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Integrated Simulation of a Condensate Tube Reliability Based on Transient Conditions

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ABSTRACT

An integrated simulation method is employed to investigate the reliability of a fluid tube based on transient conditions. The method works by mapping transient CFD loads and coefficients onto the corresponding FEM model. The two parts of the problem need to be dealt with; namely the fluid part as well as the tube structure part. The reliability of the tube is evaluated using Monte Carlo simulation. Transient conditions were used as the cause of potential failure because they constitute the most critical loads that affect the tube. Most failures occur during the start-up of the system. The reason for that is the large temperature gradient during the transient phase of operation. After the system reaches steady-state, temperature gradients decrease whereby thermal stress decreases as well. The time and location of failure is not known in advance. Therefore, the whole structure is modeled and simulated and the whole transient period is investigated. Once the maximum thermal stress is determined, fatigue life can be calculated based on stress life method. This process is iterated in a stochastic fashion so as to estimate the reliability of the component.

Keywords: *Integrated Reliability Simulation, Condensate Tube, Transient Conditions, Thermal stresses, Thermal Fatigue, 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 fluid tube failure has possible consequences ranging from leakage to potential personnel injury. One of the major causes of tube failures is the transient thermal cycling loads. In this work, the reliability of a fluid tube based on transient conditions is investigated using an Integrated Simulation Tool (IST). The tool was validated in Ref. [Al-Habahbeh et al, 2011]. It is based on multi-physical analysis 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 tube structure part. The IST includes randomization of the simulation based on Monte Carlo simulation.

Most of reliability research available in the literature focuse 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. [Vandevelde et al., 2004] compared the reliability 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 interactions. In this context, [Constantinescu et al., 2004] 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 we can deduce the importance of the IST used in this work for the purpose of investigating the reliability of the fluid tube.

