Fluid-Structure Interaction Analysis for Pressurizer Surge Line subjected to Thermal Stratification

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1. Introduction

Fluid-Structure Interactions (FSIs) occurring inevitably in operating reactor component systems can cause excessive force or stress to the structures resulting in mechanical damages that may eventually threaten the structural integrity of components. To solve FSI problems, results from one field (fluid-thermal) analysis are applied as loads in other fields (structural) analysis.

If two media with different densities flow inside a pipe, thermal stratification can occur. Warm water is lighter than cool water and therefore tends to float on top of the cooler and heavier water, resulting in the upper portion of the pipe being hotter than the lower portion. Under these conditions, differential thermal expansion of the pipe metal can cause the pipe to deflect significantly. Unexpected piping movements are highly undesirable because of potential high piping stress that may exceed design limits for fatigue and stress.

In PWRs, there are great possibilities of occurrence of thermal stratification at the feed water lines of the steam generator, at the pressurizer surge line and at the injection pipes of the emergency core cooling systems. The most affected pipe by the thermal stratification is reported to be the pressurizer surge line [1].

Therefore in this study, a thermal-stress simulation is performed using ANSYS FSI. For the pressurizer surge line, thermal loads are transferred from ANSYS CFX to ANSYS Multiphysics in order to determine the heat transfer between the fluid and the solid body. From this information, stresses are determined and ultimately a fatigue analysis is performed [2].

2. CFD Analysis

The geometry and dimensions of the pressurizer surge line considered in this study are shown in Fig. 1. In the case of out-surge flow, cold fluid at a specified temperature of 51.7°C occupies inside the pipe maintaining the steady-state condition initially, and then at a certain time hot water at a specified temperature of 218.3°C is considered to begin to flow down into the pipe top nozzle which is connected to the pressurizer at a velocity of 0.07 m/s. In case of the in-surge flow, hot fluid of 218.3°C occupies inside the piping system initially, and then cold water of 51.7°C begin to flow into the pipe nozzle which is connected to the hot leg at a velocity of 0.07 m/s [3].

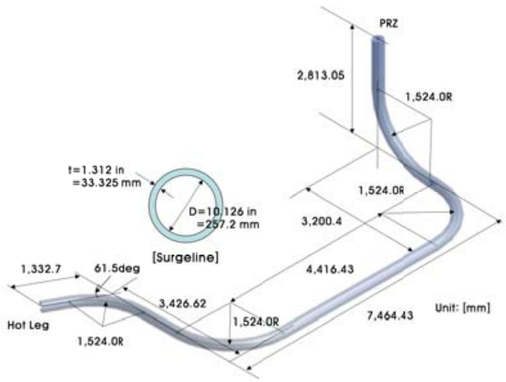

Fig. 1. The geometry and dimensions of the pressurizer surge line

The flow and thermal fields in the surge line are very complicated, because mixing of two fluids having different temperatures as well as both convection heat transfer between the surging water and the wetted wall and heat conduction through the pipe wall occur simultaneously. Figure 2 shows the transient temperature distributions at the wetted wall surface at several elapsed times after the beginning of out-surge.

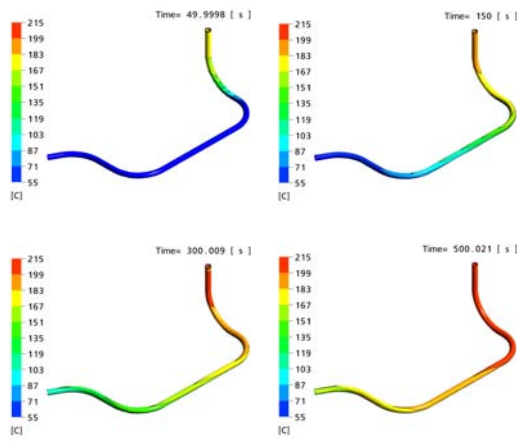

Fig. 2. Transient temperature distributions at the wetted wall surface for out-surge case

3. Stress Analysis

3.1. Analysis using simplified temperature distribution

For simplicity, the temperature is taken arbitrarily to be applied to the lower half and upper half of the pipe by top-to-bottom temperature differential ΔT. This kind of temperature distribution is the most conservative case which is used by many engineers for simplicity when there is no available data from CFD analysis.

3.2. Analysis using CFD analysis results

The stress analysis is performed to get the thermal stress distributions in the surge line using the finite element model taken directly from the CFX model. Temperature distributions of the surge line are obtained from the thermal hydraulic analysis as shown in Fig. 2, and they are used as an input to the structural analysis to get the stresses.

3.3. Results and Discussion

The transient evolutions of the maximum equivalent stresses and deflections for 3 loading cases of in-surge, out-surge and simplified temperature distributions are shown in Fig. 3. The maximum equivalent stress is found at the bottom nozzle of the pressurizer for all cases. Comparisons of maximum values of equivalent stresses and deflections for various temperature loadings are made in Fig. 4.

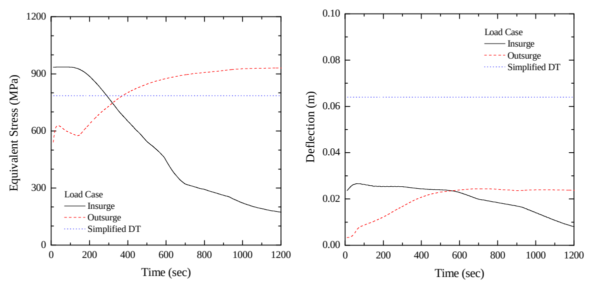

Fig. 3. Transient evolutions of the maximum equivalent stresses and deflections for various load cases

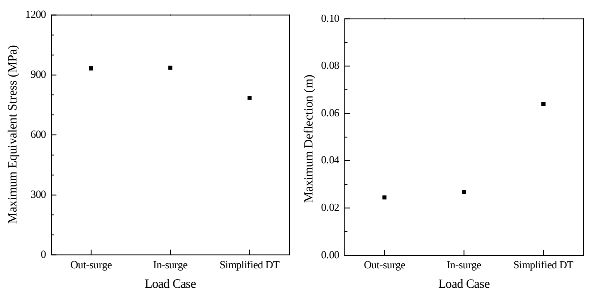

Fig. 4. Comparison of the maximum stresses and deflections for various load cases

The in-surge case is more severe than the out-surge case. Upper half and lower half distribution of the top-to-bottom temperature differential in pipe gives the most conservative result for the deflection but the most unconservative result for the stress point of view.

The maximum alternative stresses for all loading cases are summarized and their corresponding usage factors are calculated as shown in Table 1. As indicated in the table, the responses for in-surge case are almost the same as those for the out-surge case and they are more for stress and less severe for deflection than those generated from the simple application of the temperature half-and-half distribution in the surge line.

Table 1. Summary of fatigue analysis

Loading condition	Maximum alternative stress (MPa)	Number of cycles allowed ($\times 10^3$)	Usage factor
Out-surge	932/2=466.0	7.980	0.125
In-surge	936/2=468.0	7.871	0.125
Simplified ΔT	785/2=392.5	17.845	0.056

4. Conclusions

The 3-dimensional transient temperature distributions in the wall of a pressurizer surge line subjected to thermal stratification is calculated by CFD analysis. The thermal loads from CFD analysis are transferred to structural analysis code. From this information, thermal stresses are determined and ultimately a fatigue analysis is performed. In addition, the thermal stress and fatigue analysis results obtained by applying the realistic temperature distributions from CFD calculations are compared with those by assuming the simplified temperature distributions to identify some requirements for a realistic and conservative thermal stress analysis from a safety viewpoint.

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