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High-Fidelity Reliability Prediction of a Tube Bundle

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Abstract

The reliability of shell and tube heat exchanger is predicted using a 2-stage physics-based simulation. The first stage uses stochastic porous models of the bundle to estimate operational and environmental uncertainties in flow conditions, such as flow velocity and inlet temperature. The results are used for the second stage, which is the CFD simulation of the sub-model. The most critical part of shell and tube heat exchangers is the tube bundle. The technique integrates stochastic fluid-structure interaction with fatigue and Monte Carlo simulations. Heating loads are transferred between models by mapping of actual temperature distributions. A sensitivity analysis is conducted to determine the significant factors that may lead to failure, as it is impractical to consider all input variables. In the sub-model, which is a tube bank, air flow and heat transfer inter-effects between the three tubes and the fins are measured. Thermal stresses are highest at the bonding regions between the water tubes and the fins, and that is because of the high temperature gradient combined with different material properties. Thermal stress in the model is relatively low, however, it has a high effect on fatigue life, and consequently on reliability result. The presented model can be used as a useful tool for reliability-based design of shell and tube heat exchangers.

Keywords: *Reliability Prediction, Physics-based Modeling, Shell and Tube Heat, Exchanger, Thermal stress, Fatigue Life, Fluid-Structure interaction*

1. Introduction

Several available methods are capable of estimating the reliability of heat exchangers. However, one method stands out as the most cost-effective approach. This method is called physics-based reliability prediction. It is the most rigorous method compared to its cost. It is described as “High-Fidelity” technique; as Monte Carlo Simulation is combined with load transfer by mapping of actual distributions. Since the most critical part of shell and tube heat exchanger is the tube bundle, the reliability of this component is evaluated using a high-fidelity method. The technique integrates stochastic fluid-structure interaction with fatigue and Monte Carlo simulations. All significant factors that may lead to failure are investigated in this technique. The method is shown to be highly capable of analyzing the reliability of this component, as well as forecasting its future performance.

Reliability can be 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 [2]. It can be determined by different methods such as mathematical techniques, historical data-based approaches, and accelerated-life testing. However, the first method is based on simplifying assumptions, and the second method requires the availability of historical data, whereas the last method is expensive. Therefore, physics-based reliability prediction remains the most rigorous method compared to its cost. This approach can be described as “High-Fidelity” method provided that certain conditions are met. These conditions include load mapping between domains while maintaining the spatial distribution of the

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load of concern. This process is normally done in conjunction with Monte Carlo Simulations (MCS). The paramount advantage of this method is that it can be applied early during the design phase.

Shell and tube heat exchangers contain a tube bundle enclosed by a shell. The bundle is the heart of the heat exchanger where any malfunction may lead to catastrophic consequences. Therefore, it must be reliable enough so as to avoid potential failures. The high-fidelity reliability assessment technique is used to evaluate the reliability of this component. The technique works by mapping CFD loads and coefficients onto a corresponding FEM model. 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 component, as well as providing valuable information on its service life performance.

Previous related work includes a thermal model developed by Bassi *et al.*, [9] where they used Latin Hypercube Sampling (LHS) to generate random variables from probabilistic distribution of critical parameters, taking into account the uncertainty sources. They did parametric studies to generate a failure surface based on a stress failure criterion. However, their work was restricted to a single physics. Two more references on the subject have not used stochastic modeling. These include Asghari [4], who obtained heat transfer coefficient (h) for surfaces in contact with air flow by running a steady-state CFD model. The obtained h was used for transient analysis instead of the one obtained analytically, because walls do not exhibit uniform temperature, and using hand calculation for h from the Nusselt number would result in erroneous calculation. The other reference is Bedford *et al.*, [8], who used a CFD-based time-averaged heat transfer coefficient (h) for thermal stress analysis. They exported h over the model boundaries. h was imported into the structural Finite Element Analysis (FEA) code where a steady-state thermal analysis was performed, which accounts for non-uniform thermal loading.

Most of the reviewed reliability research available in the literature focuses on single-physics structures. For example, Basaran and Chandaroy [3] 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.*, [4] compared the reliabilities of two solder joints. 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 interaction. One such example is the work done by Constantinescu *et al.*, [5], 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 for investigating the reliability of the tube bundle.

A failure of the tube bundle in a shell and tube heat exchanger may lead to serious consequences. One of the main causes of this component's potential failure is the thermal cycling fatigue. In this work, the reliability of the bundle is investigated using a high-fidelity reliability assessment tool. The tool was validated in Ref. [1]. 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 structure part. The tool performs stochastic simulations based on Monte Carlo simulation.

In order to conduct proper reliability evaluation, uncertainties in environmental, operational, and manufacturing parameters need to be considered. The end result would 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 bundle by providing a probability that it will survive operating conditions. A flow chart representing this tool is shown in Figure 1.