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

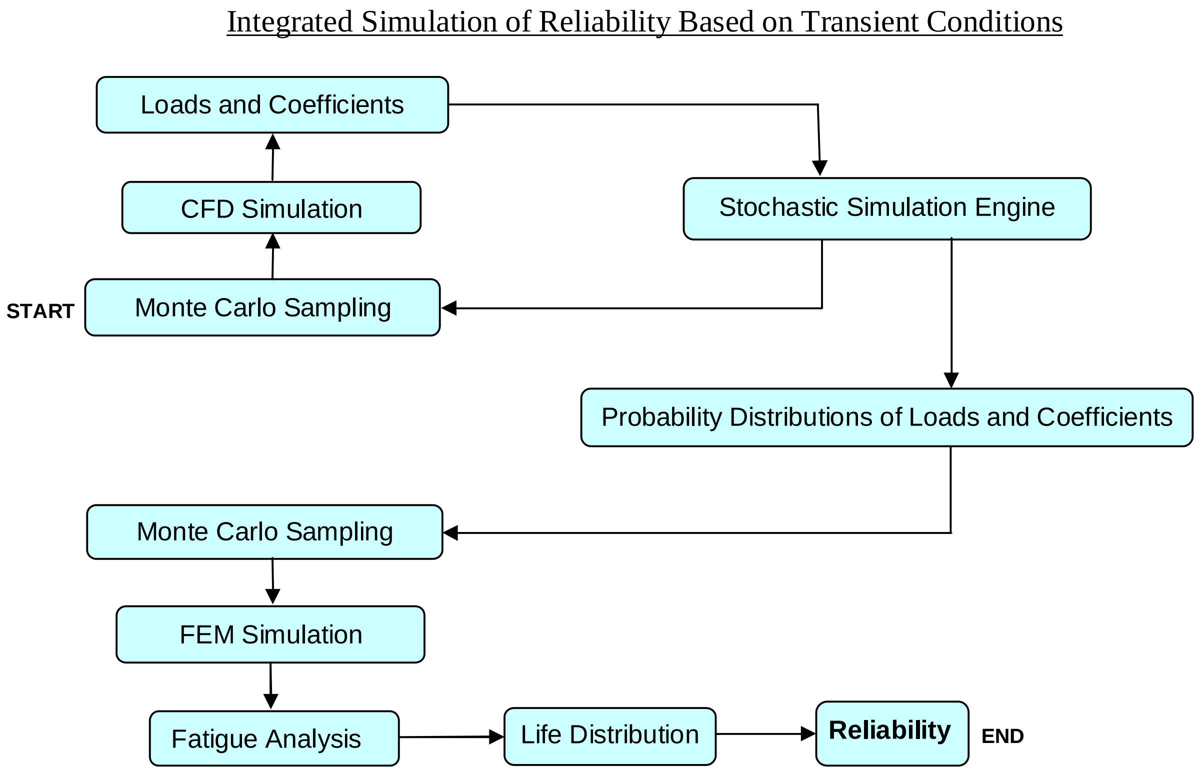


Fig. 1: Flow Chart of the Integrated Simulation Tool (IST) [Al-Habahbeh et al, 2011]

The sampler used in the IST relies on 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 involved in the IST are explained in details by applying the procedure to the fluid tube case.

CFD SIMULATION

The first step in the IST procedure is the CFD simulation. The geometric model used in the simulation is shown in Fig. 3. It represents a straight-cut section of the tube. Water enters the right side and leaves the left side. Adverse effects arise when water first enters the tube. The repetition of such occurrence is the reason for thermal cycling and consequently leads to service life limitation. The model is meshed into 95,000 elements as shown in Fig. 2. After the convergence of the CFD solver, the results for the temperature distribution are obtained. A sample of these results is shown in Fig. 3.

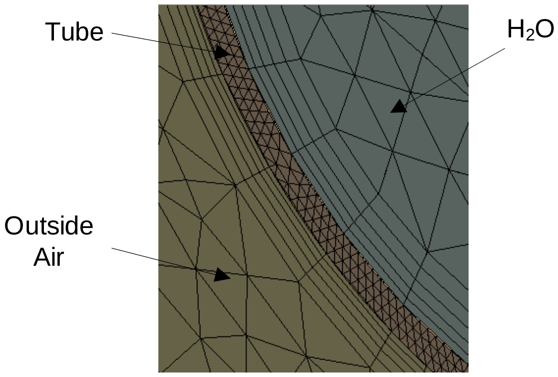


Fig. 2: CFD Finite Volume Mesh

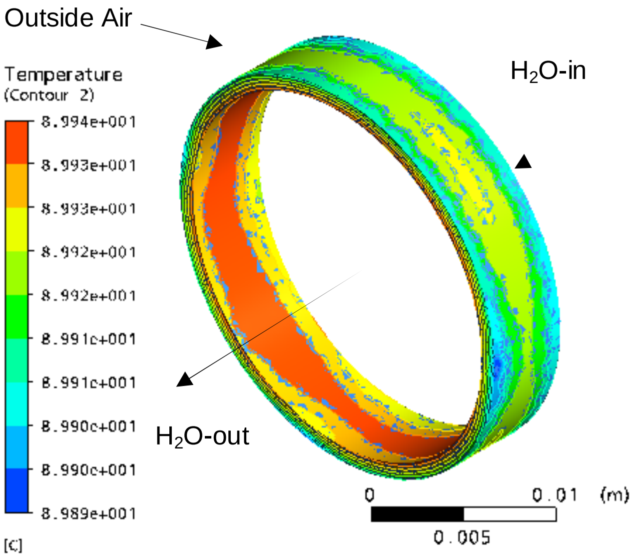


Fig. 3: CFD Model of the Condensate Tube

TRANSIENT THERMAL ANALYSIS

Transient heat transfer in the 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 tube, as the maximum thermal stress occurs during the transient phase. The transient analysis output is used for subsequent transient FEM analysis. The parameters involved in the computation include the temperatures and the heat transfer coefficients of both air and H_2O. One-way thermal fluid–solid interaction (FSI) analysis is conducted, while conjugate heat transfer is used to model heat conduction across the tube wall. The domains of the model are: 1) Water running in the pipe, 2) Tube material, and 3) Ambient air.

