ASEE
125 YEARS AT THE HEART OF ENGINEERING EDUCATION
2018 ASEE ANNUAL CONFERENCE & EXPOSITION
JUNE 24–27, 2018
SALT PALACE CONVENTION CENTER
SALT LAKE CITY, UT

Paper ID #23557

Designing 3-D Printed Heat Exchangers in a Senior-level Thermal Systems Course

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Abstract

A senior-level technical elective course for Mechanical Engineering students at South Dakota State University is ME 418 *Design of Thermal Systems*. The purpose of this course is to introduce students to a systems approach to the design, modeling, and simulation of thermal systems. In the Fall 2017 semester, the authors introduced a new design project to the course – one in which students were asked to design and simulate the performance of an air-to-water heat exchanger to be made through an additive manufacturing process.

The students worked in groups to design the heat exchangers. Because of the very low thermal conductivity of the plastic material, fin efficiency and wall thermal resistance became primary considerations in the design, which gave students a much better understanding of these concepts. The instructor expected that students would take advantage of the additive manufacturing method, which allows for more complicated geometries to be realized than traditional manufacturing, to integrate heat transfer enhancement structures such as vortex generators into their designs. However, the student designs were very similar to conventionally manufactured heat exchangers.

After completion of the project, the heat exchangers were manufactured on the small, inexpensive 3D printers housed in the department and were tested in a wind tunnel constructed for the purpose. The team with the best performing design was announced to the class. The “contest” aspect of the project and the knowledge that their designs would be manufactured served as motivation for the students. Student survey results showed that half the students thought the 3D printed heat exchanger design project increased their enthusiasm for the course and 83% of the students thought it improved their ability to design and optimize a thermofluids system under real-world constraints.

Introduction

Senior-level students in the undergraduate mechanical engineering program at South Dakota State University are required to take five technical elective courses. These courses generally focus on the application of the knowledge the students have gained in their core courses. One of the courses offered is ME 418 *Design of Thermal Systems*, in which the students apply the fundamentals they learned in *Thermodynamics*, *Fluid Mechanics*, and *Heat Transfer* to the design of systems that involve fluid flow and heat transfer.

Educational research has shown that project-based learning is a good fit for courses where the desired learning outcome is the application of knowledge rather than the acquisition of knowledge. Mills and Treagust [1] state that project tasks more closely simulate the environment a student will work in as a professional engineer much better than traditional lecture-based coursework. Students who participate in project-based learning are more motivated and have better teamwork and communication skills. Prince and Felder [2] state that project-based learning may be beneficial in courses that deal with the design process or product design and development.

Wood [3] shows that a “realistic toy” project can have many benefits for student understanding of the design process. He discusses a two-week-long project in which student design paper helicopters and which the students point to as the most educational activity in an entire design class. Other researchers show that introducing a class project as a competition among student teams can serve to increase motivation and time spent on a learning activity [4-6].

A competition, in the form of a 3D printed heat exchanger design project, was assigned to the students in the ME 418 *Design of Thermal Systems* course. The project was to be worked on in groups of two or three students. The objectives of this project were to increase students’ enthusiasm for the course, give students experience working with design projects with real-world constraints, and, because 3D printing is currently being investigated by NASA to potentially provide spare parts, to introduce them to in-space manufacturing technologies.

Project Outline

The students worked in groups of two or three students on this project. They received a handout with the problem statement which asked them to design a water-to-air heat exchanger to be 3D printed out of ABS plastic material ($k = 0.2$ W/m-K). More conductive 3D printing materials are available, but they were not used because they are generally much more expensive. The objective given to the students was to maximize the heat transfer from the water, which enters the heat exchanger at 60°C, to the room-temperature air blown over the outside. Students were given a schematic explaining constraints on the heat exchanger geometry (Figure 1).

As can be seen in Figure 1, some guidelines related to the limitations of the 3D printed material had to be considered. In order to ensure that the walls of the heat exchangers were watertight, a minimum wall thickness of 1.2 mm (3 layers of material) was imposed. In addition, the heat exchangers were briefly dipped in acetone, which is a solvent for ABS, to cause the ABS to fill any small holes prior to testing. A two-layer minimum fin thickness was specified for non-watertight features such as fins, and the perimeter of the heat exchanger was to be printed with at least 5 layers of material. The inlet and outlet port design was provided to the students in a Solidworks file so that the fittings for connecting the heat exchangers to the experimental flow loop could be standardized.

