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Correlation for overpressure during ignited spurious hydrogen release

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Introduction

- An under-expanded hydrogen jet from high-pressure equipment or storage tank is a potential incident scenario.
- Previous experiments demonstrated that delayed ignition of a highly turbulent under-expanded hydrogen jet generates a blast wave able to harm people and damage property.
- The resulting overpressure strongly depends on the ignition location and delay time.
- The present study aimed at developing an engineering correlation for predicting the maximum overpressure that could be produced by a hydrogen jet for known storage pressure and release diameter.

Validation tests description

Similitude analysis

- A total of **78 tests** were selected to analyse the phenomenon and validate the correlation.
- Steady state and unsteady horizontal hydrogen jet fires.

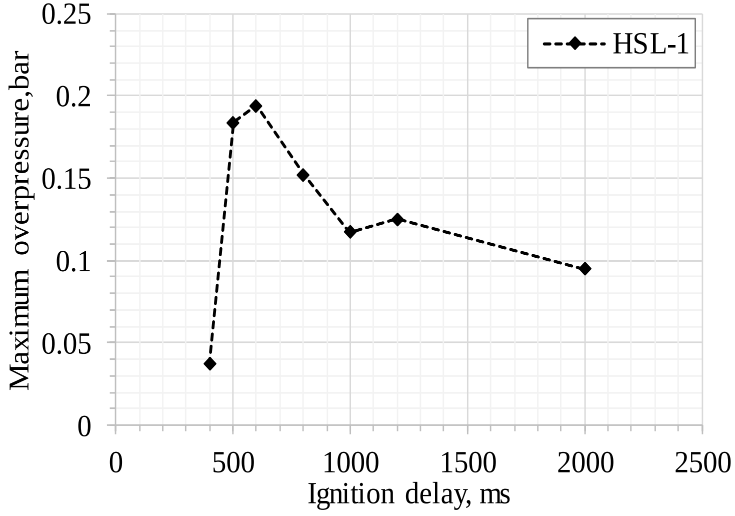
Number of tests	78
Storage pressure, MPa	0.5-65.0
Storage temperature, K	80-290
Release diameter, mm	0.5-52.5
Ignition delay, s	0.02-20.45
Ignition location, m	0.2-4.0

Effect of ignition position and delay

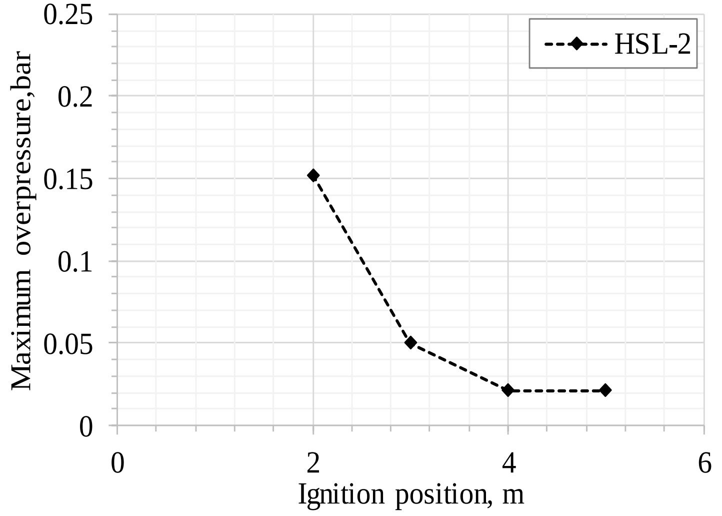
Example for HSE tests series

- Blast wave overpressure from delayed ignition of a turbulent hydrogen jet from 20 MPa storage through 6.4 mm nozzle.

Effect of ignition delay for a fixed ignition position at 2 m from the nozzle along the jet axis



Effect of ignition position for a fixed ignition delay time of 0.8 s



The similitude analysis

Effect of storage conditions

- The main parameters affecting the overpressure produced by delayed ignition of hydrogen under-expanded jets are identified as the hydrogen storage pressure and release nozzle diameter.
- The increase of either parameter increases the volume of the fast-burning turbulent hydrogen-air mixture in the jet and thus the overpressure in the blast wave.

