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Predicted Wear on the Tube Outside Surface due to Foreign Object in the Secondary Side of Steam Generator

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1. Introduction

It is necessary to evaluate the effects of foreign objects on steam generator tubes and to use this information to take appropriate safety precautions to prevent nuclear accidents. Foreign objects may include loose parts from the feed water system and items lost by workers during o/h, and may flow into the secondary side of steam generators during operation. A foreign object could damage steam generator tube walls if there is relative motion between the tube and the foreign object. This is especially true for foreign objects that land on the tube sheet because the velocity of cross flow, which creates a contact force between the tube and foreign object, is relatively high there [1,2]. During steam generator overhauls, foreign objects are detected by non-destructive methods such as the visual test and/or the eddy current test. Confirmed foreign objects should be removed for nuclear safety.

The Foreign Object Search and Retrieval System (FOSAR) can be used to remove foreign objects from the steam generators with a square tube array. However, the FOSAR cannot be used (or can be used in only a very restricted area, such as the outside of the tube bundle) in the steam generators with a triangular tube array. In order to continue nuclear power plant operations without removing foreign objects, the integrity of the steam generator tube must be verified. This paper introduces a practical method developed to evaluate the effects of foreign objects detected on tube sheets in the secondary sides of steam generators.

2. Methods and Results

2.1 Thermo-Hydraulic Analysis

Information about the flow properties of the secondary sides of steam generators is required to assess the flow-induced vibration of steam generator tubes. Moreover, these data are essential to calculate the contact forces between tubes and foreign objects. To identify the flow-induced vibration of steam generator tubes, the mixed flow velocity, mixed flow density, and void fraction are needed.

The data obtained directly from ATHOS3 are the mixed flow velocity, mixed flow density, pressure, enthalpy, quality, void fraction, coolant temperature, and tube side temperature.

2.2 Establishment of Zones

It is possible to choose either a rectangular or cylindrical polar coordinate system in ATHOS3. Considering that the cross-sectional shape of a steam generator is round, it is more convenient to use the cylindrical polar coordinate system (see Fig. 1). However, the row-column numbering system, which is similar to the rectangular coordinate system, is preferable in the operation of nuclear power plants. Therefore, a zonal approach (see Fig. 2 and 3) based on the rectangular coordinate system was introduced in order to manage the thermo-hydraulic database[1,2].

This zonal concept has the advantage that a tube at the boundary of a specified zone has unique physical properties because the lines between zones do not cut a tube. A tube in the center of a zone is chosen as a representative tube. The flow properties around a representative tube are assumed to be the flow properties inside the zone that contains this representative tube.

2.3 Effective Mass for Modal Analysis

Most of the foreign objects found in the secondary sides of steam generators are detected on the tube sheet, and foreign object contact with tubes is made between the tube sheet and the first tube support structure (such as the flow distribution baffle) or the first tube support plate. Therefore, information about the modal shape function and the natural frequency of the dominant mode at the first tube span on the tube sheet is required to evaluate tube wear caused by relative motion between the tube and foreign object. In order to obtain the data for the modal analysis, the effective mass distribution per unit length of the tube is required.

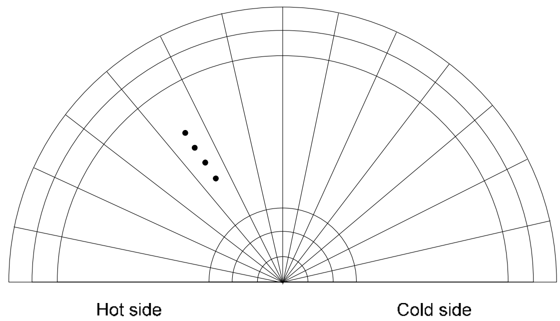

Fig. 1. Plan view of the computational domain for thermal-hydraulic analysis of the steam generator.

