Experimental Comparison of a Traditionally Built versus Additively Manufactured Aircraft Heat Exchanger

David Saltzman[1], Michael Bichnevicius[2], Stephen Lynch[3], Timothy W. Simpson[4]
Penn State University
University Park, PA 16802

Edward W. Reutzel[5], Corey Dickman[6], Richard Martukanitz[7]
Applied Research Lab—Penn State
University Park, PA 16802

This study compared the performance of both baseline and enhanced traditionally built heat exchangers (aircraft oil coolers), to both baseline and enhanced additively manufactured (AM) heat exchangers of similar geometry. Three dimensional (3D) X-ray computed tomography scans were performed on the baseline traditionally built heat exchanger in order to develop a solid model for AM fabrication using a laser-based powder bed fusion process with AlSi10Mg powder. Two AM heat exchanger geometries were constructed to replicate the baseline traditionally built geometry, with one AM heat exchanger containing additional small air-side enhancement features. The air-side pressure drop for the AM heat exchangers was double that of the traditionally built baseline heat exchanger. Heat transfer was increased by about 10 percent for the baseline AM and by 14 percent for the enhanced AM heat exchanger when compared to the traditionally built baseline heat exchanger. Both of the AM heat exchangers performed as well as the enhanced traditionally built model, but both had a higher pressure drop. Ongoing research seeks to ascertain the specific causes of the increased pressure drop and improved heat transfer, in order to provide a foundation for enhancement of future AM-built heat exchanger designs.

Nomenclature

AM	additive manufacturing
BAM	Baseline Additively Manufactured
BTM	Baseline Traditionally Manufactured
CAD	computer aided design
CT	computed tomography
DMLS	direct metal laser sintering
EAM	Enhanced Additively Manufactured
ETM	Enhanced Traditionally Manufactured
gpm	gallons per minute (water)
HX	heat exchanger
ITDc	Initial Temperature Difference in degrees Celsius
MFR	mass flow rate
PG	pressure gauge
SLM	selective laser melting
TC	thermocouple

[1] Graduate Student, Mechanical and Nuclear Engineering, 114 Research West.
[2] Undergraduate Student, Mechanical and Nuclear Engineering, 114 Research West.
[3] Assistant Professor, Mechanical and Nuclear Engineering, 331 Reber, AIAA Senior Member.
[4] Professor, Mechanical and Nuclear Engineering, 209 Leonhard Building.
[5] Head Laser System Engineering and Integration, Engineering Science and Mechanics, 4420D Applied Science.

[6] Research Associate, Center for Innovative Materials Processing through Direct Digital Deposition, Applied Science Building.
[7] Director, Center for Innovative Materials Processing through Direct Digital Deposition, 4400D Applied Science Building.

I. Introduction

HEAT exchangers (HX) are used in many different applications to remove unwanted heat generated during operation of high performance machines and equipment ranging from compact electronics to nuclear reactors. Heat exchangers play a key role in keeping the components of a system at a desired temperature. For example, aircraft engines have moving parts under high loading and use oil to keep these parts lubricated. Consequently, the oil becomes extremely hot leading to a decrease in oil viscosity which can cause insufficient lubrication. The oil must be cooled using a specific type of heat exchanger called an oil cooler.

Aircraft engine oil coolers, typically comprising a brazed assembly of numerous individual components, have been used in the aviation industry for many years and have been optimized for weight, performance, and cost. However, for specialized military and aerospace applications, the performance of the heat exchanger is often the primary design goal. Complex designs can improve performance but are difficult to fabricate with traditional techniques. Additive manufacturing (AM) through layer-wise fabrication (such as powder-bed fusion) may allow complex designs that enable increased heat exchanger performance and reduce part weight, while limiting the number of individual components required for the final part. However, little is currently understood about the design tradeoffs required to build an AM HX and the potential performance enhancement (or reduction) that may occur.

The objective in this work was to design, manufacture, and test a heat exchanger designed for light aircraft that was fabricated using AM and compare it to a traditionally manufactured model. A performance test rig was designed and built to characterize liquid and air stream heat transfer and pressure drop for the heat exchanger. The heat exchanger was scanned via a three-dimensional X-ray computed tomography (CT) technique to develop a CAD model for AM fabrication. The heat exchanger was fabricated using a laser-based powder bed fusion process and its performance was compared to the traditionally manufactured heat exchanger. Heat transfer enhancement features were added to the baseline AM heat exchanger design to understand the ability to fabricate complex features and their impact on performance.

II. Previous Studies

Heat exchanger design is largely dictated by the process and environment in which the heat exchanger operates. Shell and tube heat exchangers can handle large flow rates, while compact and "micro heat exchangers" usually have high heat transfer, low flow rates, and larger pressure drops [1]. In the realm of compact heat exchangers (CHE), the most well-known geometries are plate (PHE), plate-fin (PFHE), printed circuit (PCHE), and spiral heat exchangers (SHE), which all utilize additional features to enhance heat transfer [2]. As shown in [3, 4], by replacing standard pin features with S-shaped features in the liquid and gas streams of a PCHE, the overall size and pressure drop for both fluids can be greatly reduced. However, the photo-etching and diffusion bonding technologies used to create many PCHE are mostly used for small features and channels which can lead to large pressure drops or low mass flow rates.

