CFD Analysis of Random Turbulent Flow Load in Steam Generator of APR1400 Under Normal Operation Condition

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1. Introduction

Regulatory guide 1.20 revision 3 of the Nuclear Regulatory Committee (NRC) modifies guidance for vibration assessments of reactor internals and steam generator internals. The new guidance requires applicants to provide a preliminary analysis and evaluation of the design and performance of a facility, including the safety margins of during normal operation and transient conditions anticipated during the life of the facility. Especially, revision 3 require rigorous assessments of adverse flow effects in the steam dryer cased by flow-excited acoustic and structural resonances such as the abnormality from power-uprated BWR cases.

For two nearly identical nuclear power plants, the steam system of one BWR plant experienced failure of steam dryers and the main steam system components when steam flow was increased by 16 percent for extended power uprate (EPU). The mechanisms of those failures have revealed that a small adverse flow changing from the prototype condition induced severe flow-excited acoustic and structural resonances, leading to structural failures. In accordance with the historical background, therefore, potential adverse flow effects should be evaluated rigorously for steam generator internals in both BWR and Pressurized Water Reactor (PWR). The Advanced Power Reactor 1400 (APR1400), an evolutionary light water reactor, increased the power by 7.7 percent from the design of the 'Valid Prototype', System80+. Thus, reliable evaluations of potential adverse flow effects on the steam generator of APR1400 are necessary according to the regulatory guide.

This paper is part of the computational fluid dynamics (CFD) analysis results for evaluation of the adverse flow effect for the steam generator internals of APR1400, including a series of sensitivity analyses to enhance the reliability of CFD analysis and an estimation the effect of flow loads on the internals of the steam generator under normal operation conditions.

2. Mesh Dependency Test and Sensitivity Analysis

Before performing the CFD analysis, the territory of the analysis should be determined for effective CFD analysis under limited computational resources because an accurate simulation of the effect of boiling phenomena on the u-tubes is practically impossible using CFD codes. It is more convenient to use a conservative assumption and design requirements calculated by design codes.

Thus, the territory of CFD analysis is confined to the upper regions of internals, above steam separators, because this study focuses on the evaluation of adverse flow load in the upper internals of steam generator such as steam dryer failure in the case of BWR. The flow conditions on the separator outlets and steam outlet are treated to the boundary condition using design data. Also, steam dryer vane assembly is assumed by the porous media model to simulating the pressure drop of the main steam flow. In Fig. 1, a grid model for the CFD analysis is presented.

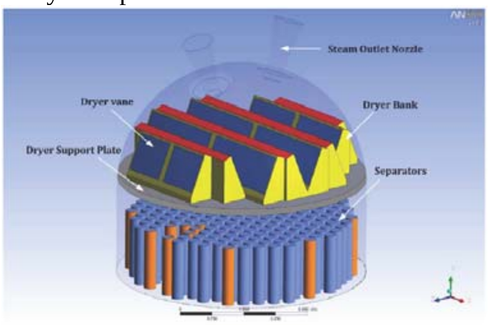

Fig. 1. CFD grid model and upper internals of steam generator

2.1 Numerical models & Boundary Conditions

To obtain an effective and reliable CFD analysis methodology, a series of mesh dependency tests were performed, as presented in Table 1.

An accurate estimation of the flow load on the internals is determined by an accurate prediction of the flow velocity, and thus the mesh dependency test is produced by comparing a tendency of mass flux and averaged flow velocity in each dryer bank under the varied mesh distributions. In addition, the k-w model and shear stress transport (SST) model are used to reveal the sensitivity of the turbulence models.

Table 1: Sensitivity analysis test matrix

Cases	# of nodes (Million)	First layer thickness (m)	# of layer	Remarks
Case1	5	NA	NA	First layer sensitivity
Case2		0.01	5	
Case3		0.005	7	
Case4		0.0025	10	
Case5	11.4	0.005	7	Total mesh distribution sensitivity
Case6	43.9			
Case7	63.4			
Case8	85.7			

