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Three-dimensional CFD analysis of hydrogen-air-steam explosions in APR1400 containment

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HIGHLIGHTS

- Full-scale 3D CFD analysis of hydrogen explosions in APR1400 containment is presented.
- A new cost-effective lumped parameter code to CFD coupling strategy is proposed.
- In the Station Black-Out accident, the three-way valve is a major safety improvement.
- Most critical conditions are found in the In-containment Refueling Water Storage Tank.

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ABSTRACT

The present study concerns the three-dimensional CFD analysis of hydrogen explosions in APR1400 containment. Initial conditions for combustion simulations are obtained by a cost-effective coupling with a lumped parameter code for preceding mixture distribution analysis. Three severe accident scenarios are examined: Small-Break Loss-Of-Coolant Accident (SB-LOCA) and Station Black-Out (SBO) with activated as well as deactivated three-way valve. Only in the last case, thermal ignition of the hydrogen-air-steam mixture could be triggered. Flame propagation in the containment and particularly in the In-containment Refueling Water Storage Tank (IRWST) is investigated in detail. Additional generic scenarios demonstrate the methods ability to reproduce strong Flame Acceleration (FA) and even the hazardous Deflagration-to-Detonation Transition (DDT).

1. Introduction

1.1. Advanced Power Reactor 1400

This brief description of the nuclear reactor follows closely the specifications and explanations in Liang et al. (2014).

The Advanced Power Reactor 1400 (APR1400) with an electric power output of 1400 MW houses two primary coolant loops. Each loop consists of one steam generator and two reactor coolant pumps which are connected to the reactor pressure vessel by one hot leg and two cold legs. The reactor containment building is of cylindrical shape, capped by a hemispherical dome. A height from the reactor cavity floor to the apex of the containment dome of 79.4 m and an inner radius of the containment wall of 22.86 m results in a free gas volume of approximately 90,000 m^3. The containment building is constructed of pre-stressed concrete, complemented by an inner steel liner to prevent accidental release of radioactive material to the environment. The containment design pressure is reported to be 5.1 bar. To improve seismic resistance, the reactor containment building is founded on a common basemat with the auxiliary building. Four units each are currently under construction in South Korea and the United Arab Emirates.

As for other Pressurized Water Reactors (PWR), the hydrogen produced during the in-vessel phase of a core meltdown accident is directly released to the containment through a cold-leg or hot-leg break in case of a Loss-Of-Coolant Accident (LOCA) in APR1400. For a high pressure Station Black-Out (SBO) accident, the primary system is depressurized through an In-containment Refueling Water Storage Tank (IRWST). This annular tank is located in the lower part of the containment, stores the refueling water, and serves as a water source for cavity flooding and the containment spray system. It is further utilized as a discharge location for the reactor coolant system's safety bleed operation.

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The so-called Containment Spray Actuation Signal (CSAS) activates the pumps which ensure a constant water supply to the spray system. Before being injected into the containment, the temperature of the water from the IRWST is decreased at heat exchangers. The main spray nozzles are mounted at four spray rings installed on the liner in the containment dome. Auxiliary spray nozzles are mounted at two spray rings installed in the annular compartment below the operating deck. The CSAS can be triggered automatically by a pressure sensor in the containment or manually by a control room operator.

The Hydrogen Mitigation System (HMS) is designed for the amount of hydrogen resulting from 100% oxidation of the fuel rod cladding in degraded core accidents. It limits the average volumetric hydrogen concentration in the containment to 10%. The HMS consists of 30 Passive Auto-catalytic Recombiners (PAR) and 10 glow plug type igniters in the investigated APR1400 configuration.

1.2. Investigated accident scenarios

Three accident scenarios are investigated: Small-Break Loss-Of-Coolant Accident (SB-LOCA) and SBO with activated as well as deacticated three-way valve. Information on the sequence of events is provided by KEPCO E&C, the manufacturing company of APR1400. According to experiences of KEPCO E&C, the regions of primary interest in terms of hydrogen risk analysis are the steam generator compartment and the IRWST.

1.2.1. Small-Break Loss-Of-Coolant Accident (SB-LOCA)

For the LOCA scenario, two release points are taken into account. Representing the initiating event, the first release point is located at the break of the hot leg (connecting the reactor pressure vessel with the steam generator) and has an area of 0.02 square feet. The second release point is located on the lower half of the reactor vessel, resulting from reactor vessel breach.