For the study in this paper, liquid to air cross-flow heat exchangers used in the aviation industry were evaluated. These heat exchangers must be as compact, lightweight, and as efficient as possible to accommodate imposed size constraints and weight limitations on aircraft [5]. These aircraft heat exchangers are used in fuel-air aftercoolers, air-conditioning radiators, electronics cooling, and engine oil coolers [6]. The design, material selection, and geometry of each aircraft heat exchanger varies because of the different operating conditions and working fluids used. The fabrication methods used in the manufacturing process for each type of HX directly affect the final cost for the part [6]. A complex HX consisting of a brazed assembly with numerous components with small, intricate features will be expensive to manufacture using traditional methods and might suffer defects from the manufacturing process.

Limitations of traditional manufacturing techniques may allow for additive manufacturing (AM) to become a viable option for creating compact, high-performance heat exchangers. Many different types of AM processes exists; each with their own benefits and weaknesses [7]. However, to use AM for an air-liquid heat exchanger, the AM process must be able to create internal channels, thin and small features, and use a material that is thermally conductive and durable. With these constraints taken into account, a laser-based power-bed fusion (PBF) process is selected for this initial study. Stimpson, et al. [8] demonstrated the use of PBF AM techniques to fabricate heat sinks with micro-channels having hydraulic diameters of less than 0.5 mm. Heat transfer can be further enhanced in micro-channels when compared to straight smooth channels by making the channels wavy to disrupt the boundary layer [9]. The micro-channels are an effective design feature to increase heat transfer but result in higher pressure drops and lower flow rates. Additionally, uncontrolled surface roughness, which is a function of build time, material, and build direction, is a byproduct of the PBF AM process [10]. However, in Ventola, et al. [11], PBF AM was used to intentionally create different amounts of surface roughness on an external heat sink fin. It was found that adding surface roughness increased heat transfer as much as 40% when compared to a smooth external heat sink fin due to the disruption of the thermal boundary layer.

Other studies have used AM to create unique macro-scale features on heat sinks. For example, Wong, et al. [12] used PBF AM to create novel 3-D heat sinks, and they found that the innovative geometries were superior in both heat transfer and pressure drop relative to a traditional pin-fin geometry. Another interesting study was performed by Thomson, et al. [13], which used laser-based PBF to additively manufacture a heat pipe made from a titanium alloy. The heat pipe performed well and validated that an AM process can make a component that would be difficult to fabricate using traditional machining processes. Boomsma, et al. [14] created complex features in the form of compressed metal foams. These heat sinks performed better than the commercially available heat sinks they were compared against because the compressed foams exhibit high conduction through the structure as well as enhanced convection. De Jaeger, et al. [15] found that metal foams could be bonded to a substrate in a number of different methods; brazing resulted in the lowest thermal contact resistance. The advantage of an AM process is that the substrate and the air-side material (foam, fin, etc.) can be fully integrated during the layer-by-layer build with no thermal contact resistance.

There is increasing interest in understanding how AM technology can impact heat transfer. However, most experimental studies use a heat sink geometry that involves only one working fluid. These studies can be used to generate design correlations for heat transfer with AM-fabricated parts, but they are unable to capture the complexity of a functional part in full detail. The study in this paper presents the first-of-its-kind direct performance assessment of a fully functional air-to-liquid heat exchanger manufactured via laser-based PBF and compares it to the baseline traditionally manufactured design.

III. Experimental Set-up

A. Test Configuration

A test rig was designed and constructed to measure heat transfer and pressure drop in the air stream and liquid stream of the heat exchangers as depicted in Fig. 1. The liquid-side fluid enters at an elevated temperature while the air side enters at ambient temperature. The heat exchangers were placed in an insulated box open to the air-side flow to minimize heat loss to the surroundings.

In this study, the liquid-side fluid is water, which is heated up to 60˚C using four hot water heating elements that dissipate a total power of up to 7000 watts. The water pump allows for a maximum flow rate of 0.35 kg/s but was held constant at 0.185 kg/s (3 gpm) for all tests conducted in this study. Since all the heat transferred into the air is replaced by the liquid side heaters, the system is able to reach a thermal equilibrium during testing, which enables long run times for accurate performance data collection. The liquid side inlet and outlet temperatures were measured with thermocouples located in the water flow immediately upstream and downstream of the heat exchanger. The pressure drop on the water side was recorded but the sensitivity of the pressure transducer was not appropriate to distinguish differences in the pressure drops (35kpa) recorded across the oil coolers. A future upgrade will include more sensitive pressure transducers to measure the liquid side pressure drop.

