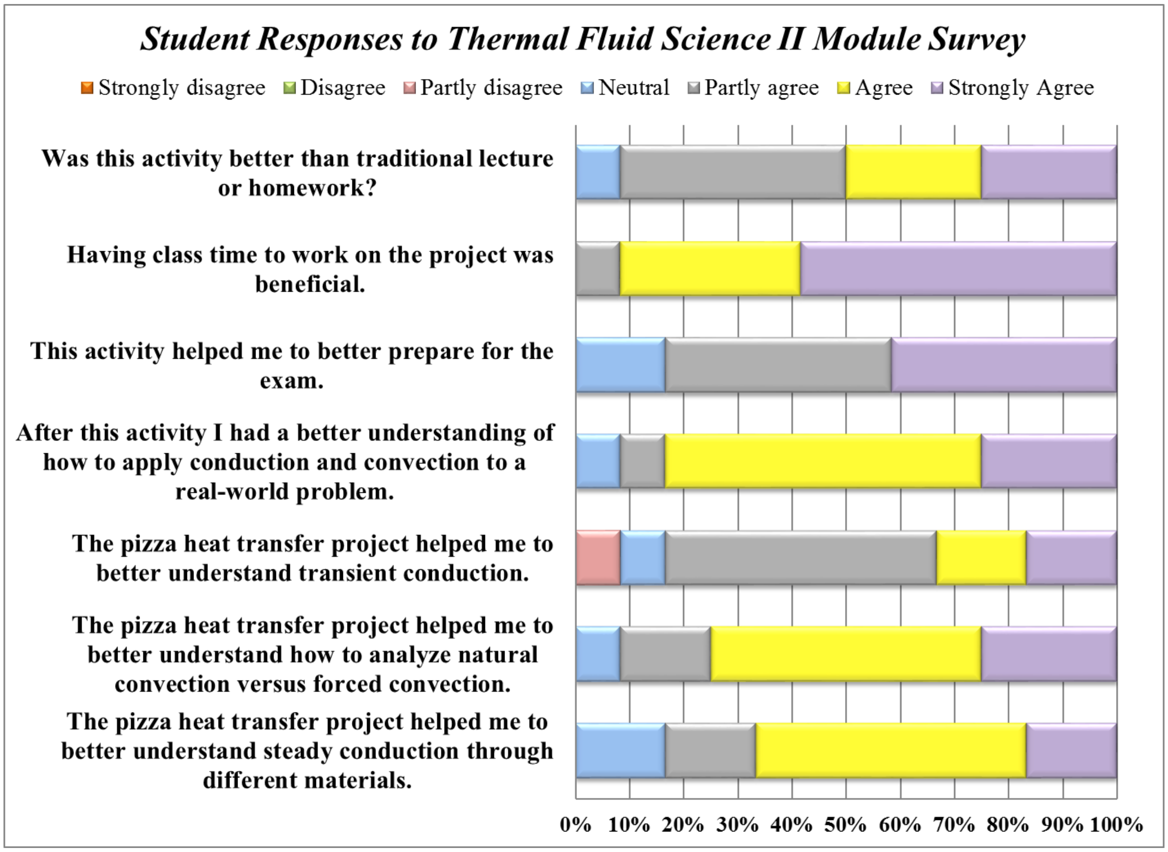

Figure 3: Student responses to anonymous survey given in Thermal Fluid Sciences II (MCET 530)

A few follow-up questions on future surveys could be on how well the students thought the activity helped them to connect information across topics within heat transfer, but also across heat transfer and thermodynamics.

A preliminary quantitative assessment was done by comparing two scores, the class average from a heat transfer-focused exam and final course average for the class, between the sections that completed the module and ones that did not. The Fall 2018 and Fall 2019 show an improvement in both the class averages and the heat transfer-focused exam average when compared with the Fall 2017 and Spring 2018 sections. However, an improvement was only seen when the Fall 2018 and Fall 2019 sections were compared with the Spring 2019 sections' class average. This may be because the Spring 2019 sections' exam average was well-above a typical average. Typically the author strives for an exam average of 85%.

Table 1: A comparison of scores between students who completed the module and those who did not

Semester	Section	Students Enrolled	Project in Course	Class Average	Exam Average
Fall 2017	01	35	No	87	83
Spring 2018	01	38	No	88	84
	02	34	No	86	84
Fall 2018	01	38	Yes	89	86
Spring 2019	01	43	No	88	93
	02	42	No	84	91
Fall 2019	01	34	Yes	88	89

Assessment of the module shows that focusing on a real-world situation related to heat transfer and thermodynamics is engaging to students. The majority of students perceived this activity to be a more effective approach in improving their understanding of heat transfer principles, which is supported by exam and course averages. Therefore, the topic of the module will remain unchanged. However, as indicated by student surveys, the transient component of the module can be improved upon. A better assessment can be conducted in future work as well. Expanding the survey questions to inquire about student perception of connections made across topics, and then designing an exam problem to quantitatively assess connections made.

Conclusions

This paper describes the author's early efforts to develop an entrepreneurially-minded course module requiring students to connect information across topics within heat transfer, and then to thermodynamics, to solve a real-world problem. This hands-on module uses a project-based approach where students conducted an experiment to investigate the cooling of pizza. Students had to apply the 1st Law of Thermodynamics and fundamental heat transfer principles, such as conduction and convection, to determine the optimal temperature to eat the pizza and an estimated delivery time.

To date the author has implemented the project into her course twice and plans to conduct a more in-depth study in the future. Preliminary results indicate the developed module increased student engagement in, and understanding of, heat transfer topics. Exam scores between the sections that completed the module and did not complete the module were also compared to provide quantitative data regarding increased learning effectiveness. Preliminary findings conclude that students perceive this module to be a great tool for not only improving learning effectiveness and engagement, but also helping them connect information. A comparison of exams scores and class averages between the two semesters the module was delivered and the three semesters the module was not, showed an improvement in scores in two of the three semesters.

Future work will consist of administering a pre- and post-survey, once at the beginning of the semester and then at the end, to gauge improvement in student learning of basic heat transfer concepts and connections made between topics. In addition to improved student surveys, future work will also evaluate the developed module using quantitative data from well-designed exam problems to validate preliminary findings. Statistics regarding reliability will be developed as the study is continued.

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