Root Cause Analysis of SI Line-Seated Thermal Sleeve Separation Failures Occurred at PWR Plants

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1. Introduction

At conventional pressurized water reactors, a thermal sleeve (named simply 'sleeve' hereafter) is seated inside the nozzle part of each safety injection (SI) branch pipe to prevent and relieve potential excessive transient thermal stress in the nozzle wall when a cold water is injected during the safety injection mode Recently, mechanical failures that the sleeves are separated from the SI branch pipe and fall into the connected cold leg main pipe were occurred in sequence at Yonggwang units 5 and 6 and Ulchin unit 5 [1]. There were many activities and efforts to figure out the causes of those failures with experts' reasoning, but the proposed causes were derived from superficial views rather than physically concrete grounds or analysis results. The prerequisites to find out the root causes of failure mechanism will be to identify the flow situation in the pipe junction area connecting the cold leg with the SI pipe and to know the vibration characteristics of sleeves.

This paper investigates the flow field in the pipe junction thru a numerical simulation and vibration characteristics of thermal sleeves thru a modal analysis, from which the root causes of sleeve separation mechanism are analyzed.

2. Problem and analysis model

The pipe structure and flow area to be analyzed in this study is shown in Fig.1. The flow field is simulated numerically for the two cases of reactor operation. One is the reactor normal operation condition with the main coolant mean flow velocity of 11.65 m/sec, and the other is the reactor emergency operation condition of safety injection with a flow velocity of 3.0 m/sec and the main coolant mean flow velocity of 1.0 m/sec [2].

Fig. 1 Schematic geometry of thermal sleeve and nozzle.

Concerning the actual location of sleeve inside the nozzle part of SI line, some visual inspections supports the fact that it can be different from the original design due to imperfect dimension, use of unsuitable material, or under-qualified fabrication and installation of sleeve. In this regard, both the intact case where the sleeve is seated on the SI pipe as designed and an unusual case where it is drooped by 20mm in the downward direction. The major parameters affecting the potential separation of sleeves are expected to be the vortex-induced-fluid pressure gradient and shear force acting on the sleeves, annular gap velocity, and modal characteristics. Therefore, the fluid force components acting on sleeve and the gap velocity of the annular flow between the thermal sleeve and the SI pipe are predicted in this study.

3. Flow analysis model

The Reynolds averaged governing equations for conservation of mass, momentum, energy, and turbulent quantities for the present problem in a Cartesian coordinate system can be expressed as in reference [3]. The main coolant flow and/or safety injection flow are simulated using the standard k–ε turbulent model. The wall function method is used for the tube wall boundary conditions and no slip and adiabatic boundary conditions are assumed for inner wall surfaces of both pipes. The flow fields are simulated using the general purpose computational fluid dynamics code CFX-5.6 [4] employing the element based finite volume modeling. To solve the problem, the spatial domain of SI pipe flow field including the sleeve is discretised into hexahedral finite control volumes using a mesh so as to make a grid arrangement with fine meshes of which either surface is parallel to the solid surfaces, while the remaining domain of main coolant flow field is discretised into tetrahedral volume element.

4. Modal analysis

To investigate the vibration characteristics of the thermal sleeve, modal analyses are performed using a commercial computer code ANSYS 8.1 [5]. The boundary condition at the 329.1 mm from the bottom of the sleeve is fixed. Also, to simulate the sleeve separated from the nozzle and being in contact with the build-up pads as shown in Fig. 1, several nodes are simply supported at the bottom of the sleeve. The Block Lanczos method [6] is used for the eigenvalue and eigenvector extractions to calculate 60 natural frequencies. It uses the Lanczos algorithm where the Lanczos recursion is performed with a block of vectors. The effect of coupling between the thermal sleeve structure and surrounding fluid is taken into consideration in the modal analysis.

5. Results and discussion

Typical numerical calculation results are displayed in Figs 2-5. Fig. 2 is the velocity vectors on the half symmetry plane of solution domain. An enlargement of the local region of thermal sleeve skirt being exposed to the main coolant flow is shown in Fig. 3 from which the existence of vortices in the SI branch pipe is identified. Figs. 4 and 5, respectively show the streams for both cases of normal and safety injection flow conditions, from which it can be seen that the present simulations are physically plausible.

On the basis of the numerical analysis results, the flow-induced force components acting on the sleeve wall surface in the longitudinal direction F_Z and in the two radial directions crossing each other at right angle F_X and F_Y have been calculated for all of 4 cases made by the combination of 2 different flow conditions and 2 different sleeve seating conditions. For the case of normal flow condition regardless of sleeve location, the sleeve is lifted upward and is pulled inward in the radial direction by a relatively large amount of force to be separated from the fixed or hinged circumferential support groove line, which is made by the method of local explosive expansion, while for the case of SI flow condition, there is no significant force exerting on the thermal sleeve except the fact that some force acts on the thermal sleeve to pull down it in the SI flow direction. Comparing the force components for both cases of sleeve seating location which are either seated as designed or drooped by 20 mm downward in any reasons, the force pulling the sleeve inwards increases by around two times, while the radial force decreases considerably during the SI mode.