To achieve engine condition mass flow rate on the air side, the test rig uses a high-volume, low pressure blower that can deliver the 0.4 kg/s required through the oil cooler being tested. The blower is controlled by a variable frequency drive that allows for different mass flow rates to be tested through the air side of the oil cooler. The temperature and pressure at both the inlet and the exit of the oil cooler was measured in order to develop a performance curve. A venturi is used to record the air mass flow rate through the oil cooler. Flow conditioning, including straws and screens, was used upstream of the oil cooler in order to create a more uniform velocity profile entering the heat exchanger.

Figure 1 also shows how the oil cooler was placed into the air stream. Since the oil cooler's dimensions and features are unique, the test section had to be built to accommodate this specific oil cooler. Velocity profiles entering and exiting the oil cooler have been recorded and the profile is symmetric but higher near the center line of the pipe. This is expected because there is no smooth convergence from the pipe into the oil cooler fins in the current set-up. The air is supplied by a blower (not pictured) which is upstream of the air mass flow meter.

B. Uncertainty

For the pressure drop measurements on the air side, the uncertainty at low flow rates (0.13 kg/s) is calculated to be about 3% while at the higher flow rates (0.26 kg/s) the total uncertainty is under 0.7%. The uncertainty analysis was performed for one oil cooler using a Kline-McClintock [16] uncertainty analysis and assumed constant for all other tests since all the probes and data recording process are constant between tests.

The heat transfer both from the water stream and to the air stream, was measured by using the mass flow rate, specific heat, and measured temperature change of each corresponding fluid. For low air side flow rates (0.1 kg/s), the uncertainty in total heat transfer was calculated to be 7% and 3% for the water and air, respectively. At higher air mass flow rates (0.25 kg/s) the total heat transfer uncertainty was 4% and 2.25% for the water and air, respectively. The gain or loss of energy of each fluid was calculated independently, and the energy balance between the two fluids was within the uncertainty for its respective air mass flow rate.

