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Effect of tunnel slope on hydrogen dispersion

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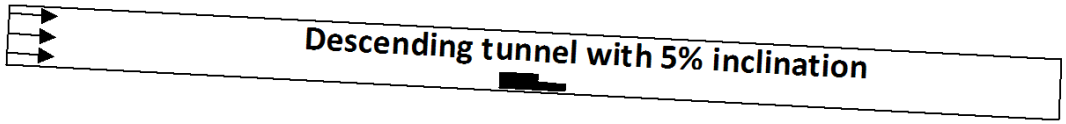
Introduction

HyTunnel project – current study motivation

- **HyTunnel-CS: Contributes to the safe use of hydrogen vehicles through tunnels**
  - "Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar Confined Spaces"
- **Buoyancy helps hydrogen dispersion in sloped tunnels?**
- **Previous knowledge from tunnel fires in sloped tunnels:**
  - The '*stack-effect*', due to buoyancy, affects the flow & dispersion field: Smoke moves to the upper end of the tunnel
  - *Adverse* consequences may exist, e.g. for ventilated *descending* tunnels: Smoke may be trapped inside the tunnel



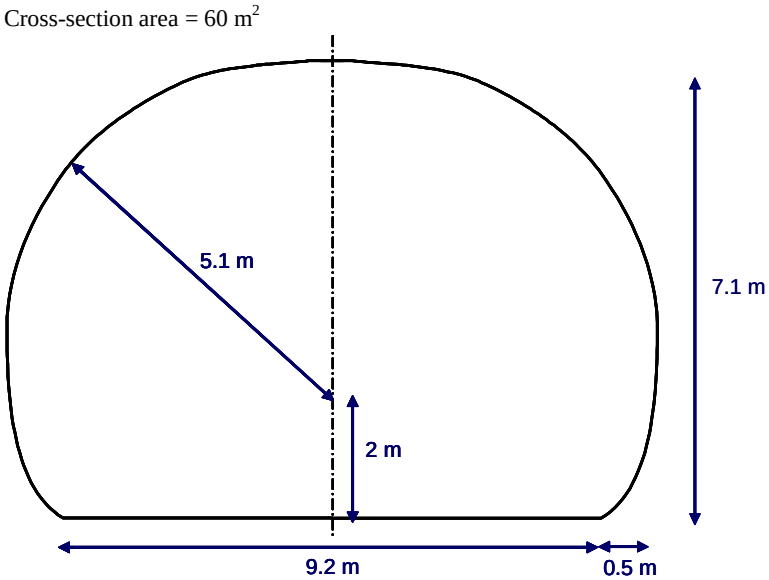
Effect of tunnel slope and ventilation

Summary

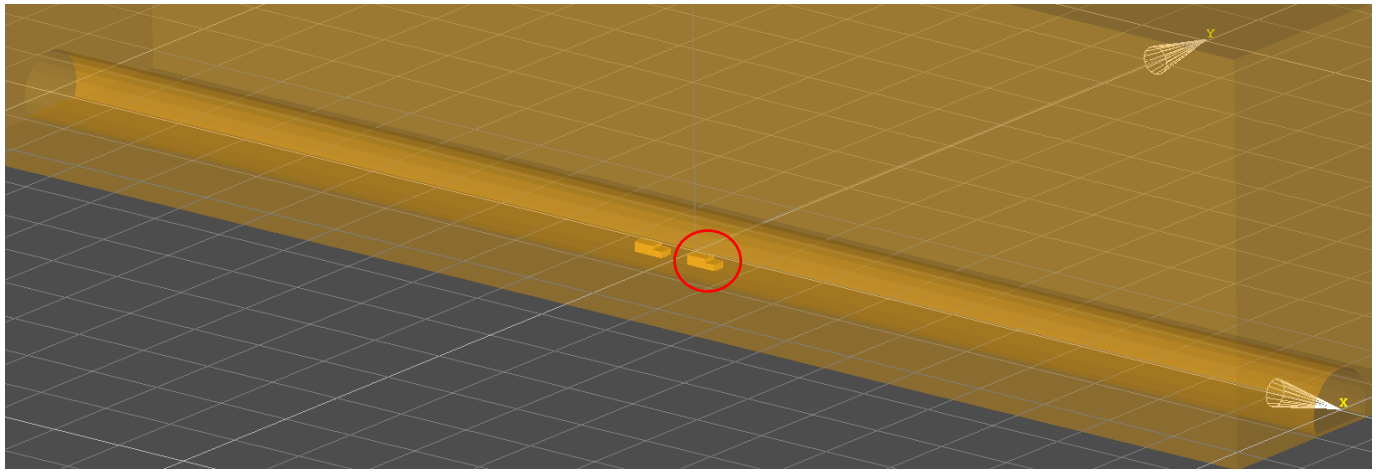
- **About 20 cases were studied investigating:**
  - The effect of tunnel <u>inclination</u>
    - Different slopes were tested
    - Two nozzle sizes were assumed
  - The effect of <u>ventilation</u>
    - Several ventilation rates and the no ventilation case were tested
    - In both straight and inclined tunnel
  - The effect of <u>release orientation</u>
    - Straight tunnel and 0.5 m/s ventilation rate

Cases setup

Geometry



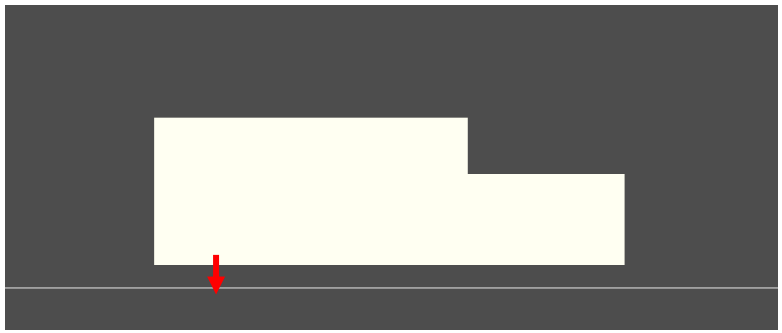
- **Tunnel considered**
  - Horseshoe cross-section
    - **200 m** length, 7.1 m max height
  - Two cars (4.2 x 1.8 x 1.3 m)
    - H_2 release beneath the front car
  - Slope: **0.0%, 2.5%, 5.0%** (descending)
  - Without or with ventilation (**0** , **0.5** , **1** , **2** m/s)

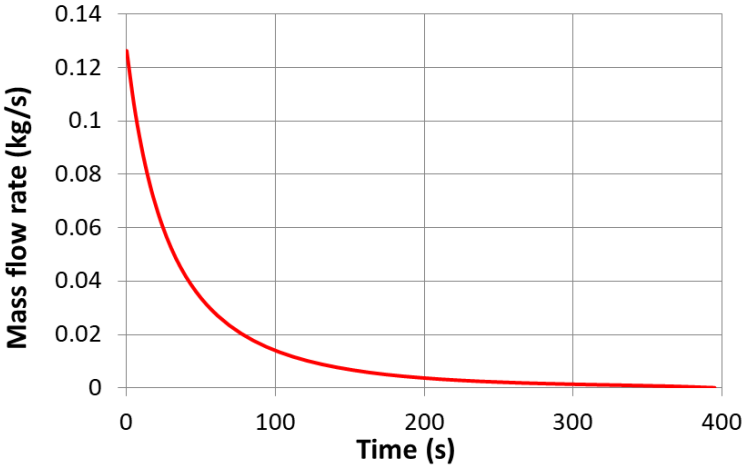


Cases setup

Source

- **H_2 release considered**
  - 6 kg of H_2, released from a 700 bar CGH2 car tank
  - Position: At the bottom of the car, at 0.2 m from the ground
  - Direction: Towards the ground
  - TPRD diameter: 2 mm (4 mm also tested)
  - Duration: 400 s (100 s for the 4 mm cases)
  - Blowdown: Flow rate decreases with time

