Hy Responder

Hazard distances from hydrogen flames and fire fighting

Content

Objectives of the lecture

1. Distinguish between different types of hydrogen fires: from microflames to jet fires and fireballs
2. Evaluate hydrogen flame lengths with the aid of nomograms, dimensional and dimensionless correlations
3. Assess the average location of jet flame tip
4. Predict the hazard distances to protect people and structures
5. Explain the effect of different factors on the flame length of jet fire: nozzle size and shape, jet attachment, buoyancy, barriers or walls
6. Compare the flame lengths and heat fluxes of jet fires of hydrogen and other common fuels (CNG and LPG)
7. Explain the pressure effects of hydrogen jet fires
8. Identify the main hydrogen fires detection methods
9. Recognise the mitigation techniques for hydrogen fires
10. Implement the hydrogen fires extinction practices

Dimensionless numbers

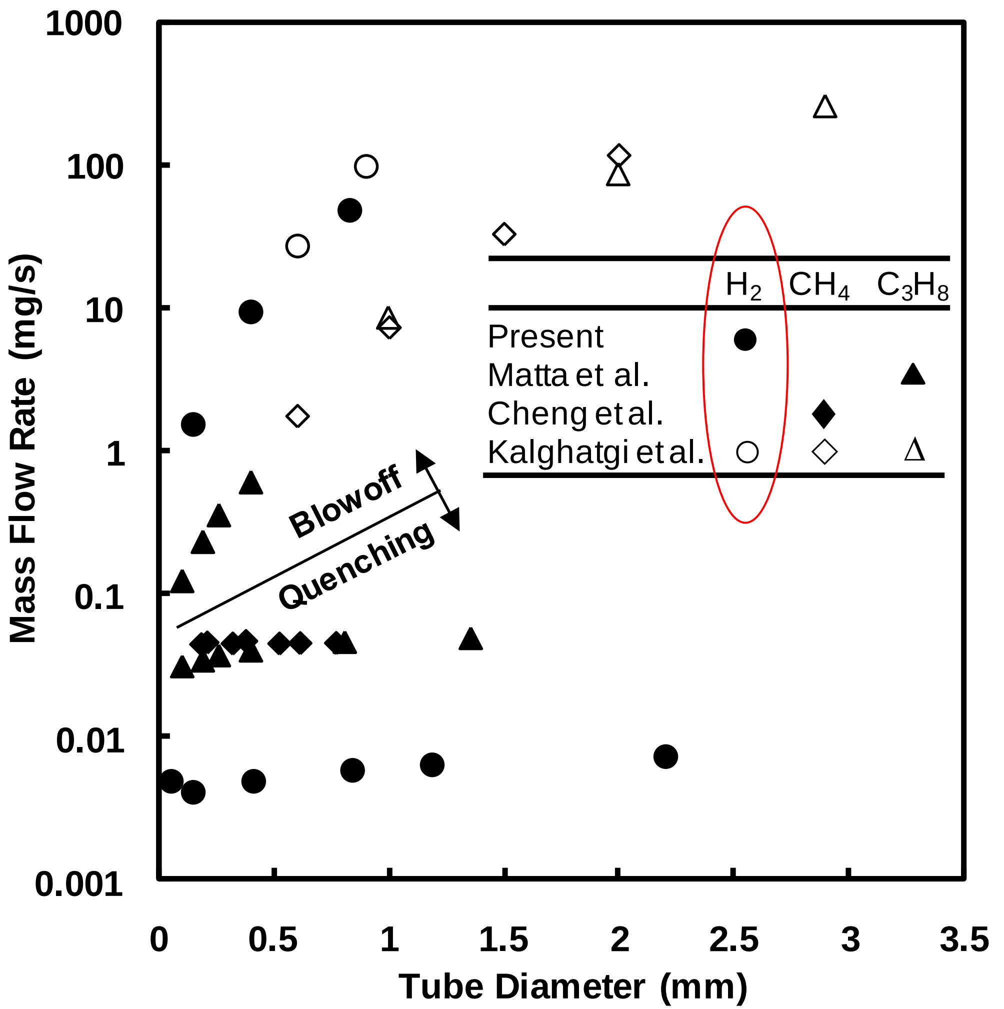
- The Froude number, $Fr=U^2/gd$, where U - velocity, d – characteristic size, g – acceleration due to gravity, is a ratio of **inertial to gravity** force (multiplied by the product of density by area ρA).
- The Reynolds number, $Re=Ud\rho/\mu$, where ρ – density, μ – viscosity, is a ratio of **inertial to viscous** force.
- The Mach number, $M=U/C$, where C – speed of sound, is a ratio of **inertial force to inertial force at sonic flow**.
- The speed of sound in ideal gas is: $C = \sqrt{\gamma \frac{RT}{M}}$

Temperature, T (°C)	Speed of sound, c (m/s)
35	351.88
30	349.02
25	346.13
20	343.21
15	340.27
10	337.31
5	334.32
0	331.30
−5	328.25
−10	325.18
−15	322.07
−20	318.94
−25	315.77

Types of hydrogen flames/fires

- From microflames (10^{-9} kg/s) to high debit flames (10 kg/s).
- Laminar diffusion and turbulent non-premixed flames.
- Buoyancy- and momentum-controlled jets.
- Subsonic, sonic and under-expanded supersonic jet flames.
- Fireballs during storage tank failure in a fire.
- Liquefied hydrogen (LH_2) fires - little knowledge.
- Impinging flames.
- Jet flames in the presence of obstacles, surfaces and in enclosures.

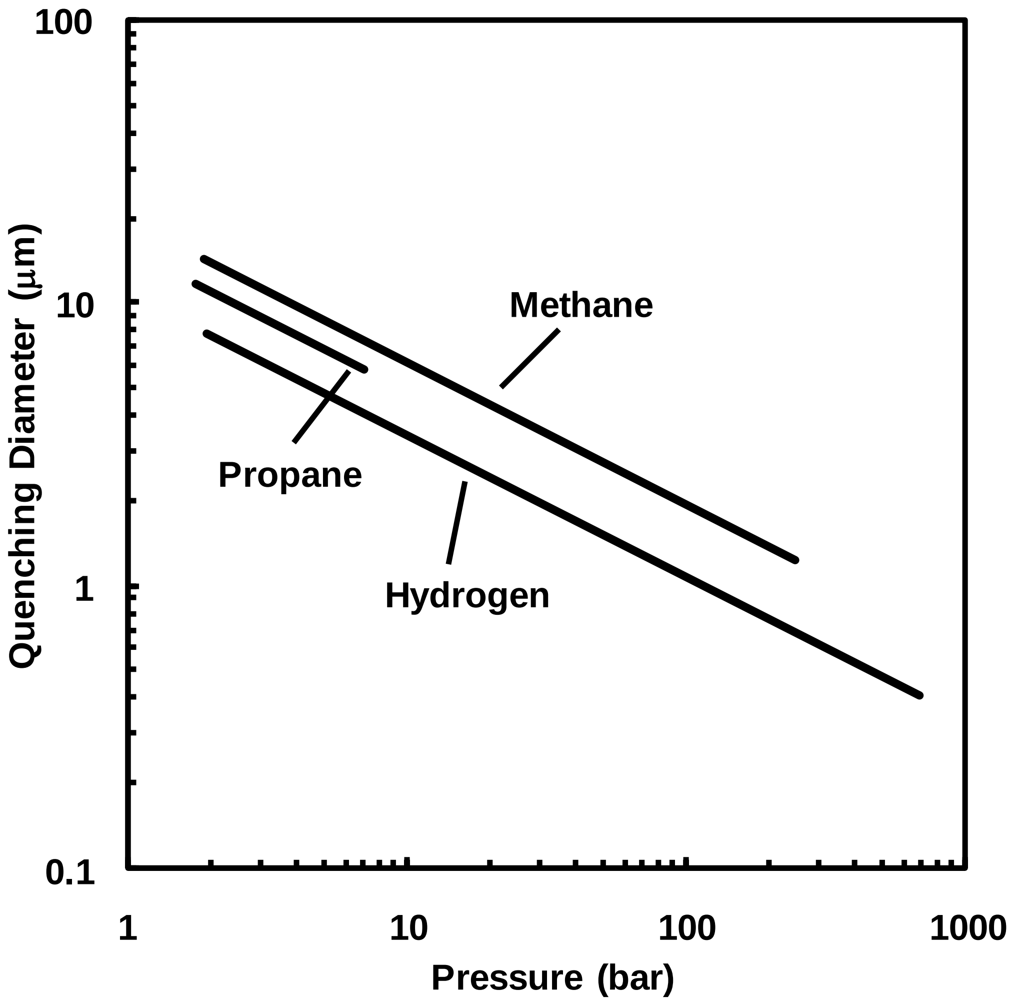
Quenching limits and blow-off



- Tube burner is used.
- **Quenching limits are nearly independent of diameter.**
- Hydrogen has the lowest quenching limit and the highest blow-off limit.

Hazard distances from hydrogen flames and fire fighting

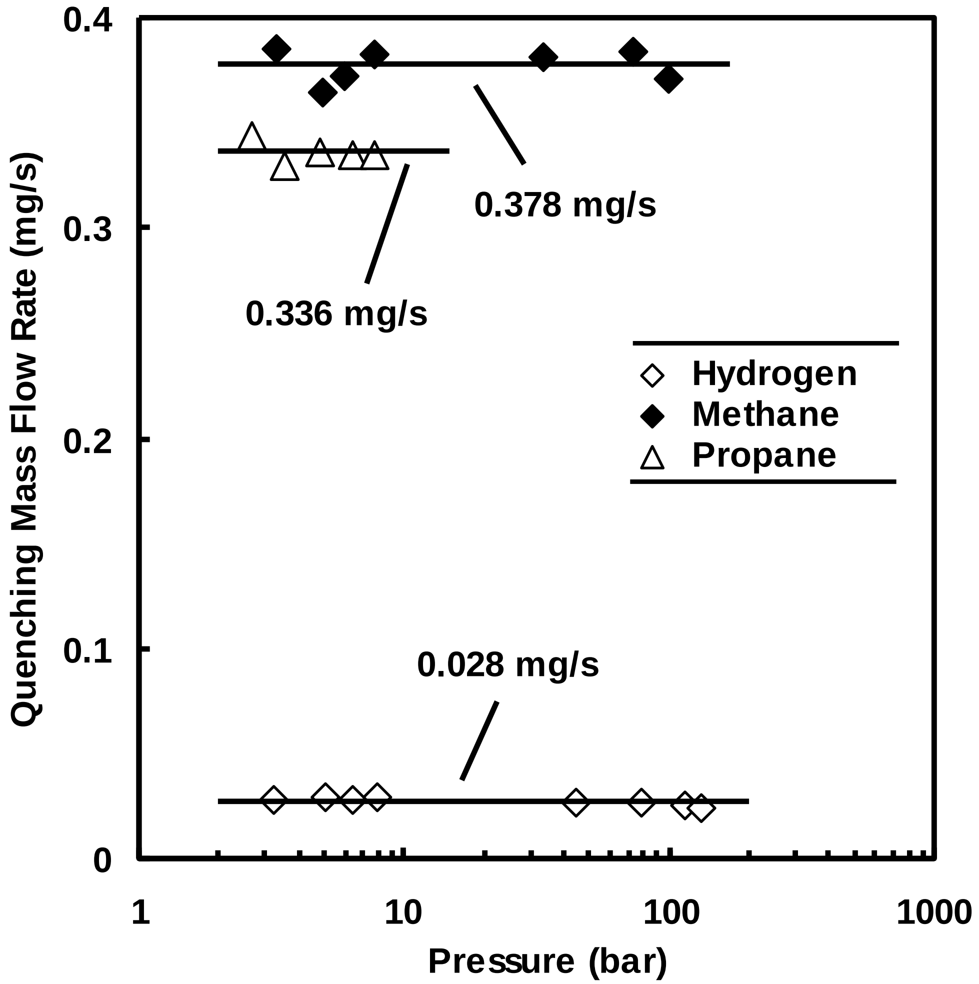
Quenching diameter



For hydrogen at 690 bar,

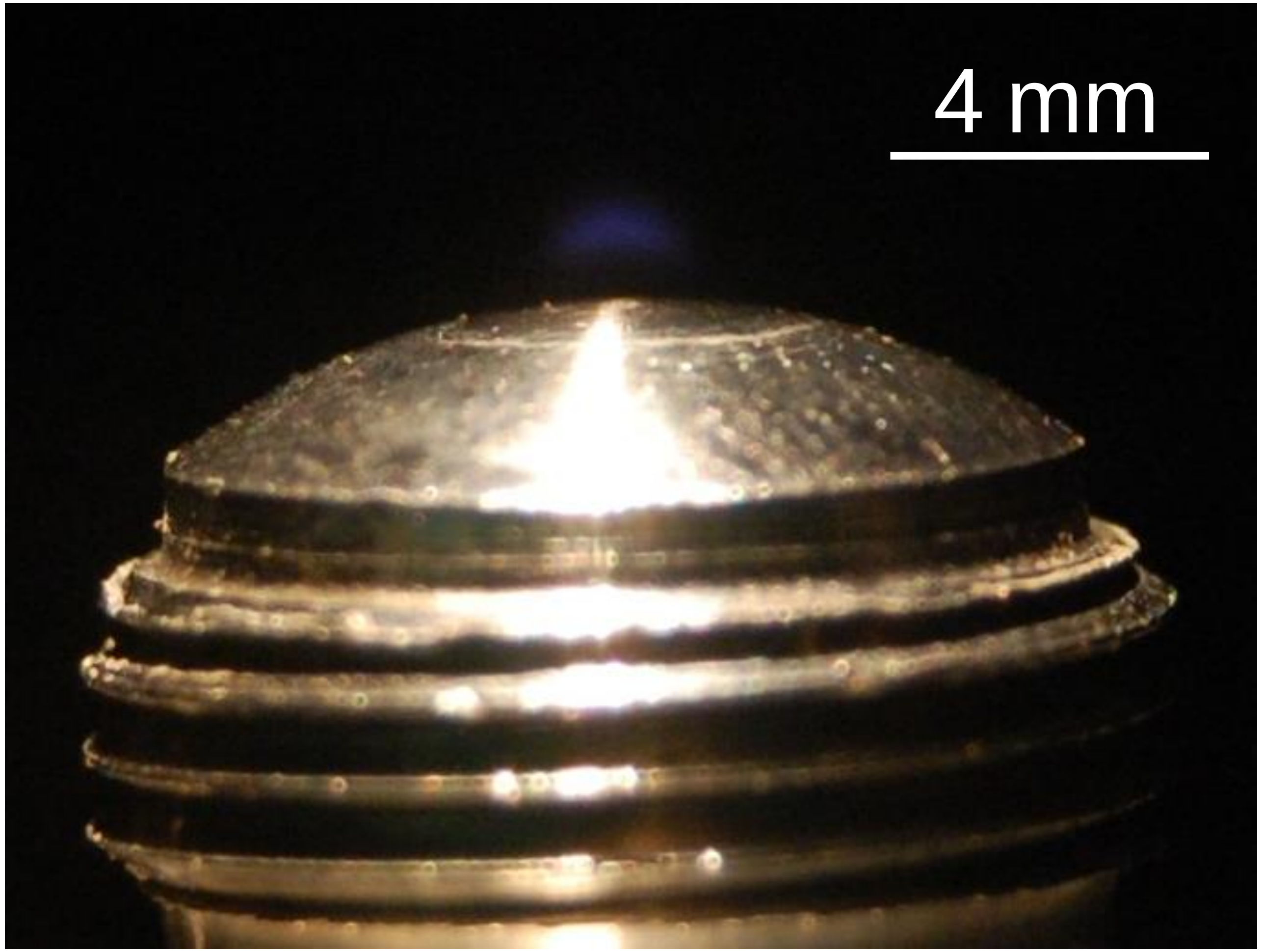
any hole larger than 0.4 µm will support a stable flame.