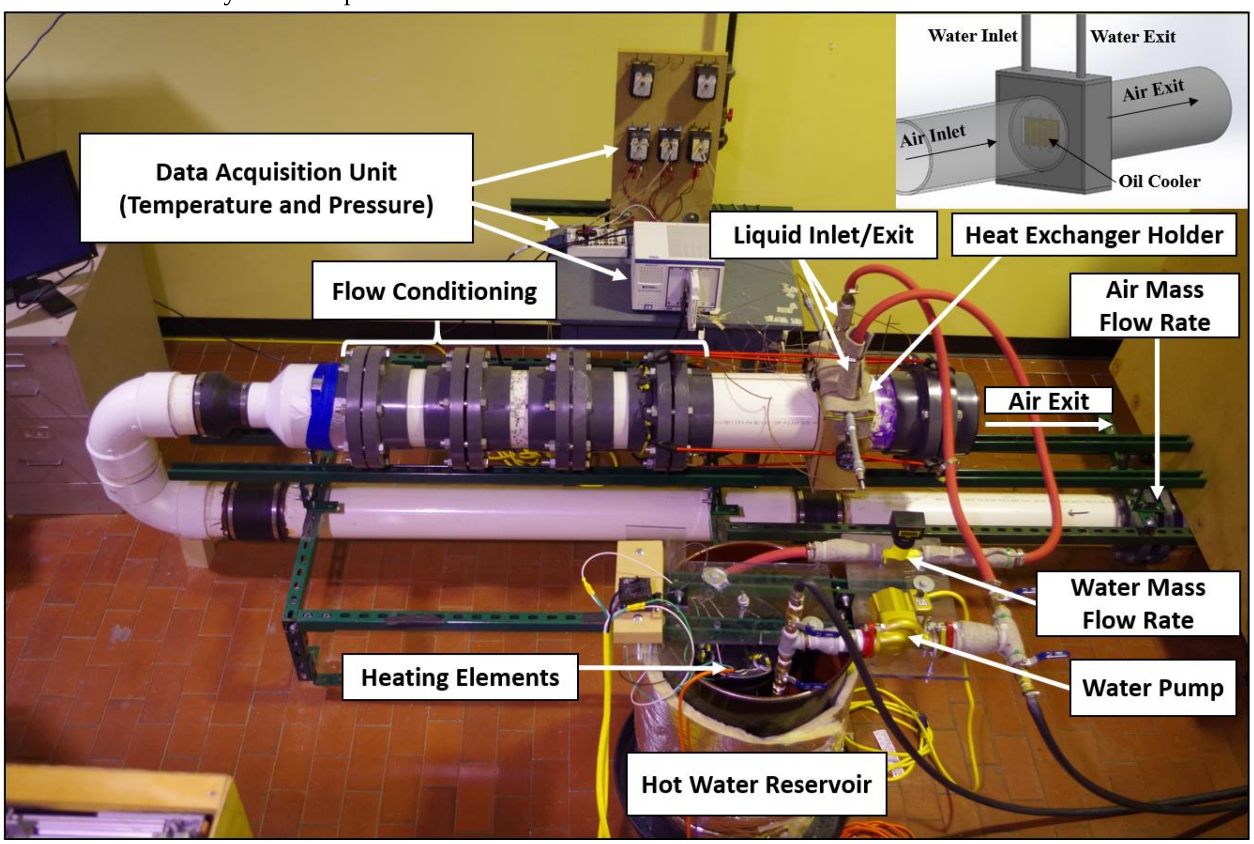

Figure 1. Heat exchanger performance test set-up

IV. Oil Cooler Design: Traditionally and Additively Manufactured

The traditionally manufactured oil coolers for this study were supplied by Airflow Systems, Inc., and are used for engine oil cooling on performance racing aircraft. The oil cooler geometry is a tube-fin style of construction fabricated from aluminum, with flattened tubes in the liquid side that draw from and dump to large plenums attached to the tubes. The liquid tubes contain heat transfer enhancement features on the inside to promote convective heat transfer and provide additional heat transfer surface area. On the air side, louvered fins span between adjacent tubes to promote air mixing with high heat transfer surface area. The total inlet area on the air-flow side is 7.9 cm by 13.3 cm. An X-ray computed tomography (CT) scan was performed on the part to capture the internal and external features, for replication in a CAD model. The aluminum powder used for the PBF AM part built and tested in this study was AlSi10Mg [17], which is widely used in aluminum castings and in PBF AM. In the PBF AM process, the layer by layer fabrication creates a staircase effect which, among other things, affect the surface roughness of the part [18].

Despite having an exact digital replica from the CT scan, it was not possible to fabricate the baseline heat exchanger exactly using laser-based PBF process. This is because geometries such as overhanging features, horizontal channels over a certain size, and material islands will not be produced accurately [19]. While many argue that "complexity is free" when it comes to AM [20], the reality is that even AM cannot fabricate all of the necessary internal features, particularly metallic components with intricate internal features [21]. Consequently, the geometry of the traditional oil cooler was slightly altered in certain regions to accommodate the AM process (e.g., reduce overhangs, minimize supports, and avoid thin walls). Additionally, some external features have also been modified on the AM heat exchanger design to simplify fabrication. These external features had supports connected to the build plate to support the heat exchanger.

The major geometry changes needed to additively manufacture the traditionally built oil cooler were as follows:

1. Vertical walls in the manifold region were angled to prevent unsupported surfaces, see Fig. 2.
2. Air-side and liquid-side extended features were angled (15° from vertical), see Fig. 2.
3. The exterior manifold boundaries were squared-off for simplicity and to reduce the number of required external supports, see Fig. 3.

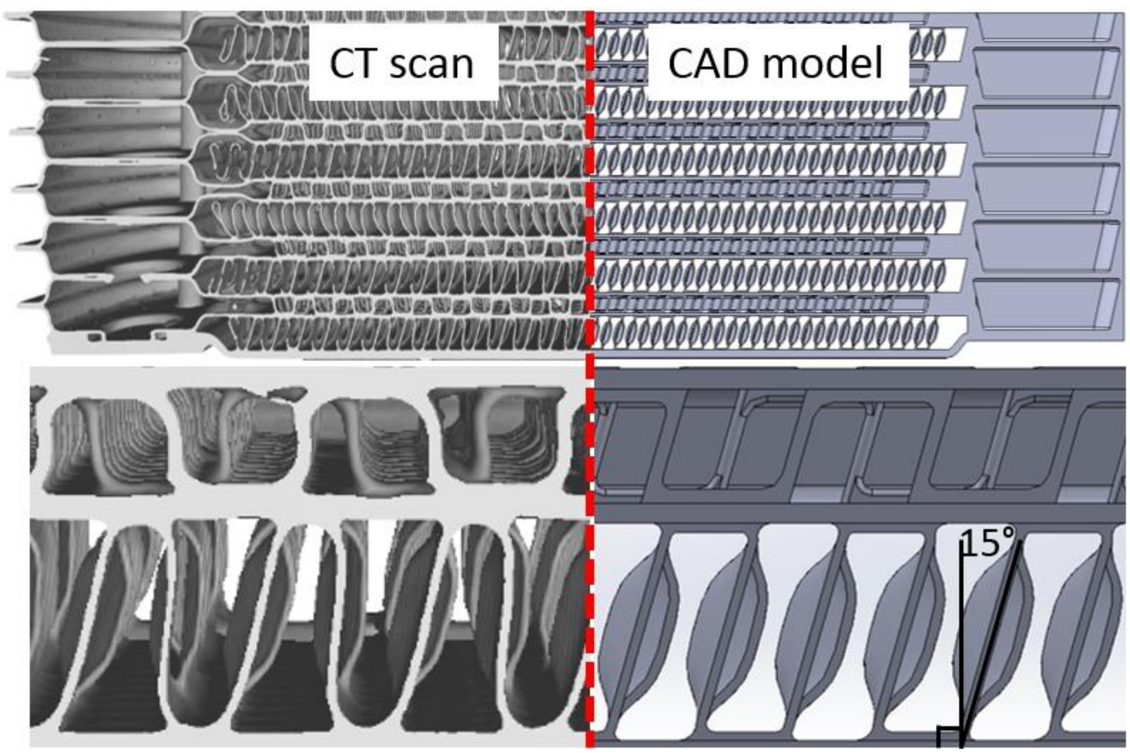

Figure 2. Comparison of the CT scan and CAD model used for the AM process. *Sectioned view through mid-plane of heat exchanger in air-flow axial direction (Top) Close-up of air-side fins and liquid features (Bottom)*