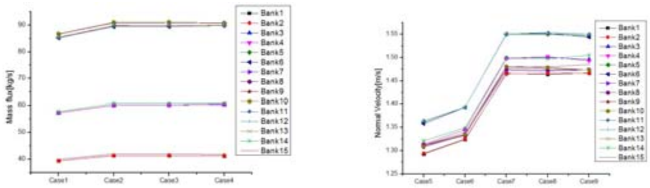

Fig. 2. Mesh dependency test results
(Left : Averaged velocity versus first layer thickness, Right : Averaged velocity versus total mesh distribution)

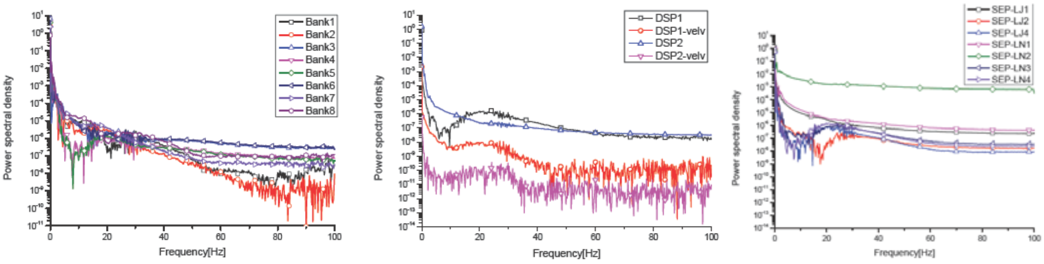

Fig. 3. Transient analysis results for power spectral density of random turbulent flow load
(Left : Bank plates, Middle : Dryer support plate, Right :Max. load on the separator outer wall)

As shown in Fig. 2, case 3, the first layer thickness and number of layers of mesh are independent of the calculated averaged velocity, passing through each dryer bank section; case8 with total mesh distribution is not affected by the calculated results. Therefore, transient analysis is performed using these mesh conditions under normal plant operation conditions.

In transient analysis, detached eddy simulation (DES) model is adopted for simulating the random turbulence fluctuation. The DES model can capture the unsteady flow structure of the separated shear layer by resolution of the developing turbulent structure. Normal operation conditions of plant are applied as shown in Table 2 and initialization of transient calculation is used for an initial guess of the flow field which is obtained from the steady-state calculation results.

Table 2: Initial condition

Condition	Value	Remark
Reference pressure	1000 psi	
Temperature	550°F	Isothermal
Total inlet mass flow rate	2493.9 lb/s	Uniform inlet

3. Calculation results

From the streamline and vector contour of the main steam flow, most of the injected steam flow from the separator outlet is found to directly collides with the dryer separator support plate (DSP). After passing through the DSP, most of the steam flow is divided into each dryer bank section and pressure of the steam flow is found to drop due to the porous media of the dryer vane. The steam flow flowing from the dryer bank is gathered at the steam dome and finally discharged to the main steam line via two steam outlet nozzle.

A small amount of the injected steam flow from the separator outlet cannot be delivered to the dryer bank and is re-circulated along the outer wall of steam generator. This secondary flow of the main steam has an effect on the flow load at the bottom of the separator outer wall.

As shown on the right in Fig. 3, maximum power spectral density (PSD) of pressure is measured at the bottom of the outer separator wall at about 10^{-3}. Also, the bottom of the DSP (DSP1), is directly affected by the injected steam turbulent flow, and is found to have a maximum PSD. In the case of the bank outer plate, PSD values are relatively lower than those for DSPs and separator walls because the turbulent flow intensity around the bank wall is attenuated while that flow passes through the steam generator internals, such as the dryer vane assemblies.

4. Conclusions

According to reg. guide 1.02 revision 3, a comprehensive vibration assessment program must be performed to reveal adverse flow effect on the upper internals of steam generator using CFD methodology. First, a mesh dependency test is performed to determine the standard mesh distribution, which is independent of the analysis results.

Under plant normal operation conditions, the effects of pressure spectral density of the steam turbulent flow on the internals, which are affected by highly turbulent flow load, is estimated. In the case of the separator, especially the bottom section of the outer wall, the maximum PSD value is measured, which originates from the secondary flow. These calculated results for the turbulent flow loads will be applied to the structural analysis to predict the safety margin of the structural integrity.

REFERENCES

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[2] T.J. Park, Moisture Separation Performance for APR+ SG Dryer Assembly, Doosan Heavy Industries, 2010