2021

Fatigue Analysis of a High-Performance Heat Exchanger

Mingkan Zhang
Oak Ridge National Laboratory, United States of America, zhangm1@ornl.gov

Patrick Geoghegan
Oak Ridge National Laboratory

Yoram Shabtay
Heat Transfer Technologies LLC

James Tancabel
The University of Maryland

Jiazhen Ling
The University of Maryland

See next page for additional authors

Authors

Mingkan Zhang, Patrick Geoghegan, Yoram Shabtay, James Tancabel, Jiazhen Ling, and Vikrant Aute

Fatigue Analysis of a High-Performance Heat Exchanger

Mingkan Zhang[1]*, Patrick Geoghegan[1], Yoram Shabtay[2], James Tancabel[3], Jiazhen Ling[3], Vikrant Aute[3]

[1]Oak Ridge National Laboratory, Energy Science and Technology Directorate,
Oak Ridge, TN, USA

[2]Heat Transfer Technologies LLC,
Prospect Heights, IL, USA

[3]The University of Maryland, College Park, Center for Environmental Energy Engineering
College Park, MD, USA

* Corresponding Author
Zhangm1@ornl.gov

ABSTRACT

Air-to-refrigerant heat exchangers (HX) are key components in Heating, Ventilation, Air Conditioning, and Refrigeration (HVAC&R) systems. For such HXs, the air-side convective resistance is the dominant factor which limits the heat transfer performance. Using non-round shape-optimized tubes and headers can successfully solve the problem leading to high performance HXs. However, the non-round shape tubes and headers may cause some fatigue issues in practices causing the failure during use. Therefore, it is desired to conduct fatigue analysis of such HXs designs to seek designs which can provide both high performance and high strength simultaneously. In present work, a framework of fatigue analysis of high-performance HXs has been developed and implemented. In the framework, the HXs were modeled using commercial Finite Element Analysis (FEA) software, SIMULIA™ Abaqus FEA. Based on the stress analysis results, a fatigue analysis was conducted using fe-safe software for multiple metal materials to estimate the HX lifetime before failure occurs.

1. INTRODUCTION

Serving as the main heat transfer component, air-to-refrigerant heat exchangers (HXs) are implemented in many vapor compression-based HVAC&R systems. The performance of HXs highly influences the overall performance of the HVAC&R system. Previous studies have revealed that the air-side heat transfer resistance is the dominant factor which limits the performance of such HXs (Sommers & Jacobi, 2005). Studies have been conducted to seek approaches that minimize the resistance of the air-side heat transfer. From aerodynamics, it has been discovered that an airfoil is perfectly streamlined and creates little airflow resistance comparing to the round shape (Lutz & Wagner, 1998), which inspires the methodology to use non-round shape-optimized to lower the resistance of the air-side heat transfer. Different tube shapes and headers have been studied to seek the shape-optimized tube (Hilbert et al., 2006; Huang et al., 2016; Zeeshan et al., 2017). Shapes optimization for design of air-to-refrigerant HXs has been reviewed by Tancabel et al. (Tancabel et al., 2018). Consequently, it has been concluded that small diameter non-round shape- optimized tubes can significantly reduce the air-side resistance and improve the performance of such HXs (Bacellar et al., 2016, 2017; Huang et al., 2016).

This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan(http://energy.gov/downloads/doe-public-access-plan).

Preview studies about the shape-optimized tubes only focused on the resistance and heat transfer performance of the HXs. However, to manufacture the HXs with non-round shape tubes and implement them in the HVAC&R system, the strength and robustness of the HXs also need to be considered. For example, whether the non-round shape tubes and headers are strong enough to bear the saturation pressure of refrigerants.

Therefore, it is desired to conduct fatigue analysis on the non-round shape tubes and headers under high refrigerant pressure. Such analysis could provide the answers to the questions about stress concentration as well as the lifetime of the HXs.

Table 1: Properties of materials.

