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Regimes of indoor hydrogen jet fire and pressure peaking phenomenon for jet fires

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Outline

- Hydrogen jet-fires and CFD model
- Numerical study of jet fires in enclosure:
    - Well ventilated fire
    - Under ventilated fire regimes:
        - self-extinction
        - external flame
        - transitional
        - micro combustion
- Pressure peaking phenomenon for jet fires

Two regimes of indoor fire exist (one vent):

- Well-ventilated (complete combustion of hydrogen inside)
- Under-ventilated (insufficient air to completely burn H2)

Advanced CFD model (chemistry at large scales):

- The Reynolds averaged Navier-Stokes (RANS) CFD model.
- The renormalization group k-ε turbulence model (Y&O).
- The eddy dissipation concept (EDC) combustion model (Magnussen et al.).
- The 18-step chemical reaction mechanism of hydrogen combustion in air with 8 species (Peters & Rogg).
- The in-situ adaptive tabulation (ISAT) algorithm accelerating chemistry calculations by 2-3 orders of magnitude (Pope).

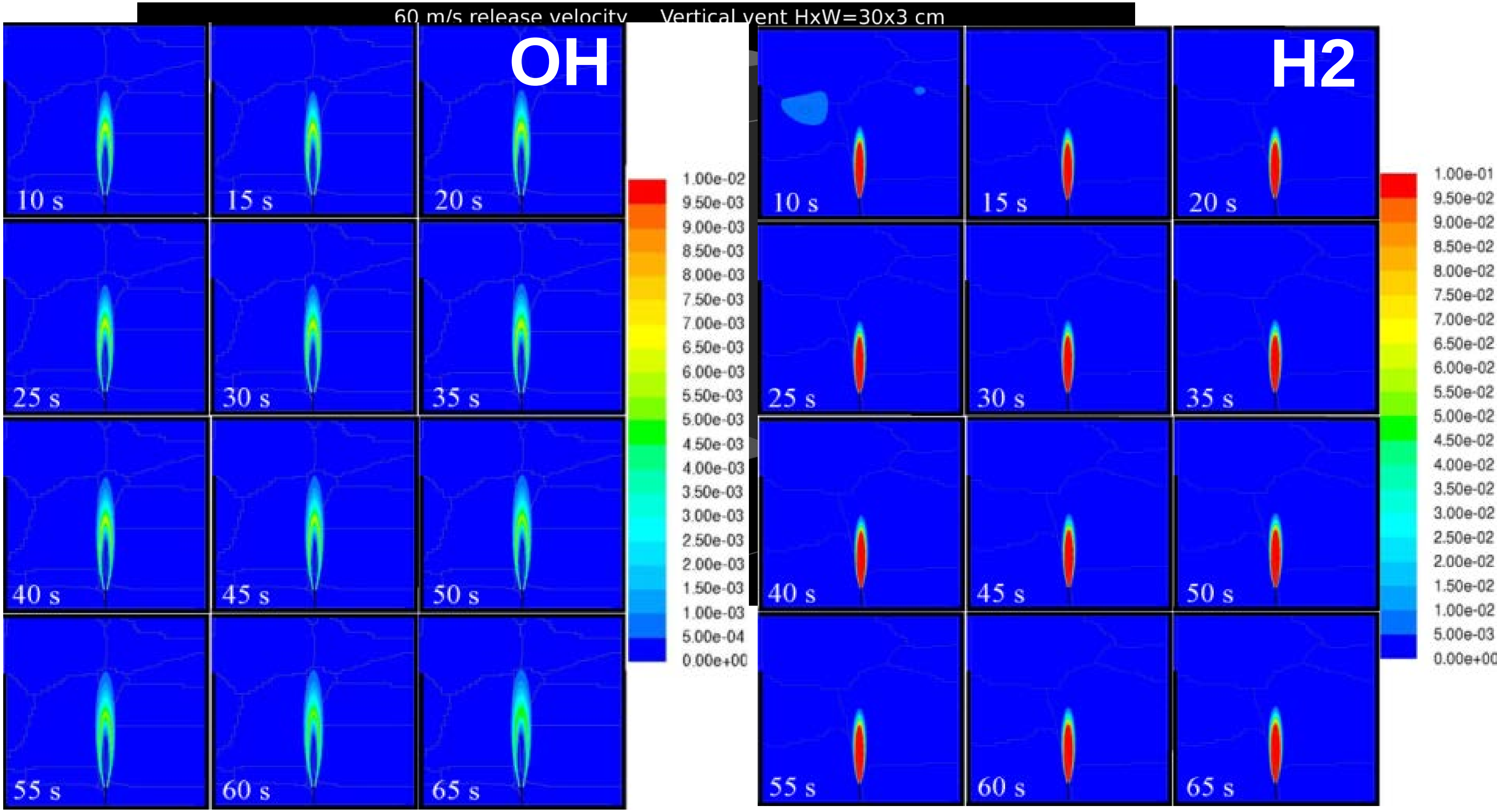
Numerical experiments

Thirteen numerical experiments with a single and double vents were performed (fuel cell like enclosure *LxWxH*=1x1x1 m; vertical upward release of H2 from either 5 or 20 mm pipe with exit 10 cm above the floor centre; vents located centrally at the top and bottom of one wall):

No.	Vent size, HxW	Velocity, m/s	Flow rate, g/s	Fire regime
1	Horizontal 3x30 cm (5 mm)	600 m/s	1.0857	Self-extinction
2	Horizontal 3x30 cm (5 mm)	300 m/s	0.5486	Self-extinction
3	Horizontal 3x30 cm (5 mm)	150 m/s	0.2714	External flame
4	Vertical 30x3 cm (5 mm)	600 m/s	1.0857	External flame
5	Vertical 30x3 cm (5 mm)	60 m/s	0.1086	Well ventilated
6	Vertical 13.9x3 cm (5 mm)	600 m/s	1.0857	Self-extinction
7	Vertical 13.9x3 cm (5 mm)	300 m/s	0.5486	External flame
8	Vertical 13.9x3 cm (20 mm)	75 m/s	2.0895	External flame
9	Vertical 13.9x3 cm (20 mm)	600 m/s	16.7	External flame
10	2 vents 3x15 cm (5 mm)	60 m/s	0.1086 g/s	Well ventilated
11	2 vents 3x15 cm (5 mm)	150 m/s	0.2714 g/s	Transitional
12	2 vents 3x15 cm (5 mm)	300 m/s	0.5486 g/s	Micro-combustion
13	2 vents 3x15 cm (5 mm)	600 m/s	1.0857 g/s	External flame

