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Characteristics of the Pressure Wave Propagation in Cooling Water of Reactor Cavity at a Steam Explosion

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1. Introduction

During severe accidents, the reactor pressure vessel can be penetrated by molten corium, which can then come into contact with the cooling water [1]. This interaction has the potential to result in a steam explosion. This phenomenon consists of four essential stages: premixing, triggering, propagation, and expansion [1,2]. Specifically, the explosion produces powerful pressure waves that can impact the structural integrity of the reactor cavity. Although there have been many studies that have used computational fluid dynamics (CFD) and hydrodynamic codes to simulate steam explosions [1-4], there is still a lack of research on how these pressure waves affect the components and structures in the containment building. The objective of this study is to obtain important information for assessing the characteristics of pressure wave propagation in the cooling water of the reactor cavity during a steam explosion [5]. This will be achieved by employing the arbitrary Lagrangian-Eulerian (ALE) and fluid-structure interaction (FSI) techniques [5].

2. Methodologies

2.1 Material models for TNT, water, and air

The Jones-Wilkins-Lee (JWL) state equation is employed to simulate the explosion of TNT, which establishes the correlation between pressure and specific internal energy during an explosion [6]. In order to simulate their behavior under shock wave conditions, the Gruneisen equation of state and a linear polynomial equation are employed to model water and air, respectively [6]. The null material model is selected for air and water because of its capacity to calculate fluid stresses, incorporate strain rate, and define dynamic viscosity [7]. These models are necessary for the precise simulation of the interaction between structures and fluids during a steam explosion.

2.2 Arbitrary Lagrangian–Eulerian and fluid–structure interaction methods

The ALE method effectively manages fluid-structure interactions and large deformations by integrating the advantages of Lagrangian and Eulerian algorithms [8, 9]. The ALE method is employed in this investigation to simulate the interaction between the reactor structures (modeled as Lagrangian elements) and the cooling water (modeled as Eulerian elements) [8, 9]. The relative displacement between coupled Lagrangian nodes and the fluid is monitored by the FSI method, which is based on a penalty-based formulation [8, 9]. This method is used to proportionally determine these coupling forces [8, 9].

2.3 Mesh sensitivity of fluid model using 1D ALE method

In order to determine the optimal mesh size for the fluid model, a mesh sensitivity analysis is applied to five different mesh sizes (10, 30, 50, and 90 mm) [5]. The empirical predictions (Cole's model) are compared to the peak incident pressures from the numerical simulations in the analysis [5]. The results indicate that a mesh size of 50 mm is appropriate for simulating the propagation of pressure waves in the reactor cavity, as shown in Fig. 1 [5]. This mesh size achieves a balance between computational efficiency and accuracy [5].

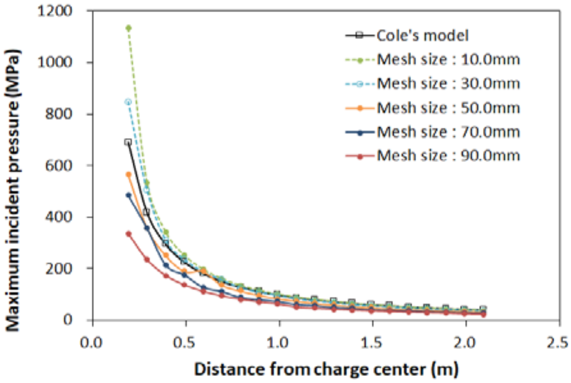


Fig. 1. Comparison between 1D ALE analysis and empirical results of the incident pressure [5].

2.4 FE modeling

The reactor cavity's concrete, reinforcements, liner plate, and basemat are modeled using finite element methods [5]. To accurately simulate dynamic loading effects, the concrete is modeled using solid elements, with varying element sizes utilized in areas that cooling water [5]. Beam elements are employed to model the reinforcements, while shell elements are employed to model the liner plate [5]. To simulate the real-world behavior of the reactor cavity structures under dynamic loading, boundary and symmetry conditions are implemented in the finite element model [5]. In order to simulate incident pressure waves, the ALE analysis incorporates fluid models for cooling water and air [5]. For the FSI analysis, the combined model with structures is employed to simulate reflected pressure waves [5]. The equivalent mass (4.9 kg) of the TNT model is determined by the thermal energy of molten corium, and it is positioned at the corner of the reactor cavity to simulate a steam explosion, as depicted in Fig. 2 [5].

