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Feasibility of shock attenuation by simple obstacles in mitigating severe accident explosive loads

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ABSTRACT

Fukushima severe accident showed that explosions are no longer exclusive in nuclear power plants and creative safety features would be beneficial to preserve the integrity of vital components against such explosions. Based on this motivation, simple obstacles are suggested as a means to attenuate shock waves that may arise from severe accident explosions and the effectiveness is investigated by computations employing fully compressible viscous Navier–Stokes equations of the FLUENT code. Two- and three-dimensional computations for a shock tube filled with air are performed and the computed peak pressure and arrival time are validated against existing experimental data and analyses. Effects of structural shapes and rectangular rigid obstacles on shock attenuation in simple geometries are preliminarily analyzed and the results show that the end wall peak pressure is reduced by about 18–30%. As a demonstration in a plant scale, a high pressure source of 0.2 m radius semicircle is positioned at the bottom center of the two-dimensional hypothetical reactor cavity model (5.4 m by 9.4 m) and multiple rigid obstacles are positioned at the half-way between a reactor vessel and the pressure source. Incident circular shock wave is dispersed by the obstacles and the peak pressures at the reactor vessel bottom head center and the 45° regions are reduced by about 35% and 50%, respectively. This study implies the feasibility of simple obstacles for attenuating shock waves from the explosions expected under nuclear power plant severe accidents.

1. Introduction

After Fukushima accident, a new need is raised for preserving integrity of vital components and structures in a nuclear power plant against blast waves from hydrogen explosions during severe accidents in nuclear power plants (Tsuruda, 2013). Explosive events expected under severe accidents are steam and hydrogen explosions as schematically shown in Fig. 1. One imaginable scenario is a steam explosion which may occur when the corium ejected from a reactor vessel penetrates deep water flooded in a cavity and another scenario is a hydrogen explosion which may take place when the hot corium on a dry cavity floor ignites combustible gases (mainly hydrogen and carbon monoxide) already generated during the processes of zirconium-steam reaction and molten core concrete interaction (MCCI).

Huge amount of research has been performed for about 30 years after Three-Mile Island core melting incident in relation with hydrogen explosions and they may include hydrogen source rate, distribution in containment, and deflagration and detonation, transition from deflagration to detonation (DDT), and design of hydrogen removal by using igniters and passive autocatalytic recombiners (PARs) and so on (Sahina and Sarwar, 2013). For a steam explosion, a plenty of experimental and analytical research has been also carried out on the mechanism and the phenomena and their impacts on the structures. Nevertheless, there still exist debates and controversies on the experimental findings and further research is needed (Hansson et al., 2013).

Therefore, it would be beneficial especially for conventional operating reactors if we find simple and passive means of attenuating or mitigating explosive loads to the reactor vessel and neighboring structures under such explosion events as shown in Fig. 1. Regarding this prospect, the present authors are looking for cost-effective mechanical and/or hydrodynamic methods for attenuating such shock waves that are generated from the explosions that may occur during the nuclear power plant severe accident scenarios.

Measures of attenuating shock loads in air and water can be broadly classified into three categories: (1) mechanical measures using barrier, foam, porous media, etc. (Berger et al., 2010; Chaudhuri et al., 2013; Sha et al., 2012) (2) hydrodynamic methods such as water sheet or mist in air (Willauer et al., 2009; Cheng

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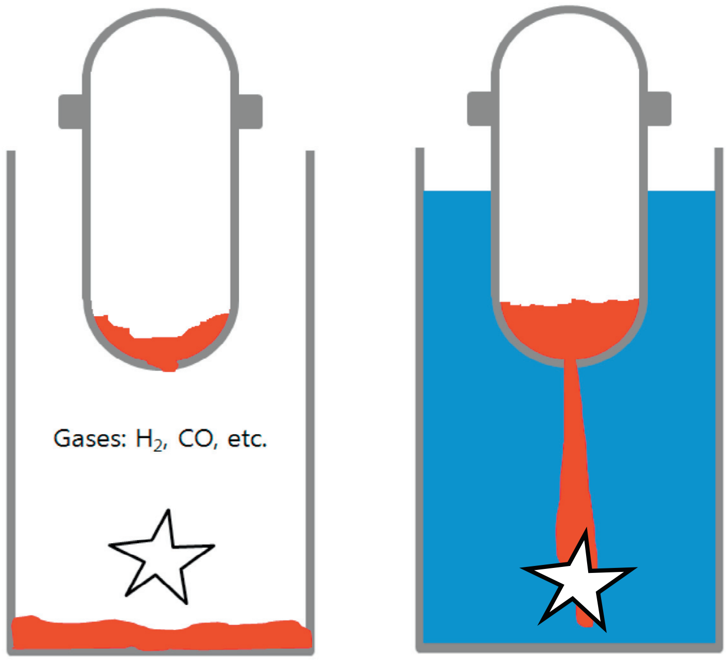

