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Analysis of a Hydrogen Flame Propagation in the IRWST of the APR1400 NPP

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1. Introduction

For a loss of coolant accident (LOCA) of a nuclear power plant, most of the hydrogen generated in the reactor pressure vessel is released through a cold-leg or hot-leg break. But in the case of a high pressure accident such as a station black-out (SBO) especially for the APR1400, the hydrogen generated in the reactor pressure vessel is blown to the pressurizer, and it is released in the in-containment refueling water storage tank (IRWST). The IRWST, which is an annular tank to store the refueling water, located in the lower part of the containment is designed to be used as a water source for a cavity flooding and the containment spray system and also as a discharge location for the primary system's safety bleed operation. The hydrogen-steam behavior in the IRWST during a hypothetical severe accident is very important because the IRWST in the APR1400 containment is a large annular compartment with four vent holes on the ceiling. The hydrogen safety at the IRWST of the APR1400 is one of the remaining issues to be investigated. In the previous study [1], the characteristics of the hydrogen flame in the IRWST expected during the SBO and total loss of feed water (LOFW) accidents were evaluated based on a sigma-lambda criteria from the simulation results by the GASFLOW code [2]. And it was found that the hydrogen mixture is non-flammable for most of the accident time when the non-condensed steam is released into the free volume of the IRWST, but there exists a small period of time with a high possibility of a flame acceleration during the SBO accident because most of the steam discharged from spargers is well condensed.

In this study, the characteristics of a hydrogen flame propagation in the IRWST have been investigated by using a mechanistic combustion model of the GASFLOW code. The effect of the IRWST vent holes on the propagation of the hydrogen flame was also evaluated.

2. Validation of the combustion model with FLMAE experiment

In order to use the mechanistic combustion model in the GASFLOW code for the evaluation of the characteristics of the hydrogen flame propagating in the IRWST, the combustion model was validated by conducting numerical analyses of the FLMAE experiments [3].

FLAME is a large (30.5 m long) rectangular channel (The size of its square section is 2.44 m x 1.83 m) designed and built for U.S. Nuclear Regulatory Commission. And the purpose of the experiment with the FLMAE facility was to research on flame acceleration and deflagration-to-detonation (DDT) and to explain its relevance to nuclear reactor safety. Around 30 tests were conducted depending on the initial hydrogen concentration in the FLAME chamber and blockage and vent ratios of the chamber. It was found that the flame acceleration and DDT occurred in some cases of the test series.

For the validation of the combustion model in the GASFLOW code, tests F-8, F-10 and F-22 were chosen and numerically simulated. Tests F-8 and F-10 were carried without venting and obstacles. Their conditions for the hydrogen concentration were 18.4 vol% and 12.3 vol% respectively. For test F-22, plate-type obstacles were installed periodically with a distance of 1.83 m. For the numerical analyses of the FLMAE tests, a Cartesian mesh with 201 x 17 x 13 grid points was used.

Fig. 1 shows the calculated temperature contours in the chamber at each time for test F-10, in which the colored thick contour lines depict the flame fronts.

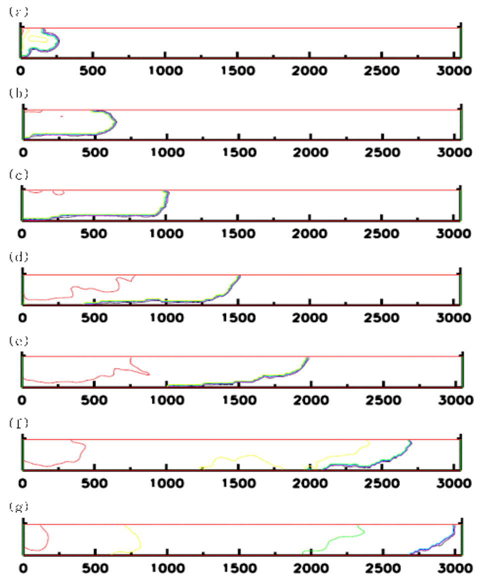

Fig. 1 Numerical results for FLAME F-10 test, the flame location depicted by temperature contours at (a) t = 0.4 s, (b) t= 0.8 s, (c) t = 1.2 s, (d) t = 1.6, (e) t = 2.0 s, (f) t = 2.4 s, (g) t = 2.5 s

It is shown in the figure that the flame front is considerably curved by buoyancy and the flame propagation speeds are spread along the vertical locations. The flame arrival time at the exit of the chamber was compared between the numerical and experimental results. The calculated flame speed at the exit is about 30 m/s which is very similar to the experimental results.