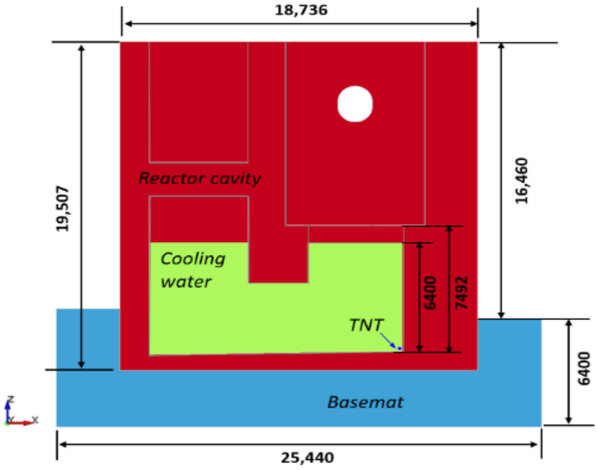
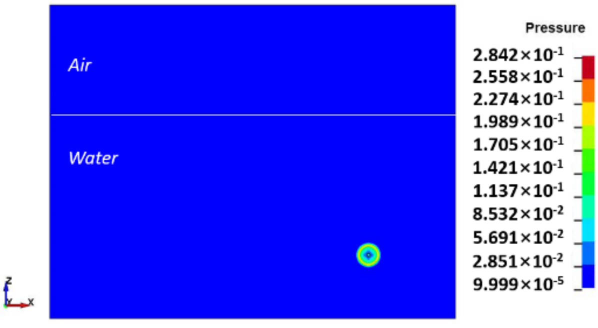


Fig. 2. TNT detonation position for numerical analysis (unit: mm) [5].

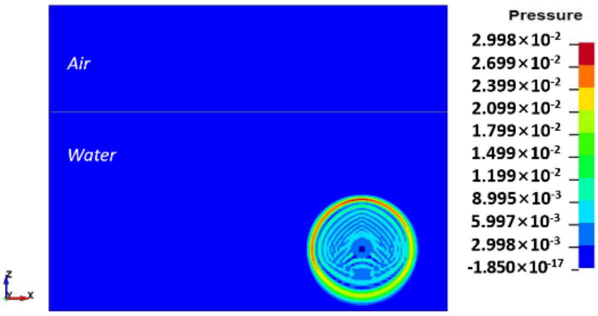
3. Numerical results

3.1 Characteristics of the incident shock wave propagation

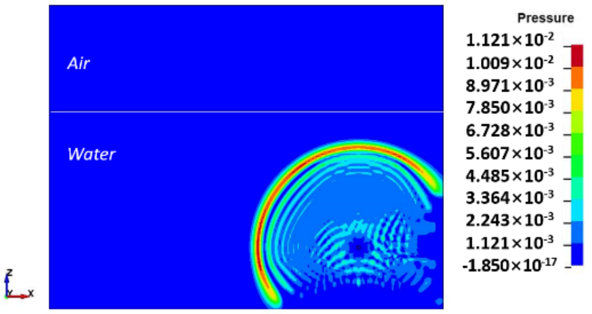
The propagation of pressure waves within the cooling water after a TNT detonation for steam explosions is analyzed through different time frames [5]. Initially, the incident shock waves radiate spherically outward from the detonation point, as shown in Fig. 3(a) [5]. These waves expand along both the x and z axes at different intervals, as seen in Figs. 3(b) and 3(c) [5].



(a) t=0.2 ms



(b) t=1.4 ms

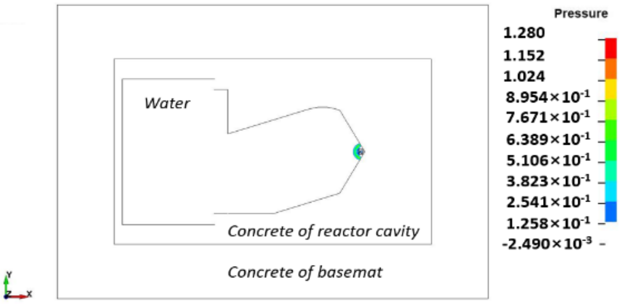


(c) t=3.0 ms

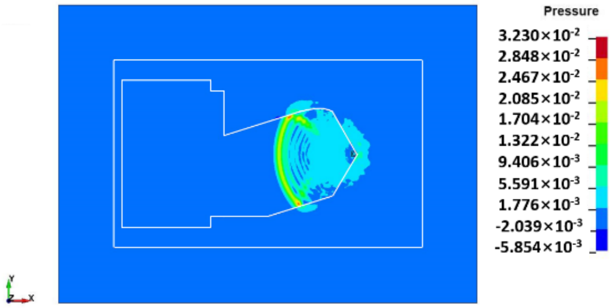
Fig. 3. Propagation contour of the incident pressure waves in the cooling water at different times (unit: GPa) [5].