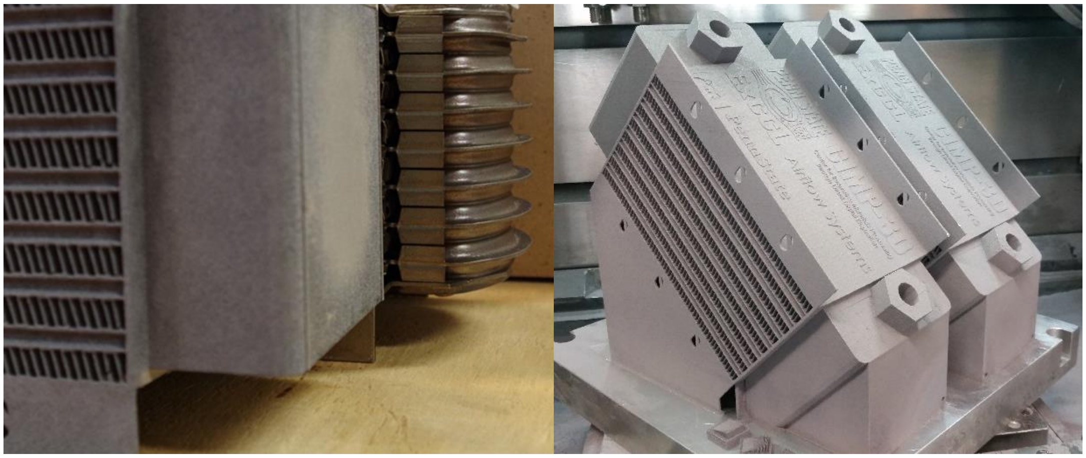

Figure 3. Comparing the manifold geometry. *Photograph of the traditionally built and additively manufactured heat exchangers (Left) Additively manufactured heat exchangers attached to build plate with supports. (Right)*

Four different oil coolers were tested. Figure 4 shows the naming convention for each of the oil coolers. The traditionally manufactured oil coolers have the same liquid side geometries, but the air-side fins and extended features were altered to enhance heat transfer in the enhanced traditionally manufactured (ETM) model. The baseline AM heat exchanger (BAM) is intended to replicate the baseline traditionally manufactured geometry, but as described earlier, it is not an exact replica because of limitations in the laser-based PBF process. However, the number of liquid side turbulation features, the air-side fin spacing and louver features, and the cross-sectional flow areas remain constant. The enhanced additive manufactured heat exchanger (EAM) is the same geometry as the BAM but has small vortex generators added on the air side, attached to the liquid tube wall. Note that the EAM did not replicate any of the features of the ETM model, but was instead an enhancement of the BAM. The liquid side geometries on both additively manufactured oil coolers are the same as the traditional geometries, unless defects in printing occurred. Table. 1 compares the dimensions and mass of the oil coolers being tested. The additional mass in the AM oil coolers is most likely due to increased wall thickness in the manifold regions, which was incorporated as a precautionary measure to reduce the chances of pressure-induced leaks. In this initial study, the mass of the additively manufactured oil cooler was not optimized.