Ambient air is assumed an ideal gas, and its density is found using the state equation:

$$\rho = P/RT \tag{1}$$

Where ρ is the air density (in kg/m^3), P is the atmospheric pressure (in Pa), R is the Air Gas Constant (in J/(kg.K)), and T is the temperature (in Kelvin). Table 1 shows the air properties used for the CFD simulations:

Table 1: Air Properties Used in CFD Simulation

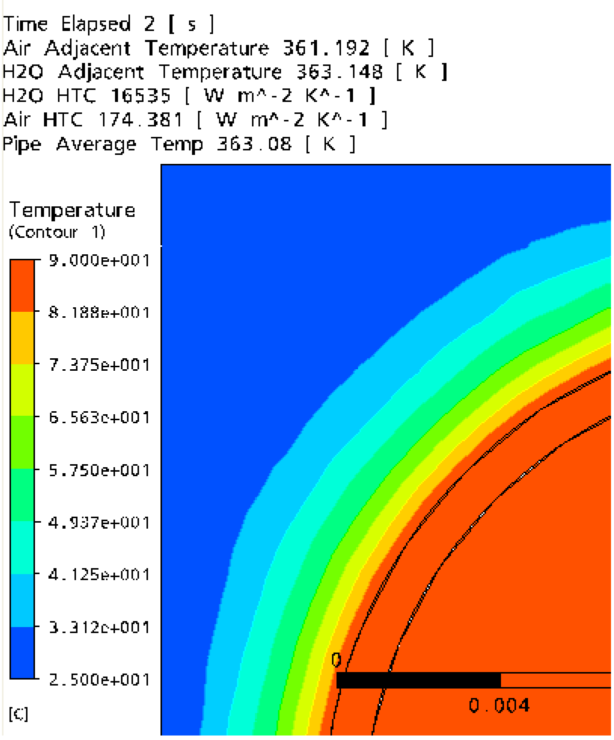
Pressure (P)	Air Gas Constant (R)	Temperature (T)	Air Density (ρ)
atm	*J/kg.K*	*°C*	*kg/m^3*
1.0	287	25	2.9

Table 2 shows the water flow data used in the simulations:

Table 2: Water Properties Used in CFD Simulation

Parameter	Value	Unit
Tube cross-sectional	400	mm^2
Water flow rate	2.0	kg/s
Water-in temperature	90	°C
Water pressure	2.4	atm

The ambient air natural convection flow is assumed laminar, while k-ε turbulence model is used for the water flow. As a result of the CFD analysis, temperature contours on the tube walls are shown in Fig. 3. The temperature change in the tube, water, and ambient air after 2 seconds is shown in Fig. 4. The direction of heat flux is outward (from water to air through the tube).



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Time Elapsed 2 [ s ]
Air Adjacent Temperature 361.192 [ K ]
H2O Adjacent Temperature 363.148 [ K ]
H2O HTC 16535 [ W m^-2 K^-1 ]
Air HTC 174.381 [ W m^-2 K^-1 ]
Pipe Average Temp 363.08 [ K ]
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Fig. 4: Transient Temperature Distribution After 2 s

The variation of the adjacent air temperature with time is shown in Fig. 5, where steady-state is reached after two seconds. Similarly, the change of the adjacent water temperature with time is shown in Fig. 6, where steady-state is reached after two seconds.

The change of the average air heat transfer coefficient with time is shown in Fig. 7, where steady-state is reached approximately after one second. Similarly, the change of the average water heat transfer coefficient with time is shown in Fig. 8, where steady-state is reached approximately after four seconds.