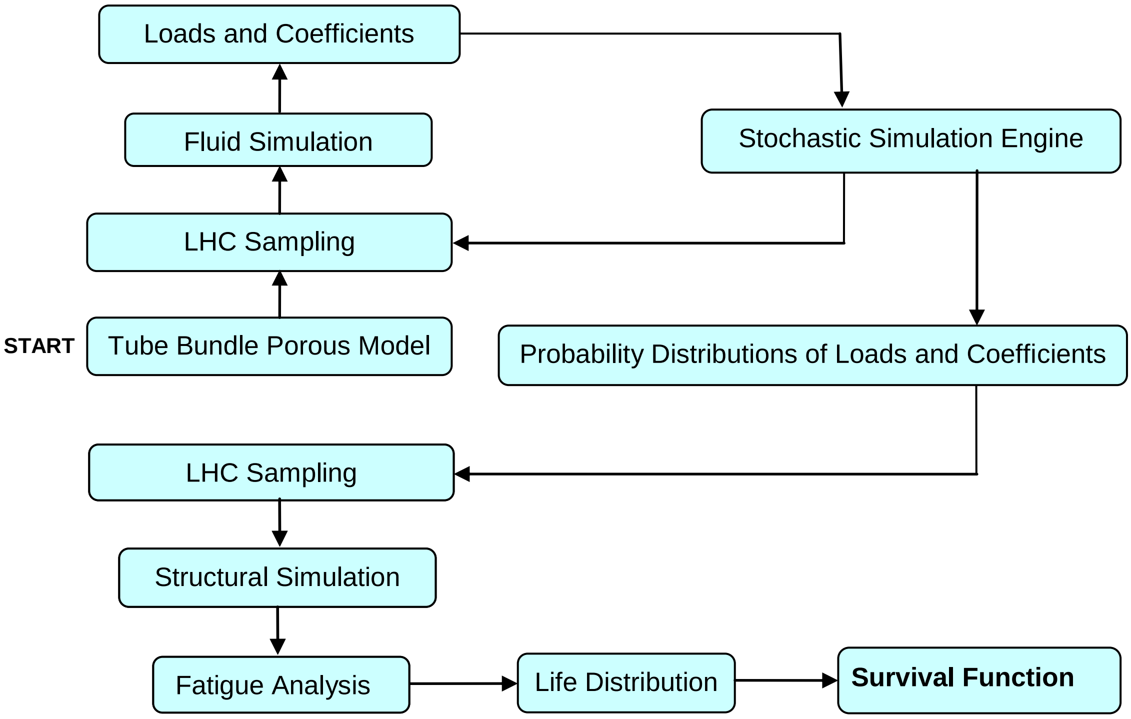

Figure 1. Reliability Simulation Method [1]

The sampler used in the above tool utilizes 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 detail by applying the procedure to the tube bundle.

2. CFD Simulation

This step depends on the data provided by the stochastic porous model which due to its complexity, will be explained in another paper. CFD simulation is the first step in the reliability assessment procedure. A representation of part of the tube bundle is shown in Figure 2. Water runs into the tubes, while air runs externally across the fin-connected tubes. However, only a small section of this representation will be modeled due to the high cost of computation.

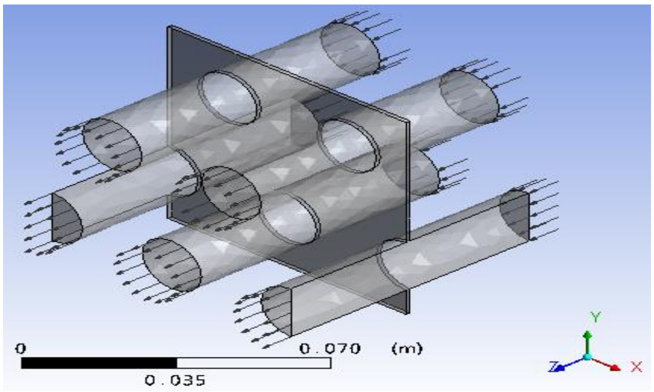

Figure 2. Representation of the Tube Bundle

The model used in CFD simulation is shown in Figure 3. The model represents a tube bank which is part of the tube bundle. The tubes are connected by a fin. Water flows from left to right through the tubes, while air flows from front to back. The boundary condition at the two walls parallel to the fin is adiabatic with no slip. This condition is imposed because no significant heat transfer is expected across the fins. Heat flux passes from air to fins and tubes, then from tubes to water. Free slip surfaces are imposed at the straight edges of the tubes halves. This condition takes advantage of the symmetry of the tubes cross section in order to reduce computational time. Free slip surfaces are also located at the top and bottom of the model, because in reality, air is only restricted by the fins and the tubes.

The model is converted to a finite volume mesh, with a total number of elements just below 950,000, as shown in Figure 4. The elements used were mainly tetrahedrals. When hot air enters the model, it causes thermal expansion and consequently thermal stress. The repetition of such occurrence is the reason for thermal cycling and eventually leads to service life limitation. After imposing the above mentioned boundary conditions on the model, a steady-state conjugate heat transfer problem is started. It took 140 iterations to reach the convergence criteria of ($1 \times e^{-5}$ RMS). After the convergence of the CFD solution, the temperature distribution results are obtained and mapped onto the corresponding FEM model of the tube bank. The velocity profile is shown in Figure 5, and the air temperature profile is shown in Figure 6.

