An Effect of a Barrier for Reducing a Safety Distance around a Hydrogen Energy Facility

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1. Introduction

An installation of a barrier at a hydrogen refueling station (HFS) is being considered to reduce a safety distance between a HFS and a protection facility which is required by Korea Gas Safety Codes [1-3]. Research experience about the safety distance between a Very High Temperature Reactor (VHTR) and a hydrogen production facility may be effectively used to evaluate the effect of the barrier existence for reducing the safety distance between the HFS and the protection place [4-6]. According to the previous research results, a peak overpressure limit is used as the basic criteria of the determination of the safety distance. In addition, a Computational Fluid Dynamics (CFD) analysis may be used as an accurate evaluation tool to provide the 3-dimesnional information of an overpressure and a time history of the overpressure variation. However, to apply the CFD analysis for evaluating the safety distance from the HFS with the barrier to the protection place, it is necessary to establish the accurate CFD analysis methodology on the basis of a comparison result between a CFD result and a test data with the barrier.

2. Hydrogen Explosion Test with the Barrier

2.1 Test Facility

Stanford Research institute (SRI) performed a hydrogen explosion test using a hydrogen-air mixture volume 5.2 m^3 with the stoichiometric condition in an open space by varying the ignition method and the barrier existence like as Fig. 1 and Table 1 [7]. The barrier was located at 4 m from the tent, where the hydrogen gas was located, and its dimension is height 2 m, wide 10 m, and thickness 0.1 m. They measured the peak overpressure at 11 m, 21 m and 41 m from the tent as well as the peak overpressure at 2 m behind and front from the barrier such as P2 and P4 in Fig. 1.

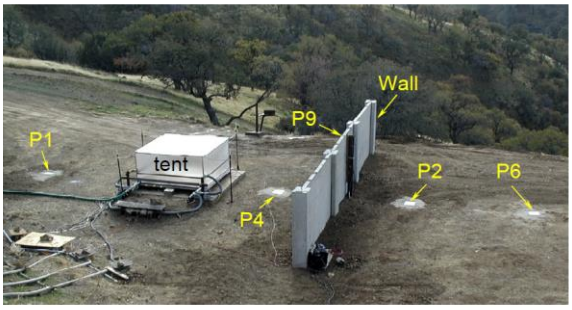


Fig. 1. SRI Facility [7]

Table 1: Initial conditions at Test-101 [7]

Test No.	H2-Air Volume	H2 Con. (Vol. %)	Ignition	Barrier
4-01	5.2 m^3	30.0	Spark	X
4-02	5.2 m^3	29.9	Spark	O
5-02	5.2 m^3	30.0	10g C-4	O
6-01	5.2 m^3	30.0	10g C-4	X

2.2 Test Results

The measured overpressure data (Fig. 2) showed that the electric spark 40 J for the ignition developed the deflagration phenomenon in Tests 4-01 and 4-02, whereas the high explosive material 10g C-4 produced the detonation in Tests 5-02 and 6-01. In Tests 4-02 and 5-02, the overpressure at 11 m from the ignition point, which is located approximately 6 m behind the barrier, was reduced to approximately 30 – 40 % of the overpressure measured in Tests 4-01 and 6-01 without the barrier. The measured overpressures at 21 m showed approximately 18 – 28 % decrease owing to the barrier. However, the overpressures at 41 m did not show the difference resulted from the barrier existence.