3.2 Characteristics of the reflected shock wave propagation

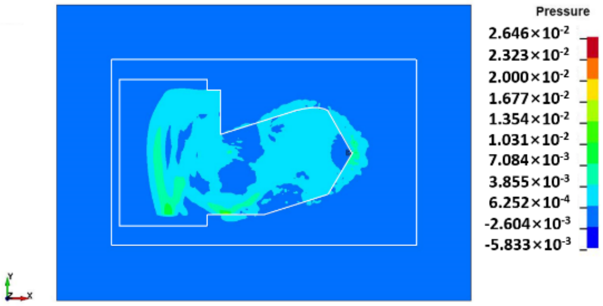
An analysis of the reflected pressure waves in the reactor cavity is then conducted [5]. The structural walls of the reactor cavity interact with the incident shock waves [5]. The shock waves are then reflected and dispersed in a spherical pattern upon impacting the corner of the reactor cavity [5]. This results in numerous reflections within the cavity, particularly at the interfaces between the cooling water and the walls of the reactor cavity, as illustrated in Figs. 4(a) to 4(c) [5]. The reflected waves continue to propagate toward the corner regions of the cavity, despite their diminished magnitude, as illustrated in Fig 4(d) [5]. As shown in Fig. 4(e), the pressure distribution within the cooling water and reactor structures returns to a relatively uniform ambient state at 50.0 ms [5].



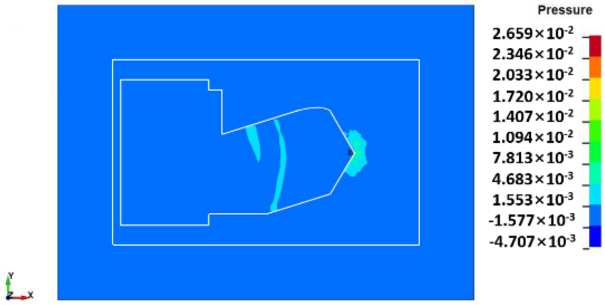
(a) t=0.1 ms



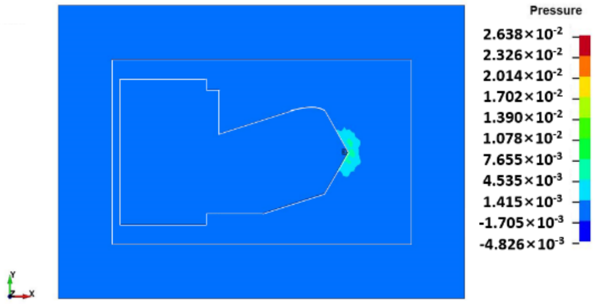
(b) t=3.0 ms



(c) t=8.0 ms



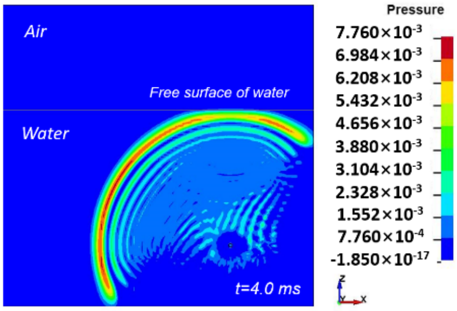
(d) t=15.0 ms



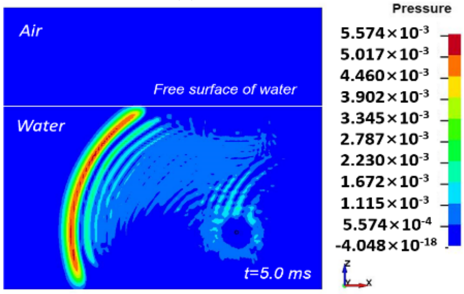
(e) t=50.0 ms

Fig. 4. Propagation contour of the reflected pressure waves in the reactor cavity and basemat at different times (unit: GPa) [5].