According to these boundary conditions, peak hydrogen concentrations occur in the steam generator compartment close to the release points. Due to the different density of hydrogen compared to air and steam, and since the steam generator compartments are unclosed on top, an upwards-oriented buoyant plume develops. Hydrogen eventually accumulates in the containment dome. This general behavior is well investigated, cf. e.g. Kim et al. (2006). Mixing occurs by large-scale convection flows as well as molecular diffusion in the long term.

1.2.2. Station Black-Out (SBO)

At least a *total* station blackout is characterized by loss of offsite power, onsite power, standby power generators and emergency power generators. The scenario represents similar conditions than in the hazardous Fukushima-Daiichi accident. Due to the loss of electric power, many safety measures fail – apart from passive systems. The scenario is very unlikely but implicates severe consequences.

To counteract the pressure build-up after core degradation, the reactor coolant system is depressurized by bleeding the water, steam and hydrogen from the pressurizer into the water of the IRWST. Most of the steam that is released through the spargers is thus condensed in the IRWST water because of its subcooled temperature. As a result, comparably dry hydrogen accumulates in the free gas volume of the IRWST. At the same time, the gas mixture is partially leaking into the annular compartments above the IRWST through the venting stacks. In order to avoid hydrogen accumulation in the IRWST, the release location is switched from the IRWST to a steam generator compartment by a three-way valve when the core exit temperature exceeds 650 degree Celsius. In this case, three release points of hydrogen and steam are taken into account. The first and second release point are located in the steam generator tower, each having a circular area with a 12 inch diameter. The third release point is located on the lower half of the reactor vessel – identical to the second release point in the SB-LOCA scenario.

The hydrogen behavior in the APR1400 following a SBO has been examined in several studies before. For example in a work of Korea's Atomic Energy Research Institute (Kim et al., 2005), the three-dimensional CFD code GASFLOW was used for hydrogen distribution analysis. Sources of hydrogen and steam were calculated by the lumped parameter code MAAP. It was concluded that the gas mixture in the IRWST is basically combustible but might quickly become non-flammable by oxygen starvation if igniters are switched on. However, the leakage of unburned hydrogen through the venting stacks into the annular compartments was identified as an issue. Modifications were proposed to improve the hydrogen mitigation strategy compared to the base design.

In another independent study of Korea's Institute of Nuclear Safety (Kim et al., 2006), peak hydrogen concentrations of up to 60% were predicted in the IRWST using the lumped parameter code MELCOR. It should be mentioned that this study was based on an older design without the three-way valve installed. Evaluation of empirical criteria showed that flame acceleration as well as onset of detonation is possible during some periods when conditions are critical. Corresponding CFD combustion analysis was not performed however.

Recently, Kim and Hong (2015) proposed a coupling between the GASFLOW code for hydrogen distribution analysis and OpenFOAM for combustion analysis. The methodology is applied to an SBO scenario in the APR1400. Concerning the combustion model, a single-step hydrogen oxidation reaction is assumed and the Partially Stirred Reactor (PaSR) concept is applied to account for turbulence-chemistry interaction. The approach is thus quite different to the one used in this study, cf. Section 2.1.

It has to be pointed out that the three-way valve is already installed in the current design of APR1400 and that the hydrogen mitigation design analyzed in the previous studies (Kim et al., 2005; Kim et al., 2006) is different compared to the current study.

1.3. Scope of the present study

The purpose of this paper is to investigate the possibility of FA and DDT for the given accident sequences inside both the full containment and separate IRWST by means of an advanced CFD explosion solver. Initial conditions are derived from lumped parameter simulations (MAAP5 code) and prepared for three-dimensional CFD analysis in an intermediate step. Besides realistic initial conditions according to Severe Accident Management Guidelines (SAMG), conservative initial conditions are taken into account to demonstrate the solver's ability to reproduce strong FA and DDT events. In the latter case, unrealistically high hydrogen and low steam concentrations are assumed.

2. Computational method

2.1. CFD explosion solver

Only the main features of the solver are briefly described since the focus of the presented study is placed on the simulation results. Contrary to the state-of-the-art in *large-scale* explosion modeling, the entire combustion process is computed within a single solver framework. Consequently, the use of empirical transition criteria to select between multiple regime-optimized solvers can be avoided. A robust model is thus necessary to cover all underlying regimes from slow (quasi-) laminar deflagration shortly after weak