HyResponder

Confined spaces

European Hydrogen Train the Trainer Programme for Responders

Confined space

Content

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Objectives of the lecture

1. Identify the main hazards of hydrogen use indoors
2. Explain pressure peaking phenomenon
3. Use nomograms to evaluate the possibility of pressure peaking phenomenon
4. Describe the main regimes on hydrogen indoor fires
5. Distinguish between passive and forced ventilation
6. Understand the effect of deflagration venting

Hazards and risk of hydrogen use in enclosures

- Oxygen depletion and asphyxiation
- Effects of high temperature and heat flux from jet fires
- Overpressure effects
- Structural collapse
- “Domino” effects
- Damage to environment
- Injury and loss of life

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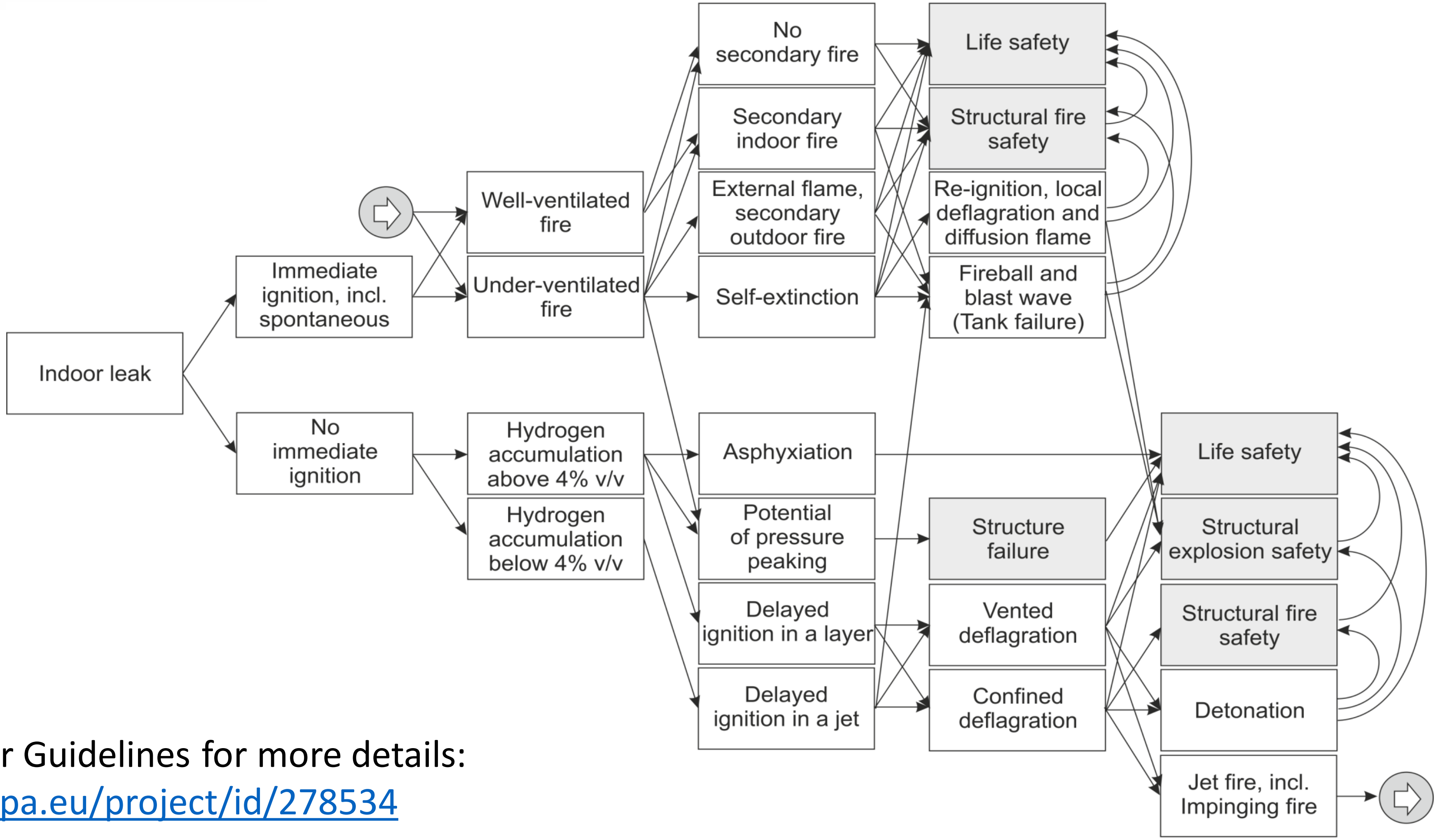
Hydrogen phenomena and consequences



Please see HyIndoor Guidelines for more details:
https://cordis.europa.eu/project/id/278534

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Indoor hydrogen releases and dispersion

Hydrogen energy applications often require that systems are used indoors, e. g.

- industrial trucks for materials handling in a warehouse facility;
- fuel cells located in a room;
- hydrogen stored and distributed from a gas cabinet;
- some hydrogen system components/equipment inside indoor or outdoor enclosures.

The knowledge gaps were closed through the HyIndoor project:

- Hydrogen release inside a confined or semi-confined enclosure;
- Indoor hydrogen-air deflagration;
- Jet fire and under-ventilated fire;
- Hydrogen detection for confined spaces.

Please see HyIndoor Guidelines for more details:
https://cordis.europa.eu/project/id/278534

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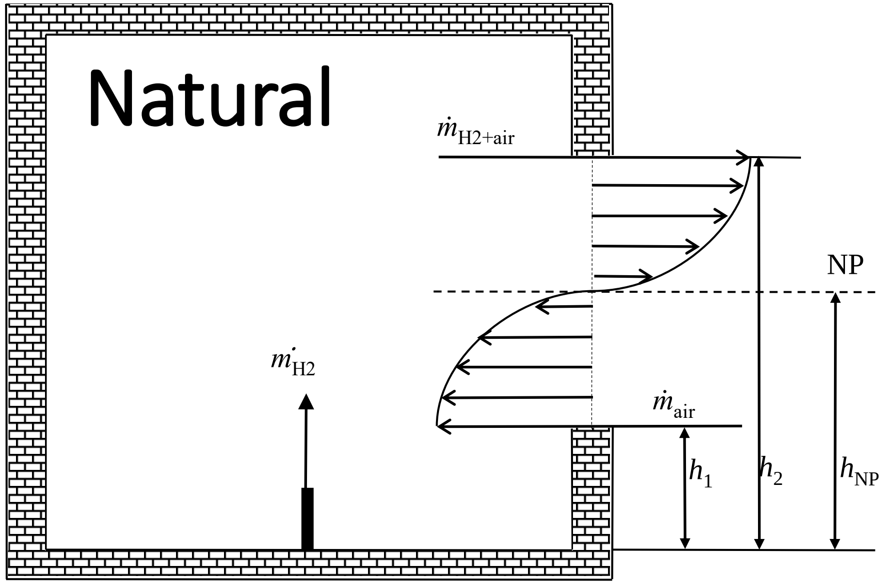
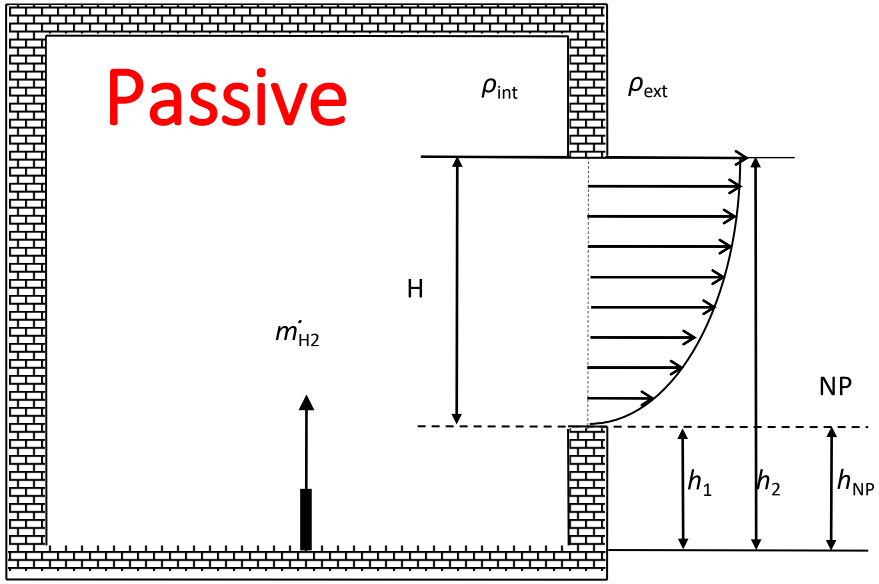
Natural vs. passive ventilation





- **Natural ventilation** equations for air ventilation are derived in the assumption of **equality** of flow in and out (**neutral plane is at half vent height**).
- **Passive ventilation**: neutral plane for lighter than air gases can be **anywhere below half of vent height**.

Reference paper: V. Molkov, V. Shentsov, J. Quintiere. Int. J. Hydrogen Energy, 2014, 39: 8158-8168.

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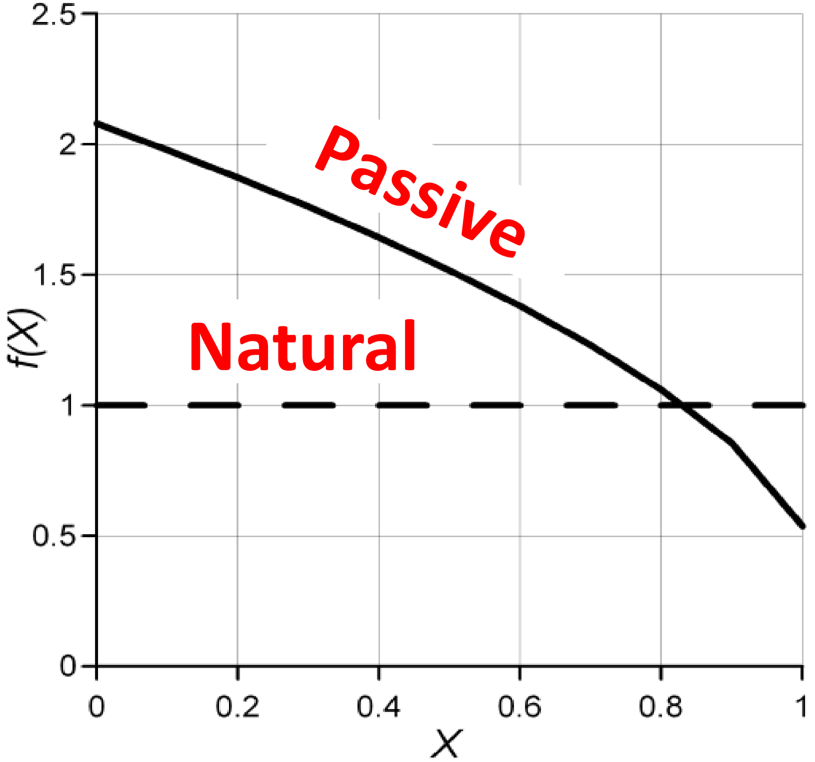
Safety implications

Difference:

$$X = f(X) \cdot \left[\frac{Q_0}{C_D A (g' H)^{1/2}} \right]^{2/3}$$

$$f(X) = \left(\frac{9}{8} \right)^{1/3} \cdot \left\{ \left[1 - X \left(1 - \frac{\rho_{H_2}}{\rho_{air}} \right) \right]^{1/3} + (1 - X)^{2/3} \right\}$$



Natural ventilation equation should not be used:

- Underestimate by ×**2 (lean)**
- Overestimate by ×**2 (rich)**

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Ventilation nomogram

- The nomogram is developed by UU to calculate the maximum concentration for sustained hydrogen leak in an enclosure with one vent.

Allows to calculate:

- Steady-state hydrogen uniform concentration for the given release rate (Q) and vent size ($H \times W$).
- Parameters of the vent to get desired concentration for the given release rate.
- The release rate to get desired concentration for the given vent sizes.