Name	Density (kg/m^3)	Young's Modulus (GPa)
Al6061-T6	2700	68.9
Copper	8960	117
Welding material	2600	71

In this paper, a framework of fatigue analysis of high-performance HXs has been developed and implemented. There are several steps of the framework. The HXs with different non-round shapes are first modeled based on the designs from which the high-performance at the airside achieves. Then the HX geometry models are imported into SIMULIA Abaqus FEA (SIMULIA, 2017a), a commercial FEA software, in which the stress analysis models are developed, including boundary conditions assignment, mesh creation, and simulation. Finally, the stress analysis results are read by fe-safe (SIMULIA, 2017b), a fatigue analysis code, to conduct fatigue analysis. Based on the loads and materials, it returns the lifetime of the design before failure occurs. This paper studies high- performance HXs from the point of view of fatigue analysis, bridging the gap between designs based on heat transfer and mechanical performance while also providing a guidance to seek designs of a high-performance HX which can provide both high performance and high strength simultaneously.

2. FRAMEWORK OF FATIGUE ANALYSIS

Previous studies have revealed that a HX with non-round shape tubes showing in Figure 1 can offer a low air-side heat transfer resistance and high heat transfer performance (Bacellar et al., 2016, 2017; Huang et al., 2016). The FEA modeling in present work was developed based on a 1 kW HX, which was additively manufactured in Titanium from Bacellar et al (Bacellar et al., 2017). Four different tube designs were studied in this paper as depicted in Figure 1., including two single-hole tubes and two double-hole tubes. Those designs are patent pending. Note that the external geometriesof all four tubes are same shape. Two materials, Al6061-T6 and Copper, were tested to reveal the materials strength.Tubes connected to the header through a layer of Welding material as the joining material. The properties of the two materials as well as Welding material are provided in Table 1.

The designs were digitalized by using CAD software SOLIDWORKS (SOLIDWORKS, 2019), where the geometry files were created. Then the files were imported by SIMULIA Abaqus FEA, in which the simulation domain was defined (single tube simulation or entire HX simulation), the constrains were assigned (Tie between header and Welding material, and between Welding material and tube), the boundary conditions and loads were set (6 MPa baseline at the inner tube wall and header), and the mesh was created. After the model setup was completed, the stress analysis simulations began. Finally, the stress analysis results were read by fe-safe and used to run the fatigue analysis. The fatigue analysis relies on fatigue properties which are usually collected by experimental tests. To analyze the materials whose test data are not available, fatigue properties can be approximated using the Approximate Material Function (SIMULIA, 2017a). This function uses Bäumel-Seeger's method (Bäumel et al., 1990) to generate approximate fatigue parameters based on the UTS (ultimate tensile strength) and elastic modulus of the material.

To validate the stress analysis modeling, a comparison between the numerical model results to the experimental data was performed. The experimental setup is shown in Figure 2 (a). A single tube was tested by injecting pressurized gas from one end of the tube, while the other end is sealed. This was repeated for both copper and aluminum tubes. The distance between the highest and lowest points of the tube was measured before and after pressurization, indicating the deformation of the tube. The highest pressure applied was up to 20 MPa. A significant deformation was observed after the highest pressure was applied. To mimic the experimental setup, a numerical model for a pressurized single tube was developed as shown in Figure 2 (b). After pressures was applied to the tube, deformations in the model were measured and compared to the experimental data. Figure 3 depicts the comparison results by using aluminum. The results show a very good agreement between the numerical model results and the experimental data. After the stress analysis modeling has been successfully validated, the framework of fatigue analysis was implemented the HX.

