Evaluation of Hydrogen Explosion Resistance for Containment Vessel

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1. Introduction

In this study, the maximum allowable pressure that the vessel shall withstand when the hydrogen explosion occurs is determined by utilizing numerical blast simulations.

Generally, the combustion of a gas can be classified into two categories: deflagration and detonation. The wave travels at subsonic speed in case of deflagration, but the speed of pressure wave in detonation is supersonic (1500~2000 m/s). It is known as the maximum pressure when deflagration occurs in the closed vessel filled with hydrogen gas and air is 8~10 bar with initial pressure of 1 bar. The deflagration limit of hydrogen-air composition is between 4.0 vol. % H_2 and 75.0 vol. % H_2 [1]. However, the explosion pressure when detonation occurs can increase up to 15 ~ 20 bar and it is enlarged when the pressure wave reflects on the wall. The composition limit for hydrogen-air mixture to cause the detonation is between 18.3 vol. % H_2 and 59.0 vol. % H_2 [2]. Of course, these are not absolute values and can vary depending on the initial pressure, ignite energy, and geometry of the vessel etc. The detonation pressure was considered to determine the maximum allowable pressure for the containment vessel to withstand, and the structural integrity is evaluated in this blast loading case.

2. Loading due to hydrogen explosion

2.1 Estimation of equivalent hydrogen explosion pressure

It can be assumed that the explosion load P(t) affecting the wall of containment vessel decrease exponentially with time such as:

$$\mathrm{P(t)} = P_{ref}\exp(-t/\theta) \qquad (1)$$

Where, t: time, θ: duration time of blast load, P_{ref}: reflected pressure.
The reflected pressure is calculated by [3]

$$\mathrm{P}_{ref} = P_{max}\left(5\gamma + 1 + \sqrt{17\gamma^2 + 2\gamma + 1}\right)/4\gamma \qquad (2)$$

Where P_{max} is the maximum incident pressure and γ is the specific heat ratio.

The equation of motion of a cylindrical shell containment vessel in radial direction can be represented as [4, 5]

$$d^2w/dt^2 + \omega^2 w = P(t)/\rho h \qquad (3)$$

Where w is the radial displacement, ω is the natural frequency, ρ is the density, and h is the thickness of the shell.
The solutions of Eq. (3) are given as follows if $\mathrm{w}(0) = \mathrm{u}(0) = 0$

$$\mathrm{w(t)} = \frac{P_{ref}}{(\omega^2+\theta^{-2})\rho h}\left(\frac{sin\omega t}{\omega\theta} - cos\omega t + \exp(-\frac{t}{\theta})\right) \qquad (4)$$

$$\mathrm{u(t)} = \frac{P_{ref}}{(\omega^2+\theta^{-2})\rho h}\left(\frac{cos\omega t}{\theta} + \omega sin\omega t - \exp(-\frac{t}{\theta})/\theta\right) \qquad (5)$$

u(t) : velocity of the displacement in radial direction.

From Eq. (4), we can get the maximum strain value (ε_{max}). Then the equivalent static pressure imposed on the container wall can be calculated by:

$$P_{equ} = \frac{Eh\varepsilon_{max}}{R} \qquad (6)$$

where, R is the radius of a cylinder.

Finally, the equivalent static pressure is considered in the vessel design to withstand the explosive loading caused by the hydrogen-air reaction.

However, to get the solution of Eq. (4) and (5), we need to determine the blast duration time (θ) and the reflection pressure (P_{ref}) and the maximum incident pressure (P_{max}) is also required. The blast duration time and incident pressure usually can be determined from experiments or numerical analysis. In this study, these values are determined by the numerical analysis utilizing commercial finite element analysis software, LS-Dyna[6], which is specialized in the crashworthiness and blast loading simulations.

One of the important input parameters in the blast simulation is the properties of gas. However, it is generally very difficult to define the properties of explosive gas accurately because they can very according to the composition ratio of gas, characteristics of mixture, mixing ration with oxygen, and compression ratio, etc. For the blast simulation, hence, the TNT (trinitrotoluene) equivalent method is usually used to determine the mass of TNT that is equivalent to the mass of gas during explosion since the explosion characteristics of TNT, such as explosion pressure and energy, have been studied by vast amount of experiments and it is generally accepted that they have high reliability. The equation of TNT equivalent method is given as follows:

$$W_{TNT} = \frac{\mu \times M \times E_c}{1120} \qquad (7)$$

Where,

W_{TNT} : TNT equivalent (kg)
μ : Explosion yield factor (using 0.5 for closed loop)
M : Leaked flammable gas amount (kg)
E_c: Combustion heat caused by the explosion material (kcal/kg), 28671.13 kcal/kg for hydrogen gas

The credible hydrogen leakage was determined about 0.4 g in conservative manner in this study. Therefore, the equivalent amount of TNT is 0.00512 Kg

2.2 Numerical blast simulation

The geometry and material properties are given in Table 1.

