2021 ASEE ANNUAL CONFERENCE
Virtual Meeting | July 26–29, 2021 | Pacific Daylight Time
Paper ID #32654

# Improving Student Motivation Using a 3D Printed Heat Exchanger Project

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## Abstract

The importance of hands-on experiences in engineering education has been recognized for decades. Yet creating and running an effective hands-on experience, especially in the thermal sciences is challenging. This paper will outline a project that asks students to design, build, and test a heat exchanger. In addition to being hands-on, the project incorporates two high-impact educational practices. First, the project is collaborative as groups of 4-5 students work on designing their heat exchangers. Second, the project serves a sort of "capstone project" for the thermal science classes by integrating topics from thermodynamics, fluid mechanics, and heat transfer. While attempts to incorporate designing, building, and testing of heat exchangers as part of a mechanical engineering curriculum are not new, these projects presented challenges with manufacturing in addition to the thermal design. With the invention of thermally conductive plastics that can be used with a 3D printer, students can have a hands-on thermal science design experience within an 8-week time frame. In order to facilitate testing of the designs, a heat exchanger testing apparatus was built by previous students as their capstone design experience. An outline of the necessary components for the heat exchanger testing apparatus, the 3D printer, and the printer material is presented. The assignment and a few examples of student-generated designs are provided. Finally, the results of a survey that seeks to understand how the project affected the student's motivation and self-assessed learning are discussed.

## Introduction

The importance of hands-on experiences in engineering education has been recognized for decades [1], yet creating and running an effective hands-on experience, especially in the thermal sciences, is challenging. Several design-build-test projects involving heat exchangers as part of a mechanical engineering curriculum have been made [2-5]. Sherwin and Mavromihales reported a project for students who built cross-flow air-water heat exchangers out of metals tubes that was carried out for several years [2]. Forsberg presented a capstone design and construction project involving a water-water heat exchanger demonstrator with three modules for double-pipe, cross-flow, and shell and tube exchangers that became a laboratory demonstration device for use in other parts of the curriculum [3]. With the more recent development of 3D printer technology, faculty have implemented thermal science design experiences that mitigate the traditional manufacturing challenges. Michna and Letcher motivated students with a heat exchanger design contest where models were printed from ABS plastic that incorporated a new challenge in terms of overcoming conduction resistance [4]. Elmer and Kraut developed a module where chemical engineering students design, print, and test plates for a plate and frame heat exchanger [5]. In this work, we use a thermally conductive plastic from TCPoly to decrease the conductive thermal resistance to the point that the air-side resistance becomes the dominate resistance as is typical for more traditional metal air-water heat exchangers.

Such design-build-test experiences are helpful for engineers who are about to enter the workforce. This is evidenced by the statements by ABET's Engineering Accreditation Commission, whose student outcomes state that students must have the "ability to apply engineering design to produce a solution… " and students must be able to "develop and conduct appropriate experimentation…" [6]. Additionally, prior research shows that design-build-test experiences can improve student's motivation [7] [8] [9]. Therefore, as part of an effort to develop an authentic design-build-test experience for students in the thermal sciences, this project seeks to understand our students' experience with a 3D-printed heat exchanger design project.

3D printing is becoming an important enabling technology in new heat exchanger designs. For example, commercial companies like Fast Radius [10] and EOS [11] have commercially available 3D printed heat exchangers. There is also a significant amount of research being done using 3D printing to improve heat exchanger design [12] [13] [14]. Therefore, it is important that students have experience with 3D printed thermal designs as they enter the workforce or graduate school.

The article below describes an 8-week heat exchanger design-build-test project in a capstone thermal sciences course at Trine University. Described are the course, the requirements and constraints of the assignment, and the construction and testing methods and equipment used. Some example student designs are shared, and the results of a student survey are presented to assess the level of engagement that students had with the material.

## Project Course

As context for the heat exchanger design project, the content of the required course, Thermofluid Component Design (TFCD), is described here. TFCD is a Trine University course for senior level mechanical engineering students that asks students to apply the principles of thermodynamics, fluid mechanics, and heat transfer to system design. Learning outcomes include the ability to apply principles of fluid mechanics, heat transfer, and thermodynamics to pump selection, piping system, and heat exchanger design. Student work in the course consists first of several homework assignments that result in the development of computer codes that model pressure changes as a function of flow rate through pumps or fans, piping networks, and duct systems. Students then participate in an initial project that asks them to validate the performance of a small (approximately 8” x 6” x 2”), finned, air-water heat exchanger; student activities consist largely of the development of a computer code to simulate heat transfer through a heat exchanger and subsequent comparison of their predictions to experimental data that they acquire. This brings students to the middle of the semester, and in a second project that lasts about 8 weeks, students are asked to modify and use their computer codes to design their own 3D-printable heat exchanger, which should be constructed and have its performance validated by the end of the semester.

