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Evaluation of Jet Impingement Phenomenon and Pipe Whip Behavior Under Pipe Break Conditions

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ABSTRACT

When a sudden rupture occurs in high energy lines, ejection of inner fluid with high temperature and pressure causes jet impingement loads to adjacent components as well as thrust forces on the ruptured pipe itself. The present study is to examine jet impingement phenomenon and pipe whip behavior under postulated pipe break conditions. In this context, typical numerical models were generated by taking a MSL (Main Steam Line) piping, a steam generator and a quarter of containment building in a 4-loop nuclear power plant. Subsequently, a series of numerical analyses was carried out by changing break locations; one is computational fluid dynamics analyses to assess ejected fluid characteristics and to define load magnitudes. The other is finite element analyses to calculate displacements of the broken pipe due to the thrust force as well as stresses of the steam generator and containment building due to the jet impingement load. From the numerical analysis results, it was proven that the jet direction was the most significant factor. Moreover, structural evaluation showed that displacements of MSL piping due to pipe whip bahavior were small compared to the overall dimensions of structure and component. Also, the maximum stresses at the containment building and steam generator were sufficiently lower than their yield strengths, which remained in elastic regime.

INTRODUCTION

If a HELB (High Energy Line Break) accident occurs in NPPs (Nuclear Power Plants), it is necessary to consider environmental effects such as release of radioactive material as well as secondary structural defects. Due to the requirements for protection of NPPs against postulated ruptures of high energy piping system, ANSI/ANS 58.2 provided design concept and requirements (1988). However, in DSRS (Design-Specific Review Standard) section 3.6.2 was accepted by NRC (Nuclear Regulatory Commission), there are concerns about the modelling of jet load in ANSI/ANS 58. Some assumptions related to jet load may lead to non-conservative assessment of neighboring SSCs (System, Structure and Components). Also, in NUREG-0800 section 3.6.2 (2007), jet vibration including resonance effect due to the jet injection was not considered in the ANSI/ANS 58.2. In this study, a series of numerical analyses was carried out under HELB; one is CFD (Computational Fluid Dynamics) analyses to define load magnitude by considering jet direction. The other is FE (Finite Element) analyses to calculate displacements of the broken pipe due to the thrust force as well as stresses of the steam generator and containment building due to the jet impingement load.

JET IMPINGEMENT EVALUATION

CFD model and analysis method

CFD analyses were performed by using commercial program of FLUENT (2016), which are based on FVM (Finite Volume Method), for evaluating the hydrodynamic load on the target area by jet impingement. The

continuity equation and the momentum equation applied for the jet impingement evaluation can be expressed as follows (2016):

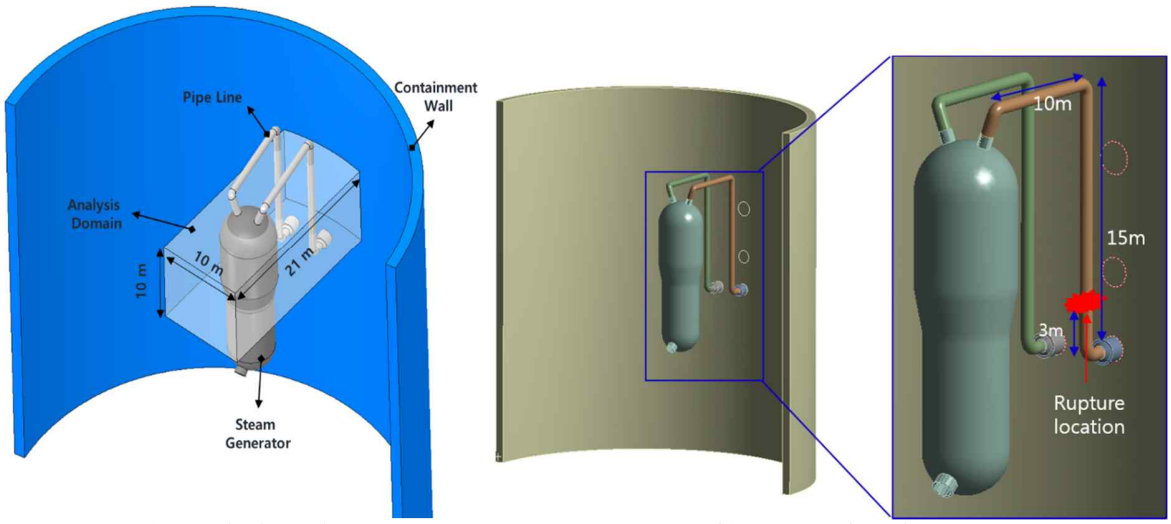
$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V}\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{V}\right) + \nabla \cdot \left(\rho \vec{V}\vec{V}\right) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} \tag{2}$$