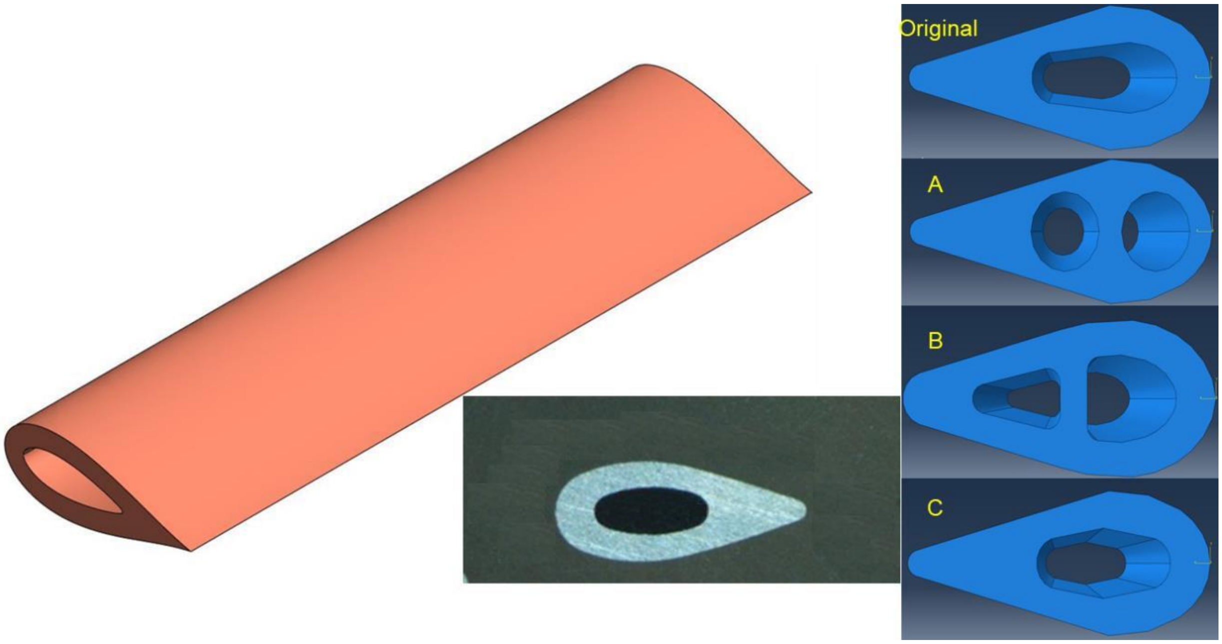

Figure 1: The non-round shape tube and four designs (patent pending).

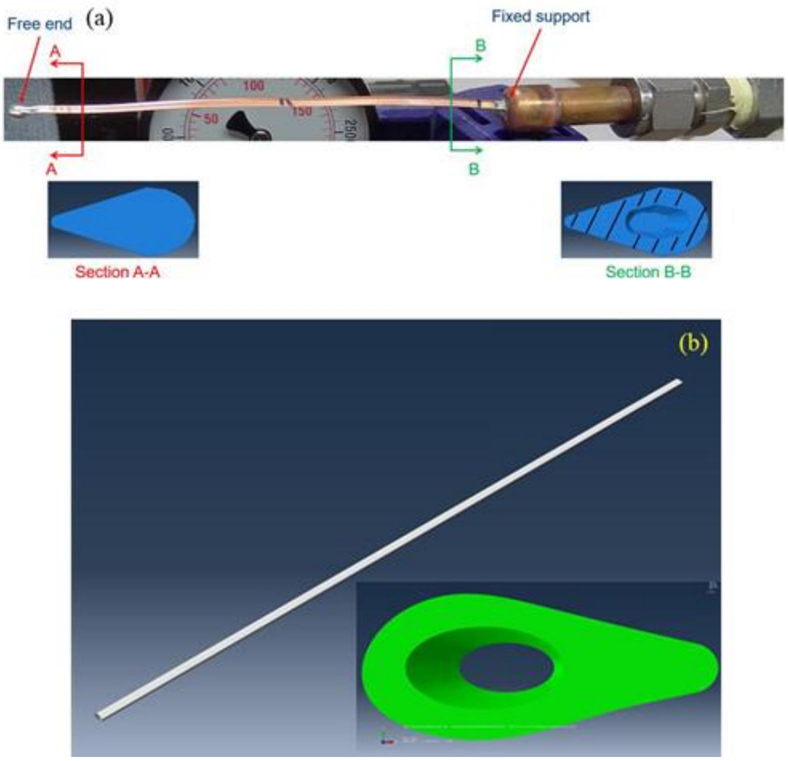

Figure 2: The experimental (a) and numeral (b) setups of the deformation test.