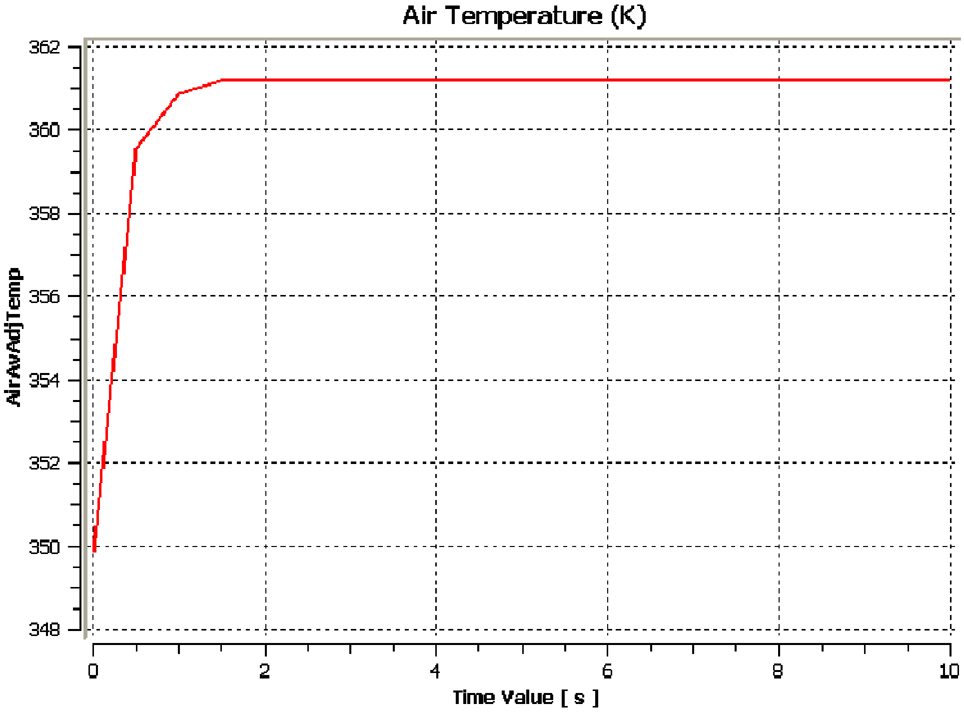

Fig. 5: Adjacent Air Temperature as a Function of Time

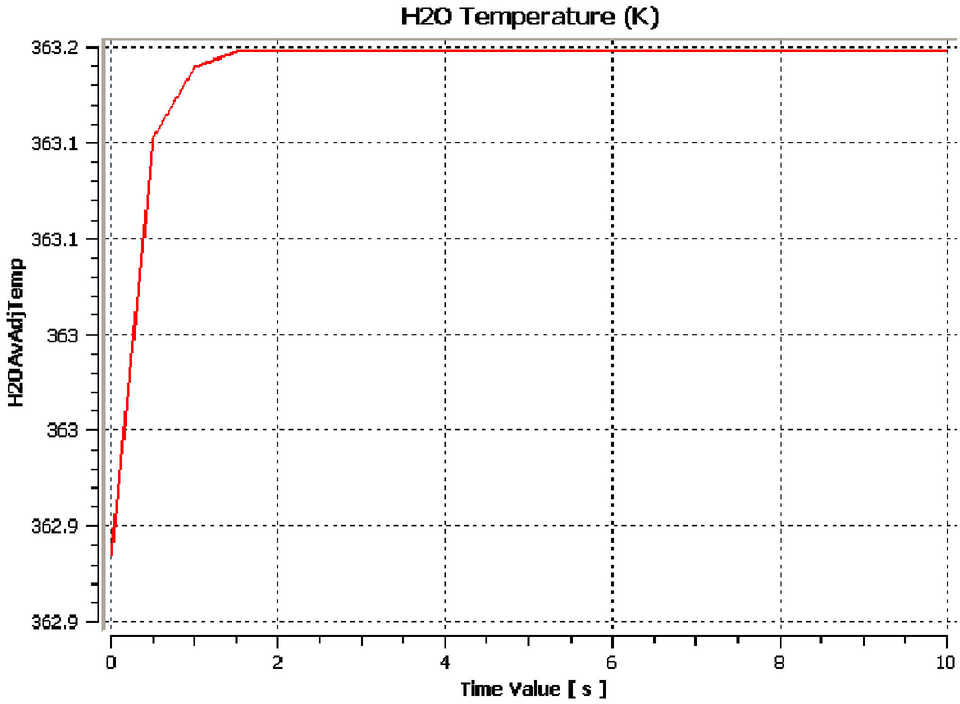

Fig. 6: H_2O Adjacent Temperature as a Function of Time

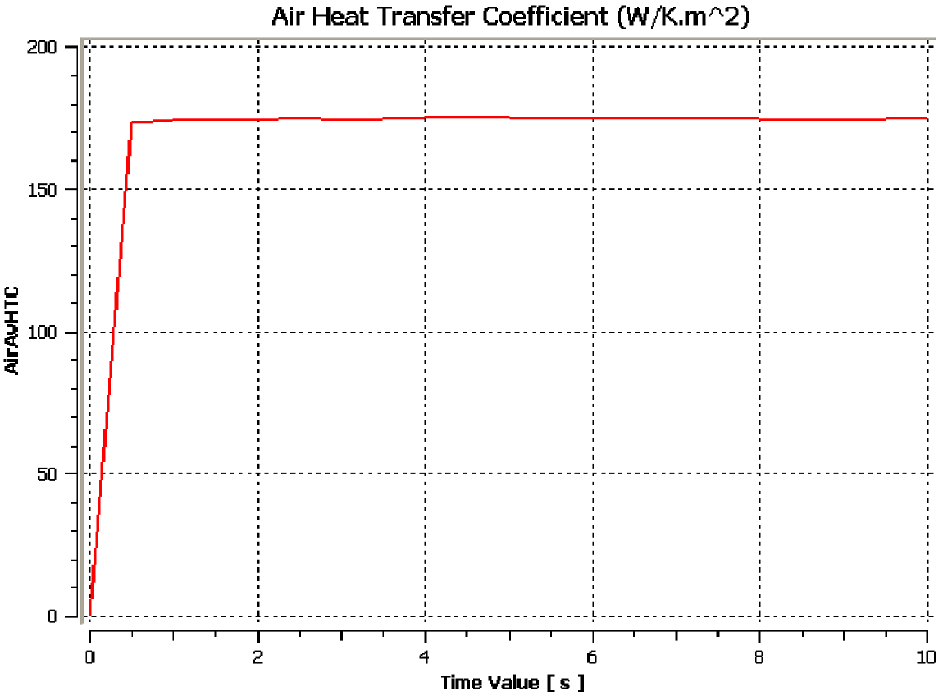

Fig. 7: Air Heat Transfer Coefficient as a Function of Time

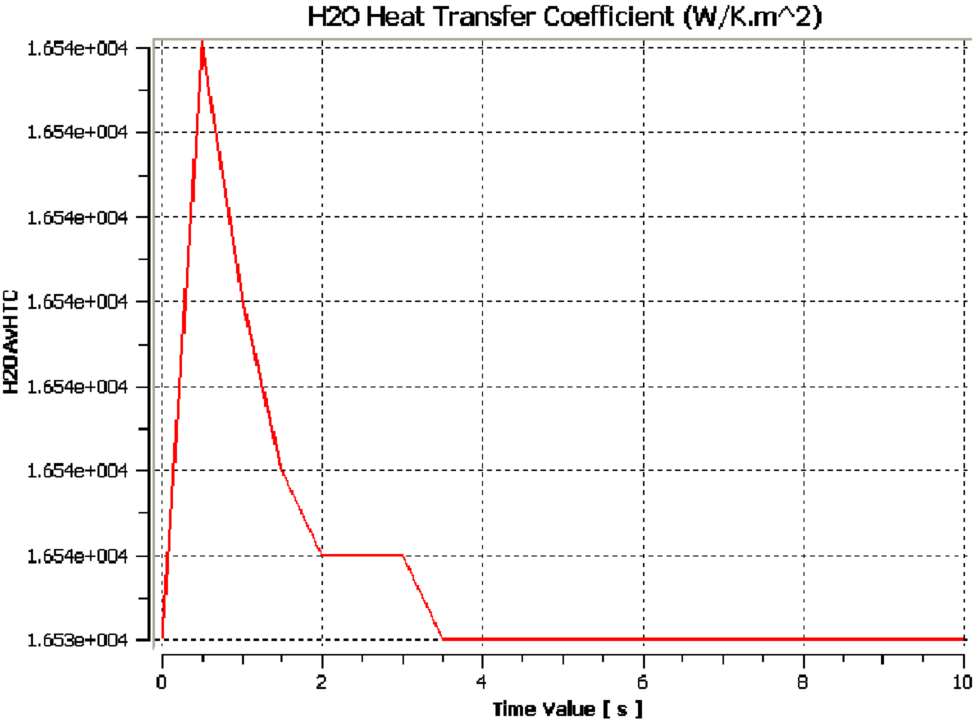

Fig. 8: H_2O Heat Transfer Coefficient as a Function of Time

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. The means of these distributions are 16,535 W/K.m^2, 175 W/K.m^2, 90°C, and 25°C respectively. One example of these distributions is shown in Fig. 9. The right vertical line on the graph represents the mean, while the left one represents the standard deviation.

