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High-Fidelity Reliability Assessment of a Finned Tube

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ABSTRACT

As a critical component of a larger subsystem, the finned tube must be reliable enough so as to avoid potential catastrophic failures. Therefore, a High-fidelity reliability assessment technique is employed to evaluate the reliability of this component. The technique accounts for all possible causes of failure. These causes are entered into the reliability assessment tool as input parameters. Only those parameters that have tangible effect on reliability are included. The uncertainties in these parameters are addressed by generating random samples using their probability distributions. The resulting points are run through stochastic CFD simulation. The spatial distributions of the resulting CFD loads and coefficients are mapped onto the surfaces of corresponding FEM model. This is the reason for using the term "high-fidelity" in describing this procedure. Consequently, the method can be classified as a stochastic fluid-structure interaction problem. Extensive analysis steps are involved in the procedure in order to account for all the significant factors that may lead to failure. The method is shown to be highly capable of investigating this type of component, as well as providing valuable information on its service life performance.

***Keywords**: High-Fidelity Reliability, Finned-Tube, Thermal stress, Fatigue Life, Computational Fluid Dynamics, Finite Element Method, Fluid-Structure interaction*

INTRODUCTION

Reliability is defined as the ability of a system to operate under normal and abnormal conditions subject to a defined failure rate and for a specific life time [Yang, 2007]. A finned-tube failure may

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lead to serious consequences. One of the main causes of this component's failure is the thermal cycling fatigue. In this work, the reliability of a finned tube is investigated using a high-fidelity reliability assessment tool. The tool was validated by [Al-Habahbeh et al, 2011]. It is based on multi-physical analyses and works by mapping CFD loads and coefficients onto the corresponding FEM model. Two parts of the problem need to be dealt with; namely the fluid part and the finned-tube structure part. The tool performs stochastic simulations based on Monte Carlo methods.

Most of the reviewed reliability research available in the literature focuses on single-physics structures. For example, [Basaran and Chandaroy, 2000] determined the reliability of a solder joint subjected to thermal cycling loading by FEM instead of laboratory tests. Fatigue life predictions were done using thermo-mechanical FEM analysis. While [Vandevelde et al., 2004] compared two solder joints reliabilities. The comparison was based on non-linear FEM. They also investigated the effect of thermal cycling conditions. However, less interest was shown in the multi-physical reliability problems, such as those involving fluid-structure interactions. One such example is the work done by [Constantinescu et al., 2004], where they presented a computational approach for the lifetime assessment of structures under thermo-mechanical loading. Their method is composed of a fluid flow, a thermal and a mechanical finite element computation, as well as fatigue analysis. However, transient analysis and reliability evaluation were not considered in their work. From the above review one can infer the importance of the reliability assessment tool used in this work for the purpose of investigating the reliability of the finned tube.

In order to conduct proper reliability evaluation, uncertainties in environmental, operational, and manufacturing parameters need to be considered. The end result will guarantee the elimination of costly over-design, while still ensuring the safety of the component. The reliability assessment tool enables the quantification of the safety of the finned tube by providing a probability that it will survive operating conditions. A flow chart representing this tool is shown in Fig. 1.

