Applicability Assessment of the Top-Hat Jet/Plume Model for Hydrogen Explosion Risk in NPP-Integrated Hydrogen Facilities

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***Keywords :** hydrogen, jet, gaussian distribution, explosion, detonation, top-hat jet

1. Introduction

The global demand for carbon neutrality has increased interest in hydrogen production technologies. Nuclear power, with its stable electricity and high-temperature heat, has driven research on NPP-integrated hydrogen production. Safety assessment of hydrogen explosion risks in these facilities is essential, with hydrogen leakage evaluation being important. While leakage is generally assessed using the Gaussian model, this paper examines the applicability of the Top-hat model in comparison.

2. Methodology

In this section, the Gaussian and Top-hat Jet/Plume models used for hydrogen leakage evaluation are presented, describing their leakage release models and approaches to estimate the detonable mass of hydrogen.

2.1 Gaussian Distribution Jet/Plume Model

Generally, initial hydrogen leakage under high-pressure conditions leads to a jet expansion, as shown in Fig. 1.

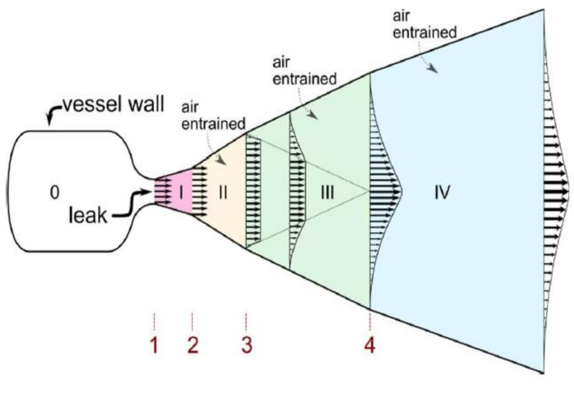

Fig. 1. High-pressure jet/plume release model[1]

In Fig. 1, the Gaussian distribution Jet/Plume model for hydrogen leakage can be applied from region IV onward, where the velocity (u), density (ρ), and mass fraction (Y) are expressed by Eqs. (1), (2), and (3), respectively, following the one-dimensional formulation described by Houf and Winters [2]. In Eqs (1) - (3), μ_{cl} and ρ_{cl} denote the centerline velocity and density, respectively. B represents the half-width, where the velocity decreases to half of its centerline value, and λ is the spreading ratio, defined as the ratio of density spreading relative to velocity spreading. Based on the experimental results reported by Houf and Winters, a spreading ratio of λ = 1.16 is commonly employed. However, in this study, a more conservative value of λ = 1.5 is adopted to reflect safety-oriented considerations.

$$(1)\ u = u_{cl} \exp\left(-\frac{r^2}{B^2}\right)$$

$$(2)\ \rho = (\rho_{cl} - \rho_{amb}) \exp\left(-\frac{r^2}{\lambda^2 B^2}\right) + \rho_{amb}$$

$$(3)\ \rho Y = \rho_{cl} Y_{cl} \exp\left(-\frac{r^2}{\lambda^2 B^2}\right)$$

In the Gaussian distribution jet/plume model, the detonable mass of hydrogen is calculated by Eq. (4)[3].

$$(4)\ m_{det} = \int_{S=0}^{\infty}\left(\int_{r_{Y_{UDL}}}^{r_{Y_{LDL}}} \rho Y 2\pi r dr\right) dS$$

2.2 Top-Hat Jet/Plume Model

In the case of the Top-hat jet/plume, unlike Fig. 1, the initial hydrogen leakage simplified into two region, as shown in Fig. 2.

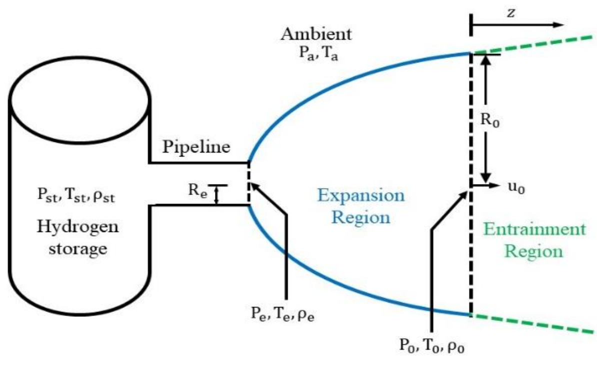

Fig. 2. Top-hat jet/plume release model

In the Top-hat jet model, the jet radius (R_0), velocity (u_0), and density (ρ_0) at the beginning of the entrainment region are given by Eqs. (5), (6), and (7), respectively, while the mass fraction of the jet is expressed by Eq. (8) In Eq. (8), *z* represents the hydrogen jet/plume dispersion distance [4][5][6].