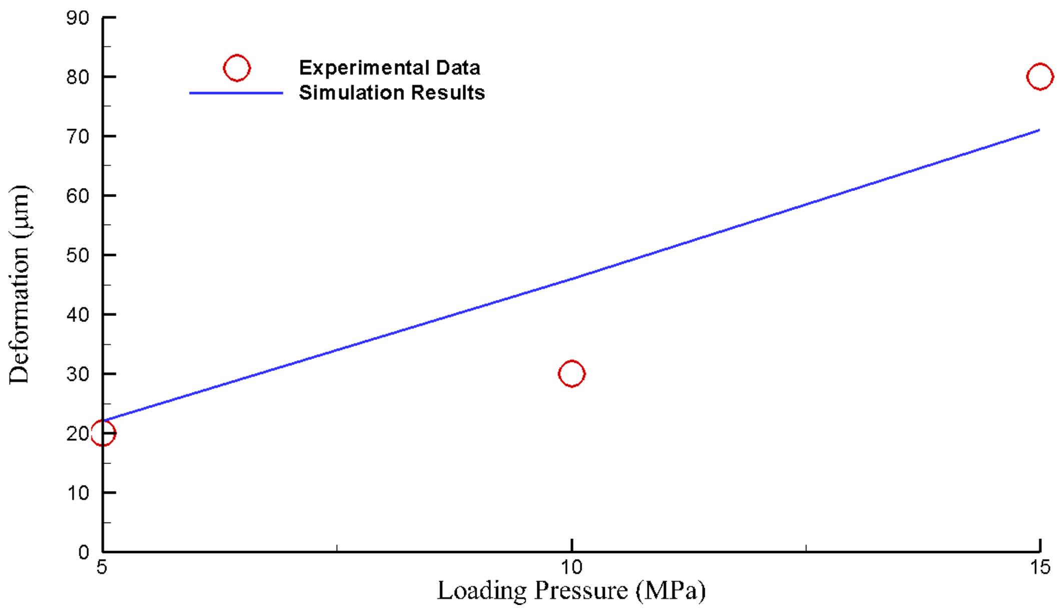

Figure 3: Experimental vs numerical Al tube deformation results.