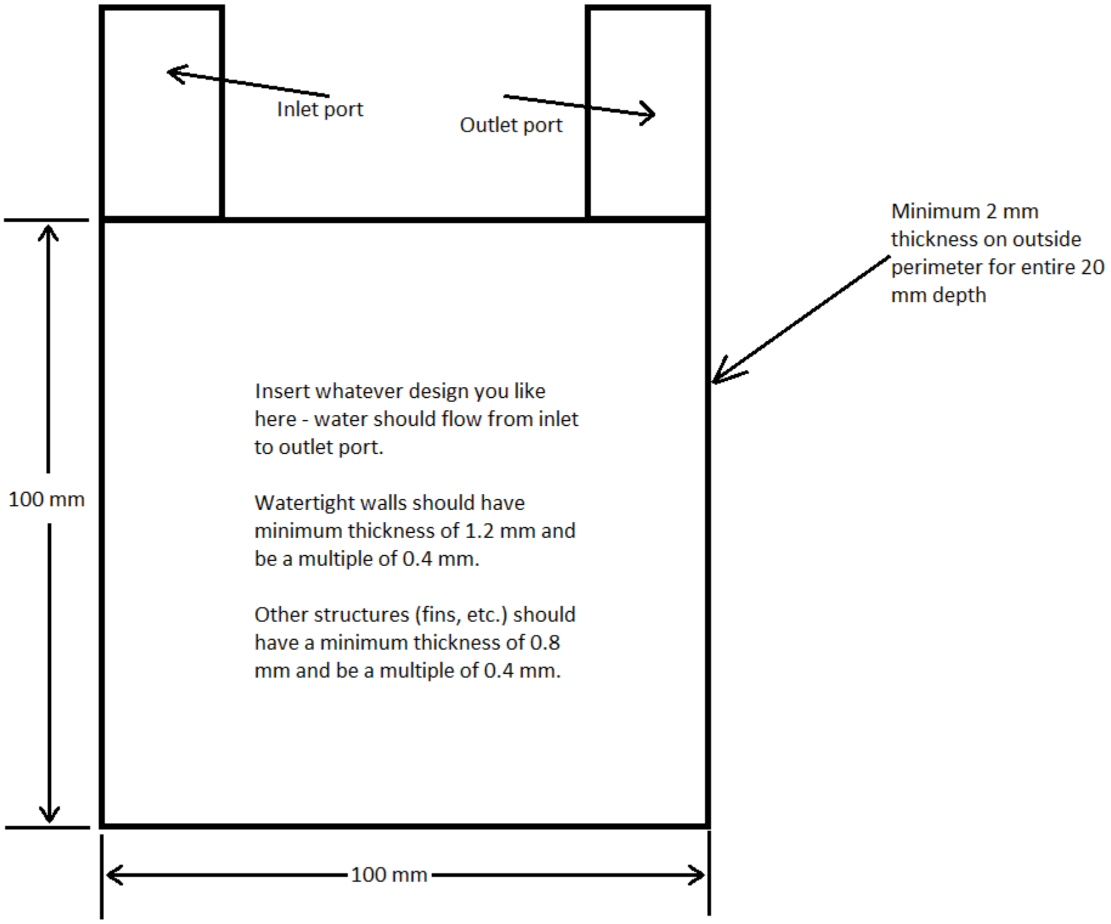

Figure 1. Geometrical requirements for the heat exchanger.

Because this project was meant to simulate heat exchangers printed in space, designs that required support material were not allowed. Broken support material pieces, while completely innocuous on earth, can turn into very dangerous debris in a zero-g environment. Potential dangers of support material in space are inhalation and choking. The students imported the models of their heat exchangers into a 3D slicing software, which specified the printing paths and created the file required by the 3D printer. Once the part was imported, the students could check whether support material was called for by the software. If it was, they made changes to their design until it was no longer necessary for successful printing.

The students were given information about the testing conditions for the heat exchangers. The geometry of the simple wind tunnel in which the heat exchangers were to be tested is shown in Figure 2.

