Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

Methodology of Hydrogen Gas Jet/Plume Modeling and Calculate Hydrogen Detonable Mass for NPP Risk Assessment

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***Keywords:** hydrogen, accident, detonable mass, jet/plume, gaussian distribution,

1. Introduction

When installing a hydrogen production facility to NPP, the impact of a hydrogen explosion on NPP safety must be considered. To assess the impact of a hydrogen explosion, it is necessary to determine the hydrogen detonable mass. For calculating the hydrogen detonable mass, it is assumed that a guillotine break accident occurs in the pipeline connected to the hydrogen production equipment or hydrogen buffer tank. In the event of a guillotine break accident in a pipeline connected to a high-pressure hydrogen storage tank, hydrogen gas will be released in a choked flow and will form a jet/plume. After modeling the hydrogen gas jet/plume, the detonable mass is determined using this model. In this model, hydrogen detonable mass is calculated by integrating over the predefined explosion region.

2. Methodology

In the event of a hydrogen gas release accident, the modeling of the hydrogen gas jet/plume and the calculation of the hydrogen detonable mass are carried out according to the procedure shown in Figure 1.

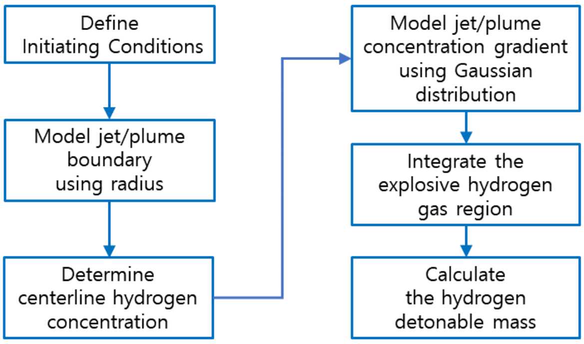

Fig. 1. Procedure for modeling hydrogen jet/plume and calculate hydrogen detonable mass

2.1 Initial assumptions

The initial expansion region of the hydrogen gas jet/plume leaking from a high-pressure hydrogen storage tank is defined as shown in Figure 2.

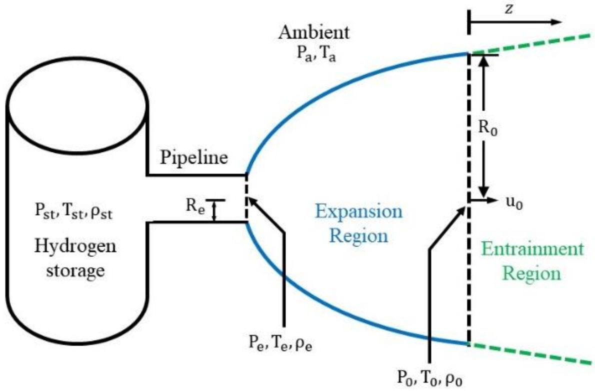

Fig. 2. Hydrogen jet/plume expansion region

The density in the expansion region in Figure 2 is calculated using the ideal gas law. The radius R_0 (m) and velocity u_0 (m/sec) of the expansion region are calculated as shown in Eq (1) and (2) [1].

(1) $u_0 = \frac{G}{\rho_e} + \frac{P_e - P_a}{G}$

(2) $R_0 = R_e \left(\frac{G}{u_0 \rho_0}\right)^{0.5}$

where, G ($kg/m^2 sec$) represents the mass flux of the hydrogen gas jet/plume, P_e and P_a (Pa) represent the pressure at the failure opening cross-section and the ambient pressure, respectively. ρ_0 (kg/m^3) represents the hydrogen gas density at the end of the expansion region.

2.2 Determine hydrogen jet/plume boundary & centerline concentration

The modeling of the boundary of the hydrogen gas jet/plume can be achieved through the radius of the entrainment region R (m). The radius of the entrainment region is expressed as shown in Eq (3)[2]. The mass fraction of hydrogen gas is given by Eq (4). The centerline mole fraction of the hydrogen gas jet/plume can be converted to an expression for the mass fraction of hydrogen gas as shown in Eq (5) [3].

