Effect of Water-Steam Boundary Oscillations on the Structural Integrity of Once-Through Steam Generator Tube

Yong Wan Kim,[a] Han Ok Kang,[a] Suhn Choi,[a] Keun Bae Park,[a] Sung Quun Zee,[a]
[a] Korea Atomic Energy Research Institute, 150 Dukjin-dong, Yuseong-gu, Daejeon, Korea, 305-353
E-mail : ywkim@kaeri.re.kr

1. Introduction

Once-through helical type steam generator is widely used for integral type reactor due to its compactness. Primary coolant flows outside of the tube and secondary coolant flows inside of the tube for most of once-through steam generators. The random oscillatory phenomena of the steam and water boundary conditions in the transition boiling zone have been observed in once-through steam generator tubes [1-3]. Movement of the boiling boundary results in the oscillations of tube wall temperature. This oscillation cause thermal stresses which may cause the fatigue failure of the tube. Characteristics of the oscillations are mainly influenced by the heat transfer coefficient, flow rate, and other design parameters. Effect of this oscillation on the thermal stress and fatigue damage of the tube was studied in this paper.

2. Method of Analysis

2.1 Statement of the problem

As shown in Figure 1, secondary coolants evaporate inside the tube. Water-steam boundary in the tube has an oscillating nature during operation of the steam generator. The frequency and the amplitude of oscillation are influenced by a lot of design parameters, such as flow rate, heat transfer coefficient, and geometry of the tube etc. Stress state of the tube is dominated by the wall temperature distribution of the tube.

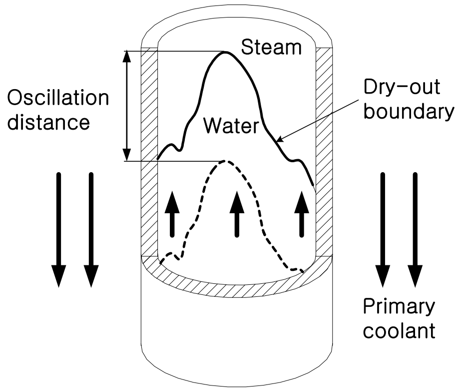


Figure 1. Schematic of the dry-out boundary oscillation.

Tube wall temperature can be calculated as follows:

$$\rho c \frac{\partial T}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left[kr\frac{\partial T}{\partial r}\right]$$

$$-k\left.\frac{\partial T}{\partial r}\right|_{r=R_i} = h_i(\tau)\left[T(R_i,\tau) - T_i\right]$$

$$-k\left.\frac{\partial T}{\partial r}\right|_{r=R_o} = h_o(\tau)\left[T(R_o,\tau) - T_o\right]$$

By using of tube temperature distribution, thermal stress can be evaluated from the following equations.

$$\sigma_r^T = \frac{\alpha E}{(1-\nu)r^2}\left[\frac{r^2+R_o^2}{R_i^2-R_o^2}\int_{R_o}^{R_i} rT(r)dr - \int_{R_o}^{r} rT(r)dr\right]$$

$$\sigma_\theta^T = \frac{\alpha E}{(1-\nu)r^2}\left[\frac{r^2+R_o^2}{R_i^2-R_o^2}\int_{R_o}^{R_i} rT(r)dr - \int_{R_o}^{r} rT(r)dr - r^2T(r)\right]$$

$$\sigma_z^T = \frac{\alpha E}{(1-\nu)}\left[\frac{2}{R_i^2-R_o^2}\int_{R_o}^{R_i} rT(r)dr - T(r)\right]$$

These equations have nonlinear nature due to nonlinear nature of the material coefficient and heat transfer coefficient. The analytic explicit solution can be obtained if constant heat transfer coefficient is assumed [4]. Finite element method was used in the present analysis to evaluate time-dependent distribution of the thermal stress. Primary coolant temperature and secondary coolant temperature calculated by Kang[3] have been used for the input of the present transient finite element analysis.

2.2 Finite element model

In order to obtain stress variation as a function of time, finite element program ABAQUS was used [5]. It has been assumed in the present analysis that the strain rate due to the thermal transient loading is much less than the strain rate caused by the stress wave propagation in the elastic body. The temperature distribution for each time step is obtained from the heat transfer analysis and the nodal temperature with a pressure loading is then used for the input of the stress analysis. Also, finite element analysis only with thermal loading has been carried out. In order to investigate oscillation frequency, analyses were done for 0.01 Hz, 0.1Hz, 0.5Hz, 1Hz, and 5Hz. Three sections along the tube were analyzed. Three separate 2-dimentsional analysis have been done for the end of the tube outlet, 1.5m from tube outlet, and 3m from tube outlet. Titanium alloy PT-7M material properties have been used for the thermo-mechanical transient finite element analysis.