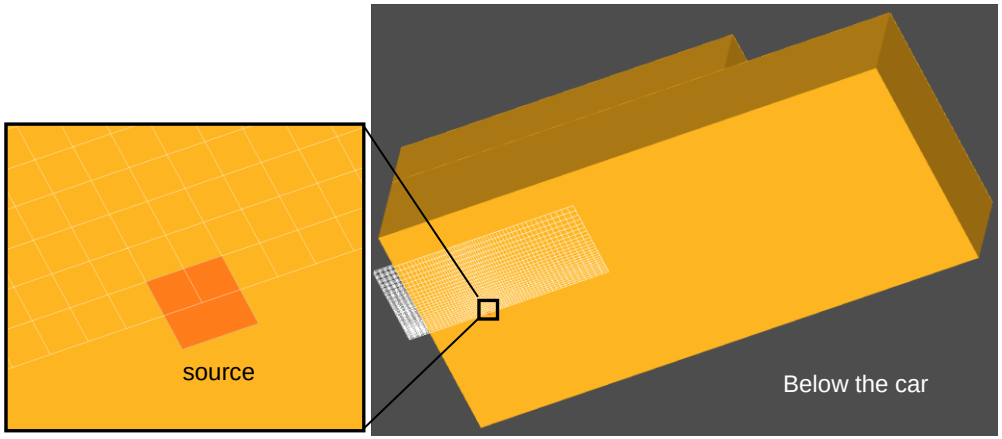


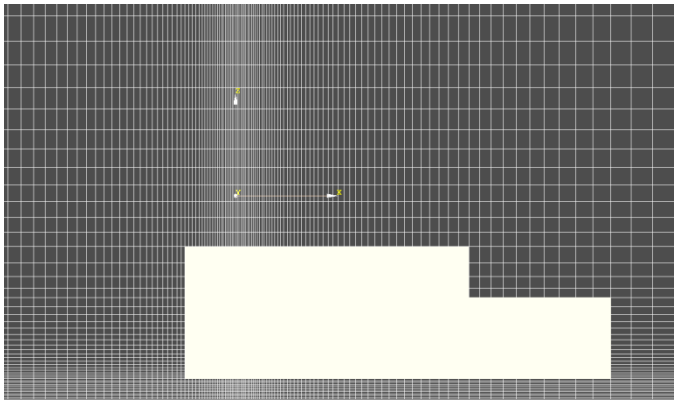


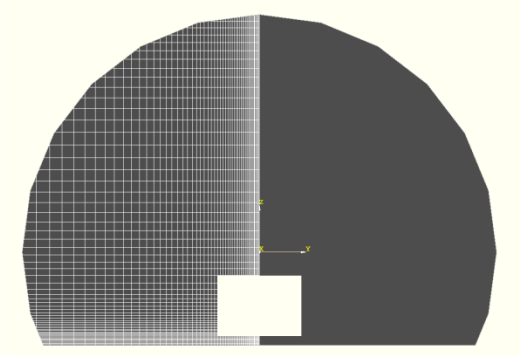
Cases setup

Numerical details

- **ADREA-HF CFD code**
- **H_2 release simulation**
  - Notional nozzle approach
    - Nozzle decreases with time – sonic velocity
- **Computational grid**
  - 4 cells at the release
    - 2 solved due to symmetry
  - 1.0 M active cells (half tunnel)
    - 0.8 M active cells at ventilation cases
- **Domain**
  - 260 x 40 x 42 m^3 (no ventilation)
  - 200 x 10.2 x 7.1 m^3 (ventilation)
  - Half domain is solved due to symmetry

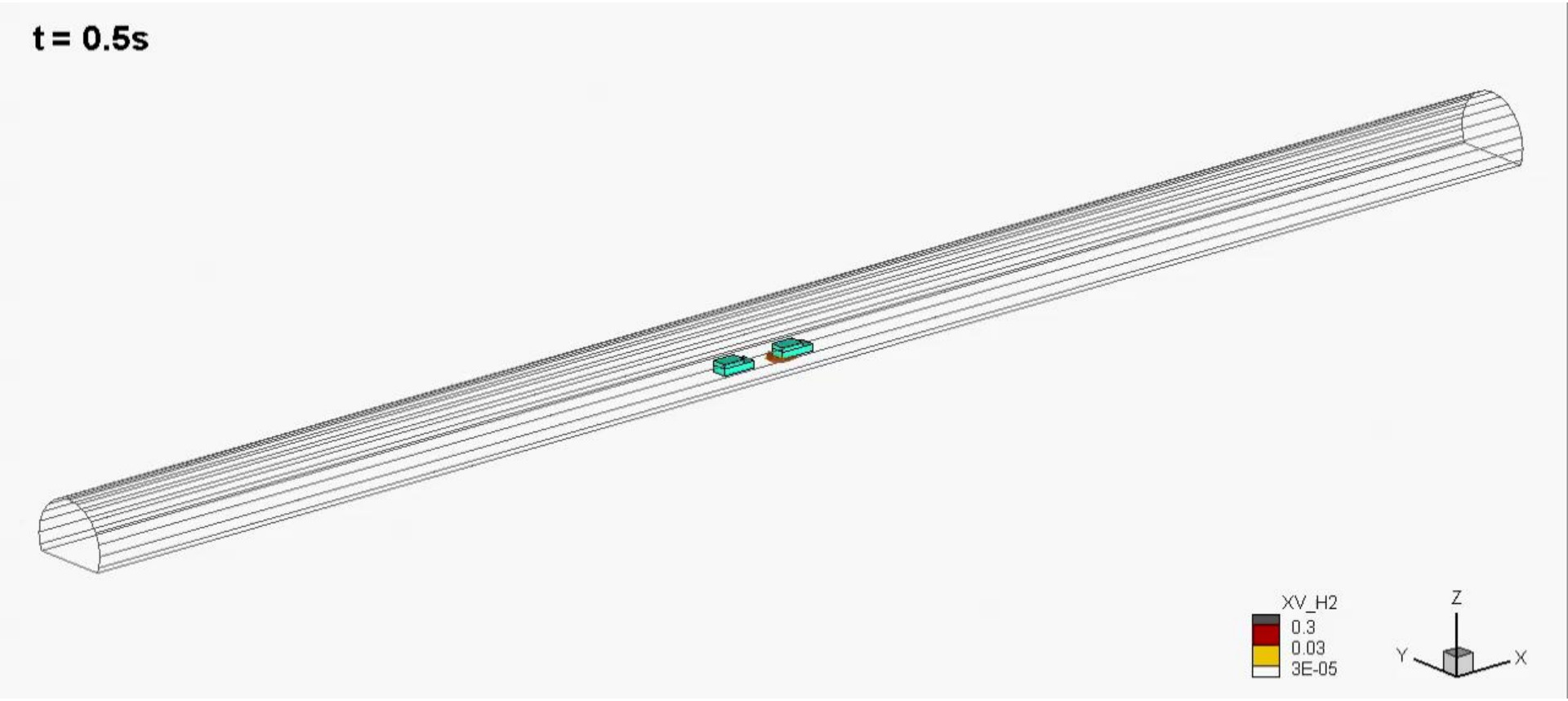


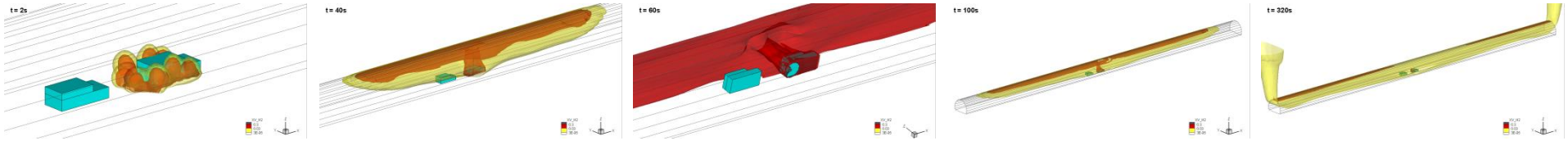




Results – No ventilation cases

Overview of cloud propagation – no slope

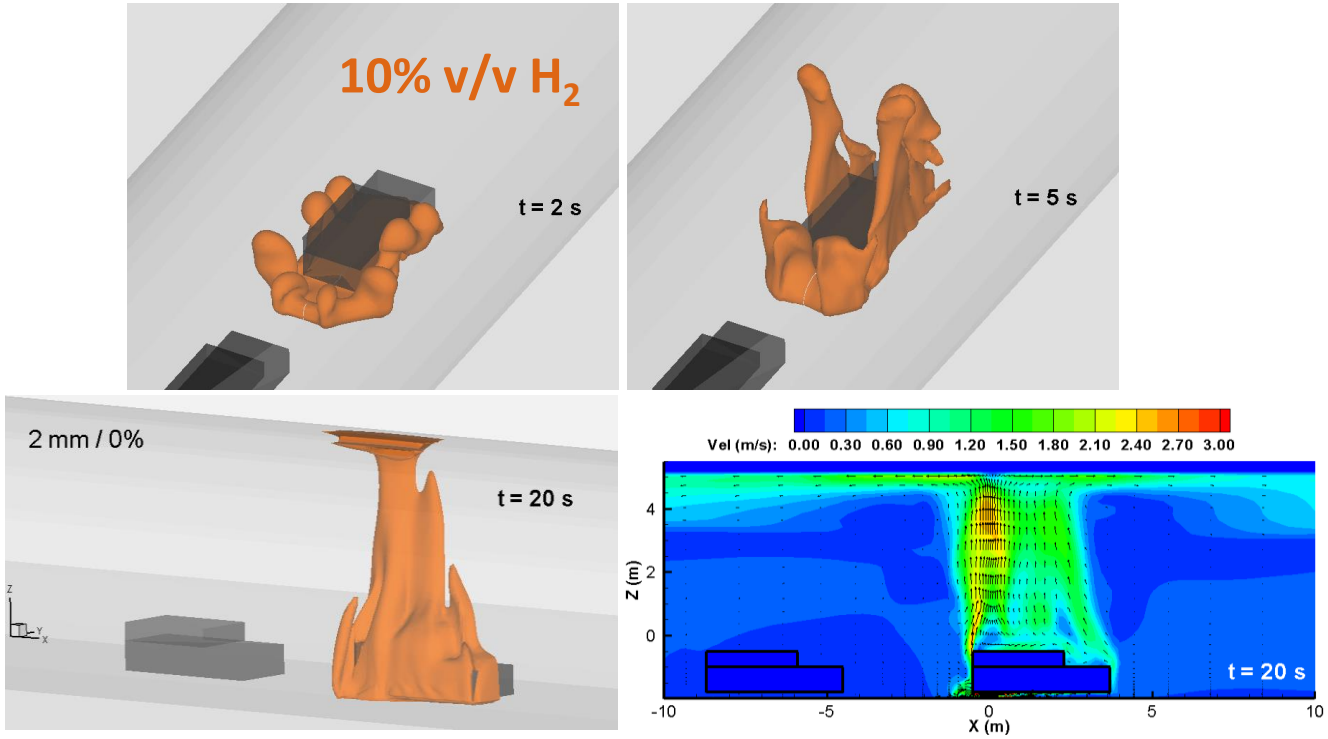




Results – No ventilation cases

Initial stages

- **Hydrogen of 10% v/v at 2 s, 5 s and 20 s**
  - H_2 spreads below the car and elevates quickly surrounding the car