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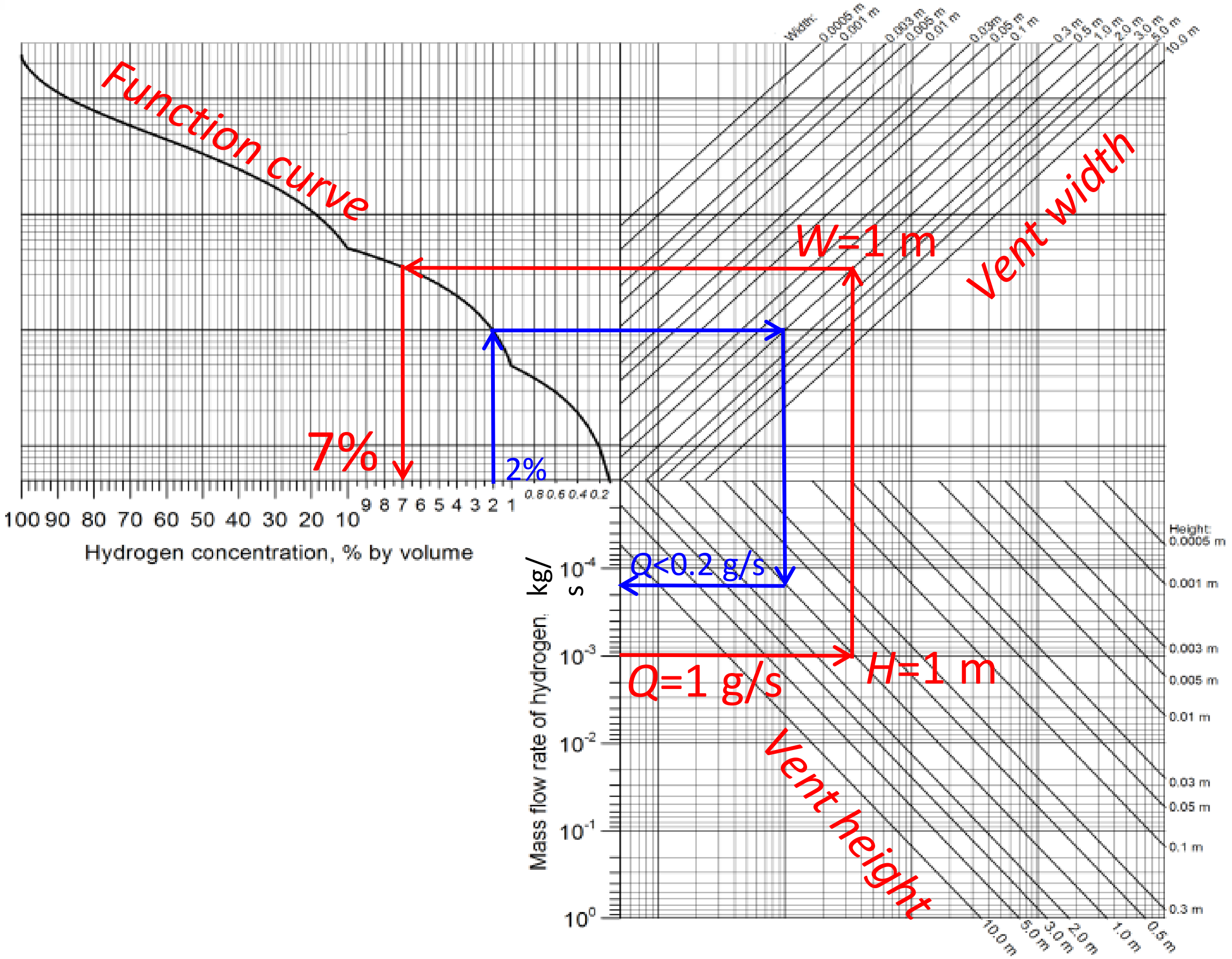
Nomogram ($C_{max\ steady\text{-}state}$)



Calculation examples:

- Release rate (1 g/s)
- Vent Height (1 m)
- Vent width (1 m)
- Function curve
- Concentration (7%)

1. RCS require no more than 2% v/v (50% LFL)
2. For the same 1 × 1 m vent release rate Q < 0.2 g/s

Pressure peaking phenomenon (1/4)

Pressure peaking is the phenomenon observed for the gases which are very light (lighter than air), which can result in overpressure exceeding the structural strength limit of an enclosure or a building in the case of sufficiently high hydrogen release rate.

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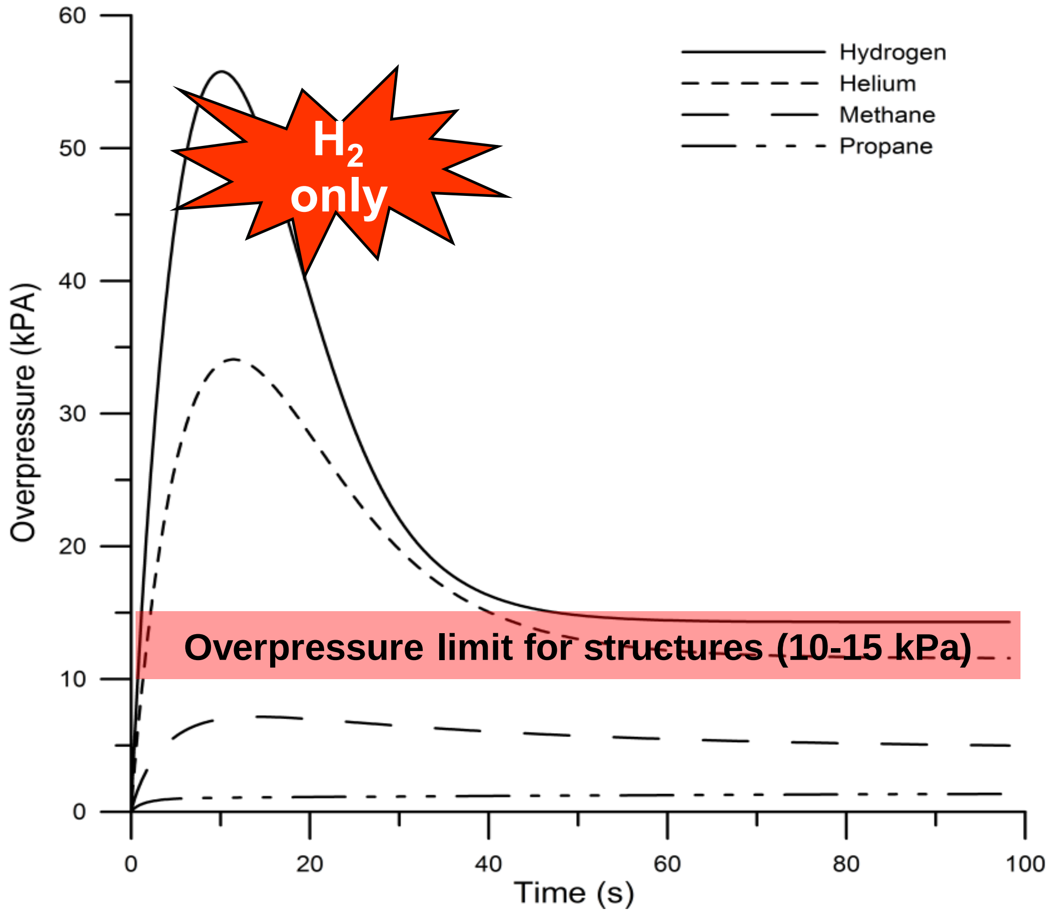
Pressure peaking phenomenon (2/4)

Unignited release



Garage: 4.5×2.6×2.6 m with a "brick" vent.
Car: mass flow rate 390 g/s (H_2: 350 bar, 5.08 mm orifice).

$$V_{vent} = CA\left\{\left(\frac{2\gamma}{\gamma-1}\right)\frac{P_S}{\rho_{encl}}\left[\left(\frac{P_S}{P_{encl}}\right)^{\frac{2}{\gamma}} - \left(\frac{P_S}{P_{encl}}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{\frac{1}{2}}$$

Definition: it is a transient peak in the pressure dynamics during hydrogen release in enclosures with vent(s).

Solution: decrease TPRD diameter (increase fire resistance of tank).

Reference paper: S. Brennan, V. Molkov. Int. J. Hydrogen Energy, 2013, 38: 8159-8166.

Pressure peaking phenomenon (3/4)

Ignited release

- The phenomenon is the most pronounced for hydrogen as it has the lowest density.
- It was described for the first time for unignited release of hydrogen by (Brennan et al 2013).
- With 5 mm TPRD and 350 bar storage in case of unignited release, e.g. due to TPRD fault, the garage would be demolished in less than in few seconds with overpressure peak above 60 kPa.
- TPRD opening in a fire conditions is expected to be much higher compared to a probability of unscheduled faulty opening of TPRD followed by an unignited release
- For an ignited release, a flow rate from the source is expected to be even smaller to generate PPP
- The difference in volumetric flow rate from the same source due to combustion is assessed as a_c=22 times (Makarov et al. 2018)

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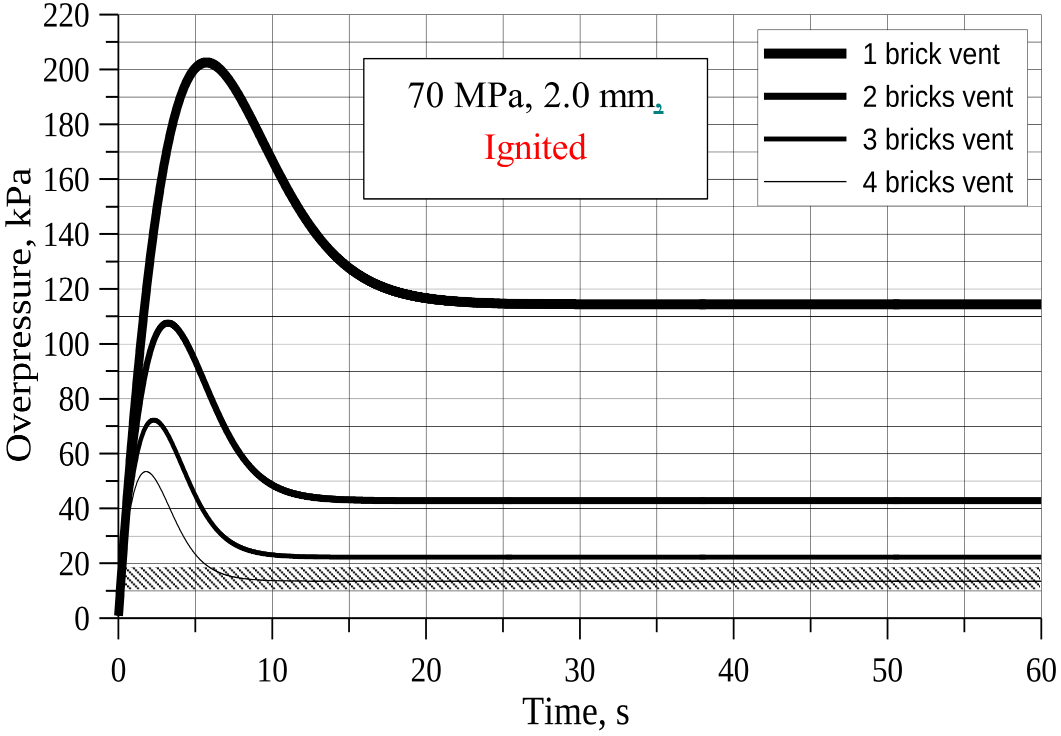
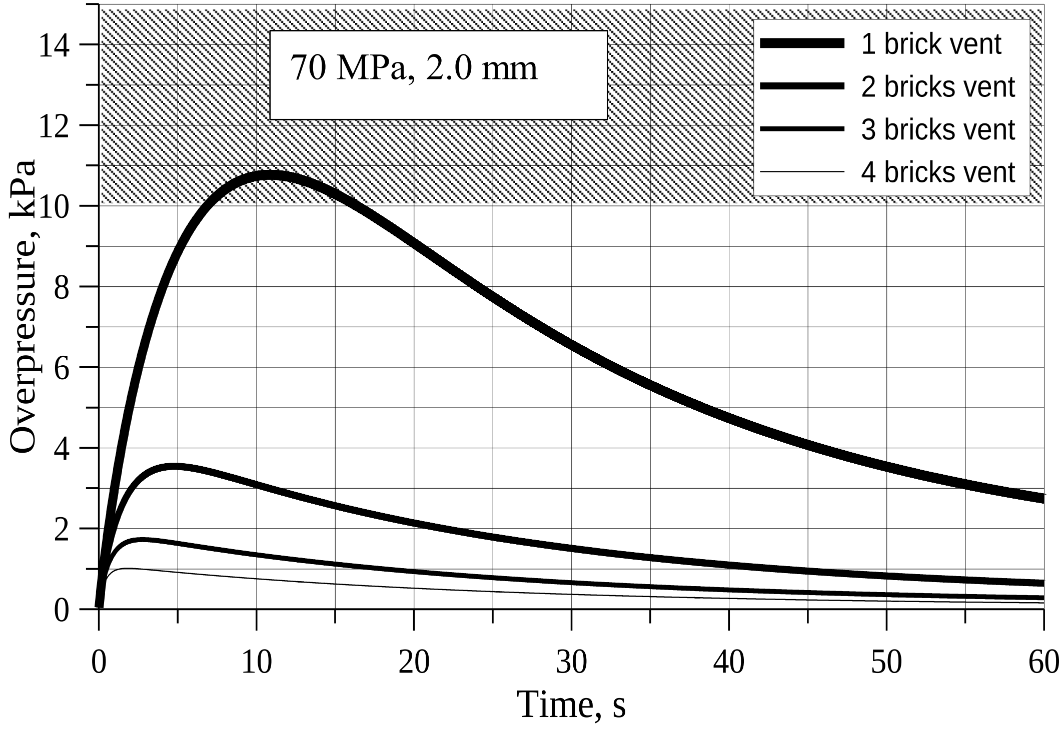
Pressure peaking phenomenon (4/4)