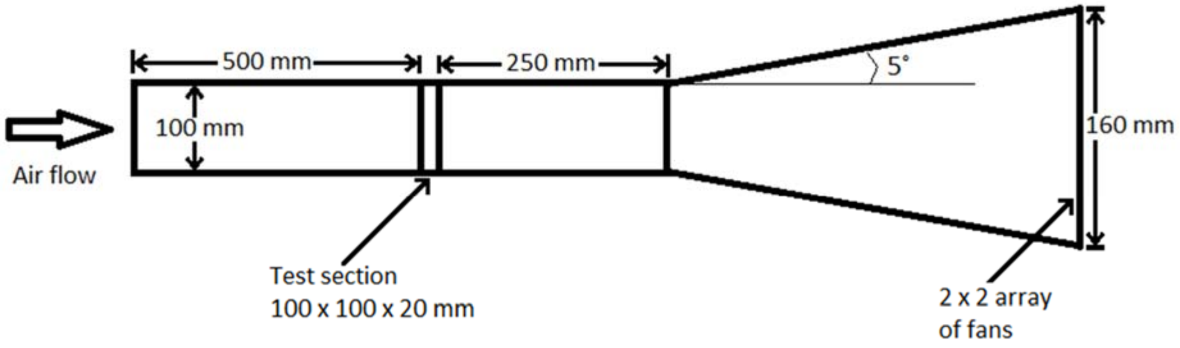

Figure 2. Schematic of the wind tunnel to be used to test heat exchanger performance.

Finally, the students were given the fan curve supplied by the manufacturer of the fans and an approximation of the pump curve for the pump to be used to provide the heated water to the heat exchangers.

The students were asked to provide the Solidworks file(s) for their heat exchanger along with a report detailing their design process and predicted heat exchanger performance. They were also asked to simulate the performance of their heat exchanger design at the conditions for the test (using the given water inlet temperature and fan and pump curves).

This simulation included using correlations for water- and air-side pressure drops, along with the pump and fan curves, to approximate the flow rates of water and air for each design being considered. Once flow rates were known, Reynolds numbers could be calculated for use with the appropriate heat transfer correlations to obtain approximate Nusselt numbers and heat transfer coefficients under these conditions. Once heat transfer coefficients were known, the total thermal resistance of the heat exchanger (including convective resistances for the air and the water, as well as the conduction resistance across the ABS) was calculated. Finally, an effectiveness-NTU analysis was used to estimate the heat transfer rate at the given conditions.

Students were free to choose what software was used in their simulations. One group chose Matlab, with the remaining groups choosing Engineering Equation Solver (EES). EES has optimization tools that can be easily used by undergraduate students. These tools were used by several groups to determine parameter values (dimensions) which maximized the heat transfer for their design within the given constraints.

Students were also told that their designs would be manufactured on one of the department's 3D printers and tested in a simple wind tunnel fabricated to the specifications above. The group with the heat exchanger with the highest measured heat transfer rate would receive a prize (a 3D printed trophy).

Project Results

Since this was the first time this project was given to students, not all went to plan. Unfortunately, time constraints did not allow for the testing of the heat exchangers before the end of the semester. Each of the heat exchangers took 24-36 hours to print, and some work to remove the raft (the solid layer of material used to anchor the print to the base of the printer) was required. In addition, the wind tunnel used to test the heat exchangers was not fabricated before the semester ended.

The printed heat exchangers are shown in Figure 3.