(3) $R = \frac{R_0}{Y} \sqrt{\frac{T_a}{T_0}\left[Y + \frac{M_{H_2}}{M_{air}}(1 - Y)\right]}$

(4) $Y_{cl} = \left[1 + \frac{2E_0}{R_0}\left(\frac{\rho_a}{\rho_0}\right)^{0.5} z\right]^{-1}$

(5) $y_{cl} = \left[1 + \left(\frac{1}{Y} - 1\right)\frac{M_{H_2}}{M_{air}}\right]^{-1}$

where, T_a and T_0 (K) represent the ambient temperature and the temperature at the end of the expansion region, respectively. M_{H_2} and M_{air} represent the molecular weight of hydrogen and air, respectively. Additionally, E_0 means the entrainment coefficient.

2.3 Using gaussian distribution for jet/plume dispersion

The Gaussian distribution can be used to define the vertical dispersion distance relative to the horizontal dispersion distance of a hydrogen gas jet/plume. The probability density function of the Gaussian distribution is utilized as shown in Eq (6). The maximum value of the Gaussian distribution corresponds to the hydrogen gas concentration at the centerline, as given by Eq (7). The Gaussian distribution function values may not match, thus requiring the use of a scale factor α. The scale factor α is set as shown in Eq (8). In Eq (8), y_{cl} represents the concentration at the centerline of the hydrogen gas jet/plume.

(6) $f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$

(7) $f_{max}(x) = \frac{1}{\sigma\sqrt{2\pi}}$

(8) $\alpha = \frac{y_{cl}}{f_{max}(x)}$

Figure 3 is an example of applying the Gaussian distribution at a dispersion distance (z) of 100 m from the hydrogen gas jet/plume leakage, from a storage tank with a temperature and pressure of 7 MPa and 293 K, and a failure opening diameter of 0.1 m. When applying the Gaussian distribution, the standard deviation (σ) was set to 1/6 of the total length (2R).

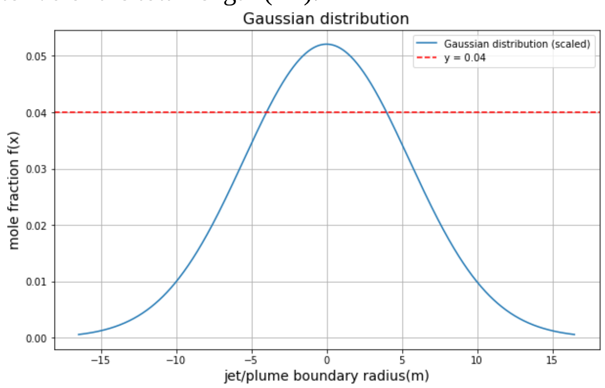

Fig. 3. Gaussian distribution of the jet/plume radius at dispersion distance 100 m

2.4 Determine hydrogen detonable mass

The volume of hydrogen gas jet/plume up to the dispersion point V_{jet} (m^3) can be calculated by Eq (9) [1]. The mass of the hydrogen gas jet/plume m_{jet} (kg) is calculated by Eq (10). The density of the hydrogen gas jet/plume ρ (kg/m^3) is calculated as shown in Eq (11) [3][4].

(9) $V_{jet} = \int_0^z \pi R^2 \, dz$

(10) $m_{jet} = \int_0^z \pi R^2 \rho Y \, dz$

(11) $\rho = \left[\frac{R_{id} T_a}{P_a}\left(\frac{Y}{M_{H_2}} + \frac{1-Y}{M_{air}}\right)\right]^{-1}$

According to Eq's (9-11), the hydrogen detonable mass m_{det} (kg) is defined as Eq (12).