<u>Slope has negligible effect during the first seconds</u>

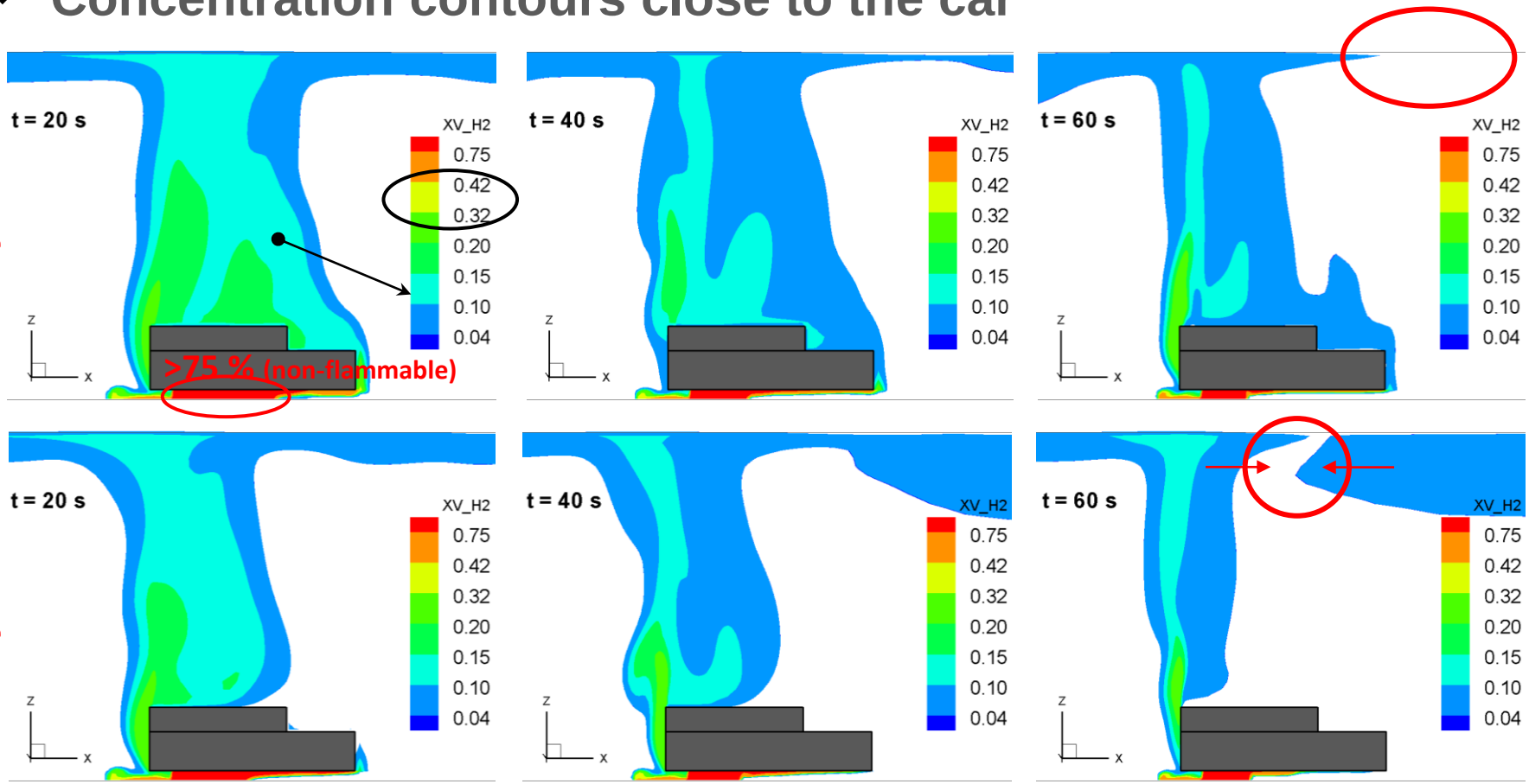
Results – No ventilation cases

Intermediate stages

❖ Concentration contours close to the car

0% slope

5% slope



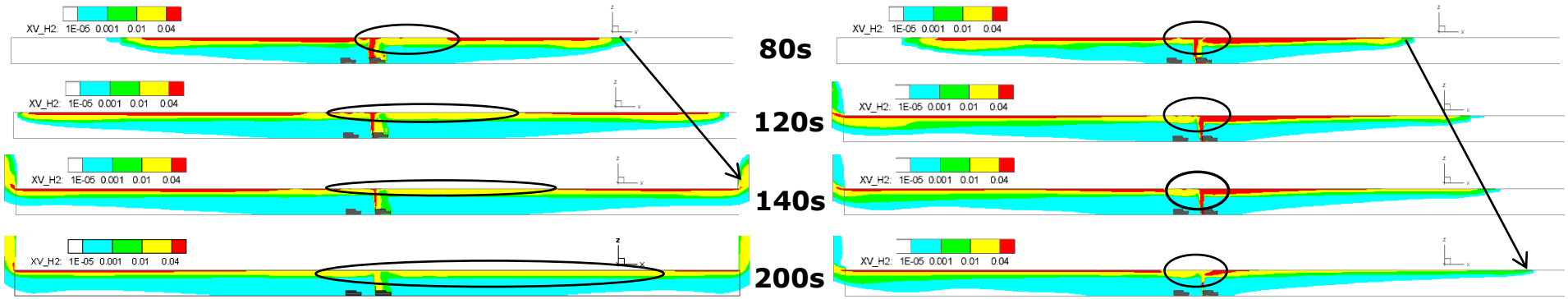
Slope has small effects around the car

Results – No ventilation cases

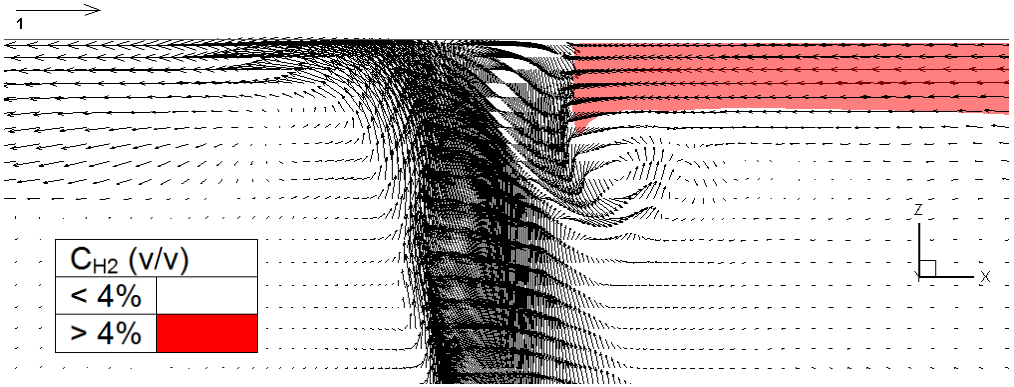
Later stages

❖ **Propagation of H_2 with time**

Slope **0%** | Slope **5%** →

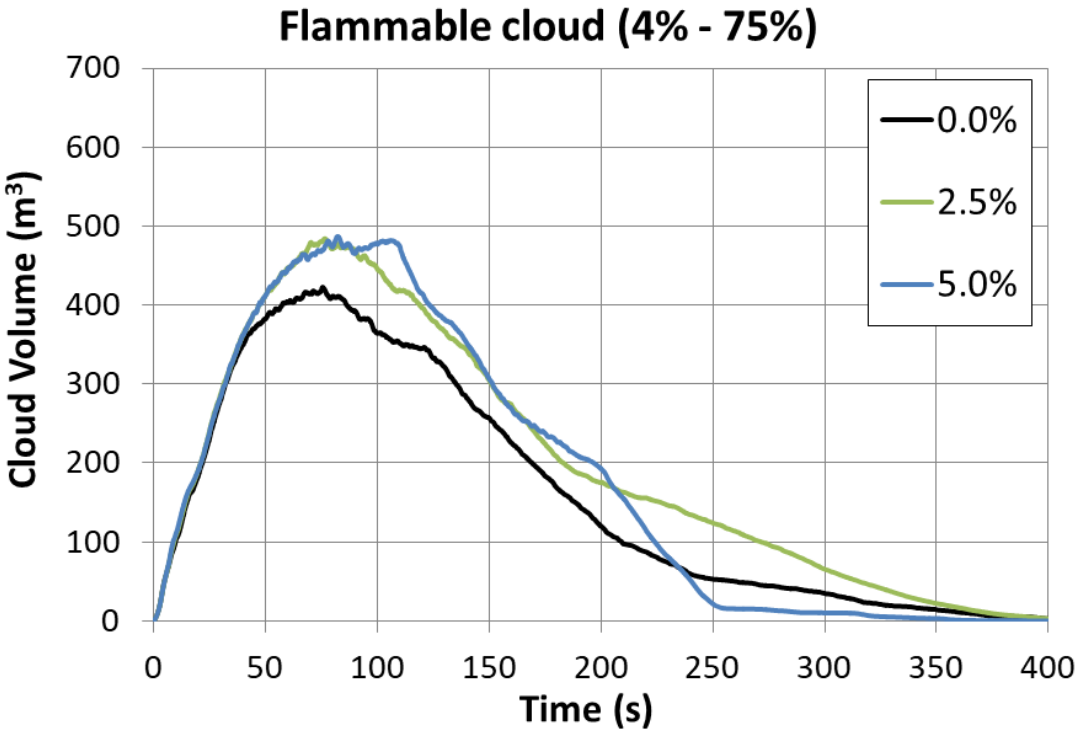


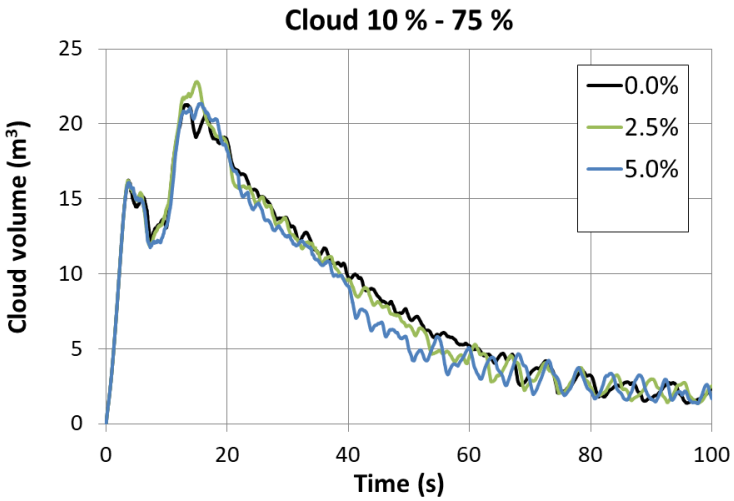
Slope can have adverse effects: For example, the 'air-curtain' effect can block the movement of part of hydrogen towards the upper part of the tunnel - example from **240 s** of the **2.5%** slope case →

