

Technical Memorandum
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To: Lockheed Martin Corporation

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Subject: Penn State University
EDSGN 100: Introduction to Engineering Design
Client-Driven Design Project, Spring 2016

Purpose. The purpose of this memorandum is to suggest a new design for a heat exchanger that utilizes Additive Manufacturing (AM). This new design will allow Lockheed Martin to manufacture their heat exchangers with much less waste materials, more geometric features, and lower costs.

Background. Additive Manufacturing constructs the objects via the layer deposition of material until the desired part geometry is achieved. The advantages of AM techniques are minimized waste material and highly complex geometry of final designs. AM allows the manufacturer to save money on material costs as well as preserve the limited natural resources that we have access to.

An optimal heat exchanger should be suitable for Additive Manufacturing. It also requires a metal with high thermal conductivity, high tensile strength, high corrosion resistance, economical efficiency, and robust heat transfer rate. In addition, our heat exchanger may incorporate a different air flow, but the surface area, the mating members, and overall size factor must remain constant.

To calculate the heat transfer rate through each fin, we use the equation:

$$Q = h * A * (T_f - T_a) * e_f \text{ where } h \left(\frac{W}{m^2 \times ^\circ C} \right) \text{ is the convective film coefficient (Eq. 1)}$$

A (m^2) is the total surface area of the fin

T_f ($^\circ C$) is the temperature at the base of the fin

T_a ($^\circ C$) is the fluid (in this case, air) temperature

e_f is the fin efficiency of the selected material

Sponsor. This design project is sponsored by Lockheed Martin (LM), an American global security and aerospace company headquartered in Washington, D.C. With more than 130,000 employees all over the world, Lockheed Martin is one of the leading firms in each of its five

main business segments: aeronautics, information systems and global solutions, missiles and fire control, mission systems and training, and space systems. In addition to that, Lockheed Martin also has branch companies in Canada, Australia, and the U.K., and joint stocks in several other aviation-related companies.

Project Description. Among the five options that we were presented with, the heat exchanger has the most far-reaching applications. Heat exchangers can be applied in almost every system, from a small computer processor to large industrial equipment. Moreover, since our group is comprised of mostly mechanical and chemical engineering majors, pursuing heat exchangers seems to relate the most to our present knowledge and future careers.

To complete this project, our design must meet certain criteria from Lockheed Martin. Not only must our heat exchanger be additively manufactured, but its production cost and build time should also be reasonable for mass production. Also, since this heat exchanger is designed to remove the heat of certain electrical components in computer circuit card assemblies (CCA), its mating features must stay the same as in the scale model. In addition, its internal air-flow through geometry can change, but the surface area and overall size factor should remain constant.

Procedures. The design procedure began with redesigning the heat exchanger. Since LM requires that the size factor and surface area of the heat exchanger remain the same, few modifications changing the slot pattern on the gas-entering side were made. Several different types of patterns (zigzag and hexagonal to name a few) were drawn in SolidWorks 2015 x64 edition. Each pattern was calculated for the surface area and total heat transfer using Equation 1 to select the optimal design. Our calculations were done on the basis of the following assumptions:

- The fluid is typical air at 25°C.
- The highest temperature of the CCA is 60°C (Foster, 1992).
- The fin efficiency of copper in the cuboid, the shape of our heat exchanger, is 1.
- The surface area is the total area that the air flow will contact in each slot.
- The heat convective film coefficient is $5 \frac{Btu}{hr \times ft^2 \times ^\circ F}$ or approximately $28.4 \frac{W}{m^2 \times ^\circ C}$ for forced convection.

The final design was then sent to the Penn State Maker Commons to print the prototype.

Our next step was to determine the suitable AM technique and material. The selected AM technique must satisfy our choice of material, maintain the average product quality, and still keep the cost as low as possible. Therefore, the material was selected based on the data of thermal conductivity, tensile strength, and prices per pound.