(12) $m_{det} = \int_0^{z_{LDL}} \pi R^2 \rho Y \, dz - \int_0^{z_{UDL}} \pi R^2 \rho Y \, dz$

3. Modeling Results

Under the conditions in Table I, the jet/plume of hydrogen gas leaked due to a guillotine break accident in the pipeline connected to the hydrogen storage tank is shown in Figure 4-6. Under the same conditions, Table II summarizes the hydrogen detonable mass for each standard deviation (σ) when the LDL is set to 14% and the UDL is set to 75%.

Table I: Modeling Initial Conditions

Symbol	Variable	data
P_{st}(Pa)	Storage pressure	7e+06
T_{st}(K)	Storage temperature	293
T_a(K)	Ambient temperature	293
R_e(m)	Pipeline radius	0.05

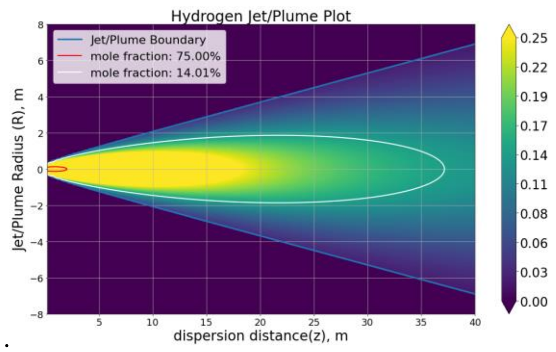

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Fig. 4. Hydrogen jet/plume concentration gradient at standard deviation (σ) = 2 × R/4

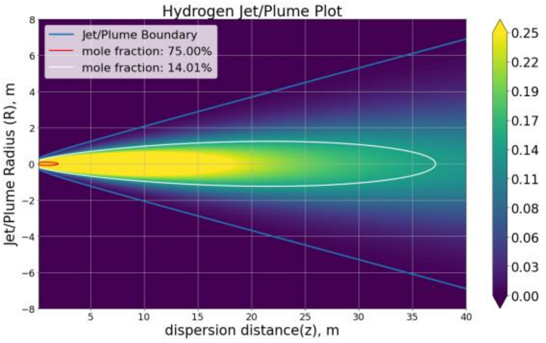

Fig. 5. Hydrogen jet/plume concentration gradient at standard deviation $(\sigma) = 2 \times R/6$

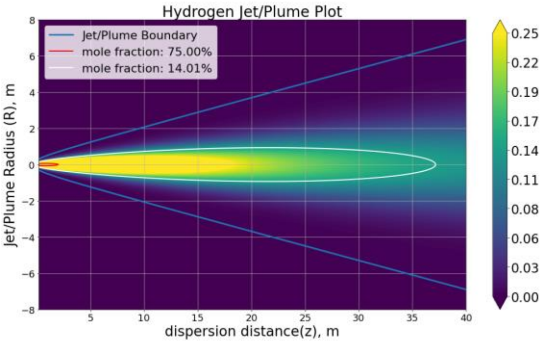

Fig. 6. Hydrogen jet/plume concentration gradient at standard deviation $(\sigma) = 2 \times R/8$

Table II: Hydrogen Detonable Mass

standard deviation (σ)	detonable mass(kg)
$2 \times R/4$	5.65
$2 \times R/6$	2.51
$2 \times R/8$	1.41

4. Conclusions

To evaluate the impact of NPP accidents caused by hydrogen explosions from hydrogen production facility, an analysis of the hydrogen detonable mass was conducted. The mass analysis involved modeling the boundaries of the jet/plume of leaking hydrogen based on the initial temperature and pressure conditions of a hydrogen storage tank. A Gaussian distribution was applied to the modeled hydrogen jet/plume to model the contours according to hydrogen concentration. Using this model, the hydrogen detonable mass was calculated. The hydrogen detonable mass can vary depending on the standard deviation setting of the Gaussian distribution. Therefore, it is important to set the standard deviation correctly to determine the hydrogen detonable mass. By appropriately setting the standard deviation based on experimental data or technical guidelines, the hydrogen detonable mass within the hydrogen jet/plume can be determined. Using the calculated hydrogen detonable mass, overpressure calculations can be performed to assess the safety impact on the NPP.

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