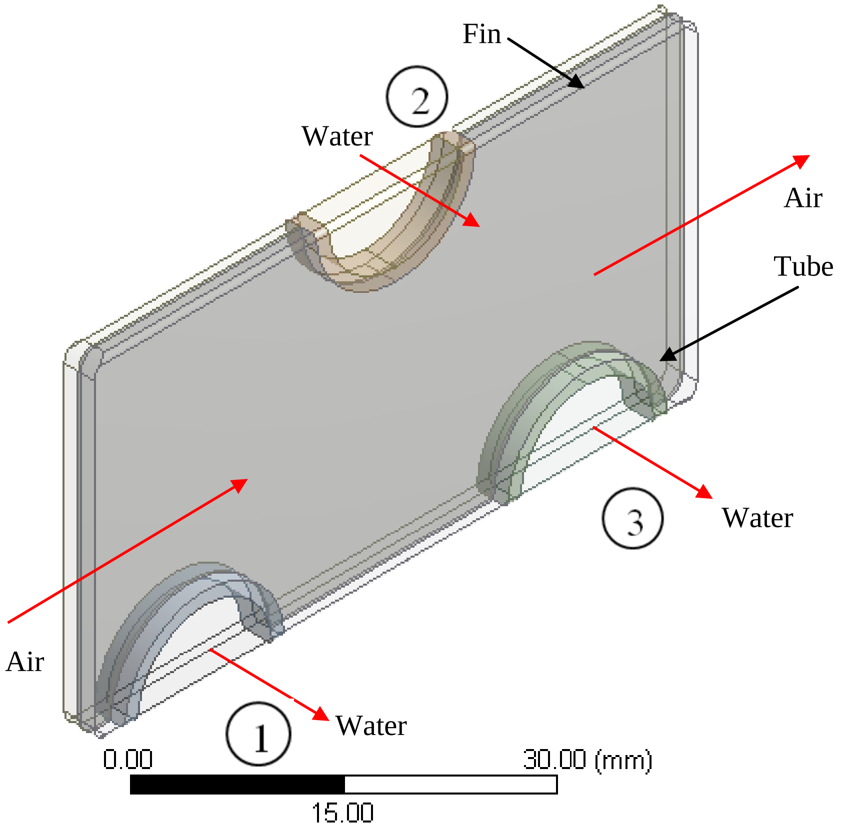

Figure 3. Tube Bank Model

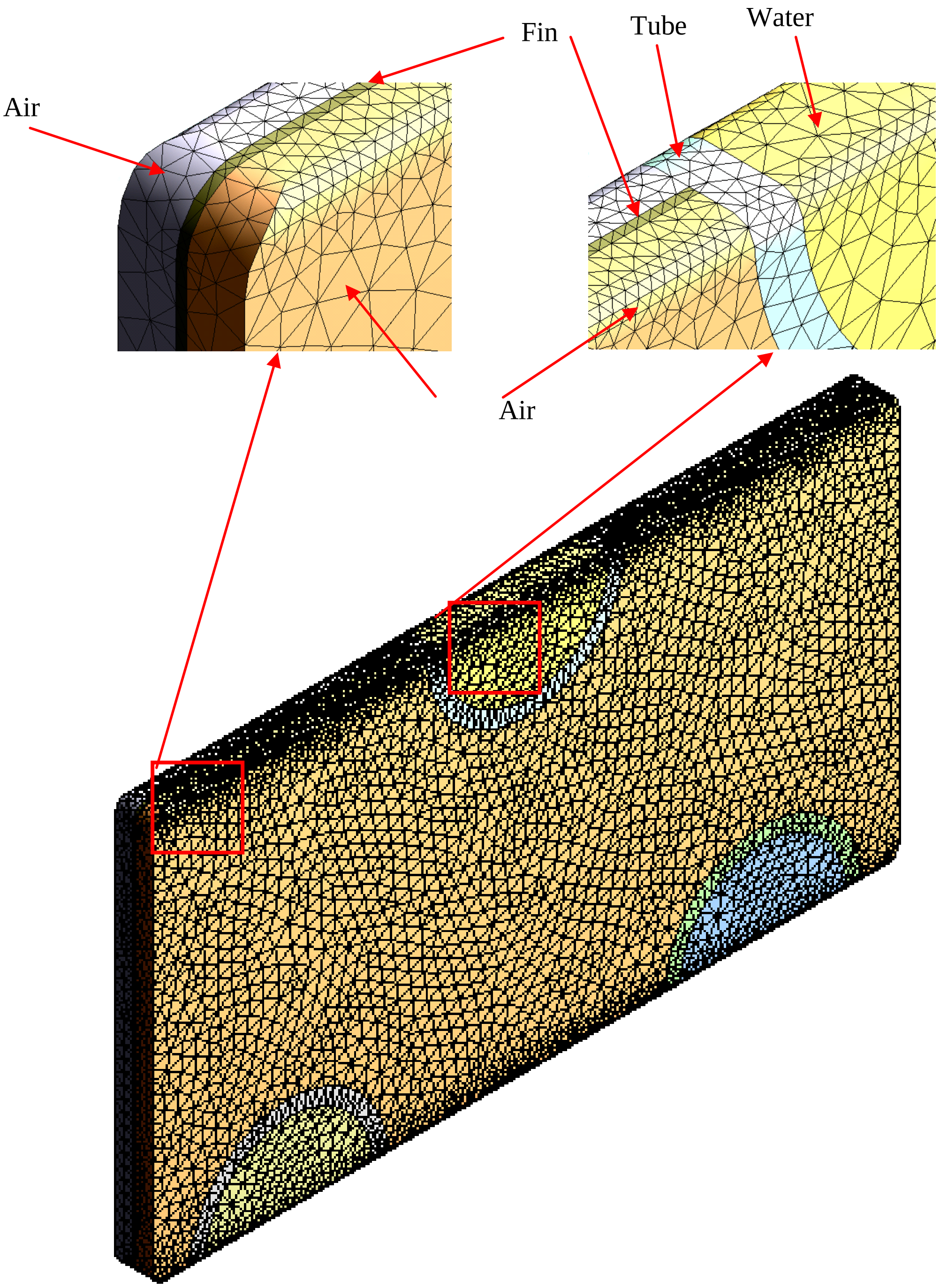

Figure 4. The Meshed Tube Bank Model