Next, the cost of our heat exchanger was estimated using the model of Yim and Rosen, 2012. Accordingly, the overall cost was estimated by:

$$\text{Overall Cost} = P + O + M + L \quad (\text{Eq.2})$$

where P is the machine purchase cost, O is machine operation cost, M is the material cost, and L is labor cost. First, the machine purchase cost P was calculated by the following equation

$$P = \frac{\text{Purchase price} \times T_b}{0.95 \times 24 \times 365 \times Y_{\text{life}}} \quad (\text{Eq.3})$$

where T_b is the build time (hour) and Y_{life} is the useful life of a machine (year). Our group decided to make the Y_{life} 1 year, the common warranty of a machine. T_b was estimated by dividing the volume of the materials of our design (in cubic inches) by the building rate of a selected AM machine (in cubic inches/hour). The available technology at Lockheed Martin was unknown, so it was assumed that the fastest machine was provided. The building rate value, the electrical requirements, and the machine's price (in the calculations below) were then taken from additivemanufacturing.com and the site of Sculpteo, a French 3D printing company.

The operation cost would have been calculated by:

$$O = C_o \times T_b \quad (\text{Eq.4})$$

where C_o is the machine operation rate (dollars/hour). However, this operation rate could not be found in the available resources, so the operation was instead calculated with the formula provided by Bryn Mawr College as follows:

$$O = (\text{machine power}) \times T_b \quad (\text{Eq.5})$$

where the machine power of the machine (in kilowatts) was taken as the product of the machine's voltage (in voltage, on additivemanufacturing.com), the standard current through U.S outlets (20 amperes), and 10^{-3} .

After that, the material cost was estimated as:

$$M = V \times \rho \times (\text{material price}) \times 10^{-3} \quad (\text{Eq.6})$$

where V (in cm^3) is the needed volume of metals taken from SolidWorks 2015 x64 Edition

ρ (in g/cm^3) is the metal's density, taken as 8.96g/cm^3

Material price (in \$/kg) is taken from the site of M. Vincent & Associates

Finally, the labor cost was usually negligible in the cost estimation (Thomas & Gilbert, 2014).

Results and Discussion. As a result of our rigorous research on heat exchangers, the original heat exchanger had its internal geometry, surface area, material, and manufacturing process changed to fit with the additive manufacturing process.

Design: internal geometry and surface area

In the original design of the heat exchanger, the fins, which are the actual points of exchanging the heat with the surrounding air, were in basic horizontal pattern that ran up the heat exchanger like a ladder. This basic design is outlined in Figure 1. After consulting outside sources (Engineering Design TA and online sources), we determined that the basic horizontal makeup should remain the same, but that there should also be a horizontal zigzag pattern between the horizontal fins. The new design is outlined in Figure 2. This alteration reduces a small portion of air flow but gives almost double surface area of the metal that contacts with the air, thus effectively exchanging more heat.

The new surface area is calculated by summing all the contact area in each triangular slot of all 39 horizontal fins. Each fin has two right triangular slots on the sides and 9 other triangular slots in the middle. Each of these slots contacts the air flow through 3 faces, each of which is 7 inch long (as equal to the length of the whole heat exchanger) (see Figure 3). So the total surface area in each fin is:

$$A_{1\text{ fin}} = \left(0.13 + 0.15 + \sqrt{0.13^2 + 0.15^2}\right) \text{ in} \times 7 \text{ in} \times 2 \text{ slots} \\ + \left(0.27 + 2 \times \sqrt{0.13^2 + 0.15^2}\right) \text{ in} \times 7 \text{ in} \times 9 \text{ slots} = 48.72 \text{ in}^2$$

So the surface area of 39 fins is $A = 48.72 \text{ in}^2 / \text{fin} \times 39 \text{ fins} = 1900 \text{ in}^2$

From Eq.1, the heat transfer rate through each fin is:

$$Q = h \times A \times (T_f - T_a) \times e_f \\ = 28.4 \frac{\text{W}}{\text{m}^2 \times ^\circ\text{C}} \times 1900 \text{ in}^2 \times \left(\frac{1 \text{ m}^2}{1,550 \text{ in}^2}\right) \times (60 - 25)^\circ\text{C} \times 1 \approx 1218 \text{ W}$$

Material

After researching different materials on their thermal conductivity, tensile strength, and price, the metals under consideration are narrowed down to four options: copper, aluminum, aluminum alloys, and stainless steel (see Table 3). Copper was chosen due to its highest thermal conductivity $\left(386 \frac{\text{W}}{\text{m} \times ^\circ\text{C}}\right)$ and reasonable tensile strength (220 MPA). Its cost might be higher than the other metals, but the potential benefits with respect to conductivity and structure are well worth the extra cost.