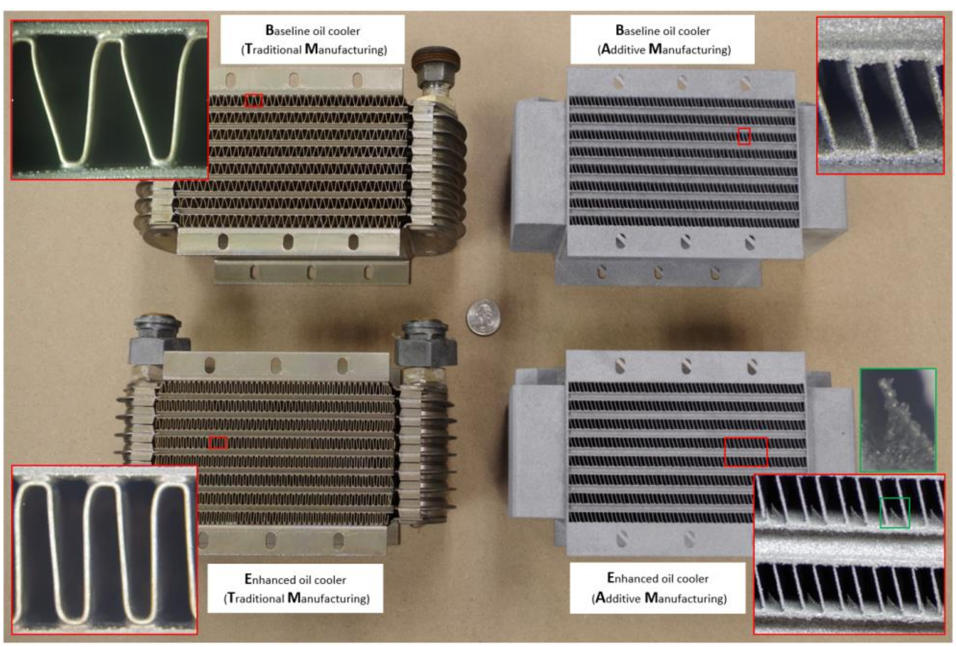

Figure 4. Naming convention and comparison between tested oil coolers

Table 1. Comparing dimensions and mass of oil coolers tested

Oil Cooler	BTM	ETM	BAM	EAM
Overall size (L x W x H) [cm]	21 x 9.25 x 11.5		20 x 9.25 x 11.5	
Mass without fittings [kg]	0.927	0.965	1.241	1.248
Average air-side fin thickness [mm]	0.30 ± 0.02		0.33 ± 0.04	
Manufacturing material	Stamped Aluminum		AlSi10Mg	
Manufacturing method	Brazing		AM - PBF	
Air-side fins per inch (FPI)	10.5	>15	10.5	10.5
Number of vortex generators	0	0	0	1,155

The AM laser-based PBF heat exchangers were manufactured on an EOSINT M 280 machine and the total machine run time was 160 hours. This included both heat exchangers and a small sectioned piece of the air-side and liquid-side features. The section piece was intentionally designed unbounded by walls so that optical analysis could be performed on the interior of the heat exchanger, as shown in Fig. 5.

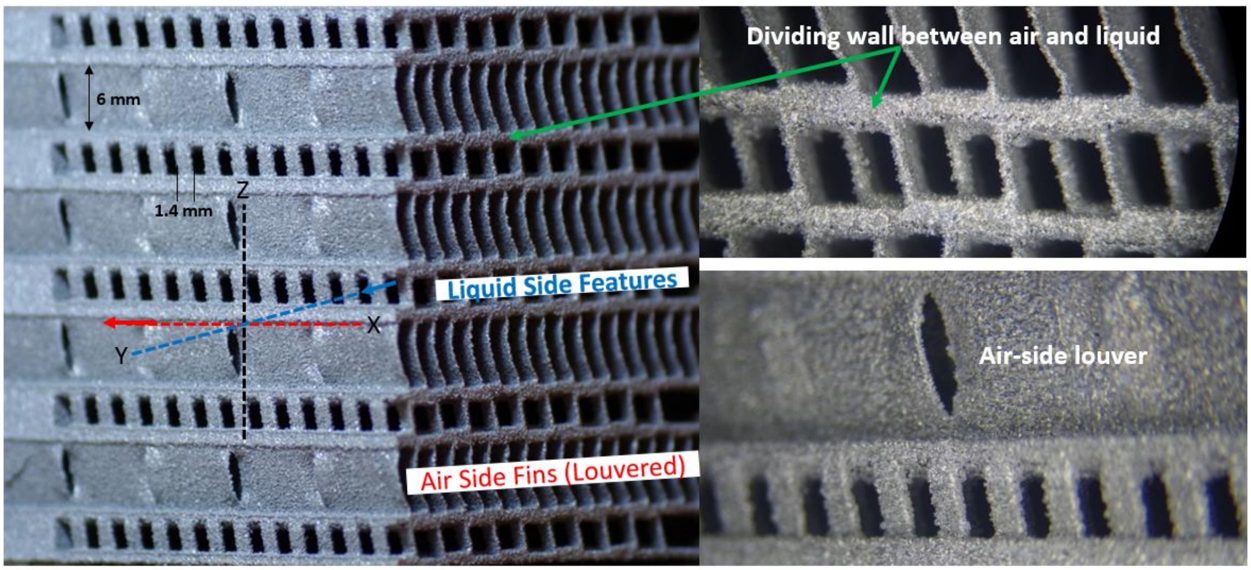

Figure 5. Close-up views of additively manufactured test piece that was not bounded by walls, to view internal features

Figure 6 shows the cracked air-side fin features created from the AM process. These cracks only seem to appear on the first row of fins and do not propagate into the rest of the core. If redesigned, extra material should be placed at the base of the first and last rows of fins to keep the fins more secured during the build.

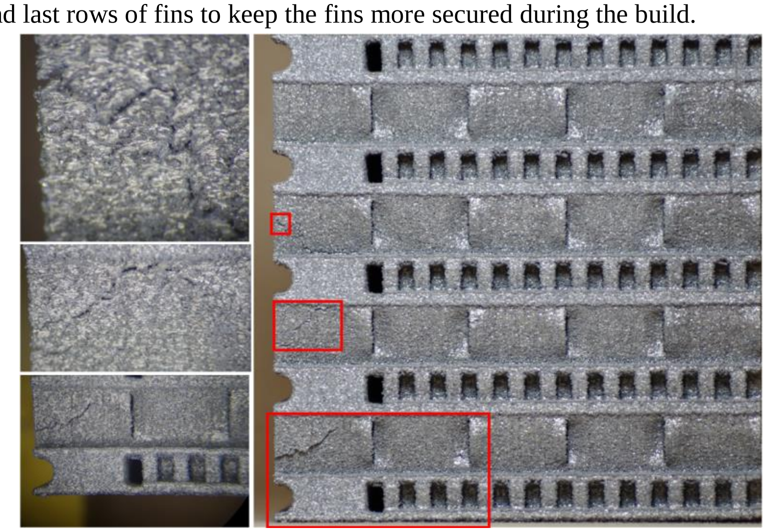

Figure 6. Photographs of air-side fin cracks on test piece.

