Effects of the Pressurized Water Reactor Main Steam Line Break Location on the Blowdown Loading

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1. Introduction

As a pre-requisite for the structural integrity evaluation during blowdown following a MSLB, it is necessary to determine the blowdown load acting on the SG internal structures including tubes conservatively through a thermal hydraulic analysis of the SG secondary side during the transient process.

The thermal hydraulic analysis has been performed generally using a simple lumped model or one-dimensional numerical model [1-3]. However, those models have limitations in predicting the transient variations of the steam velocity, pressure and hydrodynamic load at a local point and the most conservative condition. Furthermore, it cannot be confirmed if the blowdown loads predicted by either of the models are conservative to evaluate every part of the SG internal structures.

For this reason, a multi-dimensional numerical approach using CFD codes has been recently applied to simulate the transient hydraulic response of the SG secondary side to the MSLB case where the pipe break is assumed to occur at the location just upstream the main steam isolation valve (MSIV) [4]. The results provides a good understanding of the transient flow field inside the SG secondary side during blowdown along with fundamental information and knowledge needed for determining the blowdown loading. Jo, Min and Jeong et al. [5] validated the CFD model used for the numerical simulation of the MSLB by conducting a benchmark computation of the experimental model [6].

In this study, the transient hydraulic response of the SG secondary side to the MSLB case where the pipe break is assumed to occur at the SG outlet nozzle end, another weld point on the MSL, was numerically simulated using a CFD code.

The present CFD calculation results was compared with those in ref. [4] to investigate the effect of break location (friction loss) on the blowdown load in the SG secondary side.

2. Analysis

2.1 MSLB Analysis Model

The MSLB analysis model includes both the upper space of the SG in which the steam occupies and the SG outlet nozzle. The SG is modeled as a simple cylinder with the steam volume that is approximately equal to that in the actual SG. Both the inner diameter and height of the SG model are 4 m. The nozzle inner diameter is 0.61 m and extends 0.5 m vertically from the SG. This solution domain is shown in Fig. 1. To simulate transient thermal hydraulic responses of the SG secondary side to the sudden MSLB numerically, a CFD analysis model is set up for the transient multi-components flow through the analysis model.

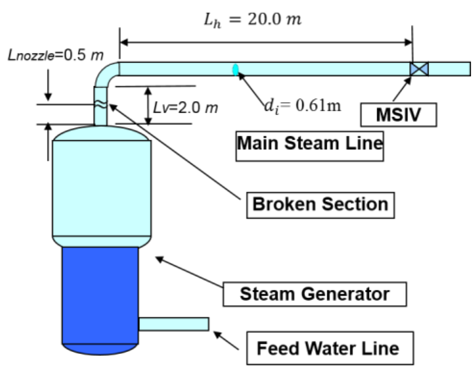


Fig.1 Simplified MSLB analysis model

Governing equations

The transport equations of velocity, pressure, temperature and turbulence are solved for vapor. The bulk motion of the fluid is modeled numerically by using single velocity, pressure, temperature and turbulence fields. The Reynolds averaged governing equations for conservation of mass, momentum, energy, and turbulent quantities for the present problem in a Cartesian coordinate system as found in ref. [4, 5] are implemented in the CFX code [7]. To calculate the turbulent viscosity μ_t , the $k-\omega$ based shear stress transport (SST) turbulence model [8] is applied to the present problem. In the present simulation, the properties of the saturated vapor and liquid are retrieved directly from a database of tabular form built in the CFX code [7].

Boundary and Initial Conditions

Initially, the saturated steam at 7.34 MPa is flowing through the steam line which ends at the inlet of the turbine generator. To model the steam generation by heat transfer from the primary coolant to the secondary side coolant for a short period during the blow down process following the MSLB accident, a constant amount of steam is assumed to be generated from the bottom of the SG upper space part at the same mass flow rate of the feed water and flows into the main steam line. For simplicity, it is also assumed in a conservative manner that a double ended guillotine break of the main steam line occurs at the SG outlet nozzle end in a very short time of 1.0 *ms* during the normal plant operation. This is modeled by assuming that the pressure at the pipe end instantly decreases from the initial state of 7.34 *MPa* to the atmospheric pressure finally. Thus, the opening condition is applied as the outlet boundary condition of the SG side broken end. No slip and adiabatic boundary conditions are assumed for the inner boundaries of the SG and pipe.

2.2 Numerical Analysis

Since rapid transient variations of thermal-hydraulic parameters including velocity and pressure are expected to occur in the SG and the main steam line due to the sudden pipe break, such calculation domains are discretized into fine mesh. A very small time step of 0.1 *ms* for the transient numerical calculations is determined enough to simulate the blowdown-induced dynamic pressure disturbance in the SG which is propagated from the broken pipe end in the event of the MSLB accident.