where, V, ρ and p are flow velocity, density and pressure in the flow field, respectively, τ is the deviatoric stress tensor, g is gravitational acceleration.
In order to obtain initial condition for LES (Large Eddy Simulation) turbulent model under HELB conditions, a CFD analysis was conducted using standard k-ε model. As the LES turbulent model directly calculates the flow characteristics without applying the average of time increment, it can be applied to sudden change of unsteady flow with the time such as jet impingement phenomenon. In that reason, a very small mesh size is required due to unsteady state with short analysis time and it needs very high computational resources and time.

Analysis conditions

Figure 1 represents analysis region and 3D CAD model of the containment building including the steam generator, MSL piping and head fitting used for the jet impingement evaluation. The rupture in the MSL pipe was assumed to be directly injected to the containment building and steam generator. Rupture diameter is 0.7286 m. As it is necessary to consider a very small mesh for LES turbulence model, 10 m × 10 m × 21 m of jet impingement region was adopted around the break location in the whole model. The number of mesh at the analysis region was about 3 million with tetrahedral and a half of the jet impingement is shown in Figure 2. The steam is injected into the air through the rupture of MSL piping. The velocity of the injected steam is 409.46 m/s, temperature is 526.55 K. The initial temperature of the air in the containment building is 293 K and subsonic flow with Mach number of 0.728 is considered.



(a) Analysis region (b) Rupture location

Figure 1. Geometry for CFD analysis

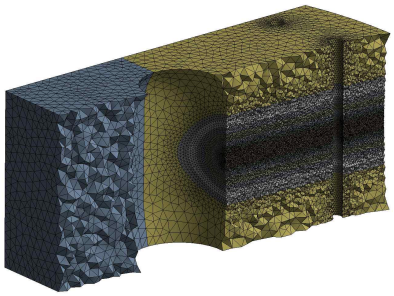
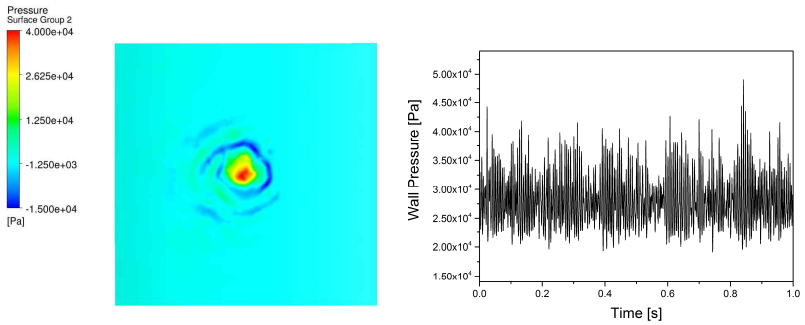


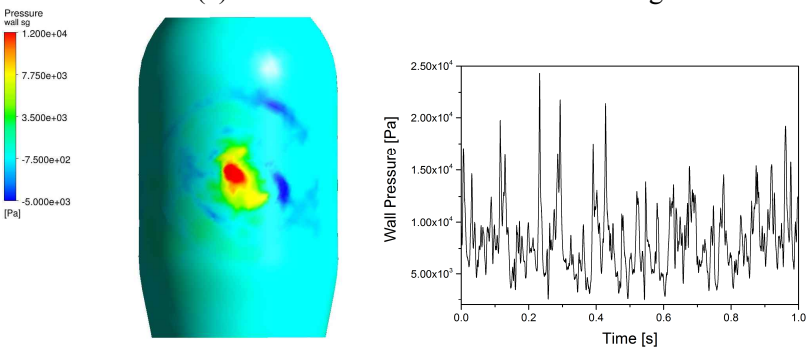
Figure 2. A half of jet impingement region in CFD model

Analysis results

Figure 3 shows snapshots of pressure distributions and histories according to jet directions. The pressure due to the jet impingement load was concentrated at the target and change rapidly with time in the target and period of vibration was short. The maximum pressure of containment building was 30% higher than that of steam generator, approximately. It can be seen that the fluctuation of the load acting on the steam generator is not larger than that occurring in the containment building due to the distance of between target and break location.