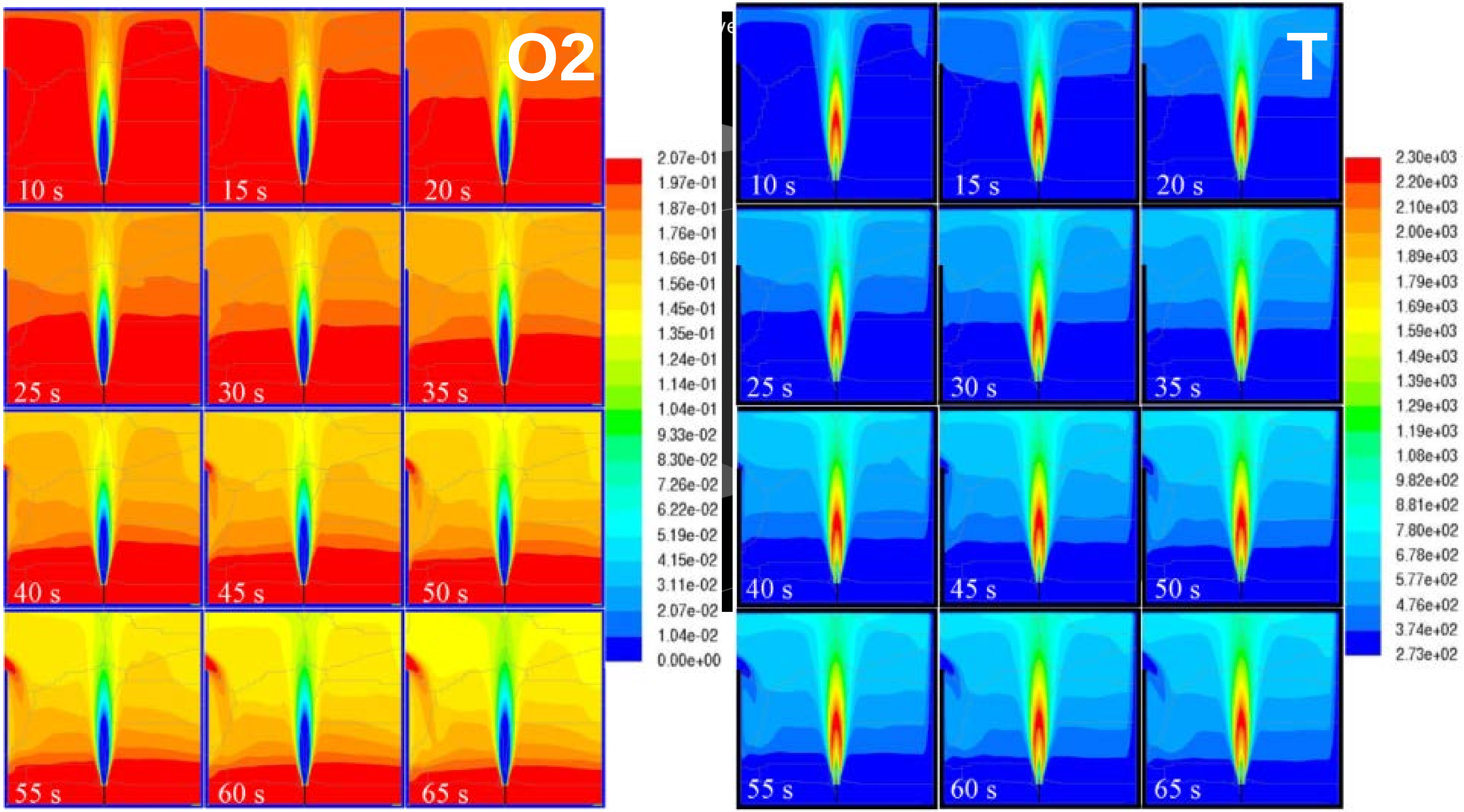
Well-ventilated fire (1 vent) 1/3

No.5: vertical vent 30x3 cm; release 60 m/s - 0.11 g/s.



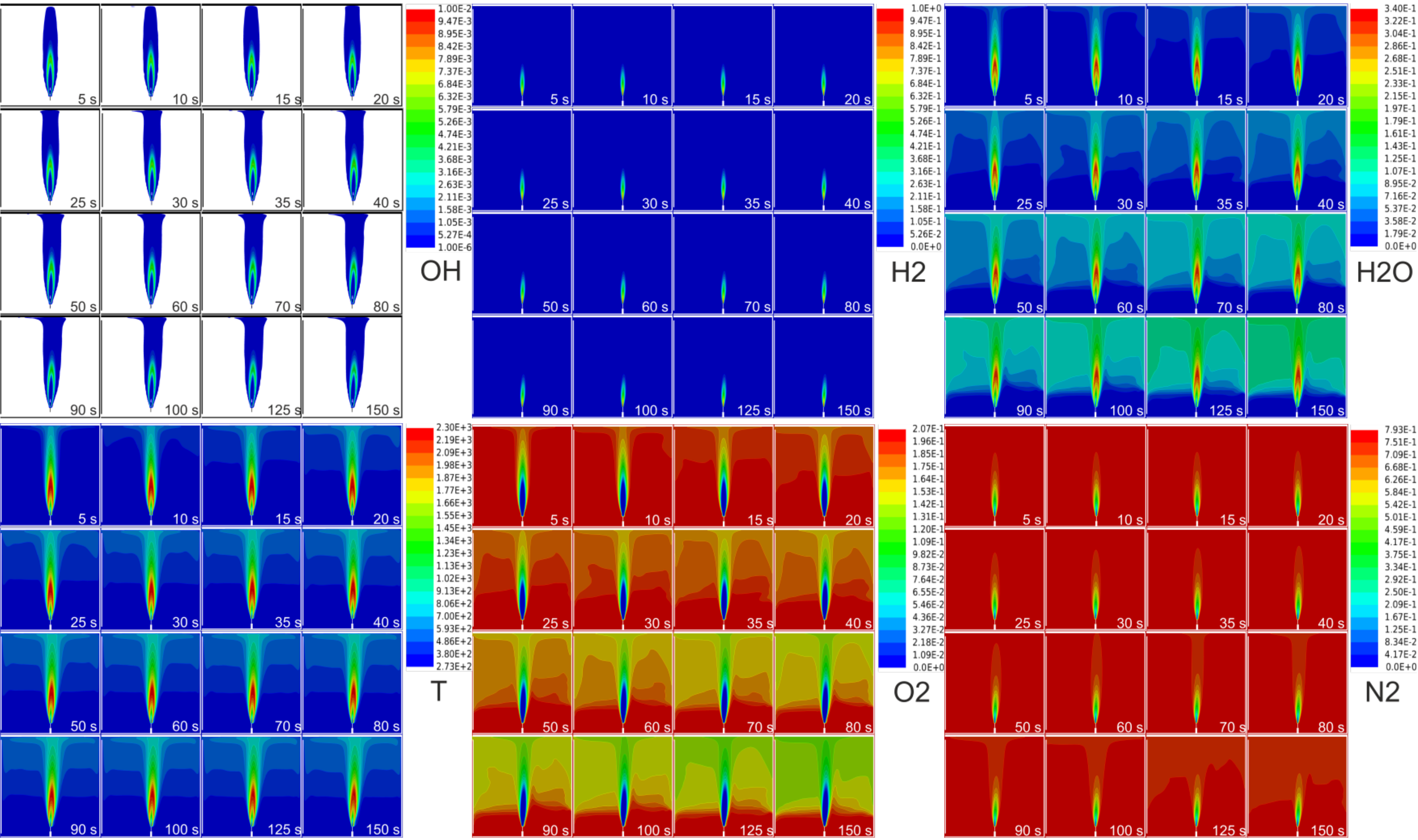
Well-ventilated fire (1 vent) 2/3

No.5: vertical vent 30x3 cm; release 60 m/s - 0.11 g/s.