## Project Requirements

In the fall of 2020, five teams consisting of 4 or 5 students each were asked to simulate, design, construct, and test a small air-water heat exchanger. A list of constraints was provided, including, but not limited to:

- Size of exchanger: no larger than 6” x 8” x 2”, which is the size of the test section in the heat exchanger testing apparatus (described further below).
- Amount and type of printing material – unlimited amounts of the commonly available polylactic acid (PLA), or one roll (0.5 kg) of thermally conductive polymer. The currently used thermally conductive polymer is a nylon-based filament by TC Poly called Ice9 Rigid.

- Print time – no more than 24 hours if using the department's printer. This constraint ensured that design groups had a reasonable opportunity to access to the printer during the last weeks of class. Retrospectively, this constraint limited the size of thermally conductive polymer designs to about 0.25 kg or about one-half of a roll of filament and adherence to it became the chief constraint the drove at least one group's design.

Groups were required to present their design, predictions (developed using Matlab), and results in a 15-minute presentation at the end of the semester. In the fall of 2020, five student groups designed heat exchangers. Four of those groups successfully printed heat exchangers. Three groups successfully tested their prints with one group being unsuccessful due to leaks in their fittings. The team that did not get their heat exchanger printed was required to write a report on their design.

## Testing Apparatus

A heat exchanger testing apparatus was previously constructed by a student design team in order to enable the TFCD design project. The apparatus was utilized in this project to test the performance of the heat exchangers. The facility, approximately 8 feet in length, is shown in Figure 1. Key components, numbered in the figure, include: 1) a centrifugal blower that typically ran at a flow rate of 400-800 CFM under testing conditions, 2) a 6" x 8" x 2" plexiglass test-section in which the tested heat exchanger is placed, 3) an air-side flow meter (ELECTRA-flo/S5-CM) , 4) an electric water heater and reservoir, 5) a circulation pump for the hot water system (Fluid-o-Tech PO 70-400, 0.69 gpm), 6) a water flow meter, and 7) a computer running Labview, which displays and records measurements of flow rates and temperatures before and after the heat exchanger. Calorimetry on the water side is used as the accepted experimental measurement of the heat transfer rate within the heat exchanger. Air side calorimetry instrumentation is installed, but measurements tend to be unreliable due to poor spatial sampling of the non-uniform velocity and temperature field in the duct after the outlet of the heat exchanger.