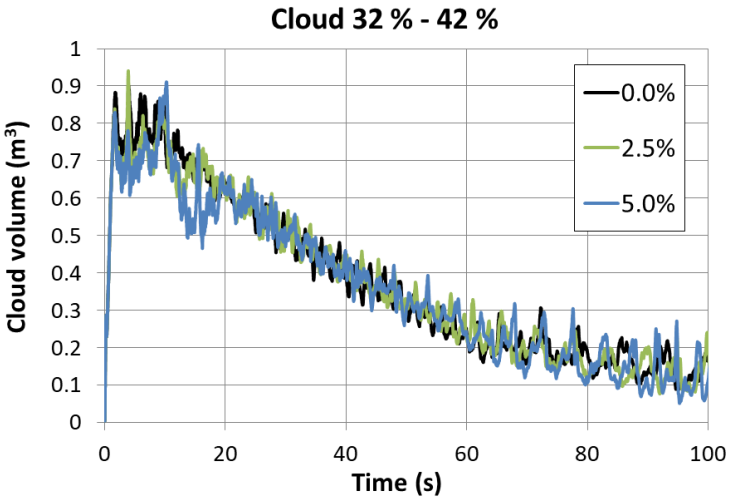


Results – No ventilation cases

Whole-tunnel cloud volumes

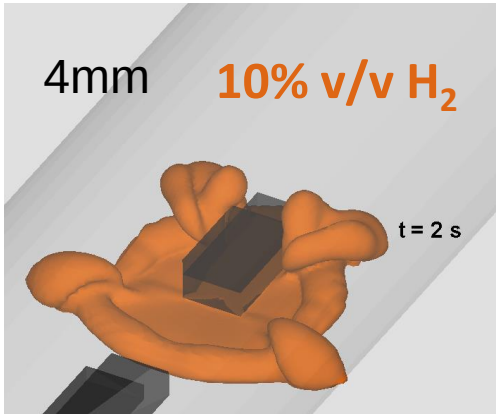


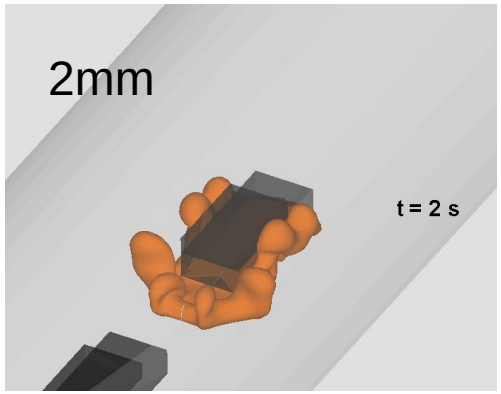




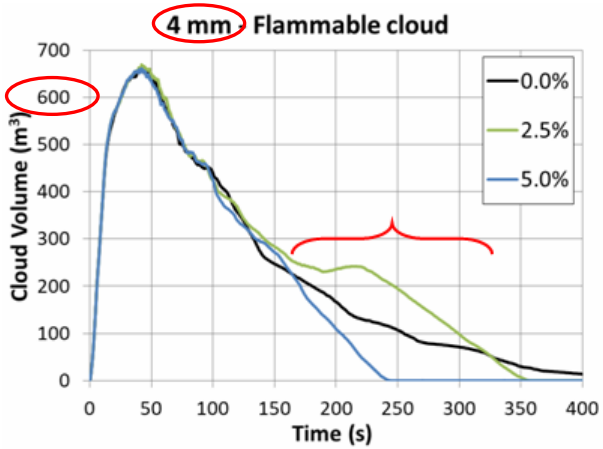
Results – No ventilation cases

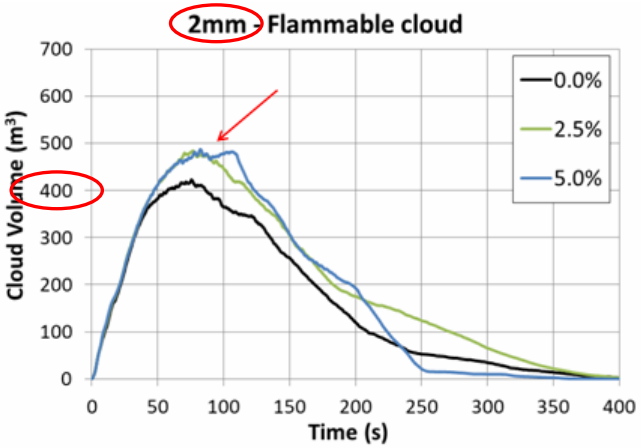
What if PRD was 4mm instead of 2mm?

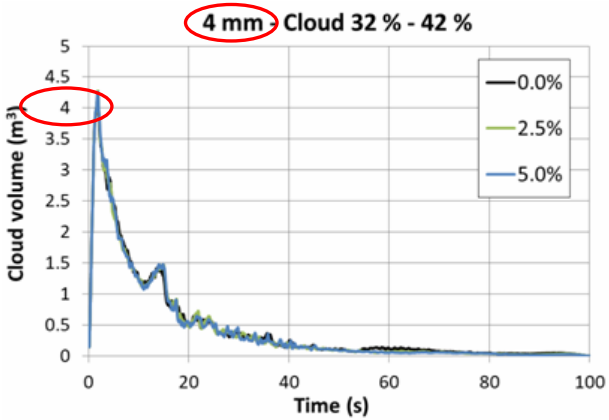


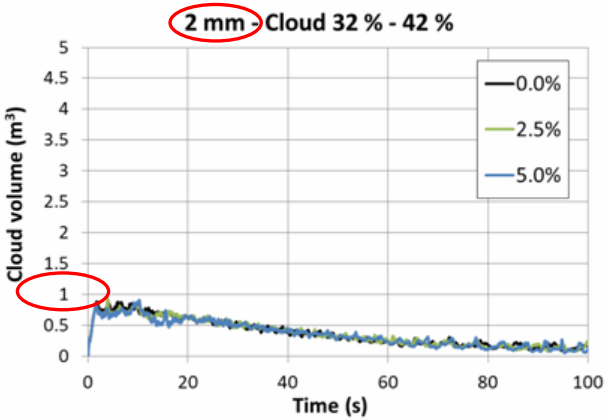


PRD	4 mm	2 mm
Release duration	100 s	400 s



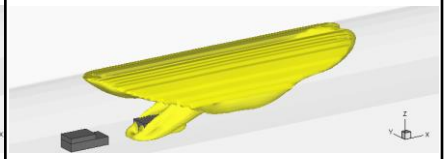
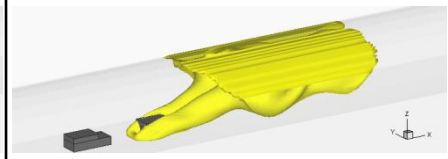
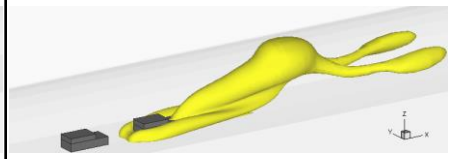
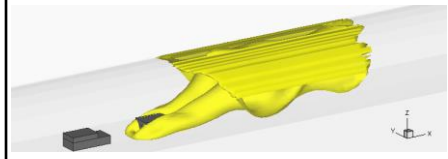
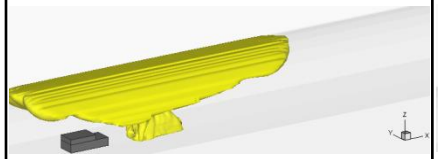
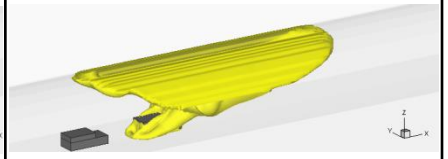
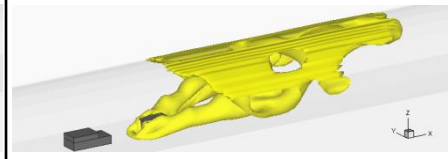
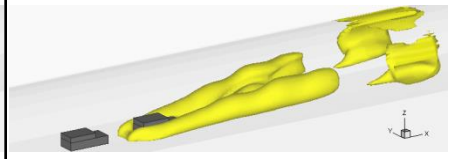
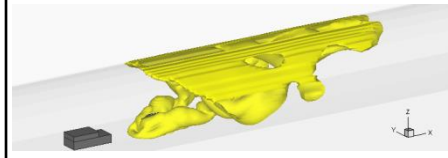






