Evaluation of Dynamic Pressures from Ex-Vessel Steam Explosion using TEXAS-V

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1. Introduction

An Ex-vessel steam explosion might occur when hypothetical severe reactor accident causes reactor vessel fails and the molten core pours into the water in the reactor cavity. A steam explosion is a fuel coolant interaction process where the heat transfer from the melt to water is so intense and rapid that the time scale for heat transfer is shorter than the time scale for pressure relief. A steam explosion is a complex, highly nonlinear, coupled multi-component, multi-phase phenomenon [1].

For the last several decades several computational models have been developed to evaluate the steam explosion energetics. The models have been verified with a number of experiment data and recently successfully analyzed in-vessel and ex-vessel steam explosions in new and advanced reactor designs. The TEXAS-V code is one of the models that have a unique feature employing the jet breakup model for the mixing phase and explosion models for the explosion triggering and propagation in one-dimensional fashion. The one-dimensional approach to analyze the steam explosion in this model, however, has a limitation to simulate the reactor case that has multi-dimension in nature. Therefore, in this work, the limitation of the TEXA-V code is supplemented by employing a commercial CFD code that evaluates the dynamic steam explosion pressure propagation from the FCI mixing zone to the reactor cavity wall. In this paper, the initial effort of this attempt is reported and explained the results.

2. The Analysis Methodology for Steam Explosions and Propagations in an Ex-Vessel Cavity

2.1 TEXAS-V Model for Steam Explosions

The TEXAS-V model is a one-dimensional mechanistic model for fuel-coolant interaction; mixing, rapid fragmentation/vaporization, shock propagation and expansion during the steam explosions developed by Corradini and co-workers [2]. It is important to note that the current FCI models including TEXAS-V are still lack in capability of providing fundamental reasons of substantially lower energetics of molten corium than those observed in various simulants. Thereby steam explosion energetics for reactor applications estimated by the current mechanistic models can be considered to be conservative. For the applicability of the 1-D TEXAS-V code to the reactor case, the calculation is carried out by parametrically varying the diameter of the mixing zone to maximize the explosion energetics for the given initial and boundary conditions that provides more conservatism on its estimation of steam explosion energetics.

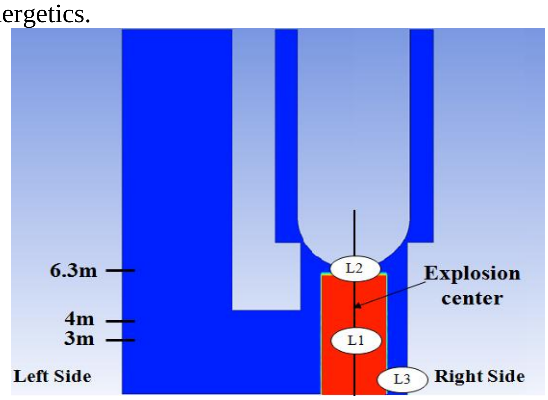

Fig. 1 Geometry of CFX computational model of reactor

2.2 CFD Model for Explosion Pressure Propagation

For the explosion propagation under the cavity water from the explosion zone, a commercial CFD code, CFX 5.7.1 [3] was employed. A typical PWR cavity geometry was selected and modeled in two-dimension for the CFD analysis as shown in Figure 1. In the figure, the geometry of the reactor cavity and the pre-set FCI explosion (mixing) zone were defined. In order to examine the effect of the water level and mixing zone size, three different heights, 3m, 4m, and 6.3m, representing the water height were tested. The explosion pressure of 55 MPa was set for the initial explosion pressure at the zone. The radius of the explosion zone was assumed to be 1.5m. In this analysis, CFX modeled water in the cavity to be compressible and the k-ε turbulent model for the effect of turbulence. The CFD model employed in this analysis has a relatively coarse numerical grid for the shock-front capturing, causing the numerical oscillation and thus the calculation often did not converge. For the remedy, all discontinuous initial conditions were relaxed with the differential sigmoid-type function suggested by Leskovar et al. [4].

3. Results for EVSE Energetics and Pressure Propagation in the Cavity

3.1 TEXAS-V Initial and Boundary conditions and Results

For the TEXAS analysis, the base case was selected when the RPV failed at the bottom due to the ICT failure and the cavity water was passively filled up to

Table 1. Initial and Boundary Conditions for TEXAS-V

Parameter		Conditions
Amb. Pressure		0.2 Bar
Corium Jet	Composition	70w/o UO_2-30w/o ZrO_2
	Temperature	2950 K (100 K Superheat)
	Diameter	0.5 m
	Velocity	2 m/s
Water	Free Fall	0.1m
	Pool Height	6.3m
	Temperature	303 (90K Subcooling)
Trigger	Position	Cavity Bottom
	Strength	1.5 MPa

the level of 6.3 m from the reactor cavity floor. The initial and boundary conditions for the analysis were set as shown in Table 1. Under the conditions, the TEXAS-V analysis results as shown in Figure 2 showed that the maximum explosion pressure reached up to approximately 55 MPa at the bottom of the cavity and decreased along the axial direction.