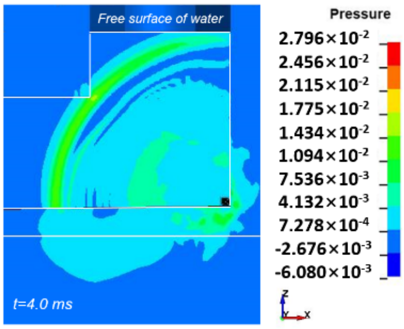
The analysis also investigates the interaction between the free surface of the cooling water and these pressure waves [5]. As *seen* in Fig. 5, the surface is reached by both incident and reflected waves within 4.0 ms [5]. The waves undergo a transformation into tensile shock waves upon reflection as a result of the acoustic impedance difference between air and cooling water [5]. In the event that rarefaction waves propagate back through the cooling water-air interface, the cavitation surface cutoff effect results in a rapid pressure drop on the free cooling water surface that approaches zero [5]. It is important to note that the reflected pressure waves do not have a significant impact on the reactor pressure vessel, which is located 0.6 meters above the free cooling water surface [5].



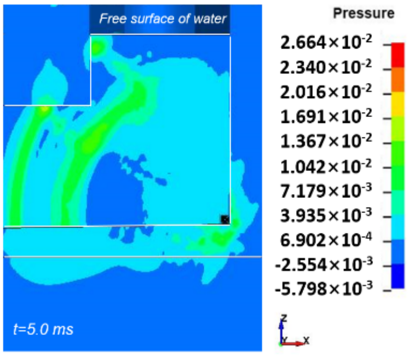
(a) t=4.0 ms



(b) t=5.0 ms



(c) t=4.0 ms



(d) t=5.0 ms

Fig. 5. Propagation contour of the incident (a, b) and reflected (c, d) pressure waves near the free water surface (unit: GPa) [5].

4. Conclusion

This study aims to investigate the propagation of pressure waves resulting from a TNT detonation at a steam explosion. As indicated by the numerical results, the corner is directly affected by the incident pressure waves, which results in pressure-structure interactions that generate reflected pressure waves. Reflected waves propagate spherically and undergo multiple reflections at the interfaces between the cooling water and the inner walls. Additionally, the reflected pressure waves travel from the TNT charge center to the free cooling water surface, where their pressures are rapidly reduced and approach near zero.

Acknowledgements

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REFERENCES

[1] S.H. Kim, Y.S. Chang, S.C. Song, Y.J. Cho, Structural assessment of fully flooded reactor cavity and penetration piping under steam explosion conditions, Int. J. Press. Vessels Pip., 131, p.36-44, 2015.
[2] S.H. Kim, Y.S. Chang, Y.J. Cho, M.J. Jhung, Modeling of reinforced concrete for reactor cavity analysis under energetic steam explosion condition, Nuc. Eng. Technol., 48, p.218-227, 2016.
[3] L. Cizelj, B. Končar, M. Leskovar, Vulnerability of a partially flooded PWR reactor cavity to a steam explosion, Nucl. Eng. Des., 236, p.1617-1627, 2006.
[4] Z. Chunyu, C. Pengb, Z. Juanhuab, L. Jimingb, L. Yulanc, Z. Shishunb, W. Biao, Evaluation of the structural integrity of the CPR1000 PWR containment under steam explosion accidents, Nucl. Eng. Des., 278, p.632-643, 2014.
[5] S.K. Ha, Y.H. Yoon, Numerical simulation of pressure wave propagation and its effect on damage to the reactor cavity under TNT detonation for steam explosion, Buildings, 13, 2152, 2023.
[6] LS-DYNA. Keyword User’s Manual: Volume II, Material Models; Livermore Software Technology Corporation (LSTC): Livermore, CA, USA, 2017.
[7] T. Trevino, Applications of Arbitrary Lagrangian Eulerian (ALE) Analysis Approach to Underwater and Air Explosive Prob-lems. Master’s Thesis, Naval Postgraduate School, Monterey, CA, USA, 2000.
[8] D.J. Benson, Computational methods in Lagrangian and Eulerian hydrocodes, Comput. Methods Appl. Mech. Eng., 99, p.235-394, 1992.
[9] G. Yang, G. Wang, W. Lu, X. Zhao, P. Yan, M. Chen, Cross-section shape effects on anti-knock performance of RC columns subjected to air and underwater explosion, Ocean Eng., 181, p.525-266, 2019.