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Structural assessment of fully flooded reactor cavity and penetration piping under steam explosion conditions

Seung Hyun Kim [a], Yoon-Suk Chang [a,*], Sungchu Song [b], Yong-Jin Cho [b]

[a] Department of Nuclear Engineering, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do 446-701, Republic of Korea
[b] Korea Institute of Nuclear Safety, 34 Gwahak-ro, Yuseong-gu, Daejeon-si 305-338, Republic of Korea

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ABSTRACT

Steam explosion may occur in a nuclear power plant by molten core-coolant interactions when the external reactor vessel cooling strategy is failed. This phenomenon can threat the integrity of reactor cavity, penetration piping and support structures. Even though extensive researches have been performed to predict influences of the steam explosion, due to complexity of physical phenomena and environmental thermal-hydraulic conditions, it is remained as one of possible hazards. The present study is primarily to examine load carrying capacity of the reactor cavity under various steam explosion conditions through a series of numerical analyses; both hydro-dynamics and computational fluid-dynamics analyses were carried out in accordance with ten postulated conditions having different failure modes, explosion locations, corium conditions and turbulence models. Subsequent finite element analyses were conducted for the reactor cavity and penetration piping with support structures to calculate stresses and displacements. From the numerical analysis results, failure modes and corium conditions were identified as crucial parameters while the effect of explosion location was negligible. Moreover, structural assessment results showed that the reactor cavity had minor to medium potentials for localized damage but sustains the function of safety barrier to avoid release of radioactive substances under the steam explosion conditions.

1. Introduction

In order to mitigate hypothetical severe accidents in an advanced water reactor, either core catcher or ERVC (External Reactor Vessel Cooling) strategy is frequently adopted in the design stage. However, when molten core penetrates RPV (Reactor Pressure Vessel) lower plenum and contacts with coolant in the reactor cavity, serious structural damage may occur. A steam explosion can cause intensive and rapid heat transfer, and lead to the formation of pressure waves. Additionally, production of fragments may threat the integrity of surrounding reactor cavity and associated components due to resulting dynamic effects [1,2].

The steam explosion phenomenon is usually classified into four phases representing premixing, triggering, propagation and expansion processes [3]. At first, in the premixing phase, the molten jet breaks up and a coarsely mixed region of molten corium and coolant is formed. The explosive system can be remained in this metastable state until the melt is quenched or a steam explosion is triggered. The triggering event is a disturbance, which destabilizes the vapor film around a melt particle allowing liquid–liquid contact and leads to locally enhanced heat transfer, pressurization and fine fragmentation. During the propagation phase, an escalation process takes place resulting from heat transfer after the triggering event. Finally, during the expansion phase, thermal energy of the coolant is converted into mechanical energy so that high-pressure mixture against inertial constraints imposed by the surroundings governs possibility of the steam explosion. If the localized high-pressure is quickly stabilized, only the kinetic energy transmitted to the materials around the interaction zone becomes the unique damaging agent.

Details of each process taking place prior to and during the steam explosion have been studied for a number of years to address the transferability of experimental results to actual reactor conditions. Representatively, TROI, FITS, KROTOS and FARO experiments were performed by using real molten core. Moreover, to resolve the remaining open issues on the FCI (Fuel–Coolant Interaction) processes and their effect on steam explosion energetics, CHYMES/

* Corresponding author. Tel.: +82 31 201 3323; fax: +82 31 204 8114.
E-mail address: yschang@khu.ac.kr (Y.-S. Chang).

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CULDESAC [4], PM-ALHA/ESPROSE.m [5], IFCI [6] and TEXAS [7] analysis codes were developed. Also, the OECD project SERENA (Steam Explosion REsolution for Nuclear Applications) consists of experimental and analytical parts was launched in 2007 to enhance understanding and modeling techniques of the FCI key features for reactor applications [8]. Nevertheless, establishment of appropriate evaluation methods and mitigation actions on the steam explosion has become a state-of-the-art. Structural assessment of the reactor cavity and associated components due to the steam explosion requires also uncertainties evaluation relating to the complex phenomena.

The goal of this research is primarily to examine load carrying capacity of the reactor cavity as a barrier under typical steam explosion conditions through a series of numerical analyses. Both hydro-dynamics and CFD (Computational Fluid Dynamics) analyses are carried out under ten postulated conditions with different failure modes, explosion locations, corium conditions and turbulence models to estimate the pressure histories. Corresponding FE (Finite Element) analyses and subsequent structural assessment are also conducted by considering the reactor cavity and associated components such as penetration piping and support structures. Finally, the resulting pressure histories, stresses and displacements are compared and discussed in detail.