Well-ventilated fire (2 vents) 3/3

No.9: 2 vents 3x15 cm; release 60 m/s - 0.11 g/s.

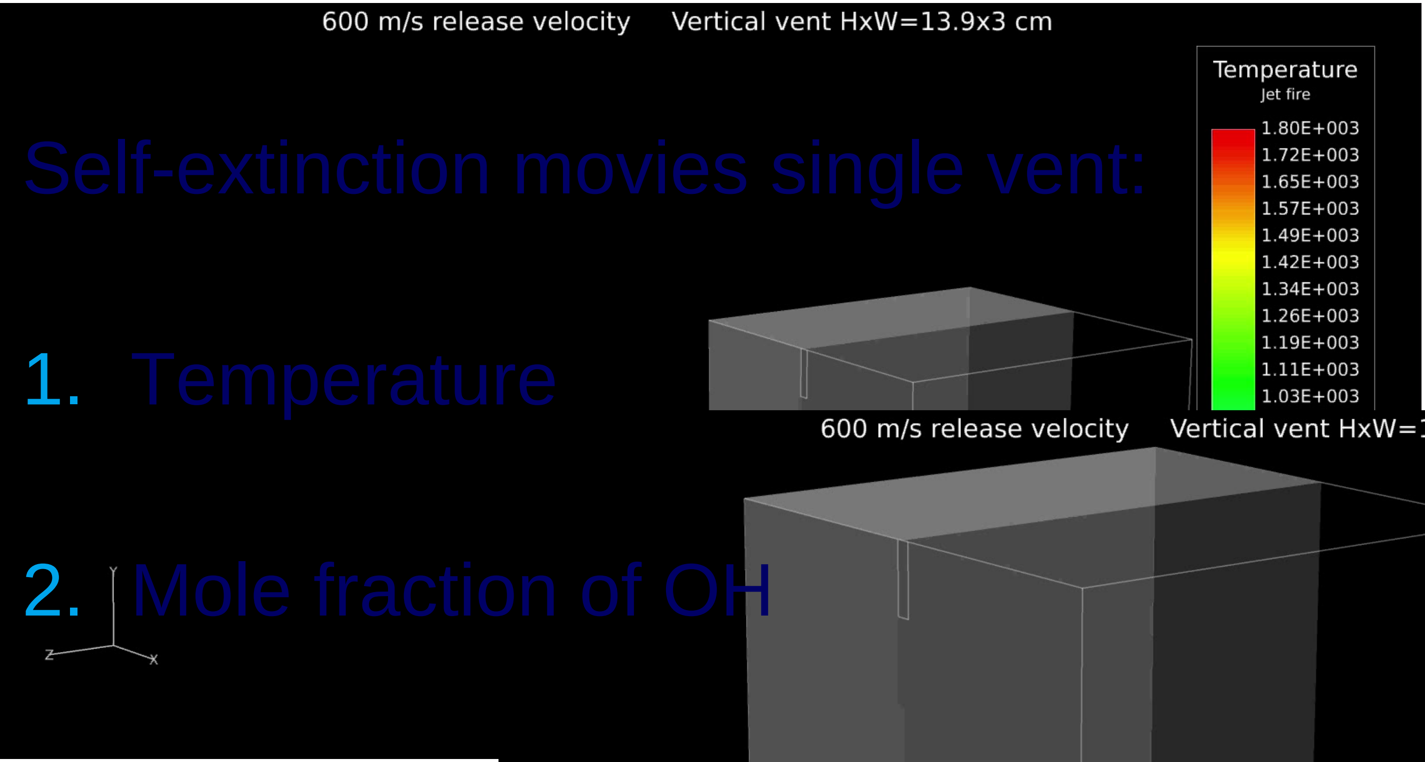


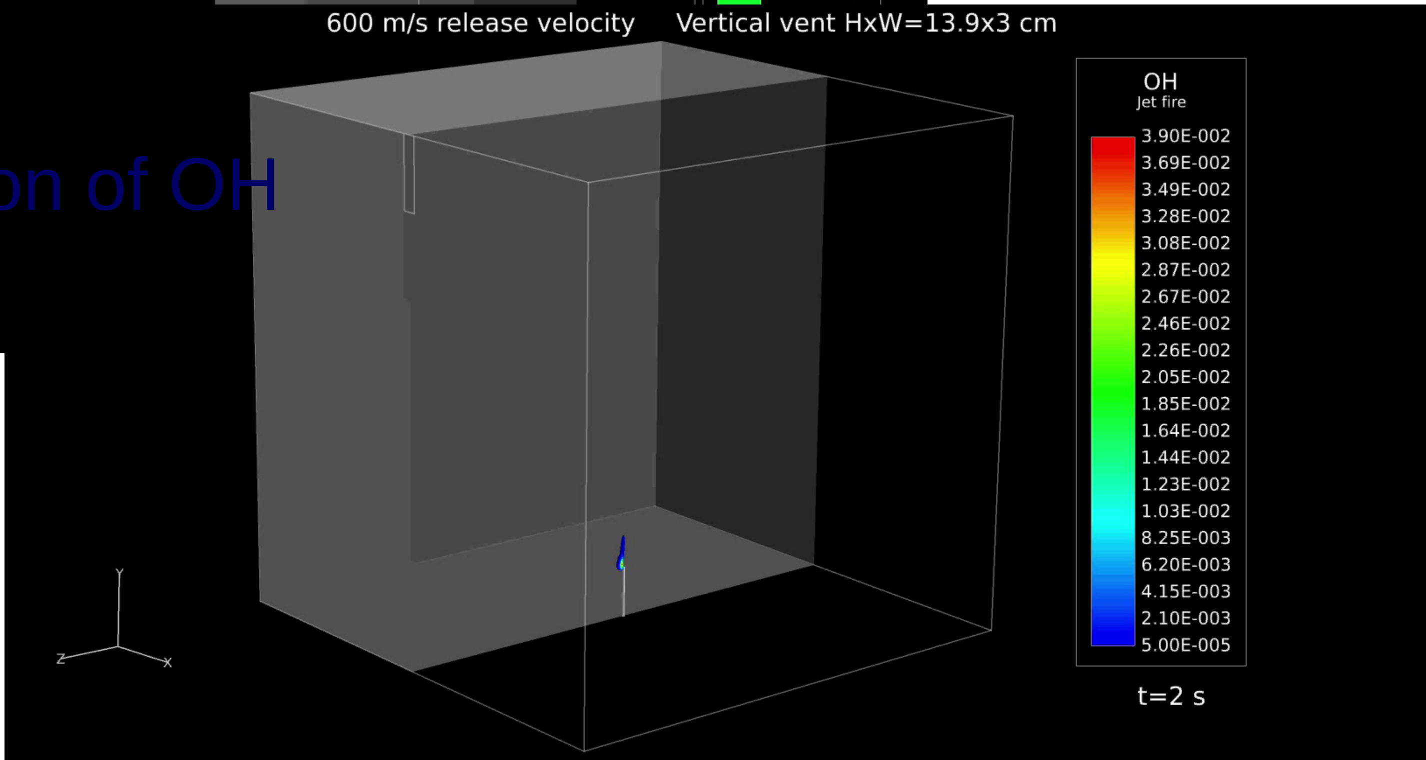
Under-ventilated: self-extinction

No.6: Vertical vent 13.9x3 cm; release 600 m/s - 1.09 g/s

Self-extinction movies single vent:

1. Temperature
2. Mole fraction of OH

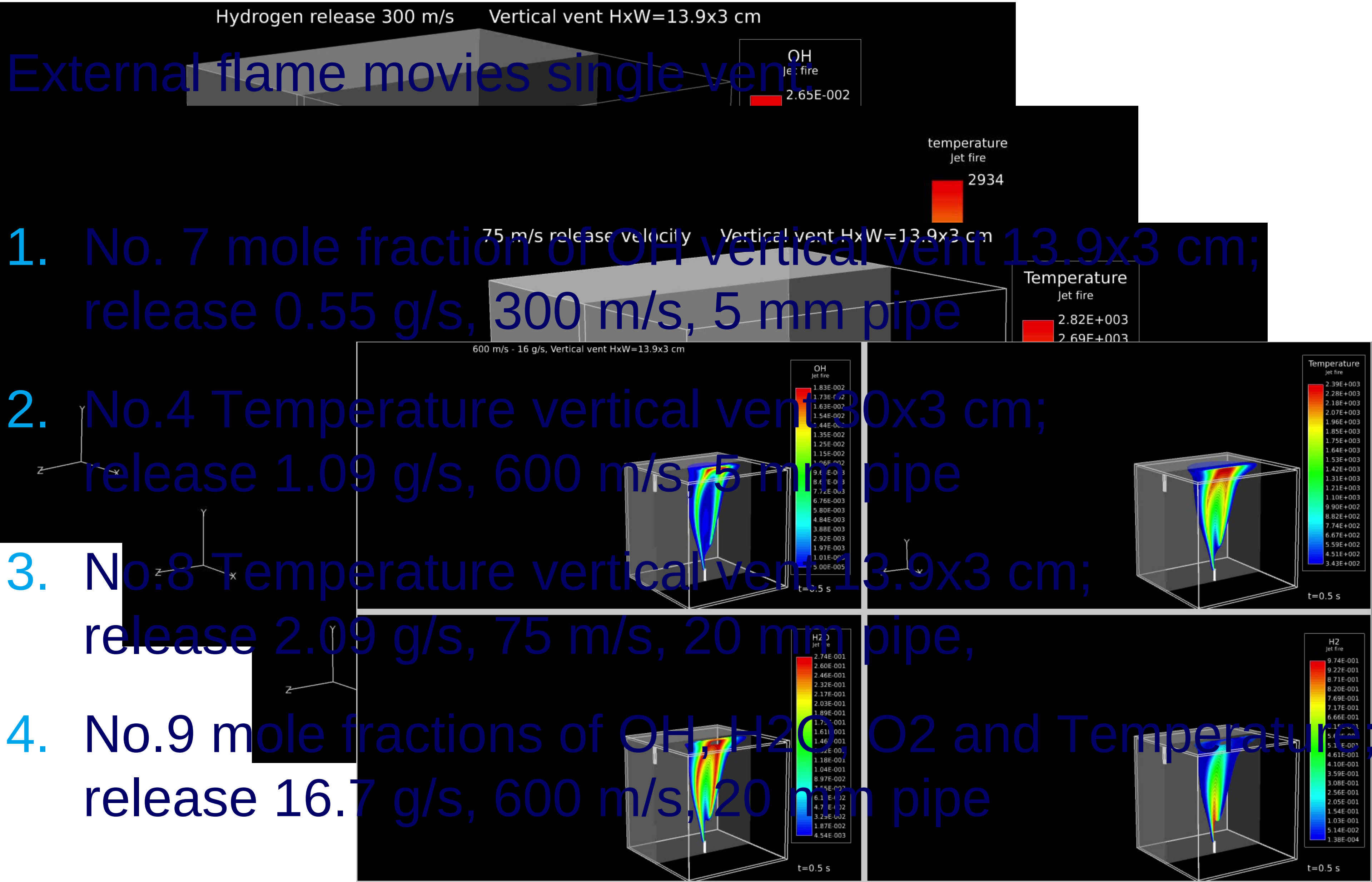




Under-ventilated: external flame, 1 vent

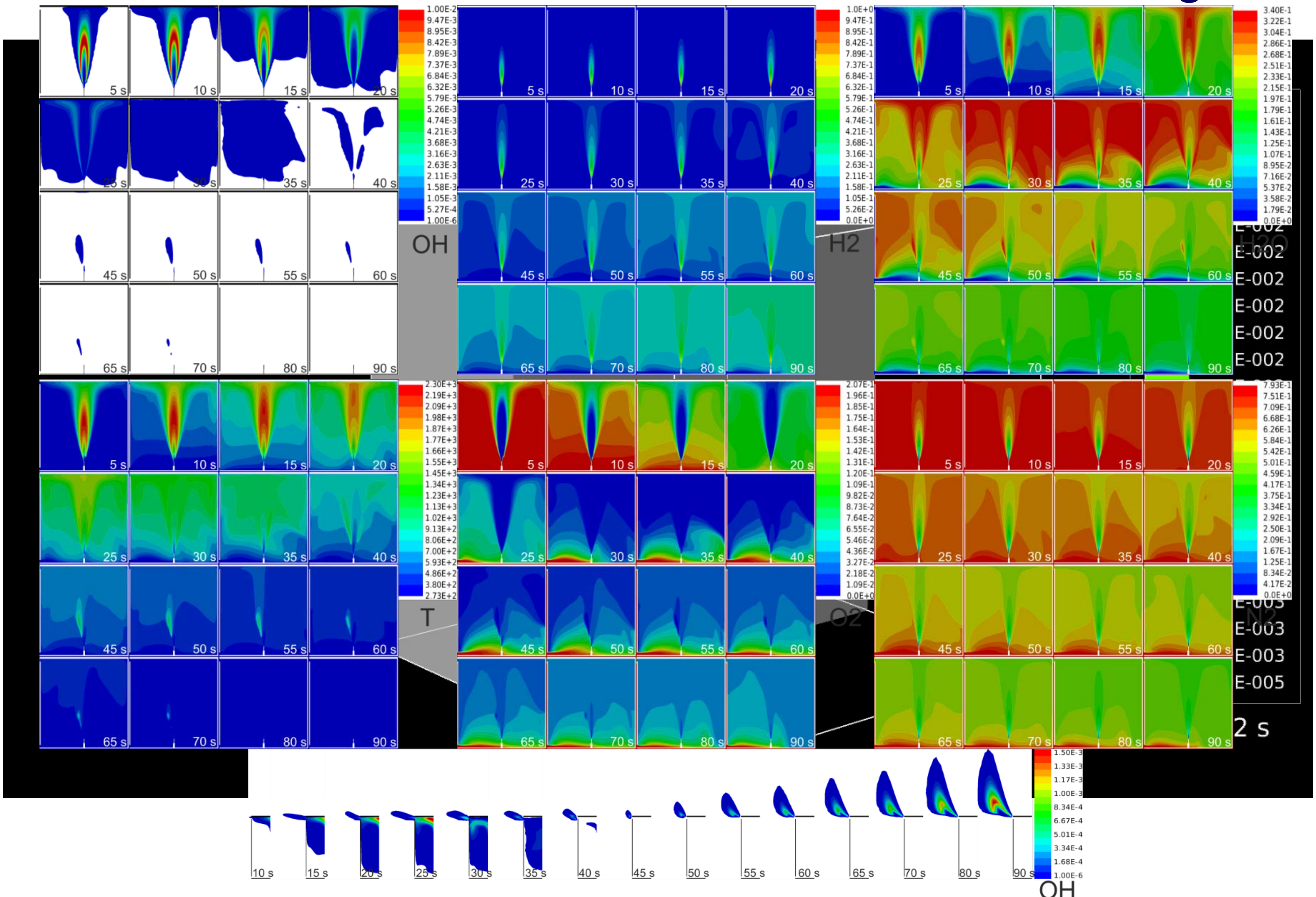
External flame movies single vent:

1. No. 7 mole fraction of OH vertical vent 13.9x3 cm; release 0.55 g/s, 300 m/s, 5 mm pipe
2. No.4 Temperature vertical vent 30x3 cm; release 1.09 g/s, 600 m/s, 5 mm pipe