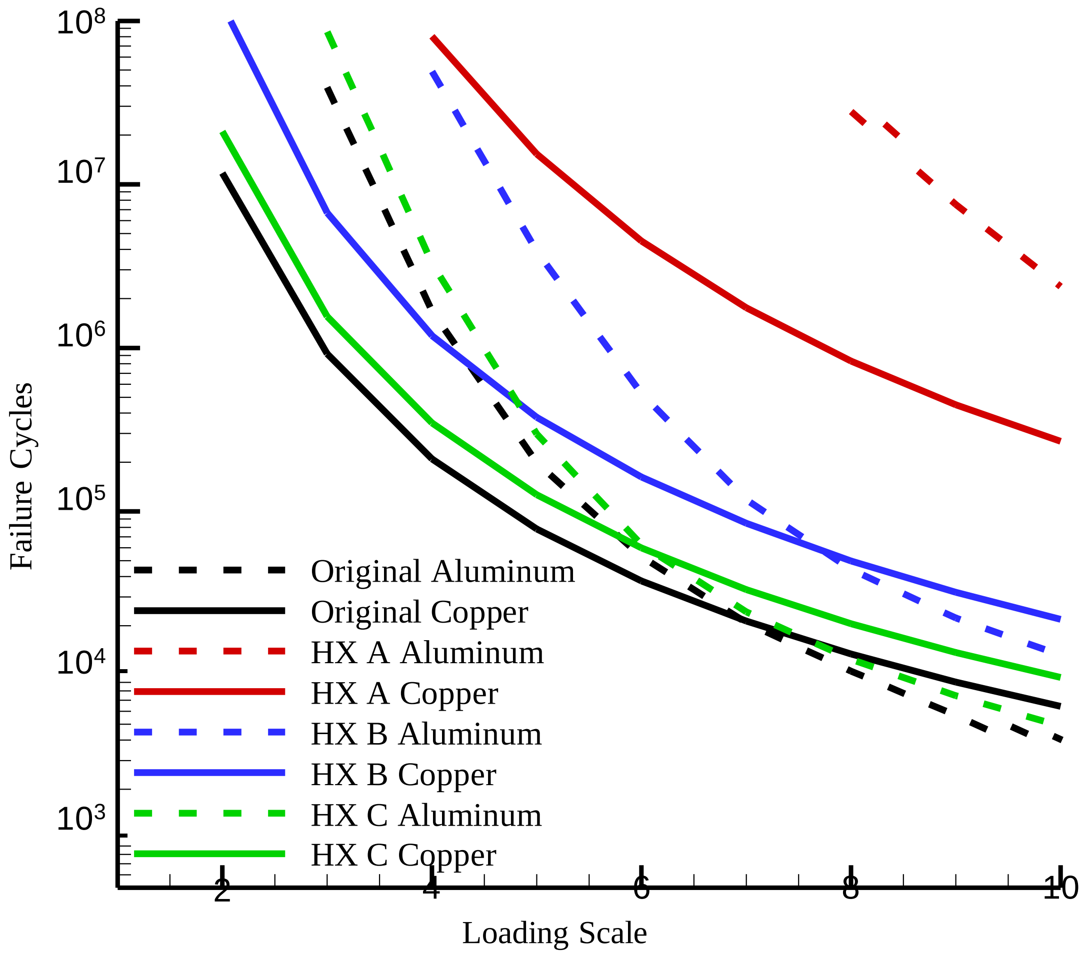

Figure 4: Failure cycles VS loading scale for different designs with different materials.

3. RESULTS AND DISCUSSIONS

3.1 Fatigue Analysis of Single Tubes

The framework was firstly utilized to conduct fatigue analysis of single tubes. As described above, the four kinds of tubes, which have different cross-section designs with either one hole or two separate holes of the tube, are made of two materials. The baseline loading is 6 MPa pressure applied to the inner surfaces of the tubes to mimic the hydraulic pressure caused by the static and dynamic pressures from the refrigerants. Since saturation pressure varies with different types of refrigerants, in the fatigue analysis, the loading was scaled up to 10 times. Note that the loading scale-up is the operation of fatigue analysis only, so in stress analysis only baseline loading needs to be simulated, which significantly reduces the total simulation time of the framework. The loading was periodically applied to the tube. For example, in one loading cycle, the applied pressure is from the scaled loading (12 MPa if scaled up to 2) to zero, then back to the scaled loading starts the next loading cycle. After the fatigue analysis is accomplished, the returned result is called "failure cycles", which is the number of loading cycles the tube experiences until the first failure occurs, indicating the lifetime of the part.

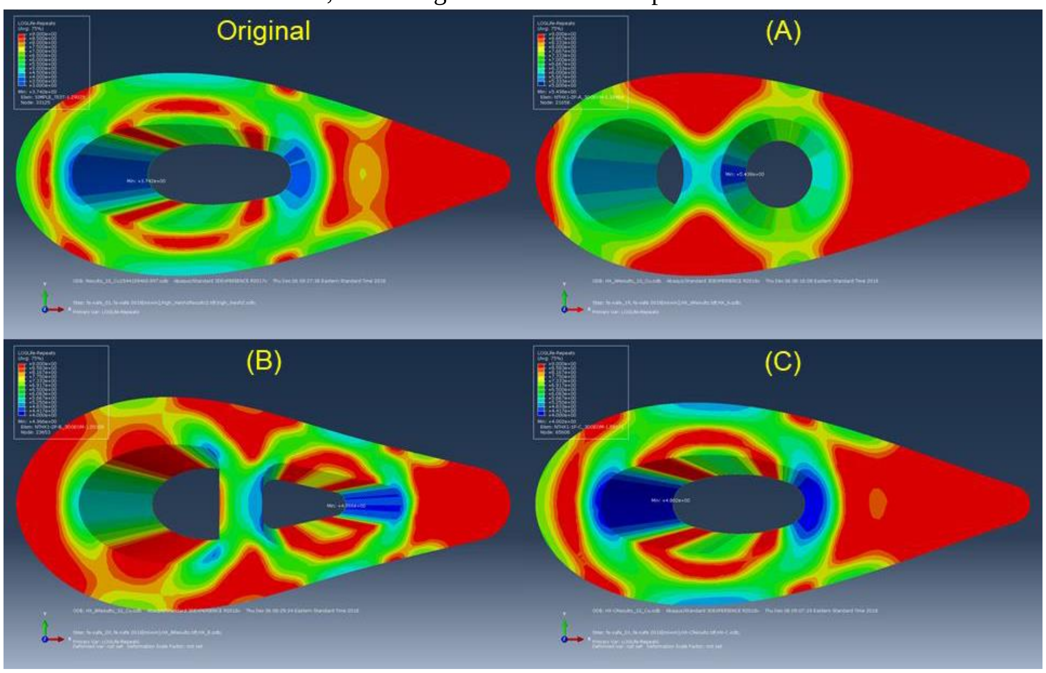

Figure 5: Contours for log value of the failure cycle using Copper.
Design Original, (A) (B) and (C) are from Figure 1.