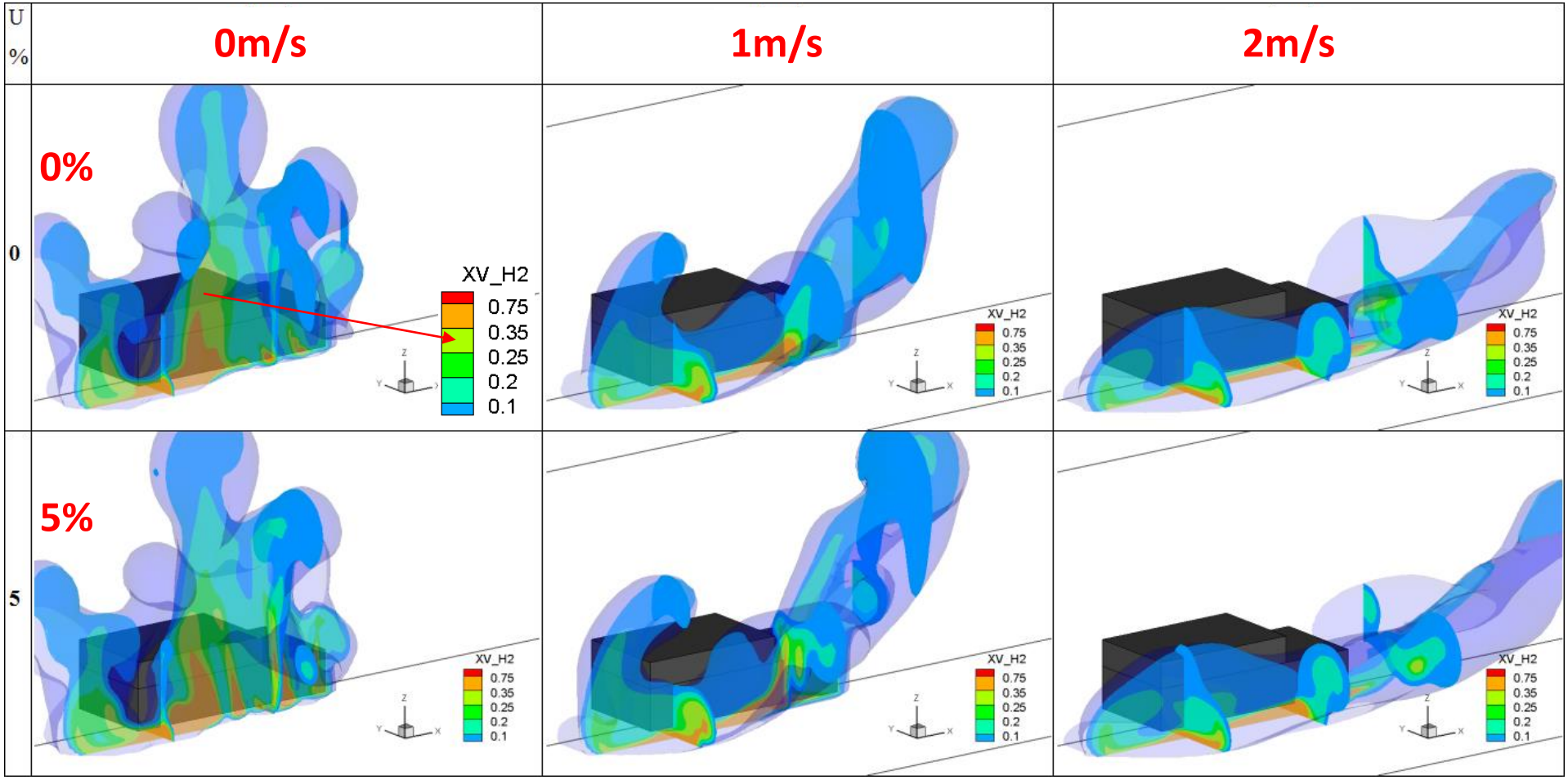
Results – Ventilation cases examined

Isosurfaces of 2% v/v at 20s shown

Veloc> *Slope*	0m/s	0.5m/s	1m/s	2m/s
0%				
2.5%				
5%				
			1m/s till 5s **(then stops)**	
5%				

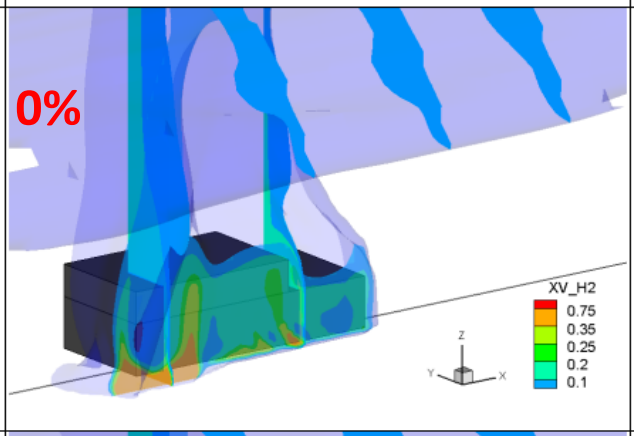
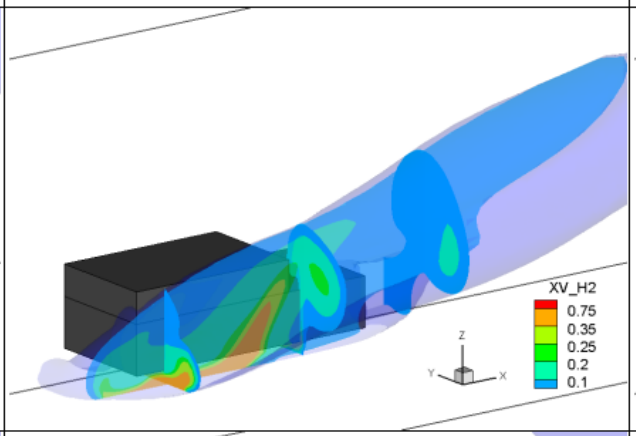
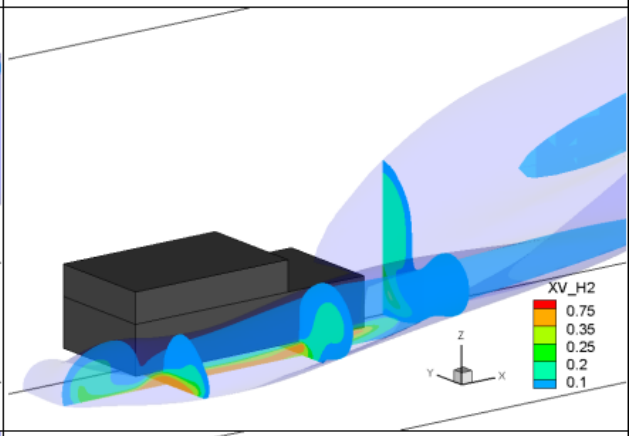
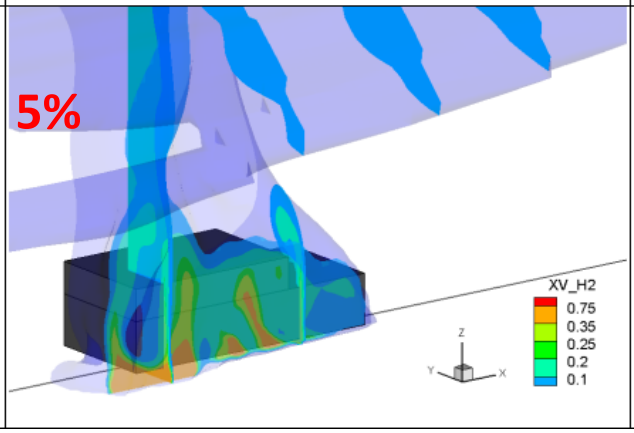
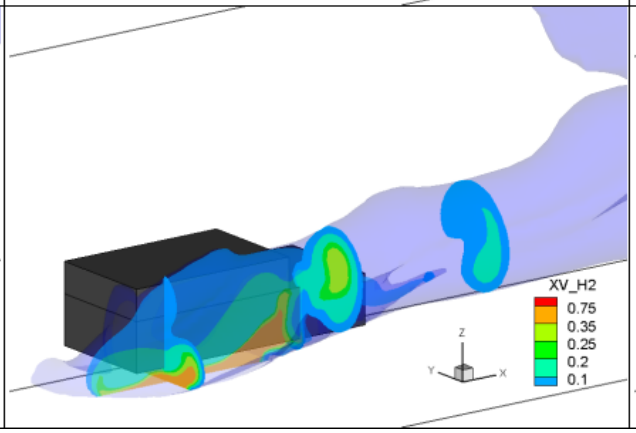
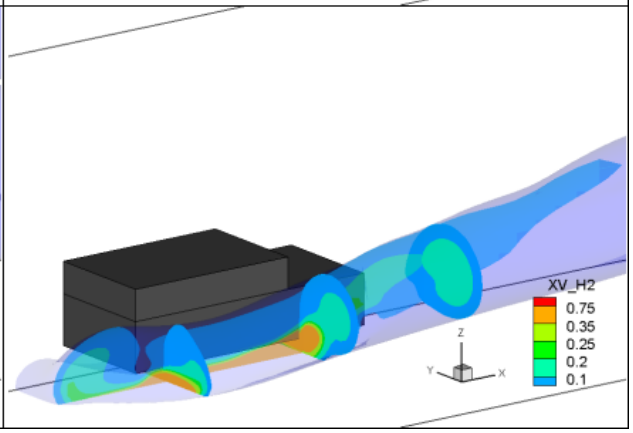
Results – Ventilation cases