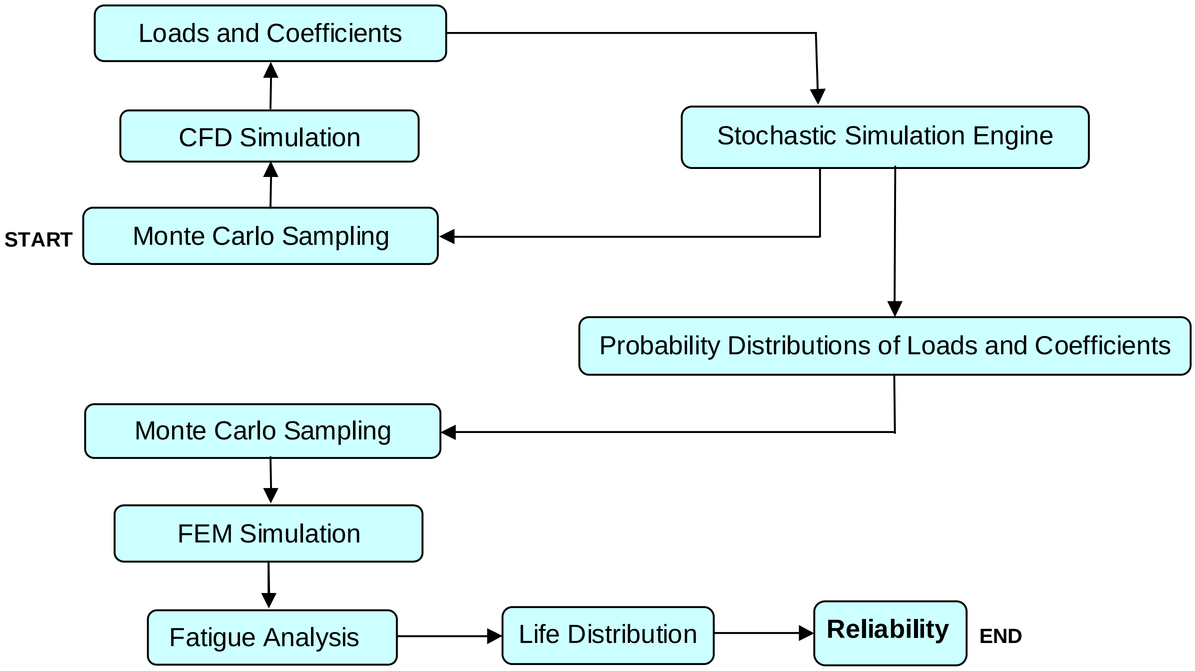

Fig. 1: Flow Chart of the Reliability Assessment Tool [Al-Habahbeh et al, 2011]

The sampler used in the above tool utilizes a technique called Latin Hypercube Sampling [LHS]. LHS is a variance reduction technique used by analysts to reduce computational cost, while maintaining the accuracy of the solution. The steps that the tool performs are explained in details by applying the procedure to the finned tube component.

CFD SIMULATION

This is the first step in the reliability assessment procedure. The geometric model used in the simulation is shown in Fig. 2. The corresponding model dimensions are shown in table 1. The model represents a straight-cut section of the finned tube. Water enters the right side and leaves the left side. When hot water first enters the finned tube, it caused thermal expansion and consequently thermal stress. The repetition of such occurrence is the reason for thermal cycling and eventually leads to service life limitation. The model is meshed into 216,000 elements as shown in Fig. 3. After the convergence of the CFD solution, the temperature distribution results are obtained. A sample of those results is shown in Fig. 4.