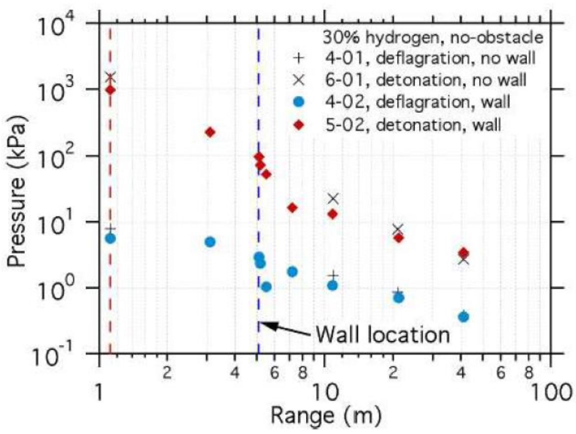


Fig. 2. Test Results in the SRI Hydrogen Explosion Test [7]

3. CFD Analysis

3.1 Grid Model and Flow Field Models

SRI's Test 4-02 was first selected as for a CFD validation case because the hydrogen deflagration is a more reasonable accident scenario in an open space such as the HFS. A 3-dimensional and half symmetric grid model (Fig. 3) for simulating the tent and its environment region to 27 m was generated on basis of the test facility by using the blockMesh and OpenFOAM-v1912 [8]. A total of 3,214,280 hexahedral mesh cells was produced, and a dense mesh cell distribution with an approximately

2 cm cell length was located around the tent region (2.2 m × 2.2 m × 1 m) to resolve the rapid propagation of the flame. A coarse mesh distribution with an approximately 25 cm cell length from the boundary of the tent region to the far region was generated by considering the computational time and the hardware capability for assuring the pressure wave propagation.

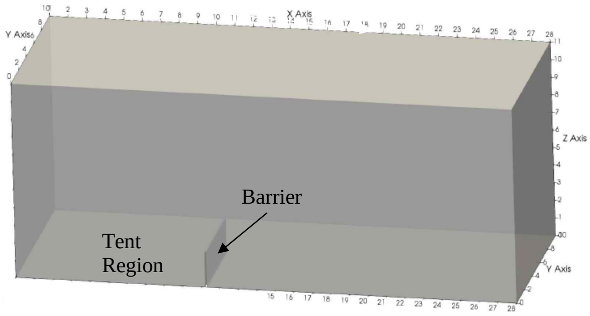


Fig. 3. Grid model for the SRI facility

The deflagration phenomenon was treated as a compressible flow, combustion flow, turbulent flow, buoyant flow and transient flow. The governing equations in this study were the mass conservation, Navier-Stokes momentum, total energy, flame propagation with a pimple solver algorithm in OpenFOAM-v1912 [8]. The modified XiFoam solver [9] was chosen for the simulation of the hydrogen deflagration in the tent in Test 4-02. XiFoam calculates the flame propagation by using a transport equation for the combustion regress variable "b" like as Eq. (1). The variable b has a range from 0 to 1 where b =1 means an unburned state and decreases as the hydrogen combustion proceeds. A turbulent flow was modeled by the shear stress transport k-ω model [8].

$$\frac{\partial}{\partial t}(\rho b) + \nabla\cdot(\rho\vec{u}b) - \nabla\cdot\left(\frac{\mu_t}{Sc_t}\nabla b\right) = \rho_u S_u \xi|\nabla b| \qquad (1)$$

where,
Sc_t : turbulent Schmidt number
S_u : laminar flame speed
ρ_u : density of unburnt mixture
ξ : flame wrinkling

To simulate the ignition energy 40 J provided by the electric spark device in the tent, we developed the spark ignition model (Eq. (2)) representing the pressure, temperature, and volume of the activated region owing to the spark because the local ignition process by the spark was too complicated to model exactly [4,5]. The selected parameters determined by the spark ignition model for the activated region were the radius 6 cm, pressure 109 kPa, temperature 1,000 K. The initial condition of the hydrogen-air mixture in the tent was given by using the hydrogen mass fraction as shown in Fig. 4. An opening condition that can simulate a wave passing through the surfaces was applied to all of the surrounding surfaces except for the bottom and half cut surfaces in the grid model. The time step size used in the transient calculation of 0.1 s was approximately 0.01 ms for obtaining converged solutions.