Figure 4 shows that the number of failure cycles change with loading scale. Note that the maximum loading cycles in the fatigue analysis are 10^8, so data are not shown if the failure cycles are greater than 10^8. Figure 4 indicates that all the tubes are able to bear more than 10^8 loading cycles without failure under the baseline loading. The dashed and solid lines indicate the curves from tubes made of Al6061-T6, and Copper, respectively. It shows that curves from Copper tubes have gentler slopes than Aluminum tubes. As a result, the lifetime of Copper tubes is lower than Al6061-T6 when the loading scale is low. However, when the loading scale increases, Copper tubes can last more cycles than Al6061-T6.

In Figure 4, the black, red, blue, and green colors represent the results for original design, design A, design B, and design C tubes, respectively. Figure 5 and 6 depicts contours for log value of the failure cycles when the loading scale equals 10 for Al6061-T6 and Copper, respectively. By comparing the original design and design C, it can be found that design C improves the original design by expanding the hole and changing the oval shape to a polygon. From Figure 4, only a little improvement from the original design to design C can be observed. Figure 5 shows that for original design, the lowest failure cycles happen at the two ends of the oval-shaped hole. When design C changes the oval shape to a polygon, it absorbs some stress to the sides of the hole. However, the lowest lifetime still occurs at the two ends of the hole in design C. It explains why only little improvement from original design to design C has been observed.

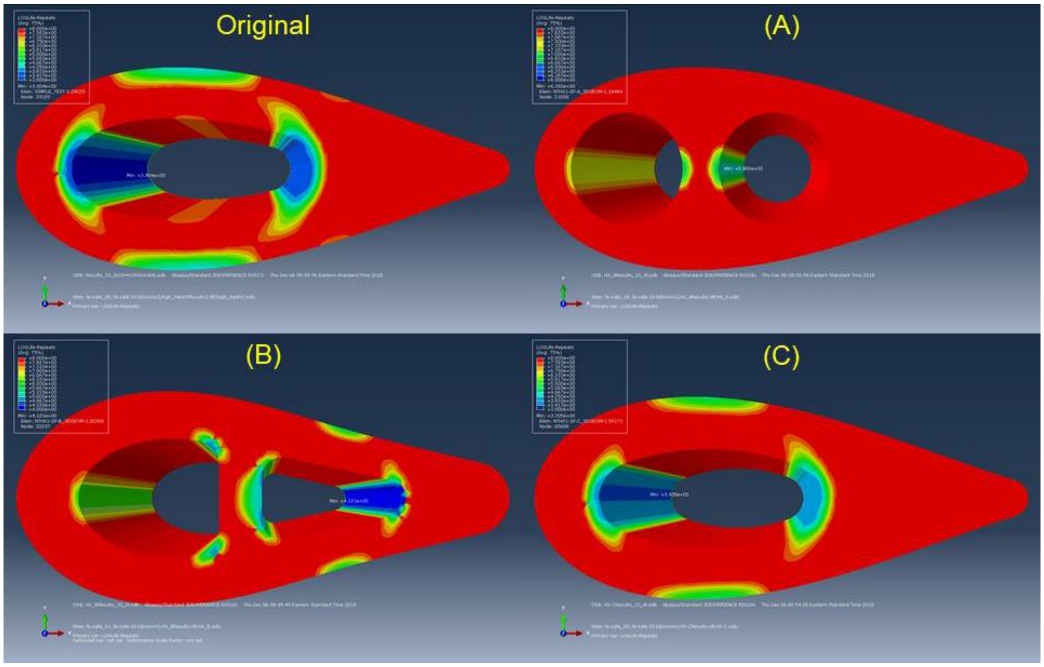

Figure 6: Contours for log value of the failure cycle using Aluminum.
Design Original, (A) (B) and (C) are from Figure 1.

From Figure 4, one can identify that the lifetime of the tubes with double-hole cross-section (design A and B) are much greater than the ones with single-hole (original design and design C). It is because in the double-hole designs, an extra structure exists in the middle of the cross-section that provides support, leading to a stronger tube and longer lifetime. The contours of design C in Figure 5 and Figure 6 show that this extra structure shares the load which significantly increases the lifetimes at the two ends of the oval shape hole compared to the original design.