To facilitate the convergence of the solution, the steady-state solution is obtained first and then it is used as the initial condition for the MSLB-caused transient blowdown problem. The iterative computation for each time step of 0.1 *ms* terminates when the maximum of the absolute sum of dimensionless residuals of momentum equations, energy equation, or pressure correction equation is less than 0.0001. Using the numerical approach mentioned above, calculations have been performed for the analysis model having the same physical dimensions of the main steam line pipe and initial operational conditions as those for an actual operating PWR plant.

The transient velocity and pressure of steam are monitored at three central points with different levels “P1” and “P2” in the SG model”, which are apart from the top of the SG model vertically downwards by 1 m and 2 m, respectively, as shown in Fig. 2.

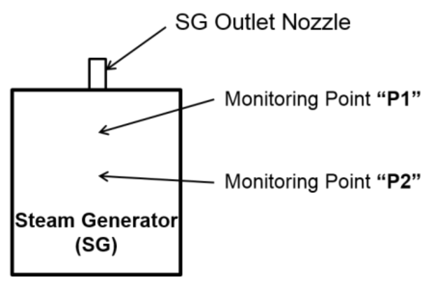


Fig. 2 Monitoring points

3. Results and Discussion

Some typical calculation results are provided and discussed below. To investigate the effects of the break location on the blowdown loading, the CFD calculation results for the present MSLB model are compared with those for the MSLB model of which the MSL break is assumed to occur at the location just upstream the MSIV [4].

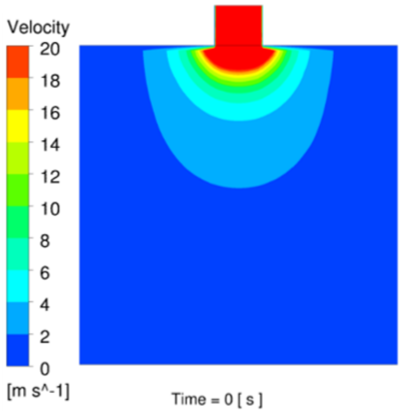


Fig.3 Steady velocity distribution of steam inside the SG during the normal reactor operation

Figure 3 shows the calculated steady velocity distributions of steam inside the two SG analysis models during the normal reactor operation. As seen from the figure, the steam velocities in the lower spaces of all the SG models that are occupied by the U-bend portion of the tube bundles maintain at about 2.0 m/s or less, similarly. These steam flow velocity distributions are approximately close to those in practical PWR operating SGs [4, 9]. For the CFD analyses of the transient thermal hydraulic response of the SG secondary side to a sudden MSLB at the SG outlet nozzle end point, the pre-calculated steady distributions of three components of steam velocity, pressure, temperature, and density are used as initial conditions.

Figure 4 displays the transient velocity distributions of steam inside the SG following the MSLB accident. As shown in the figure, the steam velocity inside the SG quickly increases after the MSLB accident. The transient velocity distributions vary throughout the SG secondary side and do not have a space-dependent monotonically varying pattern while those at the initial condition has a monotonically increasing pattern from the bottom of the SG steam space to the outlet nozzle. This implies that the steam velocity at a local point is oscillating during the blowdown. At some local points the steam velocities may have a high value of over 20.0 m/s which amounts to about 10 times the initial condition. This may result in an excessive dynamic hydraulic load to the internal structures and tubes.