Above-flammable contour slices at 5s



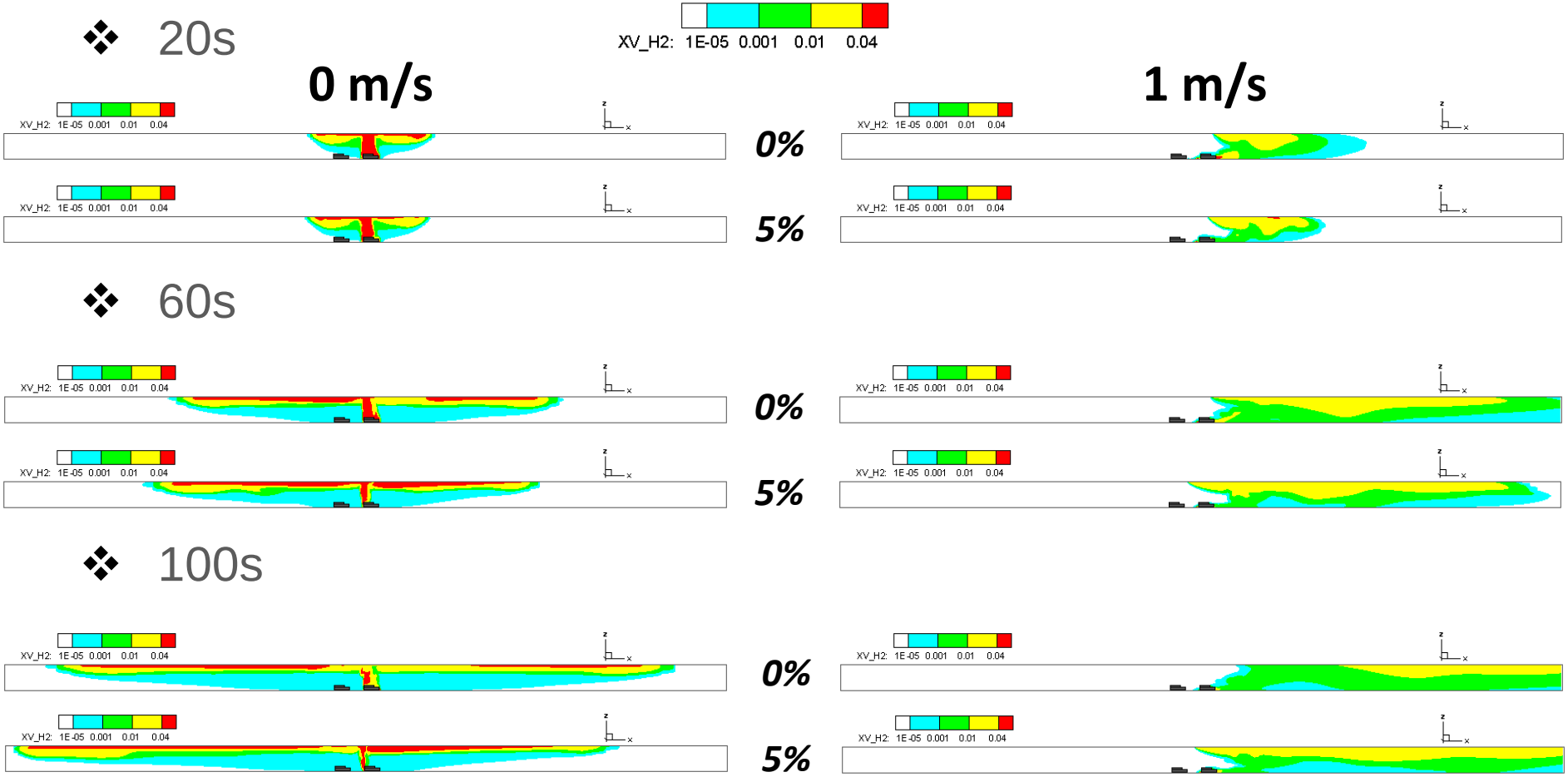
Results – Ventilation cases

Above-flammable contour slices at 20s

U %	0m/s	1m/s	2m/s
0			
5			

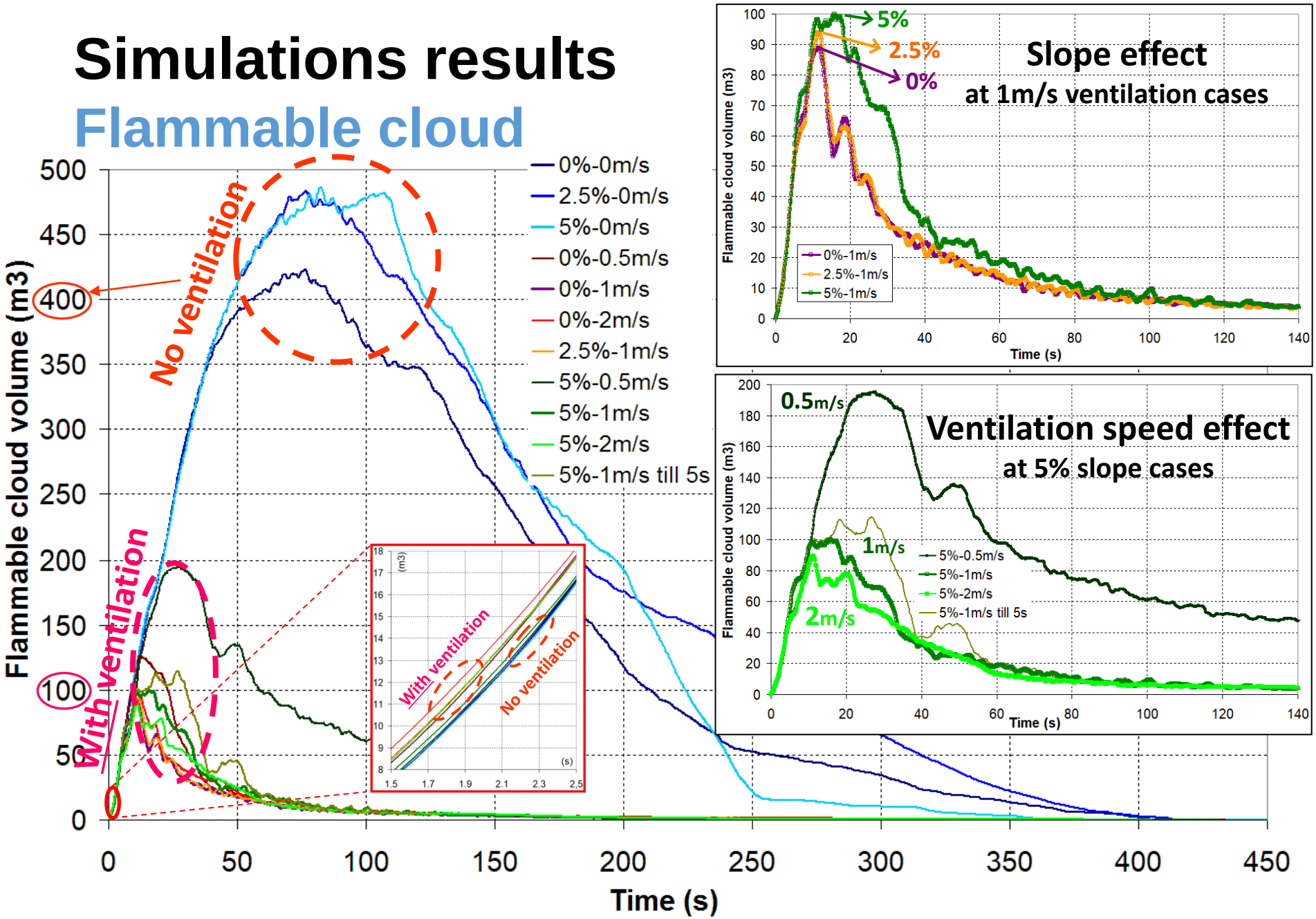
Results – Ventilation cases

Contours at whole tunnel – various times



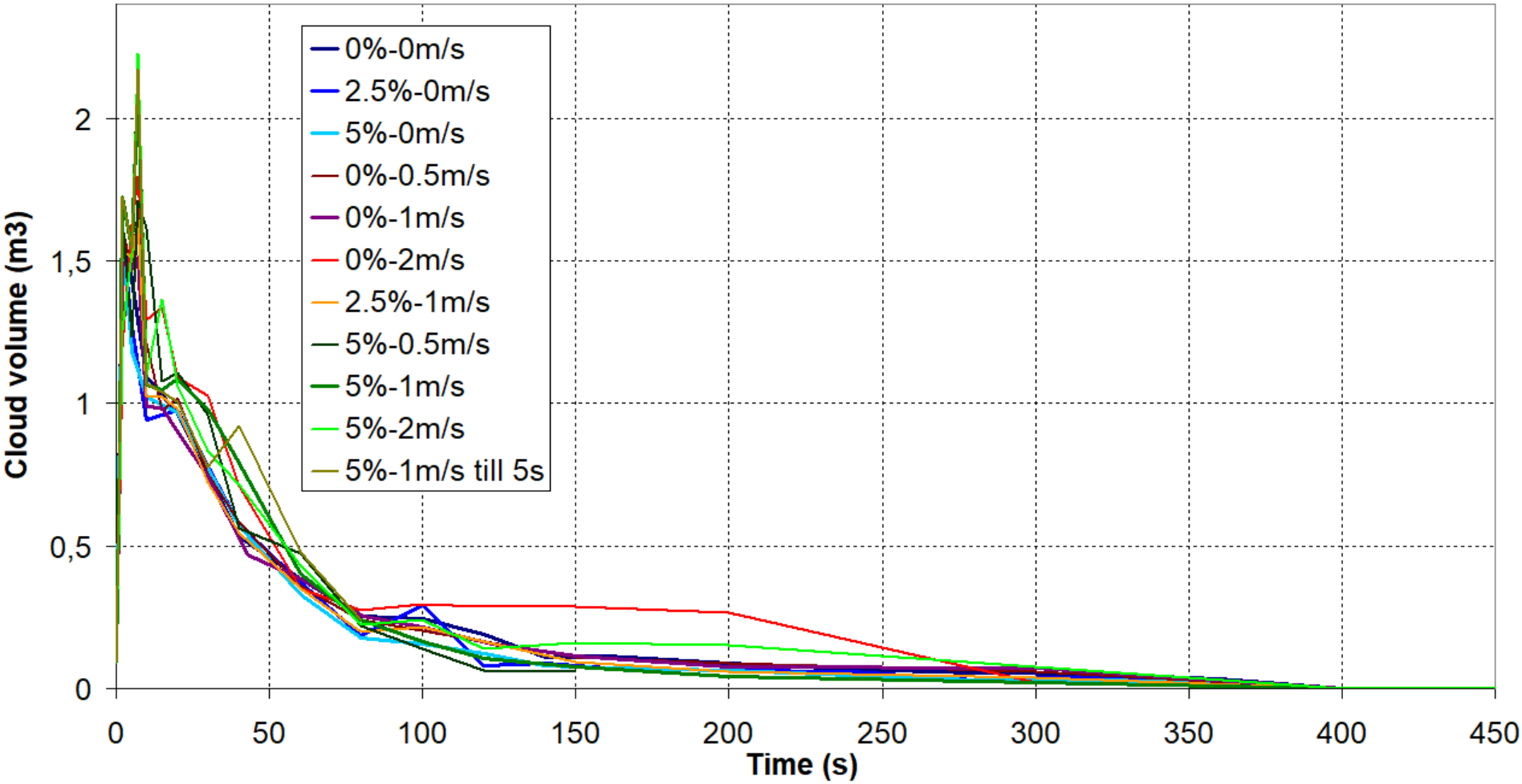
Simulations results

Flammable cloud