Overpressure ignited vs unignited





Overpressure dynamics of hydrogen jet fire in the garage: TPRD diameter 2 mm and storage pressure 70 MPa (release rate 107 g/s) Ignited (left) vs unignited (right)

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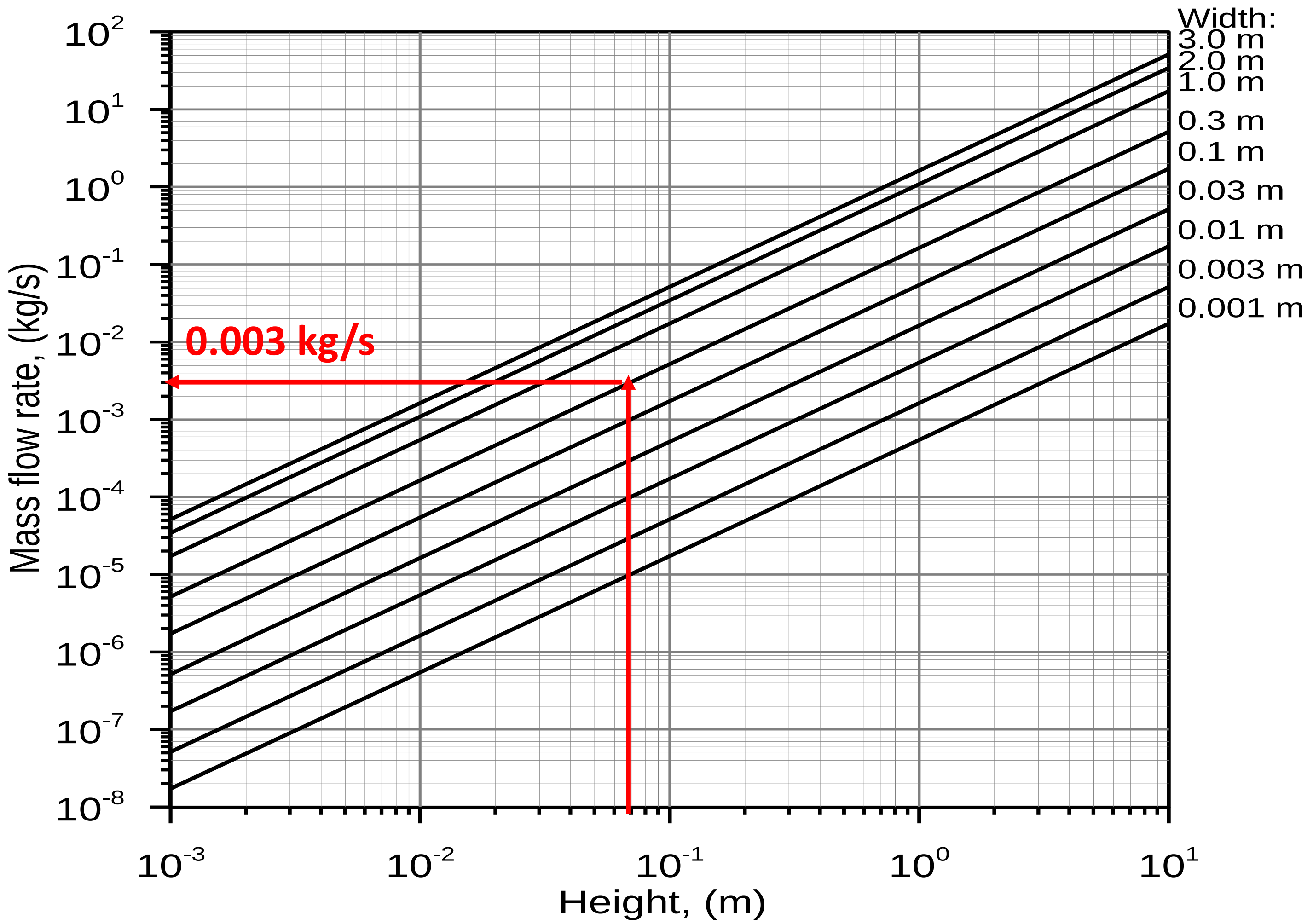
Pressure peaking phenomenon: step 1 of 2



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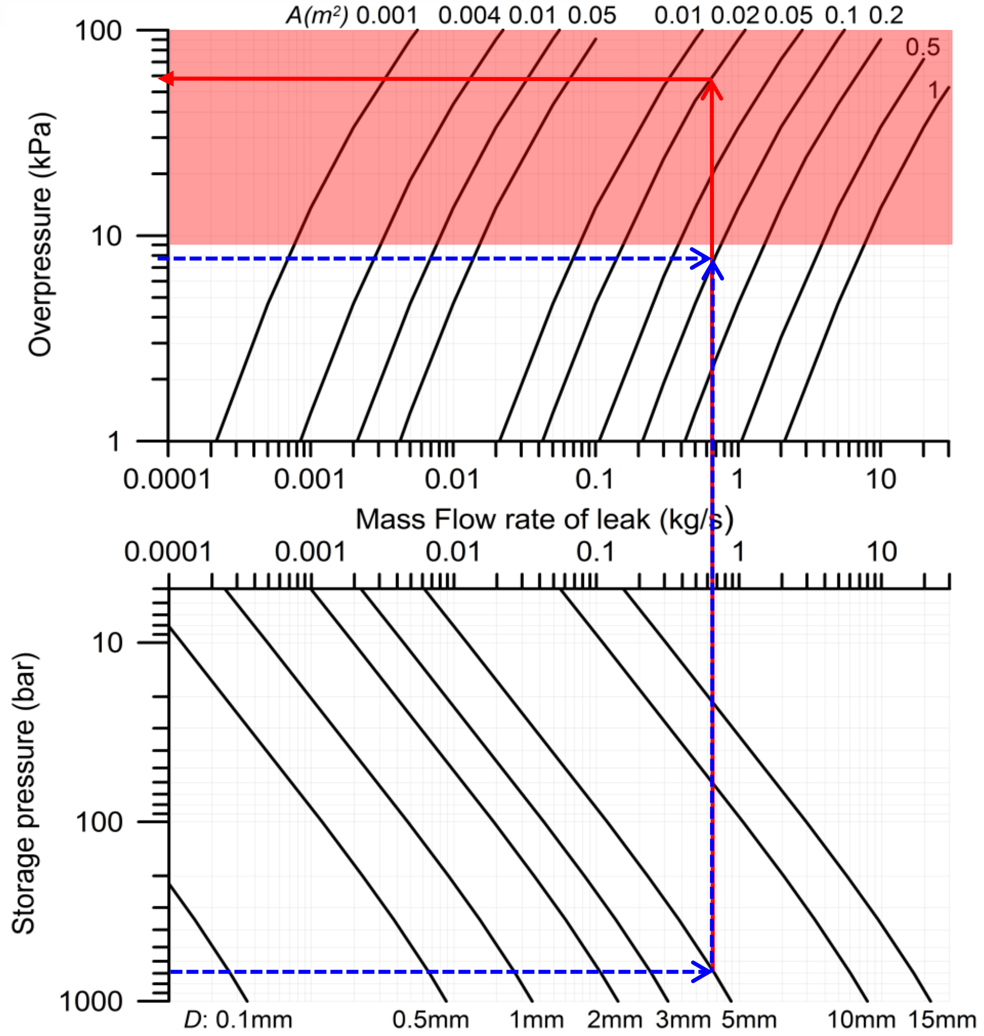
Pressure peaking phenomenon: step 2 of 2



The nomogram use:

1) Pressure p = 700 bar;

Orifice diameter D = 5 mm

Vent size area A 0.07m × 0.3m = 0.021 m²

<u>Overpressure 60 kPa</u>

2) Overpressure 8 kPa below the limit for structures.

Then the venting area in a garage should be A = 0.1 m², e.g. about 0.3m × 0.32m (0.1m × 1m).

Garages in cold climate zones would not have such large vent area (and thus would be destroyed).

Non-reacting (unignited) releases.

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Pressure peaking phenomenon – e-Laboratory

Pressure peaking phenomenon for unignited releases

Constant mass flow rate

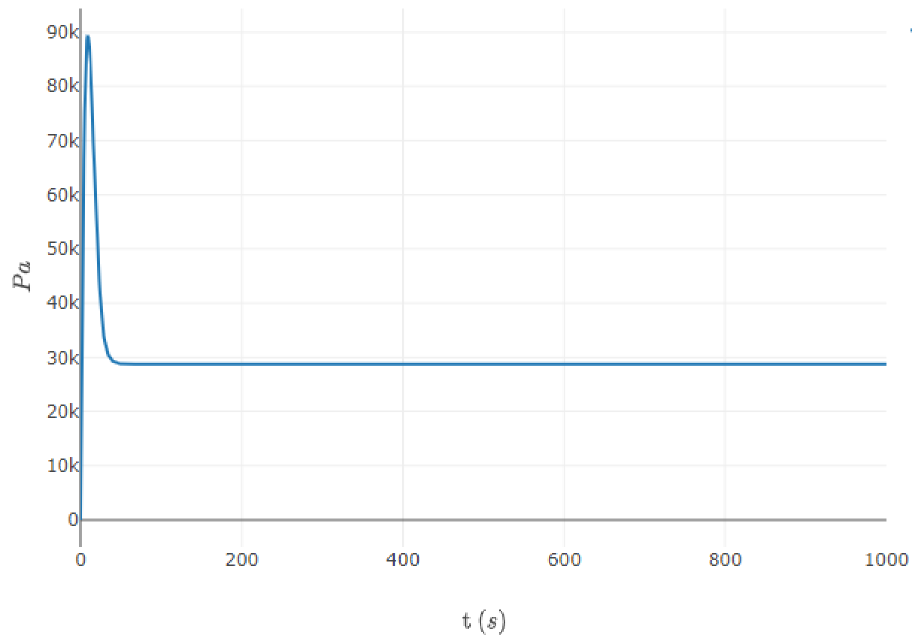
URL: https://elab.hysafer.ulster.ac.uk/

Login: HyResponderTrainer **Password**: safetyfirst

Tank blowdown

Name	Symbol	Value	Unit
Atmospheric pressure	p_{atm}	1.01325e+5	Pa
Enclosure temperature	T_{encl}	293.15	K
Enclosure volume	V_{encl}	30.42	m³
Vent height	H_{vent}	0.05	m
Vent width	W_{vent}	0.25	m
Hydrogen mass flow rate	$\dot{m}_{H_2}$	0.59	kg/s
Coefficient of discharge	C_D	0.6	
Time step for integration	Δt	1	s
Number of time steps for integration	n_{max}	1000	
Time	t	view	s
Mass of gases in enclosure	m_{encl}	view	kg
Vent mass flow rate	$\dot{m}_{vent}$	view	kg/s
Overpressure	$p_{g_{encl}}$	view	Pa

Plot | Export to CSV | Change inputs | Dataset name | Save



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Passive ventilation in an enclosure – e-Laboratory

Ambient pressure

p_{atm} 101325 Pa

Ambient temperature

T_{atm} 293 K

Hydrogen mass flow rate

$\dot{m}_{H_2}$ 0.00001 kg/s

Discharge coefficient

C_D 0.1

Vent height

H 0.2 m

Vent width

W 0.2 m

Calculate Reset

Passive ventilation in an enclosure with one vent: uniform hydrogen concentration

Steady-state hydrogen uniform concentration for the given release rateand vent size

Parameters of the vent to get desired concentration

Calculation of the release rate to get desired concentration for thegiven vent sizes

Name	Symbol	Value	Unit
Ambient pressure	p_{atm}	1.01325e+5	Pa
Ambient temperature	T_{atm}	293	K
Hydrogen mass flow rate	$\dot{m}_{H_2}$	1e-5	kg/s
Volume fraction of hydrogen	X	0.151146	
Discharge coefficient	C_D	0.1	
Vent height	H	0.2	m
Vent width	W	0.2	m