The experimental tests showed that the obstacles in the chamber accelerate the flame propagations by enhancing the turbulent mixing. The maximum flame speed at the exit in test F-22 was around 700 m/s and the DDT was observed. Fig. 2 is the plot of the flame arrival time versus distance from the ignition point to the flame front.

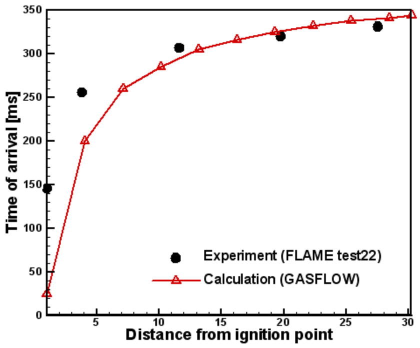

Fig. 2 Comparison of the flame arrival time for test F-22

From Fig. 2, it can be concluded that the combustion model used in this study predict well the flame acceleration.

3. Analysis of Hydrogen Combustion in the IRWST of the APR1400

As explained above, the IRWST is one of the hydrogen discharge locations for the APR1400. It was found in the previous study that the hydrogen mixture cloud developed in the IRWST free volume is in a condition with a high possibility of flame acceleration when dry hydrogen without steam is released. In this study, the characteristics of the flame propagation of the hydrogen-air mixture in the IRWST were mechanistically evaluated.

Fig. 3 is the perspective view of the 3-D mesh used in the study, where 41 x 361 x 11 grid points on r-θ-z coordinates was used.

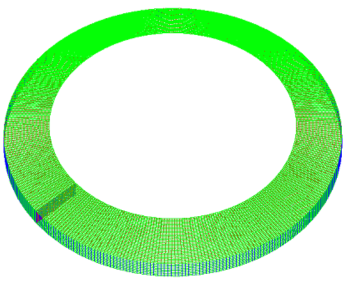

Fig. 3 Perspective view of the mesh for the IRWST

In order to figure out the effect of four vent holes on the IRWST ceiling on a hydrogen flame propagation in the IRWST, two cases with and without the vent holes were modeled and calculated. From Fig. 4, the characteristics of a flame propagation in the closed annular chamber of the IRWST are shown. It was modeled that the flame was ignited by one of the igniters installed in the IRWST. The flame is propagated in both directions and merged at an opposite location to the ignition point. When the four vent holes were not modeled, the speed of the hydrogen flame reached about 540 m/s, which means that the flame was quickly accelerated at the end stage of the flame propagation.

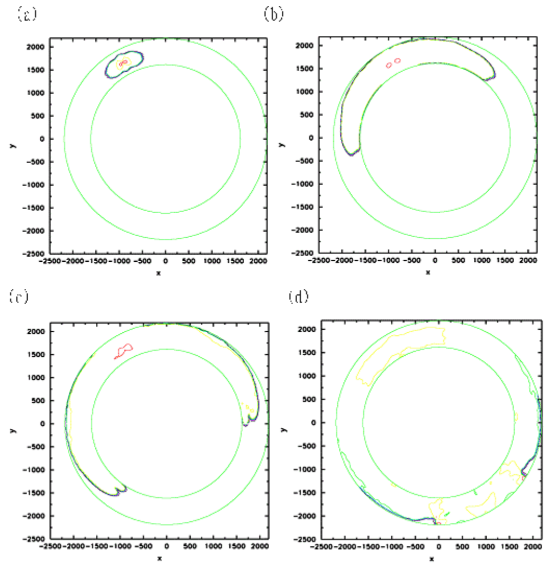

Fig. 4 Flame locations at each time for the case without the vent holes, hydrogen concentration of 15vol%, (a) t = 0.2 s, (b) t = 0.5 s, (c) t = 0.6 s, (d) t = 0.666 s

It was found in the continuous study that the speed of the flame propagation in the IRWST was heavily reduced when the four vent holes were modeled. The maximum speed of the flame was around 10 m/s in the calculation.

4. Conclusion

The numerical analysis of a hydrogen combustion in the IRWST has been conducted for the prediction of flame propagation characteristics and an evaluation of the effect of the vent holes on the flame propagation. It was found in this study that a flame acceleration occurred at hydrogen concentration of 15 vol% in the closed annular IRWST in the case without the vent holes and these vents strongly affect flame propagation. It is recommended that an experiment of a hydrogen combustion in a closed annular chamber is necessary to find out the geometrical effect on a flame propagation and to validate the numerical results.

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