Additive Manufacturing Process

This heat exchanger was requested to be redesigned and optimized for additive manufacturing. The process selected must use metals and minimum support materials as well as post processing. From the seven types of available AM processes, only powder bed fusion, binder jetting, and direct energy deposition are readily available for mass production and use metals. However, according to information from Loughborough University and Additively, a spin-off of ETH Zurich, Switzerland, binder jetting and direct energy deposition need more post processing

than powder bed fusion and thus might pose additional cost. Therefore, this heat exchanger should be manufactured with direct metal laser sintering (a type of powder bed fusion) as it is able to create the heat exchanger out of the material we wanted with the amount of accuracy we needed in a reasonable amount of time.

Cost Analysis

As mentioned above, the available technology used in Lockheed Martin is unknown, so the details for cost estimations were assumed from the best machine that we could find. It was assumed to be the ExOne M-Flex (Sculpteo, 2014). At a price of \$400,000, the ExOne M-Flex has a building rate of at least 73in³/hour and the normal operating voltage of 240V (additivemanufacturing.com, 2013). Using the written description in the procedure, the build time can be calculated as:

$$T_b = \frac{V}{\text{Building rate}} = \frac{34.46\text{in}^3}{73 \frac{\text{in}^3}{\text{hour}}} \approx 0.47 \text{ hours}$$

The volume of the needed materials were taken from SolidWorks 2015 x64 edition. Along with the durable life of one year (inferred from the offered warranty), the machine purchase cost can be calculated followed Eq.3 as:

$$P = \frac{\text{Purchase price} \times T_b}{0.95 \times 24 \times 365 \times Y_{life}} = \frac{\$400,000 \times 0.47}{0.95 \times 24 \times 365 \times 1} \approx \$22.69$$

With the material price of \$2.28/pound or \$5.23/kg (M.Vincent & Associates, 2016), the material cost for the copper is estimated using Eq.6 as:

$$M = 34.46\text{in}^3 \times \frac{1\text{cm}^3}{0.061\text{in}^3} \times 8.96 \frac{\text{g}}{\text{cm}^3} \times 10^{-3} \frac{\text{kg}}{\text{g}} \times \frac{\$5.23}{\text{kg}} \approx \$26.47$$

Followed the Eq. 5 and the voltage of 240V, the operation cost is

$$O = (\text{machine power}) \times T_b = 240V \times 20A \times \frac{10^{-3}\text{kW}}{1W} \times 0.47\text{hour} \approx \$2.26$$

Since labor cost is ignored, the overall cost of our heat exchanger given by Eq. 2 is:

$$\text{Overall cost} = M + P + O + L = \$26.47 + \$2.26 + \$22.69 + \$0 = \$51.42$$

This final cost estimation is quite high compared to the subtractively manufactured heat exchanger. However, as technology evolves, AM machines might get cheaper and reduce the machine purchase cost. Also, as AM becomes more widespread, more materials are saved during industrial production. The material cost of copper will thus decrease. In addition, as Lockheed Martin deploys economies of scale, the operation cost can go down as well. In brief, this heat exchanger might be expensive for this moment, but as resources become more available, it will be as economically efficient, or perhaps more economically efficient as the subtractively manufactured one.

Conclusions and Recommendations.

In brief, our heat exchanger for CCA has its internal geometry, materials, and manufacturing process changed for the purpose of additive manufacturing. Not only is it added with zigzag patterns between the basic horizontal fins to increase surface area, but the new heat exchanger is also made from copper using powder bed fusion to achieve the complicated geometry. Via cost analysis, our exchanger might not be readily economically efficient now (\$51.42/one), but there are plenty of rooms to cut cost in the future.

In the end, we thank Lockheed Martin for such an opportunity to work on this realistic design project. Additional clarifications of the project's results or further questions on any details can be reached via any of the following emails:

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Attachments.