$$\begin{aligned} E_{spark} &= m_{act}\overline{C_p}(T_h - T_c) = V_{act}\rho_m\overline{C_p}(T_h - T_c) \\ &= V_{act}(\rho_{m,h}C_{p,h}T_h - \rho_{m,c}C_{p,c}T_c) \\ &= V_{act}\left(\frac{P_h}{R_g}C_{p,h} - \frac{P_c}{R_g}C_{p,c}\right) \\ &= \frac{V_{act}}{R_g}(P_hC_{p,h} - P_cC_{p,c}). \end{aligned} \qquad (2)$$

where,
m_{act} : mass of the activated mixture of hydrogen-air
V_{act} : spherical volume of the activated mixture
T_h : temperature of the activated mixture
P_h : pressure of the activated mixture
R_g : gas constant of the activated mixture

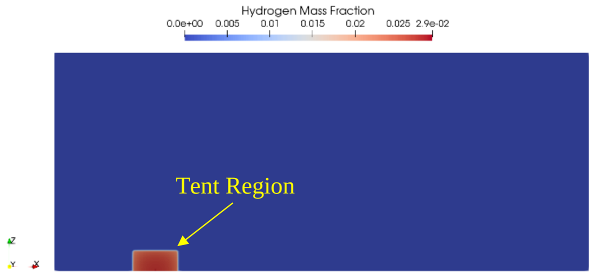
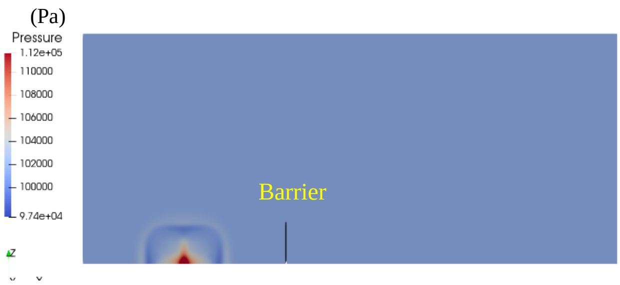


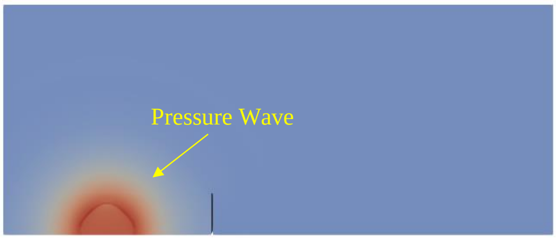
Fig. 4. Initial condition of H_2 mass fraction (front view)

3.2 Discussion on the CFD Analysis Results

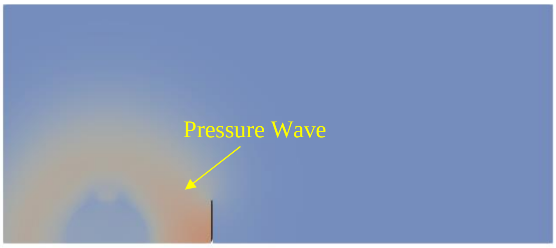
The CFD analysis results for the pressure wave propagation to the environment due to the hydrogen deflagration in the tent region as time passes are shown in Fig. 5. According to Figs. 5(c) and (d), the magnitude of the pressure wave is reduced after colliding with the barrier. The comparison results of the overpressure at the P1, P2, and P4 locations between the measured data and predicted results, as shown in Fig. 6, show that the CFD results accurately predicted the peak overpressure with an error range of approximately 10%. However, the calculated overpressure behavior shows a faster propagation of the pressure wave than the measured data. This may be explained by the fact that we simply simulate the local ignition process, where the hydrogen flame transits from a laminar flow to a turbulent flow through an instability phenomenon, with the developed spark ignition model.