$$(5)\ R_0 = R_e \left(\frac{G}{u_0 \rho_0}\right)^{0.5}$$

$$(6)\ u_0 = \frac{G}{\rho_e} + \frac{P_e - P_a}{G}$$

$$(7)\ \rho_0 = \frac{P_a M_{H_2}}{R_{id} T_0}$$

$$(8)\ Y = \frac{1}{1+\frac{2E_0}{R_0}\left(\frac{\rho_a}{\rho_0}\right)^{0.5} z}$$

In the Top-hat jet/plume model, the detonable mass of hydrogen is calculated by Eq. (9)[4].

$$(9)\ m_{det} = \int_{z_{UDL}}^{z_{LDL}} \pi R^2 \rho Y\, dz$$

2.3 Determination of Lower and Upper detonability Limits (LDL and UDL)

In hydrogen jet/plume, which have a flammable range of 4–75% by volume, the region satisfying Eq. (10) is defined as the detonable hydrogen region. In Eq. (10), the hydrogen concentration at which the left-hand side equals 0.1 is defined as the lower detonability limit(y_{LDL}). Detonation cell width(λ) with respect to hydrogen concentration is based on Fig 3[7].

$$(10)\ \left(\frac{d\lambda}{dy}\right)\left(\frac{dy}{dY}\right)\left(\frac{dY}{dz}\right) < 0.1$$

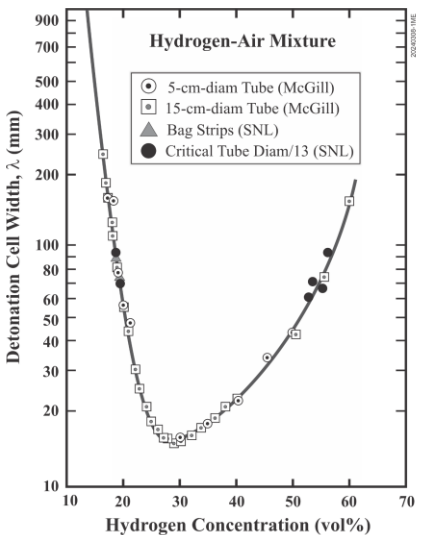

Fig. 3. Measured values of the detonation cell width as a function of hydrogen concentration

In the flammable range of hydrogen, concentrations above the stoichiometric value (≈29.5%) are considered fully detonable. Consequently, the upper detonability limit(y_{UDL}) is defined by the upper flammability limit, corresponding to a hydrogen concentration of 0.75.

3. Comparison of Results between Models

For comparison of the detonable mass of hydrogen, jet/plume modeling was performed for both models under the conditions in Table I. The lower detonability concentration(y_{LDL}) is obtained by solving Eq. (10) with the corresponding parameters. In the comparison of the two jet models, both the orifice coefficient (C_D) and the ambient temperature were set to 1.0 and 293 K, respectively. Fig. 4–11 shows the jet/plume model results for the input conditions in Table I with detonable regions indicated, while Table II summarizes the corresponding detonable hydrogen mass for each model.

Table I: Input assumptions for jet model comparison

Case Number	Storage Pres'(MPa)	Storage Temp'(K)	Pipe Diameter (mm)	y_{LDL}
1	1.5	303	50	0.1840
2			100	0.1623
3	10	333	50	0.1563
4			100	0.1312

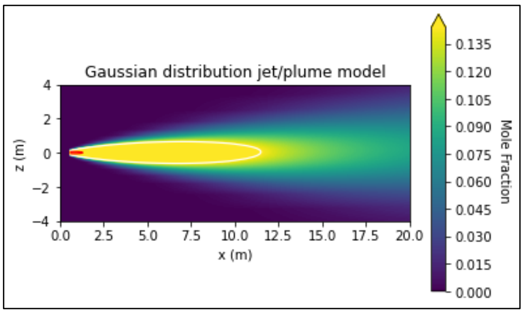

Fig. 4. Gaussian Distribution jet/plume model(Case-1)

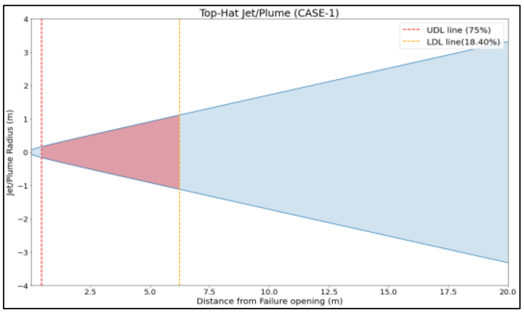

Fig. 5. Top-hat jet/plume model(Case-1)