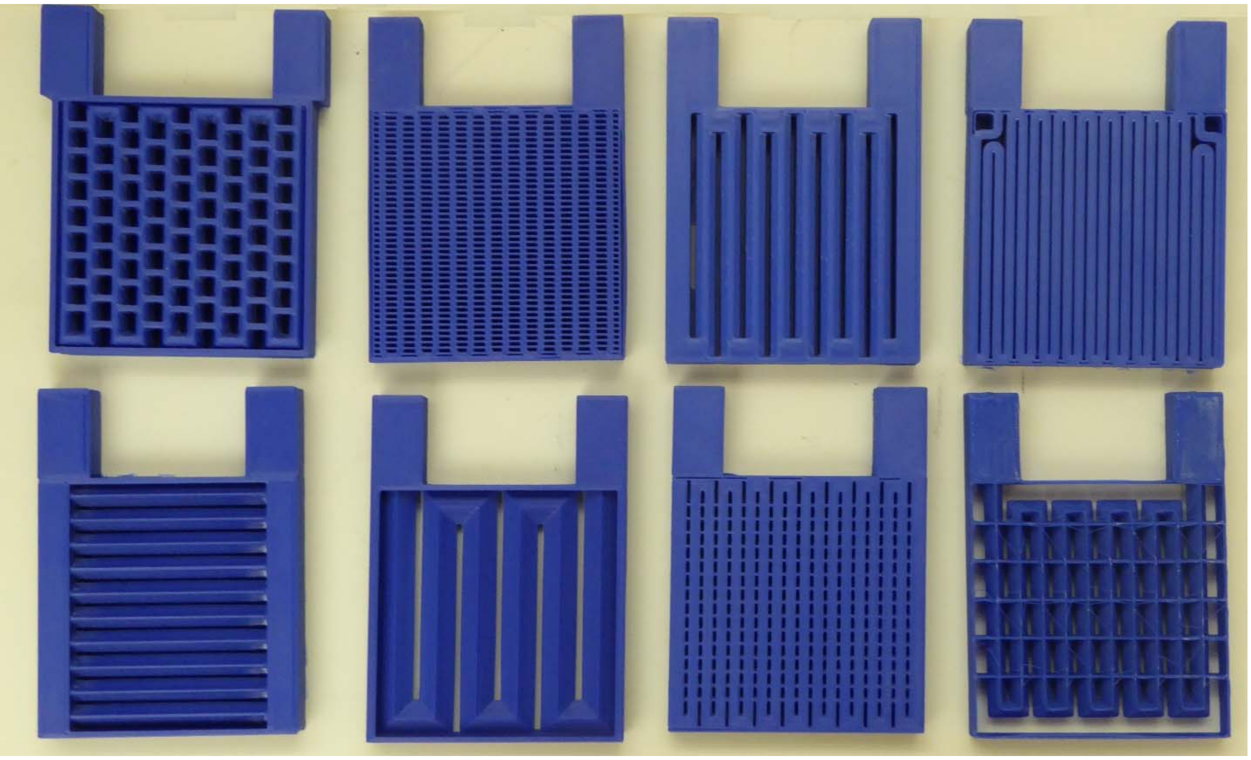

Figure 3. 3D printed heat exchangers designed for the project.

When the heat exchangers were printed and tested, more problems arose. Since the water-side thermal resistance was the least significant of the three resistances (air-side and tube wall resistance were approximately equal, but an order of magnitude higher than the water-side resistance), many of the optimized designs had very small internal channels for the water flow. This resulted in one of two problems: no flow due to a totally blocked water channel or water leakage due to excessive pressure drop in the narrow channels.

The wind tunnel for testing the performance of the heat exchangers is shown in Figure 4.

