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Methodology for Estimating Mass of Flammable Hydrogen in Leakage Accidents Based on Atmospheric Stability

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1. Introduction

For the licensing and installation of an integrated hydrogen production facility with a nuclear power plant, it is essential to ensure that the hydrogen production facility located near the nuclear site maintains a sufficient safe stand-off distance to prevent any impact on safety due to a potential hydrogen explosion. To evaluate the impact of a hydrogen explosion on the nuclear power plant, the primary task is to estimate the flammable hydrogen mass as it disperses into the atmosphere. This paper presents an atmospheric dispersion model for hydrogen gas and a methodology for evaluating the flammable hydrogen mass within the model.

2. Methodology

Hydrogen gas produced in hydrogen production facilities is generally stored or transported at high pressure relative to atmospheric pressure. For a conservative assessment, hydrogen leakage accidents are assumed to occur due to a guillotine break at the nozzle of a storage tank or in a transport pipeline. Since hydrogen gas leaking from susch a rupture experiences critical flow, it is assumed to form a jet release. The jet release model for a hydrogen gas leakage accident is assumed to follow the Top-Hat jet/plume model, as shown in Figure 1[1][2].

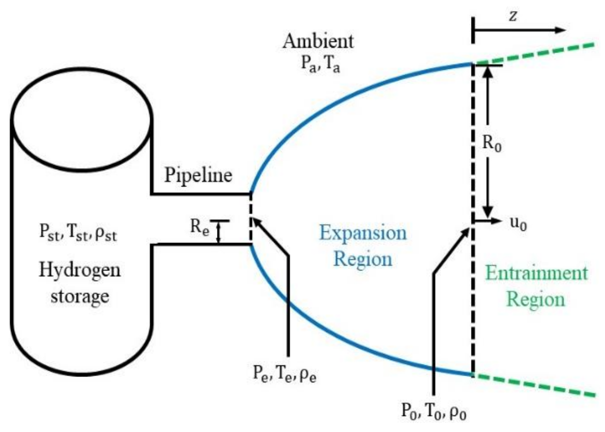

Fig. 1. Hydrogen jet release model

2.1 Determination of Hydrogen Jet/Plume Boundary Radius

The radius of the expansion region downstream (R_0) is determined by the rupture cross-sectional radius and the mass flux (G), as expressed in Eq (1). The radius of the leaked hydrogen gas jet (R) can be calculated using the downstream expansion region radius (R_0) and the centerline mass fraction (Y_{cl}) of the jet, as given in Eqs (2). centerline mass fraction (Y_{cl}) of the jet described by Equation (3), where E_0 and ρ_a represent the entrainment coefficient and ambient density, respectively[1].

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

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

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

2.2 Calculation of Hydrogen Jet/Plume Centerline Dispersion Distance & Concentration

As the dispersion distance increases, the mass fraction of the hydrogen gas jet gradually decreases. The dispersion distance corresponding to the mass fraction of the hydrogen gas jet is derived using Eq (3) and is given by Eq (4). The centerline concentration of the hydrogen gas jet is expressed in Eq (5).

(4) $z = \frac{R_0}{2E_0}\left(\frac{\rho_0}{\rho_a}\right)^{0.5}\left(\frac{1}{Y} - 1\right)$

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

2.3 Hydrogen Jet/Plume Concentration Profile Modeling

When hydrogen gas is released as a jet, it disperses into the atmosphere following a Gaussian distribution with a standard deviation centered along the jet centerline. The horizontal dispersion distance of the hydrogen gas is determined by the standard deviation of the Gaussian distribution, and this value is obtained from the Pasquill-Gifford model. The dispersion coefficients corresponding to different atmospheric stability classes, as categorized by Pasquill-Gifford, are presented in Table 1[5].

