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Effects of Flow Density and Gap Velocity on Wear Depth of Steam Generator Tube

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1. Introduction

Turbulence excitation which is one of the main reasons of fretting-wear phenomena invokes the wear mechanism between a tube and its supports by small amplitude. Through the amplitude of turbulence excitation, the calculation of normal work rate has been performed to resolve fretting-wear problems. The analysis of fretting-wear needs nonlinear dynamic model. But this model is very complex and time consuming. Another approach proposed by M. Yetisir [1] is very useful to evaluate the fretting-wear. By using the energy method for wear analysis, this study investigates the effects of the flow density and the gap velocity on wear depth of steam generator tube. The flow density and the gap velocity are obtained from thermal-hydraulic analysis of the OPR 1000 steam generator. Fig. 1 shows the numerical procedure to perform the wear analysis of the steam generator tube.

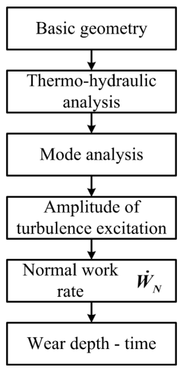

Figure 1. Flow chart for analysis

2. Methods and Results

2.1 Effective mass and mode analysis

The effective mass can be determined from primary and secondary side flow density and the density of tube metal as below.

$$m = m_t + m_{pf} + m_a \ , \quad \text{where } m_a = C_m \rho_s \frac{\pi d^2}{4} \tag{1}$$

, where d and ρ_s are tube diameter and secondary side density respectively. m_t, m_{pf} and m_a are the mass per unit length for tube, primary coolant water inside the tube and the added mass respectively. C_m is the coefficient of added mass [2].

The natural frequency and mode shapes for single span tube can be expressed by

$$f_i = \frac{\lambda_i^2}{2\pi L^2}\left(\frac{EI}{m}\right)^{1/2} \tag{2}$$

$$\tilde{y}_i = \cosh\frac{\lambda_i x}{L} - \cos\frac{\lambda_i x}{L} - \sigma_i\left(\sinh\frac{\lambda_i x}{L} - \sin\frac{\lambda_i x}{L}\right) \tag{3}$$

$$\tilde{y}_i = \sin\frac{i\pi x}{L} \tag{4}$$

Eq. (3) and eq. (4) are mode shape functions associated with a clamped-clamped(pinned) condition, and a pinned-pinned condition, respectively.

2.2 Amplitude of turbulence excitation

To calculate the wear depth by using the energy method of modified Archard formula, it needs the amplitude of turbulence excitation. The value can be obtained from the information of mode analysis and thermal hydraulic data.

The amplitude of turbulence excitation recommended in the ASME code section III Appendix N [3] is expressed by

$$Y_{rms} = \left\{\sum_i \frac{LG_f(f_i)\phi_i^2(s)}{64\pi^3 M_i^2 f_i^3 \zeta_i}\right\}^{0.5} \tag{5}$$

, where L is the span length, and i is the i -th eigen mode, ϕ_i is the normal component of mode shapes, ζ_i, the damping ratio, of 1.5% is applied for conservative analysis. M_i and G_f are the modal mass and the power spectral density due to the random turbulence excitation respectively, and J_{ii} is joint acceptance which reflects the relative effectiveness of the forcing function to excite the *i*-th vibration mode.

2.3 Normal work rate and volume wear rate

From the Archard formula, the volume wear rate is proportional to the normal work rate as below

$$\dot{V} = K\dot{W}_N \tag{6}$$

, where K is experimental fretting wear coefficient. From experiments, the value of $14\times10^{-15}/Pa$ for the fretting wear coefficient is adopted.

Normal work rate can be indicated in terms of shear work rate and the coefficient of friction [1]

$$\dot{W}_N = 16\pi^3 mLf_i^3 Y_{rms}^2 \zeta_i / \mu \qquad (7)$$

Dissection method is applied to the multi-span problem.

2.4 Wear depth evaluation

Most of the wear topology at the U-bend region show the flat wear as shown in Fig. 2. The wear-out depth *h* for the flat wear topology can be expressed as below

$$h = \frac{d(1-\cos\theta)}{2}, \text{ where } \theta = \left(\frac{6V}{d^2 w}\right) \qquad (8)$$

, where *w* is the width of tube support.

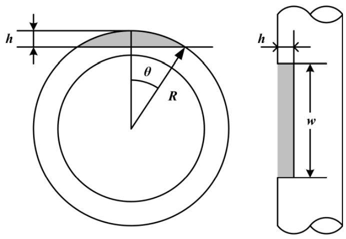

Figure 2. Wear topology (flat wear)

2.5 Effects of flow density and gap velocity

The calculated results of the normal work rates with the variations of the secondary side density and the gap velocity are tabulated in Table 1. ρ_w and ρ_s are primary and secondary side density respectively. From the Table 1, it is shown that two times increase of flow density leads to 4 times increase of normal work rate, and it also increases 15 times of normal work rate due to 2 times increase of gap velocity.

Table 1. The prediction of work-rate for 2-span tube

f_i (Hz)	$\overline{Y_{rms_{\max}}}$	ρ_ω (Kg/m^3)	ρ_s (Kg/m^3)	V_n (m/s)	$\dot{W}_N$ (w)
36.99	1.03e-02	700	200	1	5.13e-05
37.95	5.23e-03	700	100	1	1.35e-05
35.28	2.02e-02	700	400	1	1.86e-04
36.99	2.58e-03	700	200	0.5	3.20e-06
36.99	4.13e-02	700	200	2	8.20e-04

The normal work rates with respect to the flow density and the gap velocity are shown in Fig. 3 ~ Fig. 4 respectively. The wear work rate increases enormously due to increase of the normal gap velocity and the secondary side flow density. From these results it can be concluded that the flow density and the gap velocity would be dominant parameters to the normal work rate.

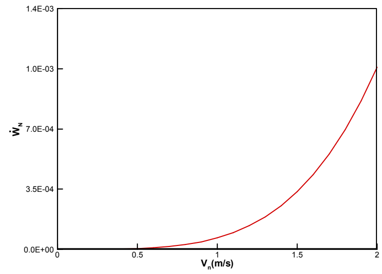

Figure 3. Normal work rate vs V_n

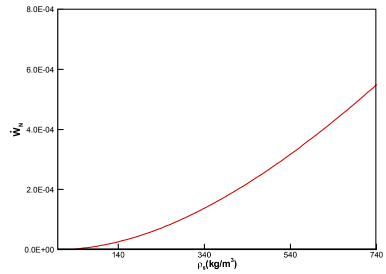

Figure 4. Normal work rate vs ρ_s

3. Conclusion

Tube wall thickness losses caused by the turbulence-induced interaction between steam generator tube and its support were predicted by using the modified Archard formula and work rate concept.

From the calculation results, both the flow density and the normal gap velocity around the steam generator tube are the dominant parameters for the wear-out rate of tube thickness. The wear work rate increases enormously due to increase of the normal gap velocity and the secondary side flow density.

Most of the tube wears are detected at the flow exit region of U-bend tube. Because the hot side region has lower secondary density and higher normal gap velocity in nuclear steam generator, the normal gap velocity has a role of dominant wear parameter. But the cold side region has opposite trends against the hot side region. It turns out that the wear phenomena would not be localized around the hot side or the cold side at the flow exit region of U-bend tube. These results agree very well with ECT reports of steam generator tube.

REFERENCES

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