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Structural assessment of jet impingement loads under postulated main steam line break conditions

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ABSTRACT

When a sudden rupture occurs in high energy lines, the ejection of inner fluid with high temperature and pressure causes jet impingement loads on adjacent components and structures, as well as on the ruptured pipe itself. This study examines the jet impingement phenomenon under postulated HELB (High Energy Line Break) conditions. In this context, typical numerical models were generated considering the SG (Steam Generator), MSL (Main Steam Line) piping, and containment. Subsequently, two sets of numerical analyses were carried out by changing the break locations. One set is computational fluid dynamics to assess the ejected fluid characteristics and define pressure histories. The other uses finite element analyses to calculate the stresses and displacements of the SG, piping, and containment building caused by the jet impingement loads. As a result, detailed analyses provided more realistic and conservative data than those in the ANSI/ANS 58.2 standard used in the current HELB design while the jet loads did not threat secondary structural integrity after the MSL piping break.

1. Introduction

If, as a design basis accident, a HELB (High Energy Line Break) occurs in a NPP (Nuclear Power Plant), it is necessary to consider the environmental effects, such as the release of radioactive material and secondary structural failure. To protect NPPs against such postulated ruptures of the high energy piping system, the ANSI/ANS 58.2 standard provides design concepts and requirements (Society, 1988). However, although NUREG-0800 Section 3.6.2 was accepted by the NRC (Nuclear Regulatory Commission) (NRC, 2007), concerns remain about ANSI/ANS 58.2, which might lead to a non-conservative assessment of neighboring SSCs (Systems, Structures, and Components) (NRC, 2007).

Four controversial issues beset ANSI/ANS 58.2. First, it does not consider blast waves in evaluating the dynamic effects associated with a HELB. However, the effects on the surrounding SSCs of the instantaneous fluid load caused by the blast wave from a high-pressure pipe rupture should be assessed. Second, in characterizing the geometry of the jet, some physically incorrect assumptions could underlie the approximating methodology. The standard assumes that a jet issuing from a high-pressure pipe break will always spread at a 45-degree angle up to an asymptotic plane and then sustain a 10-degree angle. However, at a given axial position, subsequent spread rates depend on the ratio between the static pressure in the outermost jet flow region and the ambient static pressure. Moreover, applying the formulas in the standard could lead to non-conservative pressures away from the jet centerline. Finally, the standard does not consider jet vibration. It was reported that strong discrete frequency loads and significant amplification of the impingement loads are observed when resonance occurs within the jet (Vipin et al., 2015).

Many design and research activities have been carried out to investigate jet impingement under specific HELB conditions. In particular, ZOI (Zone of Influence) methodology and program of pressurized heavy-water reactors and pressurized water reactors were developed based on the jet impingement model in ANSI/ANS 58.2 (Lee et al., 2010). Even though experimental research has also examined deformation at various distances from a jet using this standard, the relevant structural assessments have not been conducted (Kastner and Rippel, 1988). Most CFD (Computational Fluid Dynamics) analyses were performed under diverse environmental conditions. For instance, effects of released flow and rupture during jet impingement were assessed while influence on neighboring components and structures was not quantified (Dong et al., 2010; Zaccari et al., 2014; Lee and Kim, 2017). As a lesson learned from these studies, further detailed CFD and FE (Finite Element) analyses were recommended for accurate delineation of

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the jet impingement loads and vibration including resonance effect to resolve unanticipated non-conservatism.

The goal of this research is thus to examine complex jet impingement phenomena, addressing the second of the four issues described previously, using postulated MSL (main steam line) break conditions as a typical HELB. In this context, two sets of detailed numerical analyses are carried out by changing the break locations. One set is CFD analyses to assess the ejected fluid characteristics and define pressure histories. The other uses FE analyses to calculate the stresses and displacement of the SG, MSL piping, and containment caused by the jet impingement loads. The results of both analyses are compared with those obtained from ANSI/ANS 58.2.