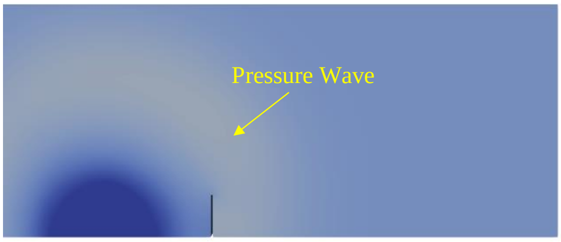
(a) 0.003 s



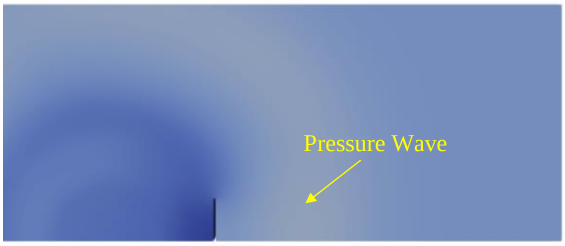
(b) 0.02 s



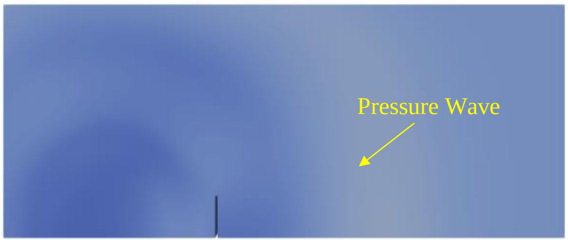
(c) 0.03 s



(d) 0.04 s

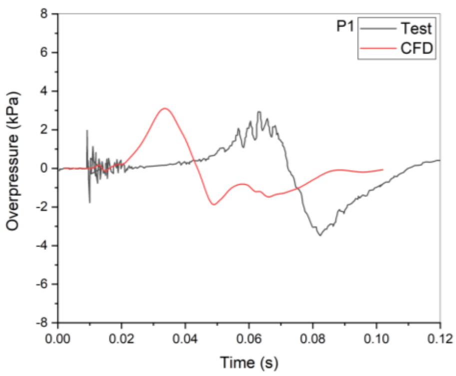


(e) 0.05 s

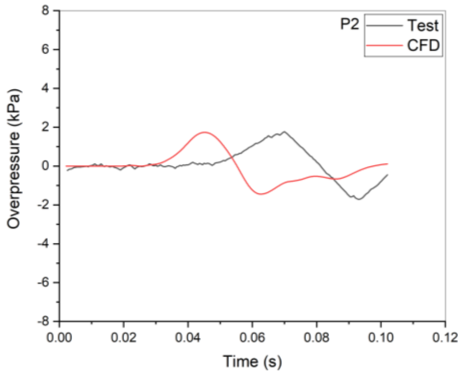


(f) 0.06 s

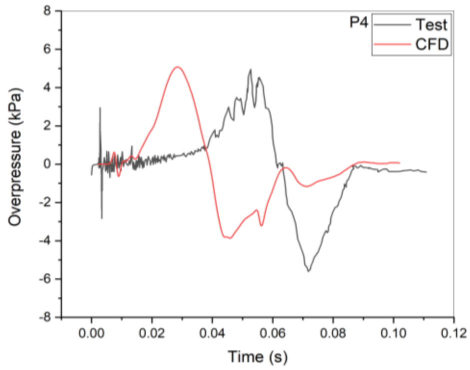
Fig. 5. Calculated pressure distribution (front view)



(a) P1 located at 4m left from the tent



(b) P2 located at 2m behind from the barrier



(c) P4 located at 2m front from the barrier

Fig. 6. Comparison of the overpressure behavior at P1, P2, and P4 between test data and CFD results

4. Conclusions and Further Work

We performed a CFD analysis for the hydrogen explosion test results with the barrier at the stoichiometric condition in an open space to develop an analysis methodology for predicting the peak overpressure variation due to the barrier. The CFD analysis results accurately predicted the peak overpressure at the front and behind locations from the barrier in the test with an error range of approximately 10% when compared to the test data. As a further work, we will analyze other test results to establish the accurate CFD analysis methodology for simulating a various accident scenario.

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