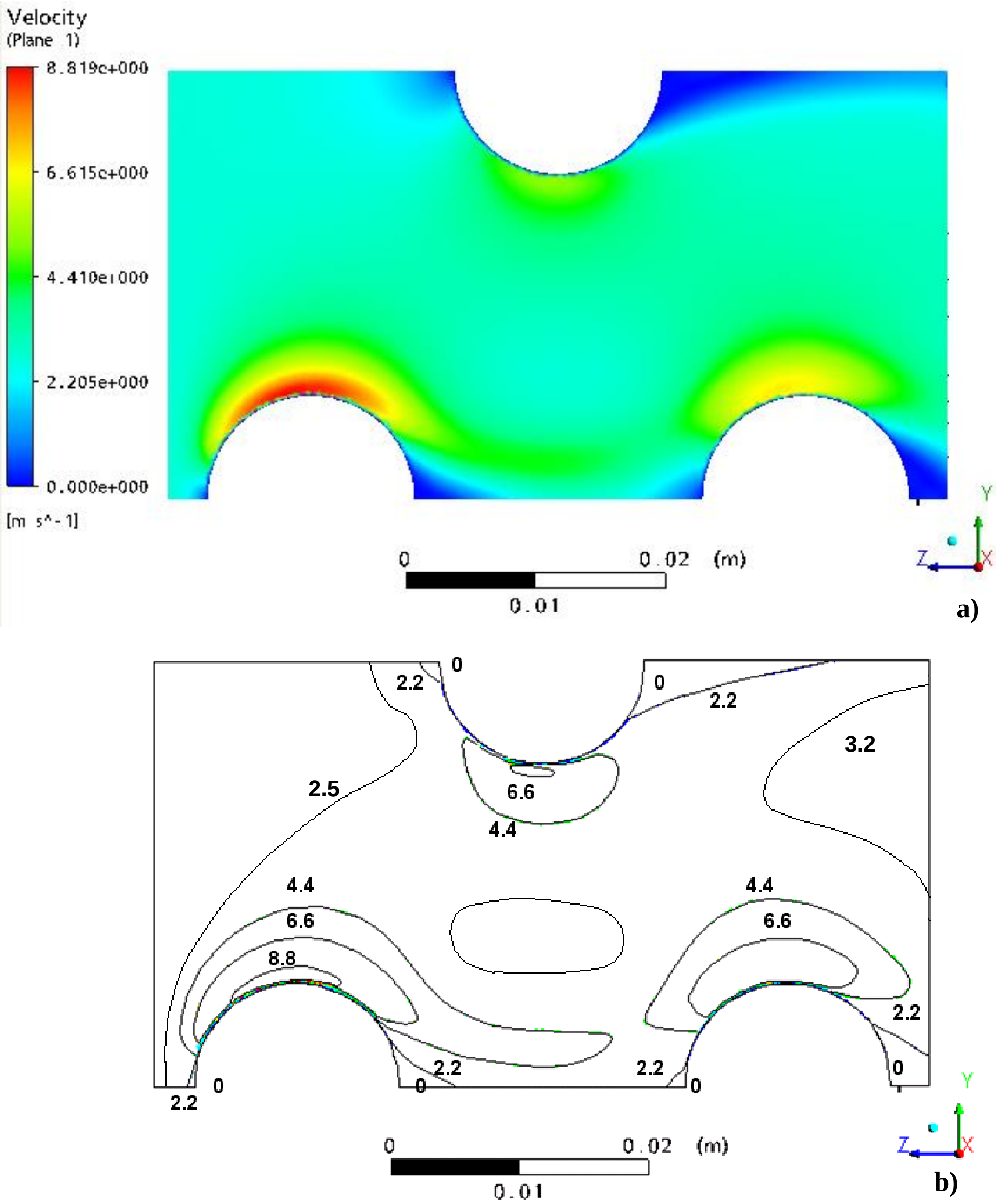

Figure 5. Air Velocity Profile for the Multi-Tube-Finned Model (m/s): a) Color Map, b) iso-contours

