Simulations of hydrogen dispersion from fuel cell vehicles' leakages inside full-scale tunnel

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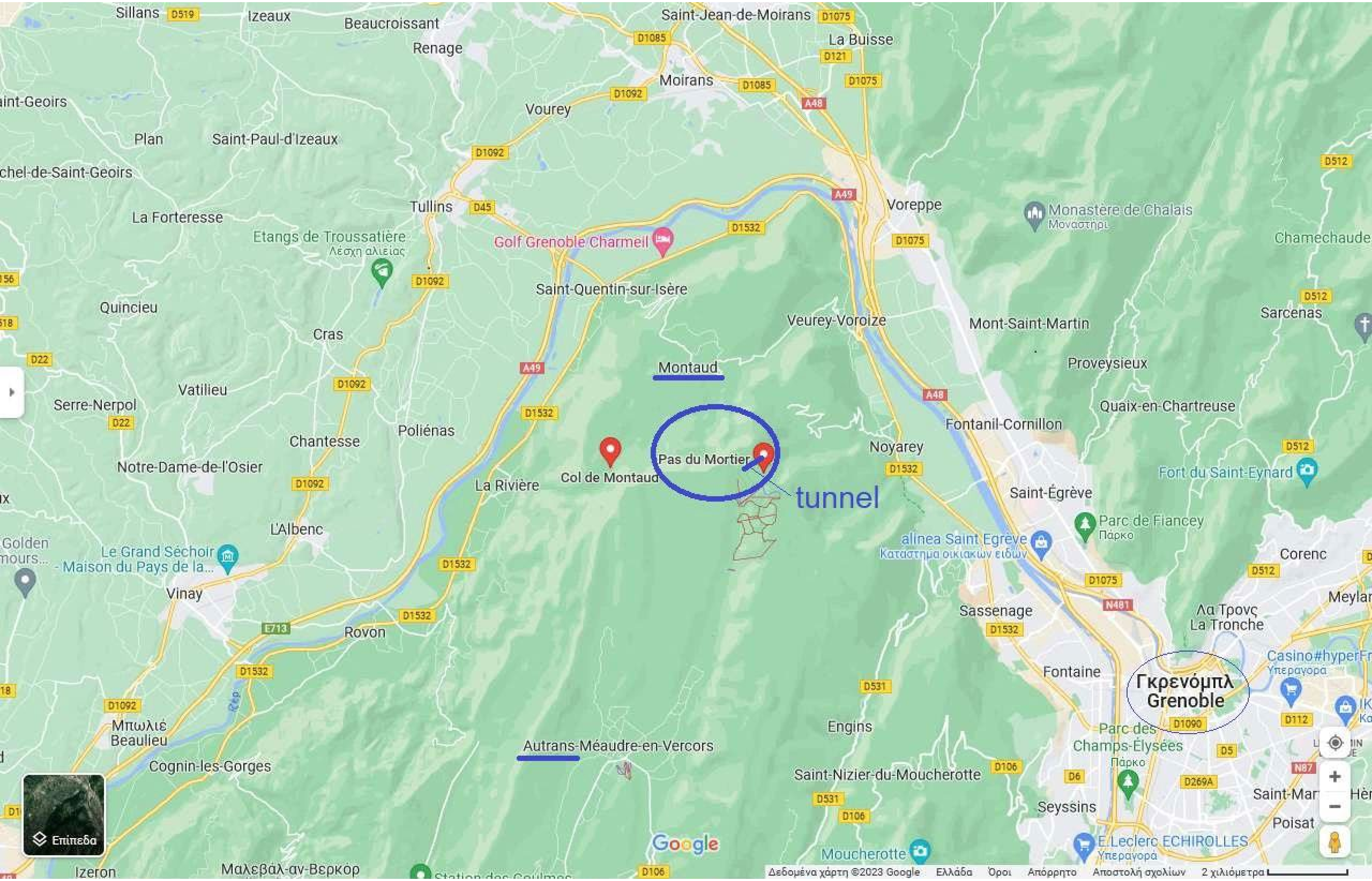
Introduction