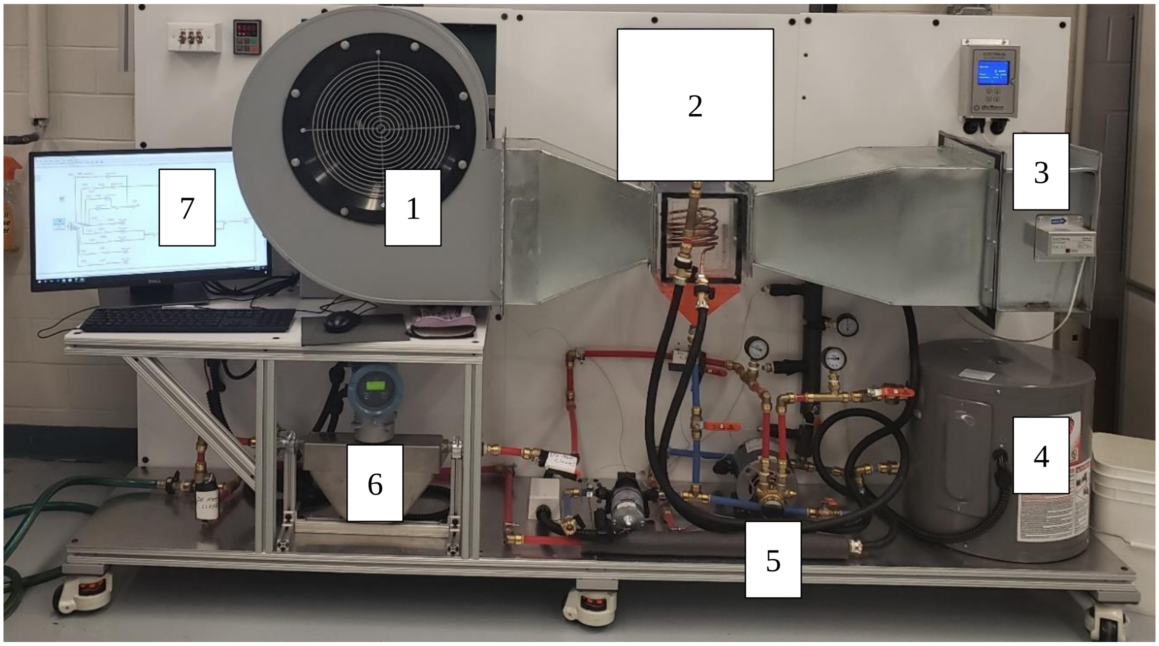

Figure 1. Heat exchanger testing facility used to measure the performance of student-designed air-water heat exchangers.

## Designs

Students were asked to perform a concept generation and selection process before settling on a design and generating predictive models. While faculty hoped for creativity at this stage, student designs tended to have a single multi-pass water channel, which sometimes zig-zagged back and forth, but otherwise appeared to look similar to traditional air-water heat exchangers. Produced heat exchanger designs are shown in Figure 2. Most teams had fins on their heat exchangers. While the fins were predicted to be somewhat effective in enhancing heat transfer, the fins may serve an important structural purpose as well. Teams with finned designs were able to print more consistently than the team with few or no fins (Figure 2b). The team without many fins (Fig. 4b) suffered from severe warping when using the nylon-based thermally conductive filament. Their TC-poly prototype did not successfully print, and they produced only a PLA prototype.

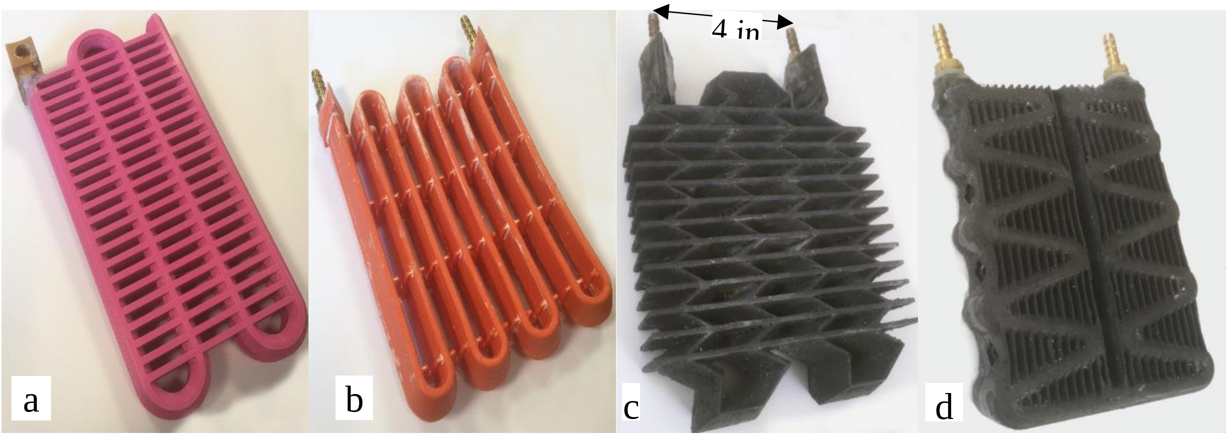

Figure 2. Designs of air water heat exchangers. (a) is a PLA prototype from a team that did not attempt a print using TC-poly filament. (b) is a PLA prototype whose TC-poly print warped and failed to print to completion. (c) and (d) are designs printed successfully using TC-poly ICE 9 Rigid filament.

The transverse structures seemed to resist warpage as the part cooled on the 3D printer bed. This is similar to the experiences of Michna and Letcher who found that students used fins for support rather than heat transfer [4].

Heat exchangers shown in Figure 2c and 2d were printed using a Rostock MAX$^{TM}$ V3.0 printer from SeeMeCNC using Ice-9 Rigid filament. TCPoly has downloadable slicing profiles for Simplify3D, Slic3r, and Cura. We used the Cura profile with minor adjustments to the profile including increasing the layer height from 0.2 mm to 0.25 mm and increasing the extrusion temperature from 285°C to 290°C. An extensive testing of printer setting has not been conducted. Moreover, in our configuration, the Rostock is incapable of printing a support material. This was explained to students early in the design process so they knew the constraint on their designs. All exchangers shown in Figure 2 were printed such that the fins required no support. Additionally, the water channels were diamond shaped such that they did not require support material either.