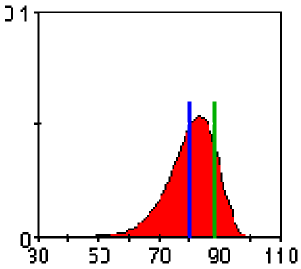

Fig. 9: Probability Distribution of H_2O-in Temperature

TRANSIENT FEM SIMULATION

The CFD results are mapped onto the corresponding FEM model. A transient FEM simulation is set-up to determine the maximum thermal stress, as shown in Fig. 10. Steady-state is reached approximately after two seconds. Maximum stress is used to predict model life based on fatigue analysis. As this case is a 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. 10: Thermal Stress Distribution in the Tube

FATIGUE LIFE

The transient thermal structural FEM analysis resulted in the maximum stress, which is used to predict the tube life based on fatigue analysis. Fatigue life is calculated using the material *S-N* curve in addition to the necessary correction factors mentioned earlier. Figure 11 shows the *S-N* curve used in the simulation. The Fatigue calculations are based on constant amplitude, zero-based, proportional loading.

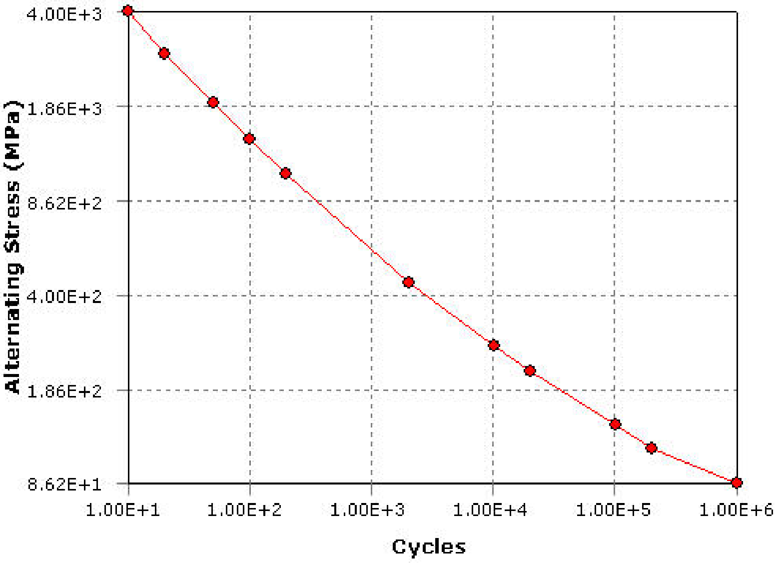

Fig. 11: Semi-Log *S-N* Curve of the Tube [ASME, 1998]

RELIABILITY ASSESSMENT

After performing the prescribed procedure successfully for one deterministic design point, the Integrated Simulation Tool (IST) shown in Fig. 1 is used to evaluate the reliability of the tube. The method is repeated 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 showed the most significant factors affecting thermal stress. These parameters include operational, geometrical, and environmental variables such as water temperature and heat transfer coefficient.

Latin Hypercube Sampling (LHS) is used in conjunction with Full Factorial Design (FFD) for the purpose of reducing computational cost. 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 in order to estimate the FEM output parameters. The reliability of condensate tube 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.

The formulation in Fig. 12 represents blocks connected by loops. These blocks represent the various tasks and iterations conducted by the software. The most important result of the MCS is the reliability relationship with time, which is shown in Fig. 13. This curve is obtained by integrating fatigue life PDF with time for various values then plotting the corresponding reliability values with time.