Leaky fittings



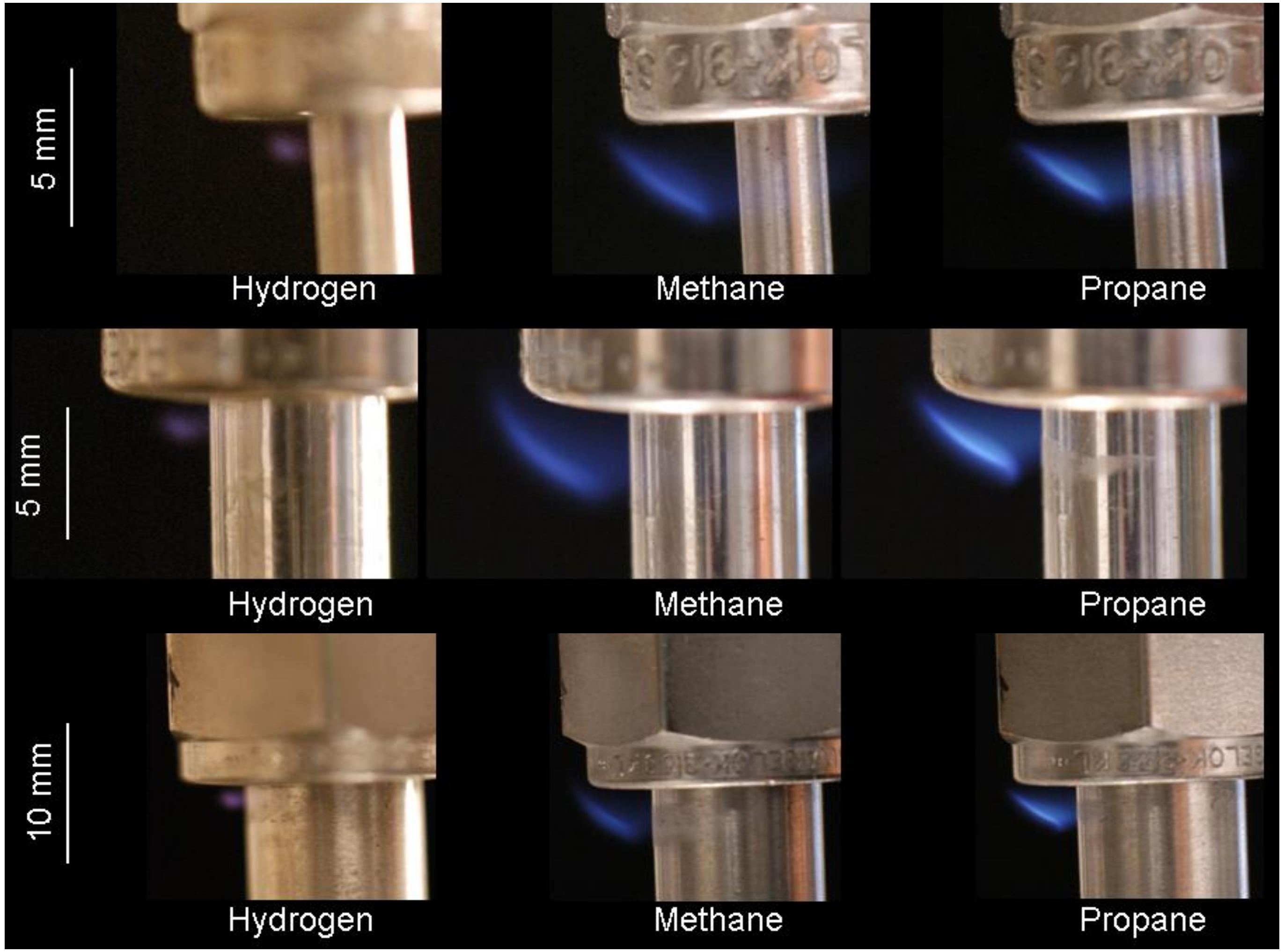
- Quenching limits for a 6 mm compression fitting are shown.
- Limits are independent of pressure.
- **Limits are about 10 times of those of tube burners.**
- Hydrogen limits are the lowest.

The length of microflames (1/2)



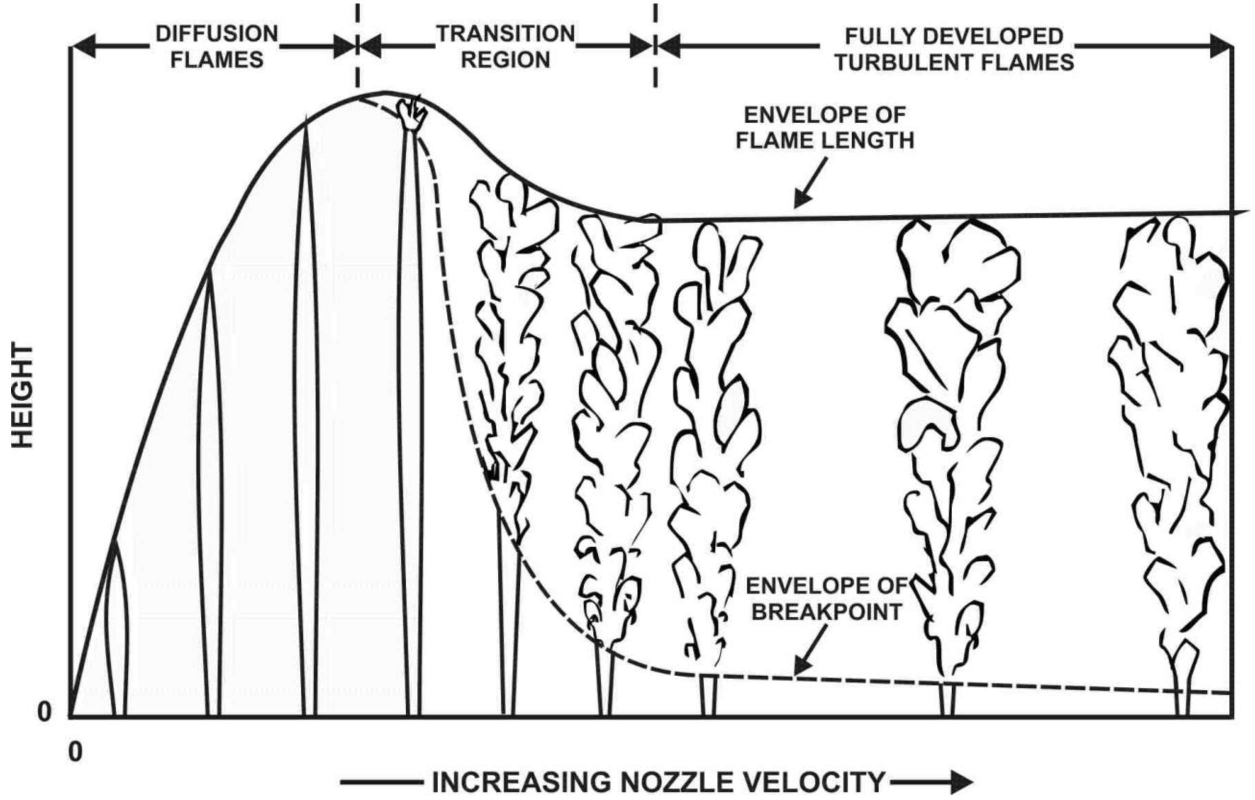
Test shown
L_F=**1 mm**,
m=7.5 mg/s,
D=0.36 mm
Stand-off height
is 0.25 mm

The length of microflames (2/2)



Laminar and turbulent jet flames

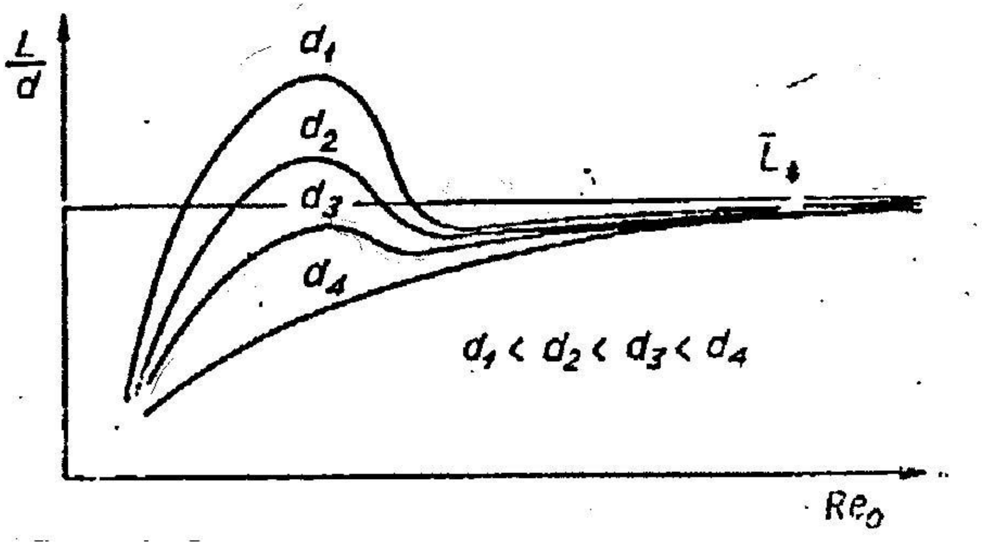
- The classic theoretical consideration of mixing and combustion in turbulent gas jets are given by Hottel and Hawthorne (1949).
- *“**The process of mixing is the controlling factor** in determining progress of the combustion”.*
- For the release of hydrogen into the still air **transition from laminar diffusion to turbulent flames** commences at **Re ~ 2000.**



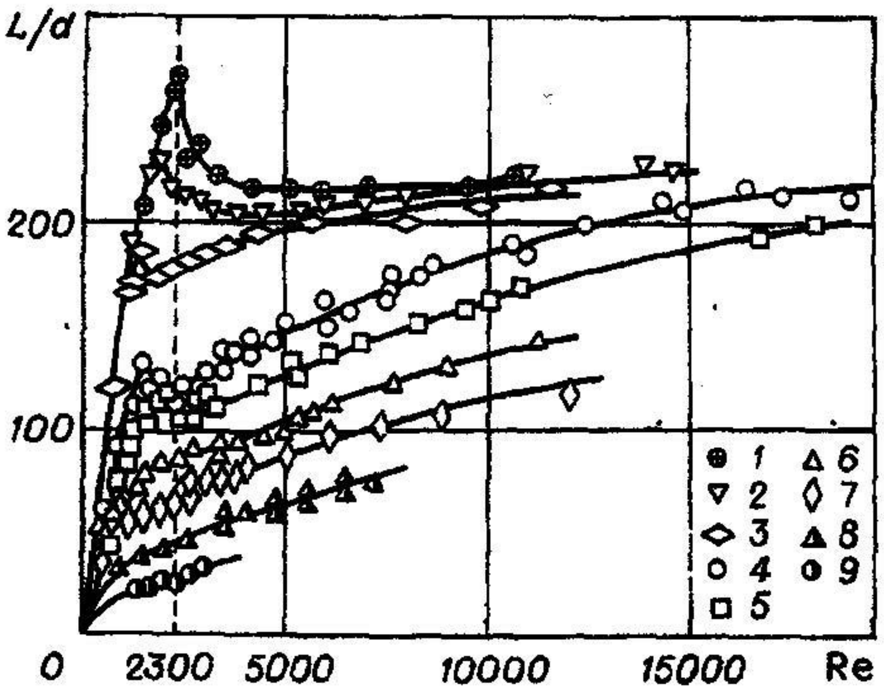
Source: Hottel, HC and Hawthorne, WR (1949). Diffusion in laminar flame jets. Proceedings of the Combustion Institute. Vol. 3, pp. 254-266.

Flame length to diameter $L_F/d=f\ (Re)$

- Dependence of the flame length to diameter ratio (L_F/d) on Reynolds number Re for different nozzle diameters
- Turbulent flame length limit L_t



Source: Baev et al (1974)



1 – 1.45 mm; 9 – 51.7 mm

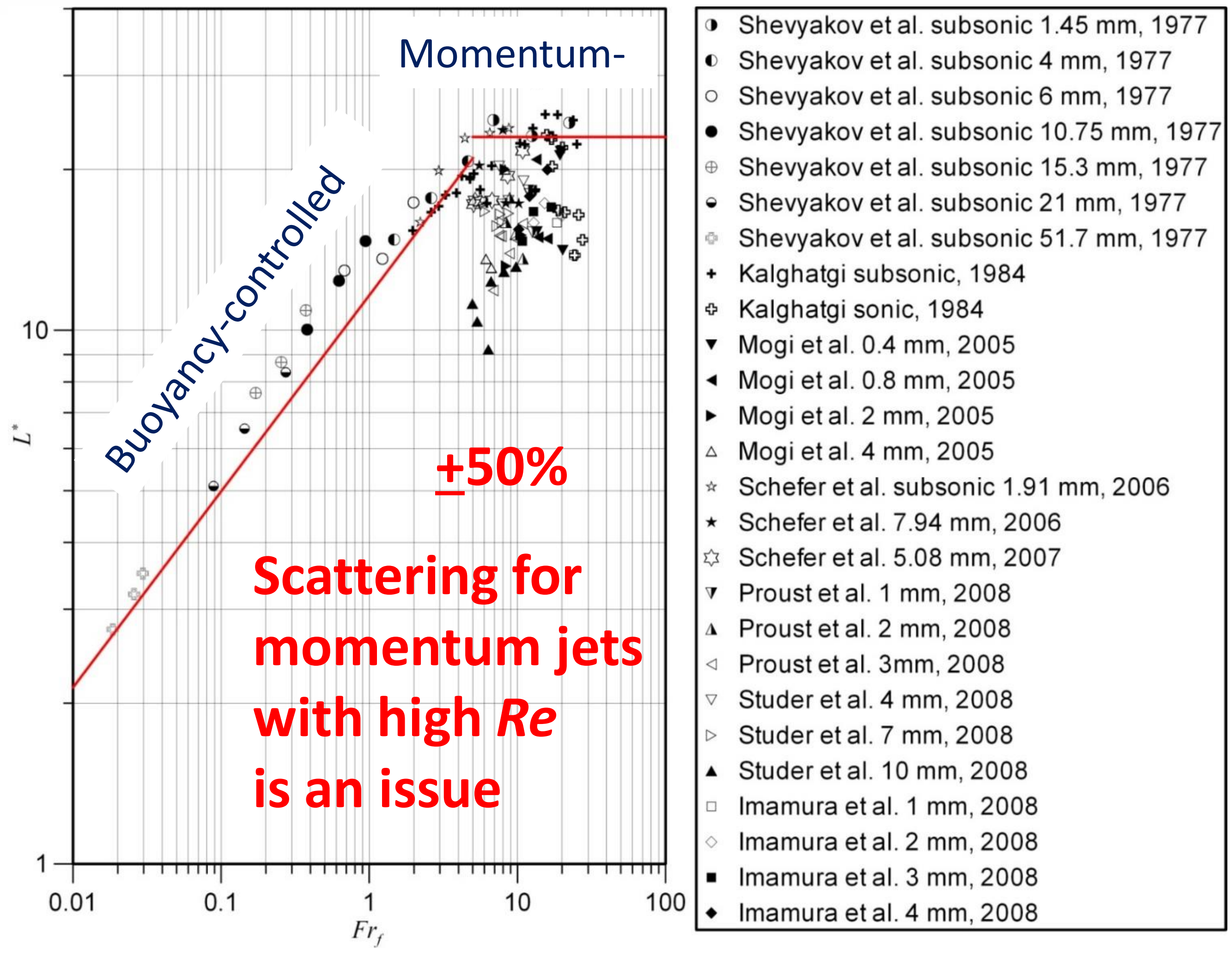
Source: Shevyakov and Komov (1977)

Can all these scattered data be correlated by one curve?

Fr-based flame length correlations

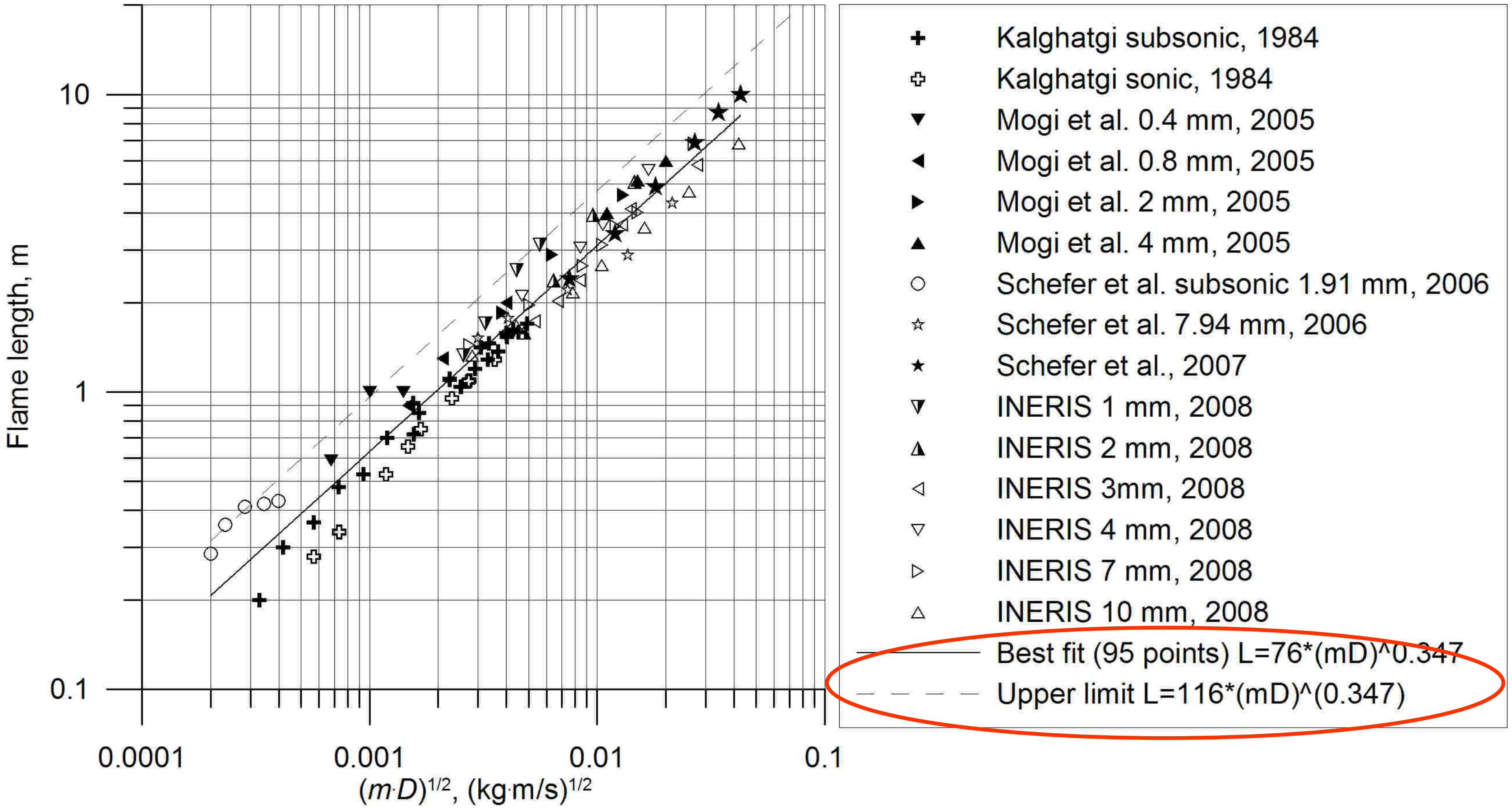
- Dimensionless flame length correlations suggested previously are based on the use of the Froude number (*Fr*) only, in one form or another.
- Recently *Fr*-based correlations were expanded to high pressure hydrogen jet fires (**under-expanded jets**). The general idea of this technique is to correlate experimental data with the **modified *Fr* number** that is built on so-called notional or **effective nozzle diameter** instead of real nozzle diameter. However, the size of the notional nozzle diameter and the velocity in the notional nozzle are dependent on the theory applied, including a number of simplifying assumptions.

