Progress in Nuclear Energy 100 (2017) 266–275

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Analysis of the dynamic pressure from ex-vessel steam explosion for pressurized water reactor

Ronghua Chen [a, **], Chenxi Li [a], Jun Wang [b], G.H. Su [a, *], Suizheng Qiu [a], M.L. Corradini [b]

[a] Shaanxi Key Laboratory of Advanced Nuclear Energy and Technology, School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an 710049, China

[b] Nuclear Engineering and Engineering Physics, College of Engineering, University of Wisconsin, Madison, WI 53706, United States

A R T I C L E I N F O

Article history:
Received 19 March 2017
Received in revised form
4 June 2017
Accepted 30 June 2017

Keywords:
TEXAS-VI
Steam explosion
Ex-vessel
TS-3 test

A B S T R A C T

In a nuclear reactor severe accident, the molten core debris may cause steam explosion when contacting with water in the reactor cavity below the reactor pressure vessel (RPV), which can endanger the containment integrity of the nuclear power plant. In this study, the improved FCI computer code TEXAS-VI considering solidification effects and the original code TEXAS-V were used to analyze the TROI TS-3 test as a benchmark experiment. Then a series of ex-vessel steam explosion simulations were performed. In the experimental comparison, the melt penetration (leading front position in the coolant) in TS-3 was well predicted by TEXAS. The pressure at different positions simulated by TEXAS-VI was notably lower than that of TEXAS-V, but in good agreement with the experiment results. The simulation results showed that the modeling of corium solidification during the mixing process and the breakup criteria in TEXAS-VI largely mitigates the rapid breakup, thereby affecting the steam explosion. Our study continued by using TEXAS-VI to analyze ex-vessel steam explosion energetics for a range of different initial conditions, with the aim to examine the impact of the fuel melt initial diameter and velocity. For conservative estimation, the cross sectional area ratio of the fuel-coolant mixing region to the injected corium was set to maximize the peak explosion impulse based on a number of parametric calculations. In scope of this study conditions, the larger the diameter and the initial injected velocity of corium were, the larger the maximum pressure and the liquid kinetic energy from the steam explosion were. The void fraction can influence the fragmentation rate during the explosion stage and mitigate the propagation of the pressure pulse during the propagation stage. The liquid kinetic energy would be affected by the pressure from the steam explosion and the void fraction at the end of mixing stage.

1. Introduction

In a nuclear reactor core severe accident, when molten core debris ("corium") comes into contact with water in the ex-vessel reactor cavity, an energetic fuel-coolant interaction (steam explosion) could occur. In this case, water evaporates rapidly, and can cause shock waves due to the rapid heat transfer between the corium and water. The shock waves and dynamic pressures can endanger the integrity of the containment building (Su et al., 2015). It is important to have a good understanding of the process.

A typical steam explosion involves four stages, namely the mixing, triggering, propagation and expansion (Board and Hall, 1976). First, for the mixing stage, the corium contacts the coolant as it is surrounded by a stable steam film and fragments into smaller particles due to fluid instabilities; i.e. Kelvin-Helmholtz (KH) instabilities, Rayleigh-Taylor (RT) instabilities and boundary layer stripping. The breakup process can occur in the jet leading edge and the main body (Theofanous and Saito, 1981). The leading edge is principally affected by the RT instability, while the jet main body is affected by KH instability. Triggering is the second stage, where the steam explosion could be self-triggered due to pressure fluctuations from coolant nearby or from outside pressure disturbances (Kim and Corradini, 1988). The pressure wave caused by the contacting walls or external loads would destabilize the stable vapor film. With the collapse of the vapor film, the fuel-coolant mixture experiences a rapid propagating steam explosion. This propagation stage can be described as a chain reaction, as the local

* Corresponding author.
** Corresponding author.
E-mail addresses: rhchen@mail.xjtu.edu.cn (R. Chen), ghsu@mail.xjtu.edu.cn (G.H. Su).

http://dx.doi.org/10.1016/j.pnucene.2017.06.019
0149-1970/

pressure shock wave spreads into the neighboring region. This then causes the neighboring melt to rapid breakup, leading to more intensive shock waves. In the KROTOS experiments (Piluso et al., 2015), the molten alumina mixes with water causing peak shock pressures over 100 MPa and explosion propagation speeds of 650–1000 m s^{-1} in the melt-water mixture (Hohmann et al., 1995). For molten corium, KROTOS tests showed lower shock pressures and propagation speeds (Huhtiniemi and Magallon, 2001). The final expansion stage can produce mechanical damage to the surrounding structures. The details of steam explosion phenomena have been intensively studied in the last decades in two major international cooperation programs: International Standard Problem (ISP) (1996–1997) (Annunziato et al., 1998) and the OECD-SERENA program (Phase1:2002–2005, Phase2:2007–2012) on FARO, KROTOS and TROI steam explosion facilities (OECD-NEA et al., 2014). Researchers have not only performed experiments, but have also developed different FCI computer codes to analyze these steam explosions. Meignen et al. (2014a) summarized complementary analyses and experimental programs. The summary report of SERENA Phase2 (OECD-NEA et al., 2014; Hong et al., 2013) concluded that the FCI process could be simulated with these computer models and able to provide reactor scale safety assessments. For the OECD-SERENA program, melt solidification effects for both the mixing and explosion phases were considered as the key reason for the corium test results compared to alumina test results. Melt solidification models were developed for such codes as TEXAS (Chen et al., 2013b), JASMINE (Moriyama et al., 2016), MC3D (Meignen et al., 2014a; 2014b).