After printing and inserting hose-barb fittings for water ports, preliminary water-flow testing showed that the printed structures would leak water between print lines even at moderate supply pressures of 1-2 psig. The leakage was expected since most 3D printed parts are not water tight after printing. To seal 3D printed parts, acetone is often used. However, the base material of TCPoly's Ice-9 Rigid Filament is nylon and acetone will not help seal nylon. Furthermore, attempts to use heat guns or hot knives proved ineffective or impractical for sealing the exchangers. Therefore, to seal the leaks, exchangers were dipped in an acid bath of nearly pure (99%) sulfuric acid for a few minutes, exposing only the external surfaces to the acid. The bath caused the filaments to swell, soften, and seal. After the bath, the exchangers were rested for several minutes in a second sodium bicarbonate-and-water solution to keep the nylon-based filament from softening further (initial tests without the second bicarbonate bath showed that parts of the structure turned into goo several hours after the acid bath). The sodium bicarbonate solution re-hardened the exchanger, and it was then demonstrated to hold water at several psig of pressure without leaking.

Students predicted heat transfer rates of 70 Watts (Figure 2b), 450 Watts (Figure 2c), and 350 Watts (Figure 2d). Experimental measurements based on water-side calorimetry indicated that the actual rates were 270 W (2b), 860 W (2c) and 750 W (2d). The experimental uncertainty is

+/-40 W. (The heat exchanger shown in Figure 2(a) was printed but not tested due to leaks at the water connection points). There was little surprise in the disagreement between the prediction and the experimental results. First, students' models relied heavily on the data from Kays and London [15] which required the students to select data that best represented their design but did not actually match their geometries. Moreover, at least one team (Figure 2d) under-predicted their airside flow rate by a factor of 2. Finally, the thermal conductivity of Ice-9 is acknowledged by the manufacturer to vary by a factor of 4 based on print direction. (We speculate there may be a similar non-isotropic behavior for PLA.) Despite the fact that prediction methods need significant revision, the project successfully demonstrated the importance of verification and validation of numerical models.

While the 99% sulfuric acid bath was effective at sealing the heat exchangers, it was somewhat hazardous and required many safety precautions. For example, the students were required to wear ppe that covered their hands, eyes, and clothes. Also, the sulfuric acid and sodium bicarbonate baths were conducted under a fume hood with an eye wash station and safety shower nearby. Finally, the baths were done under the direct supervision of the head chemical safety officer at the university. It seems likely that a weaker solution of acid and perhaps a longer soak time will also seal the leaks between the filaments without presenting the same level of hazard as working with 99% sulfuric acid. Further testing to find the weakest acceptable solution is ongoing.

## Student Response: Survey Results

After the completion of the project, students were invited to participate in an anonymous survey concerning their experience with the project. Nineteen of twenty-one enrolled students participated. Below we share the opinions of the students. While direct assessment data could offer a better measure of the degree of student learning, the class varies from semester-to-semester such that student outcome data is not readily comparable to this project implementation. Results below thus speak more to the perception of the students rather than the degree of learning they experienced.

Students were asked to respond to several statements with Strongly Agree, Agree, Neutral, Disagree, and Strongly Disagree. Students could make their own comments after responding to each statement, some of which are shared beneath the survey results below.

1) I would have rather done a computer-based design project with a report than the Design, Build, Test project.