Fr-based correlation example



Under-expanded jets are included!

The dimensional correlation (2009)



Good prediction for high and poor for small debit jets

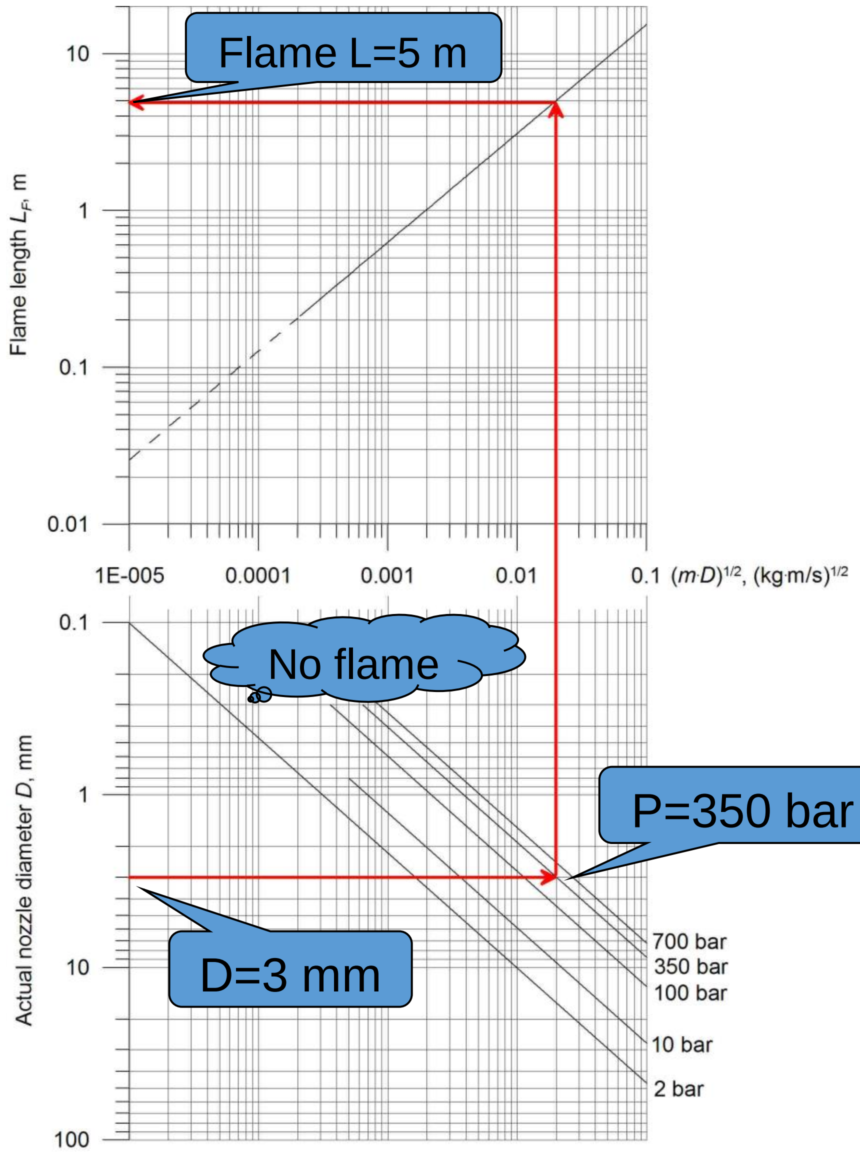
Hazard distances from hydrogen flames and fire fighting

The nomogram

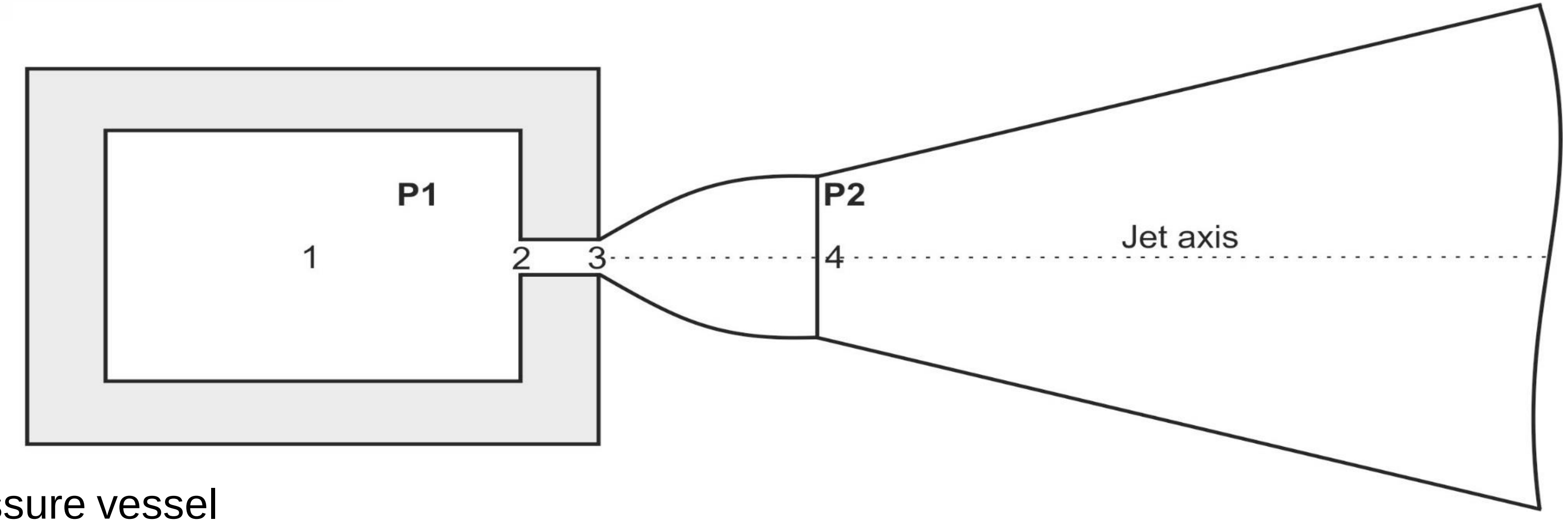
Derived from the dimensional correlation (best fit curve; please multiply by 1.5 for a conservative estimate).

Special feature:

No stable flames (**“non-combustible”** hydrogen) were observed for nozzle diameters 0.1-0.2 mm – flame blew off although the spouting pressure increased up to 400 bar.



The under-expanded jet scheme



1- High pressure vessel
2- Nozzle entrance
3- Nozzle exit (= notional nozzle entrance)
4- Notional (effective) nozzle exit (3-4: no entrainment)
P1 Storage pressure
P2 Atmospheric pressure (after jet expansion)

The notional nozzle exit, 4, parameters correspond to fully expanded jet with the pressure equal to ambient and uniform flow velocity equal to local speed of sound. In some cases, there can be essential minor and friction losses in the flow pathway 2-3 that cannot be neglected, e.g. the case of very narrow crack.

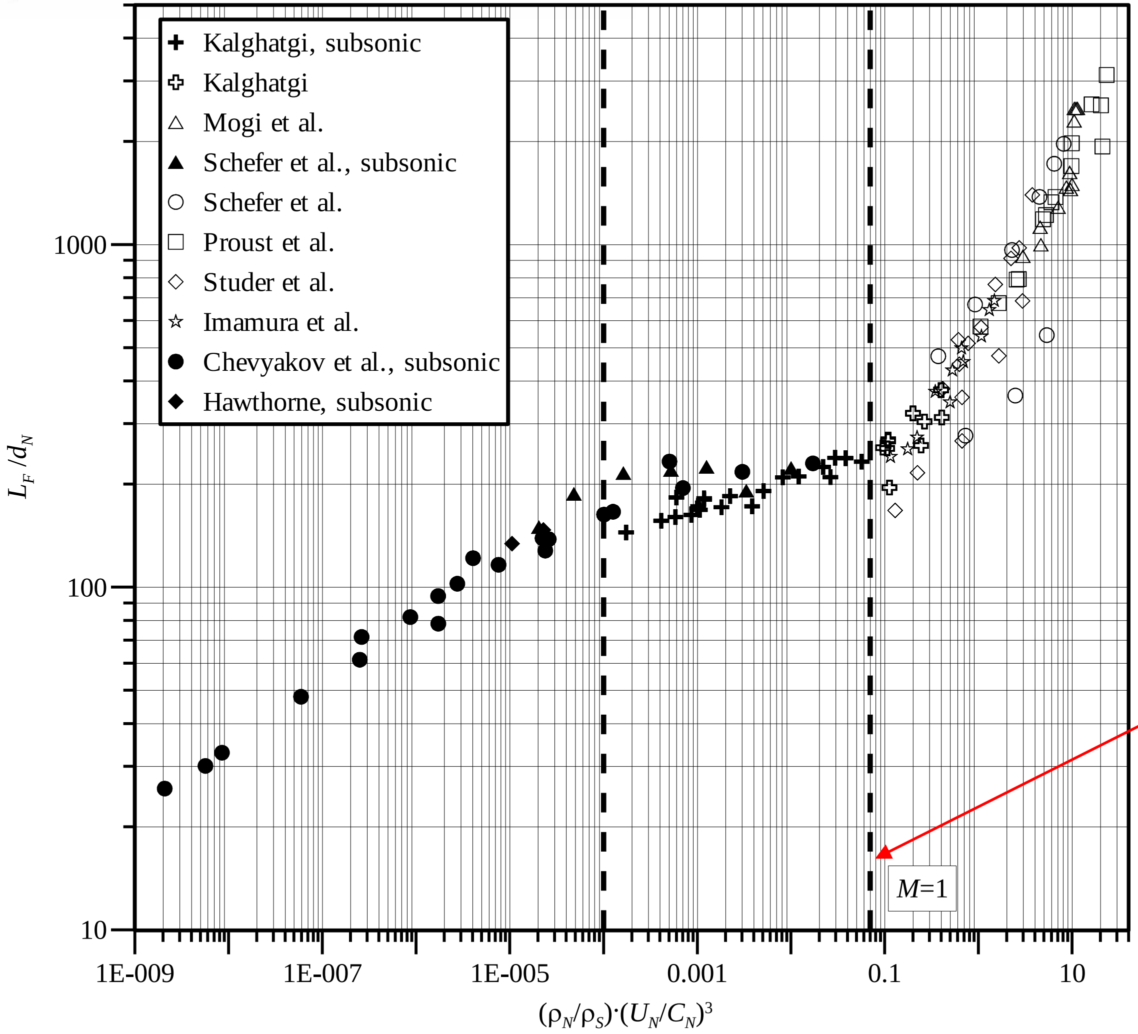
A dimensionless correlation?

- The **dimensional** correlation for flame length is $\boldsymbol{L_F \sim (\dot{m} \cdot d)^{1/3}}$
- Mass flow rate is proportional to the actual nozzle diameter squared $\boldsymbol{\dot{m} \sim d^2}$
- This implies that **dimensionless flame length $\boldsymbol{L_F/d}$** is an exponent function of **only density, $\boldsymbol{\rho_N}$, and velocity, $\boldsymbol{U_N}$, in the nozzle**
- The dimensionless density and velocity can be introduced: $\boldsymbol{\rho_N / \rho_S}$ and $\boldsymbol{U_N / C_N}$,

$$C_N = \sqrt{\frac{\gamma \cdot R_{H2} \cdot T_N}{(1 - b \cdot \rho_N)}}$$

- The correlation (next slide) is **validated:**
  - hydrogen storage pressures **up to 90 MPa;**
  - nozzle diameters **from 0.4 to 51.7 mm**.

The dimensionless correlation (2011)



Validation:

P =0.1-90 MPa

d=0.4-51.7 mm

Line M = 1 (choked flow)

M (M < 1) -> (Re, Fr)

$$\frac{\rho_N}{\rho_S}\cdot\left(\frac{U_N}{C_N}\right)^3 = \frac{g\cdot\mu_N}{\rho_S\cdot C_N^3}\cdot \mathrm{Re}\cdot Fr$$

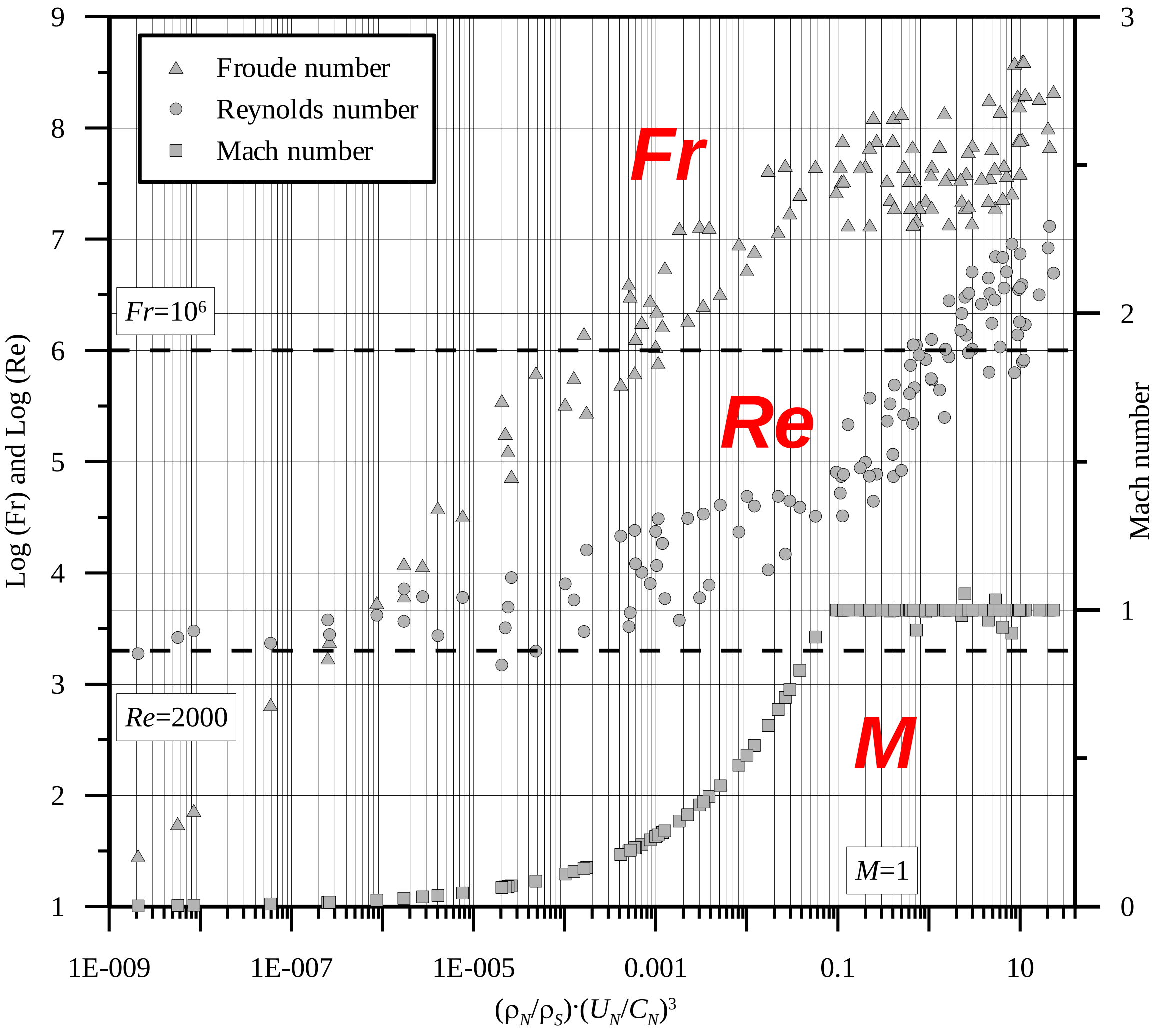
Change of *Fr*, *Re*, *M*

$$Fr = \frac{U_N^2}{d_N \cdot g} \qquad \mathrm{Re} = \frac{\rho_N \cdot d_N \cdot U_N}{\mu_N} \qquad M = \frac{U_N}{C_N}$$

***Re*=2000:** Laminar to turbulent

***Fr*=10⁶:** Buoyancy to momentum

$$\frac{\rho_N}{\rho_S} \cdot \left(\frac{U_N}{C_N}\right)^3 = \frac{g \cdot \mu_N}{\rho_S \cdot C_N^3} \cdot \mathrm{Re} \cdot Fr$$



How to determine the flame length?

- Y axis: L_f/d_n where L_f - flame length, d_n - nozzle diameter
- X axis: $(\rho_N/\rho_S)(U_N/C_N)^3$ where
- ρ_N - density at the nozzle exit, = 0.0838 kg/m^3 at normal temperature and pressure (NTP) for sub-sonic and expanded sonic jets, calculated in the same way as with similarity law for unignited jets.