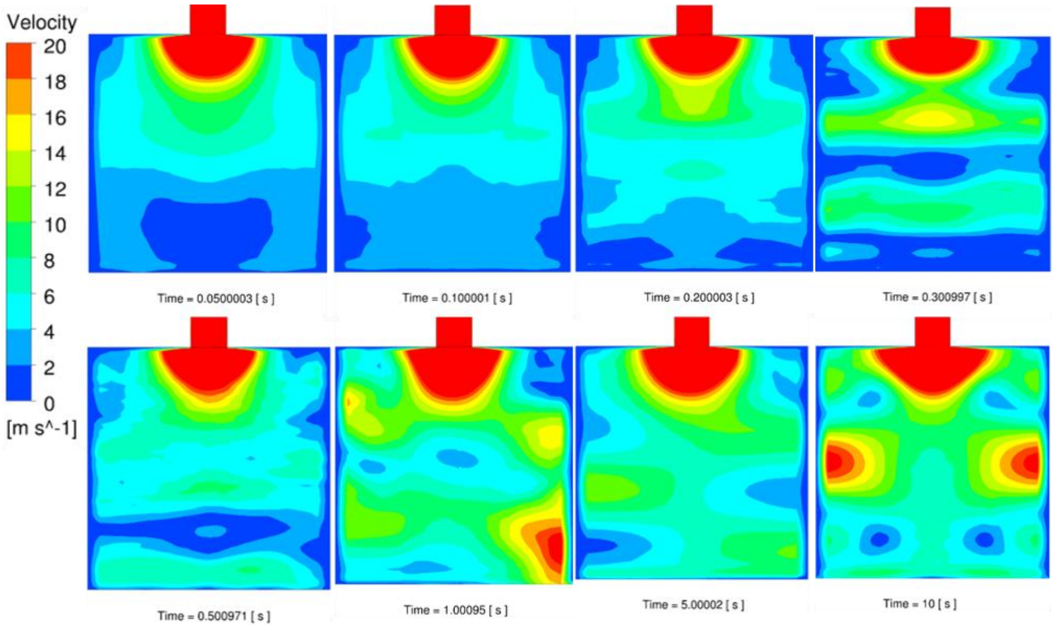
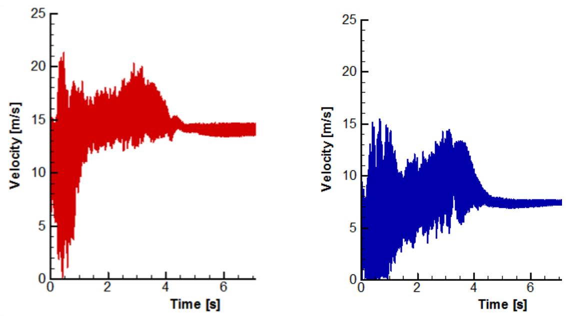


Fig.4 Transient velocity distributions of steam inside the SG following the MSLB accident

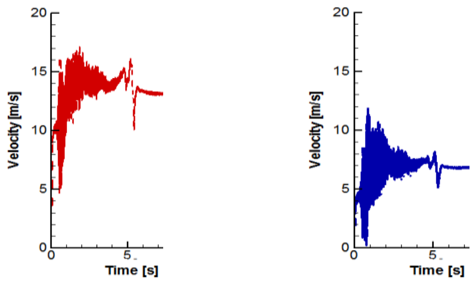
Figures 5 and 6 show the steam velocity oscillations for the transient period from the initiation of the MSLB to the elapsed time of 7.0 s at the monitoring points ‘P1’ and ‘P2’ inside the steam generator for the two cases where the steam line break occurs at the end of the SG outlet nozzle (Case 1) or at the location just upstream of the MSIV (Case 2), respectively.

As seen from the figures, the peaks of the oscillating steam velocities at both monitoring points ‘P1’ and ‘P2’ reach about 21.0 m/s and 15.0 m/s for the case 1 and about 17.0 m/s and 12.0 m/s for the case 2 during the beginning period of blowdown due to the MSLB and damps to low-amplitude oscillations with mean values of about 13.0 m/s and 7.0 m/s at the monitoring points ‘P1’ and ‘P2’ for both cases.



(a) at the point ‘P1’ (b) at the point ‘P2’

Fig.5 Transient steam velocity responses to the MSLB in the case where the break occurs at the SG outlet nozzle end

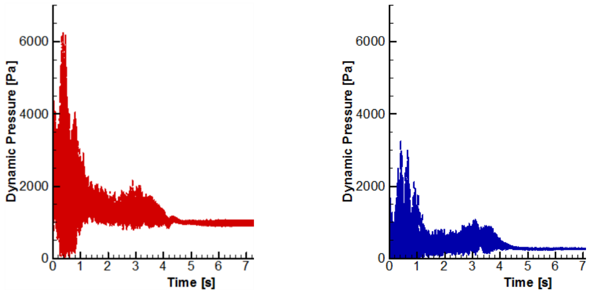


(a) at the point ‘P1’ (b) at the point ‘P2’

Fig.6 Transient steam velocity responses to the MSLB in the case where the break occurs at the location just upstream the MSIV [4]