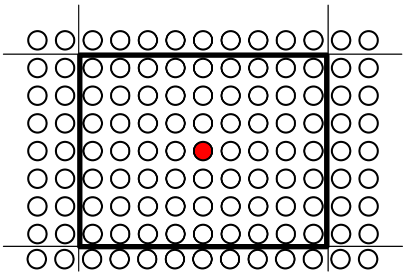

Fig. 2. Zonal boundary and representative tube for square tube array

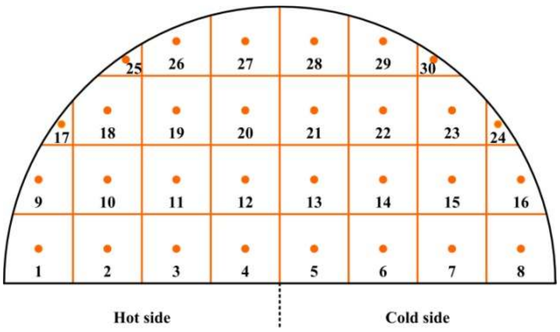

Fig. 3. Zonal approach for steam generator section.

2.4 Simplifying Tube Vibration Analysis

Numerical methods such as the finite element method (FEM) are very powerful for modal analysis. ANSYS, which is a commercial computer program based on FEM, was used to carry out the modal analysis of the entire U-tube in this paper. A steam generator tube supported by a tube sheet, support plates (or eggcrates), and anti-vibration bars (or bat-wings) can be idealized as multi-span beams with many support points. Because the vibration of a multi-span beam is very complicated, finding the dominant mode at the specified tube span is very tedious and time-consuming. The mode shape and natural frequency in the span between the tube sheet and the first support structure are required to evaluate the effects of foreign objects. Therefore, the dissected tube approach concept is introduced in this paper to simplify mode analysis.

The dissected tube approach concept is utilizing the exact mode of a single span beam instead of finding the dominant mode in the specified span for an entire U-tube. The effectiveness of the dissected tube approach concept is shown by comparing its results with those of ANSYS analysis (see Fig. 4).

2.5 Wear Evaluation

The worn-out volume can be calculated using the modified Archard formula. In the modified Archard formula, the worn-out volume is proportional to the wear work, which equals the contact force times the sliding distance. The modified Archard formula is written as follows:

$$V = KF_n l \, , \qquad (1)$$

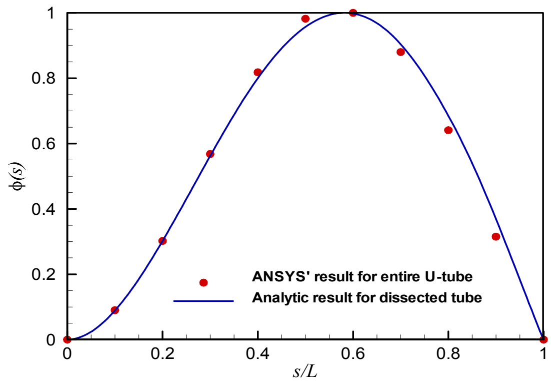

Fig. 4. Comparison of mode shapes between the results of ANSYS and dissected model.

where V is the wear volume, K is the wear coefficient, F_n is the contact force, and l is the sliding distance. The proportional coefficient between the worn-out volume and work can be obtained from fretting wear experiments.

3. Conclusions

A dissected tube model and a method for predicting wear depth were introduced in order to predict foreign object wear on the tube sheets of steam generators. This simplified vibration model is based on the zonal approach concept and single span mode analysis. The adoption of a zonal approach concept dramatically reduces the number of tubes that must be analyzed from thousands of tubes in a steam generator to selected tubes out of 30 zones. The center tube in each zone can be treated as a representative tube for all the tubes inside the zone during modal analysis because the variations of the feed water velocity and effective mass are not high, and changes in the effective mass do not affect the related frequency.

An advantage of using the dissected tube model is that the exact solution is discoverable. Comparing the results of the dissected tube model with those of the multi-span analysis, the mode shapes are almost the same and the differences in natural frequencies are below 5 % relative error. Therefore, the dissected tube model analysis is effective at producing the data required to evaluate fretting wear caused by foreign objects.

REFERENCES

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