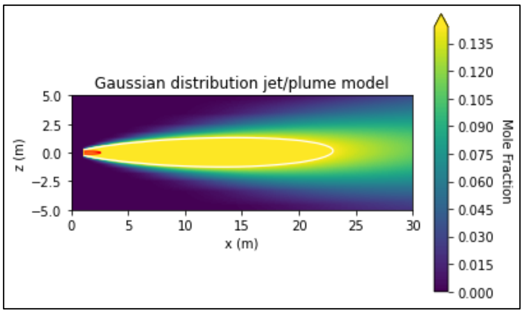

Fig. 6. Gaussian Distribution jet/plume model(Case-2)

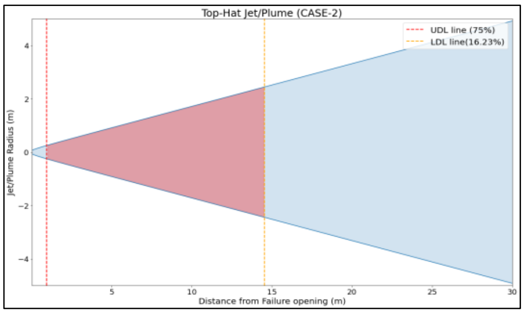

Fig. 7. Top-hat jet/plume model(Case-2)

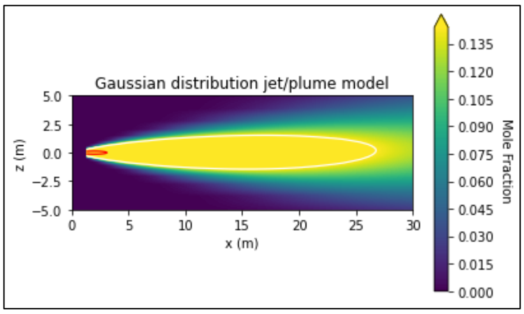

Fig. 8. Gaussian Distribution jet/plume model(Case-3)

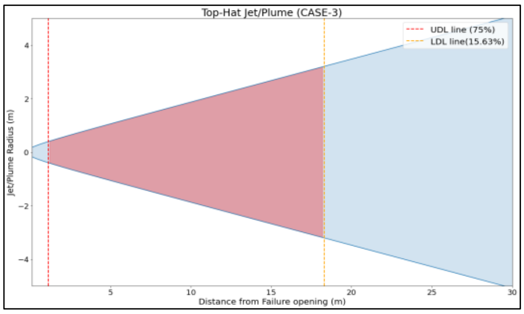

Fig. 9. Top-hat jet/plume model(Case-3)

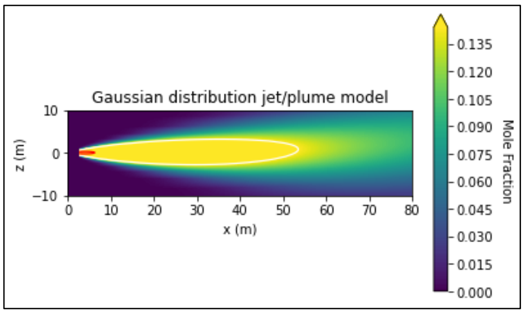

Fig. 10. Gaussian Distribution jet/plume model(Case-4)

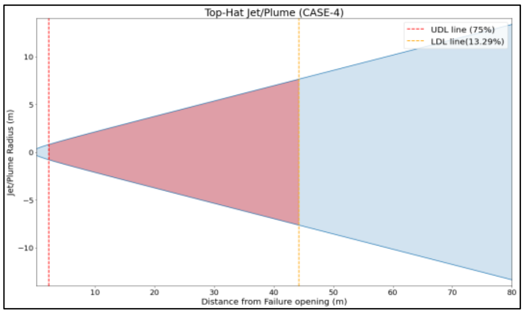

Fig. 11. Top-hat jet/plume model(Case-4)

Table II: Detonable mass of hydrogen

Case Number	Gaussian Jet/Plume Model Detonable Mass ($m_{det,gaus}$, kg)	Top-Hat Jet/Plume Model Detonable Mass ($m_{det,TH}$ kg)
1	0.08	0.19
2	0.83	2.03
3	1.42	3.87
4	16.7	45.11

4. Conclusion

This paper evaluated the applicability of the Top-hat jet/plume model for hydrogen risk assessment in NPP-integrated hydrogen production facilities. Compared with the Gaussian jet/plume model, the Top-hat jet/plume model predicts approximately 2–3 times higher detonable mass of hydrogen, thereby providing more conservative results and ensuring safety margins. Its analytical tractability, adaptability to design changes, and reliability in representing early high-pressure jet releases further support its practical use. Accordingly, the Top-hat jet/plume model is expected to serve as a conservative and efficient tool for hydrogen risk assessment, and the feasibility of regulatory approval in future licensing processes can be ensured.

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