  If the jet is under expanded, then the density is calculated by an **under-expanded jet theory** (UU)
- ρ_S - density of the surroundings = 1.205 kg/m^3 for air
- C_N - is the speed of sound in hydrogen at the nozzle exit, $$C_N = \sqrt{\gamma \frac{P}{\rho}} = \sqrt{\gamma \frac{RT}{M}}$$
- U_N - the velocity of the hydrogen at the jet exit

  $U_N = C_N$ for sonic and supersonic jets,

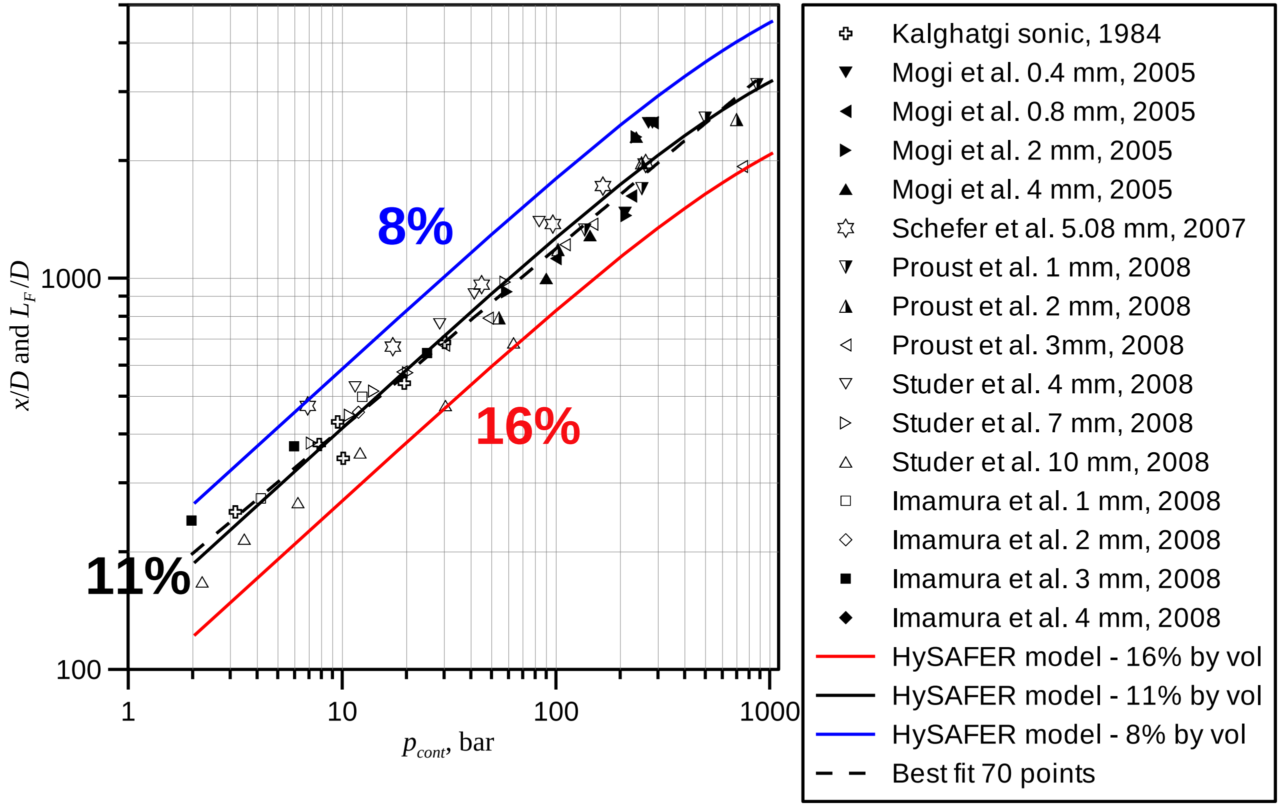
  for subsonic jets: $$U_N = \sqrt{2\frac{\Delta P}{\rho}}$$

Hy Responder

Hazard distances from hydrogen flames and fire fighting

Where is a jet flame tip location?

- **Flammable envelope** = 4 vol. % (LFL)
- **Flame tip location** = 11 vol. % in **unignited jet** (8-16 vol.%)



Flame is 2.2 times (16%) or 4.7 times (8%) longer than the distance to axial concentration 29.5% (stoichiometric hydrogen-air mixture)!

Hazard and separation distances

- Hazard distance is a recently introduced term.
- In early publications (before 2015) you may find terms such as **separation distance** = safety distance = setback distance.
- As per draft definition, ISO TC197 **hazard distance** is a distance from the (source of) hazard to a determined (by physical or numerical modelling, or by a regulation) physical effect value (normally, thermal or pressure) that may lead to a harm condition (ranging from "no harm" to "max harm") to people, equipment or environment.
- The hazard distance will be different for:
    - Unignited releases;
    - Fires;
    - Blast wave;
    - Fireball

Harm criteria

- In the case of free fires this would be temperature, heat flux and overpressure (in the case of enclosure fires - asphyxiation may also be relevant).
- For people direct flame contact as a result of a jet fire is generally assumed to result in third degree burns.
- For people not in the flame, there is still potential for exposure to high radiation heat fluxes.
- Harmful heat flux criteria are presented in the Lecture ‘Harm criteria for people and damage criteria for structures.
- 70 ^{o}C - “no harm” limit; 115 ^{o}C - pain limit for 5 min exposure; 309 ^{o}C - third degree burns for 20 s (“fatality” limit).

Hazard distances from hydrogen flames and fire fighting

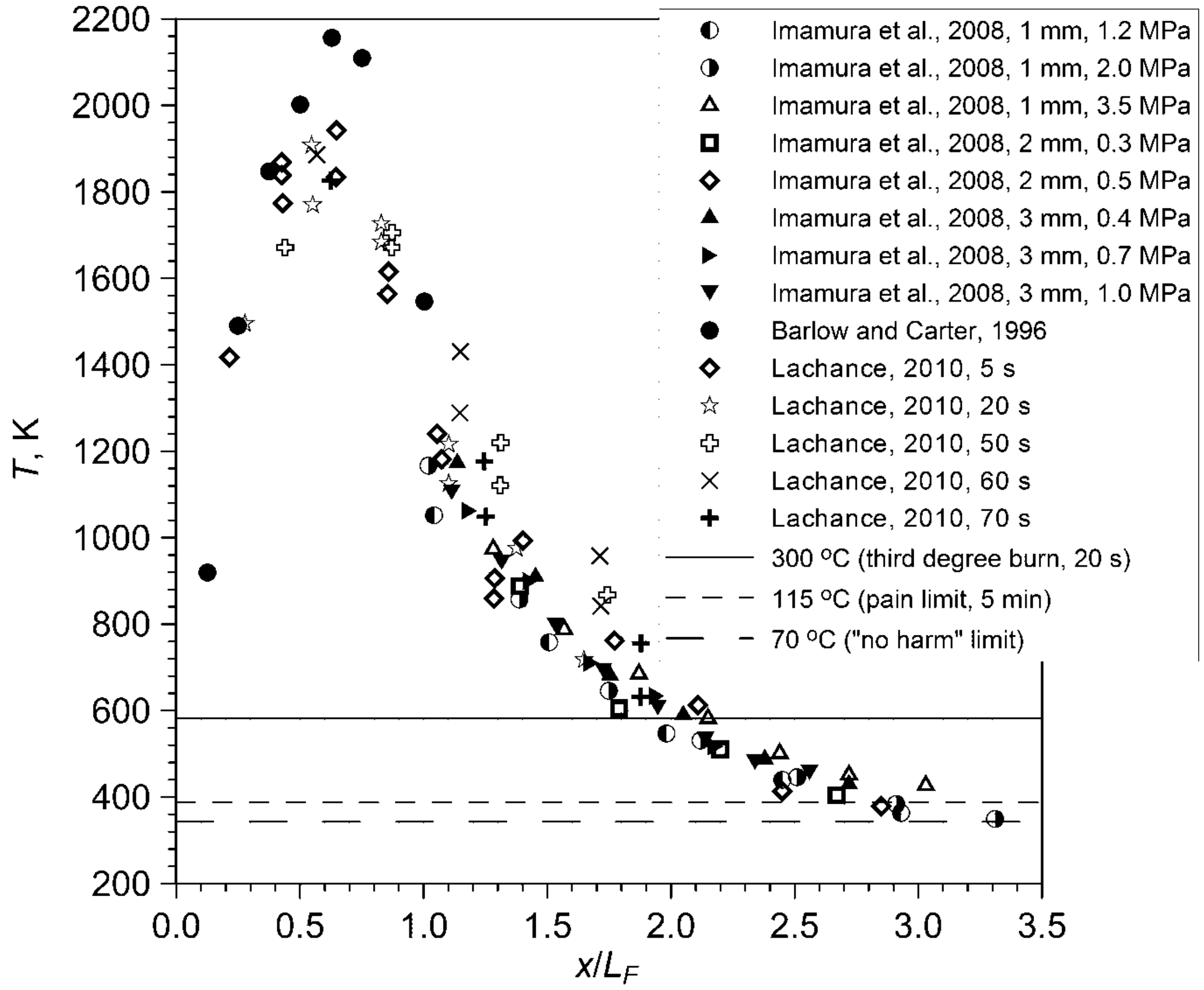
Temperature decay along jet fire axis

- **Momentum-dominated leak**
- **Jet fires (three hazard distances):**

$x = 3.5L_F$ for “no harm” (70 ^oC)

$x = 3L_F$ for pain limit (115 ^oC, 5 min)

$x = 2L_F$ for third degree burns (309^{o}C, 20 s)



Unignited versus ignited jets

$$x_{4\%} = 1708 \cdot \sqrt{\rho_N} \cdot D$$

- The ratios of a hazard distance to *LFL* (non-reacting jet) to three hazard distances based on the choice of harm criteria for jet fire are (**average flame tip location 11 vol. %** in non-reacting jet):
  - $x_{4\%}/x_{T=70°C} = x_{4\%}/(3.5 \cdot x_{11\%})$ = 2.95/3.5 = 0.84 ("no harm");
  - $x_{4\%}/x_{T=115°C}$ = 2.95/3 = 0.98 ("pain limit");
  - $x_{4\%}/x_{T=309°C}$ = 2.95/2 = 1.48 ("fatality limit" – unprotected).
- In the conservative case (**flame tip location 8 vol. %**) these ratios:
  - $x_{4\%}/x_{T=70°C(8\%)}$ = 2.08/3.5 = 0.59 ("no harm");
  - $x_{4\%}/x_{T=115°C(8\%)}$ = 2.08/3 = 0.69 ("pain limit");
  - $x_{4\%}/x_{T=309°C(8\%)}$ = 2.08/2 = 1.04 ("fatality limit" – unprotected).
- **"Unexpected" conclusion** - in the conservative case all three distances for jet fire are either longer or equal to the hazard distance based on LFL (non-reacting release).

Hazard distances from hydrogen flames and fire fighting

Flame length & hazard distance calculation – e-Laboratory

URL:https://elab.hysafer.ulster.ac.uk/

Login: HyResponderTrainer

Password: safetyfirst

Flame length correlation and three hazard distances for jet fires

Flame length correlation and three hazard distances for jet fires

H2 pressure in reservoir

p_1 20000000 Pa

H2 temperature in reservoir

T_1 293 K

Orifice diameter

d_3 0.003 m

Ambient pressure

p_4 101325 Pa

Ambient temperature

T_{atm} 293 K

Calculate Reset

Name	Symbol	Value	Unit
H2 pressure in reservoir	p_1	2e+7	Pa
H2 temperature in reservoir	T_1	293	K
Orifice diameter	d_3	0.003	m
Ambient pressure	p_4	1.01325e+5	Pa
Ambient temperature	T_{atm}	293	K
Flame length	L_F	6.259	m
No harm (70°C) separation distance	X_{70}	21.9065	m
Pain limit (5 mins, 115°C) separation distance	X_{115}	18.777	m
Third degree burns (20 sec, 309°C) separation distance	X_{309}	12.518	m

Export to CSV Change inputs Dataset name Save

Hazard distances from hydrogen flames and fire fighting

Similarity law for hydrogen concentration decay– e-Laboratory

Similarity law for concentration decay in hydrogen expanded and under-expanded jets and unignited jet hazard distances

Similarity law for concentration decay in hydrogen expanded and under-expanded jets and unignited jet hazard distances

H2 pressure in reservoir

p_1 35000000 Pa

H2 temperature in reservoir

T_1 293 K

Orifice diameter

d_3 0.005 m

Ambient pressure

p_4 101325 Pa

Ambient temperature

T_{atm} 293 K

Calculate Reset

Name	Symbol	Value	Unit
H2 pressure in reservoir	p_1	3.5e+7	Pa
H2 temperature in reservoir	T_1	293	K
Orifice diameter	d_3	0.005	m
Ambient pressure	p_4	1.01325e+5	Pa
Ambient temperature	T_{atm}	293	K
Axial distance from nozzle to 4% by vol. H2	$X_{4\%,H_2}$	32.6212	m
Axial distance from nozzle to 8% by vol. H2	$X_{8\%,H_2}$	15.6793	m
Axial distance from nozzle to 11% by vol. H2	$X_{11\%,H_2}$	11.0593	m
Axial distance from nozzle to 16% by vol. H2	$X_{16\%,H_2}$	7.20885	m
Axial distance from nozzle to 29.5% by vol. H2	$X_{29.5\%,H_2}$	3.33269	m

Hazard distances from hydrogen flames and fire fighting

Unattached and attached jets

Unattached

https://www.youtube.com/watch?v=aGEEFgShQhQ&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=9

Attached

https://www.youtube.com/watch?v=Tyj95QElNCc&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=16

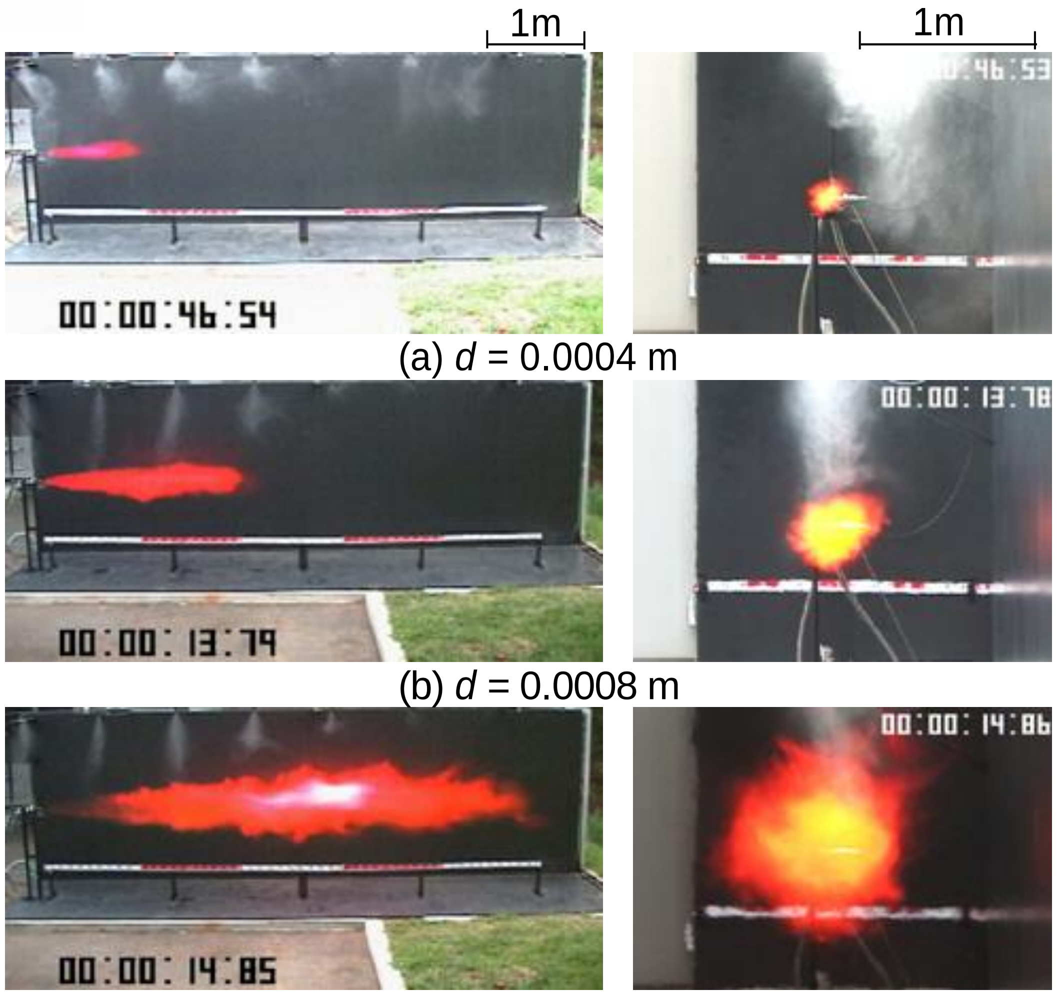
Attachment effect on jet flame length

- 205 bar (20.5 MPa), ignition delay 800 ms.
- Attached jets – 0.11 m above the ground.
- Unattached jets – 1.2 m above the ground.
- Release along the ground or walls in proximity to them can **increase the flame length**.