3. No.8 Temperature vertical vent 13.9x3 cm; release 2.09 g/s, 75 m/s, 20 mm pipe,
4. No.9 mole fractions of OH, H_2O, O_2 and Temperature; release 16.7 g/s, 600 m/s, 20 mm pipe



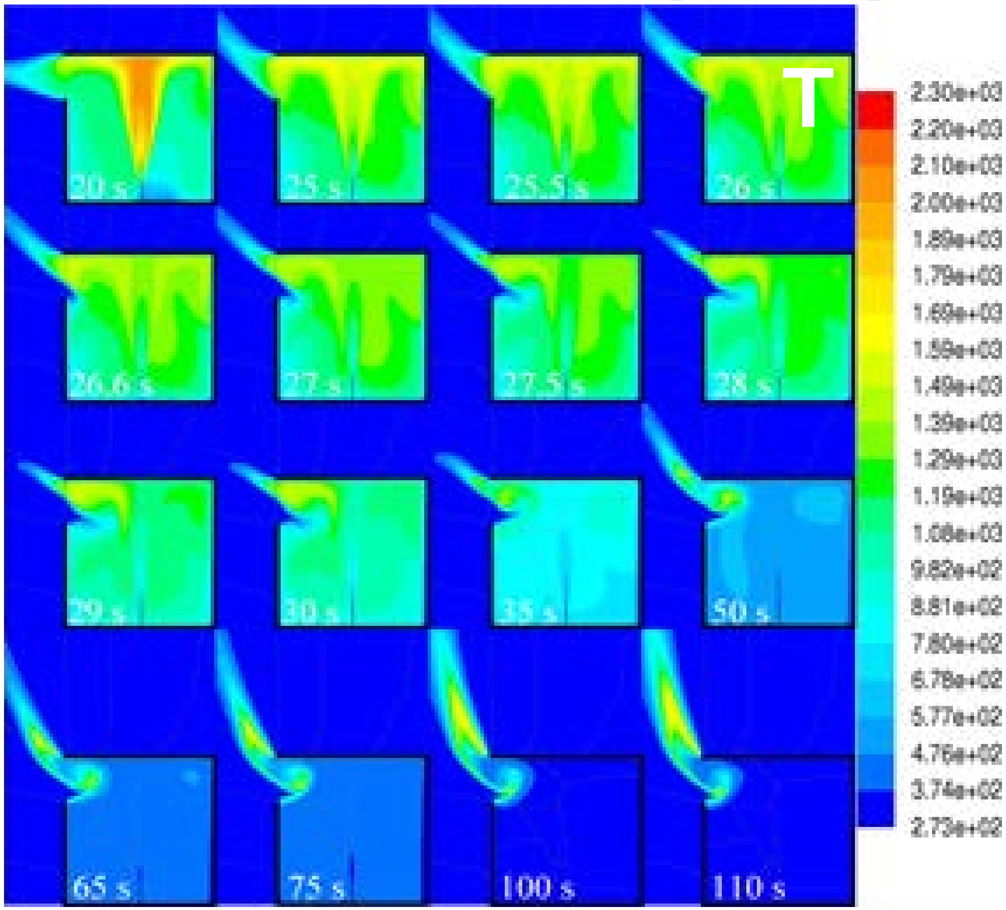
Under-ventilated: external flame, 2 vents

No.13: 2 vents 3x15 cm; release 600 m/s - 1.09 g/s.