3. Results and Discussion

Oscillation of the tube dry-out boundary has changed temperature distribution of the tube wall. Temperature variations at the inner wall and outer wall of the tube for three different locations are shown in Figure 2.

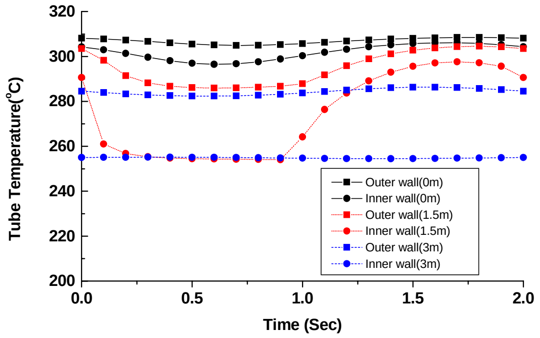
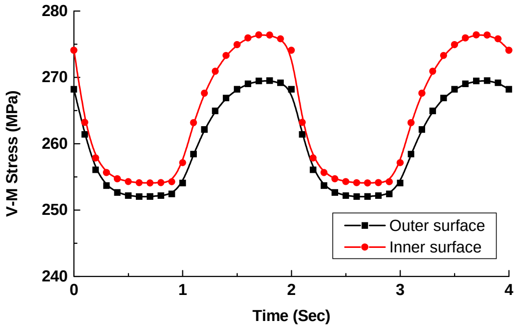


Figure 2. Temperature variation of the tube wall.

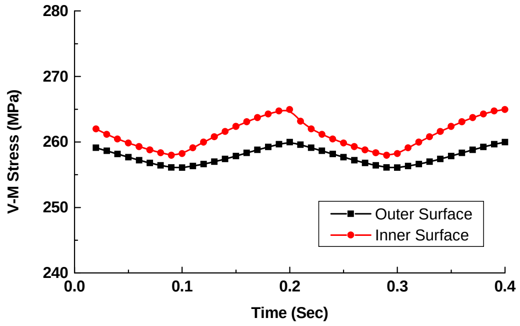
Thermal loading has shown greater influence on the stress variation than the pressure loading. Thermal stress variations was mainly caused three factors which are oscillation of coolant temperature, change of the heat transfer coefficient caused by phase change of the secondary coolant, and pulsation of the secondary coolant pressure.

Maximum stress has occurred at the inner side of the tube. Effect of oscillation frequency on the amplitude of the stress is shown in Figure 3. As the frequency increases, the amplitude of the stress variation has decreased. The tube does not have enough time to propagate heat across the tube wall in case of high oscillation frequency.

The maximum amplitude of principal stress difference (S_{alt} of ASME Sec. III) is 26.77MPa which is small enough comparing to allowable fatigue limit of titanium tube. However, it should be evaluated with other operation transients. The oscillation of the dry-out boundary should be considered to confirm structural integrity of the once-through steam generator tube although it is not necessary for conventional U-tube recirculation type steam generator.



(a)



(b)

Figure 3. Von-Mises stress variation of the tube during dry-out boundary oscillation. (a) oscillation period = 2 second(0.5Hz). (b) oscillation period = 0.2 second(5Hz).

4. Conclusion

The effect of the oscillation of the water-steam boundary on the structural integrity of the tube was studied. The movement of dry-out boundary resulted in comparatively high thermal stresses. However, it did have a significant effect on the lifetime of tube. As the oscillation frequency increases, the stress level has decreased. Unlike to U-tube recirculation type steam generator, thermal transient loading due to the oscillation of tube dry-out boundary shall be considered in the design stage to confirm structural integrity of the once-through steam generator tube.

Acknowledgement

This work has been performed under the nuclear research & development program sponsored by Ministry of Science and Technology of Republic of Korea.

REFERENCES

[1] I. Klevtsov, R. Crane, Random Thermal Stress Oscillations and Fatigue Life Estimation for Steam Generator Tubes, Journal of Pressure Vessel Technology, Vol.116, p. 110, 1994.

[2] T. Chiang, D. M. France, and T.R. Bump, Calculation of Tube Degradation Induced by Dry-out Instability in Sodium-Heated Steam Generators, Nuclear Engineering and Design, Vol.41, No.2 p.181, 1977.

[3] H.O. Kang, J.K. Seo, Y.W. Kim, J. Yoon, S.Q. Zee, A Design Guide Line for Stable Operation of SMART-P Once-Through Steam Generator, Proceedings of ICAPP'05, Seoul, 2005

[4] Y.W. Kim, J.I. Kim, and M.H. Chang, An explicit integral expression for the stress intensity factor of a semi-elliptic surface crack subjected to thermal transient loading, Int. J of Pressure Vessels and Piping, Vol 76, 631, 1999.

[5] ABAQUS/Standard User's Manual, HKS, Ver.6.2.