Orifice diameter, mm	Flame length, m Attached jets	Flame length, m Unattached jets	Flame length increase, times
1.5	5.5	3	x1.83
3.2	9	6	x1.50
6.4	11	9	x1.22
9.5	13	11	x1.18

Hazard distances from hydrogen flames and fire fighting

Round nozzles (*p* =35 MPa)



(a) *d* = 0.0004 m

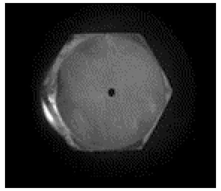
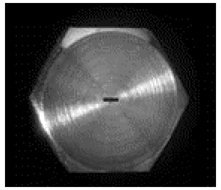
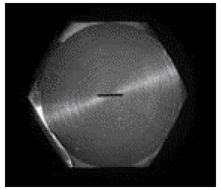
(b) *d* = 0.0008 m

(c) *d* = 0.002 m

Hazard distances from hydrogen flames and fire fighting

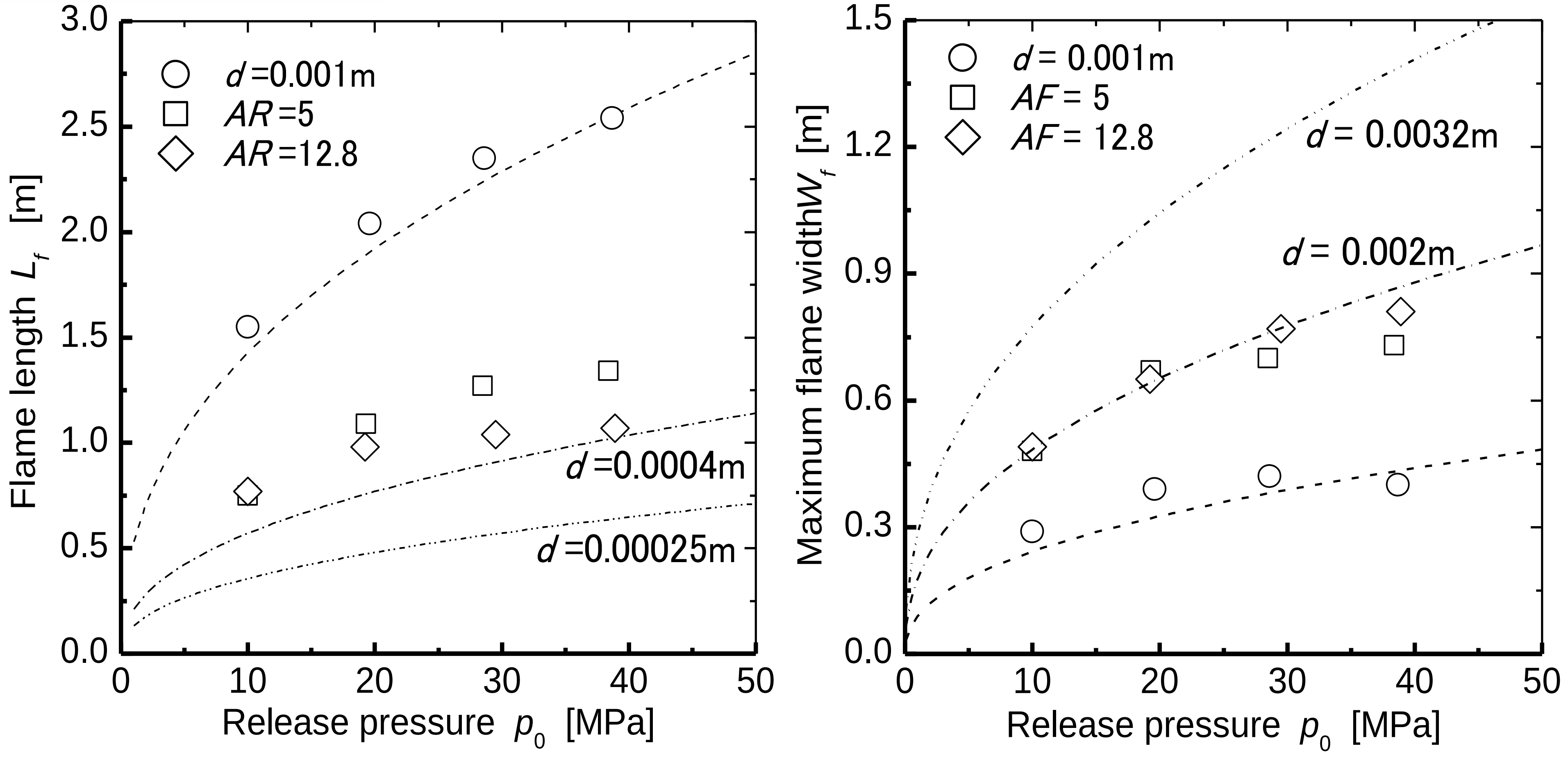
Round and plane nozzles

p=40 MPa (constant nozzle area 0.8 mm^2) **(A=constant)**

Nozzle	Side view	Front view
 d = 0.001 m		
 0.0004 × 0.002 m (AF = 5)		
 0.00025 × 0.0032 m (AF = 12.8)		

Hazard distances from hydrogen flames and fire fighting

Nozzle shape effect on flame length



Length **Width**

Hazard distances from hydrogen flames and fire fighting

Effect of a barrier wall on delayed ignition of hydrogen

Barrier 90º: 9.5 mm, 800 ms
(42 kPa; free jet only 16 kPa)

https://www.youtube.com/watch?v=bCIdzIjqxkQ&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=2

Barrier 60º: 9.5 mm, 800 ms
(57 kPa; free jet only 16 kPa)

https://www.youtube.com/watch?v=8SeqGHpTkzc&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=3

Effect of an orifice diameter on overpressure

Orifice diameter, mm	Ignition delay, ms	Max overpressure, kPa
1.5	800	Not recordable
1.5	400	Not recordable
3.2	800	3.5
3.2	400	2.1
6.4	800	15.2
6.4	400	2.7-3.7
9.5	800	16.5
9.5	400	3.3-5.4

Conclusion:

- Reduce orifice diameter ALARP to reduce overpressure following delayed ignition

Effect of ignition source location on overpressure

Orifice d = 6.4 mm. Fixed ignition delay: 800 ms.

The ignition position (pyrotechnic system) was varied from 3 m to 10 m (h=1.2 m).

Ignition position, m	Max overpressure, kPa
3	5.0
4	2.1
5	2.1
6	Not recordable
8	Not recordable
10	No ignition

Delayed ignition: Test conditions (HSL)

- Storage pressure: **205 bar** (two 50 litre cylinders).
- Stainless steel tubing ID=11.9 mm, a series of ball valves with internal bore of **9.5 mm**. Restrictors of 2 mm length and diameter: **1.5, 3.2, 6.4 mm**.
- Ignition by a match head with small amount of pyrotechnic material. Ignition **1.2 m** above the ground.
- The release point is **1.2 m** above the ground.
- Ignition point is located **2-10 m** from the release point.
- Piezo-resistive transducers pointed out upwards (except for wall mounted). Sensors are located at **axial distance 2.8 m** from the nozzle, **1.5 m** (then +1.1 m and +1.1 m) perpendicular to the axis, at height **0.5 m**.
- 260 ms to fully open the valve, 140 ms for hydrogen to reach 2 m, i.e. **400 ms is shortest ignition delay**.

Hazard distances from hydrogen flames and fire fighting

Free jet fire: 9.5 mm, 800 ms (16.5 kPa)

Daytime fire

https://www.youtube.com/watch?v=txNANqq7rJ4&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=13

Hazard distances from hydrogen flames and fire fighting

Infrared 4.1-5.3 microns (16.5 kPa)

Nighttime fire

https://www.youtube.com/watch?v=myOTYcPCw0I&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=12

Effect of ignition delay on overpressure

Orifice d=6.4 mm. Ignition 2 m from the orifice.

Ignition delay, ms	Max overpressure, kPa
400	3.7
500	18.4
600	19.4
800	15.2
1000	11.7
1200	12.5
2000	9.5

Spontaneous ignition should reduce overpressure of self-ignited release (no SI observed with a valve use).

Visibility of hydrogen flames

- Hydrogen burns with invisible in the daylight flame.
- Real jet flame can be visible due to combustion of entrained particulates.
- Radiation emitted from hydrogen flames is very low.

  The emissivity[1] < 0.1 (ADL,1960).

  Sandia National Laboratory (US) research: emissivity < 0.3.

[1]**Emissivity** is defined as the ratio of the energy radiated from a material's surface to that radiated from a perfect emitter, known as a blackbody, at the same temperature and wavelength and under the same viewing conditions.

Heat flux prediction (1/2)

1. Evaluation of the radiant fraction χ: fraction of total chemical energy release converted into energy radiated to the surroundings.

The expression of radiant fraction used in the model was derived by Molina:

$$\chi = 0.08916 \cdot log_{10}\left(t_f \cdot \alpha_f \cdot T_{ad}^4\right) - 1.2172$$

Turns and Myhr's equation for residence time evaluation: $t_f = \frac{\pi}{12} \frac{\rho_f \cdot W_f^2 \cdot L_f \cdot Y_s}{\dot{m}}$

ρ_f is the flame density and it is evaluated through the following expression: $\rho_f = \frac{P_{amb} \cdot MW_{st}}{R_u \cdot T_{ad}}$

t_f: flame residence time (milliseconds); α_f: Plank's mean absorption coefficient for the product species ($\alpha_{f,H2O}$=0.23 m^{-1}); T_{ad} : adiabatic flame temperature; Y_s: hydrogen stoichiometric mass fraction (Y_s =0.0281); L_f : visible flame length; W_f: visible flame width; $\dot{m}$: mass flow rate; P_{amb} : ambient pressure;
MW_{st}: stoichiometric molecular weight of the hydrogen combustion products in air (MW_{st}=24.52 g/mol);
R_u: universal gas constant (R_u =8314.47 g/(kmol·K).

Heat flux prediction (2/2)

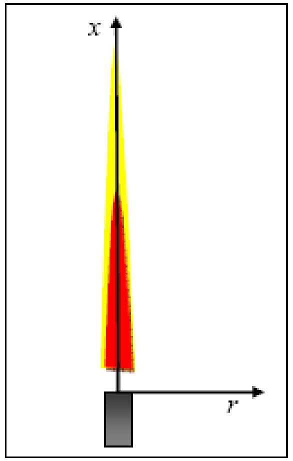
2. Evaluation of surface emissive power S: $S = \chi \cdot \dot{m} \cdot \Delta H_c$

ΔH_c: gas heat of combustion ($\Delta H_{c,H20} = -119\ MJ/kg$); $\dot{m}$: mass flow rate

3. Evaluation of the radiative heat flux at the observer location q is a product of the surface emissive power, of the view factor VF and the atmospheric transmissivity τ: $q = VF \cdot S \cdot \tau$

The view factor VF and the atmospheric transmissivity τ are **function of the model chosen to represent the flame**:

- single source emitter: the source is considered as a point located at the middle point of the predicted flame length.
- weighted multi-source model: decomposition of the jet flame axis in N points, with N decided accordingly to the characteristics of the problem. Afterwards, each point is considered as a radiation emitter and it has a different contribution on the final balance of the heat flux.



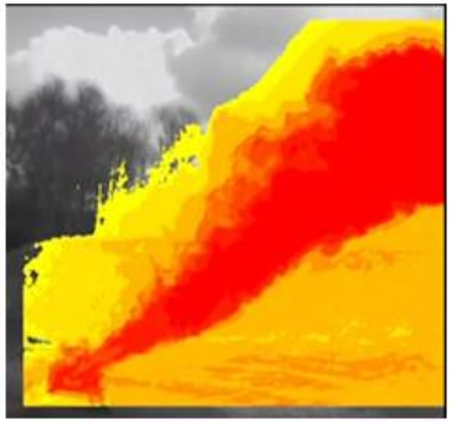
Sources: Houf et al (2013). International Journal of Hydrogen Energy, Vol. 38 8092-8099; Ekoto et al (2014), International Journal of Hydrogen Energy, Vol. 39 39 , 20570-20577

Comparison of hydrogen jets to common fuels

- Jet fires: Thermal effects

H2 @ 200 bar

CNG @ 200 bar



LPG @ 10 bar (liquid phase)

Equivalent Ø: 3,1 mm
H2 length flame: 5,5 m

Equivalent Ø: 3,1 mm
CNG length flame: 8 m

LPG length flame

Jet fires: Flame length

Fireballs (rupture of a storage tank in a fire)

Hydrogen fireball about 70 ms after tank rupture (under the vehicle)

Hydrogen fireball about 170 ms after tank rupture (under the vehicle)

Two tests:

1) stand alone hydrogen tank. Catastrophic rupture after 6 min 27 s. Diameter $D_{fb} = 7.7\ m$; time $t_{fb} = 4.5\ s$

2) hydrogen tank installed on a typical SUV. Catastrophic rupture after 12 min 18 s. Diameter $D_{fb} = 24\ m$; time $t_{fb} = 4.5\ s$ (please see two images above)

Source: Zalosh, 2007

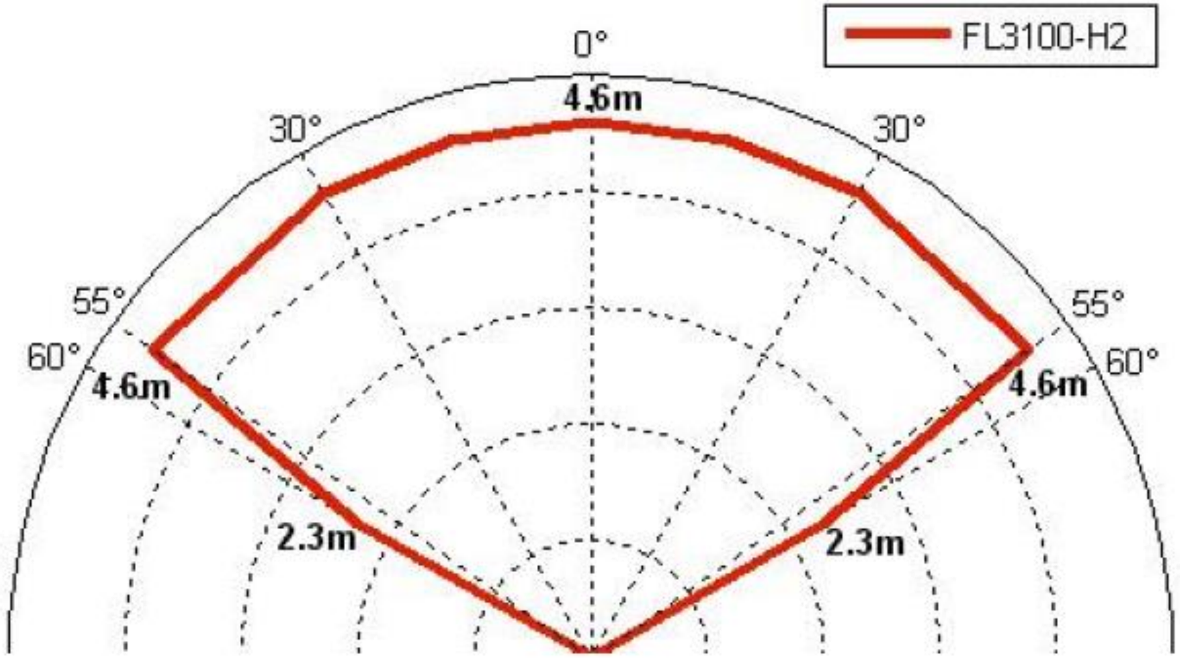
Hydrogen fire sensors

Type	Pluses	Minuses
UV/IR	Moderate speed. Moderate sensitivity. Low false alarm rate. Not blinded by CO_2 fire protections discharges. Automatic self-test.	False alarms possible in case of combination of IR and UV sources. Blinded by thick smoke and vapours. Price.
Triple IR	Very high sensitivity. Very high speed.	Price
IR/vis imaging	Images the flame. Used by NASA.	Price

Hazard distances from hydrogen flames and fire fighting

UV/IR Hydrogen fire detectors

- The detection range of a hydrogen-specific flame detector for a plume 15–20 cm (6–8 inches) high and 15 cm (6 inches) in diameter. This flame detector can detect the on-axis range of 4.6 m (15 ft) up to ± 55°, providing broad angular coverage.



Detection range of a General Monitors FL3100 UV/IR – H_2 detector.
Size of hydrogen fire: 15 cm (6 in) diameter and 15 – 20 cm (6 – 8 in) high.

Hazard distances from hydrogen flames and fire fighting

Overview of vehicle fires

Statistics:
- UK - 28,800 road vehicle fires in 2011-12
- USA - 172,500 automobile fires in 2012
- Types of vehicles: motor cars, heavy goods vehicles, light goods vehicles, public transport vehicles etc.

According to Fire statistics (2011-2012) in Great Britain:

- ➢ The majority (65%) of fires occurred in cars, 10% were in vans, 4% were in lorries and 2% in buses or minibuses.
- ➢ Fire causes: accidental, deliberate or unknown
- ➢ The majority of deliberate fires (43%) involved road vehicles – 13,900 fires.
- ➢ The number of fatalities in road vehicle fires in 2011-12 was 37.

Risks and statistics

- Recent data shows that about **10% of vessel failure is catastrophic!** This means that catastrophic failure cannot be ruled out of the risk assessment [1].
- People/customers would not be happy to know that they might die with a probability of 10^{-4} or 10^{-6}. They wish to know that everything is done for safety.
- During 2000-2006: 20 documented CNG tank failures, 11 have been attributed to vehicle fires [2]. Of these 11 incidents, the evidence suggests that the majority of the TPRDs failed to activate (localized fire).
- CNG and hydrogen storage tanks: “testing has shown that all fuel tanks regardless of working pressure are highly susceptible to rapid degradation due to localized fires” [2].

Sources:
[1] The relative frequency of failure modes. http://www.h2safe.com/case_safety.html [2] Gambone, L.R. and Wong, J.Y., Fire Protection Strategy for Compressed Hydrogen-Powered Vehicles, ICHS2, 2007).

Hazard distances from hydrogen flames and fire fighting

Upward release from a TPRD

A vehicle equipped with two cylinders (34 L capacity, at 35 MPa) fitted with a **TPRD, 5 mm in diameter.** TPRD was actuated after 14 min 36 sec (Watanabe et al, 2007).

Is 10-15 m flame length from a car acceptable?
"No harm" distance is 25-40 m and a high-pitched noise from the jet!
What if a car parked in a garage or in a multi-storey parking facility ("domino" effect)?

Source: Watanabe, S, Tamura, Y, Suzuki, J (2007). The new facility for hydrogen and fuel cell vehicle safety evaluation. Int. J. Hydrogen Energy. Vol. 32 (13), pp. 2154-2161.