Figure 4 also indicates that design A is much better than B from a lifetime point of view. Figure 5 and Figure 6 reveal that low lifetime happens at the corners of the cross-section geometry in design B, implying stress concentration in the corners. On the other hand, because design A employs two round holes, the problem of stress concentration is overcome. As a result, design A has a much greater lifetime than design B. The locations where lowest lifetime of design A occurs can be identified by Figure 5, where the tube is thin at these locations.

3.2 Fatigue Analysis of Heat Exchangers

After Fatigue analysis of single tubes was completed, Fatigue analysis of the whole HX was conducted. To simplify the model, the model contains only one tube with original design. Between the tube and header, there exists a layer of welding material that joins the tube to the header. Figure 7 shows the contours of log value of the failure cycles when the loading scale equals 10 for Copper. It shows that the header has the longest lifetime, since the header has a considerable thicker wall comparing to the tube and the welding material. Figure 7 also enlarges the contours of log value of the failure cycles in the tube and the welding material. It can be found that the lowest lifetime occurs at the internal surface of the tube, which is in the same locations, as shown in Figure 5. Surprisingly, the lowest lifetime is not in the welding material. Figure 5 shows that the lowest lifetime of the welding material is located at its edges. This is because these areas bear the stress from the bending force when the tube is deformed. The stress at the outer surface of the tube is much weaker than the inner surface because most of the energy from the load is used to deform the tube. Therefore, the welding material, which connects to the outer surface of the tube, did not share much stress from the load. As a result, the welding material has a much longer lifetime than the tube. It can be concluded that the most fragile part of the single tube HX with original tube design is the tube itself. Therefore, the lifetime of the HX is as same as the lifetime of the tube. Since the HX with Al6061-T6 head and tube leads to the same conclusion, it is not necessary to investigate such HXs in the paper.