Export to CSV Change inputs Dataset name Save

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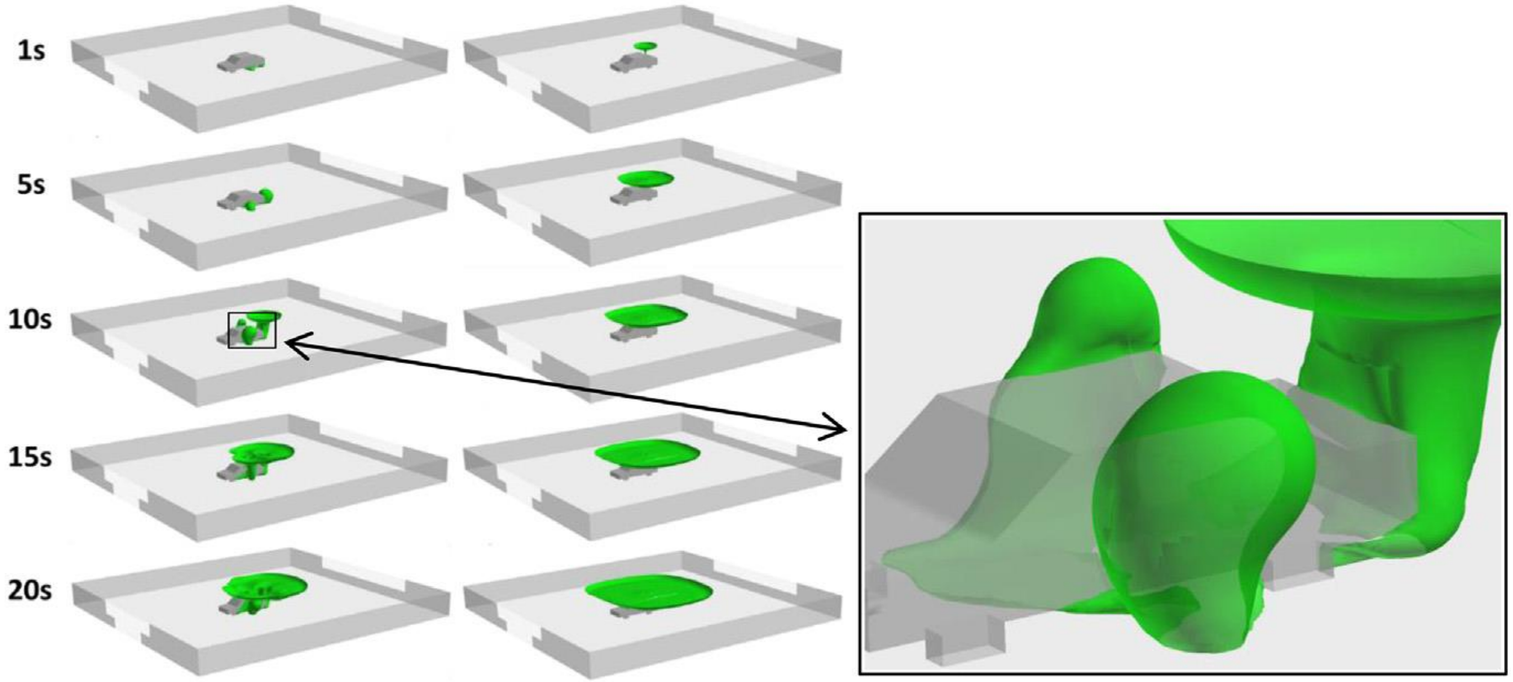
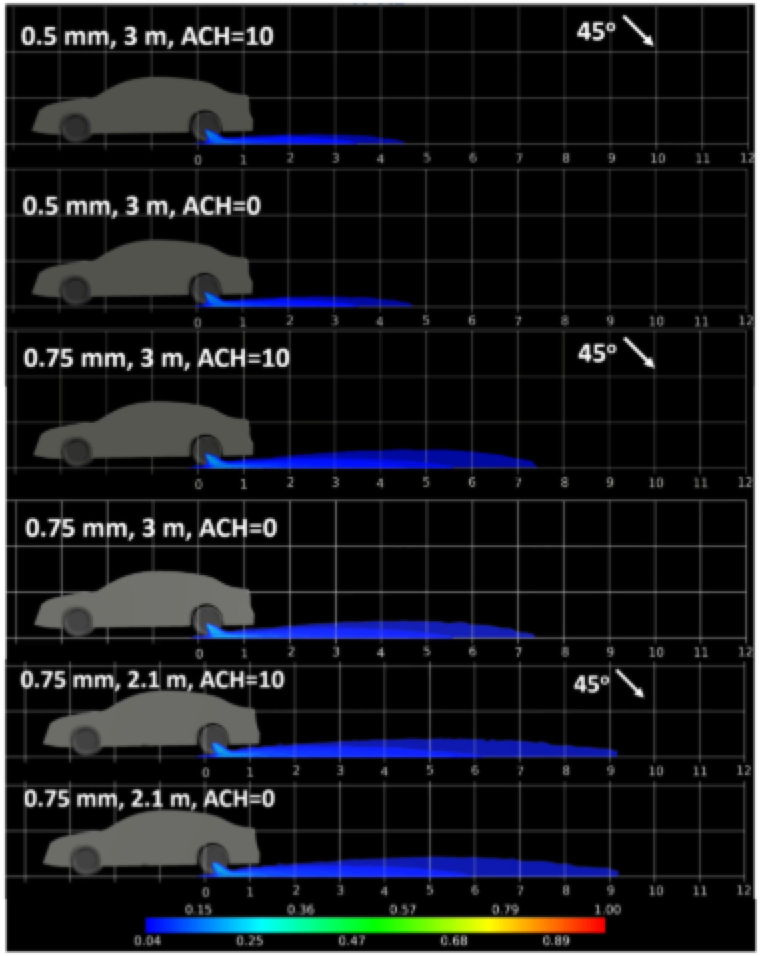
Carparks (1/2)



1% hydrogen mole fraction for release from 700 bar through a 0.5 mm TPRD diameter for downward release (left) and upward release (right).



Effect of ventilation versus no ventilation on hydrogen flammable envelope

Source: H. Hussein, S. Brennan, V. Molkov. Dispersion of hydrogen release in a naturally ventilated covered car park. Int J Hydrogen Energy, 2020, 45: 23882-23897.
V. Shentsov, D. Makarov, V. Molkov, Effect of TPRD diameter and direction of release on hydrogen dispersion in underground parking. ICHS2021, ACCEPTED

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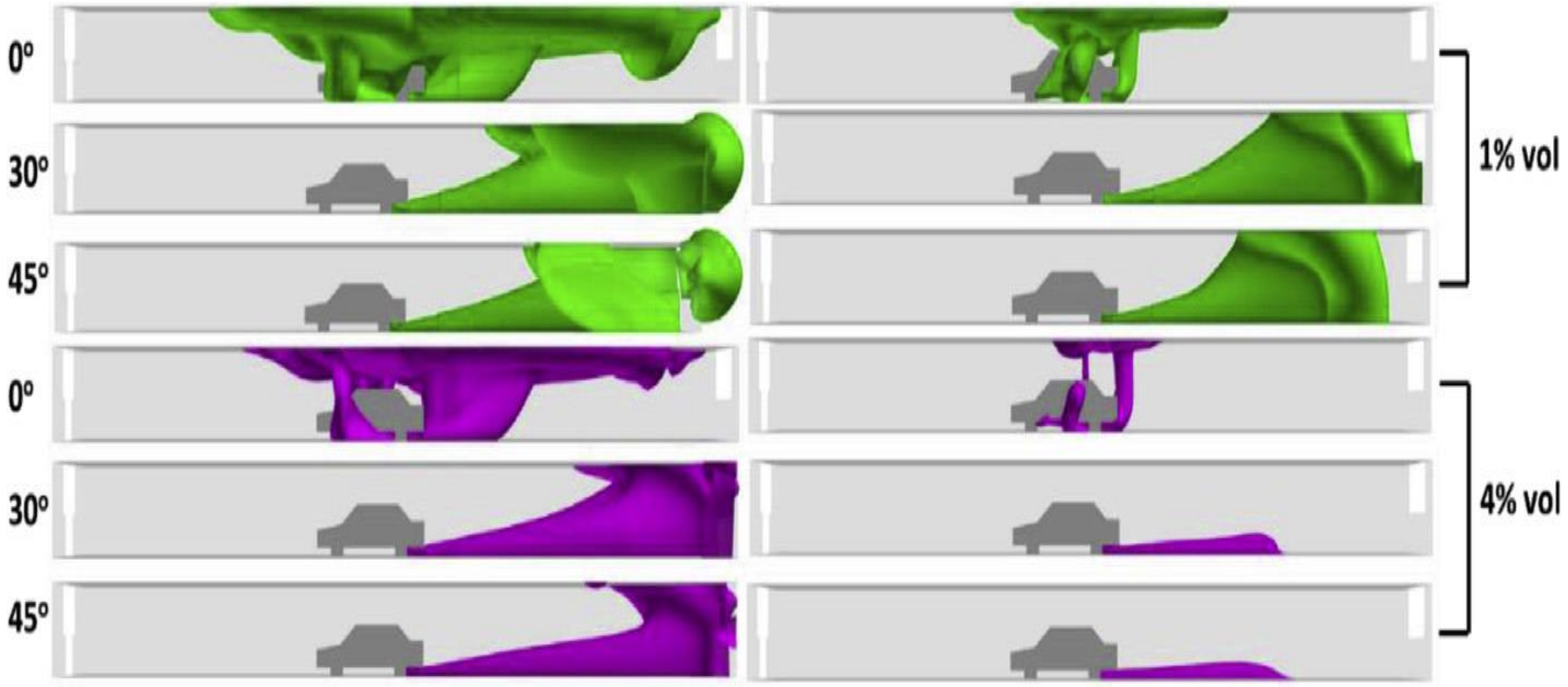
Carparks (2/2)



Iso-surface plots of 1% and 4% vol of hydrogen mole fraction for 2 mm TPRD diameter (left) compared to 0.5 mm diameter (right) for different release direction at 20 s of flow time.

Source: H. Hussein, S. Brennan, V. Molkov. Dispersion of hydrogen release in a naturally ventilated covered car park. Int J Hydrogen Energy, 2020, 45: 23882-23897.

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Tunnel

- Several studies have showed that confinement or congestion can promote more severe consequences compared to the accidents in the open atmosphere.
- A critical analysis of hazards and associated risks relevant to the use of FCH vehicles in the underground transportation systems were performed in the Deliverable 1.2 of HyTunnel-CS project.

1. **Effect of ventilation velocity on dispersion in tunnels**
2. **Deflagration-to-Detonation transition (DDT) in tunnel**

https://hytunnel.net/wordpress/wp-content/uploads/2019/09/HyTunnel-CS_D1.2_Risks-and-Hazards.pdf

Effect of ventilation velocity on dispersion in tunnels

Ventilation strongly influences hazardous gases dispersion. The exact location of vehicles and the geometry of the tunnel can be important because they affect the generated flow field.

The **positive** aspects are:

- it can dilute hydrogen concentrations minimizing the size of the flammable cloud;
- it can safely transport unlimited amount of hydrogen out of the tunnel through its portals and shafts if hydrogen concentration is below LFL.

The **negative** aspects are:

- a flammable could may be extended further away from the release;
- the turbulence may be induced by ventilation which can enhance the combustion rate thus overpressures in case of ignition.

In longitudinal ventilation, a minimum air speed is required to remove the hazardous gas and smoke. For fires in tunnels, the critical velocity is a function of heat release rate. The ventilation velocity value of **3.5 m/s** seems to be sufficient for most tunnel fires to prevent the ‘back-layer’ effect, including large fires of more than 100 MW.