Table 1. Notations

Table 2. Length and Weight Conversion Factors

Table 3. Metals under consideration

Figure 1. Original heat exchanger

Figure 2. Modified heat exchanger to improve efficiency

Figure 3. Dimensions of two types of slots in a fin



**TABLE 1
NOTATIONS**

Variable	Description	Unit
Q	Heat transfer rate through heat exchanger	W
h	Convective film coefficient	$\frac{W}{m^2 \times ^\circ C}$
A	Total surface area of the fin	m ²
T _f	Temperature at the base of the fin (air out)	°C
T _a	Fluid temperature (air in)	°C
e _f	Fin efficiency of the selected material in the exchanger shape	No unit
M	Material cost	\$
L	Labor cost	\$
O	Operation cost	\$
P	Machine purchase cost	\$
V	Volume of needed metal	ccm ³
ρ	Density of chosen metal	g/ccm ³
C _o	Operation rate	
Y _{life}	Useful life of a machine	year
T _b	Build time	hour

**TABLE 2
LENGTH AND WEIGHT CONVERSION FACTORS**

Milimeters (mm)	Centimeters (cm)	Meters (m)	Inches (in)
1	0.1	0.001	0.03937
100	10	0.1	3.937
25.4	2.54	0.0254	1
Kilograms (kg)	Grams (g)	Pounds (lbs.)	
0.00453	4.53	0.01	
0.453	453	1	
1	1000	2.205	

**TABLE 3
METALS UNDER CONSIDERATION**

Metals	Cost (\$/lbs)	Thermal conductivity at 20°C (W/(m × °C))	Tensile Strength (MPa)
Aluminum	0.74	202	40-50
Copper	2.28	386	220
Stainless Steel	0.14-0.18	12-45	505
Aluminum Alloy 6061	0.68	173	310