V. Experimental Performance Results

The performance of the oil coolers is compared in two ways: (1) pressure drop on the air side and (2) heat rejected from the liquid to air stream. Liquid side pressure drop is not evaluated because the liquid pressure transducers used during testing are not sensitive enough at low mass flow rates through the oil cooler, as stated earlier. This is one of the future improvements that will be added to the experimental set up.

A. Pressure Drop

Fig. 7 shows the air-side pressure drop across the oil cooler. The experimental data was taken using two pitot tubes installed in the flow path: one probe was seven centimeters upstream of the HX while the other was two centimeters downstream of the HX. The pitot tubes were connected to a pressure transducer to measure the static pressure between the two probes. The data for the baseline traditionally manufactured (BTM) oil cooler can be directly compared to publically available data published by the manufacturer [22]. The enhanced traditionally manufactured (ETM) oil cooler does not have any public data to directly compare with for the specific model tested. However, there is publically available data for an oil cooler of the same air-side geometry that has 14 air-side rows, instead of the 8 rows on the ETM that was tested. By normalizing the public data [23] to calculate the pressure drop and MFR across each unit cell (air-side row), then multiplying by the 8 rows on the ETM being tested, the corresponding mass flow rate and pressure drop can be estimated. This estimate assumes that the mass flow rate of air through each air-side row is equal. As expected, the ETM oil cooler had a larger air-side pressure drop due to the higher density of extended surfaces when compared to the BTM oil cooler.

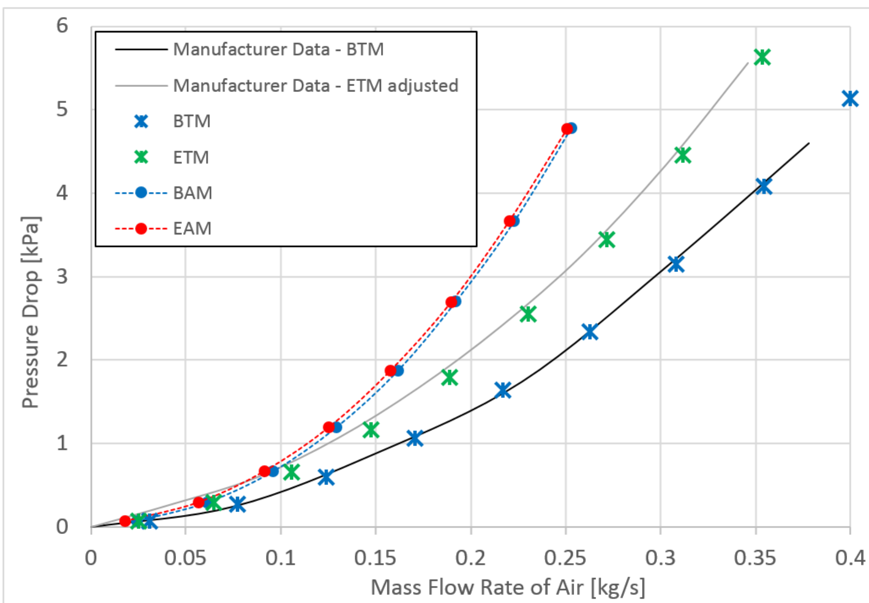

Figure 7. Air-side pressure drop across traditionally manufactured and additively manufactured oil coolers

When the two AM heat exchangers were compared, the air side pressure drop is similar yet larger than both of the traditionally manufactured heat exchangers. This is most likely due to the highly increased surface roughness on all air-side surfaces, and future work will quantify this surface roughness. Additionally, it seems that the enhancements on the EAM resulted in minimal increase in the air-side pressure drop. More aggressive enhancements could be considered in the future.

B. Heat Transfer

For each of the four oil coolers, at least three different air mass flow rates were tested, each at three different ITDc between the air and water streams. It was found that the heat rejection normalized by the initial temperature difference in degrees Celsius (ITDc) collapsed to a single value, as shown in Fig. 8 by the BTM data points. This is expected since the flow regime is not changing as a function of ITDc; only the temperature gradients are increased linearly. The different ITDc data points for the other heat exchangers are averaged on Fig. 8 for easier viewing. It is shown that the ETM has a greater heat rejection than the BTM as expected due to the additional extended fin features. For the AM heat exchangers, the EAM rejected heat slightly more efficiently than the BAM (~4%) for a given air flow rate. Furthermore, both AM heat exchangers outperformed the BTM heat rejection by over 10% at the highest flow rates. However, the air-side pressure drop for the AM heat exchangers was roughly double that of the traditionally manufactured heat exchangers as shown in Fig. 7. Future work will investigate the level of surface roughness and the potential to optimize it for this application.