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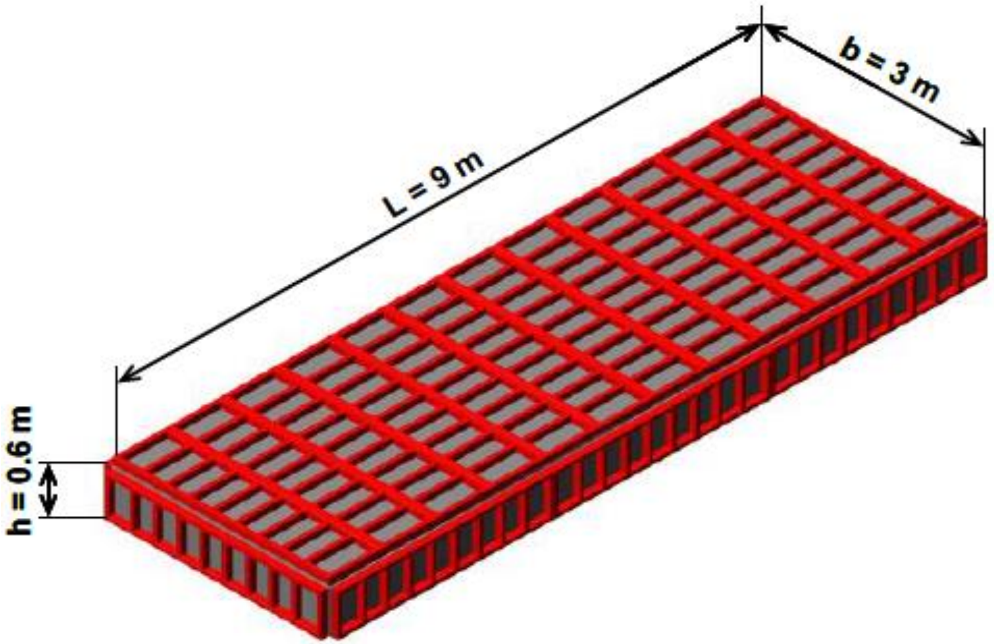
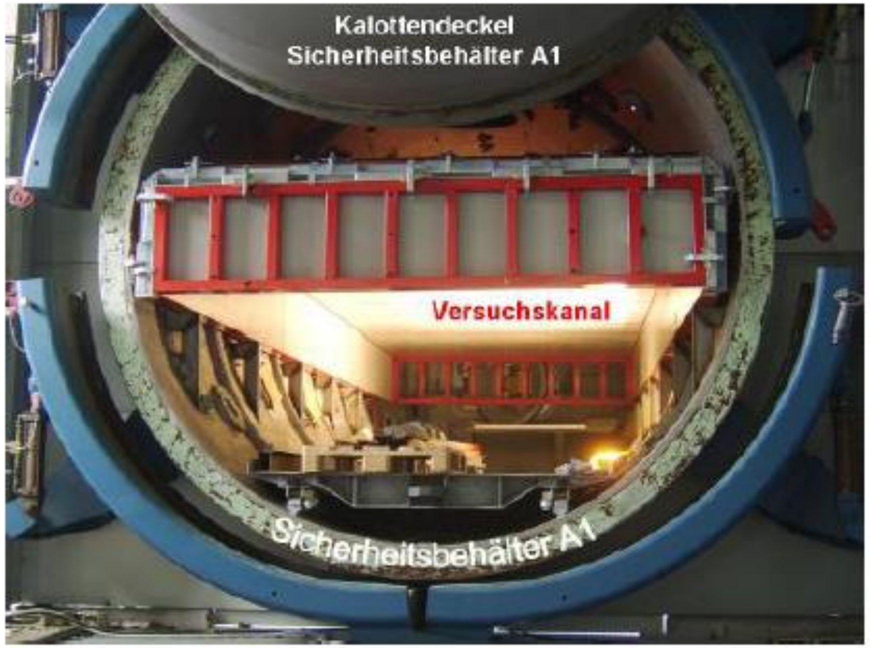
DDT in tunnel (1/3)

Deflagration-to-Detonation transition





Main dimensions of the flat layer box (left) and the thin layer box installed inside the safety vessel (right)

Source: Kuznetsov, M., Grune, J., Friedrich, A., Sempert, K., Breitung, W., Jordan, T. (2011) Hydrogen-air deflagrations and detonations in a semi-confined flat layer. In: Fire and Explosion Hazards, Proceedings of the Sixth International Seminar (Edited by D. Bradley, G. Makhviladze and V. Molkov), 125-136.

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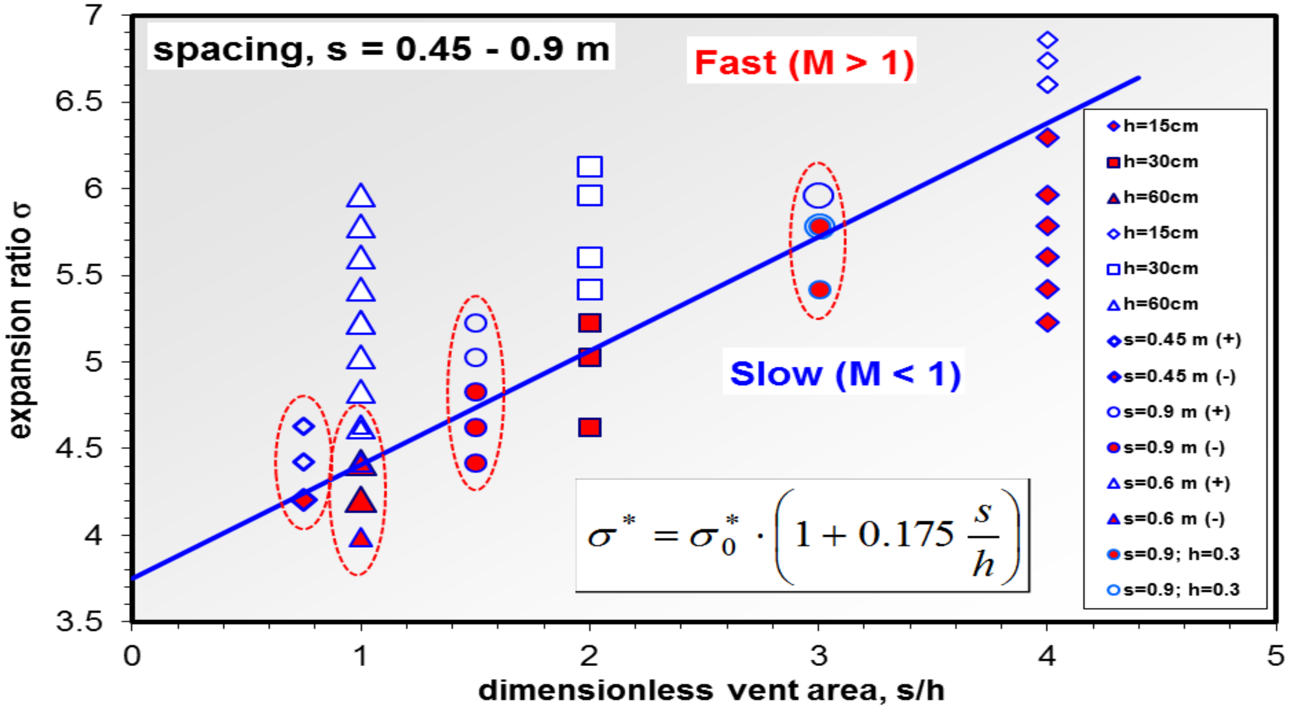
DDT in tunnel (2/3)

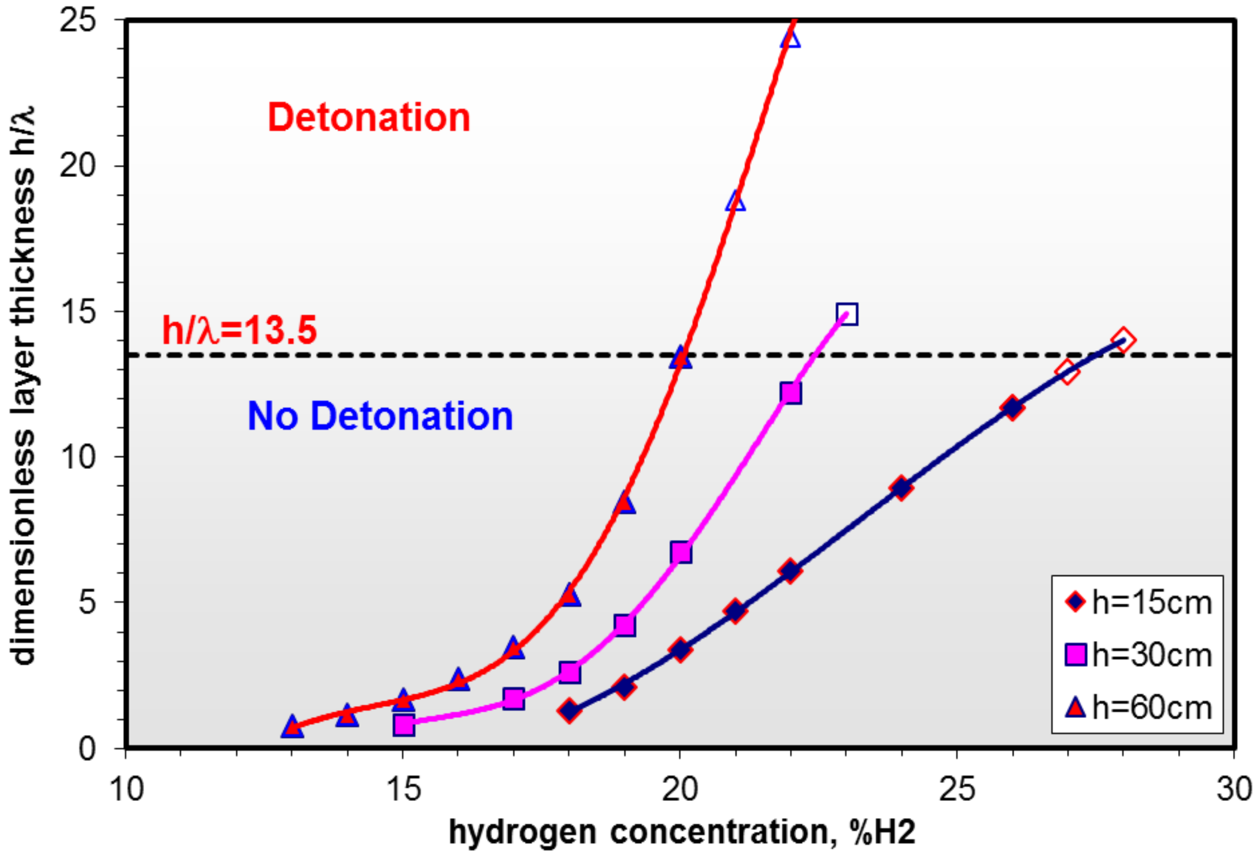


Expansion ratio σ as a function of the dimensionless vent area (defined as the ratio of layer thickness *h* and spacing between obstacles for semi-confined layer *s*)

Critical conditions for an effective flame acceleration as function of expansion ratio vs. dimensionless vent area: sonic flame and detonations (open points), subsonic flame (solid points)

Source: Kuznetsov, M., Grune, J., Friedrich, A., Sempert, K., Breitung, W., Jordan, T. (2011) Hydrogen-air deflagrations and detonations in a semi-confined flat layer. In: Fire and Explosion Hazards, Proceedings of the Sixth International Seminar (Edited by D. Bradley, G. Makhviladze and V. Molkov), 125-136.

DDT in tunnel (3/3)



Critical conditions for DDT in the relationship between the dimensionless layer thickness and hydrogen concentration: detonation (open points); no detonation (solid points)

Source: Kuznetsov, M., Grune, J., Friedrich, A., Sempert, K., Breitung, W., Jordan, T. (2011) Hydrogen-air deflagrations and detonations in a semi-confined flat layer. In: Fire and Explosion Hazards, Proceedings of the Sixth International Seminar (Edited by D. Bradley, G. Makhviladze and V. Molkov), 125-136.

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Hydrogen jet fire indoor

- Important to understand for practical applications.
- Behaviour of fire depends on the release conditions and geometry of an enclosure/ventilation.
- Well-ventilated and under-ventilated fires.