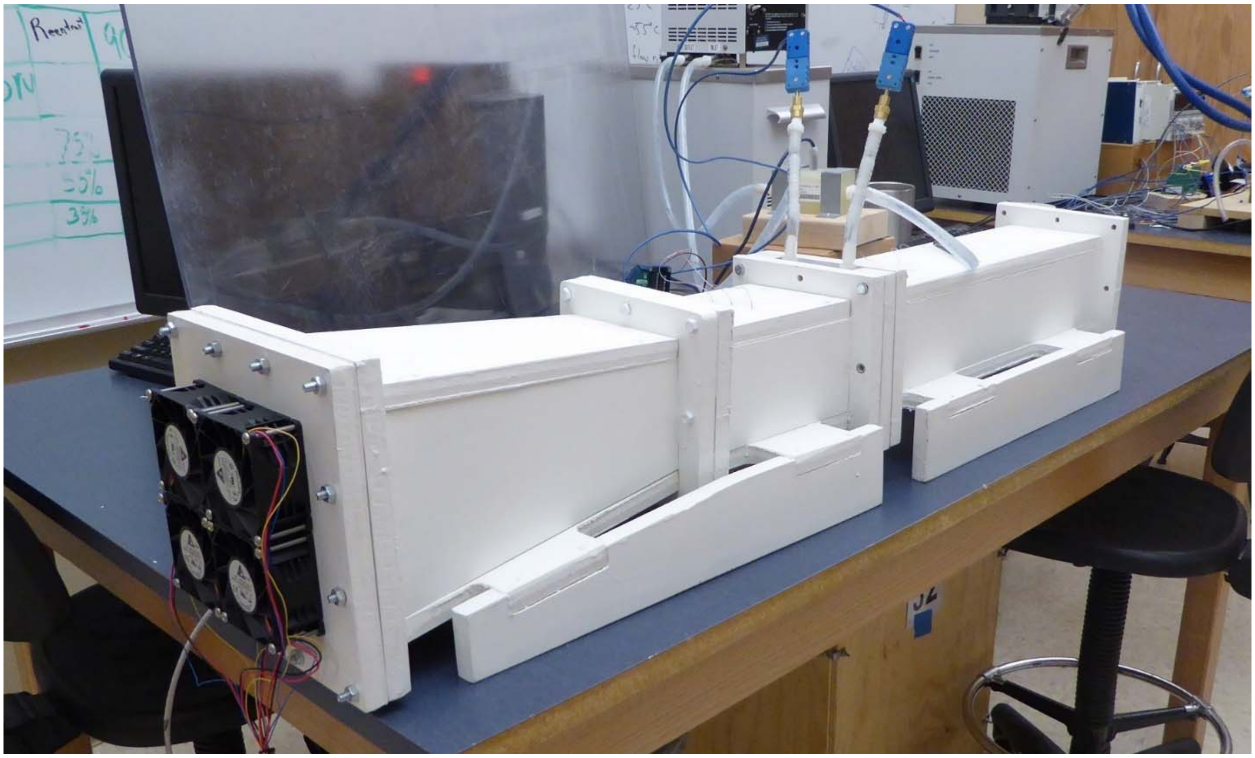

Figure 4. Wind tunnel used for testing 3D printed heat exchangers.

The heat exchangers were only tested under one flow condition, the one represented by the fan and pump curves provided to the students. This corresponded to the four fans operating at full load and the pump set to "low" on the circulating temperature-controlled bath. The inlet and outlet air and water temperatures, the water volumetric flow rate, and the air velocity were measured. The water-side measurements were used to calculate the heat transfer rate from the heat exchangers since that provided the lower uncertainty. Results for the four heat exchangers that did not leak and had a non-zero water flow rate are shown in Table 1.

Table 1. Heat exchanger performance results.

	Group 3	Group 4	Group 7	Group 11
q (W)	38.7	26.8	**61.2**	23.6

Group 7's design performed the best of the heat exchangers that did not leak and flowed water. Interestingly, their design, which is shown in the lower left corner of Figure 3, was the only one that directed the water flow through multiple parallel channels. The instructor of the course expected this to be a common feature in the students' designs, since the difficulty of manufacturing inlet and outlet headers is eliminated with 3D printing. The remainder of the heat exchangers used a design with a single, serpentine water channel from the inlet to the outlet.

Instructor Observations

The open-ended design nature of this project was meant to encourage creative solutions from the student groups working on this project. Because the conductivity of the ABS is orders of magnitude lower than the conductivity of the materials from which traditionally manufactured heat exchangers are made, students were forced to consider the factors affecting heat transfer performance of the heat exchanger in order to develop the best performing design; they could not rely on what they know of traditional heat exchangers. In a traditional heat exchanger, the air-side thermal resistance dominates, while the conduction resistance and water-side thermal resistances are very small. In a plastic heat exchanger, the conduction thermal resistance is much greater – comparable with the air-side thermal resistance. This leads to heat exchangers with much different geometry than heat exchangers with which the students are familiar (radiators, air-conditioning condensers, etc.).

The students were not explicitly told this information. Instead, they were told to start their designs with quick, “back-of-the-envelope” calculations to determine which thermal resistances were most important. Most of the groups came up with designs that reflected the importance of designing to reduce the conduction thermal resistance by including a large amount of tube area. Because the effectiveness of fins is quite low with low conductivity fin material, most of the heat exchangers were designed with few, if any, fins. Fins were, in fact, included as much to provide support for the tubes while printing (because support material was not allowed) as for heat transfer enhancement.

