Heat Exchanger- Lockheed Martin

Engineering Design 100, Section 22, Dr. Ritter

Team 4, MODZ

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Figure 1. A front and isometric view of the new heat exchanger design.
Executive Summary

Lockheed Martin has challenged the team to redesign a heat exchanger, specifically for the additive manufacturing-process (AM process). The problem is that the manufacturing of the traditionally used heat exchanger is wasteful. The actual design of the exchanger has room for improvement as well. The team used a variety of concept selection techniques including background research, concept development tree, and a weighted selection matrix to make sure the customer needs were being met. The result of our design selection was a cube lattice structure that increased the surface area and reduced the weight of the exchanger.

Introduction and Problem Statement

Team 4 (MODZ) would like to alter the current design of the heat exchanger to increase performance and reduce manufacture time and waste.

The modern heat exchanger has a high manufacturing cost and long construction time. These factors increase the cost for the consumer and create a negative impact on the environment because of the waste from manufacturing. Traditionally, large pieces of metal are cut down to size and welded together to get the small box-like exchanger with holes on one side. This method is wasteful and produces extra scrap metal. (1)

This project will investigate ways to reduce waste and production time by utilizing additive manufacturing. The increase in surface area will lead to an increase in efficiency of cooling the piece of equipment. By employing the components of the design process, we will improve the current version of the heat exchanger. One important of the heat exchanger redesign will be the prototype to confirm that the efficiency of cooling has improved, as well as the weight reduction.

Background

A heat exchanger uses multiple different processes to “transfer” heat. It is done by pushing hot air through a material with a high heat capacity so it will absorb the excess heat and cool air will leave the exchanger. The different material used in a heat exchanger determines the efficiency of the exchanger (5). There are multiple different types of heat exchangers and to efficiently redesign one of them, research must be done on all of them to know what you are dealing with.

The simplest type of heat exchanger is the double pipe heat exchanger. It uses liquid flowing through one pipe and the substance that needs to be cooled flowing in another pipe. They pass each other multiple times in a pattern and the heat is exchanged and the substance cools down (6).

While this type of heat exchanger works, it is not efficient enough to be use heavily in manufacturing. The shell and tube heat exchanger was designed with manufacturing in mind and it is the most used heat exchanger design because of the flexibility of use. It can be used in a large range of pressures and temperatures, meaning that it can be used for a multitude of processes throughout the world of industry. The shell and tube heat exchanger has four basic
parts: front header, rear header, tube bundle, and shell. The front header is where the fluid goes into the tubes of the exchanger. The rear header is where the fluid leaves the exchanger or in some cases, it returns to the front header to be cooled again. The tube bundle has all of the different parts inside the entire exchanger and where the cooling happens. The cooling itself happens with a similar process as the double pipe heat exchanger but with many more pipes, which makes it more efficient. The shell of the exchanger contains the tube bundle (7).

The heat exchanger Lockheed asked the team to redesign is called a plate heat exchanger. It has many thin plates and uses airflow across the plates to cool the air down. This heat exchanger has a much lower cost than the shell and tube heat exchanger because it is less complex and has fewer parts than the shell and tube exchanger. It also requires less space and weighs much less than the shell ad tube heat exchanger (8).

To make the plate exchanger more efficient the first move is to increase the surface area. The higher the surface area, the quicker the air will be cooled down. The next step is to pick design that reduces the weight of the exchanger, but still keeps a high surface area. The last step is to pick a material with a high heat capacity, but still keeps costs low.

Customer Needs

The main functions of the heat exchanger can be broken down into several different categories of customer needs. These needs must satisfy the requirements set forth to us by Lockheed Martin. The most important needs were applied to an Analytic Hierarchy Process (AHP) matrix and then weighted appropriately.