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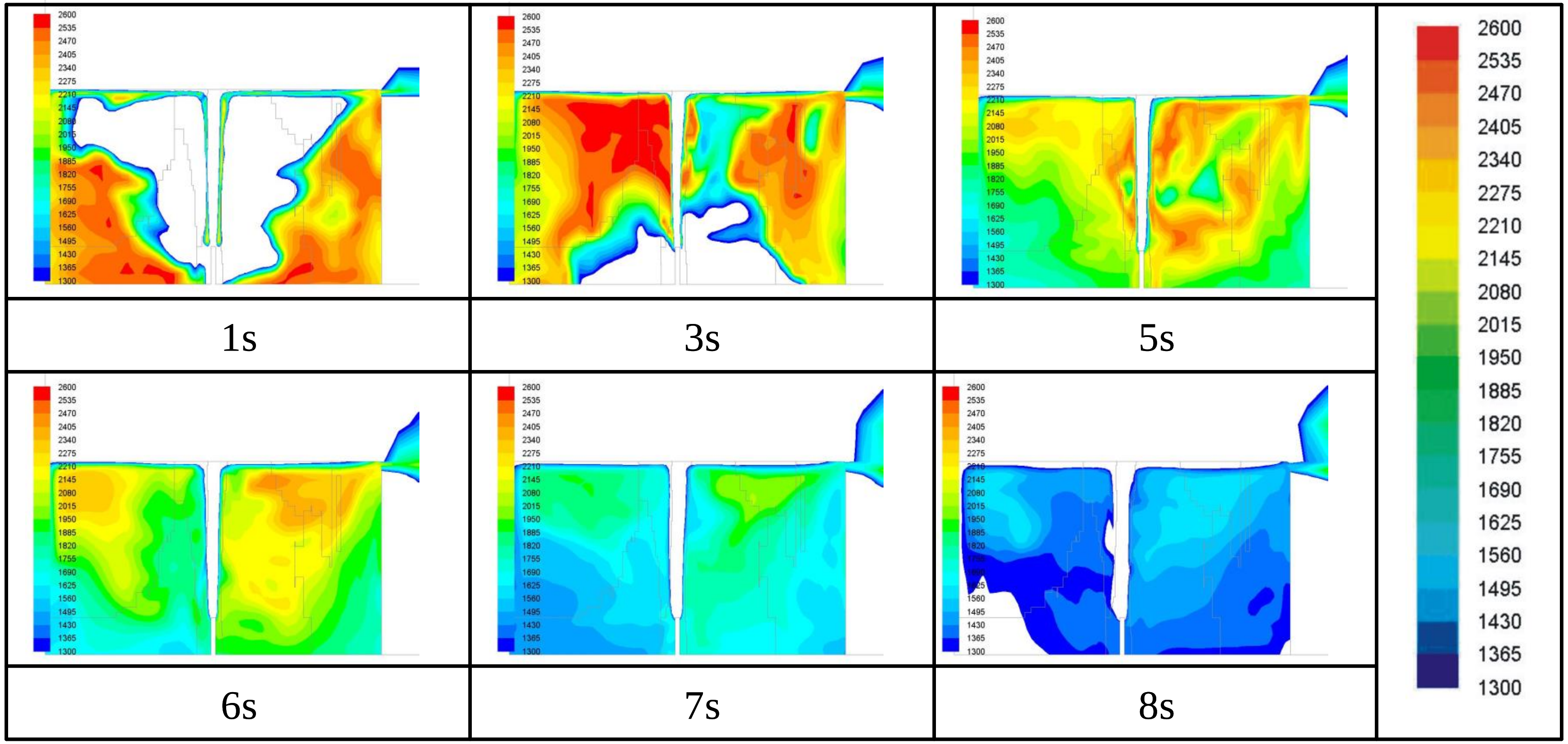
Jet fire from a TPRD of a FC car in a garage

Size of a small garage L × W × H = 4.5 × 2.6 × 2.6 m (with a “brick”-sized vent).
Mass flow rate: **390 g/s (350 bar, *D*=5.08 mm, today cars)**



Two regimes of indoor fires:

- Well-ventilated: sufficient amount of oxygen (from the air) for complete combustion of hydrogen inside an enclosure
- Under-ventilated: insufficient amount of oxygen (from the air) to burn hydrogen completely

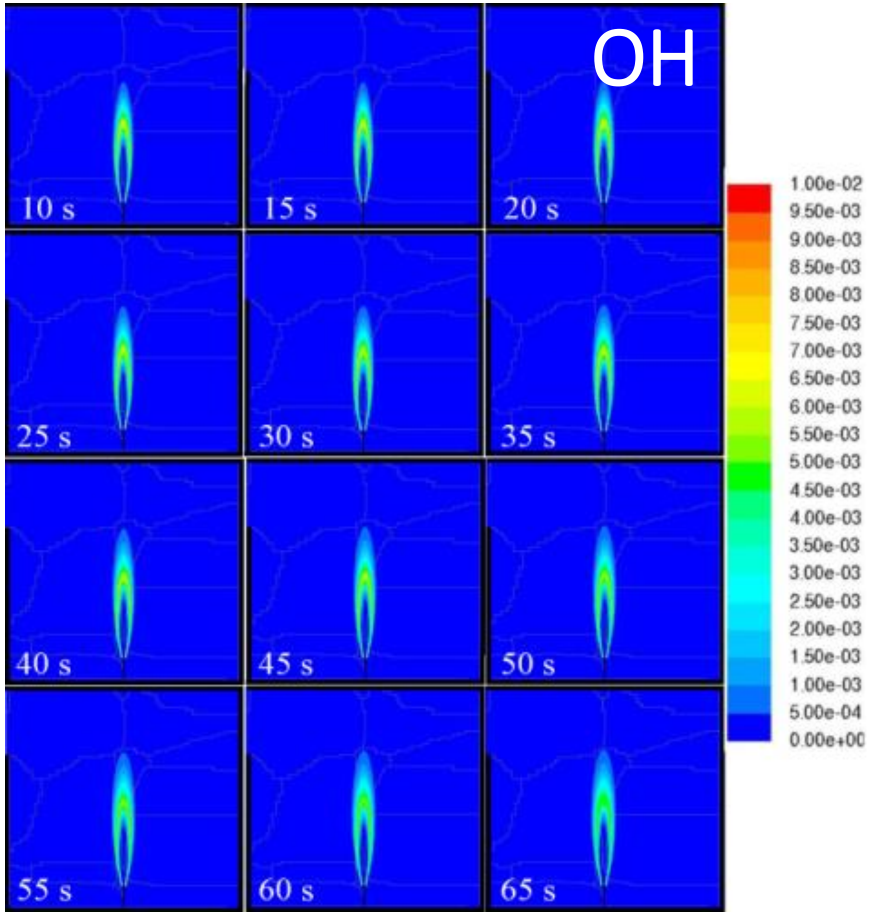
Jet fires: numerical experiments

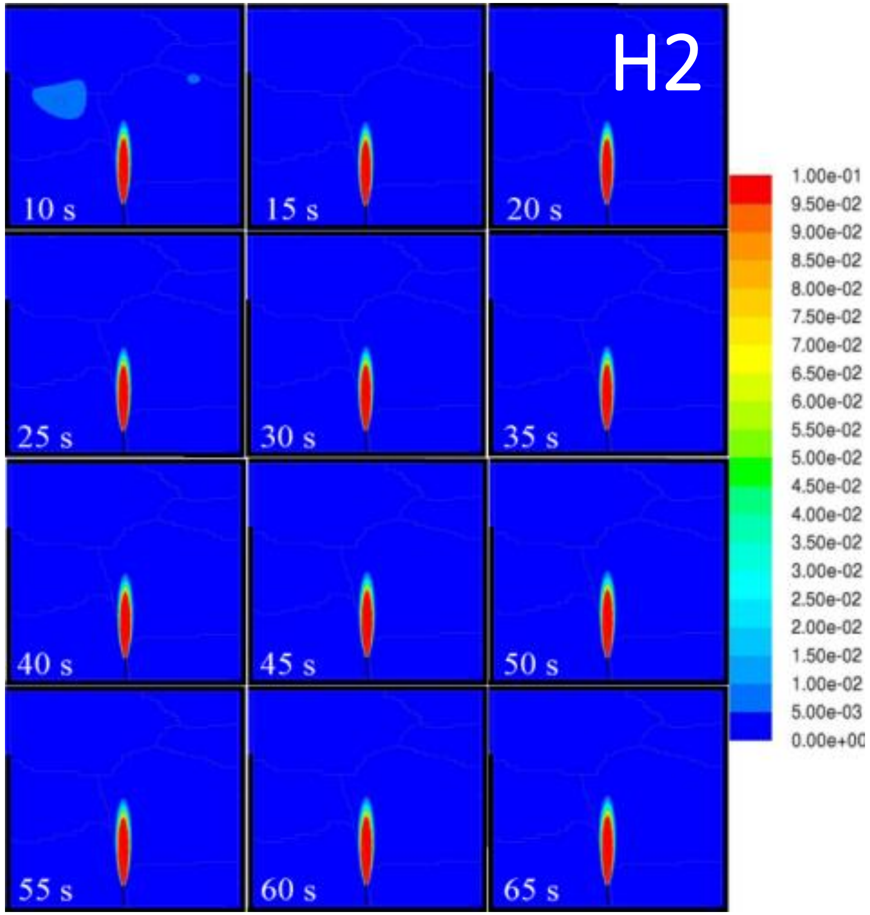
Seven numerical experiments with a single vent were performed (a FC-like enclosure L×W×H=1×1×1 m; vertical upward release of hydrogen from 5 mm pipe with exit 10 cm above the floor centre; a single vent located centrally at the top of one wall):

No.	Vent size, H×W	Velocity, m/s	Flow rate, g/s	Result
1	Horizontal 3x30 cm	600 m/s	1.0857	**Self-extinction**
2	Horizontal 3x30 cm	300 m/s	0.5486	**Self-extinction**
3	Horizontal 3x30 cm	150 m/s	0.2714	**External flame**
4	Vertical 30x3 cm	600 m/s	1.0857	**External flame**
5	Vertical 30x3 cm	60 m/s	0.1086	**Well ventilated**
6	Vertical 13.9x3 cm	600 m/s	1.0857	**Self-extinction**
7	Vertical 13.9x3 cm	300 m/s	0.5486	**External flame**

Well-ventilated fire (1/2)

No.5: vertical vent 30×3 cm; release 60 m/s - 0.11 g/s.





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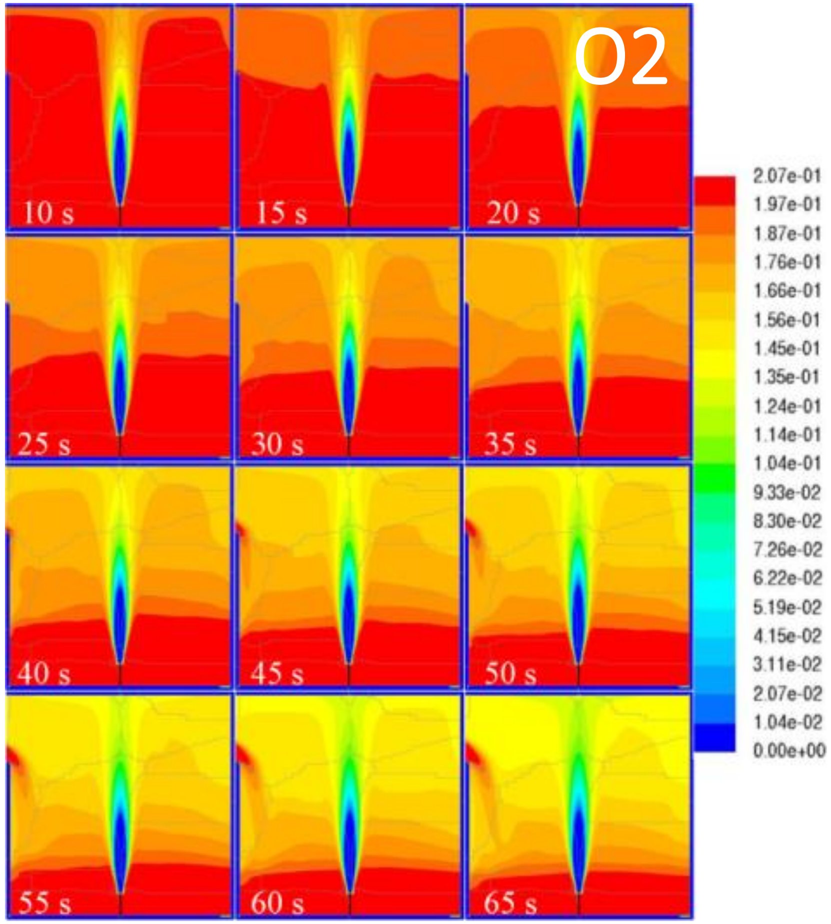
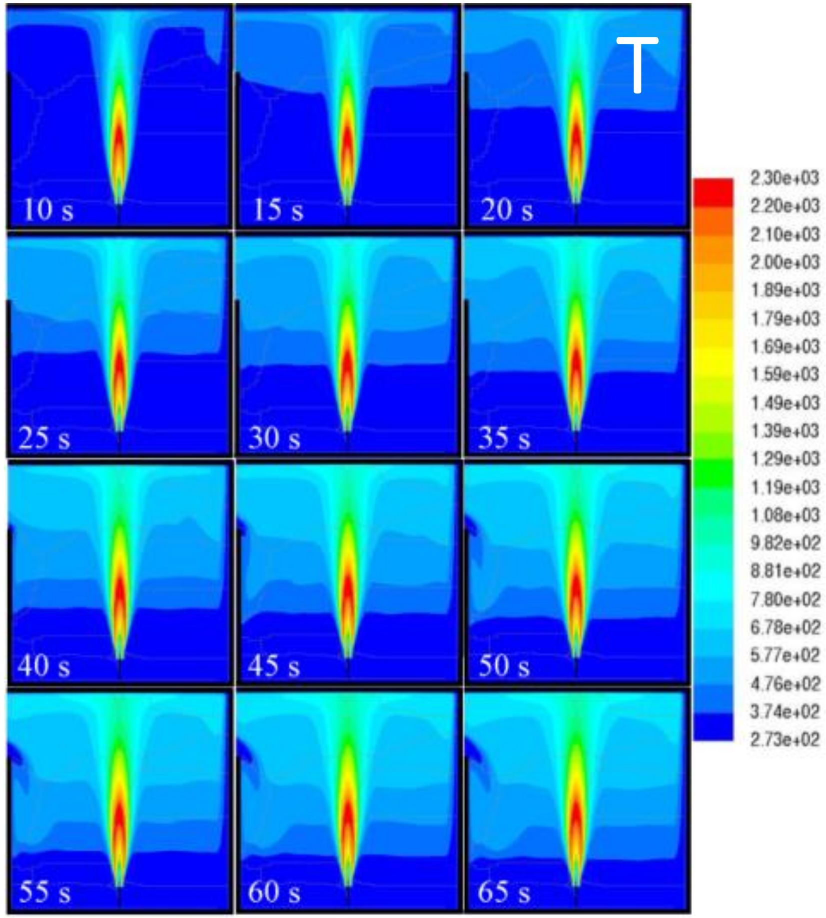
Well-ventilated fire (2/2)

No.5: vertical vent 30 × 3 cm; release 60 m/s - 0.11 g/s.