TPRD release directed downwards

- A fire was initiated on the instrumentation panel ashtrays. The TPRD was actuated in 16 min 16 sec (downward). **Blow-down in less than 5 min** (**no catastrophic tank failure, but…**).

Current size of TPRD does not allow self-evacuation and rescue operations.
What if a car is indoors?

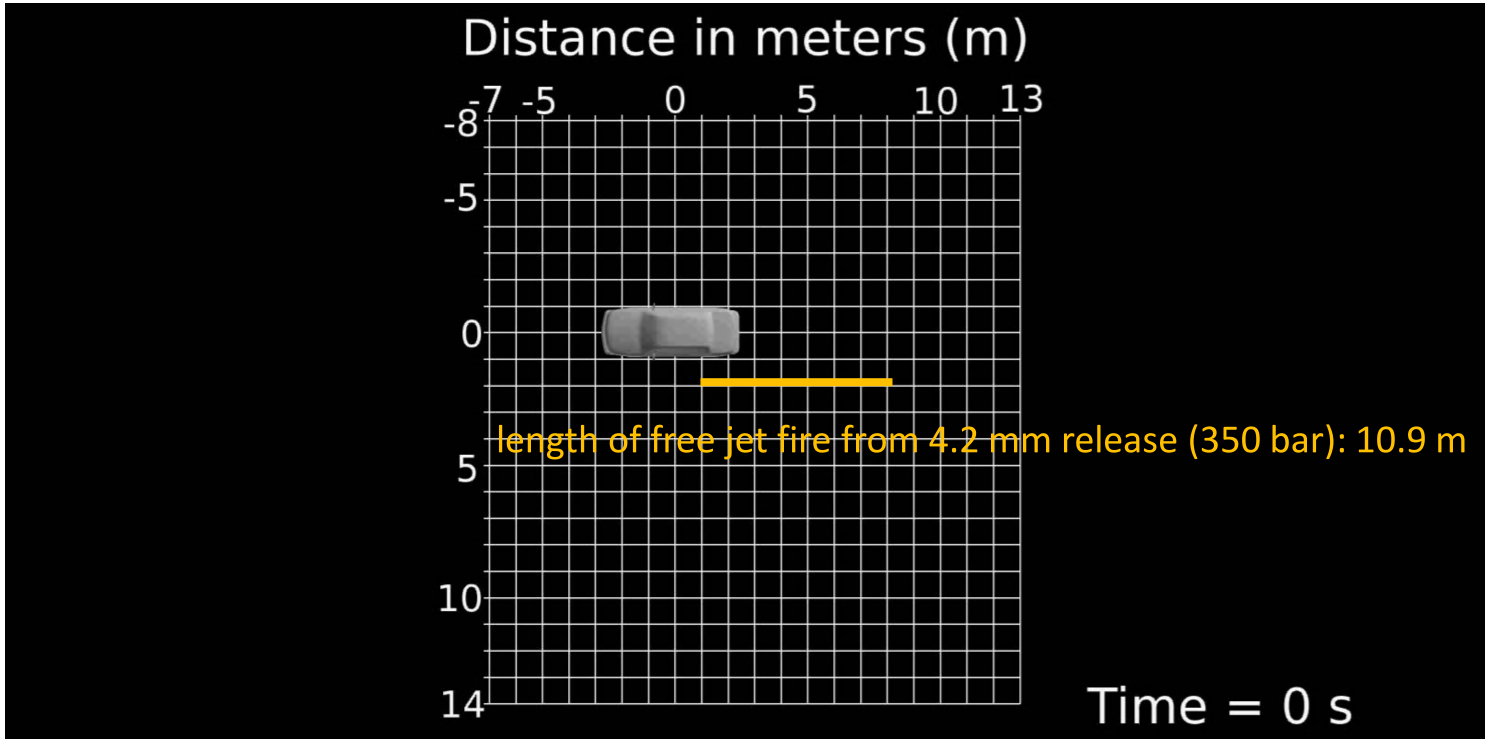
Hy Responder

Hazard distances from hydrogen flames and fire fighting

Flame length: 10.9 m down to 5.2 m

- Release 0º (flame temperature 1300ºC)

  Flame length 10.9 m (correlation), 5.2 m by CFD (longest in 2 s)



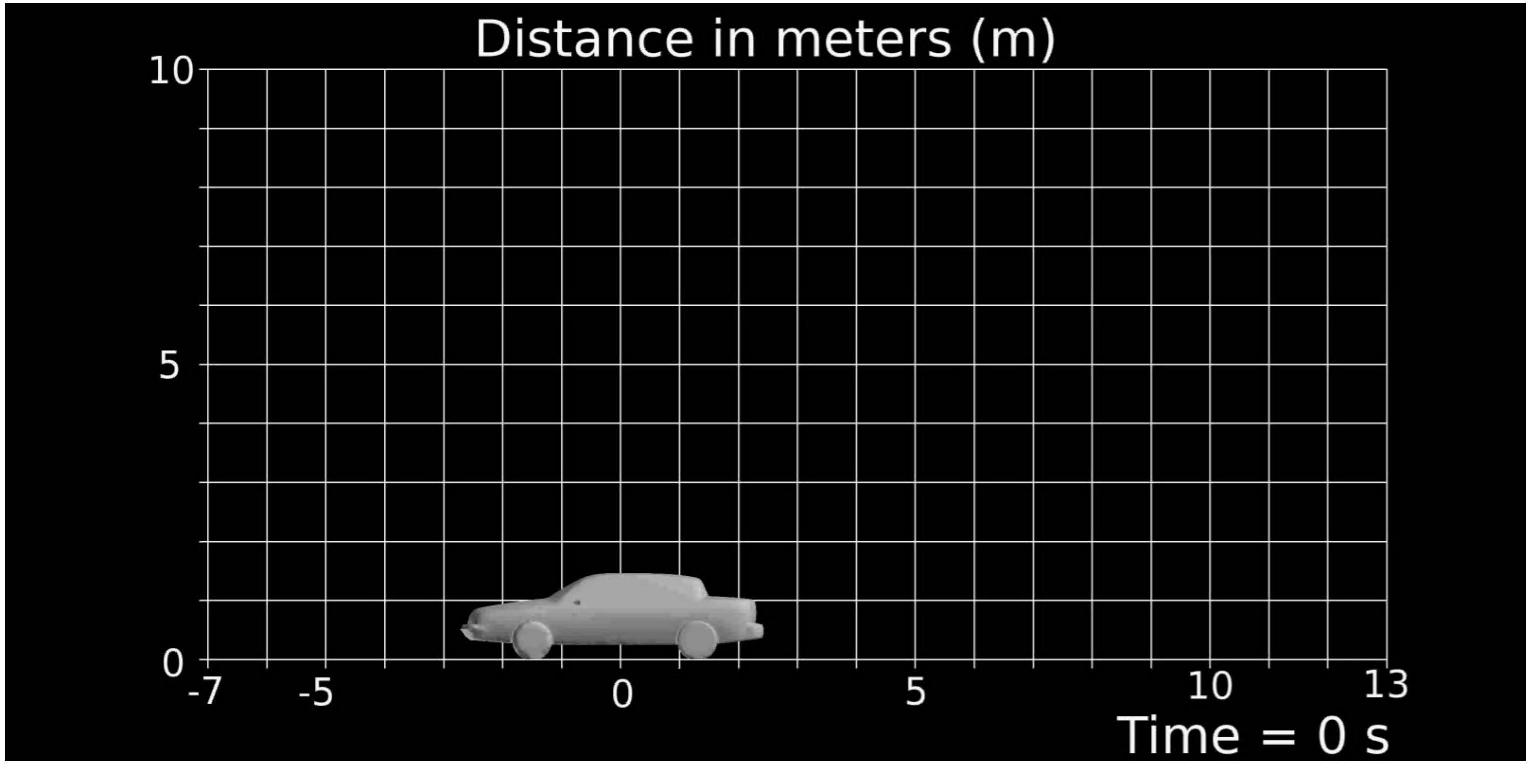
https://www.youtube.com/watch?v=RPT7KePqMrs&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=20

Hazard distances from hydrogen flames and fire fighting

No harm distance: 38 m down to 6 m

- Release 0º (temperature 70ºC envelope)

  No harm (horizontal!) 10.9x3.5=38 m (correlation), 6 m (CFD)

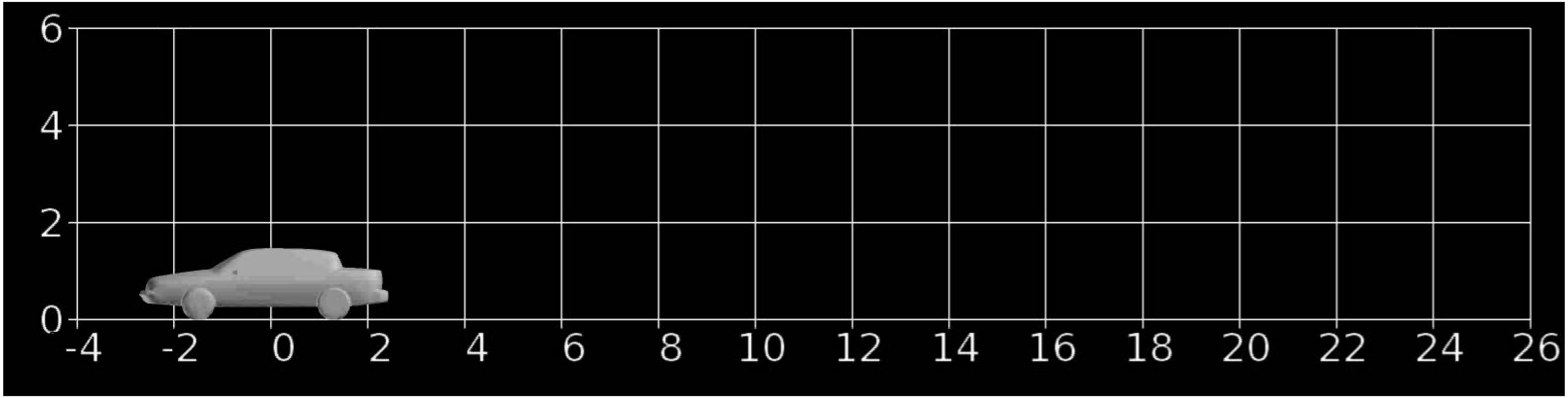


https://www.youtube.com/watch?v=uBi9GEZUEa8&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=10

Hazard distances from hydrogen flames and fire fighting

Flame length: 10.9 m down to 9.7 m

- Release 30º (evacuation route still blocked)



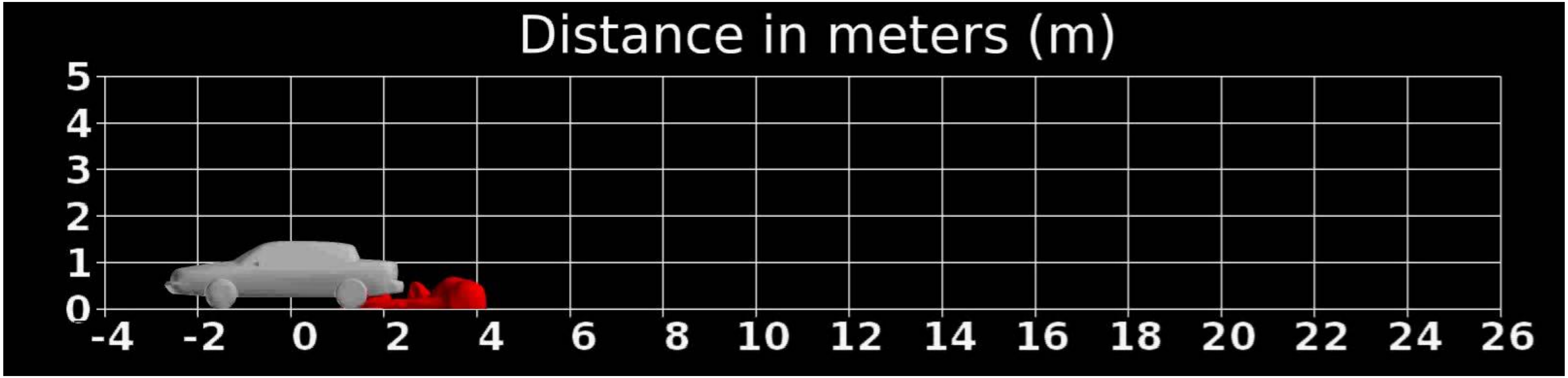
https://www.youtube.com/watch?v=1VflBVfK8Tc&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=21

Hazard distances from hydrogen flames and fire fighting

Flame length: 10.9 m "down" to 10.5 m

- Release 45º (evacuation and rescue possible)

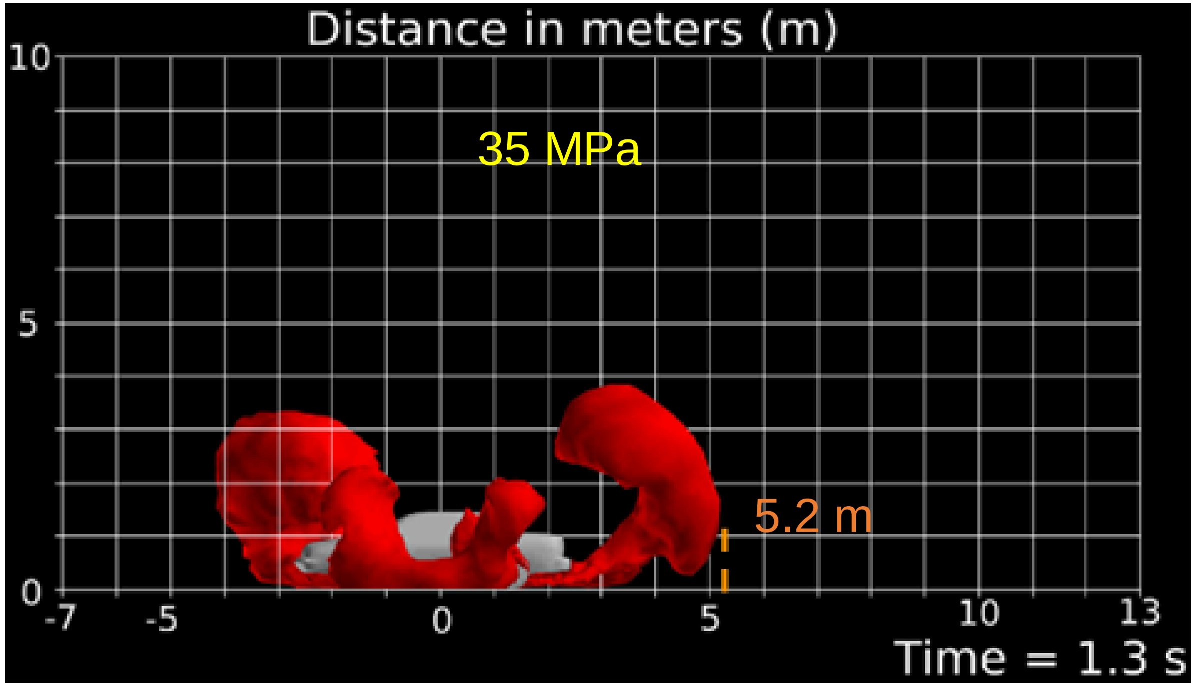
  No-harm distance decreases from 38 m (correlation) to 23 m (CFD)

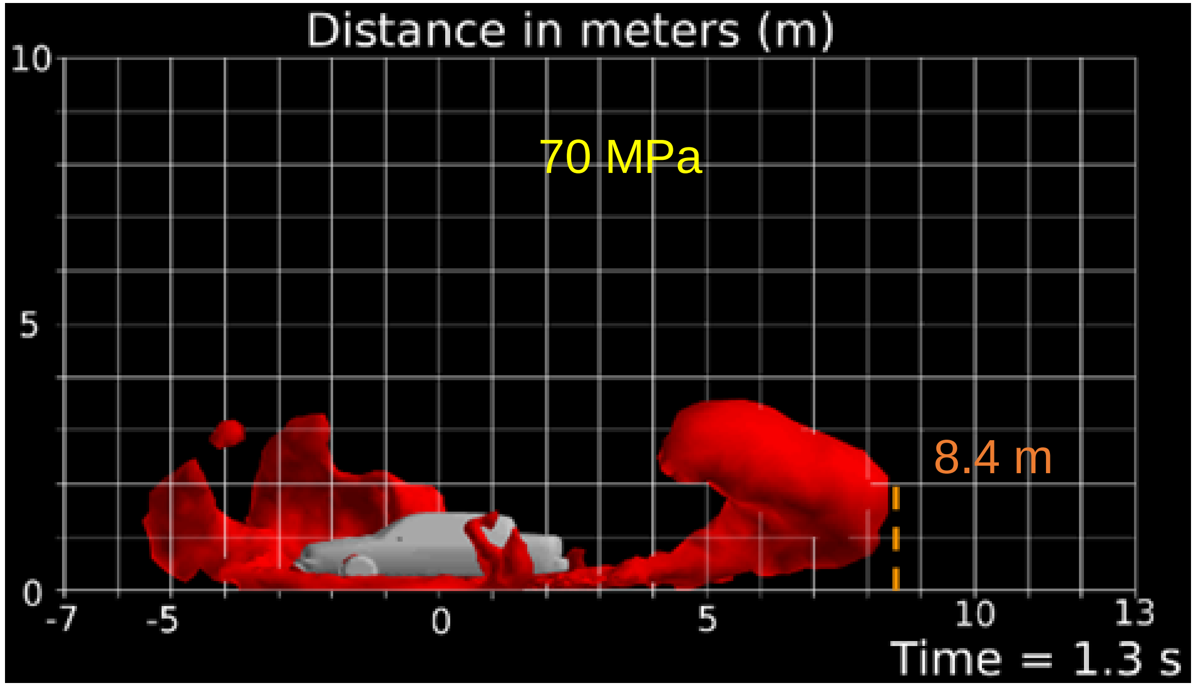


https://www.youtube.com/watch?v=0Lf_zBhgjCg&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=22