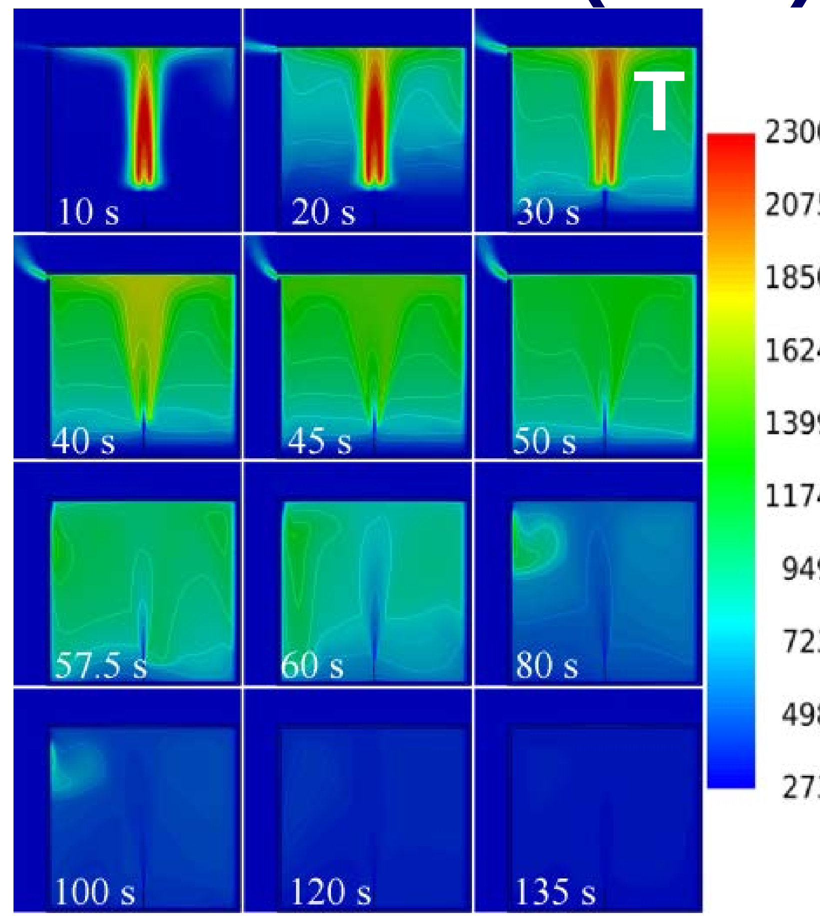
Why two modes (1 vent)?

External flame (No.4)



Vertical 30x3 cm	600 m/s

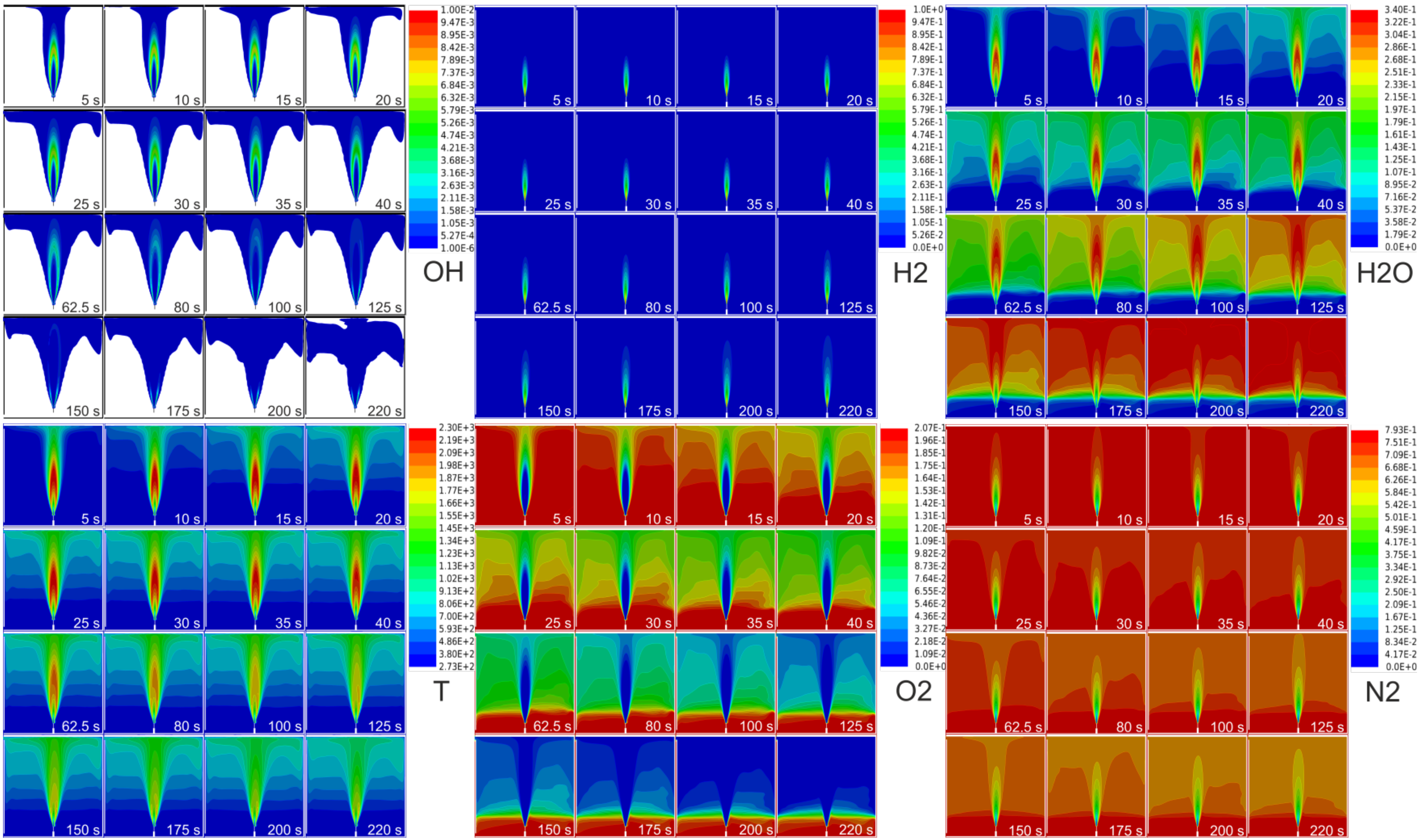
Self-extinction (No.2)