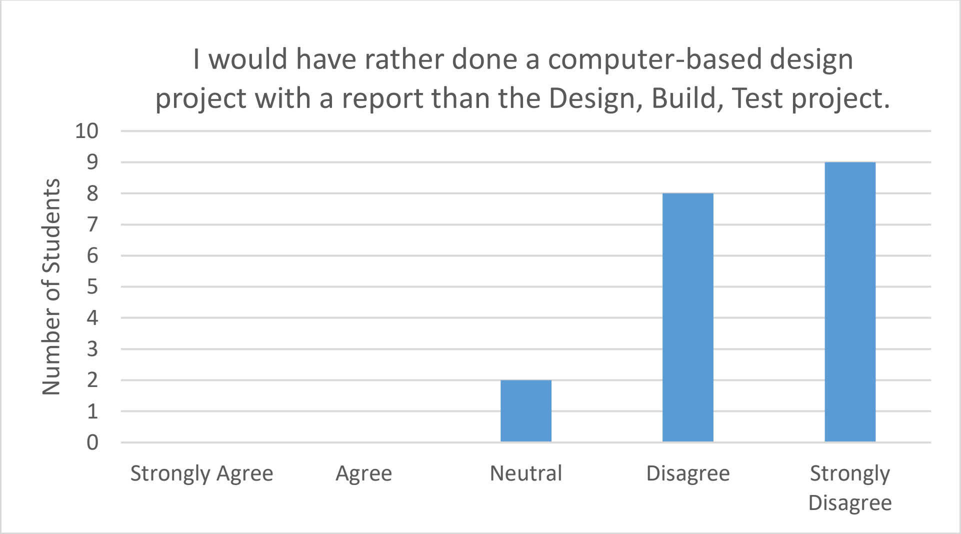

Figure 3. Number of students who preferred writing a design report to building a prototype.

Thirteen students added their own comments after this statement. In the comments, 11 of the 13 indicated that the hands-on project enhanced their enjoyment, while 2 responses indicated a dislike for reports. Highlights include:

"Both have their benefits, but a Design, Build, Test project gives the students a sense of accomplishment once it is completed that can be a huge confidence and morale booster going into the last few weeks of the semester"

"Being able to design. print, and test something starting from scratch is an amazing feeling."

"It was so much better and more engaging to build and test. Otherwise this class would have been very boring,"

Based on the feedback, it is unambiguous that these students strongly preferred construction and testing over writing, and that many felt more engaged because of it.

2) The opportunity to build and test my design motivated me to put in extra time and effort on this project compared to a project where I had to deliver a report based on a computer model.

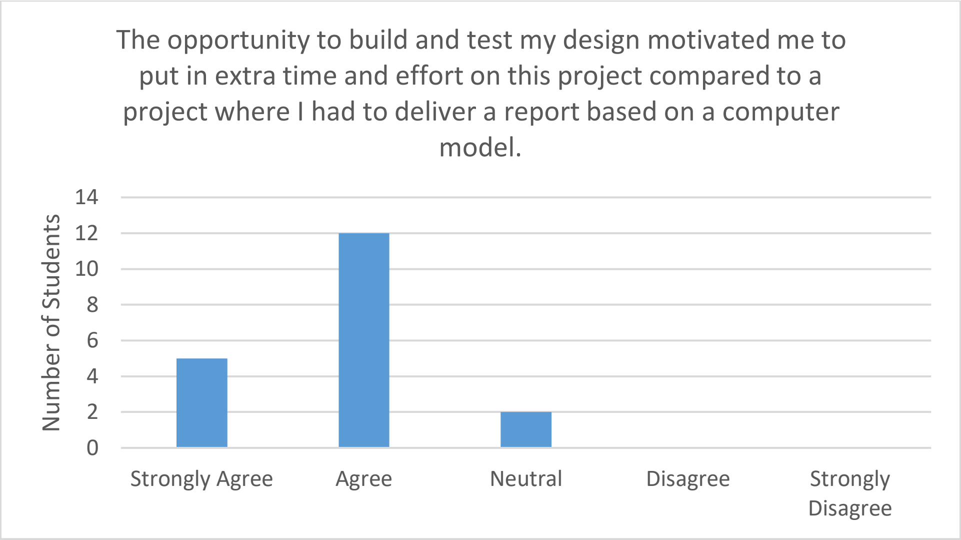

Figure 4. Number of students who felt that the project motivated them toward extra effort.

Open comments on this statement (10 of 19 added comments) include the following:

"I really enjoyed working on this project and trying to make it water tight was definitely a challenge."

“Due to the idea that you are building and testing your own design, students are more likely to dedicate extra time as they wish to prove that their own design works rather than some other person's idea.”

“See our CAD model come to life was probably the most fulfilling part of the project. It was nice to apply all the technical knowledge we have learned the last 3.5 years and actually build something with it.”

Figure 4 indicates that the vast majority of students thought they were more motivated for this project in comparison to more traditional design reports; however faculty observations of actual performance disagree. The instructor notes that only three of the five groups successfully tested their heat exchangers while one group printed a prototype during the last weekend of the semester on their own printer. Their prototype could not be tested due to a design flaw – locating the water ports too close to each other to allow space for fittings. One of the five groups, despite expressing a desire to print a prototype, failed to print a heat exchanger altogether and opted to write a design report. Hence, if completion of the assignment to the point of testing is an indicator, only about 60% of the class exhibited the necessary motivational level to complete the testing portion of the project.