2. Calculations of pressure history by jet impingement

2.1. Analysis method

Calculating jet impingement loads is important and shall be given proper consideration in the evaluation of target components and structures. The response of the target is a function of its inherent characteristics and the jet impingement loads. The latter can be determined from dynamic analyses that consider the actual phenomenon or from static analyses with a DLF (Dynamic Load Factor) as follows (Society, 1988; Lee and Kim, 2017).

$$F_s = (DLF)KK_{\phi}(P_e - P_a)V(A_t/A_j) \tag{1}$$

where F_s is the jet impingement load, *DLF* is the dynamic load factor equal to two, K is the thrust factor equal to 1.26 for steam, P_e is the fluid pressure in the pipe, P_a is the ambient pressure around the target, V is the initial velocity of the jet at the break, A_j is the cross-sectional area normal to the centerline at the jet impingement plane, and A_t is the target area. The below shape factor (K_{ϕ}) is a measure of the target for the changing momentum of the jet.

$$K_{\phi} = (1 - 0.424D_j/D_0)\sin\beta \tag{2}$$

where D_j is the diameter of the jet, D_0 is the diameter of the target, and β is the inclination angle of the jet centerline with respect to the pipe axis (Varquez-Sierra et al., 1988).

CFD analyses were performed using commercial software and the FVM (Finite Volume Method) for evaluating a hydrodynamic load on the target area caused by jet impingement. The continuity equation, momentum equation, and the transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε) can be expressed as follows (ANSYS Inc., 2016).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \tag{3}$$

$$\frac{\partial}{\partial t}(\rho \vec{V}) + \nabla(\rho \vec{V}\vec{V}) = -\nabla p + \nabla(\bar{\bar{\tau}}) + \rho \vec{g} \tag{4}$$

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\epsilon + S_k \tag{5}$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial \epsilon}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + C_1\frac{\epsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\varepsilon \tag{6}$$

where V, ρ and p are the flow velocity, density, and pressure in the flow field, respectively, G is the filter function of eddy, τ is the deviatoric stress tensor, and g is the gravitational acceleration.

For effective LES (Large Eddy Simulation), the initial conditions are determined from a steady state flow simulation using Reynolds-averaged turbulence model (standard $k-\varepsilon$ model) that is the most common and robust one. Thereby, the LES falls between DNS (Direct Numerical Simulation) and RANS (Reynolds-Averaged Navier-Stokes) turbulence models in terms of the fraction of the resolved scales. The subgrid-scale turbulence models employ Boussinesq hypothesis in the RANS models and compute stress tensors as follows.

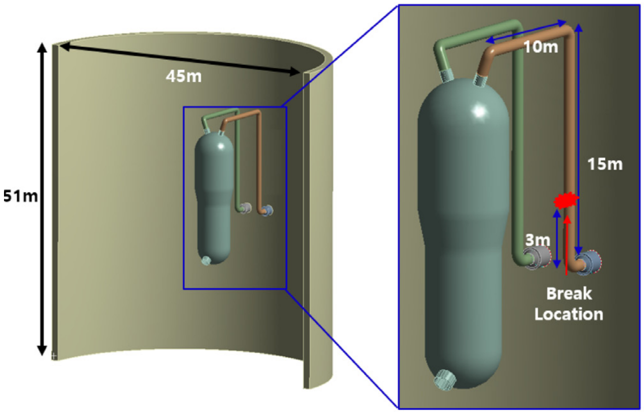
$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t\bar{S}_{ij} \tag{7}$$

where μ_t is the subgrid-scale turbulent viscosity. The isotropic part of the subgrid-scale stresses τ_{kk} is not modeled but added to the filtered static pressure term. $\bar{S}_{ij}$ is the rate-of-strain tensor for the resolved scale defined as follows (ANSYS Inc., 2016).

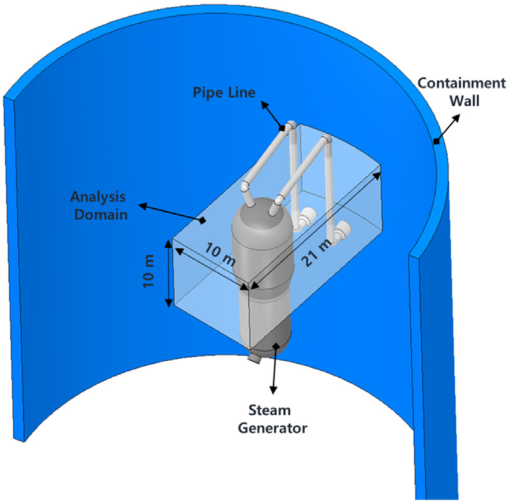
$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) \tag{8}$$

2.2. Modeling and analysis conditions

Fig. 1 represents the break locations and analysis region used in the CFD analyses as representative HELB conditions of a 1400 MWe reactor. As illustrated in Fig. 1(a), pipe ruptures near the lower sup-



(a) Break location



(b) Analysis region

Fig. 1. Geometry for CFD analysis.