Modal analyses for several kinds of finite element models are performed and some typical cases of the mode shapes calculated for simply supported condition are shown in Fig. 6. At the bottom of the sleeve, the smaller gap makes larger effective mass leading to a decrease in frequency. After the sleeve is separated from the nozzle part of SI pipe, the frequencies decrease significantly especially for lower circumferential modes.

6. Conclusion

The fluid force and modal characteristics which may lead or contribute to separate thermal sleeves inside safety injection branch pipes at PWR plants from their original seating locations were identified by performing both flow simulation in the SI pipe junction and modal analysis of thermal sleeve. To describe the failure mechanism of sleeve separation more rigorously, further detailed investigation is needed.

REFERENCES

[1] Korea Institute of Nuclear Safety, Thermal Sleeve Separation Events at YGN Units 5&6 and UCN Unit 5, a Content of Major Issues Concerning Reactor Systems and Components Safety Regulation, posted on the KINS Web at http://www.kins.re.kr/equipment/equ04/equ04x00v.asp.

[2] Korea Electric Power Corp., Yonggwang Units 5&6 Final Safety Analysis Report.

[3] J. C. Jo, Y. H. Choi, and S. K. Choi, "Numerical Analysis of Unsteady Conjugate Heat Transfer and Thermal Stress for a Curved Piping System Subjected to Thermal Stratification," ASME, J. PVT, Vol. 125, pp. 467-474, 2003.

[4] CFX-5.6 User Manual, Oxfordshire, UK, 2003.

[5] ANSYS Structural Analysis Guide, Houston, 2004.

[6] Grimes, R. G., J. G. Lewis and H. D. Simon, "A Shifted Block Lanczos Algorithm for Solving Sparse Symmetric Generalized Eigenproblems," SIAM Journal on Matrix Analysis and Applications, Vol.15, No.1, pp.228-272, 1994.

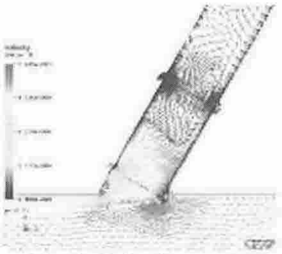

Fig.2 Velocity vectors

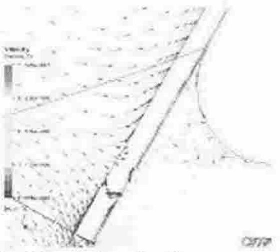

Fig.3 Local velocity vectors

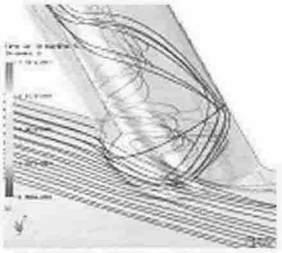

Fig. 4 Stream lines (normal)

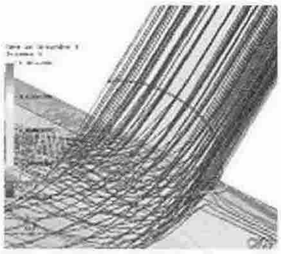

Fig. 5 Stream lines (SI flow)

Table 1 Force components exerted on the thermal sleeve

Condition of TS	Intact location as designed		Drooped by 20mm	
Flow condition	Normal	SI	Normal	SI
F_z [N]	3.38	-8.22	4.21	- 8.22
F_x [N]	-291.81	-203.69	-527.02	- 20.97
F_y [N]	-26.51	17.41	75.78	18.89

Normal flow: U_o =11.65m/s, SI flow: U_o =1m/s, V_{SI} =3m/s

Table 2 Gap velocities V_z [m/sec] in the annulus between the thermal sleeve and SI branch pipe

Condition of TS	Intact location as designed		Drooped by 20mm	
Flow condition	Normal	SI	Normal	SI
	V_z			
0.05m from TS Bottom	2.85	- 0.930	5.582	- 0.979
Mid TS	0.76	- 0.507	1.258	- 0.505
0.05m from TS Top	0.75	- 0.493	1.164	- 0.484

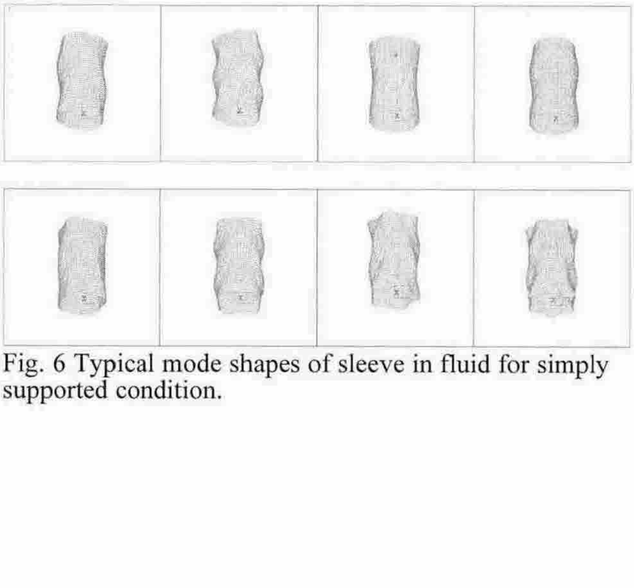

Fig. 6 Typical mode shapes of sleeve in fluid for simply supported condition.