The ex-vessel steam explosion is an important phenomenon that should be analyzed to evaluate containment integrity (Su et al., 2013). In a PWR reactor cavity geometry, steam explosion energetics are affected by the cooling of the melt jet and the pressure loads are affected by many parameters, such as the inlet diameter, the melt's velocity, the initial melt temperature, the water pool depth and the melt droplet diameters during mixing and at the triggering time. The influences of these uncertainty parameters have been studied by applying the FCI codes in recent years. The ratio of water pool depth and the melt jet breakup length would dominate the cooling performance during the melt discharge transient (Moriyama et al., 2016). The depth of water also had nearly linear impact on the potential load (Moriyama and Park, 2015). The axial and the side melt release apparently differed from each other in the pressure loads (Leskovar and Uršič, 2015). The pressure loads at the cavity walls could also be influenced by the size of the reactor cavity since the explosion pressure wave was significantly weakened once reaching the wall in a large cavity (Leskovar and Uršič, 2016).

In our study, TEXAS-VI considers solidification effects for both the mixing and the explosion phase (Chen et al., 2013b). TEXAS-VI was applied to analyze the OECD-SERENA-2 experiment, TROI TS-3, to further validate its applicability. And the ex-vessel steam explosion was analyzed by TEXAS-VI. First, the influence of the cross sectional area of the mixing region was considered. For conservative estimation, the cross sectional area of the fuel-coolant mixing region was determined by parametrically varying the diameters to maximize the explosion energetics, i.e., peak explosion impulse. Then five conditions considering the influence of the initial diameter and velocity of the melt on the steam explosion were simulated.

2. A brief introduction of TEXAS

A number of FCI computer codes have been developed to observe the steam explosion. These codes could simulate the process in fair agreement with the experiment results and contributed to the reactor scale assessment. Over the past several years, the **T**hermal **EX**plosion **A**nalysis **S**imulation model (TEXAS) has been developed and applied for the fuel coolant interaction (FCI) analysis. The original TEXAS was developed to analyze the fuel-coolant interaction experiments for LMFBR safety issues (Young, 1982). A dynamic fragmentation model based on Rayleigh-Taylor instabilities and a complete set of constitutive correlations for interfacial heat and mass transfer were developed by Chu and Corradini (1989). Several developments to the fragmentation model for propagation stage was introduced by Tang and Corradini (1993). A chemical reaction model to analyze the heat generation by oxidation metallic melt was modified by Murphy, 1992. The main elements constituting the TEXAS-VI are summarized as follows.

1) The TEXAS-VI is a one-dimensional model, transient and three-fluid, used for analysis of fuel-coolant interactions. The three fields include one Lagrangian field for molten fuel particles and two Eulerian fields for coolant liquid and vapor.
2) A complete Eulerian two-fluid model was employed to calculate the conservation equations of mass, momentum and energy between the vapor and liquid coolant phases as well as the heat transfer between water and the melt. Momentum and energy equations were applied to the Lagrangian fuel particle field.
3) In the mixing stage, the time-independent correlation based on the Rayleigh-Taylor instabilities is,

$$D_{f,k}^{n+1} = D_{f,k}^{n}\left(1 - C_o \overrightarrow{t} We^{0.25}\right) \tag{1}$$

Where, D is the fuel particle diameter, and the superscripts indicate the timestep value; We is the Weber number for the melt particles; $\overrightarrow{t}$ refers to a dimensionless timestep; C_0 is the constant related to the density of the coolant and melt particles. The solid crust layer will prohibit the interface from bending, and the surface solidification can reduce the interfacial instability and prevent particle fragmentation. Based on the impacts of the modified Aeroelastic number Ae^*, the stress intensity factor K and the Weber number We, a fragmentation criterion for mixing stage was used in TEXAS-VI to analyze the solidifying particle breakup behavior (Chen et al., 2013a).

$$IF\begin{cases} We > We_{cri}\ Then\ \text{if} \begin{cases} Ae^* > Ae\ or\ K_{IT} > K_{IC}\ \text{Breakup} \\ Ae^* \le Ae\ \text{and}\ K_{IT} \le K_{IC}\ \text{No breakup} \end{cases} \\ We \le We_{cri}\ \text{No breakup} \end{cases} \tag{2}$$

4) In the explosion stage, a semi-empirical explosive fragmentation model was used to analyze the explosion process.

$$m_{fr} = 6C_{fr}m_{f,k}\sqrt{(P-P_{th})\Big/\left(\rho_C R_{f,k}^2\right)}\,Y \tag{3}$$

Where, m_{fr} is the melt fragment mass, and Y is the compensation factor for coolant void fraction, at which fuel fragmentation ceases, i.e., Y is one at low void fraction and zero at high void fraction. C_{fr} is the fragmentation constant which is set to be 0.002. There is also a fragmentation criterion for explosion phase. The criterion was based on the concept of the water jet impingement on the particle surface and the vapor film boiling collapse.