3) I have a better understanding of fluids and heat transfer after completing this design project.

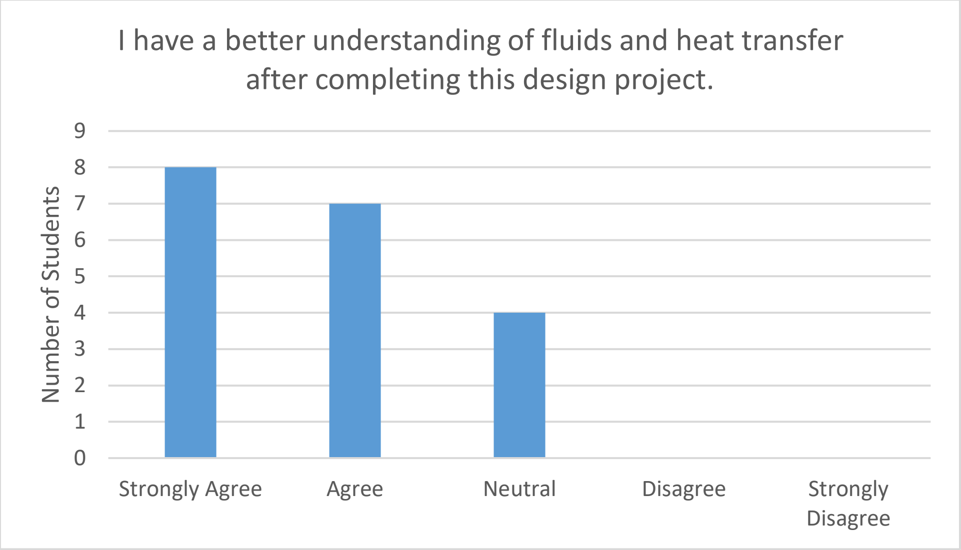

Figure 5. Number of students who felt that the project helped their understanding of thermal sciences.

The perception of the majority of students was that the project helped their understanding. However, we did not attempt any direct assessment of their degree of leaning as compared to prior implementations of TFCD.   Eleven of 19 students added comments to this statement, some of which are found below:

"I got a better understanding of a lot of the topics that went over my head in fluids and especially heat transfer. We as a group also learned a lot of different correlations in fluids and heat transfer that we never covered in those classes"

"The subject matter, no, but using them to design something yes. I do not think my understanding of these topics improved very much, but taking what we learned in theory to design the heat exchanger was difficult and extremely helpful." Ironically, this student responded to the statement with "strongly agree."

"Heat Transfer [the class] allows oneself to somewhat internalize the key points, but actually applying it has been great at driving it home."

"Building models and testing actual heat exchanger's really hones in all the theory learned over the past two years. It's one thing to do a heat exchanger problem in heat transfer, its another to apply that knowledge and actually build something."

## Lessons Learned

Three lessons learned from the Fall 2020 implementation of this design project significantly impacted the Spring 2021 project implementation. First, students are now asked to validate their air flow model by first predicting and testing a commercially available aluminum air core heater (Spectra 94700). Furthermore, students are encouraged to print their designs after concept generation and selection but before detailed computer modeling is completed. To do so, students are required to use a simplified model for concept selection where convective coefficients are approximated. Finally, to incentivize students to complete concept design and selection early, the amount of time students were allowed to print decreased from 72 hours on the day the project was assigned to 0 hours the day before the project was due.

## Conclusions

3D printing of conductive polymers has enabled us to implement an eight-week design-build-test heat exchanger project in a required capstone thermal sciences course.  Survey results indicate that students were more engaged with this project in comparison to the prospect of a more traditional design report. This agrees with the literature that states that hands-on experiences improve student engagement. While students also expressed an increase in motivation, only three of five teams completed the testing portion of the project. We hypothesize that a lack of executive functioning skills, like task planning and time management, lead to teams not building their designs despite the improved motivation. For example, McCord and

Matusovich state “…we found that feeling a time crunch can cause students to shift from a mastery mode to a coping mode of learning” [16]. Completing a design, build, and test project involves mastery-based learning that students might shift from under a time crunch. Nonetheless, students had a positive perception of the increase in their understanding of fluids and heat transfer. Future work may seek to quantify this increase in student understanding of 3D printing as well as fluids and heat transfer. Additionally, explicit instruction around task planning and time management may allow motivated students to complete the project as intended.

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