First step of the analysis - effect of storage conditions:

- The deflagration overpressure increases with storage pressure, P_s. Thus, the first dimensionless parameter could be taken as:

$$\Pi_1 = \frac{P_s}{P_0}$$

Where P_0 is the ambient pressure, Pa.

The similitude analysis

Fast-burning hydrogen-air mixture

- The acoustic theory states that for spherical symmetry the overpressure generated by expanding sphere, i.e. spherical "piston", is proportional to the square of the velocity of the "piston".
- Only the most fast-burning portion of the hydrogen jet is assumed to define the maximum overpressure in the deflagration blast wave.

$$S_{pv} = S_u \cdot (E_i - 1) \cdot \chi_K \cdot \chi_{lp} \cdot \chi_t$$

- The fast-burning portion of the jet is found for a near-stoichiometric mixture of 25-35% of hydrogen by volume with the centre assumed at the location on the jet axis corresponding to 30% by volume of hydrogen in air ($C_{30\%}$).

$$x = 5.4\sqrt{\frac{\rho_N}{\rho_S}}\frac{d}{C_{m,30\%}}$$

tunnel HP

The similitude analysis

Effect of release diameter and distance

- Experiments demonstrated that the overpressure in the blast wave depends on the release diameter d.
- The overpressure decreases with the increase of distance from the jet. Therefore, the second dimensionless parameter is defined as:

$$\Pi_2 = \frac{d}{R_w}$$

where R_w is the distance between the pressure sensor (or target) and the centre of the 25-35% hydrogen cloud.

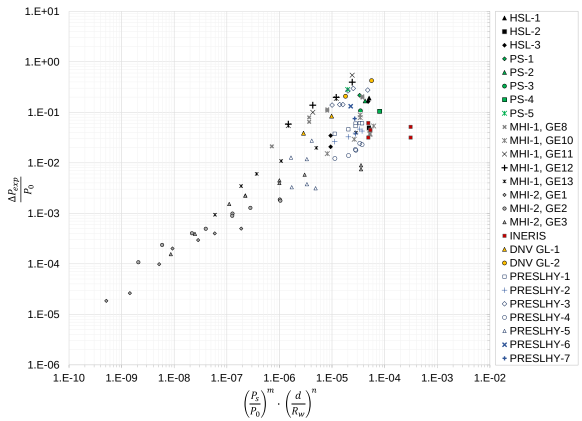
- The dimensionless overpressure in the deflagration blast wave, $\Delta P_{exp}/P_0$, can be represented as a function of the combined dimensionless numbers:

$$\left(\frac{\Delta P_{exp}}{P_0}\right)^a = f\left(\left(\frac{P_s}{P_0}\right)^m \cdot \left(\frac{d}{R_w}\right)^n\right)$$

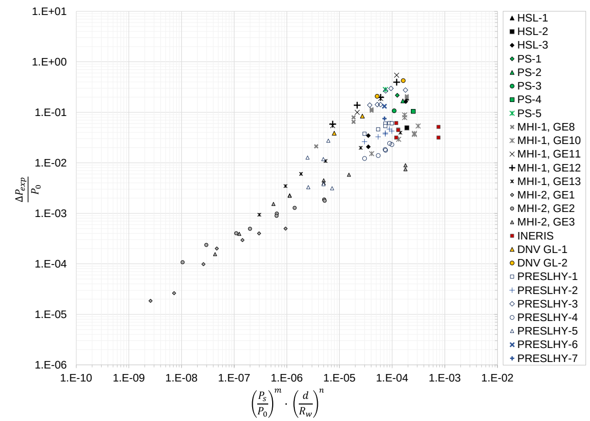
Calibration of correlation (1/2)

Similitude analysis

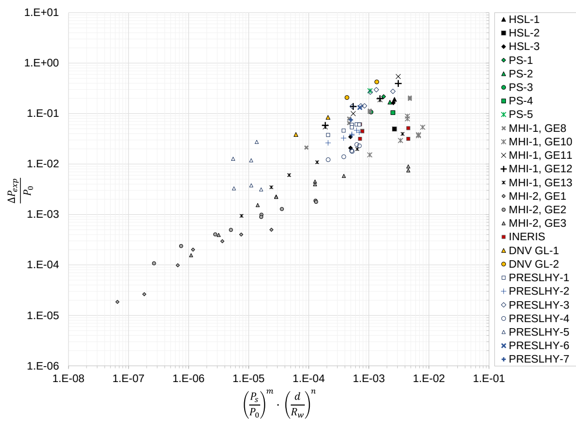
Testing of the parameter $\left(\frac{P_s}{P_0}\right)^m$ for different powers of *m* and constant *n=2.*