Hazard distances (1/2)

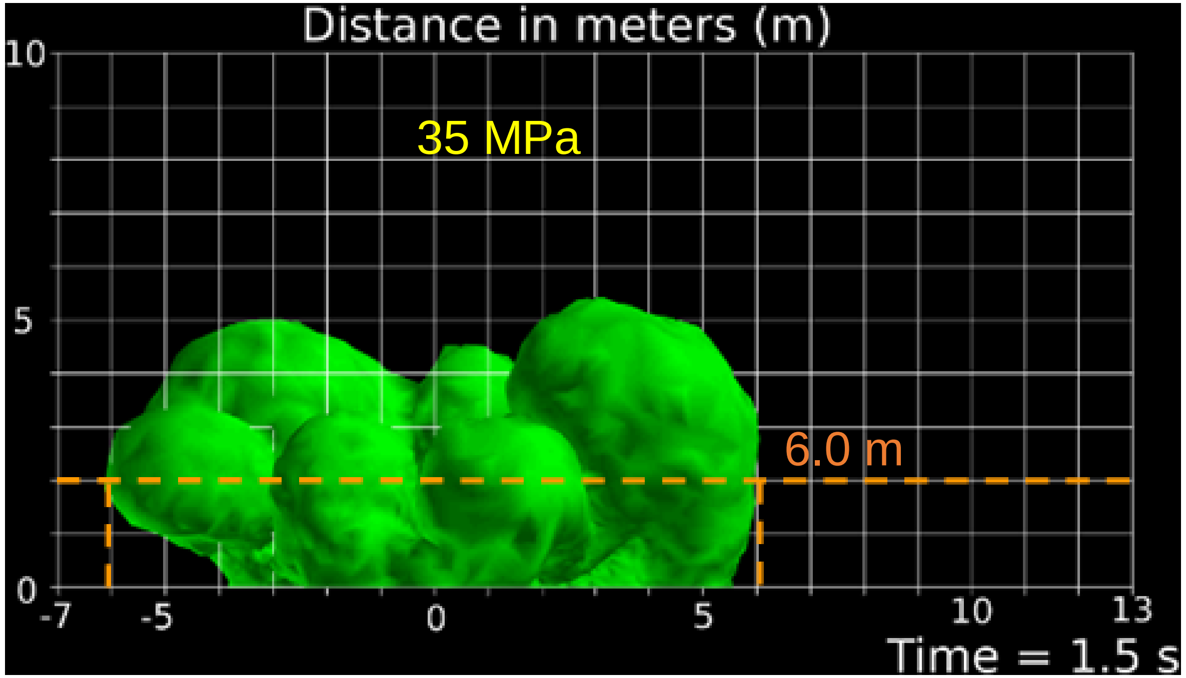
Hazard distance from visible hydrogen fire (1300 ºC flame) - Release 0º

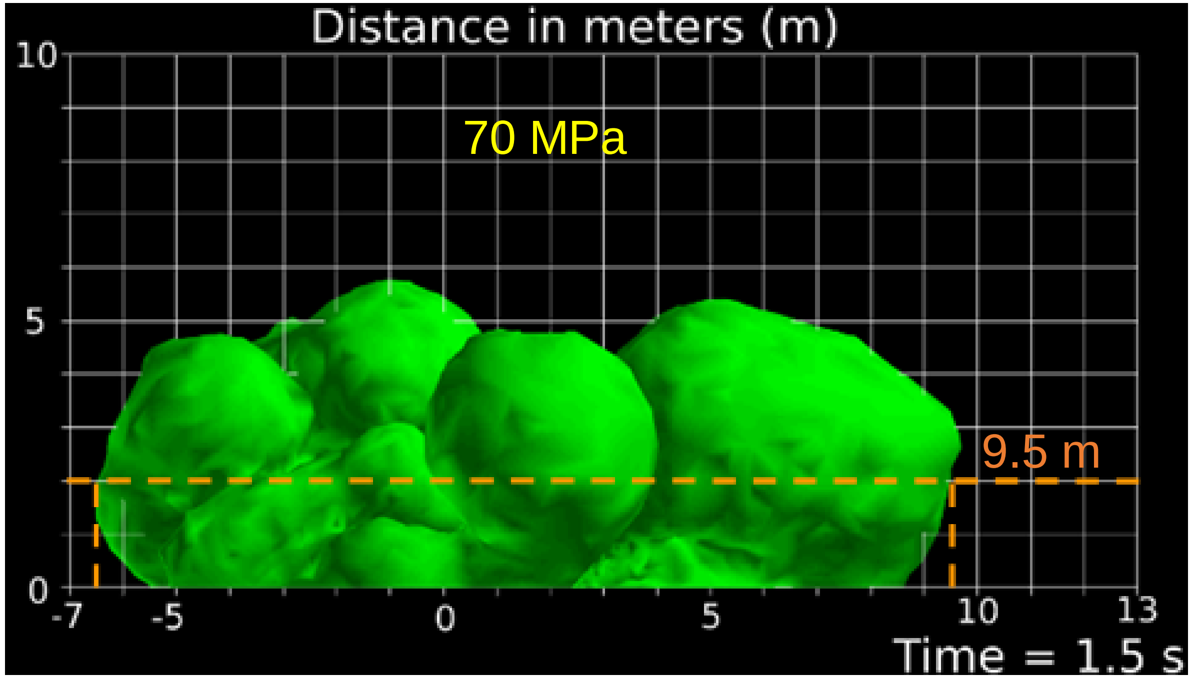




Hazard distances (2/2)

Hazard distance for people standing on the ground (below 2m) - Release 0º

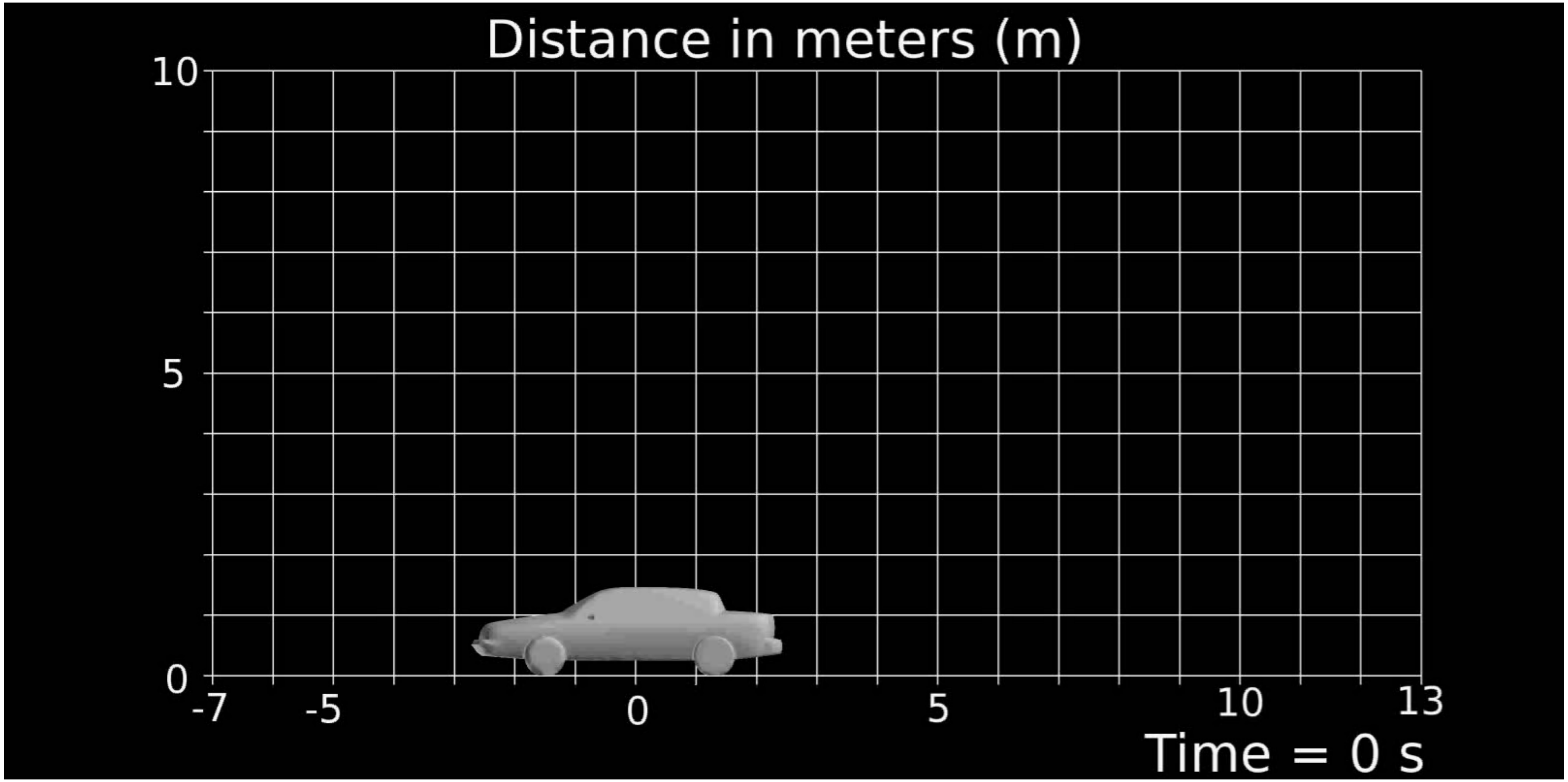




Hazard distances from hydrogen flames and fire fighting

70 °C envelope (70 MPa)

Release 0º



https://www.youtube.com/watch?v=t_Hq6lXzHKE&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=11

Jet fire prevention and mitigation

- Direction of the jet flow

The flow shall be directed so that it will not reach people or equipment. For example, flanges (components where leaks are likely) should be placed and directed in such way that a potential leak would not cause any domino effects.

- Shielding or barriers

It will reduce the rate of heat transfer to the potential targets in the vicinity of a hydrogen fire. Flame shields are specifically intended to reduce the radiant heat flux by preventing direct flame impingement on systems or equipment. The correct choice of materials for shields or barriers is very important.

- Reduction of flame length

For example through the use of innovative PRDs with decreased diameter and use of plane nozzles (see next slide).

Hazard distances from hydrogen flames and fire fighting

Innovative TPRD (350 bar)

Flame length reduction: 7.5 –> 1.8 m

https://www.youtube.com/watch?v=KKVVSBX-3As&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=15

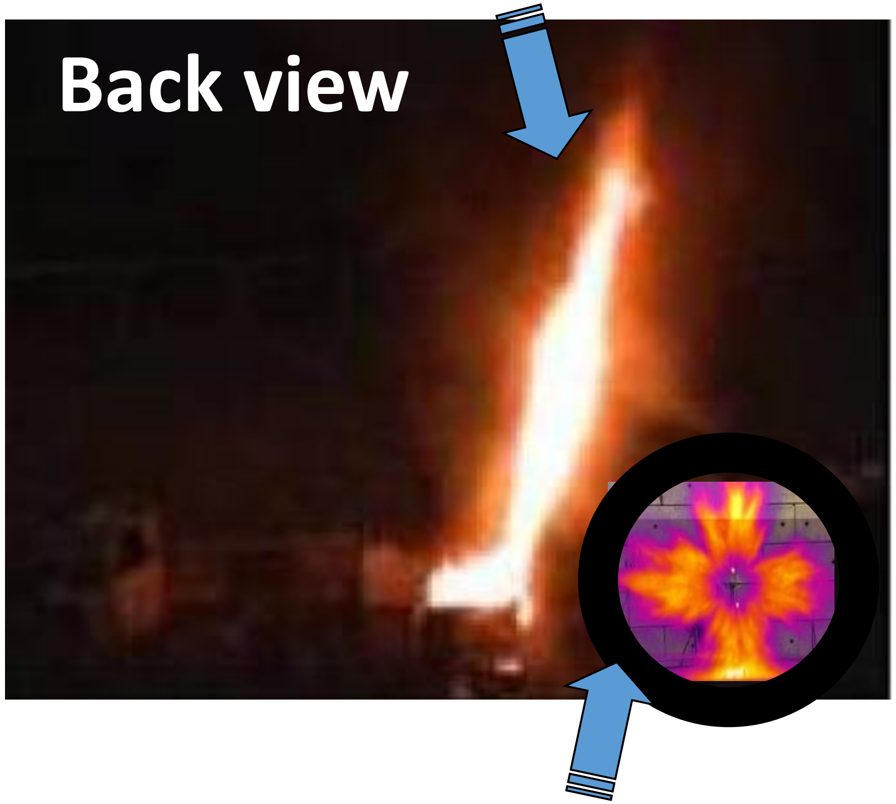
Flame length reduction: 6.1 –> 1.8 m

https://www.youtube.com/watch?v=chamCusodSk&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=14

Hazard distances from hydrogen flames and fire fighting

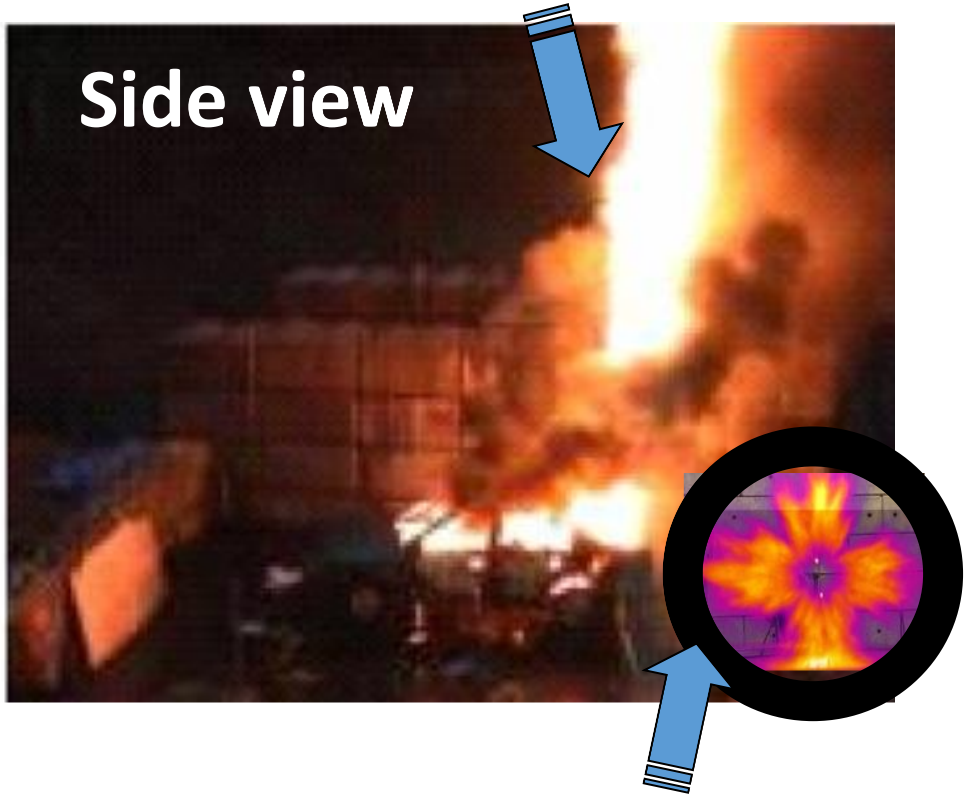
Innovative PRD: shorter flame

Current PRD



Short flame TPRD

Current PRD



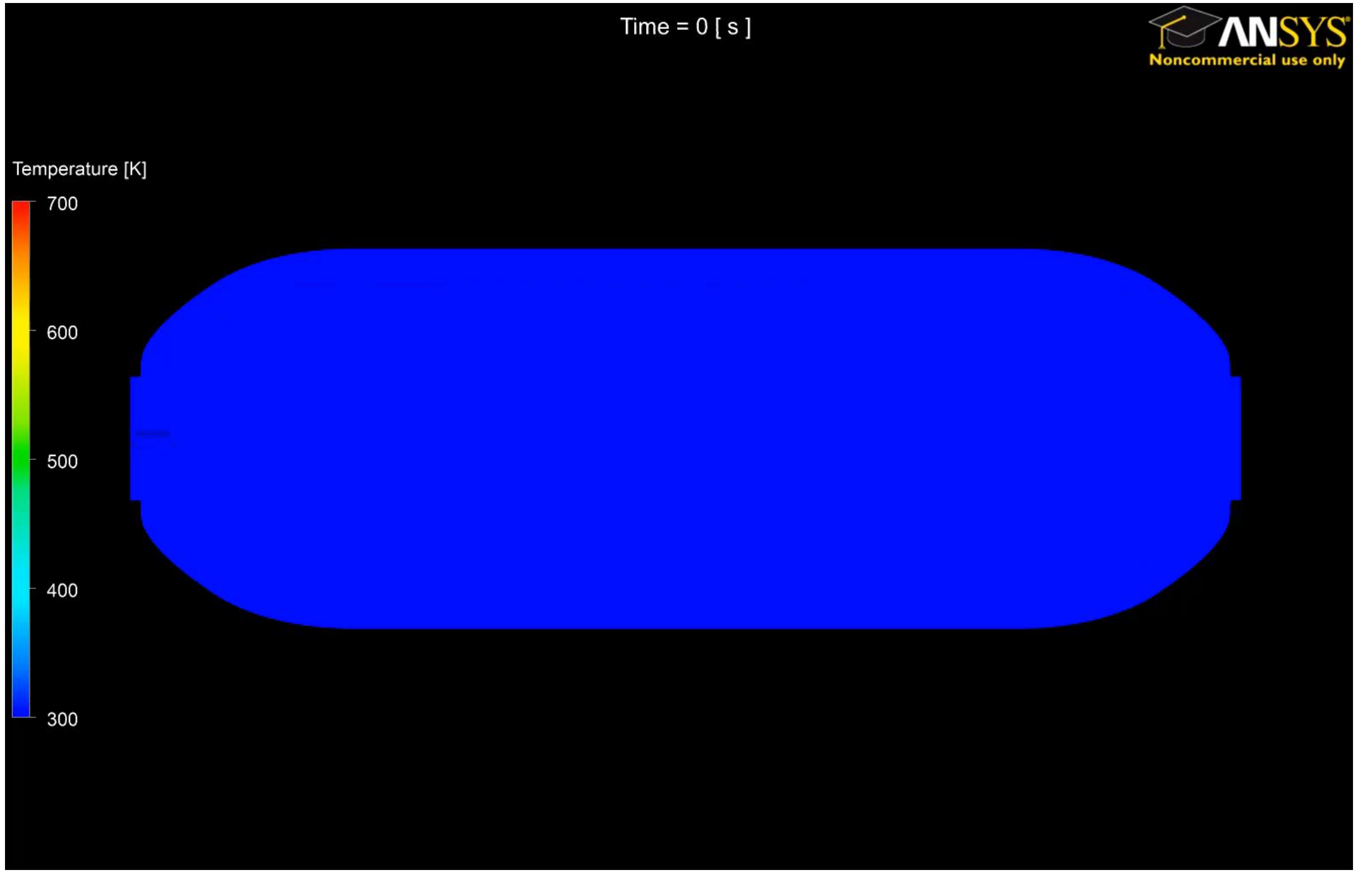
Short flame TPRD

Use of thermal insulation

- The purpose of thermal insulation is to reduce the rate of heat transfer to potential targets, e.g. hydrogen tanks located near hydrogen jet fire
- The equipment is usually protected with the materials which:
  - Have relatively low heat conductivity
  - Are non-combustible and do not produce smoke or toxic gases when subjected to high temperatures
  - Provide uniform protection
  - Allow efficient and uniform application
  - Durable and have sufficient bond strength
  - Weather-resistant