Table 1 Geometry and material properties

	Helium housing (upper)	Helium housing (lower)	Helium transfer pipe	Helium containment vessel
Radius, R (m)	0.189	0.144	0.054	0.1175
Thickness, h (m)	0.01	0.007	0.005	0.0065
Elastic modulus, E (Pa)	6.89E10	6.89E10	6.89E10	6.89E10
Density, ρ (kg/m^3)	2712.6	2712.6	2712.6	2712.6

Four cases were considered in the simulations. For each simulation, it is assumed that the equivalent TNT mass is located in only one point of the considered space in a conservative manner.

Table 2 Simulation results

Simulation case	Blast position	P_{max} (bar)	θ (sec.)	P_{equ} (bar)	Pressure by design rules[7]	Safety margin
No. 1	Helium housing (upper)	7.01	2.6e-5	10.4	38.1	3.6
No. 2	Helium housing (lower)	12.09	1.8e-5	17.9	35.1	1.9
No. 3	Helium transfer pipe	70.38	1.9e-6	31.4	65.3	2.0
No. 4	Helium containment vessel	21.13	1.01e-5	21.4	33.2	1.5

The maximum incident pressure (P_{max}) and blast duration time (θ) were determined with the numerical blast simulations.

The fifth column shows that the computed maximum equivalent static pressure with Eq. (6) when the hydrogen explosion occurs in the vessel in this study. The values shown in sixth column in the Table 2 is the maximum allowable pressure calculated according to the design rules provided by the ASME Code [7] based on current geometry.

The calculated equivalent static pressure is lower than the allowable pressure required by the relevant Code [6]. The safety margin is from 1.5 to 3.6 as shown in Table 2. Therefore, current design has enough margin in the safety point of view.

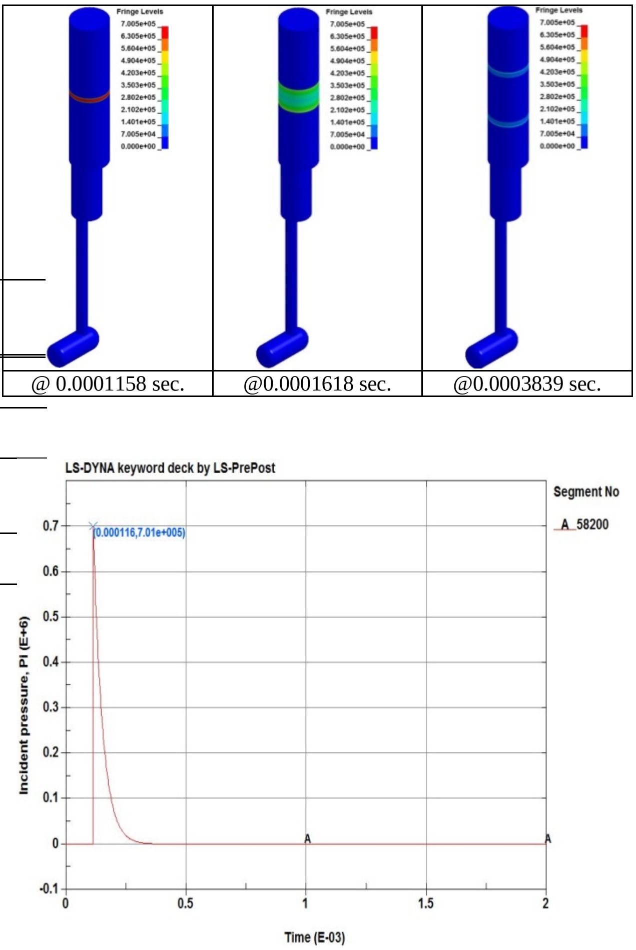

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Figure 1 Incident pressure wave contour and time history plot (helium housing upper)

3. Conclusions

The maximum allowable pressure of 30 bar that the containment vessel shall withstand was determined based on the assessment performed in this study with the analytical method considering the stress-deformation state of the containment vessel and the numerical blast simulation under the assumption of practically reasonable hydrogen leakage.

Finally, it is confirmed that all calculations and simulation results are within the acceptable range and the geometry (thickness and diameter, etc.) of the containment vessel is determined to withstand the maximum pressure of 30 bar according to the relevant Codes and Standards based on these results.

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