2. Calculation of pressure history under steam explosion conditions

2.1. Analysis method

In the present study, mixing phases (premixing, triggering and propagation phases) are analyzed by a hydro-dynamics code [7]. The code has been extensively verified to cover a range of experimental data and its key features such as rapid-fragmentation model for steam explosion are validated. For the jet breakup model, the Rayleigh–Taylor instability is assumed as a prime model for the fragmentation of a molten jet. It includes a semi-empirical relationship depicting that the fine fragmentation rate is proportional to the micro liquid jet velocity generated by the Rayleigh–Taylor instabilities and a function of fine fragmentation rate ($\dot{m}_{fr}$) as below;

$$\dot{m}_{fr} = 6C_{fr}m_p\left(\frac{P-P_{th}}{\rho_f D_P^2}\right)^{0.5}F(\alpha)g(\tau) \tag{1}$$

where, the fine fragmentation rates depend on local pressure (P), particle diameter (D_p), and model parameters such as the fragmentation coefficient (C_{fr}), particle mass (m_p), threshold pressure of vapor film coefficient (P_{th}), fuel density (ρ_f), local phase factor ($F(\alpha)$) and fragmentation of characteristic time function ($g(\tau)$).

The analysis of the expansion phase is based on the Hicks–Menzies thermodynamic approach taking into account the microinteraction zone concept [1]. It was assumed that the heat transfer from the molten core to the coolant was completed during the preceding mixing phases. The generated vapor at which high-pressure expands adiabatically and the performed work ($A_{2\to3}$) during the presumed adiabatic expansion can be calculated as

$$A_{2\to3} = \int_{V_2^{vap}}^{V_3^{vap}} pdV = -\left(\frac{P_2\left(V_2^{vap}\right)^{\kappa}}{\kappa-1}\frac{1}{V^{\kappa-1}}\right)\Bigg|_{V_2^{vap}}^{V_3^{vap}} = \frac{P_2V_2^{vap}}{\kappa-1}\left(1-\left(\frac{P_3}{P_2}\right)^{\frac{\kappa-1}{\kappa}}\right) \tag{2}$$

where V_3^{vap} and V_2^{vap} are the volumes of vapor at the start and end of the expansion phase. P_2 and P_3 are the pressures at the start and end of the expansion phase, and κ is the ratio between the vapor specific heats at constant pressure and constant volume respectively. When the fluid conditions during the mixing phases are determined, the pressure at the start of the expansion phase can be calculated by iteratively solving the following equation [1].

$$P_2 = \eta\frac{(\kappa-1)\rho_1^{cor}\alpha_1^{cor}c^{cor}\left(T_1^{cor}-T_1^{sat}\right)}{\alpha_2^{vap}\left(1-\left(\frac{P_w}{P_2}\right)^{\frac{\kappa-1}{\kappa}}\right)} \tag{3}$$

where P_w is the coolant pressure, c^{cor} and ρ_1^{cor} denote the specific heat and density of corium. T_1^{cor} and T_1^{sat} are the corium temperature and coolant saturation temperature at containment pressure. α_2^{vap} is the vapor volume fraction at the beginning of the expansion phase. An important parameter for the steam explosion is the energy conversion ratio (η) which was used as the basis in the calculation of other steam explosion parameters. Due to the assumption of the adiabatic vapor expansion, the density of the mixture during the expansion process $\rho_{2\to3}^{mix}(p)$ can be determined solely as a function of pressure.

$$\rho_{2\to3}^{mix}(p) = \frac{\rho_2^{mix}}{\left(1-\alpha_2^{vap}\right)+\left(\frac{\alpha_2^{vap}\rho_2^{vap}}{\rho_{2\to3}^{vap}(p)}\right)} = \frac{\rho_2^{mix}}{\left(1+\alpha_2^{vap}\right)+\left(\left(\frac{P_w}{P_2}\right)^{\frac{1}{\kappa}}-1\right)} \tag{4}$$

where ρ_2^{mix} is the mixture density at the start of the expansion phase and $\rho_{2\to3}^{vap}$ is the vapor density during the expansion phase [1]. In the present method, the initial conditions at the start of the expansion phase are determined by the hydro-dynamics analyses whereas the expansion phase itself is simulated by the CFD analyses taking into account the above equations representing the mixture state.

2.2. Modeling and analysis conditions

Fig. 1 represents the schematic and CFD model of the reactor cavity including the RPV, penetration piping and support structures used for the steam explosion evaluation. The mesh consists of 1,249,818 nodes having mesh quality of 98%. When explosion locations are bottom and middle, three sets of pressure history and distribution were extracted from different heights of the reactor cavity (0 m–6.5 m and 4.5 m–11 m). The aforementioned mixing phases of the steam explosion were solved by a hydro-dynamics code [7], and the results were used as initial conditions for the multiphase flow analyses in the subsequent expansion phase. The behaviors of the molten core mixture as well as liquid and vapor state coolant were analyzed by a CFD code [9] incorporating the aforementioned Hicks–Menzies thermodynamic approach with the microinteraction zone concept. To simulate the pressure waves, three fluids were treated as compressible and modeled by the homogeneous Eulerian model in which all of the fluids were assumed to share a common velocity field. Time dependent η values shown in Fig. 2 were obtained from the hydro-dynamics analyses and the value of specific heat ratio (κ) was determined at corium average temperature (3000 K). The parameters for steam explosion analyses were densities of corium (ρ_1^{cor}) of 8450 kg/m^3 and 6890 kg/m^3 at oxide layer and metallic layer, volume fraction of corium (α_1^{cor}) of 0.1, and specific heats of corium (c^{cor}) of 0.51 kJ/