Horizontal 3x30 cm	300 m/s

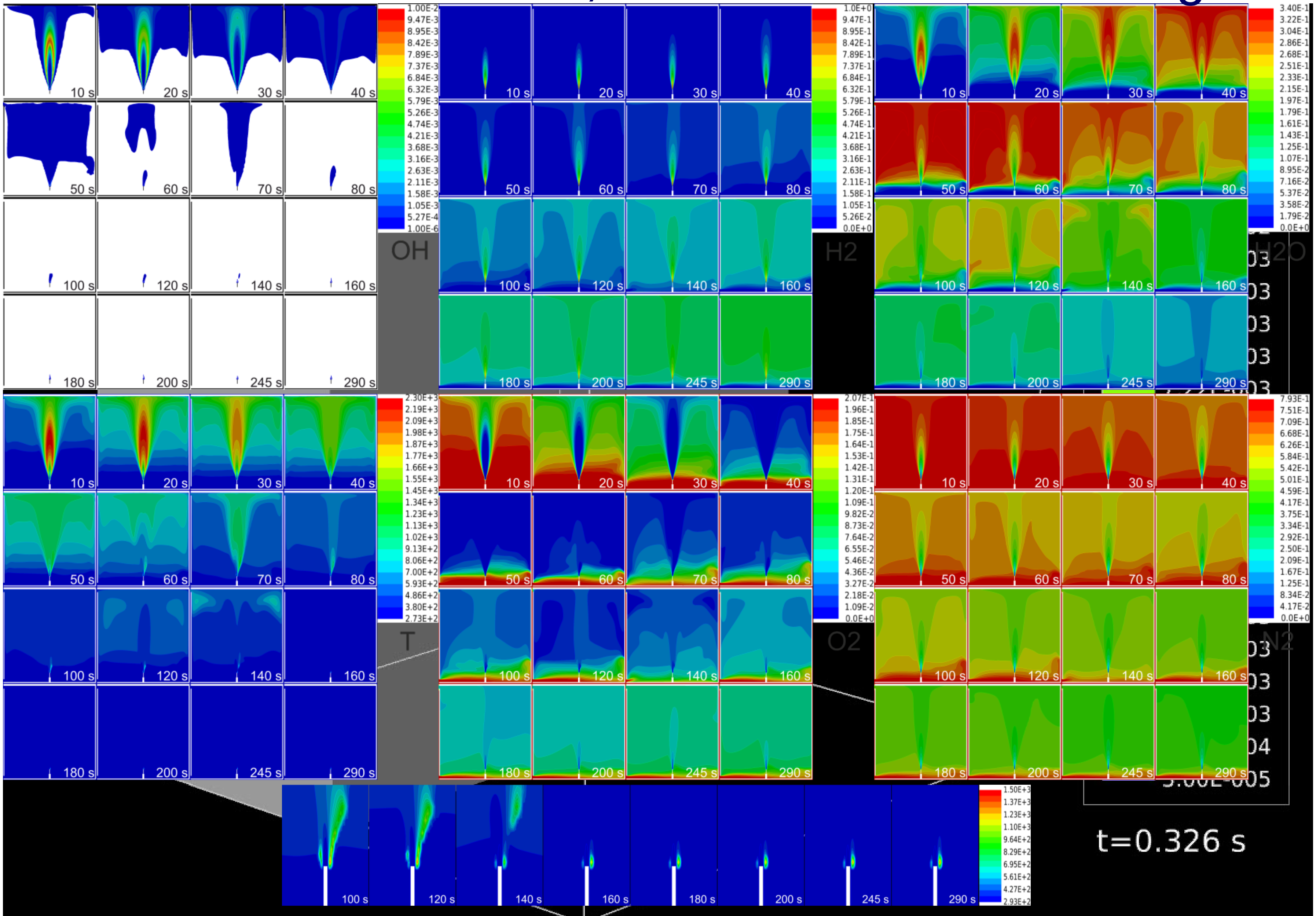
Transitional

No.11: 2 vents 3x15 cm; release 150 m/s - 0.27 g/s.



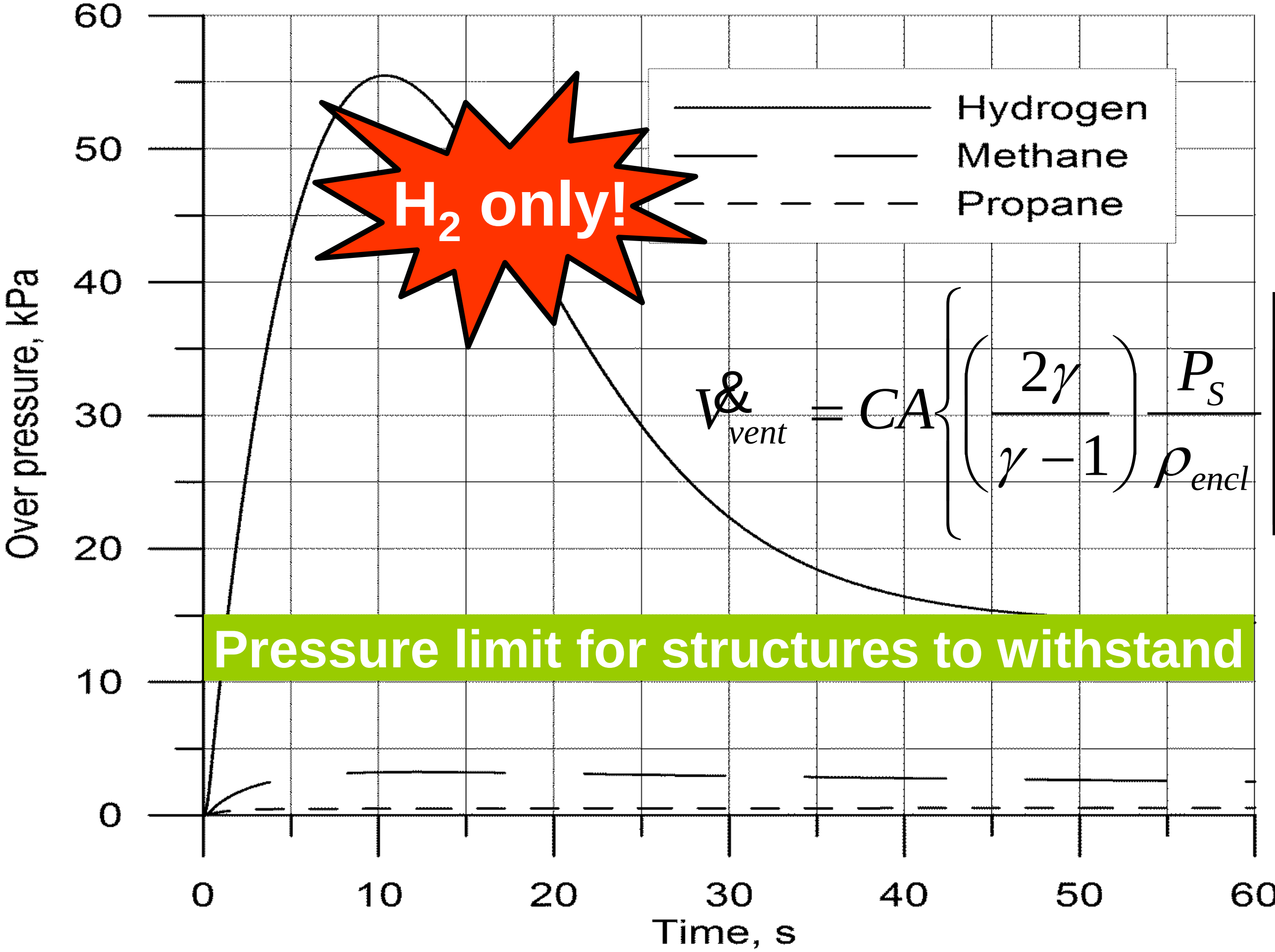
Micro-combustion

No.12: 2 vents 3x15 cm; release 300 m/s - 0.55 g/s.