- HyTunnel project*
  - Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces
- Recent dispersion experiments by CEA in a full-scale inclined tunnel
  - Only experiments of the first (2020) campaign examined, with helium
- The **aims of the work** are:
  - Analyze the experiments with CFD – understand the phenomena
  - Verify the accuracy of our CFD model in full-scale inclined tunnels

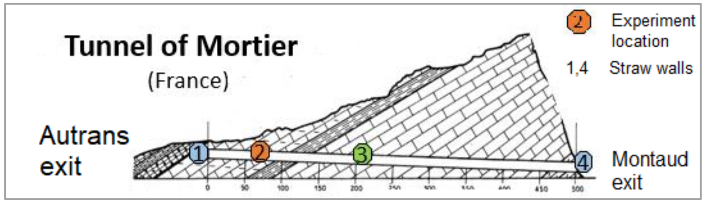
* https://hytunnel.net/

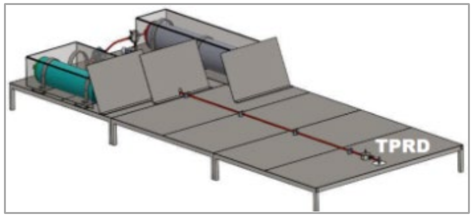
Experiments – tunnel du Mortier

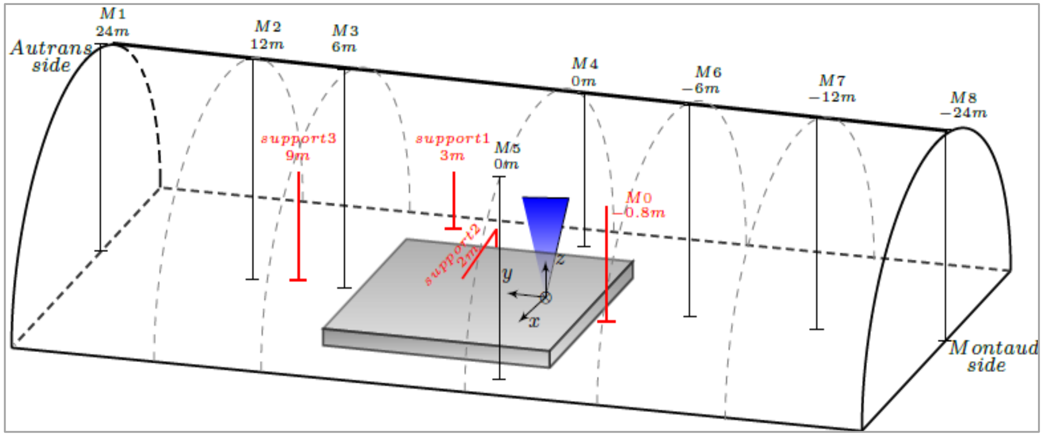


Experimental setup

- Horseshoe tunnel:
  - Slope: 3.6%
  - LxHxW: 502x5.1x7.5 m
  - 4.5x1.9 m plate as a 'car'
- Natural ventilation
- 1st (2020) campaign – helium 200 bar tank
- TPRD can point upwards or downwards
- 8 basic measurement masts