(a) Hydrogen explosion in a dry cavity (b) Steam explosion in deep water

Fig. 1. Explosion scenarios inside a reactor cavity during a severe accident.

et al., 2005; Resnyansky and Delaney, 2006), and (3) hydrodynamic methods using micro bubbles in water or liquids. (Oakley et al., 2006; Gefken and Greenfield, 2000; Moshman, 2011). For the first case, which the present authors are mainly interested, previous investigations on the interaction of incident shock wave with baffles in a tube have been performed from the viewpoint of industrial applications. Since the obstacles provide significant attenuation of oncoming shock waves, they may be possibly applied to protection against shock wave hazards in nuclear power plants. The strength of transmitted shock wave is generally attenuated due to the interaction between the shock front and the obstacle.

Several types of obstacles with various configurations were also proposed to investigate the most effective baffle-geometry to attenuate incident shock waves (Takiya et al., 1998, 2012). Takiya et al. (2012) investigated attenuation of incident shocks by means of baffle obstacles in a tube. They clearly explained about the geometrical effects of the orifice, the conical baffle and the nozzle on the shock attenuation. Numerical computations were performed to analyze the problem with respect to shock speed and arrival time at specified locations by solving unsteady 2D Euler equations. Simulations were performed for a two dimensional tube with 40 mm height with three kinds of model obstacles. Their noticeable result was that the most effective geometry to attenuate propagating shock waves by an obstacle is to use a conical nozzle in a tube.

Long (2008) studied such effects as grid dependence, numerical scheme dependence, viscous effects, 2D or 3D dimensions on the shock wave propagation speed and time variation of end-wall pressures. The computations were compared with the experimental data from his own shock tube. The shock tube utilized difference in pressures to generate high-enthalpy and high-speed flows. The mesh dependence was minor for the 2D model with 4000–8000 cells ($1.21 \times 10^{-4}\ m^2$ per one cell) and the 3D model with meshes more than 16848 cells ($3.6 \times 10^{-6}\ m^3$ per one cell). For the numerical schemes for 2D computations, coupled-implicit scheme provided good estimation of peak pressure whereas coupled-explicit scheme was good in predicting first plateau pressure and pressure decay. For the 3D case, coupled-implicit scheme was considered more suitable to catching peak pressures.

More extensive shock tube computations were performed by Lamnaouer (2010), who developed an axi-symmetric shock-tube model to simulate the shock-wave propagation and reflection in both non-reactive and reactive flows and performed diverse sensitivity simulations for the high-pressure shock tube at Texas A&M University. Computations were carried out using the CFD solver FLUENT based on the finite volume approach and the AUSM+flux differencing scheme. Adaptive mesh refinement (AMR) algorithm was applied to time-dependent flow fields to accurately capture and resolve shock and contact discontinuities as well as very fine scales associated with viscous and reactive effects. A conjugate heat transfer model was incorporated which enhanced the credibility of the simulations.

Literatures stated above provide the present authors with a good starting point of developing fundamental concept of engineering measures for mitigating shock waves that may generate from nuclear power plant severe accidents and the present study is mainly focused on the attenuation of shock waves in air (mainly considering hydrogen explosion) by geometrical means in a macroscopic point of view. On this purpose, benchmarking simulations of shock wave propagations in air for varying computational parameters such as dimension, mesh, time step size and equation of state are firstly performed for an existing shock tube. Also, shock wave interaction with an orifice which was originally analyzed by Takiya et al. (2012) is computed for qualitative comparison of density contours. Fluid dynamic computations are carried out using the fully compressible equations of the FLUENT code based on the finite volume approach and the AUSM+flux differencing scheme (ANSYS, 2011). Based on these validation analyses, simulations are performed for prediction of shock wave interactions in air with structures to find out effectiveness of geometrical shaping and obstacles to attenuate shock wave energy in a small scale and finally a demonstrative analysis is performed for a practical plant scale.