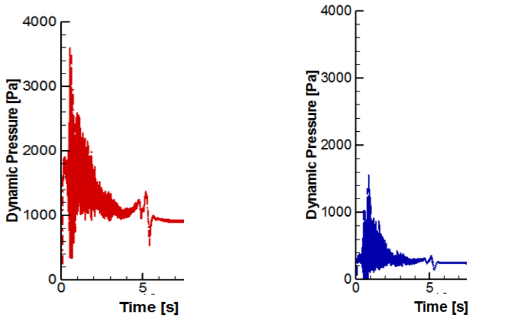
Figures 7 and 8 show the dynamic pressure oscillations for the transient period from the initiation of the MSLB to the elapsed time of 7.0 s at the monitoring points ‘P1’ and ‘P2’ inside the steam generator for the two cases where the steam line break occurs at the end of the SG outlet nozzle (Case 1) or at the location just upstream of the MSIV (Case 2), respectively. As seen from the figures, the peaks of the oscillating dynamic pressure at both monitoring points ‘P1’ and ‘P2’ reach about 6,200 *Pa* and 3,500 *Pa* for the case 1 and about 3,600 *Pa* and 1,600 *Pa* for the case 2 during the beginning period of blowdown due to the MSLB and damps to low-amplitude oscillations with mean values of about 1,000 *Pa* and 150-200 *Pa* the monitoring points ‘P1’ and ‘P2’ for both cases.

Above observations imply that the friction loss along the steam line span between the SG nozzle end and the MSIV would cause reduction in steam velocity disturbance or dynamic pressure. In other words, the consequence of the MSLB at the SG nozzle end would be much severer that those of other MSLB cases where the break locations are far from the SG.



(a) at the point 'P1' (b) at the point 'P2'

Fig.7 Transient dynamic pressure responses to the MSLB in the case where the break occurs at the SG outlet nozzle end



(a) at the point 'P1' (b) at the point 'P2'

Fig.8 Transient dynamic pressure responses to the MSLB in the case where the break occurs at the location just upstream the MSIV [4]

5. Conclusions

The transient hydraulic response of the SG secondary side to the MSLB case for which the pipe break is assumed to occur at the SG outlet nozzle end was numerically simulated using a CFD to investigate the effect of break location (friction loss) on the blowdown load in the SG secondary side. To do this, the transient responses of the steam velocity and dynamic pressure at two fixed monitoring points inside the steam generator secondary side for the present MSLB case mentioned above were compared with those for the case where the steam line break occurs at the location just upstream of the MSIV provided in the previous study.

The result shows that the friction loss along the steam line span between the SG nozzle end and the MSIV would cause reduction in steam velocity disturbance or dynamic pressure. It implies that the consequence of the MSLB at the SG nozzle end would be much severer that those of other MSLB cases where the break locations are far from the SG.

Therefore, to assure a conservative safety evaluation of the SG structural integrity, the blowdown loading on the SG internal structures including tubes during a MSLB accident in terms of the transient steam velocity, dynamic pressure and decompression wave fluctuations should be assessed for the MSLB case where the break is assumed to occur at the SG nozzle end.

REFERENCES

[1] Moody, F.J., 1990, Introduction to Unsteady Thermofluid Mechanics, John Wiley, New York.

[2] Shier, W.G.; Levine, M.M., 1980, "PWR steam line break analysis assuming concurrent steam generator tube rupture," ANS/ASME topical meeting on reactor thermal-hydraulics, 9 Oct 1980, Saratoga, NY, USA.

[3] Gallardo, S.; Querol, A.; Verdú, G., 2012, "Simulation of a main steam line break with steam generator tube rupture using trace," Proceedings of the PHYSOR 2012, 15~20 Apr 2012, Knoxville, TN, USA, American Nuclear Society.

[4] Jo, J.C. and Moody, F.J., 2015, "Transient Thermal-Hydraulic Responses of the Nuclear Steam Generator Secondary Side to a Main Steam Line Break," ASME JPVT, Vol. 137, doi: 10.1115/1.4028774.

[5] Jo, J. C., Min, B. K., and Jeong, J. J., 2016, "Validation of a CFD Analysis Model for the Thermal-hydraulic Response of PWR Steam Generator to a Steam Line Break," ASME Paper No. PVP2016-63048 (to be presented).

[6] Hamouda, O., Weaver, D.S., and Riznic, J., 2015, "An Experimental Study of Steam Generator Tube Loading during Blowdown," ASME Paper No. PVP2015-45250, 17~21 July 2015, Boston, MA, USA.

[7] ANSYS CFX User's Guide-14, ANSYS Inc., New York, 2012.

[8] Menter, F. R., 1994, "Two Equation Eddy-Viscosity Turbulence Models for Engineering Applications," AIAA J., 32(8), pp. 1598-1604.

[9] Jo, J. C., Lee, S. K., Kim, W. S., Shin, W. K., Kim, H. Y., and Ha, J. T., 1992, "A Study on the Thermal-hydraulic and Flow-induced Tube Vibration Analysis of Nuclear Steam Generators, KINS Technical Report, KINS/AR-198, Korea Institute of Nuclear Safety," KINS Technical Report, Korea Institute of Nuclear Safety, Report No. KINS/AR-198.