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Simulation videos

Well-ventilated fire:

No.5 (vertical vent 30×3 cm; release 60 m/s, 0.11 g/s) - OH

No.5 – Temperature (70 C – “no harm” temperature)

Under-ventilated fire (two modes):

Self-extinction mode:

No.6 (vertical vent 13.9×3 cm, 600 m/s) – Temperature

No.6 – OH

External flame mode:

No.7 (vertical vent 13.9×3 cm, 300 m/s) – OH

No.4 (vertical vent 30×3 cm, 600 m/s) – Temperature

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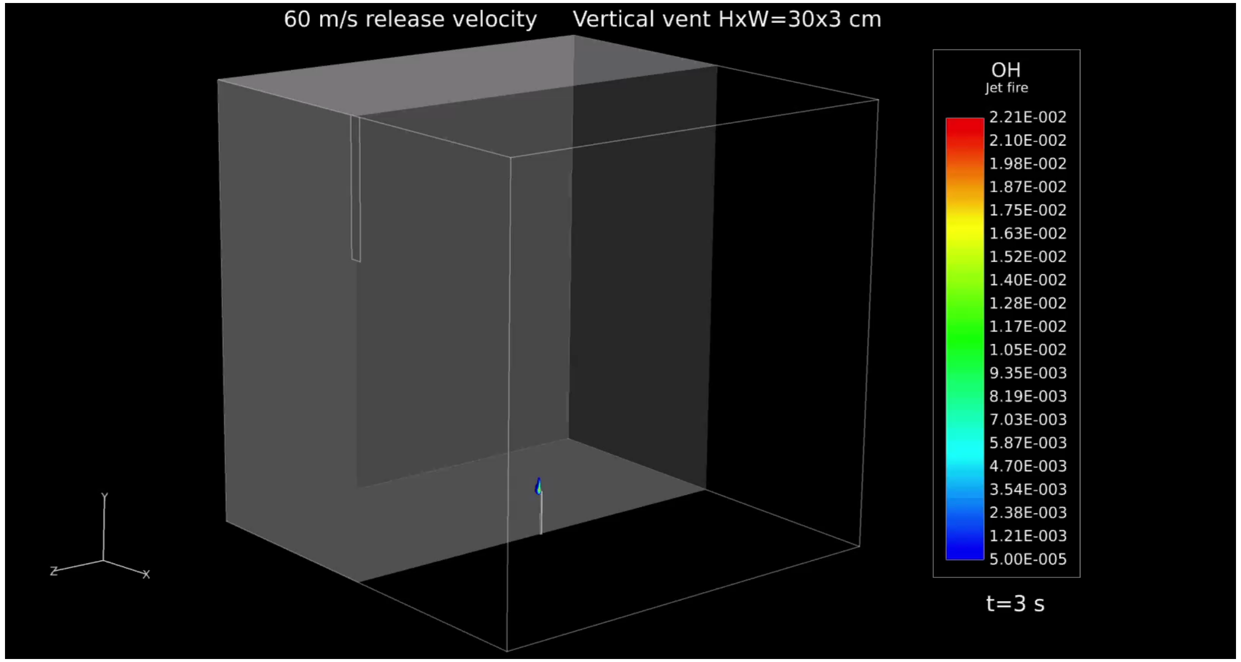
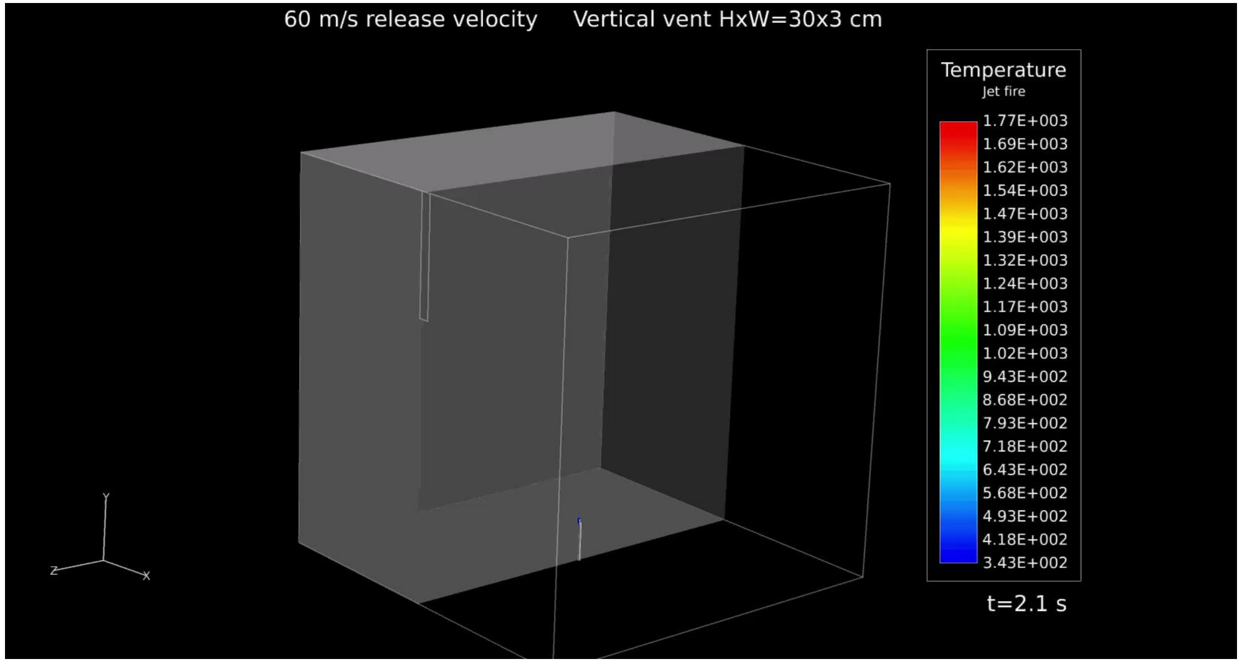
Simulation videos - Well-ventilated fire

- No.5 (vertical vent 30×3 cm; release 60 m/s, 0.11 g/s) - OH



https://www.youtube.com/watch?v=r-5BiBEd3So&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=16

- No.5 – Temperature (70 C – "no harm" temperature)



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

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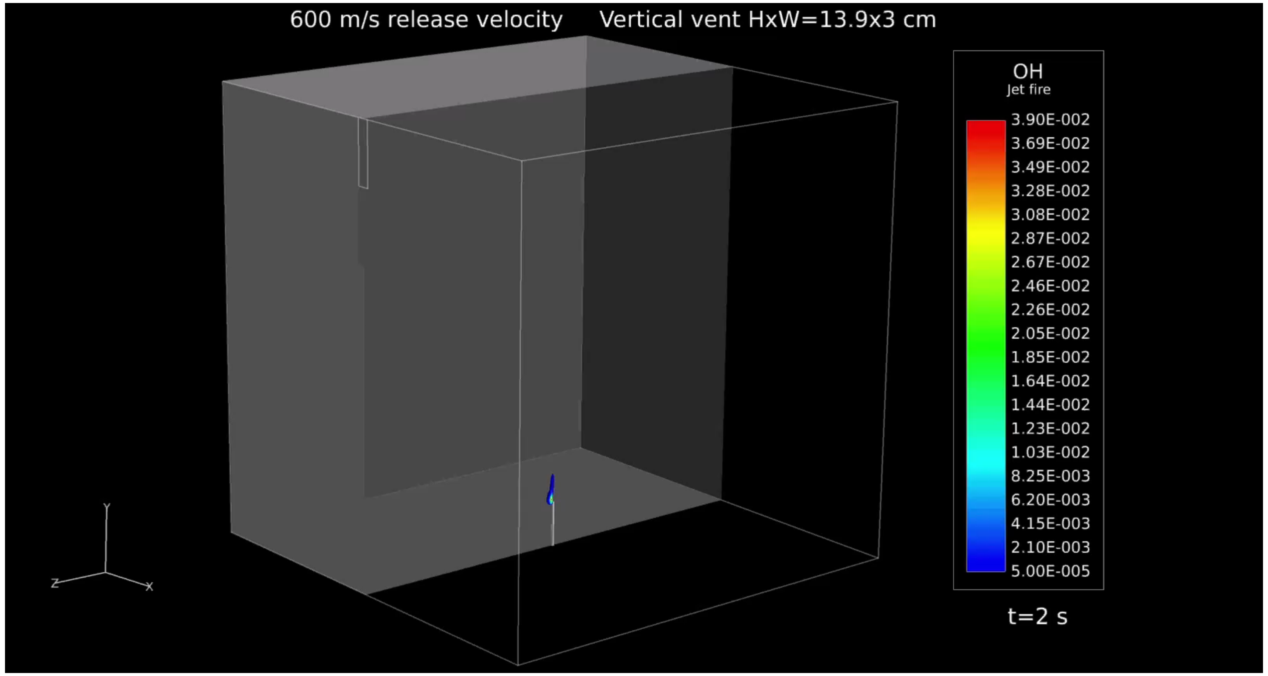
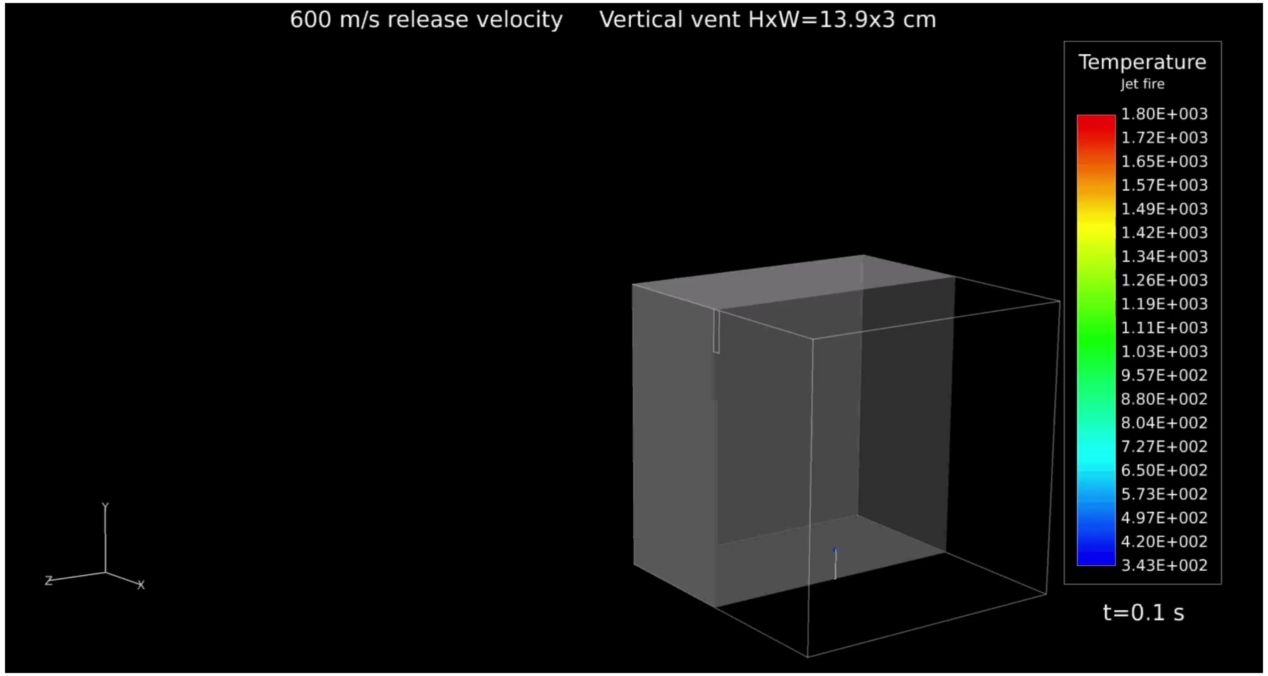
Simulation videos - Under-ventilated fire (1/2)