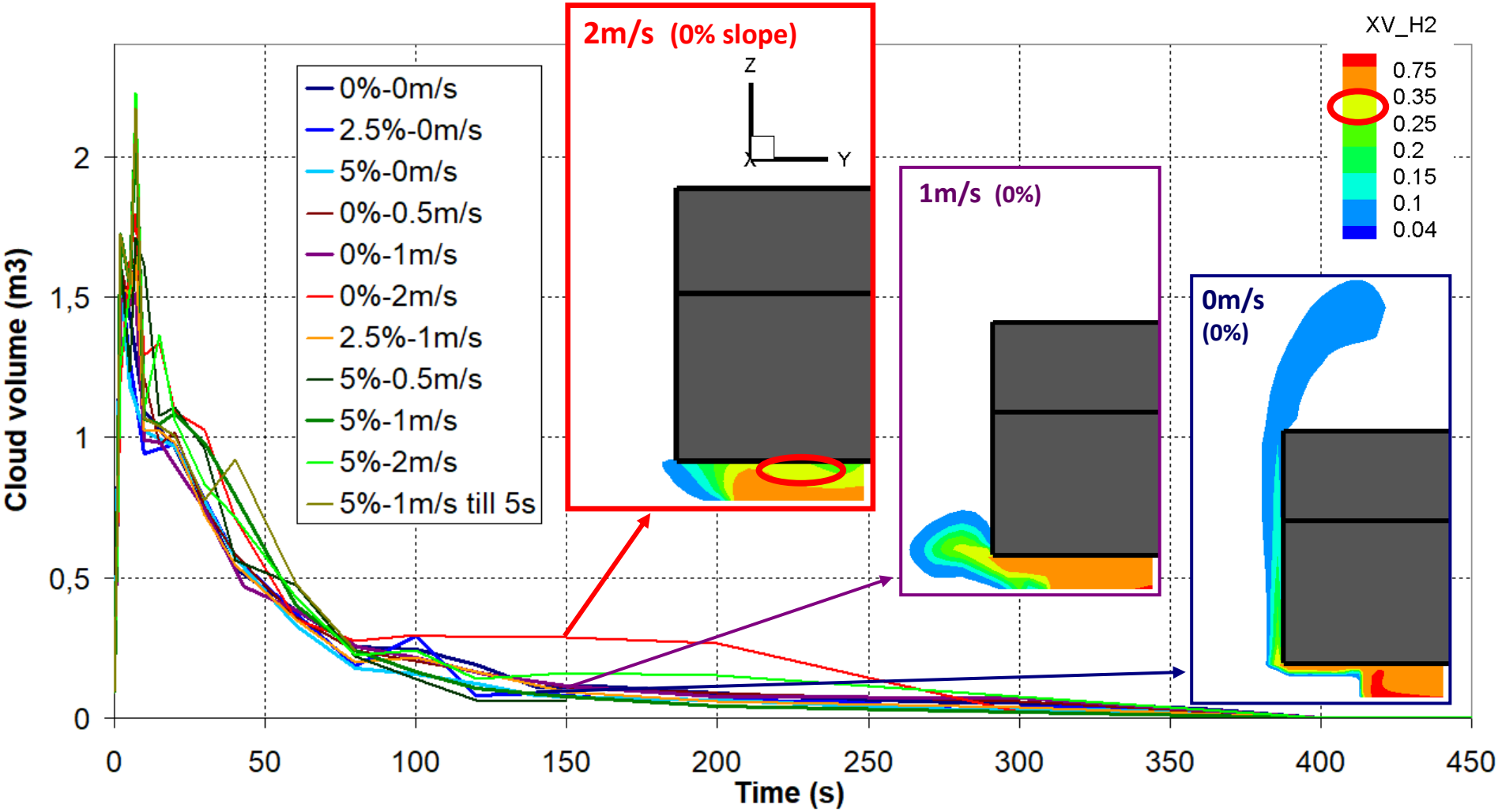
Simulations results

Cloud 25%-35% v/v - all cases very close



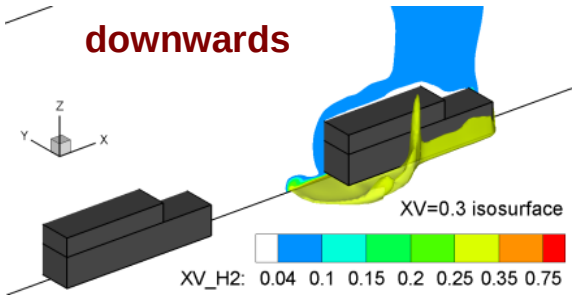
Simulations results

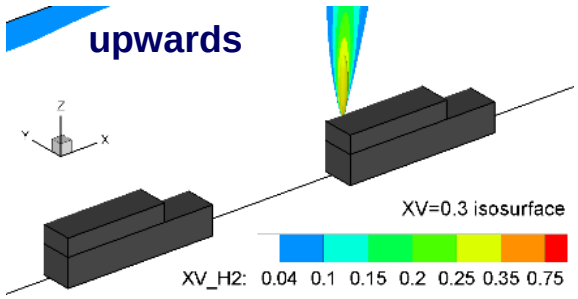
Cloud 25%-35% v/v - red curve explained

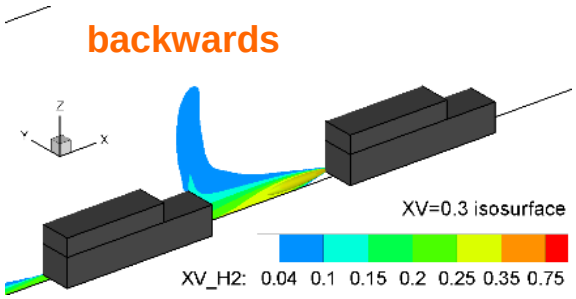


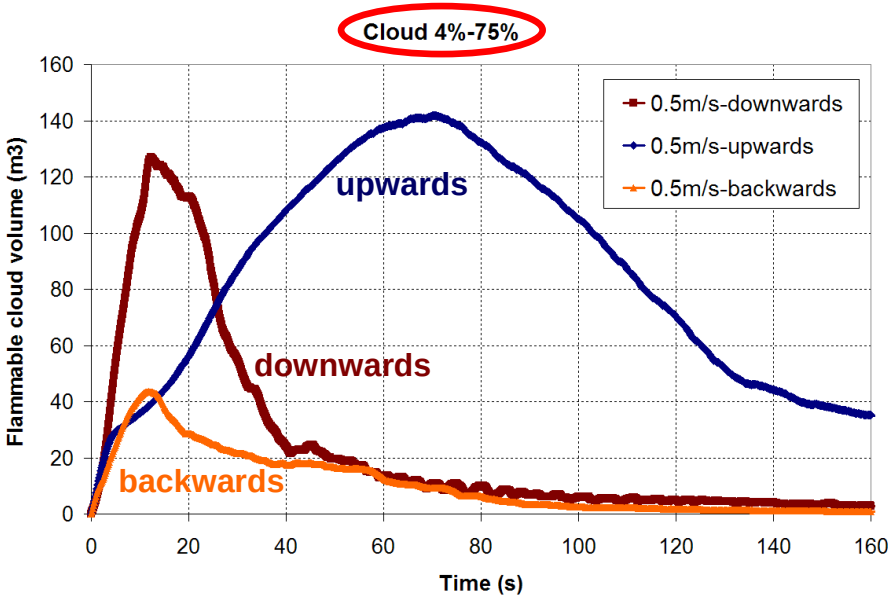
Simulations results – vent=0.5m/s, d=2mm, at 10s

