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Development of Wear Prediction Model for Steam Generator Tubes

Daeyoep Kwon [a], Heejae Shin [b], Young-Jin Oh[b], Chi Bum Bahn [a*]
[a]*School of Mechanical Engineering, Pusan National Univ., Busan, 43241*
[b]*Smart Convergence Research Department, KEPCO E&C, Gimcheon, 39663*
[*]*Corresponding author: bahn@pusan.ac.kr*

1. Introduction

In the steam generator (SG), fretting wear of SG tube is caused by flow induced vibration (FIV) between the SG tube and tube support plate (TSP). The wear damage is an important aging mechanism of SG in nuclear power plants. The Archard model [1] is commonly used for predicting SG tube wear and determining wear coefficients, as it presents volumetric wear rate as a linear function of vibration work-rate for SG tubes. However, wear growth rate of SG tube is usually not linear. Moreover, SG tube and TSP interact in complex ways through sliding and impact. As a result, predicting wear growth can be more difficult.

Fricke [2] developed an impact wear model. Lewis [3] and Guo [4] proposed an impact-sliding wear model by combining Archard model with the impact wear model. In this study, wear experimental data [5] are re-analyzed considering non-linear wear progression features. And a new impact-sliding model was proposed to predict the wear rate of SG tubes.

2. Wear Prediction Models

2.1 Archard Model

The Archard wear model [1] used to describe sliding wear and is based on the theory of asperity contact, which is shown in Eq. (1)

$$V = \frac{kFS}{H} \tag{1}$$

where V is the wear volume, F is the normal load, S is the sliding distance, H is the hardness of material, k is the sliding wear coefficient.

2.2 Work-rate Model

The work-rate $\dot{W}$ is defined as the product of sliding distance and normal force, which was proposed by Frick [6] and is shown in Eq. (2)

$$\dot{W} = \frac{1}{t}\int F_n\, ds \tag{2}$$

where t is the total time, F_n is the normal contact force.

Then, the wear volume rate $\dot{V}$ can be expressed as

$$\dot{V} = k\dot{W} \tag{3}$$

2.3 Impact Wear Model I (Fricke)

An energy-based impact wear model proposed by Fricke [2], which is shown in Eq. (4)

$$V = KNe^n \tag{4}$$

where K is the impact wear coefficient, N is the number of impact cycles, n is the exponent of model, and e is the impact energy, can be expressed as

$$e = \frac{1}{2}mv^2 \tag{5}$$

where m is the effective mass and v is the impact velocity.

2.4 Impact Wear Model II (Engel)

Another impact wear model was proposed by Engel [7], which is shown in Eq. (6)

$$V = KN\sigma^9 \tag{6}$$

where σ is the contact pressure.

2.5 Impact-sliding Wear Model I (Lewis)

The Archard model (shown in Eq. (1)) and Frike model (shown in Eq. (4)) only consider the influence of sliding or impact. The impact-sliding wear model proposed by Lewis [3], which is shown in Eq. (7)

$$V = \left(\frac{kF_nS}{H} + KNe^n\right)\left(\frac{A_i}{A}\right)^j \tag{7}$$

where F_n is the normal impact force, n is the impact wear exponent, A_i is the initial elastic contact area, A is the contact area after N cycles, and j is the exponent of contact area ratio.

2.6 Impact-sliding Wear Model II (Guo)

Another energy-based impact-sliding wear model proposed by Guo [4], which is shown in Eq. (8)

$$V = \frac{kF_nS}{H} + KN\Delta E \tag{8}$$

where ΔE is the average impact energy loss.

The energy loss during impact process can be expressed as

$$\Delta E = \frac{1}{2}mv_i^2 - \frac{1}{2}mv_{re}^2 \tag{9}$$

where m is the tube mass, v_i is the impact velocity, v_{re} is the rebound velocity.

2.7 Proposed New Impact-sliding Wear Model

The Guo model and Lewis model presented above are both impact energy-based wear models. However, measuring impact velocity is difficult. Therefore, a new model has been proposed here, which is easier to apply for predicting wear on SG tubes. This impact-sliding wear model by combines the Work-rate sliding wear model and the Engel impact wear model.

$$\dot{V} = k\dot{W} + K\sigma_{impact}^n\dot{N} \tag{10}$$

where $\dot{W}$ is the sliding work-rate, k is the sliding wear coefficient, K is the impact wear coefficient, σ_{impa}^{n} is the contact pressure.

The contact pressure can be expressed as

$$\sigma_{impact} = \frac{F_n}{A_{contact}} \quad (11)$$

where $A_{contact}$ is the contact area when N cycles.

3. Model Validation Procedure

3.1 Selection of Wear data

The experimental data used in this study were obtained from an EPRI report [5]. The report used carbon steel as the TSP material and Alloy 600 and Alloy 690 as the tube materials. The wear test system configuration is shown in Figure 1, and the wear test was conducted in a high-temperature and high-pressure environment.