Table 1. Standard deviation of Pasquill-Gifford model

Stability category	x (km)	σ_z (m) = a $\cdot x^b$	
		a	b
A	<0.10	122.8	0.9447
	0.10-0.15	158.08	1.0542
	0.16-0.20	170.22	1.0932
	0.21-0.25	179.52	1.1262
	0.26-0.30	217.41	1.2644
B	<0.20	90.673	0.93198
	0.21-0.30	98.483	0.983
C	All	61.141	0.915
D	<0.30	34.459	0.86974
E	<0.10	24.260	0.8366
	0.10-0.30	23.331	0.81956
F	<0.20	15.209	0.81558
	0.21-0.3	14.457	0.78407

The dispersion distance from the centerline at a specific concentration corresponds to the hydrogen jet/plume radius for that concentration region (R_{conc}) and is given by Equation (6) based on the Gaussian distribution equation.

$$(6)\ R_{conc} = \pm\,\sigma_z \times \sqrt{-2 \times \ln\left(\frac{y_{conc}}{y_{cl}}\right)}$$

2.4 Calculation of Hydrogen Flammable Mass

As leaked hydrogen gas disperses into the atmosphere, it mixes with air to form a hydrogen-air mixture. The hydrogen-air mixture ignites and combusts only when its concentration is within a specific flammability limit range. For hydrogen, this flammable range is between 4% (Lower Flammability Limit, LFL) and 75% (Upper Flammability Limit, UFL) by volume[6]. Thus, the hydrogen flammable mass refers to the mass of hydrogen gas within the region bounded by these flammability limits, and it can be calculated based on the dispersion distance corresponding to these limits, as shown in Equation (7)[3].

$$(7)\ m_{flam} = \int_0^{z_{LFL}} \pi R_{conc}^2 \rho Y\, dz - \int_0^{z_{UFL}} \pi R_{conc}^2 \rho Y\, dz$$

Generally, the mass of hydrogen gas between the leak source and the upper flammability limit (UFL) is relatively small and can be considered negligible. Therefore, the explosion mass is determined by applying the hydrogen explosion efficiency to the flammable hydrogen mass, as described in Eq (8).

$$(8)\ m_{flam} \cong \int_0^{z_{LFL}} \pi R_{conc}^2 \rho Y\, dz$$

3. Modeling Results

After applying the atmospheric stability classes from Table 1 to set the dispersion standard deviation, Equation (6) was continuously utilized to model the concentration gradient of the hydrogen jet/plume. The modeling results are shown in Figures 2–4. For the modeling, a guillotine break of a pipeline connected to a high-pressure hydrogen storage tank was assumed. The storage tank pressure and temperature were set to 18 MPa and 333 K, respectively, with a failure diameter of 0.02 m and a discharge coefficient (C_D) of 1.0.

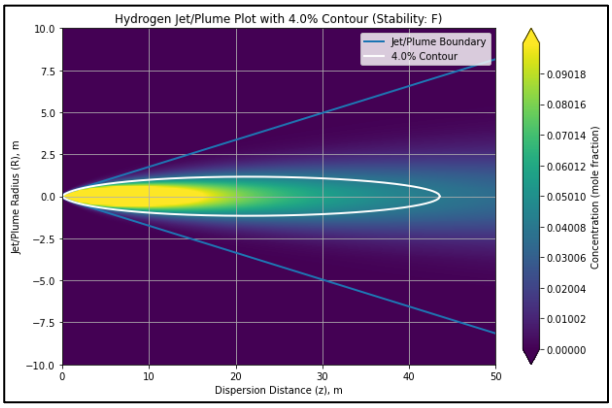

Fig. 2. Hydrogen jet/plume concentration profile model for atmospheric stability class F

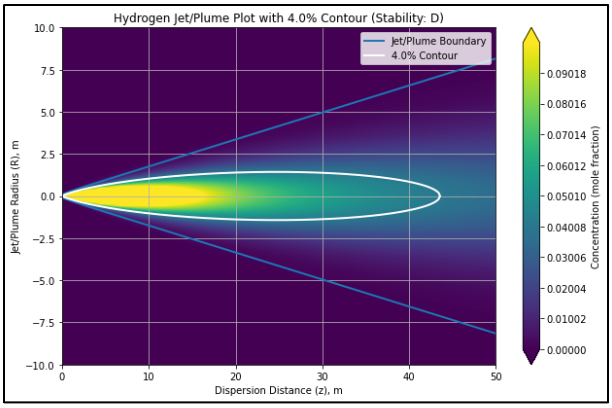

Fig. 3. Hydrogen jet/plume concentration profile model for atmospheric stability class D