(a) Jet direction to containment building



(b) Jet direction to steam generator

Figure 3. Pressure distributions and histories

STRUCTURAL INTEGRITY EVALUATION

FE model and analysis method

The FE model used in the structural evaluation is illustrated in Figure 4. Containment building was modeled by employing 8-node 3D concrete elements consist of 40,176 nodes and 29,866 elements. The steam

generator was modeled by 8-node solid elements with 23,695 nodes and 12,133 elements. Also, head fitting were modeled by employing 8-node solid elements with 9,360 nodes and 5,840 elements. MSL piping were generated by 8-node solid elements with 11,254 and 8,452 elements, respectively. Element types of each component were taken from general-purpose commercial program element library (2016).
Meanwhile material properties as the homogenous concrete could be obtained by using the following equation (2015):

$$S_c^{eq} = (1 - V_s)S_c + V_s S_s \tag{3}$$

where S_c^{eq} is the equivalent strength of homogeneous concrete, V_s is the volume fraction of rebar and determined as 0.081. S_c and S_s are the strengths of concrete and rebar, respectively. In detail, the isotropic hardening model with bi-linear elastic-plastic behavior was adopted because of the rapid strain change caused by jet impingement loading. To incorporate the dynamic effects, moduli of elasticity and strengths of the containment building as well as steam generator, MSL piping and head fitting were determined by considering DIF (Dynamic Increase Factor) ranging from 1.00 to 1.29 in Eq. (4) (2015). Table 1 summarizes material properties used for FE analyses taking into account the DIF values.

$$f'_{dy} = f'_y(DIF_y), \quad f'_{du} = f'_u(DIF_u) \tag{4}$$

where f'_y and f'_u are the yield strength and tensile strength under the static loading condition, and f'_{dy} and f'_{du} are the corresponding ones under the dynamic loading condition like the jet impingement.

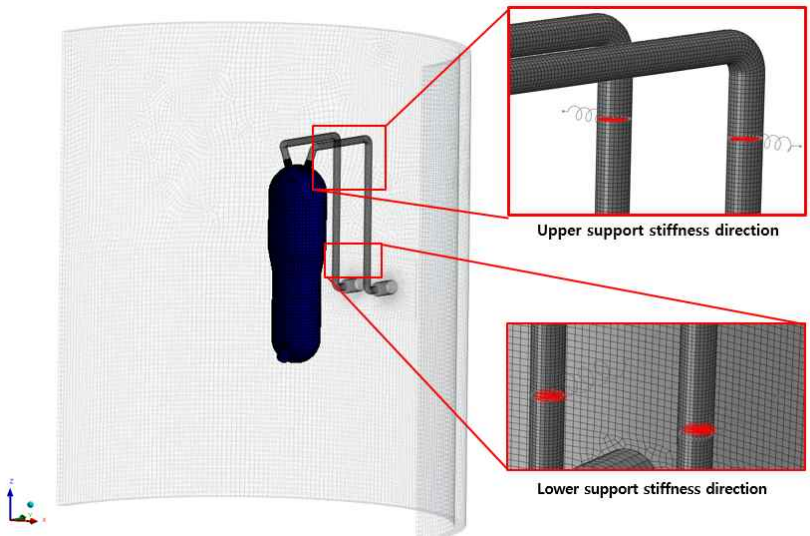


Figure 4. FE model and support locations for structural evaluations

Table 1: Material properties of each component

Component	Young's modulus (GPa)	Poisson`s ratio	Yield strength (MPa)	Tensile strength (MPa)
Containment building	31.12	0.2	75.68*	54.18
Steam generator	199.95	0.3	352.32	523.23
MSL piping	183.08	0.3	303.36	426.90
Head fitting	184.92	0.3	296.47	503.32