Self-extinction mode:
No.6 – OH

No.6 (vertical vent 13.9×3 cm, 600 m/s) – Temperature





https://www.youtube.com/watch?v=1IyOym8dZLA&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=14

https://www.youtube.com/watch?v=R26jKam0Ug0&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=13

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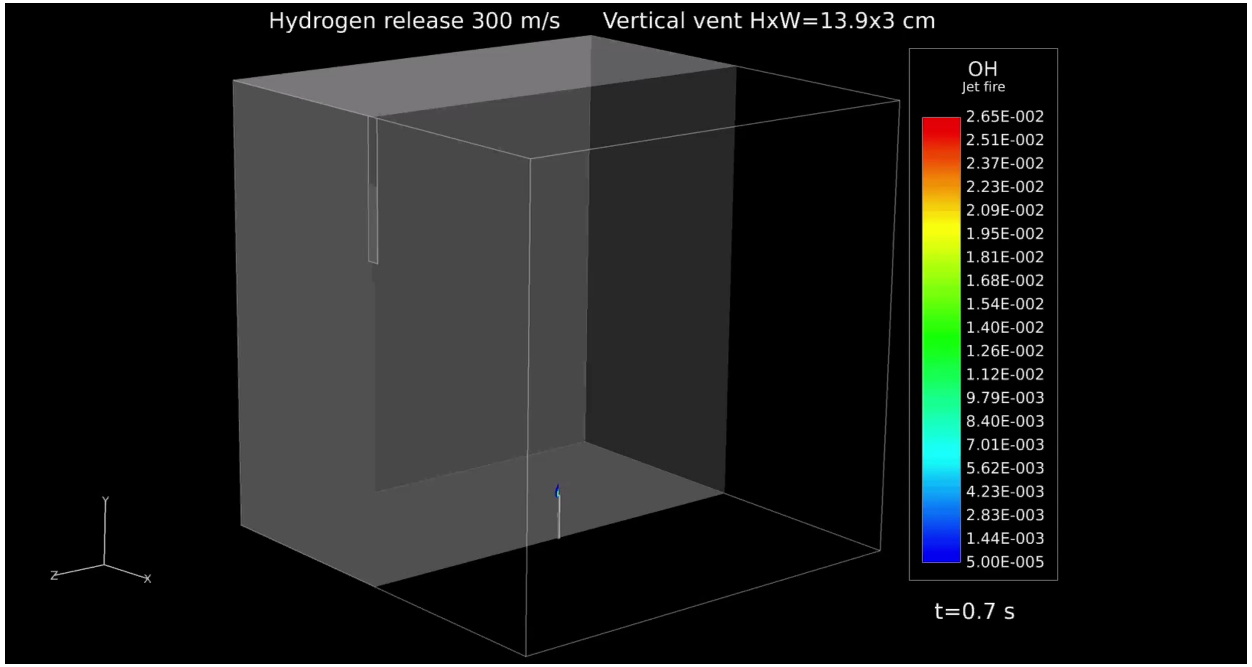
Simulation videos - Under-ventilated fire (2/2)

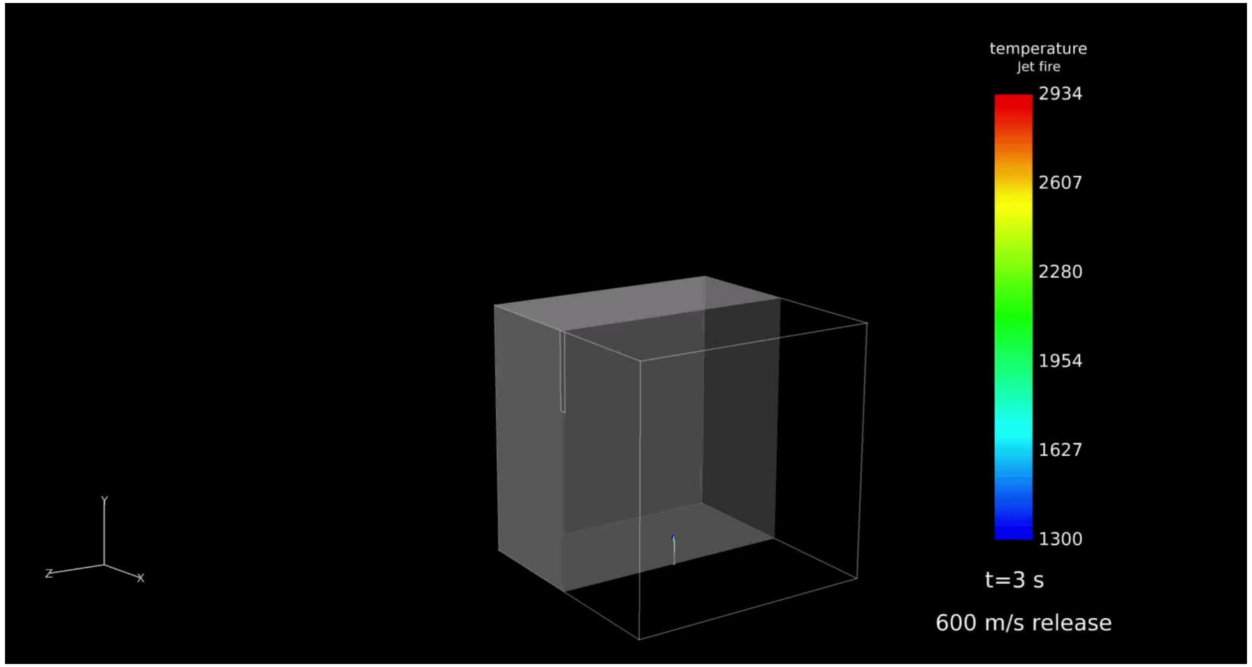
External flame mode:

No.7 (vertical vent 13.9×3 cm, 300 m/s) – OH



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

No.4 (vertical vent 30×3 cm, 600 m/s) – Temperature



https://www.youtube.com/watch?v=CA2Tkn81Du8&list=PLlphoM9ggM3Rf-Npmdq0S3WrCSpx0U4SL&index=17

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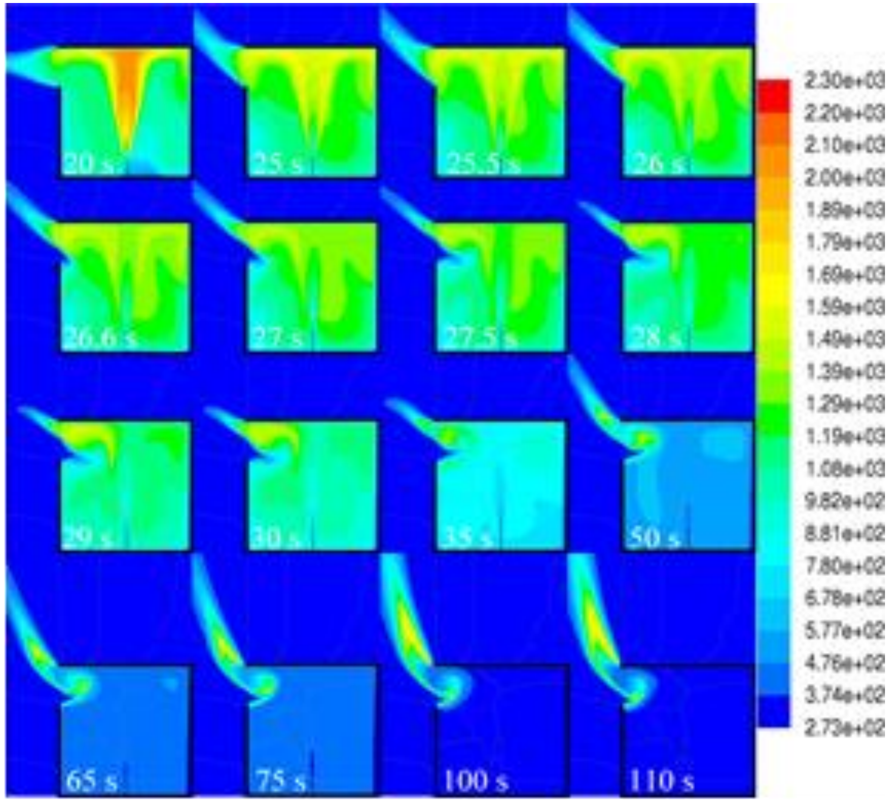
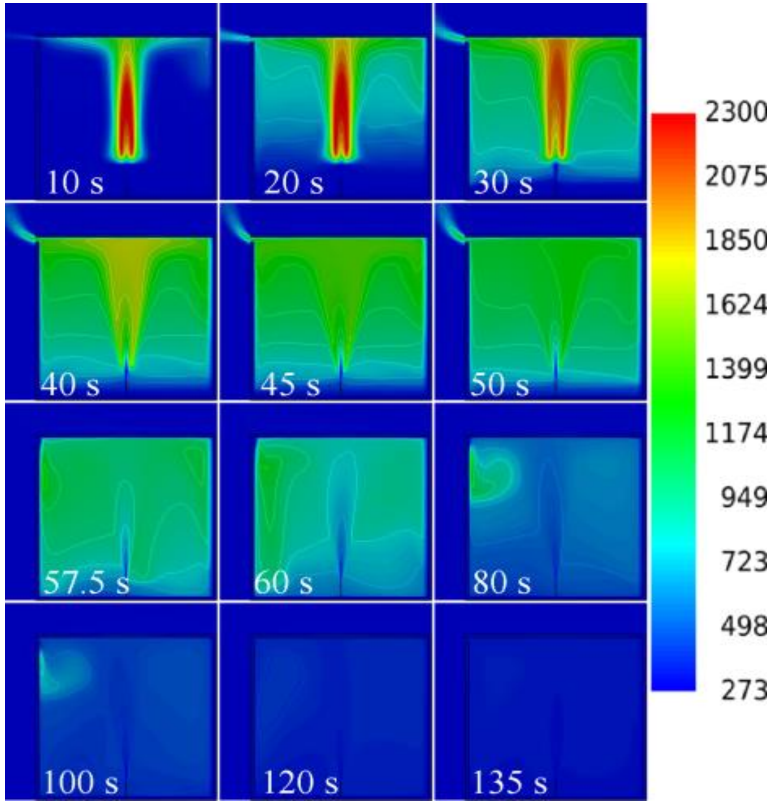
Why two modes?

External flame (No.4)



Vertical 30x3 cm	600 m/s

Self-extinction (No.2)



Horizontal 3x30 cm	300 m/s

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Self-extinction of jet fire in a 1 m^3 box

- Calculation domain hexahedron; L×W×H=7×6×4 m.
- Cubical enclosure L×W×H=1×1×1m.
- One horizontal vent H×W=0.03x0.3 m under the ceiling ("tracer box"). The vent size is calculated to ensure no air ingress after self-extinction, and that pressure peaking (unignited) is below 1 kPa.
- Mass flow rate 1 g/s (50 kW fuel cell).
- Release from a pipe of 5.08 mm diameter located 10cm above the floor.
- Box has aluminium walls of thickness 20 mm

Hydrogen indoor fire regimes

The general rule for indoor fire with one upper vent is as follows. The increase of hydrogen release flow rate changes fire regime from:

- well-ventilated fire (small leak rates), to
- under-ventilated fire with external flame (moderate flow rates), to
- under-ventilated fire with self-extinction of combustion (higher flow rates), and again to
- under-ventilated fire with external flame (very high flow rates)

Vented deflagrations

- Vented deflagration is based on a limiting of pressure build-up within an enclosure through the release of burned and unburned mixtures through a vent.
- If no venting is provided, the maximum pressures developed during the deflagration are typically 6 to 10 times higher than the initial absolute pressure.
- This is the most effective mitigation techniques for deflagrations. It is discussed in more detail in the Lecture ‘Dealing with hydrogen explosions’.

Confined space

Overlooked safety issue

- **Problem**: Hydrogen-powered car is in a **closed garage** of 44 m^3 free volume. Release from an onboard storage through a TPRD of 5.08 mm diameter at pressure 350 bar gives mass flow rate 390 g/s (volumetric flow rate is 390/2*0.0224 = **4.4 m^3/s**).
- **Consequences**: Every second of non-reacting release, pressure in the garage will increase by (44+4.4)/44=1.1 times, i.e. on 10 kPa. Civil building structures can withstand 10-20 kPa.
  Thus, in 1-2 s the garage "is gone".

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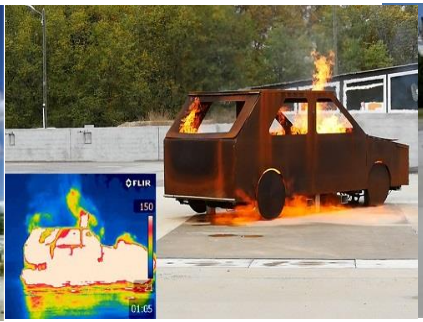


European Hydrogen Train the Trainer Programme for Responders