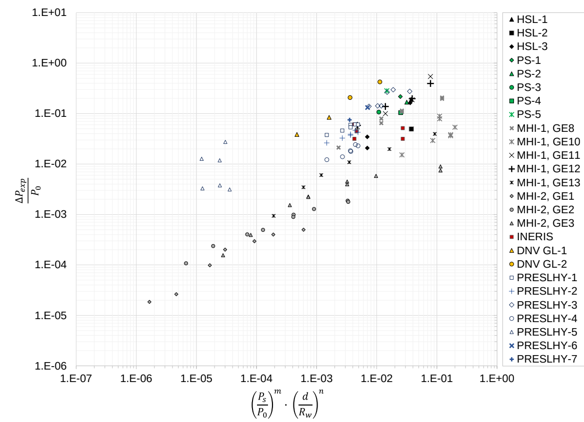
m=0.25, n=2



m=0.5, n=2



m=1.0, n=2

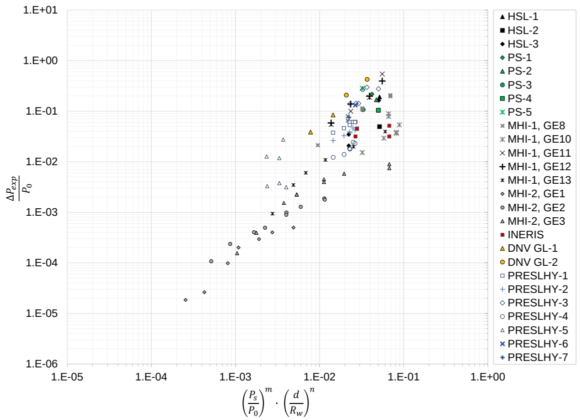


m=1.5, n=2

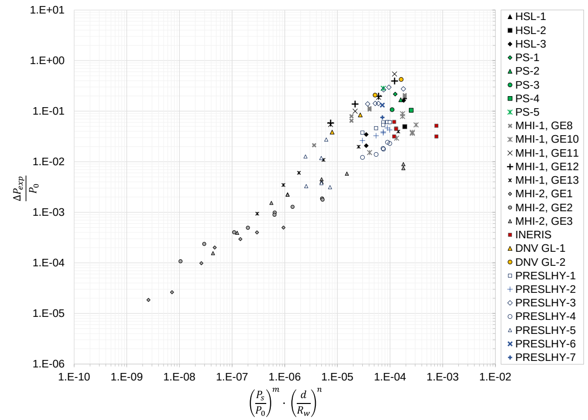
Calibration of correlation (2/2)

Similitude analysis

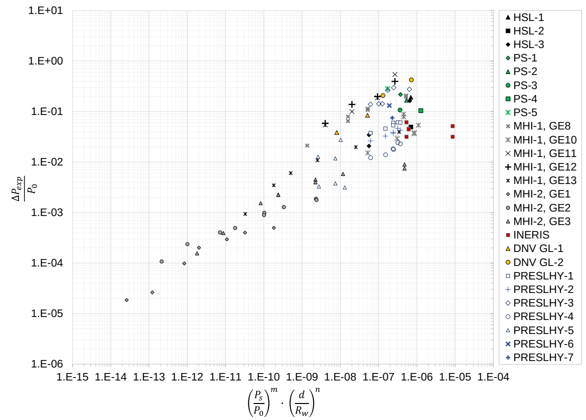
Testing of the parameter $\left(\frac{d}{R_w}\right)^n$ for different powers of *n* and constant *m=0.5.*