Indoor: pressure peaking phenomenon!

Small garage *LxWxH*=4.5x2.6x2.6 m (“brick” vent).
Mass flow rate 390 g/s (350 bar, 5.08 mm orifice).



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

Solution: decrease PRD orifice size and increase fire resistance of onboard storage

PPP for fires: methodology

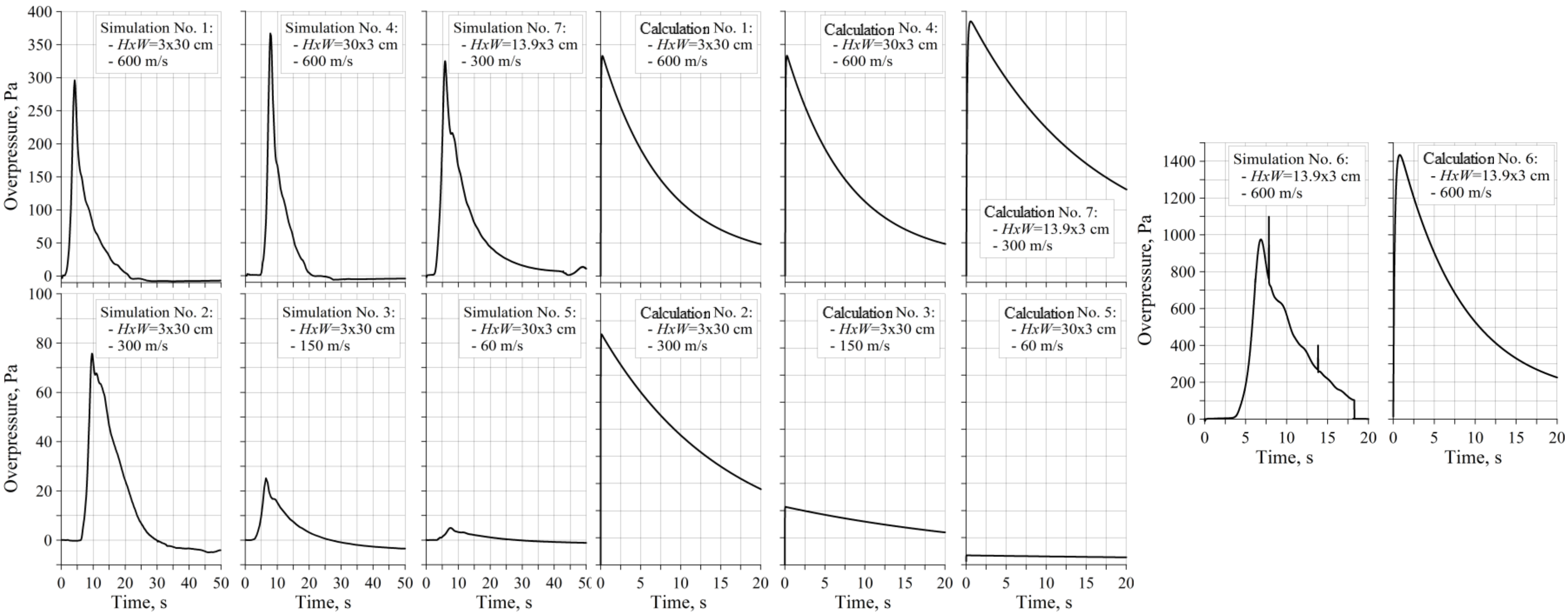
- Adiabatic flame temperature of hydrogen combustion in air is 2403 K
- Combustion of 1 g of hydrogen in air produces 9 g of water

- 9 g of water at 2403 K will occupy $V = \frac{m}{M}\frac{RT}{p} = \frac{9}{18}\frac{8.314 \cdot 2403}{101325} = 0.0986\, m^3$

- 1 g of hydrogen (unignited release at 273 K) will occupy 0.011 m, i.e. 9 times less than water produced during combustion of 1 g of hydrogen
- The densities of hydrogen at 273 K and water at 2403 K are 0.091 and 0.089 kg/m^3 respectively (almost equal!)
- Therefore, overpressure due to PPP for jet fire can be assessed PPP for unignited release with flow rate multiply by factor of 10 (9 parts of water produced and 1 part of H2 released) and apply the same methodology as for unignited releases by (Brennan and Molkov 2013)

Verification of methodology

Exp. No.	Vent size, *HxW*	Release velocity, m/s	Flow rate, g/s	Max. CFD simulated overpressure, Pa	Max. PPP calculated overpressure, Pa	Model prediction, %
No.1	Horizontal 3x30 cm	600 m/s	1.0857	300	325	+8%
No.2	Horizontal 3x30 cm	300 m/s	0.5486	75	85	+13%
No.3	Horizontal 3x30 cm	150 m/s	0.2714	25	22	-12%
No.4	Vertical 30x3 cm	600 m/s	1.0857	365	325	-11%
No.5	Vertical 30x3 cm	60 m/s	0.1086	5	3.5	-30%
No.6	Vertical 13.9x3 cm	600 m/s	1.0857	1100	1420	+29%
No.7	Vertical 13.9x3 cm	300 m/s	0.5486	325	380	+17%



Conclusions

- ❖Indoor hydrogen jet fire has been simulated using advanced CFD model with "spatial resolution" of chemical reactions.
- ❖The general rules for indoor fire with one upper vent and two vents are formulated.
- ❖The engineering tool for calculation of overpressure generated by the jet fire indoors is developed and described.
- ❖A mass flow rate of hydrogen for ignited release must be 10 times of unignited release to get overpressure value for ignited release and yet use the model of PPP for unignited release.

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Learn more!

THANK YOU

Acknowledgements

- EPSRC SUPERGEN HUB project (http://www.h2fcsupergen.com/)
- FCH JU HyIndoor project (http://www.hyindoor.eu/)

H2FC SUPERGEN THE HYDROGEN AND FUEL CELL RESEARCH HUB

Hyindoor

MSc in Hydrogen Safety Engineering (distance learning course):
http://www.ulster.ac.uk/elearning/programmes/view/course/10139

Fundamentals of Hydrogen Safety Engineering
(free eBook, www.bookboon.com, October 2012)