CFD Analyses of Hydrogen Flame Acceleration in the ENACCEF and IRWST Facilities

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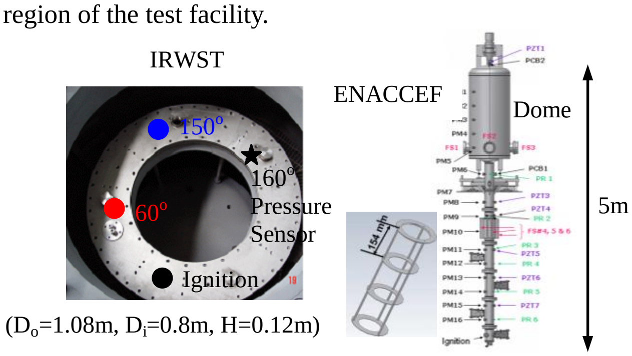
1. Introduction

A numerical analysis result by the GASFLOW for hydrogen and steam behavior during the station black-out and total loss of feed water accident of APR1400 reported the possibility of a hydrogen flame acceleration and transition from deflagration to detonation (DDT) in the in-containment refueling water storage tank (IRWST) [1]. Therefore, a scaled-down experiment was performed to investigate the physical mechanism of the hydrogen flame acceleration and pressure buildup in the IRWST annulus geometry by KAERI [2]. However, to evaluate the possibility of DDT in the APR1400 IRWST, a computational fluid dynamic (CFD) analysis with a validated CFD model on the basis of the scaled-down test results is recommended. To develop the validated CFD analysis method, the CFD analysis should be performed against the experimental results with various conditions of hydrogen concentrations and geometric configurations.

2. Hydrogen Flame Acceleration Test

The hydrogen flame acceleration test (Fig. 1) was performed using the scaled-down facility by varying the hydrogen concentration from 10.2 % to 19.5% in KAERI [2]. But, the flame acceleration test was not performed using an obstacle in the IRWST facility. Thus, the ENACCEF test results [3] were introduced even though hydrogen flame propagated upward from the bottom region of the test facility.

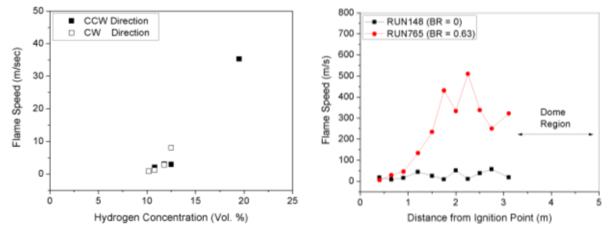


(D_o=1.08m, D_i=0.8m, H=0.12m)

Fig. 1. H_2 Flame Acceleration Test Facility

Table 1: H_2 Explosion Test Conditions

Test Facility	H_2 Concentration	Blockage Ratio (BR)
IRWST	10.2%, 19.5%	0
ENACCEF	12.5%, 11.6~8%	0, 0.63



(a) IRWST (b) ENACCEF

Fig. 2. Test Results (Flame Speed)

The IRWST test results (Fig. 2 (a)) show that the flame speed is increased to about 35 m/s from about 1~2 m/s as the hydrogen concentration increases. The ENACCEF test results confirm that the flame speed of RUN765 (BR=0.63) is increased up to about 500 times due to turbulence generated when compared to that of RUN148 (BR=0).

3. CFD Analysis

3.1 Grid Model and Flow Field Models

A 3-dimensional grid model simulating the IRWST annulus facility was developed. A total of 122,400 hexahedral cells with a 5 mm cell length were produced to capture the rapid propagation of a pressure and combustion wave. Also, a 3-dimensional grid model with a half symmetric condition representing the ENACCEF facility was generated by the hexahedral cells with a 2~10 mm cell length, and the number of generated cells was about 3,100,000. A wall condition with a constant temperature of 293 K was applied on the outer surface of the grid models. The spark ignition model [4] was introduced to simulate the spark operation by an electric device in the test facility. The governing equations used in this study were the Navier-Stokes, the energy and the species transport equations with a coupled solver algorithm implemented in the CFX-11 [5]. Turbulent flow was modeled by the DES-SST turbulent model [5]. The turbulent flame closure (TFC) model [2] was used to simulate the hydrogen combustion. The time step size used for these CFD calculations was 0.01 ~ 0.1 ms to ensure a CFL number below 1.0.