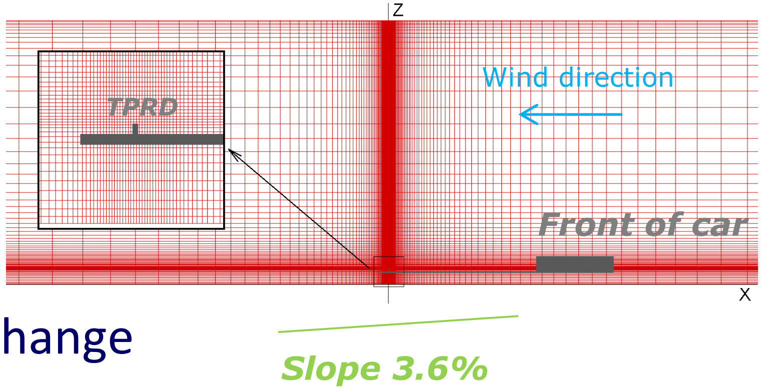




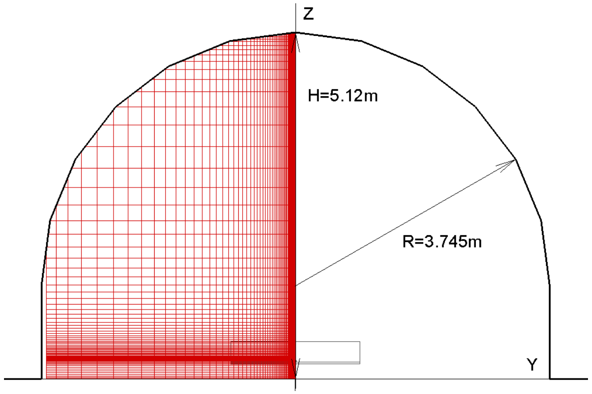
Test Number	TPRD		Initial conditions			Duration (s)	
	Diameter (mm)	Orientation	Abs Pressure (bar)	Temperature (°C)	RH (%)	Blow-down phase*	Total of test
3	2	Upward	0.854	8.5	92.6	303	437
4	2	Upward	0.837	9.9	88.3	426	582
5**	0.5	Upward	0.837	9.2	96.0	180	181
5***	0.5	Upwards	0.837	6.2	89.82	2650	2657
6	3	Upward	0.837	5.3	88.4	145	249
7	3	Upward	0.844	6.4	75.6	145	165
8	0.5	Downward	0.858	5.4	87.6	2890	3242
9	3	Downward	0.859	5.0	88.9	130	794
10	3	Downward	0.860	5.1	88.2	136	674
11	2	Downward	0.860	6.0	88.7	346	729
12	2	Downward	0.861	6.5	90.2	428	599
13	1	Downward	0.861	7.0	94.2	877	890
14	4	Downward	0.859	7.4	94.9	87	562

Tests chosen:
3 : 2mm TPRD, upwards
12: 2mm TPRD, downwards

Simulations setup



- RANS CFD model
  - ADREA-HF code
  - Convective scheme: MUSCL*
  - Slope modelled by gravitational direction change



- Simulations data
  - 302m part of tunnel – no extension outside
  - 192 x 58 x 76 cells (test 3) – symmetry at Y
  - Av. wind: **-0.56** m/s (tests 12); **-0.35** m/s (test 3)
  - X-axis towards Autrans (at right in the simulations)
  - Pre-simulations with no source to establish the flow field
  - Rough wall functions (z_0=0.001 m)
  - Max. CFL=6 (init. time step 5x10^{-5} s)

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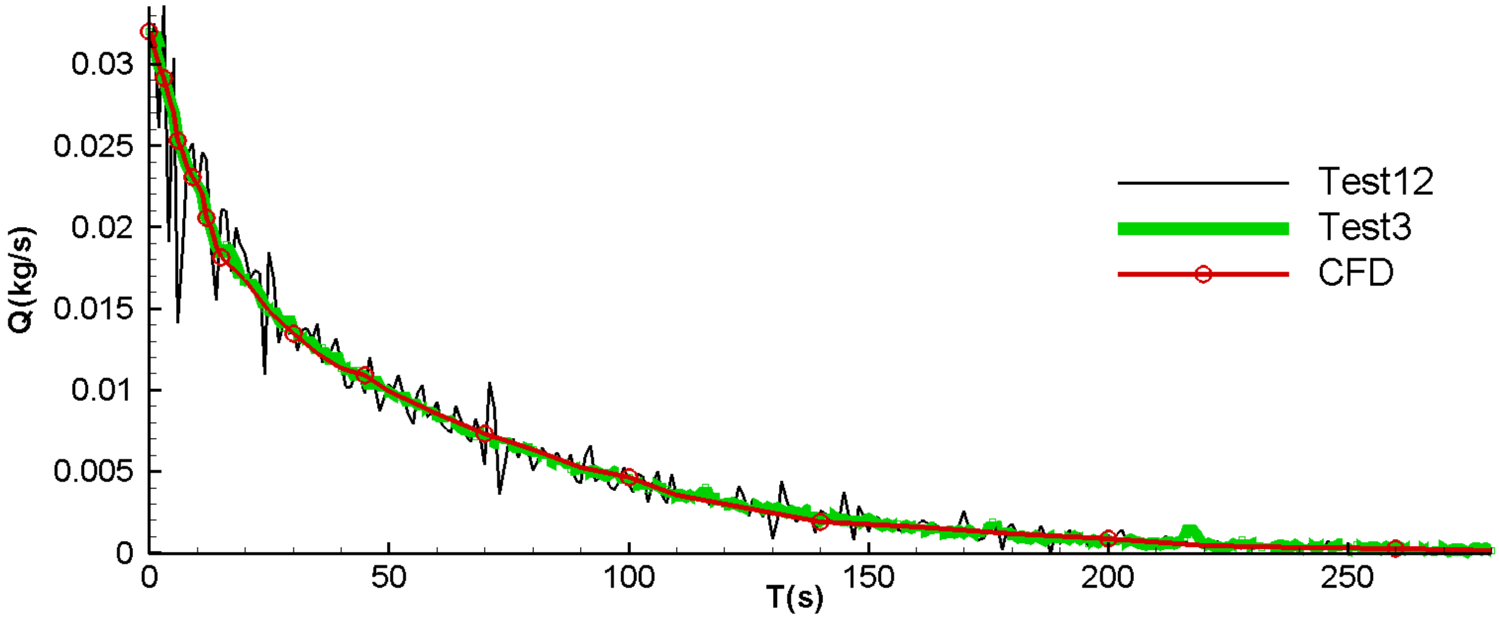
Source modeling