Sources: engineeringtoolbox.com, M. Vincent & Associates

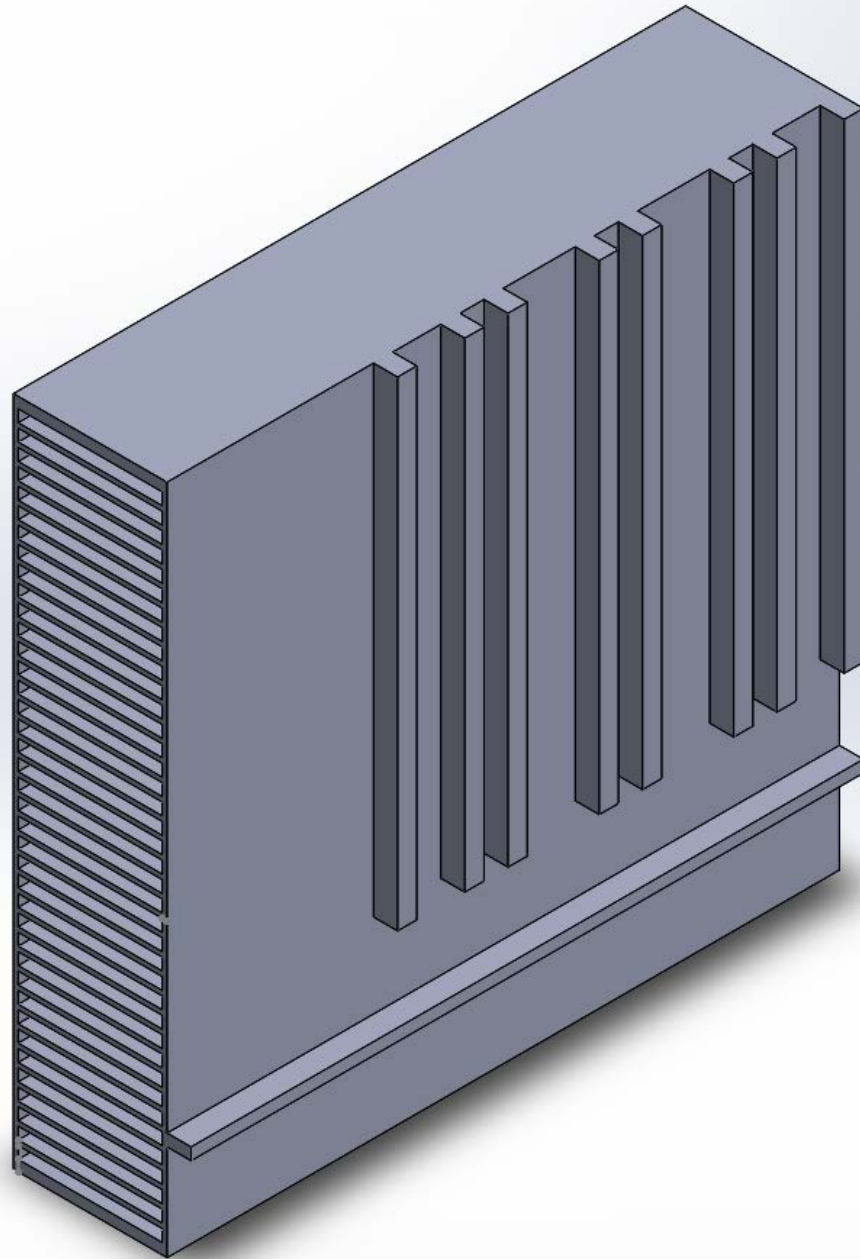


Figure 1. Original heat exchanger

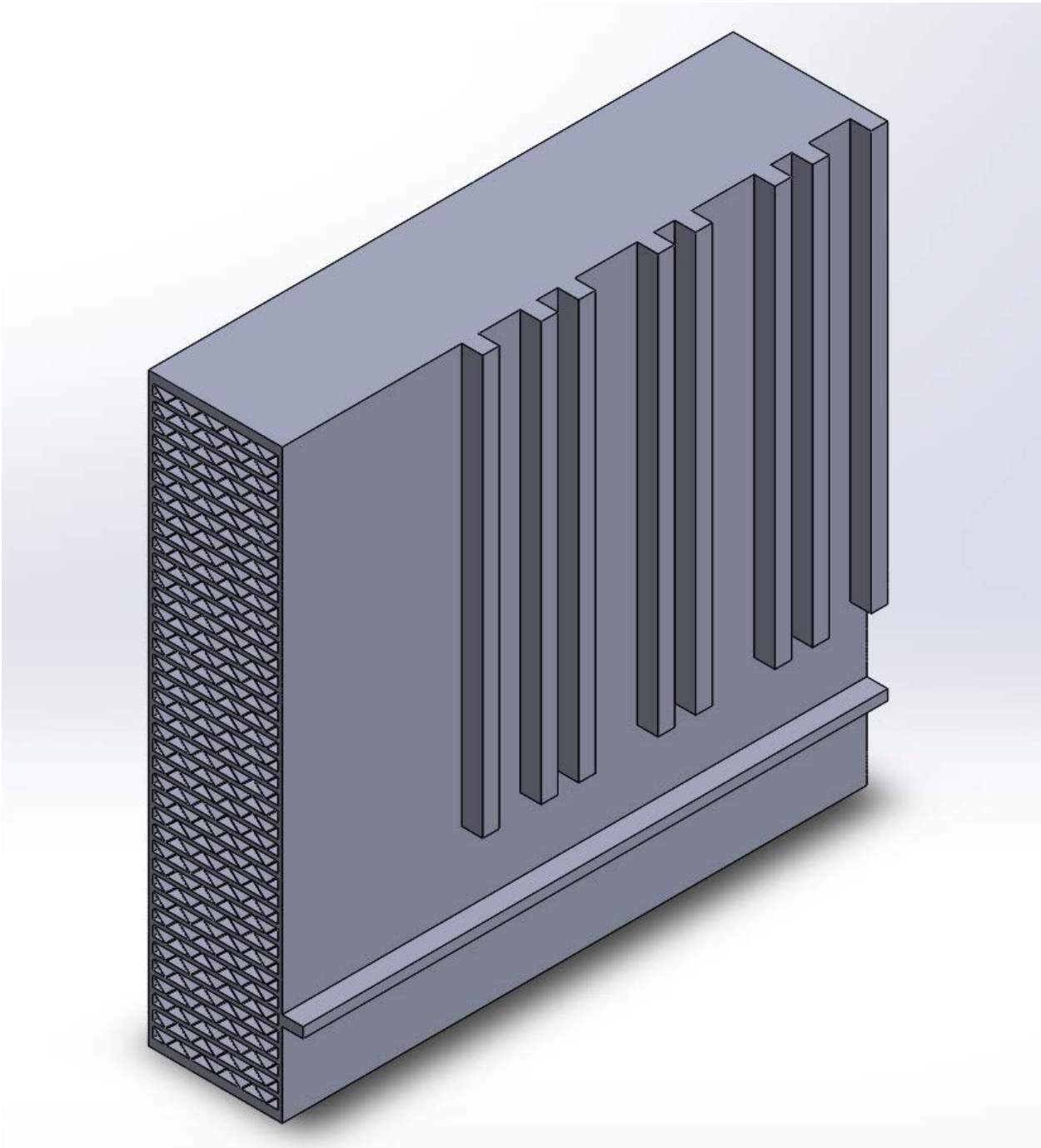