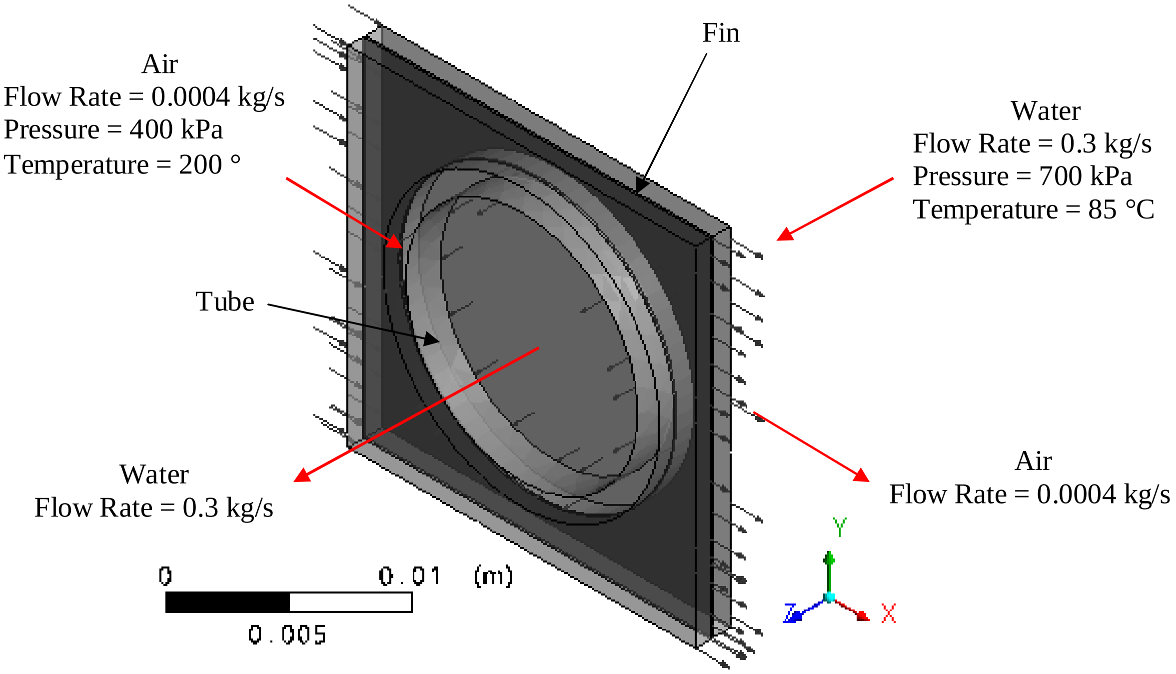

Fig. 2: CFD Model of the Condensate Tube

Table 1: Finned Tube Dimensions

Dimension	Value (mm)	Dimension	Value (mm)
Height	18	Fin thickness	0.3
Width	18	Tube Inner diameter	14
Depth	2	Tube outer diameter	17