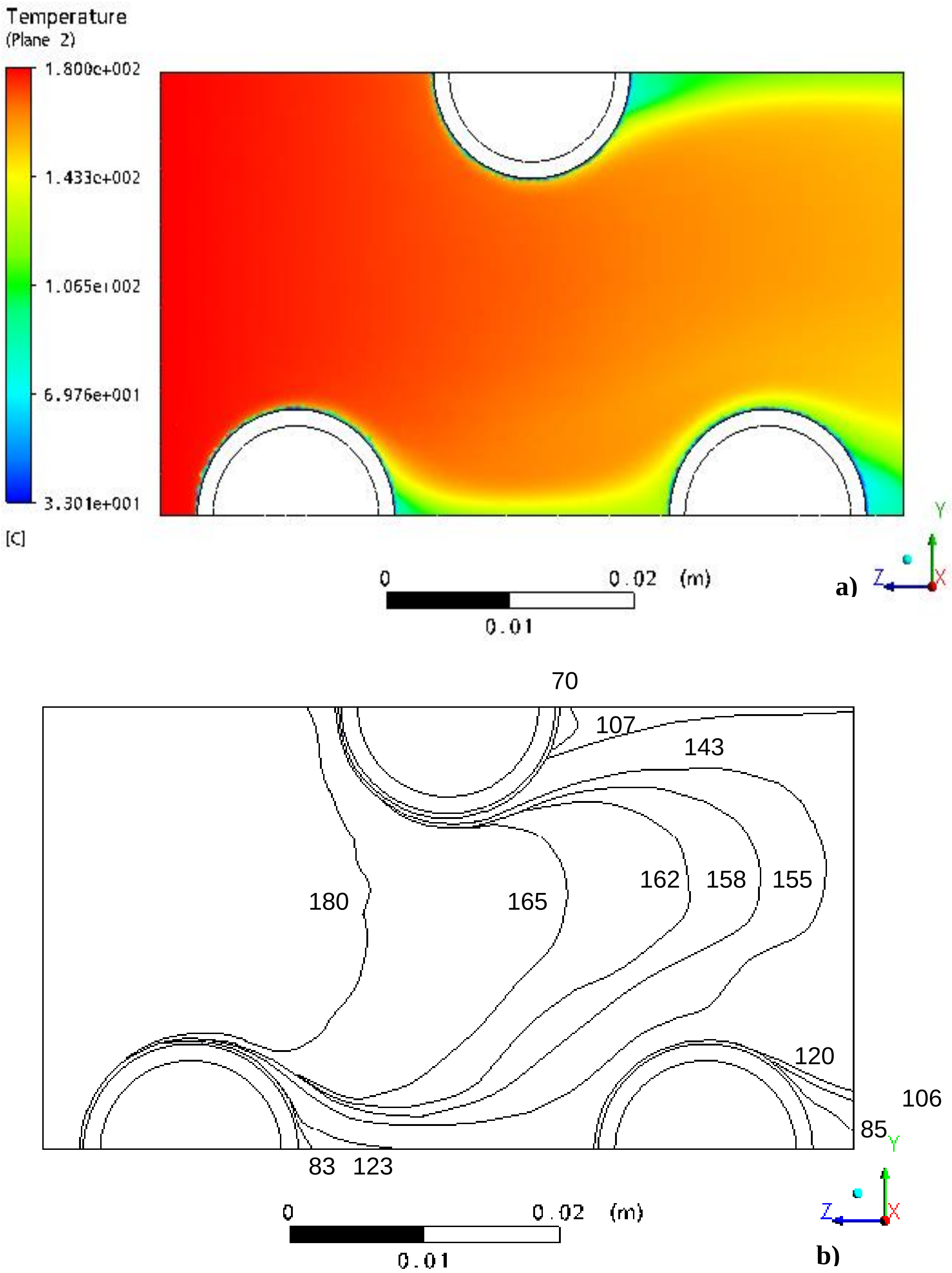

Figure 6. Air Temperature Profile for the Multi-Tube-Finned Model (°C): a) Color Map, b) iso-contours

2. Transient FEM Simulation

It is found that in similar work which had dealt with thermal stress and probabilistic modeling, a thermo-mechanical study considering only the steady-state operation and not the pulsed heating effects is not enough [10]. Additional study is necessary to consider the pulsed heating effects in the form of additional stress [10]. Miroshnik *et al.*, [11] carried out FEM of transient thermal stresses for a chest valve. A probabilistic approach to service life assessment is performed in assumption that the temperature change and the fatigue properties of the chest valve material are distributed randomly.

As shown on the high-fidelity reliability assessment chart, the CFD results are mapped onto the corresponding FEM model. The resulting temperature distribution is shown in Figure 7. A transient FEM simulation is set-up to determine the maximum thermal stress. The resulting maximum stress is shown in Figure 8. This value is used to predict the fatigue life of the tube bank. As this case involves high cycle fatigue, alternating stress is used [6].