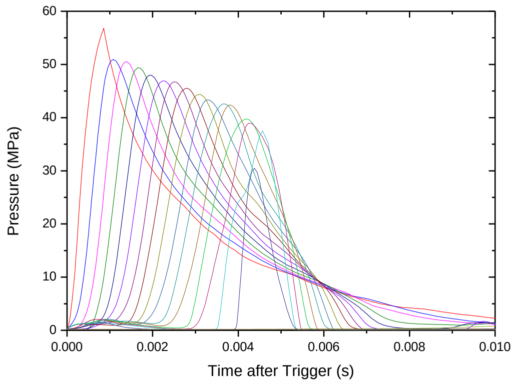

Fig. 2 The maximum pressures along the axial direction from the TEXAS-V calculation

3.2 CFD Analysis Results for Pressure Propagation

The maximum explosion pressure of 55 MPs analyzed by TEXAS-V was set to the initial pressure at the boundary of the explosion (mixing) zone and the underwater shock propagation was tested by the CFX code. Figure 3 shows the simulation results on the pressure propagation. It is noticed that the shock pressure become wide and spreading due to the numerical diffusion caused by the initial smoothening of the shock front as well as the coarse grid in the computational domain. The diffusion eventually results in lower peak pressure along the radial direction as well as the unexpected increase of the shock pressure when it approaches to the rigid cavity wall boundaries. Figure 4 shows the pressure histories at various radial locations for the calculation shown in Figure 3. By knowing the difficulties, Diab et al. [5] used the acoustic model for the same purpose. However, the evaluated pressure waves largely oscillate in harmonic frequency and have no dissipation effect that requires under-defined damping effect on or near the rigid boundary.

However, under this inherent difficulty, the calculation shows a potential to stably simulate the underwater shock propagation due to steam explosion to complement the 1-D steam explosion code like TEXAS-V without significant discrepancies.

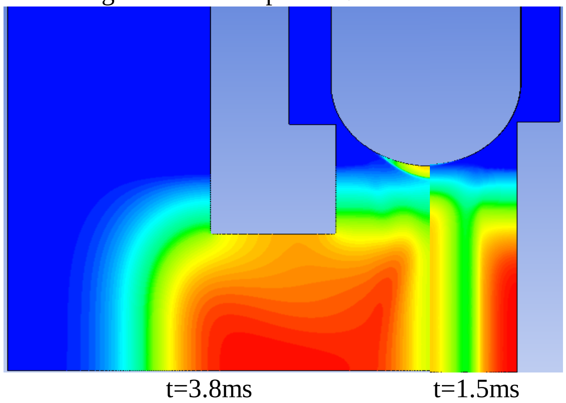

Fig. 3. Pressure contour during the propagation

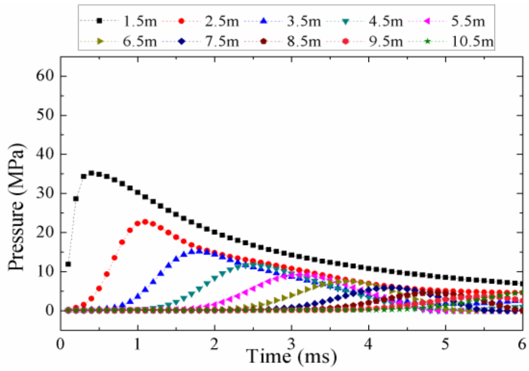

Fig. 4. Pressure measured from the explosion center to the left side of wall in the reactor model

4. Conclusion

In this study, ex-vessel steam explosion analysis for a typical LWR geometrical configuration and conditions using TEXAS-V for steam explosion energetics and CFX for complementary shock propagation in cavity water. In spite of the numerical difficulties on simulating underwater shock front, the analysis provides the characteristics of the underwater shock propagation, complementing the capacity of 1-D TEXAS-V for reactor applications.

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REFERENCES

[1] Berthoud, G., 2000, Annu. Rev. Fluid Mech. 32(2000), pp. 573-611.
[2] Corradini, M. et al., TEXAS-V User Manual, U. of Wisconsin, Madison, USA, 2002.
[3] Ansys-CFX, Version 13.0, 2009
[4] Leskovar, M., et al., JSI, Ljubljana, Report IJS-DP-9103, 2005,
[5] Diab, A., et al., Nucl. Tech., **169**, 114-125, 2010