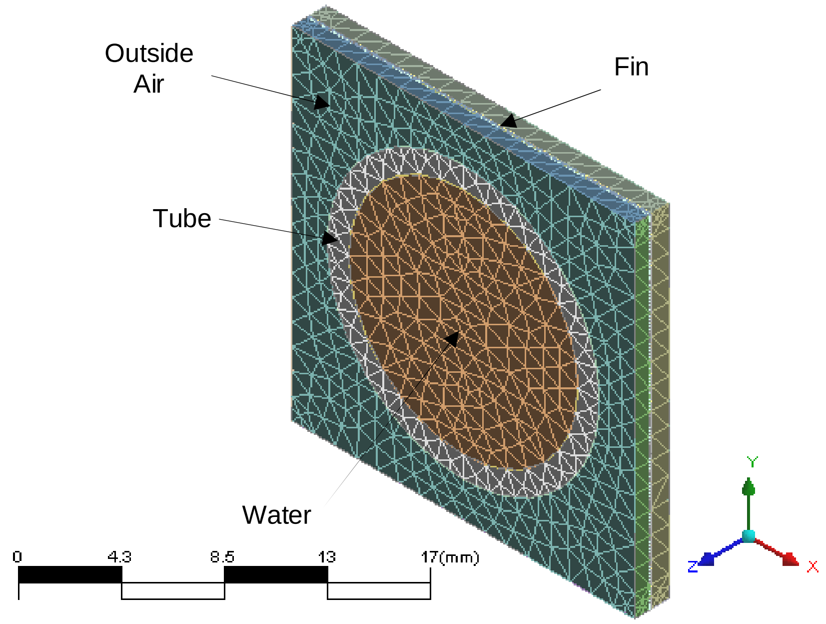

Fig. 3: CFD Finite Volume Mesh

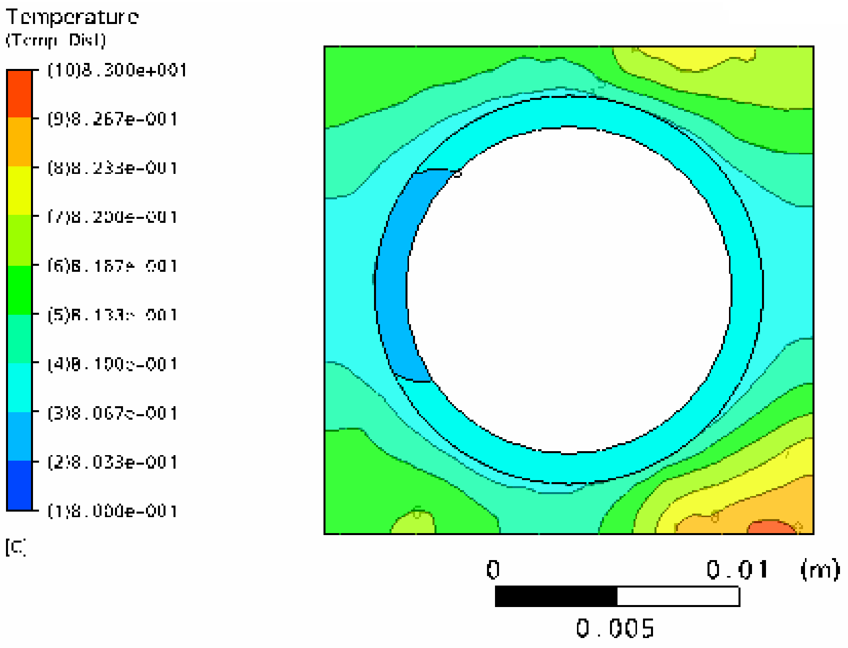

Fig. 4: Temperature Distribution in the Finned Tube Model

THERMAL ANALYSIS

Transient heat transfer in the finned tube is simulated for the time duration up to steady-state condition. The transient simulation is conducted in order to find the critical loading on the finned tube, as the maximum thermal stress occurs during the transient phase. The parameters involved in the computation include the temperatures and the heat transfer coefficients of both air and water. One-way thermal fluid–solid interaction analysis is conducted, while conjugate heat transfer is used to model heat conduction across the tube wall as well as across the fin wall. As a result of the CFD analysis, temperature contours on the fin and tube walls are shown in Fig. 4.

The most interesting CFD results are the probability distributions of the water heat transfer coefficient, air heat transfer coefficient, water adjacent temperature, and air adjacent temperature. One example of these distributions is shown in Fig. 5. The right vertical line on the graph represents the mean, while the left one represents the standard deviation.

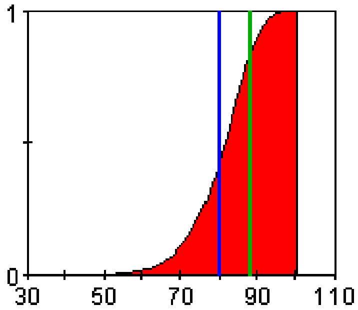

Fig. 8: Cumulative Distribution of Water Temperature

TRANSIENT FEM SIMULATION

As shown on the flow chart of the reliability assessment tool, the CFD results are mapped onto the corresponding FEM model. A transient FEM simulation is set-up to determine the maximum thermal stress. The mesh used for FEM analysis is shown in Fig. 9. The obtained maximum stress is shown in Fig. 10. This value is used to predict the finned tube life based on fatigue analysis. As this case involves high cycle fatigue, alternating stress is used [Shigley et al, 2003]. The effect of thermal stress on fatigue life is worse than the effect of mechanical stress. Since we are dealing with thermal stress, a factor of 2.5% lower cycles is used in the analysis [Oberg and McCauley, 2004]. It is necessary to investigate the whole transient period in order to find the value of the maximum stress.

