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Original Article

Ex-vessel Steam Explosion Analysis for Pressurized Water Reactor and Boiling Water Reactor

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ABSTRACT

A steam explosion may occur during a severe accident, when the molten core comes into contact with water. The pressurized water reactor and boiling water reactor ex-vessel steam explosion study, which was carried out with the multicomponent three-dimensional Eulerian fuel—coolant interaction code under the conditions of the Organisation for Economic Co-operation and Development (OECD) Steam Explosion Resolution for Nuclear Applications project reactor exercise, is presented and discussed. In reactor calculations, the largest uncertainties in the prediction of the steam explosion strength are expected to be caused by the large uncertainties related to the jet breakup. To obtain some insight into these uncertainties, premixing simulations were performed with both available jet breakup models, i.e., the global and the local models. The simulations revealed that weaker explosions are predicted by the local model, compared to the global model, due to the predicted smaller melt droplet size, resulting in increased melt solidification and increased void buildup, both reducing the explosion strength. Despite the lower active melt mass predicted for the pressurized water reactor case, pressure loads at the cavity walls are typically higher than that for the boiling water reactor case. This is because of the significantly larger boiling water reactor cavity, where the explosion pressure wave originating from the premixture in the center of the cavity has already been significantly weakened on reaching the distant cavity wall.

1. Introduction

Steam explosion, in the frame of nuclear reactor safety, is a process resulting from the interaction between the core melt (corium) and water [1,2]. Energy transfer from the corium to the coolant is so fast that a large amount of vapor is produced within a very short time. High pressure and fast expansion of vapor could potentially induce high loading on the surrounding structures. A steam explosion is also called an energetic fuel—coolant interaction (FCI). In the case of an ex-vessel steam explosion, cavity walls might not be able to bear such dynamic loads. Then, the cavity or even the

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containment might be at risk of damage or even failure [3–5]. Direct or bypassed loss of the containment integrity can lead to the release of radioactive materials into the environment, threatening the safety of the general public.

Details of processes taking place prior to and during a steam explosion have been experimentally studied for a number of years, with adjunct efforts in modeling these processes to address the scaling of experimental results to reactor conditions [1,6,7]. Despite great efforts in steam explosion research, the confidence in predicting reactor situations is not such that an unambiguous decision can be taken whether there would be an early failure of the containment due to a steam explosion or not. To resolve the remaining open issues on the FCI processes and their effect on ex-vessel steam explosion energetics, the OECD project Steam Explosion Resolution for Nuclear Applications (SERENA) was launched in 2007, consisting of an experimental and an analytical part [8,9]. To verify the progress made in the understanding and modeling of key FCI processes for reactor applications, a reactor exercise was performed at the end of the project. The exercise comprises three cases: a pressurized water reactor (PWR) central melt release, a PWR side release, and a boiling water reactor (BWR) central release.

In our ex-vessel steam explosion study, conditions of the SERENA project reactor exercise for the PWR and BWR central melt release cases were considered. Simulations were carried out by applying two different jet breakup modeling approaches. In the following sections, the modeling approach and the considered ex-vessel FCI cases are described first. Next, the PWR and BWR simulations that were performed are presented. Various premixing and explosion-phase simulation results are provided and discussed. Finally, the PWR and BWR simulation results are discussed in comparison.

2. Modeling and calculation conditions

Simulations were performed with the computer code MC3D (multicomponent three-dimensional Eulerian fuel–coolant interaction code), version 3.6.8 [10,11]. MC3D is a multidimensional Eulerian code devoted to the study of multiphase and multiconstituent flows in the field of nuclear safety. The steam explosion simulation is usually carried out in two steps. First, the premixing phase is simulated followed by the simulation of the succeeding explosion phase, using the premixing simulation results as initial conditions and applying an explosion trigger.

In reactor calculations, the largest uncertainties in the prediction of the steam explosion strength are expected to be caused by the large uncertainties related to jet breakup. These uncertainties propagate through different premixing processes and result in uncertainties in the generation rate and size of the melt droplets, distribution of the melt droplets in the premixture, droplet solidification, and void fraction, all of which influence the steam explosion strength [9]. In MC3D, two jet breakup models are provided: a global model and a local one. The global jet breakup model is based on the hypothesis that jet breakup can be achieved through a correlation considering only the local physical properties of the melt, liquid, and vapor, without considering the local velocities. The local jet breakup model is based on the Kelvin–Helmholtz instability model, which also considers the local velocities. To get some insight into these uncertainties related to jet breakup, the premixing simulations were performed with both available jet breakup models.

The global jet breakup model is, strictly speaking, applicable only for single large, very hot jets in a water pool, so that fragmentation occurs due to the friction of the vapor film, whose characteristics are governed mainly by buoyant forces. The model was validated on the FARO facility steam explosion tests [12], so extrapolations to situations far from those of FARO are questionable. In this model, the rate of volumetric jet fragmentation into droplets is deduced from the comparison with a standard case:

$$\Gamma_f = \Gamma_0 \left(\frac{T_0}{T_j}\right)^{0.75} \sqrt{\left.\frac{\mu_g}{\mu_{g,0}}\right|_{p=1\mathrm{bar}} \frac{\sigma_0}{\sigma_j} \left(\frac{\rho_0}{\rho_j}\right)^{0.5}}, \tag{1}$$

where typical FARO conditions are chosen for the standard case: reference fragmentation rate $\Gamma_0 = 0.1$ m^3/m^2/s, jet temperature $T_0 = 3{,}000$ K, vapor viscosity $\mu_{g,0} = 10^{-3}$ kg/m/s, jet density $\rho_0 = 8{,}000$ kg/m^3, and jet surface tension $\sigma_0 = 0.5$ N m. The diameter of the created droplets is a user input parameter with a default value of 3 mm, which is the typical average Sauter diameter in the FARO experiments.

The local jet breakup model is based on the Kelvin–Helmholtz instability model, which was modified to take into account the multiphase aspect. In this model, the volumetric jet fragmentation rate is calculated with the following equation:

$$\Gamma_f = N_f \frac{\sqrt{\rho_j \rho_{amb} (v_j - v_{amb})^2 - \sigma_j k_{\max} (\rho_j + \rho_{amb})}}{\rho_j + \rho_{amb}},$$
$$k_{\max} = \frac{2}{3} \frac{\rho_j \rho_{amb}}{\rho_j + \rho_{amb}} \frac{(v_j - v_{amb})^2}{\sigma_j}, \tag{2}$$

where the subscript j stands for the jet and the subscript *amb* stands for the ambient fluid, the properties of which are calculated by averaging considering the phases volume fractions. N_f is the jet fragmentation parameter with an expected value between 1 and 6. Direct comparisons with the FARO experiments lead to the use of $N_f = 2$ [13]. In this model, the diameter of the created droplets d_d is related to the wavelength λ of instability, which is established from the wave number $k_{\max}$ [Eq. (2)]:

$$d_d = N_d \lambda \ , \quad \lambda = \frac{2\pi}{k_{\max}} \ . \tag{3}$$

N_d is the droplet diameter parameter with an expected value between 0.1 and 0.5; the recommend value, based on comparisons with the FARO experiments, is $N_d = 0.2$ [13].

In this study, conditions of the SERENA project reactor exercise for the PWR and BWR central melt release cases were considered. A purpose of the reactor exercise was to verify whether the pressure loads calculated by various FCI codes are consistent with each other. This objective can be reached by applying the codes to a limited number of geometries and conditions that are generic enough to hold all the