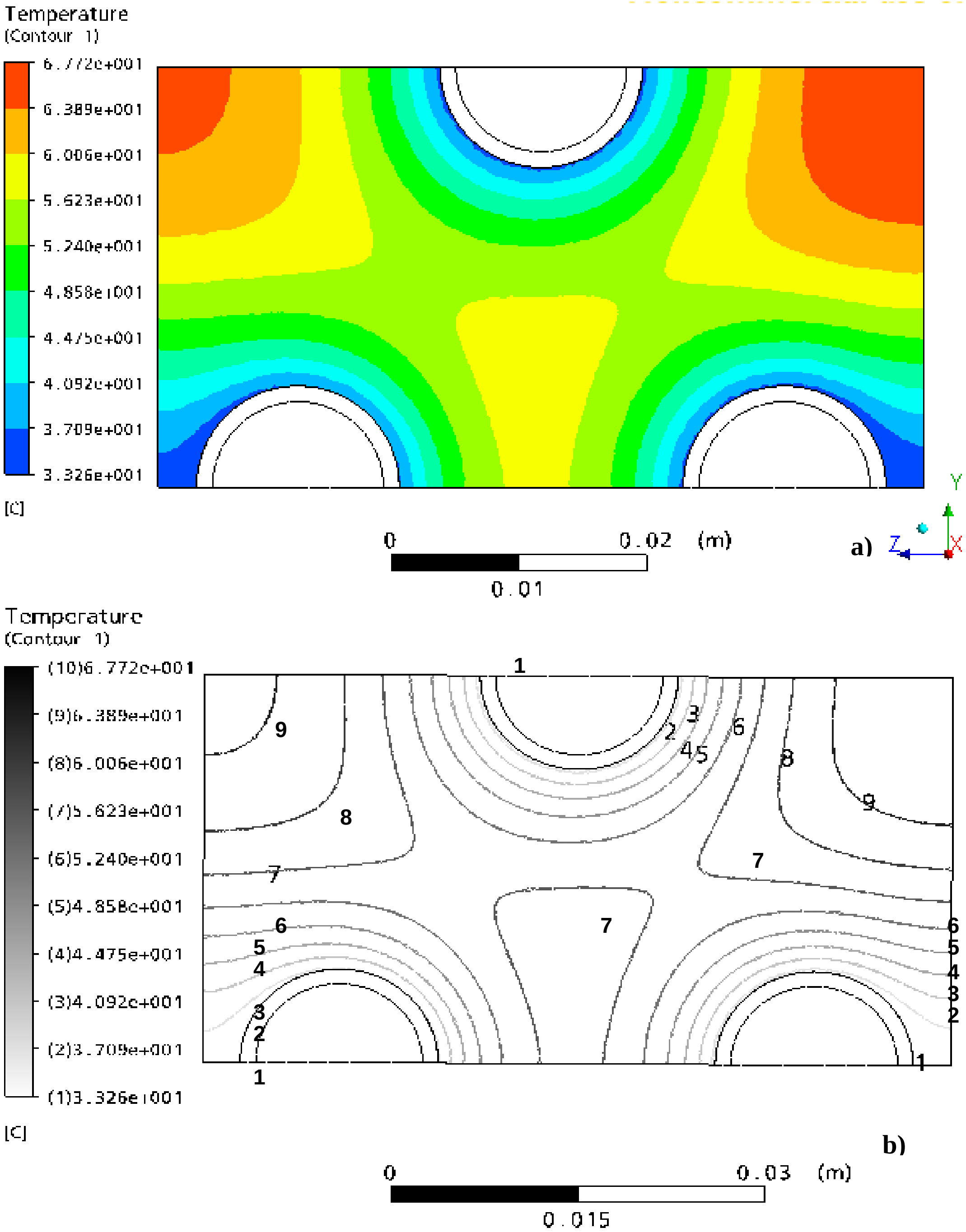

Figure 7. Temperature Distribution of the Fin and Tubes: a) Color Map, b) iso-contours