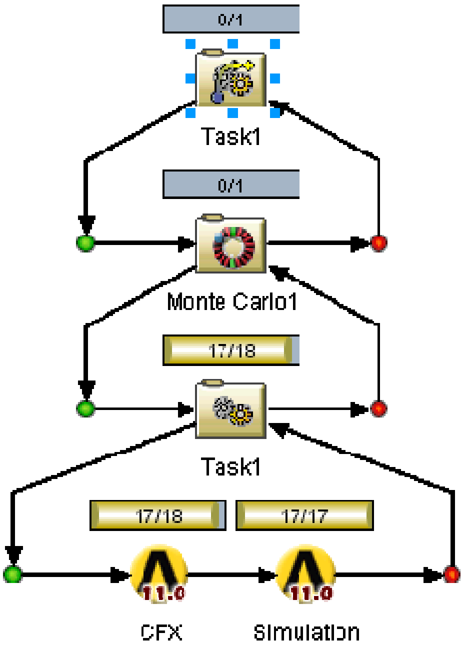

Fig. 12: Integrated Simulation Tool (IST)

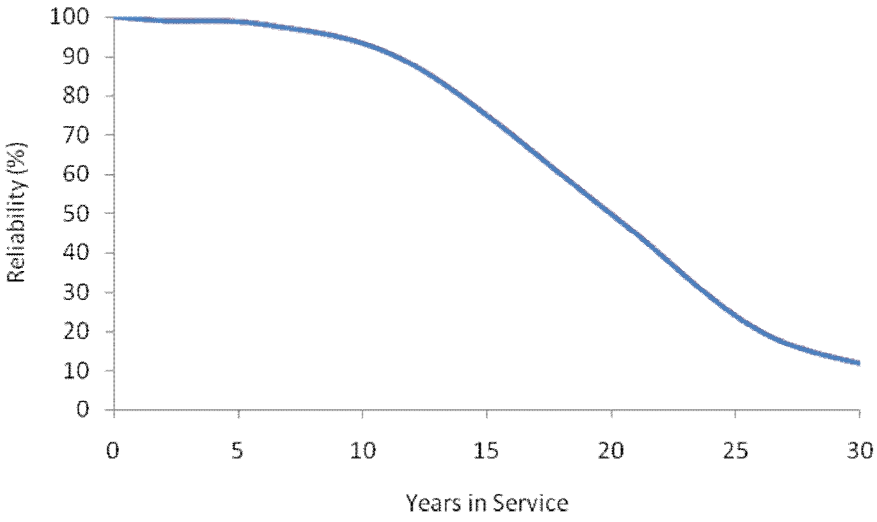

Fig. 13: Tube Reliability vs. Service Life

CONCLUSION

It can be seen that the reliability of the tube decreases rapidly after the first five years in service. That means maintenance action will be required before that time to maintain a satisfactory level of performance. The Integrated Simulation Tool (IST) is an efficient method to simulate the reliability of the condensate tube. It requires minimal mathematical manual work as it relies on high-level software interface that automates most of the tasks needed to perform the analysis. In the condensate tube, the necessity for transient simulation is evident. If other approaches that skip or approximate the transient analysis such as steady-state are used, they would have lead to erroneous results.

REFERENCES

Al-Habahbeh O.M., Aidun D.K., Marzocca P., and Lee H., (2011), Integrated Physics-Based Approach for the Reliability Prediction of Thermal Systems. Reliability & Safety, vol.5, no.2, pp.110-139.

Basaran, C. and Chandaroy, R., (2000), Using Finite Element Analysis for Simulation of Reliability Tests on Solder Joints in Microelectronic Packaging. Computers and Structures, vol.74, pp.215-231.

Constantinescu, A., Charkaluk, E., Lederer, G., and Verger, L., (2004), A computational approach to thermomechanical fatigue. Fatigue vol.26, pp.805–818.

Oberg, E. and McCauley, C.J., (2004), Machinery's Handbook: A Reference Book for the Mechanical Engineer. Industrial Press Inc., ISBN 0831127376, pp.207.

Shigley, J.E., Mischke, C.R., and Budynas, R.G., (2003), Mechanical Engineering Design. (Seventh Edition), McGraw-Hill Professional, pp.313, 319.

Structural steel fatigue data at zero mean stress, (1998), ASME BPV Code. Section 8, Div 2, Table 5-110.1.

Vandevelde, B., Gonzalez, M., Limaye, P., Ratchev, P., and Beyne, E., (2004), Thermal cycling reliability of SnAgCu and SnPb solder joints: a comparison for several IC-packages. IMEC, Kapeldreef 75, B-3001 Leuven, Belgium.

Yang, G., (2007), Life Cycle Reliability Engineering. John Wiley & Sons, Inc. pp.1, 232.