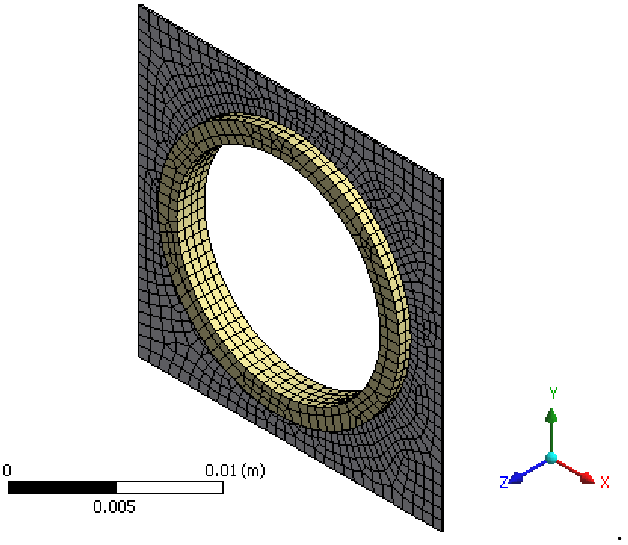

Fig. 9: Mesh used for FEM Analysis

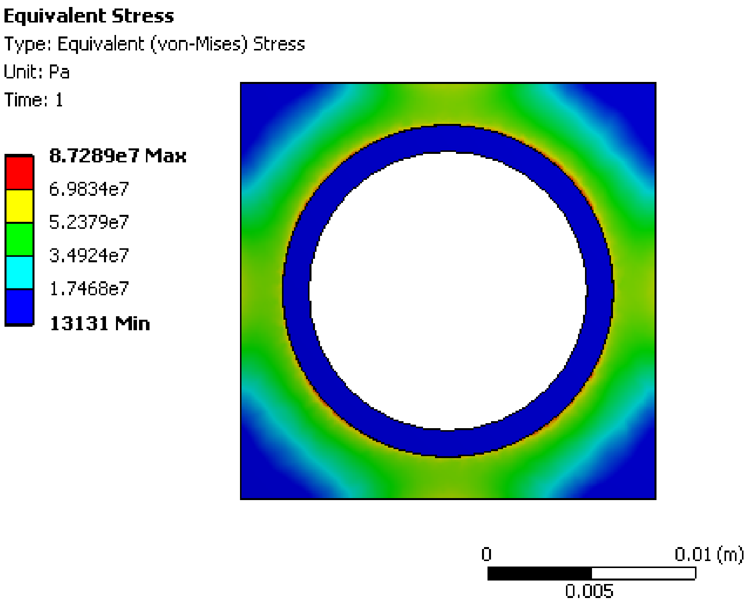

Fig. 10: Thermal Stress Distribution in the Finned Tube Model

FATIGUE LIFE

The transient FEM analysis results in the maximum thermal stress, which is used to calculate the finned tube life based on fatigue analysis. Fatigue life is determined using the material *S-N* curve in conjunction with the necessary correction factors mentioned earlier. Figure 11 shows the *S-N* curve used in this work. Fatigue life predictions are based on constant amplitude, zero-based, proportional loading. In Fig. 11, the four curves correspond to alternating stress mean values of -1.0, -0.5, 0, and 0.5, going from top to bottom of the chart.

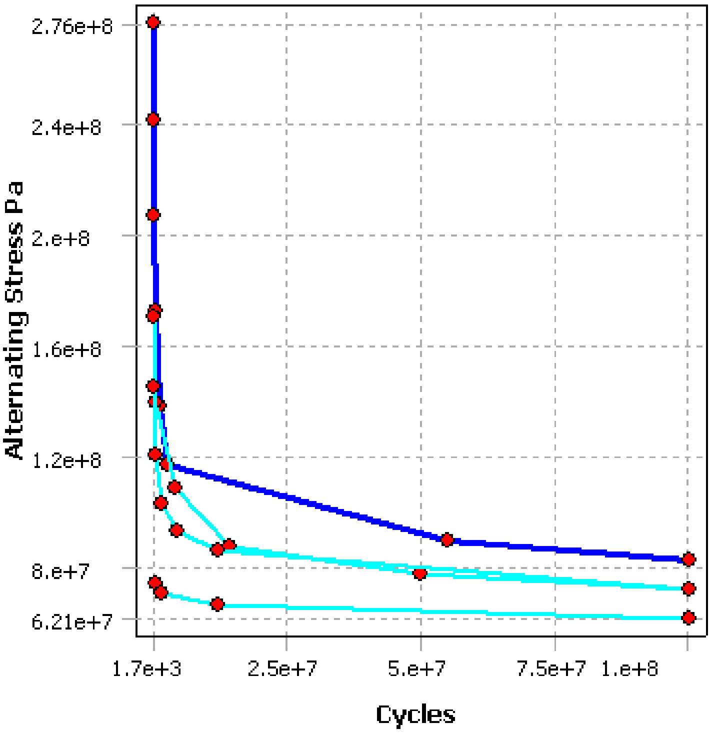

Fig. 11: Alternating Stress vs. Cycles for the Finned Tube Material

RELIABILITY ASSESSMENT

Once the prescribed procedure is completed for one design point, the reliability assessment tool shown in Fig. 1 is used to evaluate the reliability of the finned tube. The method is iterated for different values and combinations of input parameters according to their probability distributions. During this process, the input parameters are treated as random variables. The input parameters are selected based on sensitivity analysis which shows the most significant factors affecting thermal stress. These parameters include operational, geometrical, and environmental variables such as air temperature and heat transfer coefficient. Table 2 lists one example of these parameters.

Table 2: Properties of the Finned Tube Temperature

Random Variable Distribution Information	
Distribution	Weibull
Mean	85.3
Standard Deviation	9.03
Coeff. of Variation	0.2
Alpha	87.7
Beta	14.9

The reliability is calculated using Monte Carlo simulation, which is conducted using iSIGHT® software. The Design Gateway module is used to setup the problem and the Runtime Gateway module is used to obtain the results. The workflow in the Design Gateway is shown in Fig. 12.