Finally, Fig. 8 indicates that both of the additive heat exchangers provide as much heat rejection as the enhanced traditional model (ETM), despite not having the aggressive enhancement features of the ETM. Thus, further heat transfer performance gain may be achievable by designing aggressive heat transfer surfaces. An advantage of the AM technique is that these enhancements may be able to be added at minimal additional fabrication cost. Or, alternatively, it may be possible to design a heat exchanger that performs as well as the ETM but is lighter than the BTM, by removing unnecessary material from the baseline design, especially in the manifold.

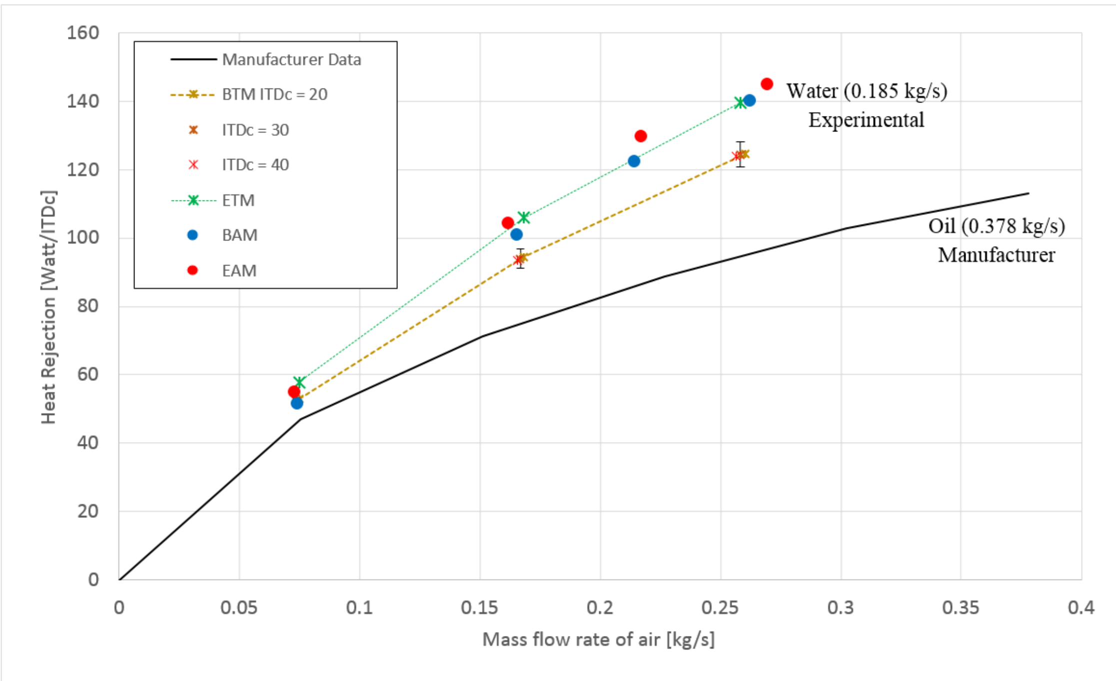

Figure 8. Comparing heat rejection for the traditional and additively manufactured oil coolers.

VI. Closing Remarks

A test rig has been designed and built to measure the performance of compact heat exchangers typically used to cool engine oil in small aircraft. The rig was validated by measuring the performance of a traditionally manufactured heat exchanger and comparing the results to public data from the manufacturer. A laser-based power bed fusion additively manufactured heat exchanger with the same dimensions and features was created to identify how the additive manufacturing (AM) processes affects fluid flow and heat transfer. Finally, a slightly enhanced additively manufactured heat exchanger was designed to take further advantage of the AM process in order to increase the heat transfer of the fluids.

Both of the AM heat exchangers increased the heat transfer by about 10%, relative to the traditionally manufactured heat exchanger on which the geometry was based. However, the air-side pressure drop was roughly doubled. Vortex generators added to one of the AM heat exchangers had little effect on air-side pressure drop but did enhance heat transfer slightly. Additionally, the vortex generators added very little additional mass to the oil cooler.

The AM process did produce a HX with noticeable build defects on the air side fins (i.e., cracked fins). The liquid side features may also exhibit build defects (less likely because the features are more stout) but these cannot be seen until a CT scan of the heat exchanger is performed or the heat exchanger is section, which is planned for future analysis. From the completion of this initial study, it is clear that modifying the original heat exchanger design for production via PBF AM is necessary, and is likely to yield additional benefits.

Further work needs to investigate and quantify how the surface roughness affects the performance of heat transfer and pressure drop on the AM heat exchangers. Additionally, the surface roughness of future heat exchangers needs to be taken into account during the design phase since it is a natural occurrence during the AM PBF manufacturing process. Furthermore, understanding the durability of the AM heat exchangers is important when reducing the wall thicknesses to try and reduce the overall part weight.

VII. Acknowledgments

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