3.2 CFD Analysis Results for the ENACCEF Test

The calculated flame position for RUN765 (BR=0.63) by the CFD (Fig. 3) reasonably predicted the test data with an error range of 20.6% even though the calculated flame arrives 18.95 ms earlier at PM16 when compared to the test result. The flame's fast passing through the obstacles and gave rise to a compression effect, which increased in 28.1 ms the pressure up to 1.265 bar at 76.2 ms in the CFD results. This calculated value accurately predicted the test result with an error range of 2.7%. In the case of RUN148 (BR=0), the flame speed (Fig. 3) by the CFD calculation predicts the test data with an error range of about 40%, except the position of about 1.2 m from the ignition point. However, the predicted pressure (Fig. 3) by the CFD results steadily increased to about 4.8 bar, which is a different behavior when compared to the test results. This may be explained by the hydrogen combustion continually taking place at the dome in the CFD calculation, whereas the flame extinction may occur at the dome in the test. Thus, the pressure did not increase above about 3 bar and started to decrease in the test results.

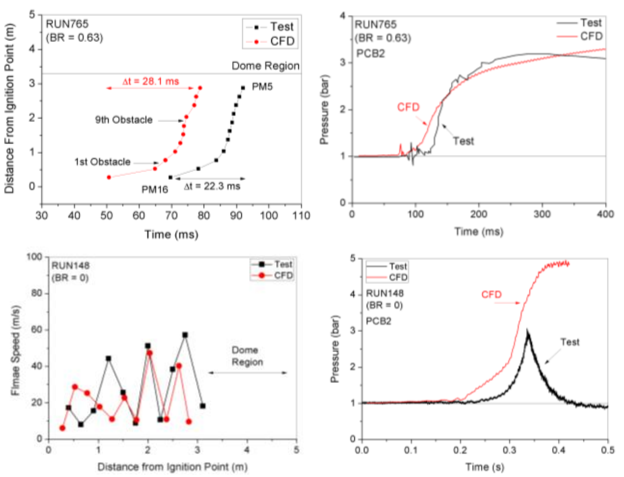


Fig. 3. Comparison of Flame Position, Flame Speed, and Pressure between the CFD and Test Results (ENACCEF)

3.3 CFD Analysis Results for the IRWST Test

The CFD results of H_2 10.2% show that the calculated flame temperature behavior at 60^o and 150^o position from the ignition point along the clockwise direction (Fig. 4) predict the start time to increase from the initial temperature with an error range of about 38%. The flame temperatures were normalized by their maximum temperature because the measured temperature values were low when compared to the CFD results. The comparison of pressure behavior between the CFD and test results (Fig. 4) shows a different pattern. The pressure of the CFD results show a continuous increase from 0 ms to 2000 ms. This may have been caused by the hydrogen combustion taking place until it burns all of the air in the IRWST facility. However, the test results (Fig. 4) show that the slightly increased pressure at 500 ms started to decrease at 1500 ms. This may be explained by flame extinction and heat loss to the outside of the IRWST facility through the wall simultaneously occurring. The CFD results for the test of H_2 19.5% show the slow flame propagation between the temperature sensor locations of 60^o and 150^o when compared to the test results, which give rise to a difference in the pressure behavior between the CFD and test results (Fig. 4).

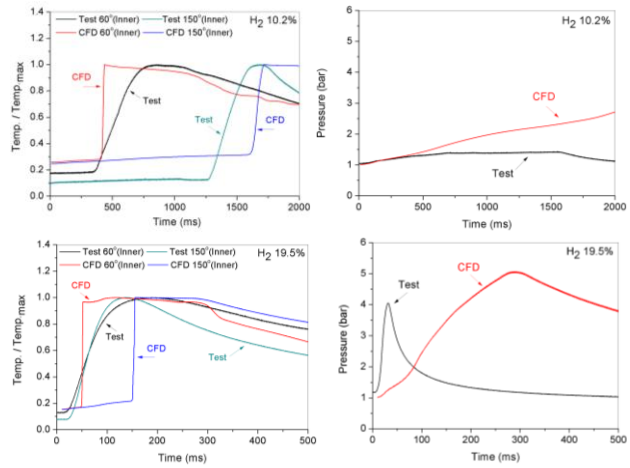


Fig. 4. Comparison of Flame Temperature, and Pressure Behavior between the CFD and Test Results (IRWST)

4. Conclusion and Further Research

From the CFD analysis results for the ENACCEF and IRWST test results, we know that the CFD code with the TFC combustion model and DES-SST turbulent model can reasonably simulate the hydrogen flame acceleration phenomena for a variety of the hydrogen concentration and geometric configurations. However, to accurately predict the flame propagation for the test result of the hydrogen 19.5% in the IRWST facility, a detailed analysis on the CFD results will be performed.

ACKNOWLEDGEMENTS

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