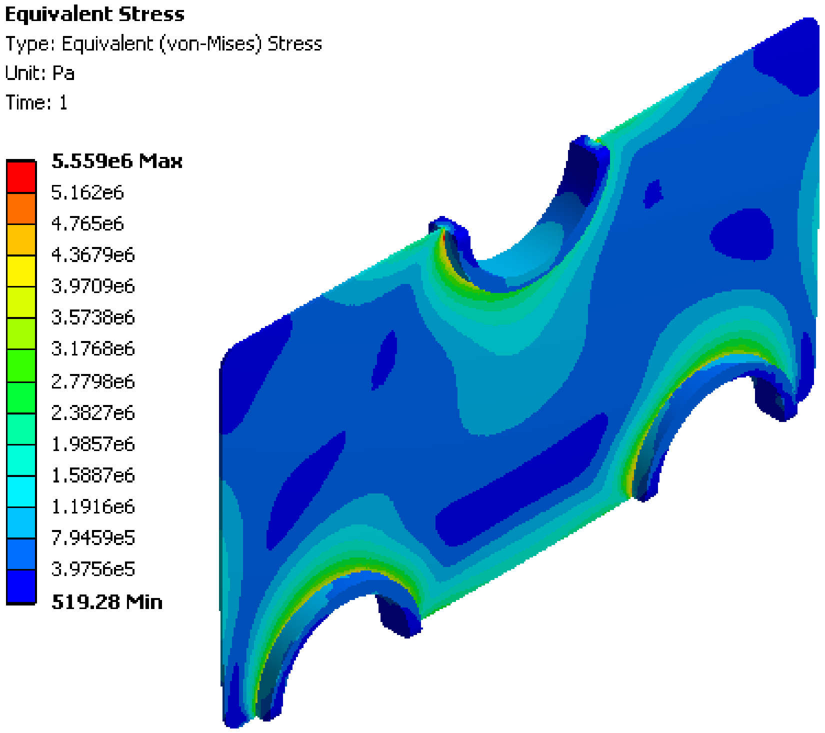

Figure 8. Stress Distribution in the Tube Bank Model

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 [7]. It is necessary to investigate the whole transient period in order to find the value of the maximum stress.

4. Thermal/Structural Analysis

The stress result in Figure 8 shows that the maximum stress occurs at the bonding regions between the tubes and the fin. This result was expected because the tubes and the fins are made up of different materials and therefore have different properties and thermal expansion coefficients. The magnitude of the maximum thermal stress that occurs in the model is relatively low. However, when taking fatigue into consideration, this amount of stress will have tangible impact on the operation of the bundle. It can be considered as a low cycle fatigue which is linked to the number of times the bundle is operated for a given period of time. In this case, the failure criteria can be defined as a function of the amount of the thermal stress and the number of cycles to failure which spans the life of the bundle.

5. Fatigue Life

In this work, fatigue is induced by thermal stress resulting from heat transfer between fluids and structure and within the structure. Due to the stochastic nature of flow conditions such as temperature and velocity, multiple Fluid-Structure Interaction (FSI) load cases are involved. The spatial location of critical fatigue life is assumed constant and corresponds to the computed maximum thermal stress. Thus, fatigue calculations should be based on non-constant amplitude, proportional loading. However, for each run, constant amplitude corresponding to maximum stress at that point is used for cycle counting. Since each point is associated with a different maximum stress and consequently different amplitude, the end result of the simulation will be non-constant amplitude, proportional loading.

In Stress-life method, maximum shear stress is used to convert from multiaxial to uniaxial stress states. This is done so as to adapt the computed stress to the *S*-*N* curve data. Moreover, loading is assumed zero-based because thermal loading increases from ambient to maximum temperature, then decreases to ambient temperature. The solution is corrected for the effect of mean stress using Gerber Theory, since it is suitable for ductile materials [16]. Fatigue calculations are based on ASME Boiler and Pressure Vessel Code, Section III, and Section VIII, Division 2. A Fatigue Strength Reduction Factor (FSRF) of 2.0 for integral parts and 4.0 for non-integral attachments has been assumed for calculating the amplitude of peak stresses [15]. In addition, due to the fact that thermal cycling affects life more than mechanical cycling, the resulting number of cycles is reduced by a factor of 2.5 [7].

The transient FEM analysis results in the maximum thermal stress, which is used to calculate the tube bank life based on fatigue analysis. Fatigue life is determined using the material *S*-*N* curve in conjunction with the necessary correction factors mentioned earlier. Fatigue life predictions are based on constant amplitude, zero-based, proportional loading.

The total deformation in the fin and the tubes is shown in Figure 9. The center of the model is the reference point for measuring the deflection. The purpose of this figure is to show the thermal expansion induced by the thermal load. We can see that at the left side of the model, the intensity of defection is higher than the right side. This is explained by noting that the temperature is higher at the left side.