Table 1. The table below represents our AHP matrix that helped identify and weight the most important customer needs

<table>
<thead>
<tr>
<th>Surface Area</th>
<th>Temperature Control</th>
<th>Efficient Air Flow</th>
<th>Heat Capacity</th>
<th>Manufacture Time</th>
<th>Cost</th>
<th>Amount of Material</th>
<th>Total</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>12</td>
<td>2</td>
<td>0.2</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>13</td>
<td>2</td>
<td>0.22</td>
</tr>
<tr>
<td>Efficient Air Flow</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>11</td>
<td>2</td>
<td>0.19</td>
</tr>
<tr>
<td>at Capacity</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>8.5</td>
<td>2</td>
<td>0.14</td>
</tr>
<tr>
<td>Manufacture Time</td>
<td>0.333</td>
<td>0.333</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>4.67</td>
<td>1</td>
<td>0.08</td>
</tr>
<tr>
<td>et</td>
<td>0.5</td>
<td>0.333</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>4.83</td>
<td>1</td>
<td>0.082</td>
</tr>
<tr>
<td>Amount of Material</td>
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<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0.085</td>
</tr>
<tr>
<td>Grand Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>58.999</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first need is High Surface Area. A higher amount of surface area within the exchanger allows for the more efficient exchange of heat, thus yielding a higher control of temperature. High surface area is second only to temperature control in the AHP matrix in Table 1, with a weight of 0.2, the reason being that the two functions go hand in hand. One cannot have high temperature control without high surface area and vice versa.

Next comes High Temperature Control. As the main function of a heat exchanger is to control the temperature, this need received the highest weight of 0.22 in Table 1. The central purpose of this design project is to develop a more efficient heat exchanger and this can only be achieved with a high level of control over the temperature.
Beyond this, Efficient Airflow is the next most important need, with a weight of 0.19 in Table 1. Airflow is another important factor to the exchange of heat, as smooth, unrestricted channels allow for the air to pass through properly, yielding a higher amount of heat exchange. The first three needs of High Surface Area, High Temperature Control, and Efficient Airflow are the “Big Three” of sorts as they are all dependent on one another. To have a high temperature control, one needs a high surface area and efficient airflow. And if one has a high surface area and airflow, then one will have a strict control of temperature.

Heat Capacity of Material becomes the next most important need with a weight of 0.14, as seen in Table 1. A high capacity of heat is needed for the exchanger to perform its intended function. If a material that denatures under high temperatures, like plastic, is used, then the heat exchanger will melt without exchanging any heat. This need did not receive as large a weight as the other three because if the heat exchanger is efficient enough, it will be able to have a large control over temperature and a material that has a lower heat capacity would be sufficient.

Manufacture Time rings in with a weight of 0.08. Quick manufacture time is important for the production of the heat exchanger. A more complex design will yield a longer manufacture time. However, this is considered the least important need because the manufacture time should be very similar across all designs given that additive manufacturing is being used and the designs need to be complex for high surface area.

Cost comes next with a weight of 0.082 in Table 1. Cost can be affected by different types of material and different methods of additive manufacturing. However, given that the exchanger must be made out of some type of metal to ensure that it does not melt, the type of material will not affect cost too greatly. Additionally, different types of additive manufacturing will yield higher rates of failure or increased amount of waste. Therefore, it is not ideal to use an AM process other than powder bed fusion, as this is the most accurate process for metals. Amount of Material has a weight of 0.085. This need is less important because AM processes are being used, so the amount of material and the amount of waste will be very similar across all types of processes, save for sheet lamination.

**Concept Generation**

Group 4 began by researching different types of heat exchangers and methods of cooling. There is liquid cooling, which uses chemicals or water to absorb the excess heat, fan cooling, and surface area cooling, which involves a large amount of heat passing over a large amount of surface area so the metal absorbs the heat. Given the project specifications, surface area cooling was the process that was to be focused on.

Group 4 then brainstormed ideas for the design of the heat exchanger. The original design of the heat exchanger utilized straight walls. Other ideas for the inside included a wavy pattern, a zigzag pattern, multiple chambers separated by different pathways, and a crystalline lattice structure. Then the pros and cons for each design were discussed. The wavy and zigzag walls would have a greater surface area, but the air could get trapped in the odd corners of each design. The multiple chambers would add surface area, but would not have efficient air flow because the hot air could still be trapped inside the outer chambers. The last design, the
lattice structure had the least amount of cons. It would add surface area, allow for efficient airflow without any air getting trapped, and increase the surface area that the air travels over. The lattice design was the obvious choice to take to the next phase of the design process.