Fire protection coatings

Fire protection coatings (e.g. intumescent) for hydrogen storage tanks (research on-going at Ulster)



https://www.youtube.com/watch?v=SW33J-Yr3Qo&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=19

Extinction of hydrogen fires

The recommendations from the US National Hydrogen and Fuel Cell Emergency Response Training, 2014

Responders should:

- listen for venting gas, and watch for thermal waves that would signal hydrogen flames
- if only one FC vehicle is involved, approach from a 45° angle as per standard procedures, and from a downhill and upwind position
- if a hydrogen fire is present:
  - Allow the hydrogen supply to burn out if safe to do so and protect adjacent exposures; then approach and extinguish.
  - If a hydrocarbon fire is also present, attack the fire with a straight water stream from a distance, but avoid directing the water stream into the hydrogen tank's pressure-relief-device vent line. Control fire spread and cool exposures.
  - If possible, direct venting hydrogen that is not burning away from ignition sources and dissipate if necessary with fog nozzle streams.
  - Spray foam on petrol or diesel leaks near FC vehicle.

Reference (1/5)

1. Molkov, V (2012). Fundamentals of hydrogen safety engineering, Part I and Part II. Available from: www.bookboon.com, free download e-book.
2. Cheng, TS, Chiou, CR (1998). Experimental investigation of the characteristics of turbulent hydrogen jet flames. Combustion Science and Technology. Col. 136, p. 81-84.
3. Dorofeev, SB (2009). Evaluation of hydrogen explosion hazards: phenomenology and potential flame acceleration and DDT. 4th European Summer School on Hydrogen Safety.
4. Birch, AD, Brown, MG, Dodson, MG, Swaffield, F (1984). The structure and concentration decay of high pressure jets of natural gas. Combustion Science and Technology. Vol. 36, p. 249-261.
5. NFPA (2009). Compressed Natural Gas (CNG) Vehicular Fuel Systems Code, 52.
6. LaChance, J, Tchouvelev, A and Engebo, A (2011). Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure. International Journal of Hydrogen Energy. Vol. 36 p. 2381-2388.
7. Saffers, JB (2010). Principles of hydrogen safety engineering. PhD thesis. University of Ulster.
8. BRHS, Biannual Report on Hydrogen Safety (2007). Network of Excellence HySAFE. Available from: http://www.hysafe.org/BRHS [accessed on 25.11.20].
9. Kanury, AM (1975). Introduction to combustion phenomena: (for fire, incineration, pollution and energy applications). New York; London: Gordon and Breach.
10. Teodorczyk, A (2006). Fast deflagration, deflagration to detonation transition (DDT) and direct detonation of hydrogen-air mixtures. Teaching Materials of European Summer School on Hydrogen Safety, 2006.
11. Kalghatgi, GT (1981). Blow-out stability of gaseous jet diffusion flames. Part I: in still air. Combustion Science and Technology. Vol. 26(5), pp. 233-239.
12. Matta, LM, Neumeier, Y, Lemon, B and Zinn, BT (2002). Characteristics of microscale diffusion flames. *Proceedings of the Combustion Institute*, vol. 29, pp. 933-938.
13. Cheng, TS, Chen, CP, Chen, CS, Li, YH, Wu, CY and Chao, YC (2006). Characteristics of microjet methane diffusion flames. *Combustion Theory and Modelling*, 10, pp. 861-881.
14. Butler, MS, Moran, CW, Suderland, PB and Axelbaum, RL (2009). Limits for hydrogen leaks that can support stable flames. International Journal of Hydrogen Energy. Vol. 34. pp. 5174-5182.
15. Sunderland, PB (2010). Hydrogen microflame hazards, Proceedings of the 8th International Short Course and Advanced Research Workshop in the series "Progress in Hydrogen Safety", Hydrogen and Fuel Cell Early Market Applications, 11 - 15 October 2010, University of Ulster, Belfast.
16. Hawthorne, WR, Weddell, DS and Hottel HC (1949). Mixing and combustion in turbulent gas jets, Third International Symposium on Combustion, Flame and Explosion Phenomena, pp. 266-288, Baltimore, USA.
17. Hottel, HC and Hawthorne, WR (1949). Diffusion in laminar flame jets. Proceedings of the Combustion Institute. Vol. 3, pp. 254-266.
18. Brennan, S, Makarov, D and Molkov, V (2009). LES of high pressure hydrogen jet fire. Journal of Loss Prevention in the Process Industries. Vol. 22 (3), pp.353-359.

Reference (2/5)

19. Baev, VK and Yasakov, VA (1974). Effect of lifting forces on the length of diffusion flames. Combustion, Explosion and Shock Waves. Vol. 10, pp. 752-758.
20. Shevyakov, GG and Komov, VF (1977). Effect of non-combustible admixtures on length of an axisymmetric on-port turbulent diffusion flame. Combustion, Explosion and Shock Waves. Vol. 13, pp. 563-566.
21. HyFacts Project. Chapter F. Hydrogen fires. Available from: https://www.h2euro.org/hyfacts/2014/06/26/training-material/ [accessed on 25.11.20].
22. Kalghatgi, GT (1984). Lift-off heights and visible lengths of vertical turbulent jet diffusion flames in still air. Combustion Science and Technology. Vol. 41, pp. 17-29.
23. Schefer, RW, Houf, WG, Bourne, B and Colton, J (2006). Spatial and radiative properties of an open-flame hydrogen plume. International Journal of Hydrogen Energy. Vol. 31, pp. 1332-1340.
24. Schefer, RW, Houf, WG, Williams, TC, Bourne, B and Colton, J (2007). Characterization of high pressure, underexpanded hydrogen-jet flames. International Journal of Hydrogen Energy. Vol. 32, pp. 2081-2093.
25. Molkov, V and Saffers, J-B (2013). Hydrogen jet flames. International Journal of Hydrogen Energy. Vol. 38, pp. 8141-8158.
26. Proust, C, Jamois, D and Studer, E (2009). High pressure hydrogen fires. *Proceedings of the Third International Conference on Hydrogen Safety*. 16-18 September 2009, Ajaccio, France, paper 214.
27. LaChance, J, Tchouvelev, A and Engebo, A (2011). Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure. International Journal of Hydrogen Energy. Vol. 36 pp. 2381-2388.
28. EIGA, European Industrial Gases Association (2007). Determination of safety distances. IGC Doc 75/07/E.
29. BSI British Standards Institution (2004). Published Document PD 7974-6:2004. The application of fire safety engineering principles to fire safety design of buildings - Part 6: Human factors: Life safety strategies - Occupants evacuation, behaviour and condition (Sub-system 6).
30. DNV Technica (2001). Human resistance against thermal effects, explosion effects, toxic effects and obscuration of vision. DNV Technica, Scandpower A/S, Det Norske Veritas, Oslo, Norway.
31. BSI British Standards Institution (1997). British Standard 7899:1997. Code of practice for assessment of hazard to life and health from fire. Guidance on methods for the quantification of hazards to life and health and estimation of time to incapacitation and death in fires.
32. Barlow, RS and Carter, CD (1996.) Relationships among Nitric Oxide, Temperature, and Mixture Fraction in Hydrogen Jet Flames. Combustion and Flame. Vol. 104, pp. 288-299.
33. Imamura, T, Hamada, S, Mogi, T, Wada, Y, Horiguchi, S, Miyake, A and Ogawa, T (2008). Experimental investigation on the thermal properties of hydrogen jet flame and hot currents in the downstream region. International Journal of Hydrogen Energy. Vol. 33, pp. 3426-3435.

Hazard distances from hydrogen flames and fire fighting

Reference (3/5)

34. Royle, M and Willoughby, DB (2009). Consequences of catastrophic releases of ignited and unignited hydrogen jet releases. 3rd International Conference on Hydrogen Safety, Ajaccio, France.
35. Mogi, T and Horiguchi, S (2009). Experimental study on the hazards of high-pressure hydrogen jet diffusion flames. Journal of Loss Prevention in the Process Industries. Vol. 22, pp. 45-51.
36. Makarov, D and Molkov, V. (2013). Plane hydrogen jets. International Journal of Hydrogen Energy. Vol. 38 (19), pp. 8068–8083.
37. Shevyakov, GG and Savelieva, NI (2004). Dispersion and combustion of hydrogen jet in the open atmosphere. International Scientific Journal for Alternative Energy and Ecology. Vol. 1(9), pp. 23-27 (in Russian).
38. HYPER (2008) FP6 STREP project "Installation Permitting Guidance for Hydrogen and Fuel Cells Stationary Applications". *Deliverable 4.3 Releases, Fires and Explosions*. WP4 Final Report.
39. Houf, WG and Schefer, RW (2007). Predicting radiative heat fluxes and flammability envelopes from unintended releases of hydrogen. International Journal of Hydrogen Energy. Vol. 32, pp. 136-151.
40. Molina, A, Schefer, RW and Houf, WG (2007). Radiative fraction and optical thickness in large-scale hydrogen-jet fires. Proceedings of the Combustion Institute. Vol. 31, pp. 2565-2572.
41. Case for safety. Relative frequency of failure modes. Available from: http://h2safe.net/case_safety.html [accessed on 25.11.20].
42. Zalosh, R (2007). Blast waves and fireballs generated by hydrogen fuel tank rupture during fire exposure. Proceedings on the 5th Seminar on Fire and Explosion Hazard, Edinburgh, UK, 23-27 April 2007, pp. 2154-2161.
43. Fire statistics, Great Britain, 2011-2012. Department of Communities and Local Government.
44. Gambone, LR and Wong, JY (2007). Fire protection strategy for compressed hydrogen-powered vehicles. 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 September, 2007.
45. Swain, MR (2001). Fuel leak simulation. Proceedings of the 2001 DOE Hydrogen Program Review. Available from: https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/30535be.pdf [Accessed 25.11.20].
46. Tamura, Y, Takabayashi, M, Takeuchi, M and Mitsuishi, H (2011). The spread of fire from adjoining vehicles to a hydrogen fuel cell vehicle. In: Proceedings of the Fourth International Conference on Hydrogen Safety, 12-14 September 2011, San Francisco, USA.
47. Stephenson, RR (2005) Fire safety of hydrogen-fuelled vehicles: system-level bonfire test. Proceedings of the 1st International Conference on Hydrogen Safety, Pisa, Italy, 2005. Available from: http://conference.ing.unipi.it/ichs2005. [Accessed 25.11.20].

Reference (4/5)

48. Watanabe, S, Tamura, Y, Suzuki, J (2007). The new facility for hydrogen and fuel cell vehicle safety evaluation. International Journal of Hydrogen Energy. Vol. 32 (13), pp. 2154-2161.
49. Li, Z, Makarov, D, Keenan, J, Molkov, V (2015). CFD study of the unignited and ignited hydrogen releases from TPRD under a fuel cell car. 6th International Conference on Hydrogen Safety, 19-21 October 2015, Yokohama, Japan.
50. NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting, 2007 Edition. National Fire Prevention Association, 2007, Boston, Massachusetts.
51. HyIndoor Deliverable D4.2 – First intermediate report on analytical, numerical and experimental studies (2014).
52. Yamazaki, K and Tamura, Y (2015). Study of a Post-fire Verification Method for the Activation Status of Hydrogen Cylinder Pressure Relief Devices. 6th International Conference on Hydrogen Safety, 19-21 October 2015, Yokohama, Japan.
53. US DoE, US Department of Energy (2008). Hydrogen safety training for first responders. Available from: http://hydrogen.pnl.gov/FirstResponders/ [accessed on 25.11.20].
54. Cirrone DMC, Makarov D, Molkov V. Simulation of thermal hazards from hydrogen under-expanded jet fire. Int J Hydrogen Energy 2019,44:8886-8892.
55. ANSYS Fluent. Theory guide. 2016.
56. Schefer R, Houf B, Bourne B, Colton J. Experimental measurements to characterize the thermal and radiation properties of an open-flame hydrogen plume. In: Proceedings of the 15th annual hydrogen conference and hydrogen expo; 2004.
57. Molkov, V., Makarov, D. and Bragin, M., ‘Physics and modeling of under-expanded jets and hydrogen dispersion in atmosphere’, in Proceedings of the 24th International Conference on Interaction of Intense Energy Fluxes with Matter, 1st - 6th March, 2009, Elbrus, Russia, 2009, p. 146.
58. Molkov, V. and Saffers, J.-B., ‘The correlation for non-premixed hydrogen jet flame length in still air’, in 10th International Symposium on Fire Safety Science, June 19, 2011 - June 24, 2011, 2011, pp. 933–943.
59. LaChance, J.L., ‘Progress in risk assessment methodologies for emerging hydrogen applications’, presented at the Sixth International Short Course and Advanced Research Workshop ‘Progress in Hydrogen Safety - Regulations, Codes and Standards’ 25th - 29th January, 2010, Belfast, Northern Ireland, 2010.
60. Wang H., Duncan I.J. Likelihood, causes, and consequences of focused leakage and rupture of U.S. natural transmission pipelines. J. Loss Prevent. Proc. 2014, 30: 177-187.
61. U.S. Department of Tranportation. Pipeline and Hazardous Materials Safety Administration. (2010). https://primis.phmsa.dot.gov/comm/publications/PIPA/PIPA-PipelineRiskReport-Final-20101021.pdf
62. Lowesmith B.J., Hankinson G. Large scale high pressure jet fires involving natural gas and natural gas/hydrogen mixtures. Process Saf. Environ. 2012, 90: 108-120.

Reference (5/5)

63. EGIG, Gas pipeline incidents 8th Report of the European Gas Pipeline Incident Data Group, EGIG 14.R.0403 (2011).
64. Casal J., Gomez-Mares M., Munoz M., Palacios A. Jet fires: a “minor” fire hazard? Chem. Eng. Trans. 2012, 26: 13-20.
65. Houf W., Schefer R. Predicting radiative heat fluxes and flammability envelopes from unintended releases of hydrogen. Int. J. Hydrogen Energy, 2007, 32: 136-151.
66. Lin CL, Chien CF. Systems thinking in a gas explosion accident e lessons learned from Taiwan. J Loss Prev Process Ind 2019, 62:103987.
67. EIGA. Determination of safety distances (IGC Doc 75/07/E). 2007. https://www.eiga.eu/publications/eiga-documents/doc-7507-determination-of-safety-distances/ [Accessed 12.02.2020].
68. Gomez-Mares M., Zarate L., Casal J. Jet fires and the domino effect. Fire Saf J. 2008, 43: 583-588.
69. Cirrone DMC, Makarov D, Molkov V. Simulation of thermal hazards from hydrogen under-expanded jet fire. Int J Hydrogen Energy 2019, 44: 8886-8892.
70. Wang Z, Shui K, You F, Dederichs AS, Markert F, Jiang J, Zhang Y, Li D, Fu Z, Xu J, He L, Huangfu W. Prediction of the failure probability of the overhead power line exposed to large-scale jet fires induced by high-pressure gas leakage. Int J Hydrogen Energy 2021, 46: 2413-2431.
71. Coccorullo I, Russo P. Jet fire consequence modeling for high-pressure gas pipelines, International conference of computational methods in sciences and engineering 2016 (iccmse 2016).
72. Molkov VV, Cirrone DMC, Shentsov VV, Dery W, Kim W, Makarov DV. Dynamics of blast wave and fireball after hydrogen tank rupture in a fire in the open atmosphere. Int J Hydrogen Energy, 2021, 46: 4644-4665.

HyResponder

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (JU) under grant agreement No 875089. The JU receives support from the European Union’s Horizon 2020 research and innovation programme and United Kingdom, France, Austria, Belgium, Spain, Germany, Italy, Czechia, Switzerland, Norway

European Hydrogen Train the Trainer Programme for Responders