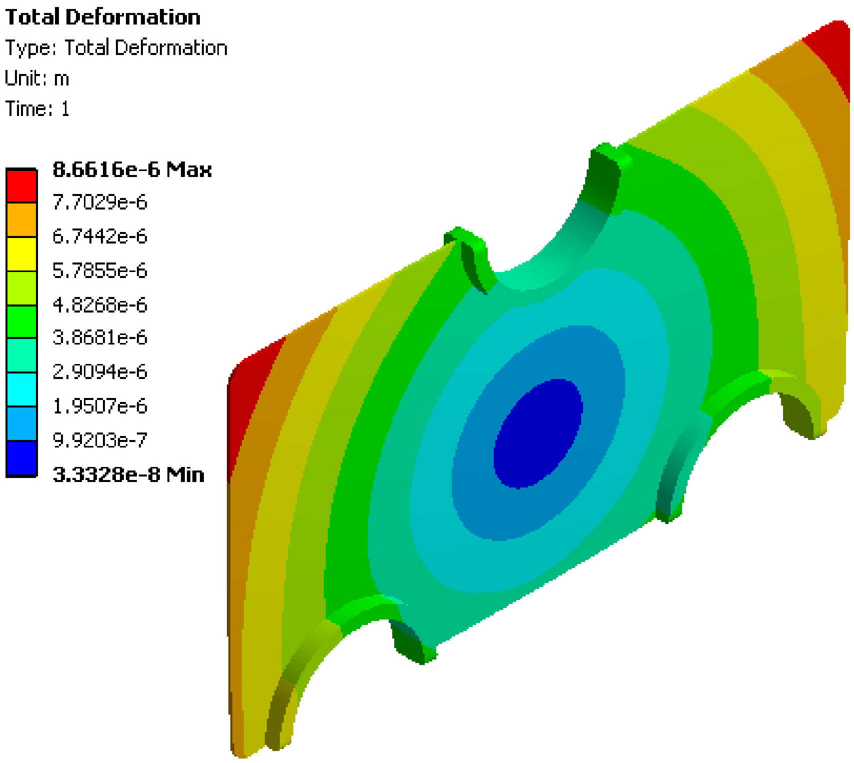

Figure 9. Total Deformation of the Tube Bank

6. High-fidelity Reliability Prediction

Similar reliability work includes a probabilistic framework to assess the fatigue life of components of nuclear power plants. It was set up by Sudret *et al.*, [12]. It intended to incorporate all kinds of uncertainties such as those appearing in the specimen fatigue life, design sub-factor, mechanical model and applied loading to study the reliability associated with the (deterministic) design value. However, their work does not include fluid simulation.

Due to the high computational time required for CFD and FEM simulations, only a limited number of iterations are possible. Therefore, various techniques are used to reduce the computational effort to a manageable size. One of those techniques is the implementation of a Response Surface Model (RSM). Other methods commonly used for reducing the computational effort include variance reduction techniques such as Latin Hypercube Sampling (LHS). The High-Fidelity Reliability Prediction chart is shown in Figure 1. The main difference between this method and the original reliability assessment tool is that the spatial load distribution is mapped over the area instead of applying the average load. That means reliability is investigated with more rigor. The process is characterized by performing complete stochastic CFD and FEM simulations and recording input and output parameters. After enough iterations are performed, regression analysis is used to form an approximation surface to determine the reliability. The output of the Monte Carlo simulation can be best viewed after creating the probability distribution histogram of the model life. This result is shown in Figure 10. As the number of iterations (sampling points) is increased, the accuracy of the distribution is enhanced.

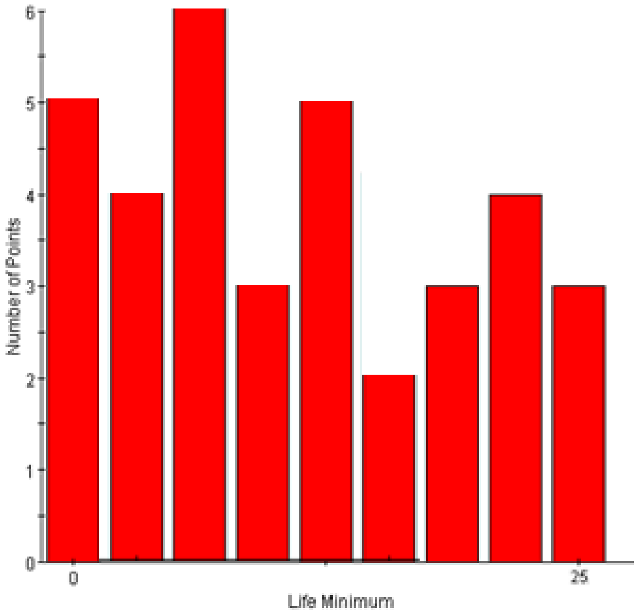

Figure 10. Probability Distribution of Model Life

Once the prescribed CFD/FEM procedure is completed for one design point, the tool shown in Figure 1 is used to evaluate the reliability of the tube bank. 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. The resulting design points shown in Figure 10 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, in order to determine the reliability of the model for different lives, numerical integration available in the high-fidelity tool is used.

7. Conclusions

The air flow and heat transfer inter-effects between the three tubes and the fins are measured in the tube bank model. The use of a central fin in addition to two walls representing two other fins helps to control the model to be as close as possible to reality. However, it is more difficult to mesh complicated models. The temperature of air as it flows through the model is reduced due to the heat loss to the fin and the water tubes. The model part with the highest temperature is the fin, specifically 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. The thermal expansion of the model is in the order of micrometers.

Thermal stresses are highest at the bonding regions between the water tubes and the fins, that is because of the high temperature gradient combined with different material properties. The lowest thermal stresses occur in the fin corners most distant from the water tubes, and that is where the temperature gradient is minimum. Thermal stress in the model is relatively low, however, it is important for the fatigue analysis. The reliability of the tube bank and consequently of the bundle can be 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.

Since they approximate the actual system, stochastic porous models of the bundle can estimate uncertainties in flow conditions, which are used for subsequent CFD simulations of the sub-models. Stochastic CFD analysis reflects uncertainties of operational and environmental conditions such as flow velocity and inlet temperature, while fatigue analysis parameters have a great effect on the reliability result.

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