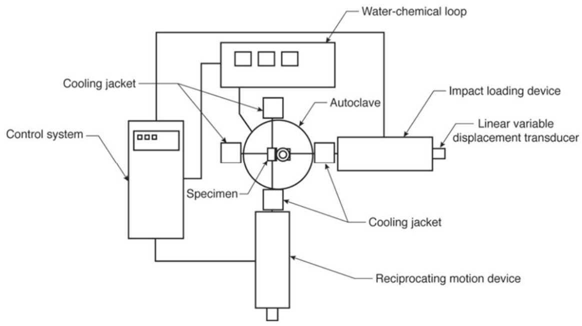

Fig. 1. Configuration of the wear test system [5]

3.2 Calculation of Wear Depth

The fig. 2. (a) shows example of a wedge-shaped worn tube surface. The geometrical relationship between wear volume and wear depth for tube can be expressed as

$$V = \tan\theta\left(aR^2 - \frac{a^3}{3} - R^2(R-h)\sin^{-1}\frac{a}{R}\right) \quad (12)$$

where, $a = \sqrt{2hr - h^2}$

$$V = \frac{L}{h}\left(aR^2 - \frac{a^3}{3} - R^2(R-h)\sin^{-1}\frac{a}{R}\right) \quad (13)$$

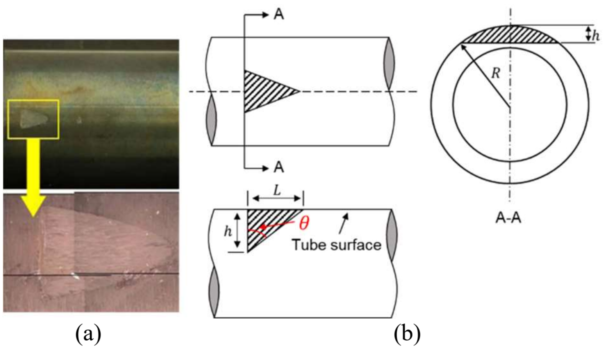

Fig. 2. (a) The photo of worn tube surface in wear test [5], (b) Schematic of wedge-shaped wear scar

3.3 Calculation of Wear Growth

Fig. 3 shows the flow chart developed using Python for calculating the wear volume of the wear specimen.

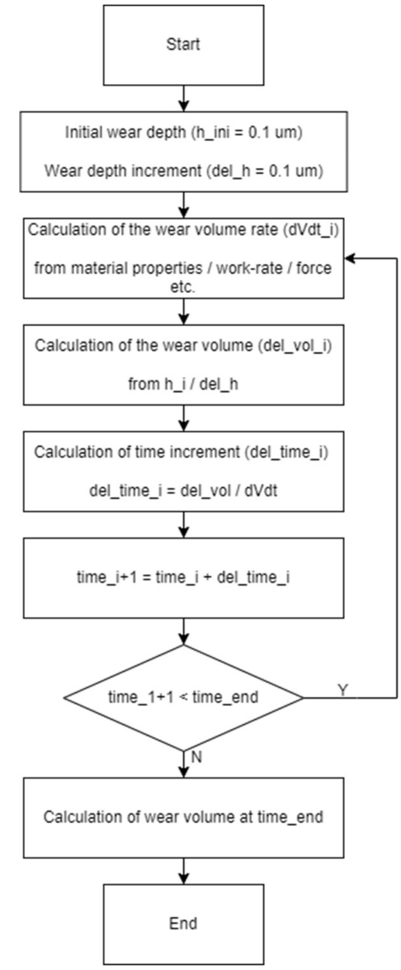

Fig. 3. Flow chart for calculation of wear volume

3.4 Simulation of Wear Test

Fig. 4. shows finite element (FE) model of impact-sliding wear test system. This model will be used to evaluate sliding work-rate and contact force.

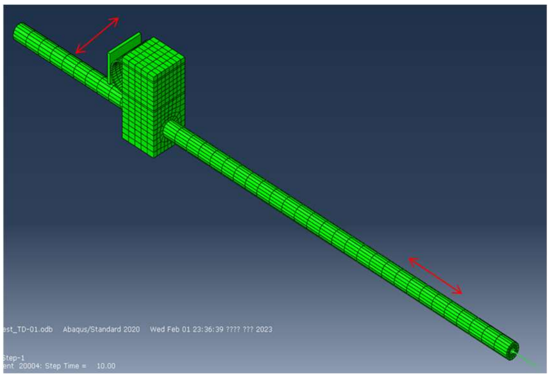

Fig. 4. Wear Test System Finite Element Model

4. Conclusions and Future Work

Based on existing wear test data, the study analyzed the shape of the worn surface and proposed wear volume formulas for each type of wear shape. Additionally, we proposed an impact-sliding wear model that can be easily applied to SG tubes and developed a FE model of the wear test system. Moving forward, we will evaluate the proposed new impact-sliding wear model using sliding work-rate and contact force obtained through the FE model.

ACKNOWLEDGEMENTS

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