This project was one of three design projects the students worked on in this course during the semester. The instructor observed the students seemed to be more excited working on this project due to the competition aspect of the project. Students also requested that the instructor create a design of his own to be included in the competition. The instructor was also pleased to see the hard work that the students put into this design project, and through discussion with the students after the project was completed observed that they did understand the concepts of thermal resistance, overall heat transfer coefficient, and heat exchanger performance calculations much better than at the beginning of the project.

The instructor also expected the students to independently perform some research on the possibilities opened up by the manufacturing method. Since additive manufacturing was to be used, some complex geometries such as vortex generators could have been fairly simply integrated into the designs. However, none of the student groups this semester included any such heat transfer enhancing geometries.

Student Survey Results

Several survey questions related to this project were included in the end-of-semester surveys administered to all students in the course. Of the 27 students enrolled in the course, 24 completed the survey. Survey questions and results are shown in Tables 2-4.

Table 2. Survey question 1 and results.

The 3D printed heat exchanger design project increased my enthusiasm for the course.					
Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Total responses
0	4	8	11	1	24

Table 3. Survey question 2 and results.

The 3D printed heat exchanger design project improved my ability to design and optimize a thermofluids system under real-world constraints.					
Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Total responses
0	1	3	17	3	24

Table 4. Survey question 3 and results.

The 3D printed heat exchanger design project increased my knowledge of in-space manufacturing.					
Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Total responses
0	6	8	10	0	24

Students overwhelmingly responded that the project increased their enthusiasm for the course, and that it improved their ability to design and optimize a real-world thermofluid system. Another objective for the project was to expose the students to in-space manufacturing technology, and the responses to the related survey question (survey question 3) were not as positive.

Students were also asked to provide open-ended feedback on this project. Some representative responses:

- I thought the project was extremely open-ended and fun to do. It was a lot of work, but integrating additive manufacturing was valuable as a mechanical engineering student. Any time we can combine different classes, it is valuable in my opinion.
- I think it was a nice idea for a project. It made us think about the manufacture of the actual device and allowed us to explore multiple geometries. I think it would have been nice to test them earlier in the semester so that we could see them perform, but time constraints didn't allow us to do that.

- I love the integration of 3D printing into any course. 3D modeling is something that I really enjoy doing and doing it more gets me more experience with it and makes me better at it. Actually building it and testing it definitely adds to the value of the project because we can compare calculated values for our design with real world results.
- It was a good project because it there wasn't a whole lot of information out there about 3-d printed heat exchangers, especially without support materials. So we couldn’t just google a design and copy it, we actually had to come up with it on our own. This allowed for a lot of free thinking and actual designing. The 3-d printing aspect was neat because it is a technology that will only become more advanced and used more.
- The project was difficult and very time consuming, but a lot was learned.

In the open-ended comments, several themes were frequently repeated. One of these was that this project was a “lot of work” or “very time consuming.” The instructor took this to be a favorable result, since student effort is often an indicator of how much learning takes place. Students in the department are also very excited about 3D printing technology, and integrating 3D printing into this course made this course more interesting for a large number of the students.

Conclusions

In the Fall 2017 semester, a project was introduced in a Design of Thermal Systems course integrating 3D printing and in-space manufacturing concepts into a heat exchanger design project. The objectives of this project were to increase students’ enthusiasm for the course, give students experience working with design projects with real-world constraints, and to introduce them to in-space manufacturing. From student survey results, the first two objectives were accomplished, but the third was not.

The instructor observed that the students showed a better understanding of the fundamental heat transfer concepts with this project than with previous heat exchanger design projects. The uniquely low thermal conductivity of ABS plastic, which was the required heat exchanger material, led to unconventional heat exchanger geometries when optimizing for maximum heat transfer. It was therefore impossible for the students to simply copy a design from another source. Because the students had to work from first principles in developing a design, their conceptual understanding of heat exchangers was improved.

Acknowledgements

The authors would like to thank the Mechanical Engineering Department at South Dakota State University and the South Dakota Space Grant Consortium (funded by NASA) for providing financial support for this project.

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