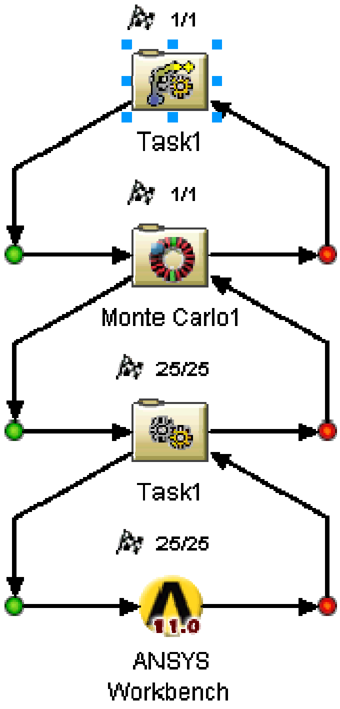

Fig. 12: Finned Tube Reliability Assessment

The formulation in Fig. 12 represents four blocks connected by three loops. The upper block represents the driver of the Monte Carlo Simulation. The Monte Carlo Simulation block is configured to generate the samples from input distributions. The lower Task is the driver of ANSYS Workbench®, where FEM iterations are run in that loop. The results of all iterations are saved in the upper task. For each input parameter, 25 random points are generated according to their probability distribution. The most interesting result of this simulation is the minimum life (shown in Fig. 13), which is defined as the number of years the weakest part of the Finned tube can endure before failure, where failure is based on fatigue analysis.

In an effort to reduce computational cost, Latin Hypercube Sampling (LHS) is used in conjunction with Full Factorial Design (FFD). The resulting design points are used to construct a response approximation surface by means of polynomial regression. The surface is used to generate enough sample points to achieve convergence. Thus, a satisfactory estimate of the FEM output parameters is obtained. Finally, Fig. 13 can be used to determine the reliability of the finned tube for different values of life by numerical integration which is available in the reliability assessment tool.

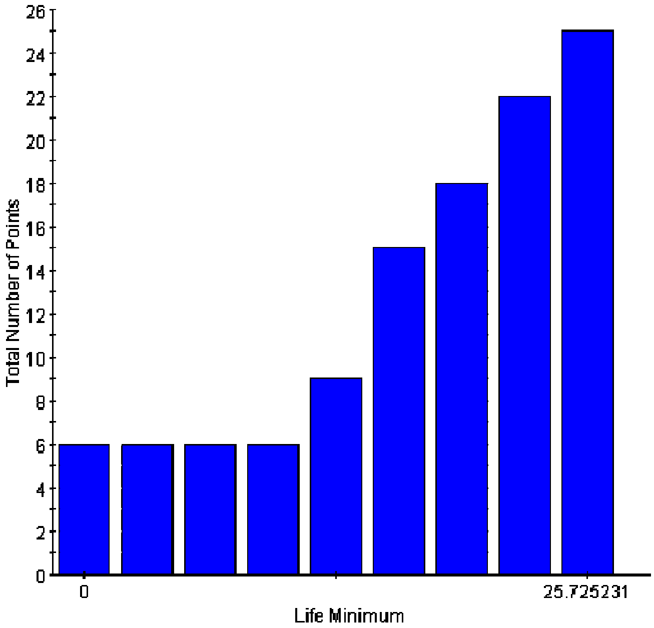

Fig. 13: Cumulative Histogram of Fatigue Life

CONCLUSION

The reliability of the finned tube can be easily determined using the stated method. It requires minimal mathematical work as it relies on high-level software interface that automates most of the tasks needed to perform the analysis.

The temperature of air as it flows past the model is reduced due to the heat loss to the fin and the water tube. The maximum temperature in the model is in the fin, it occurs at the corners of the fin most distant from the water tubes. The lowest temperature in the model is in the tubes. In addition, the lowest temperature in the fin occurs nearest to the water tubes. Maximum thermal stress occurs at the bonding region between the water tube and the fin. This is because of the high temperature gradient combined with different material properties. Minimum thermal stress occurs in the fin corners most distant from water tube, and that is where temperature gradient is the lowest. While thermal stress in the model is relatively low, it is still important for the fatigue analysis.

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