Figure 2. Modified heat exchanger to improve efficiency

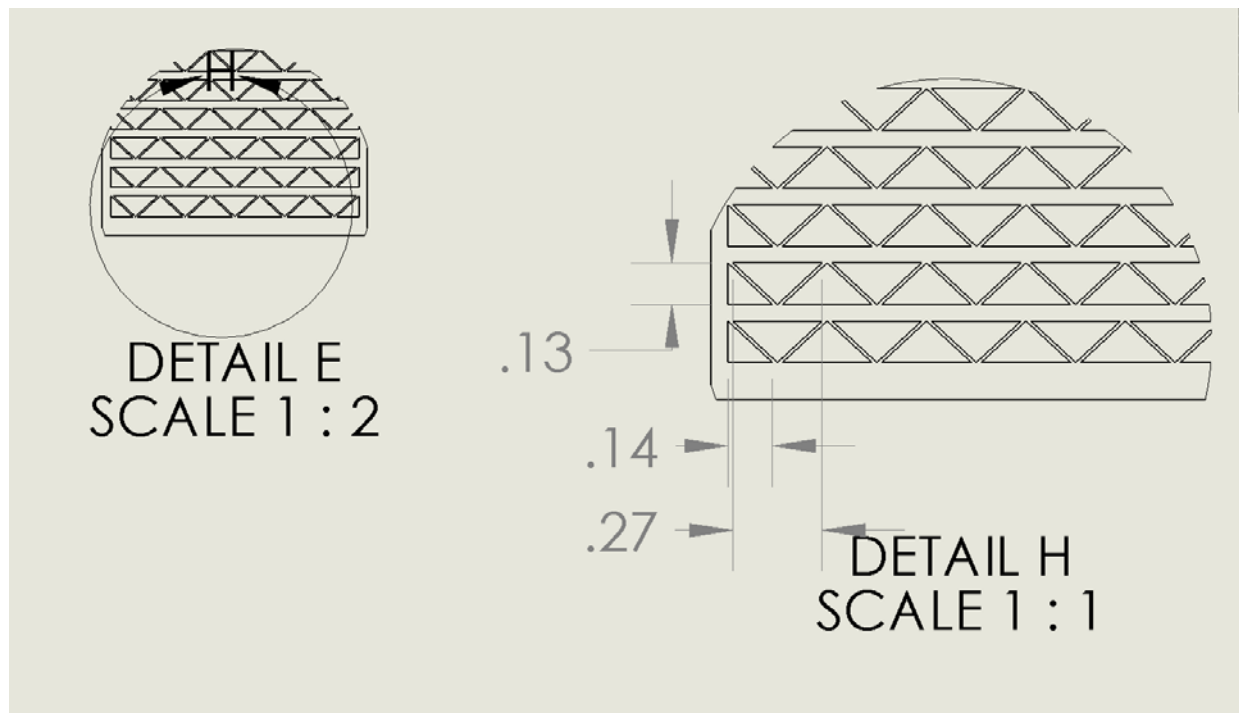


Figure 3. Dimensions of two types of slots in a fin