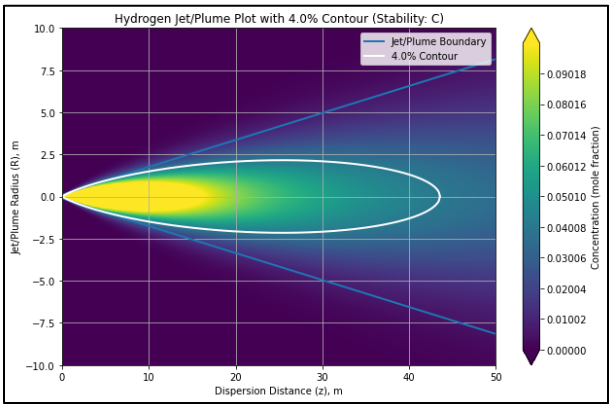

Fig. 4. Hydrogen jet/plume concentration profile model for atmospheric stability class C

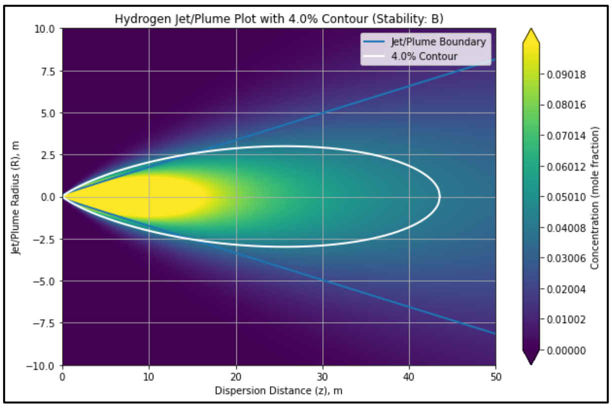

Fig. 5. Hydrogen jet/plume concentration profile model for atmospheric stability class B

The evaluation results for each model are presented in Table 2. Under the initial conditions described above, the dispersion distance to the lower flammability limit(z_{LFL}) is identical for all cases at 43.6 m.

Table 2. Evaluation Results of Leaked Hydrogen Gas According to Atmospheric Stability Classes

Stability category	Flammable mass m_{flam} (kg)
B	5.27
C	2.78
D	1.27
F	1.00

4. Conclusions

To evaluate the impact of a hydrogen leakage explosion on a nuclear power plant, it is important to estimate the hydrogen flammable mass. The hydrogen flammable mass can be assessed by applying the top-hat jet/plume model and the dispersion standard deviation based on the Pasquill–Gifford model for hydrogen dispersing into the atmosphere. The hydrogen flammable mass varies depending on the atmospheric stability class, allowing a flexible evaluation tailored to specific scenarios. By determining the explosive hydrogen mass—calculated by applying a hydrogen explosion efficiency factor to the flammable hydrogen mass—and evaluating the explosion overpressure, it is possible to propose a safe separation distance that meets regulatory guidelines. This approach is expected to secure feasibility for permitting and licensing in the installation of hydrogen plants integrated with nuclear power plants

REFERENCES

[1] Michael Epstein, Hans K. Fauske, Total Flammable Mass and Volume Within a Vapor Cloud Produced by a Continuous Fuel-Gas or Volatile Liquid-Fuel Release, 2007.
[2] Michael Epstein, Hans K. Fauske, Mass of Flammable Material Produced by Continuous Fuel-Gas and Volatile Liquid-Fuel Releases, 2001.
[3] Michael Epstein, Hans K. Fauske, Flammable Mass and Length of a Variable-Density Buoyant Fuel Jet: Gaussian Versus Top-Hat profiles, 2003.
[4] D. Burgess, J. N. Murphy, M. G. Zabetakis, H. E. Perlee, Volume of Flammable Mixture Resulting from the Atmospheric Dispersion of a Leak or Spill, 1975.
[5] F. A. Gifford, Use of routine meteorological observations of estimating atmospheric dispersion, nuclear safety 2, no.4., 1941
[6] National Aeronautics and Space Administration (NASA), Safety standard for hydrogen and hydrogen systems: Guidelines for hydrogen system design, materials selection, operations, storage, and transportation, 1997
[7] U.S. Nuclear Regulatory Commission, Regulatory Guide 1.91, “Evaluation of explosions postulated to occur at nearby facilities and on transportation routes near nuclear power plants” Washington, DC