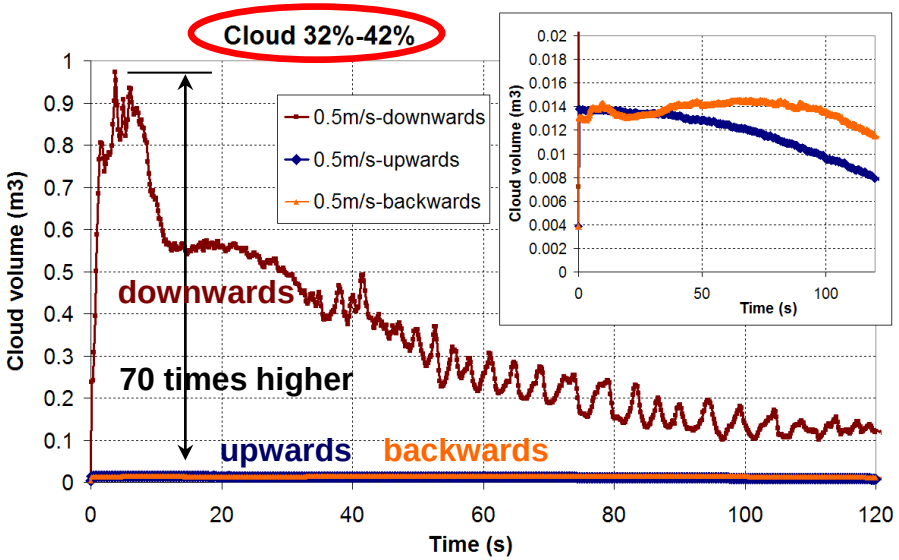
A note on the release orientation











Downwards release direction resulted in about 70 times higher 'dangerous' cloud volume
Backwards release direction is more advantageous

Effect of tunnel slope and ventilation
Conclusions (1/2)

- **Inclination**:
  - **No systematic effect** at initial stages
  - **No systematic effect** at total 25%-35% v/v
  - **Occasionally adverse effects:** e.g. higher flammable cloud at some times

  Recommendation: No special treatment in tunnels with up to 5% inclination.

- **Ventilation:**
  - **Strong effect** on the flammable cloud (several times smaller)
  - **No systematic effect** at most flammable cloud volumes (25%-35% v/v)
  - **Occasionally adverse effects**: e.g. in few cases below the car

  Recommendation: Introduce mechanical ventilation in tunnels, even 0.5 m/s has significant effect on cloud distribution.

Effect of tunnel slope and ventilation
Conclusions (2/2)

- **Usually the area around the car the most critical one**
  - For the vertically downwards release (from 700 bar storage pressure), the flammable cloud did not reach a distance of 4 m behind the car, for TPRDs with diameters in the range of 2-4 mm. The hazard distance and associated risk, however, decrease with decreasing TPRD diameter.
- **Serious influence of diameter and direction of PRD**
  - **2 mm** PRD is generally **better than 4 mm**
  - **Backwards** release better than downwards

  Recommendations:

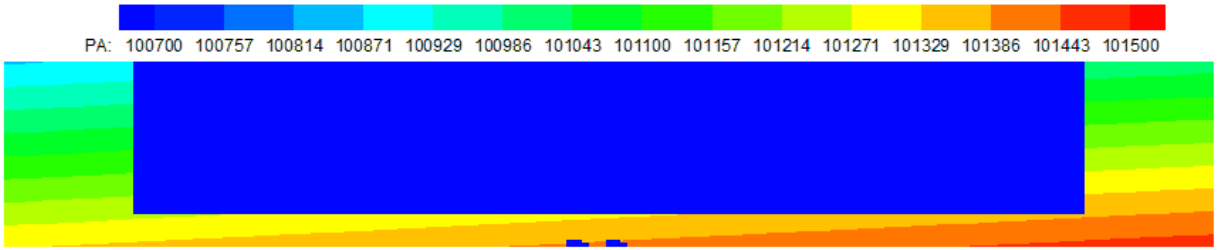
  - Release diameter and orientation have a much more important influence on hazards than the tunnel slope.
  - Avoid downwards TPRD releases.
  - Oblique releases can be considered safer.

Acknowledgements

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 826193. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

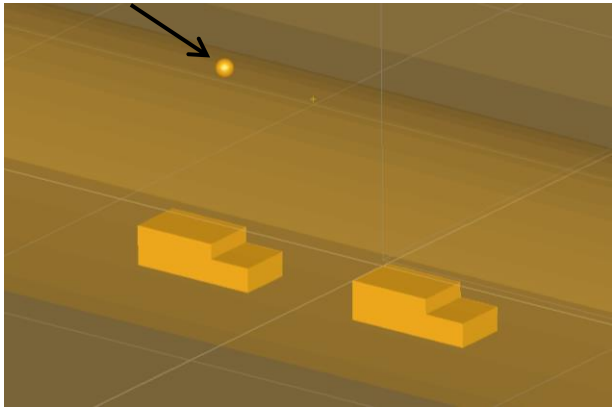
Cases setup
Numerical details

- **Turbulence model**
  - Standard *k*-*ε* turbulence model with buoyancy terms
  - Initial *k* about 0.0025 m^2/s^2
- **Discretization schemes**
  - Spatial: MUSCL (2nd order)
  - Temporal: 1st order backwards differences
    - Maximum CFL number: 8-15 *(4 at 4mm PRD cases)*
- **Slope modelling**
  - Change of gravitation orientation
  - Pressure **initialization** for inclined tunnels

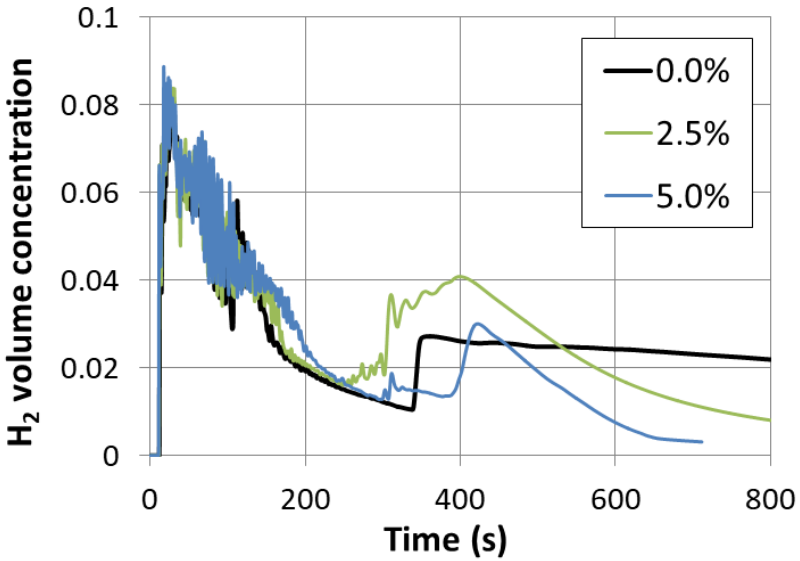


Results – No ventilation cases

Example of ‘sensor’ values



- **Concentration time-series**
  - Unstable period in the first half of the release (until 200s)
  - There are moments where slope-cases have higher values



Simulations results

Summary of all examined cases

max cloud (m3) [time of max cloud (s)]

Concent. range/ criterion	PRD 4mm				2mm			2mm		2mm				2mm	
	ventilation 0m/s				0m/s			0.5m/s		1m/s			1m/s till 5s	2m/s	
	slope 0%	2.5%	5%	10%	0%	2.5%	5%	0%	5%	0%	2.5%	5%	5%	0%	5%
4%-75%	663 [41]	669 [42]	663 [42]	625 [41]	424 [76]	484 [77]	487 [82]	127 [12]	195 [28]	89.0[12]	93.9[12]	100 [16]	115 [27]	94.7[12]	89.4[11]
10%-75%	83.0[4.8]	83.1[5.2]	86.8[6.1]	90.1[6.0]	22.2[14]	22.8[15]	21.3[16]	17.1[3.9]	21.3[11]	18.4[7.4]	19.5[7.7]	23.4[8.1]	23.3[8.1]	24.4[8.7]	24.2[8.6]
25%-35%	8.61[2]	8.46[2]	8.47[2]	8.44[2]	1.61[2]	1.59[2]	1.59[2]	1.68[7]	1.71[7]	1.51[7]	1.65[7]	2.13[7]	2.17[7]	1.80[7]	2.23[7]
Q9	40.3[2.7]	40.5[2.7]	40.7[2.7]	41.4[2.8]	4.97[3.9]	4.95[17]	4.80[17]	5.06[3.9]	5.16[2.9]	5.22[6.8]	5.43[6.9]	6.32[7.1]	6.37[7.1]	6.04[7.3]	6.87[6.8]

Q9 cloud ideally is a scaling of the non-homogeneous gas cloud to a smaller stoichiometric gas cloud that is expected to give similar explosion loads as the original cloud

$$V_9^{eq} = \sum_{LFL}^{UFL} V_i \cdot \frac{S_{L_i} \cdot E_i}{S_{L_i}^{stoich} \cdot E_{stoich}}$$

S_L = mean laminar flame speed, V = volume

E = volume expansion caused by burning at constant pressure in air