**Figure 2.** This classification tree shows the brainstorming process behind the design. This also shows the AM process picked, which will be discussed in further detail in **Description of Final Design**. The squares in blue are the ideas chosen to move on to the next phase of design.

**Concept Development and Selection**

Initially, outside sources were perused to generate ideas to use in the final design of the heat exchanger. Patents of new heat exchangers were major sources of ideas. As a whole, these patent designs were very similar. As can be seen in Figure 3, they employed many thin layers of metal placed side by side. Many of the group’s ideas were based off this concept.
**Figure 3.** This patent of a heat exchanger shows multiple layers of a heat exchanger that utilizes many thin walls.

The original Lockheed Martin heat exchanger utilizes straight walls that run directly through the box. To build on this concept while increasing the surface area, Group 4 considered using zig-zagging walls to replace the straight ones. This design would increase the total surface area of the exchanger without sacrificing too much airflow.

Beyond this, slightly curving “wavy” walls were considered to replace the straight ones. The gentle turns of these new walls would again increase the surface area while sacrificing even less airflow than the zig-zag walls. The issue with this design would be the difficulty of fitting a non-uniform shape inside of the defined box of the heat exchanger.

A third design that was considered was a system of multiple chambers. Initial small chambers would open up into larger chambers within the exchanger. This would increase surface area while likely keeping air-flow constant. An issue with this design is visualizing it and designing it in Solidworks.

The final design idea was a bit outside of the box. After a bit of research, a structure of lattices was discussed. The idea was refined to be the shell of a box such that only the posts connecting the corners would be present. From each corner a diagonal would cross to the opposite corner, creating four diagonals total. This design allows for maximum surface area while sacrificing next to no surface area, as the air will still be allowed to flow freely through the device. Additionally, given the boxy shape, the lattice structure will fit cleanly into the current heat exchanger.
Figure 4. This image depicts an isometric view of the prototype to be 3D printed.

Table 2. In this Concept Selection Matrix, the top seven criteria are weighted in terms of importance, then rated in terms of how well each design fulfills these criteria.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Wavy Weight</th>
<th>Rating</th>
<th>Weighted Score Rating</th>
<th>Zig-Zag Weight</th>
<th>Rating</th>
<th>Weighted Score Rating</th>
<th>Multiple Chambers Weight</th>
<th>Rating</th>
<th>Weighted Score Rating</th>
<th>Lattice Weight</th>
<th>Rating</th>
<th>Weighted Score Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Surface Area</td>
<td>0.2</td>
<td>2.5</td>
<td>0.8</td>
<td>0.2</td>
<td>2.5</td>
<td>0.8</td>
<td>0.2</td>
<td>4</td>
<td>0.8</td>
<td>0.8</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
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<td>2.5</td>
<td>0.55</td>
<td>0.55</td>
<td>4</td>
<td>0.88</td>
<td>0.55</td>
<td>5</td>
<td>0.66</td>
<td>0.66</td>
<td>5</td>
<td>1.1</td>
</tr>
<tr>
<td>Air Flow</td>
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<td>1.5</td>
<td>0.285</td>
<td>0.285</td>
<td>3</td>
<td>0.57</td>
<td>0.285</td>
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<td>0.57</td>
<td>0.57</td>
<td>4</td>
<td>0.76</td>
</tr>
<tr>
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<td>0.42</td>
<td>0.42</td>
<td>1</td>
<td>0.14</td>
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<td>0.28</td>
<td>0.28</td>
<td>3</td>
<td>0.42</td>
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<tr>
<td>Manufacture Time</td>
<td>0.08</td>
<td>3</td>
<td>0.24</td>
<td>0.24</td>
<td>3</td>
<td>0.24</td>
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<tr>
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<td>0.246</td>
<td>3</td>
<td>0.17</td>
</tr>
<tr>
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<td>0.255</td>
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<td>0.255</td>
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<td>0.17</td>
</tr>
<tr>
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<td>3.051</td>
<td>2.831</td>
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<td>3.051</td>
<td>3.051</td>
<td>2.831</td>
<td>3.051</td>
</tr>
</tbody>
</table>

We input all of these designs into a Concept Selection Matrix, as can be seen in Table 2, and weighted them appropriately using the values from the AHP matrix. After ranking each of the components on the different designs and added up the weights, we concluded that the Lattice design was the best form by a fairly large margin.