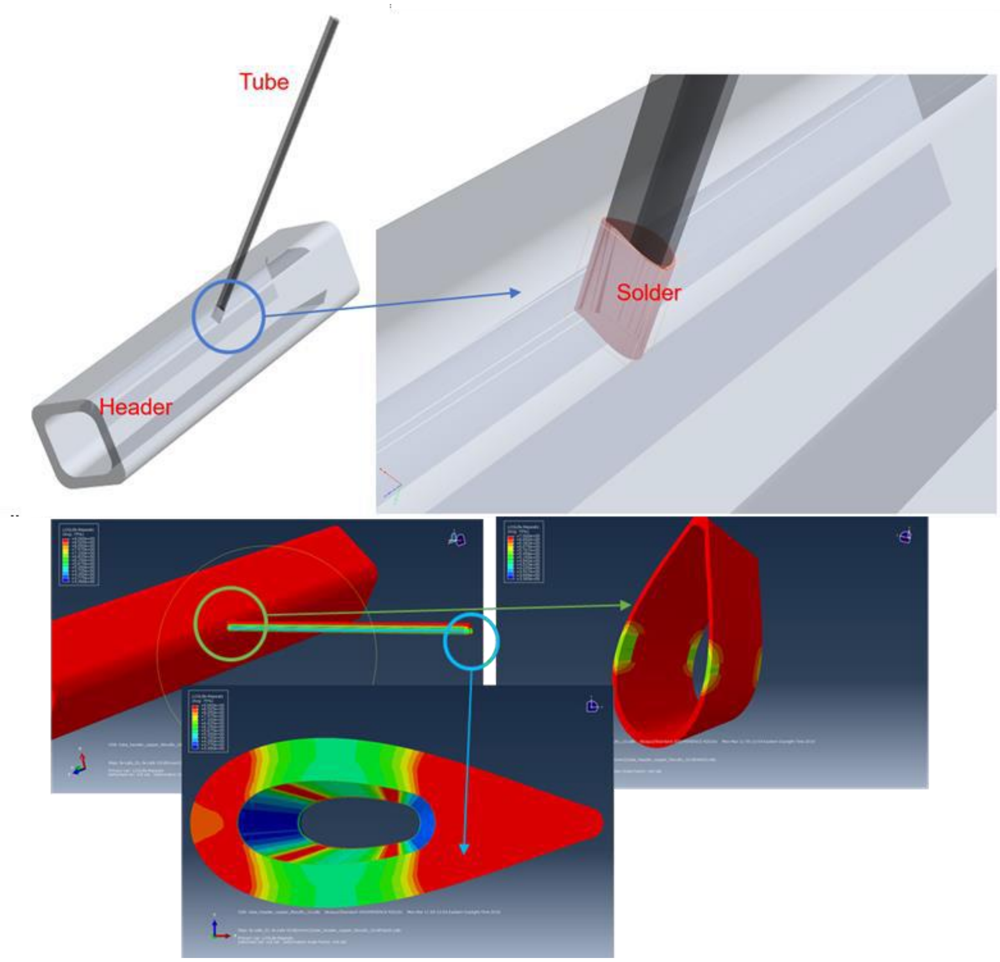

Figure 7: Contours of log value of the failure cycles of HX using Cooper.

4. CONCLUSIONS

The present work developed a framework for fatigue analysis of high-performance HXs using non-round shape tubes and headers. The framework contains several steps. The HXs with different non-round shapes are first modeled based on the designs from which the high-performance at the airside achieves. Then the stress analysis will be finished using Abaqus based on the model. In the last step, the stress analysis results are imported by fe-safe to conduct fatigue analysis. The framework for fatigue analysis was implemented to conduct fatigue analysis on the non- round shape tubes and headers of HX which may cause potential fatigue issues during manufacturing and failures during operation. Two materials, Al6061-T6 and Copper, together with four tube designs are compared. Below are the conclusions obtained:

1. All the tubes can bare more than 10^8 loading cycles without failure under the baseline loading of 6 MPa.
2. Al6061-T6 tubes have a longer lifetime than Copper when the load scale is low.
3. Double-hole tube design have longer lifetime than single-hole design, in which round-shape hole design is the best design from the point of view of fatigue analysis.
4. The tube is the weakest part of the entire HX when the original design tube is used.

REFERENCES

Bacellar, D., Aute, V., Huang, Z., & Radermacher, R. (2016). Novel Airside Heat Transfer Surface Designs Using an Integrated Multi-Scale Analysis with Topology and Shape Optimization. *International Refrigeration andAir Conditioning Conference*.

Bacellar, D., Aute, V., Huang, Z., & Radermacher, R. (2017). Design optimization and validation of high-performance heat exchangers using approximation assisted optimization and additive manufacturing. *Scienceand Technology for the Built Environment*, *23*(6), 896–911.

SOLIDWORKS. (2019). *SolidWorks Tutorials.*

Bäumel, A., Seeger, T., & Boller, C. (1990). *Materials data for cyclic loading: Supplement 1*. Elsevier.

Hilbert, R., Janiga, G., Baron, R., & Thévenin, D. (2006). Multi-objective shape optimization of a heat exchanger using parallel genetic algorithms. *International Journal of Heat and Mass Transfer*, *49*(15–16), 2567–2577.

Huang, Z. W., Li, Z. N., Hwang, Y., & Radermacher, R. (2016). Application of entransy dissipation based thermal resistance to design optimization of a novel finless evaporator. *Science China Technological Sciences*, *59*(10),1486–1493.

Lutz, T., & Wagner, S. (1998). Drag reduction and shape optimization of airship bodies. *Journal of Aircraft*, *35*(3), 345–351.

SIMULIA. (2017a). *Abaqus/CAE User's Guide*.

SIMULIA. (2017b). *fe-safe User's Guide*.

Sommers, A. D., & Jacobi, A. M. (2005). Air-side heat transfer enhancement of a refrigerator evaporator using vortex generation. *International Journal of Refrigeration*, *28*(7), 1006–1017.

Tancabel, J., Aute, V., & Radermacher, R. (2018). Review of Shape and Topology Optimization for Design of Air-to-Refrigerant Heat. *International Refrigeration and Air Conditioning Conference*, 1–10.

Zeeshan, M., Nath, S., & Bhanja, D. (2017). Numerical study to predict optimal configuration of fin and tube compact heat exchanger with various tube shapes and spatial arrangements. *Energy Conversion and Management*, *148*, 737–752.

ACKNOWLEDGEMENT

This work was sponsored by the U. S. Department of Energy's Building Technologies Office. The authors would like to acknowledge Mr. Antonio Bouza the Technology Manager for the HVAC & Appliances for his support.