*: Compressive strength

Analysis conditions

Structural evaluation of the containment building and MSL piping was performed by using ANSYS workbench (2016). Pressure histories obtained from CFD analyses were applied as thrust force of MSL piping and jet impingement load according to jet direction of containment building and steam generator as loading conditions in Figure. 3. Table 2 summarizes analysis cases according to the jet directions and break locations.
Containment building was modeled on the top and at the bottom horizontal surface of the wall. Also, radial boundary conditions were defined on each side of the containment wall by using local coordinate system. Each of the MSL piping was held up by two support mechanisms as shown in Figure 4. Instead of defining non-deforming boundary conditions, linear springs were modeled as supports. Equivalent spring stiffness values were used for these supports.

Table 2: Analysis cases for structural evaluation

Case no.	Jet direction	Break location
1	Containment building	Upper support
2		Lower support
3	Steam generator	Upper support
4		Lower support

Analysis results

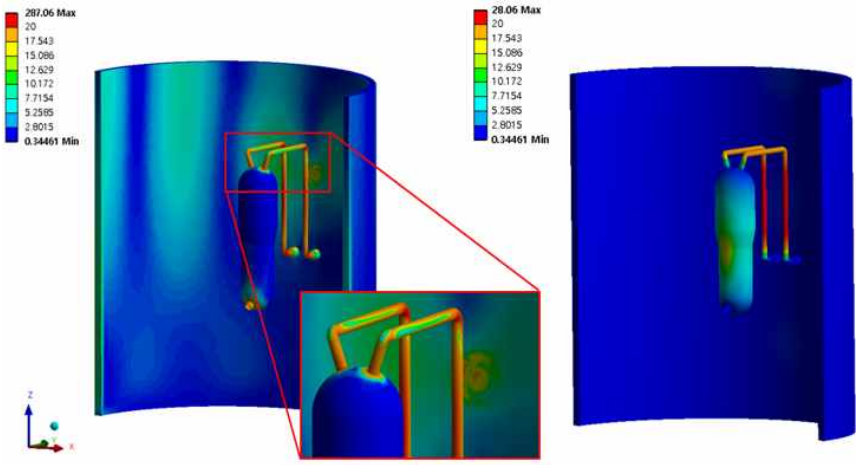
Table 3 compares resulting maximum von Mises stresses of the concrete, steam generator, MSL piping and head fitting. Figure 5 represents von Mises stress and displacement contours of each components in Case 2. The stresses were high at containment building from the jet direction stand point, however, the difference according to the break locations was not significant. Also, maximum stresses of all component under the jet direction of containment building did not exceeded their yield strengths, which means maximum stresses remained in elastic regime. Table 4 summarizes resulting maximum displacement of MSL piping due to the thrust force. The results showed similar trends with those of stress data in general. The maximum displacement of MSL piping was 25.77 mm, while it is small comparing to the overall dimensions of the RPV.

Table 3: Maximum von Mises stresses of rebar, liner plates, MSL piping and head fitting

Case no.	Max. stress (MPa) @ concrete	Max. stress (MPa) @ steam generator	Max. stress (MPa) @ MSL piping	Max. stress (MPa) @ head fitting
1	51.41	1.23	25.36	9.28
2	53.81	1.54	26.91	10.12
3	0.21	38.15	12.60	0.84
4	0.24	40.25	13.32	0.89

Table 4: Maximum displacements of MSL piping

Case no.	Max. displacement (mm)
1	23.41
2	25.77
3	12.01
4	14.07



(a) von Mises stress (b) Displacement

Figure 5. von Mises stress and displacement contours in Case 2

CONCLUSIONS

In this research, systematic numerical analyses of the containment building, steam generator, MSL piping and head fitting were carried out under typical HELB conditions and the following conclusions were derived.

1) With regard to the jet impingement evaluation, fluctuation of the load on the containment building was larger than the steam generator due to the distance from the break location. The effect of the jet direction was the most significant.
2) The displacements due to pipe whip behavior showed similar trend with stress analysis results, in general, and the movements of MSL piping were small compared to the overall dimensions of them.
3) The stresses were high at the jet direction of containment building and the difference according to the break locations was not significant. The maximum stresses at the containment building and steam generator were sufficiently lower than their yield strengths, which remained in elastic regime.

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