Description of Prototype

Figure 5. On the left is a scaled-down 3D printed model of the lattice design. On the right, is a Solidworks model of a single lattice cube used to make-up the 3D printed model.
The prototype (pictured in the above figure) is 3 lattice cubes tall, 3 wide, and 4 deep. The lattice structure is a body-centered cube and has the dimensions 0.5 in. x 0.5 in. x 0.45 in. and the thickness of the bars and shell is 0.05 in. The body-centered cube was chosen for the lattice structure because the original shape of the heat exchanger is a rectangular box. A more complex lattice structure would have to be modified to fit inside the box and by doing that the risk of trapping air goes up. The cube lattice structure allows for air to easily travel through and increased the surface area dramatically compared to the multiple chambers, zig-zagged, wavy, or straight wall designs.

Design Review

**Figure 6.** The arrow shows the edges on the cube that were rounded for better air flow and weight reduction.

In the design review, the group figured that the airflow could be affected by the corners on the inside cross of the square (see figure above). To fix the problem, the bars on the inside were filleted and smoothed to a cylindrical shape. This fix did not take away much surface area and significantly reduced the weight of the lattice structure insert. The final design had to be three cubes high, fifteen wide, and 14 deep to fit inside of the heat exchange shell we were provided with at the beginning of project.

Description of the Final Design

For the final design, Group 4 decided to use stainless steel as the material of the heat exchanger. Stainless steel has a specific heat capacity of 500 J/kgK, which is suitable for its use in this design because it will absorb heat, but not melt. (2) Stainless steel also has a density of 7480-8000 kg/m³, which is on the less dense end of metals, meaning it will be relatively low in weight (3). The price of stainless steel is $0.14-0.18 per pound, which is significantly lower in cost than the aluminum, copper, and iron, making it the best option (4). Because stainless steel was chosen for the material, the only options for additive manufacturing were powder bed fusion and directed energy deposition. Of the two, powder bed fusion is more accurate and precise, so it was chosen because of the complexity and needed precision of the lattice structure design.
The requirements given for the redesign of the heat exchanger said to reduce the weight, but increase the surface area. The lattice design did just that and increased the surface area by 11.7%. The original surface area was 1039.79 in$^2$ and the surface area after the redesign was 1161.75 in$^2$. The weight of the heat exchanger was reduced by 26.6%. The original weight was 1.06 lbs and the final weight was 0.77 lbs. SolidWorks crashed before we could run tests on the exchanger with heat or a force pushing down on it, but the prototype that was only printed in plastic was very sturdy. Given that information, it can be assumed that the actual lattice insert printed in stainless steel will be even stronger and will not melt as easily as plastic would.

**Conclusion**

To conclude, the overall redesign of the heat exchanger was a success. All of the requirements set forth by Lockheed Martin were met. The product still works efficiently, because of the larger surface area, but now has a reduced weight. Some cons associated with the design could be the complex design, which may be too much for certain types of additive manufacturing.

The design could be altered and changed many times from here. The lattice structure could be changed to a different shape if it makes the surface area larger. The material could also be changed from stainless steel to something either more or less expensive, depending on specific criteria for each exchanger and what machines they are being used on.

The team learned a lot about design refinement. The original prototype without the rounded edges was good. It still would have worked and has an increased surface area, but it needed to be better. Brainstorming ways to make something go from good to great can be difficult because it is usually a minor change (like the rounded edges). We also learned that technology can be a pain to deal with and to always be patient because SolidWorks is bound to crash.
References