m=0. 5, n=1



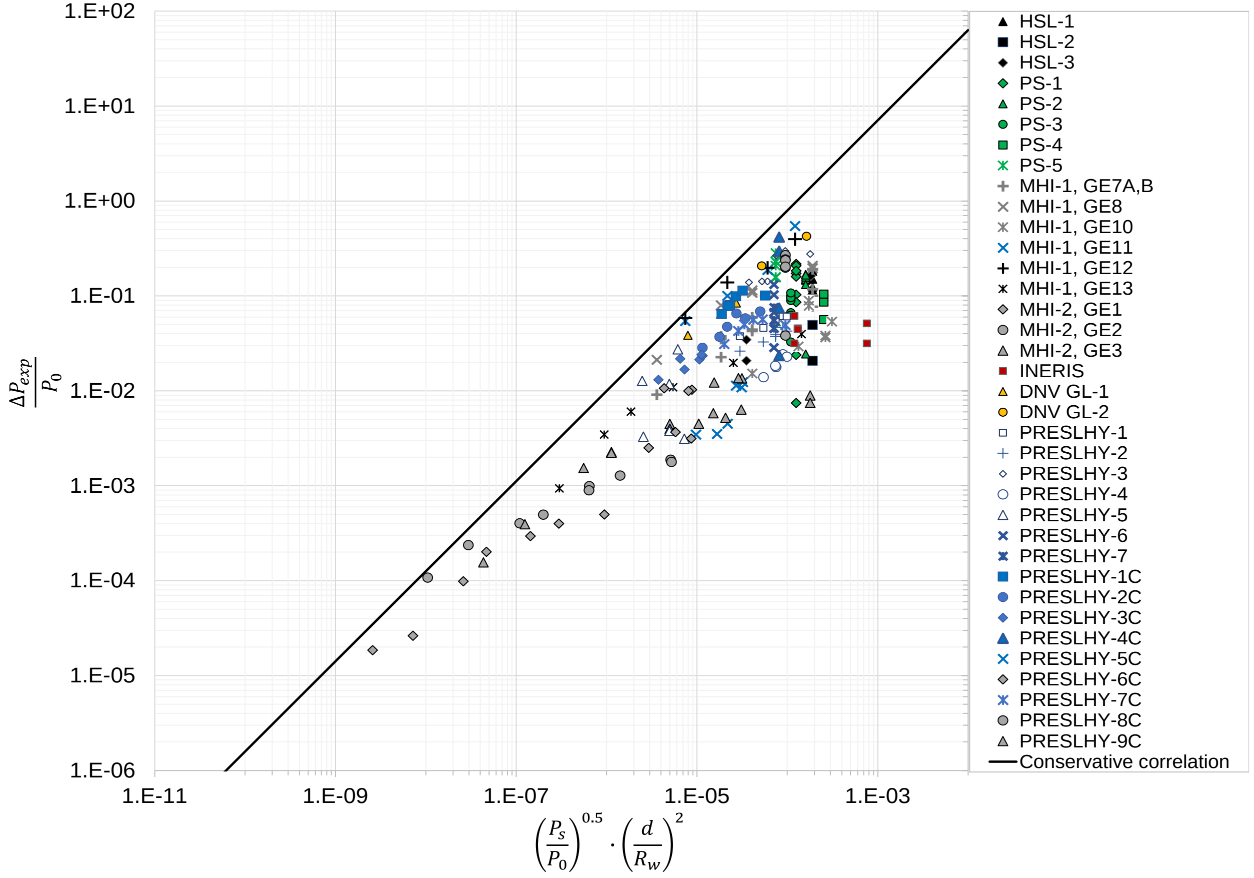
m=0.5, n=2



m=0.5, n=3

Conservative correlation

Similitude analysis

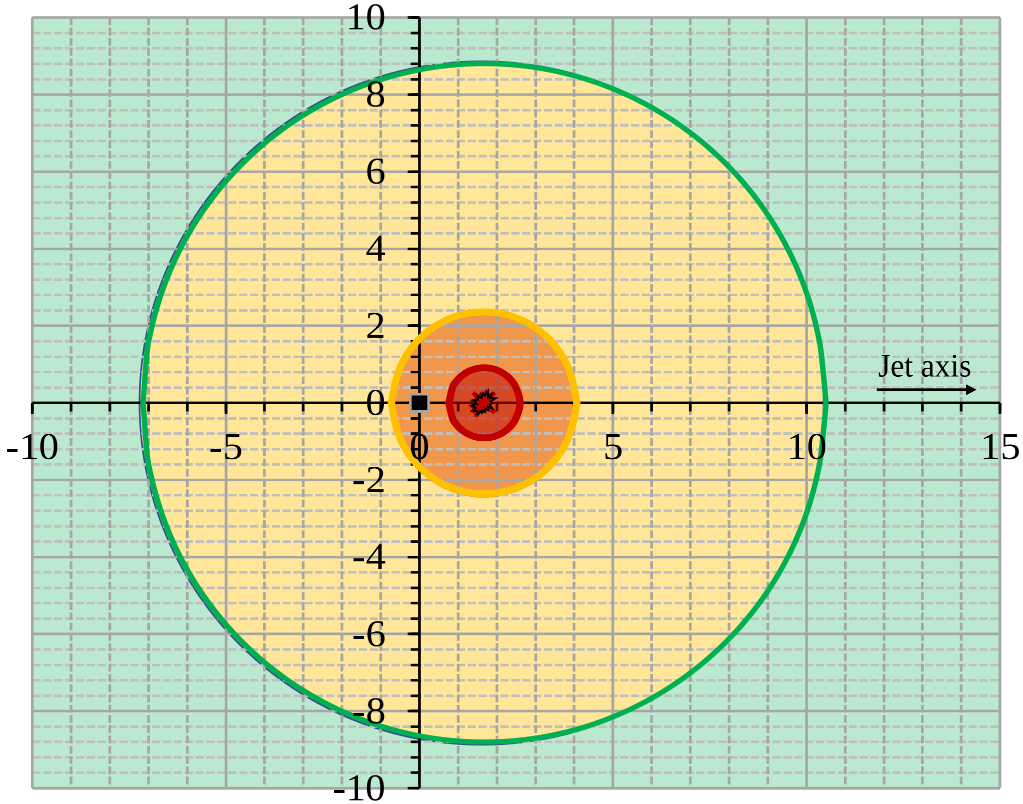


$$\frac{\Delta P_{exp}}{P_0} = 5000 \cdot \left[\left(\frac{P_s}{P_0}\right)^{0.5} \cdot \left(\frac{d}{R_w}\right)^2\right]^{0.95}$$

Use for typical hydrogen applications

Fuel cell hydrogen vehicle (1/2)

- Storage pressure = 700 bar
- Release diameter = 2 mm



■	Release source
✸	Centre of fast burning cloud
(red)	Fatality zone (ΔP≥100 kPa)
(orange)	Serious injury zone (ΔP=100-16.5 kPa)
(yellow)	Slight injury zone (ΔP=16.5-1.35 kPa)
(green)	“No-harm” zone (ΔP≤1.35 kPa)

Distance from nozzle

$R_{no\_harm} = 8.8$ m → **10.5 m**

$R_{injury} = 2.4$ m → **4.1 m**

$R_{fatality} = 0.9$ m → **2.6 m**

Use for typical hydrogen applications

Fuel cell hydrogen vehicle (2/2)

Case	P_s, MPa	d, mm	Radius of slight injury zone, m	Radius of serious injury zone, m	Radius of fatality zone, m
			P_{th} =1.35 kPa	P_{th} =16.5 kPa	P_{th} =100 kPa
Vehicle (a)	70	0.5	2.2 (2.6)	0.6 (1.0)	0.2 (0.6)
Vehicle (b)	70	1	4.4 (5.2)	1.2 (2.0)	0.5 (1.3)
Vehicle (c)	70	2	8.8 (10.5)	2.4 (4.0)	0.9 (2.6)
Train	70	5	22.0 (26.2)	5.9 (10.1)	2.3 (6.5)
Bus	35	5	18.5 (21.7)	5.0 (8.2)	1.9 (5.2)

Note: The maximum hazard distances from the release point are shown in the parenthesis.

Conclusions
… and recommendations

- A conservative correlation was derived through the similitude analysis for about 80 experimental tests available in literature on hydrogen releases.
- The use of the conservative correlation is recommended as a tool for hydrogen safety engineering to calculate the maximum blast wave overpressure achievable after delayed ignition of free under-expanded hydrogen jet for arbitrary conditions of the release.
- It was observed that for a FCHV, the “no-harm” distance for people reduces from 10.5 m to 2.6 m when a TPRD diameter decreases from 2 mm to a diameter of 0.5 mm (P=70 MPa).
- The “no-harm” distance for d=0.5 mm is comparable with a size of a vehicle.

Acknowledgements

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