- 4 cells discretization of the source – clean helium emitted
- Birch notional nozzle approach (initial area 2.23×10^{-4} m^2)
- Sonic velocity during the release
- Boundary conditions for *k*, *ε*: Zero-gradient*
- Blowdown the same for both tests



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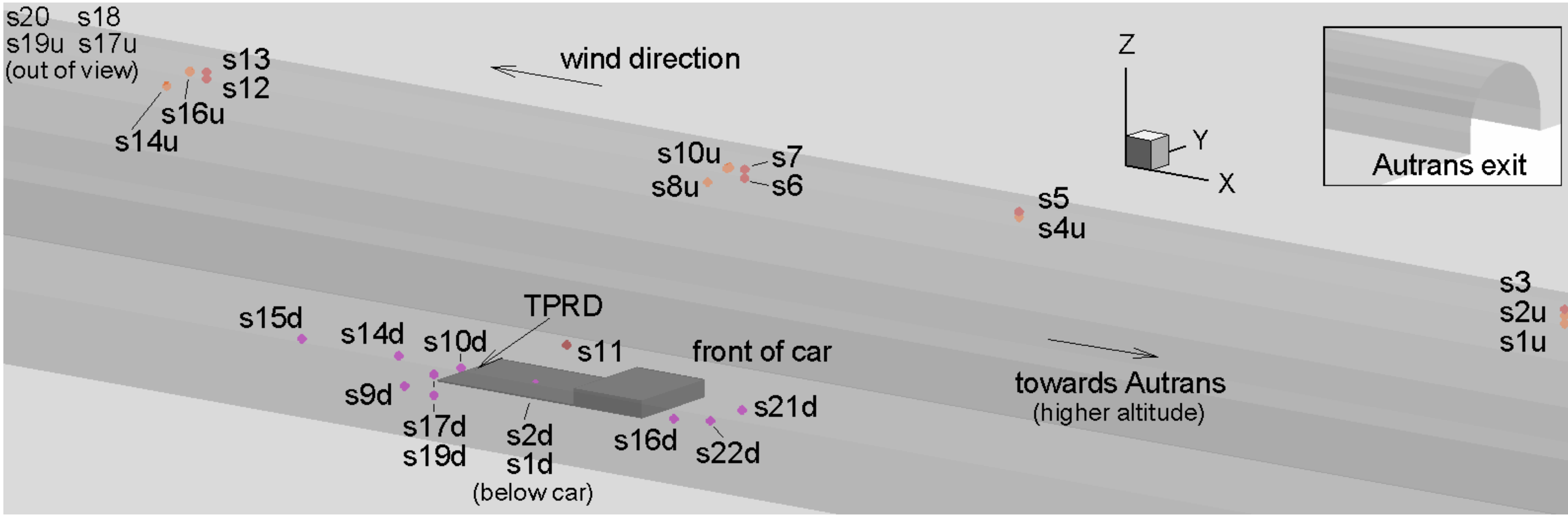
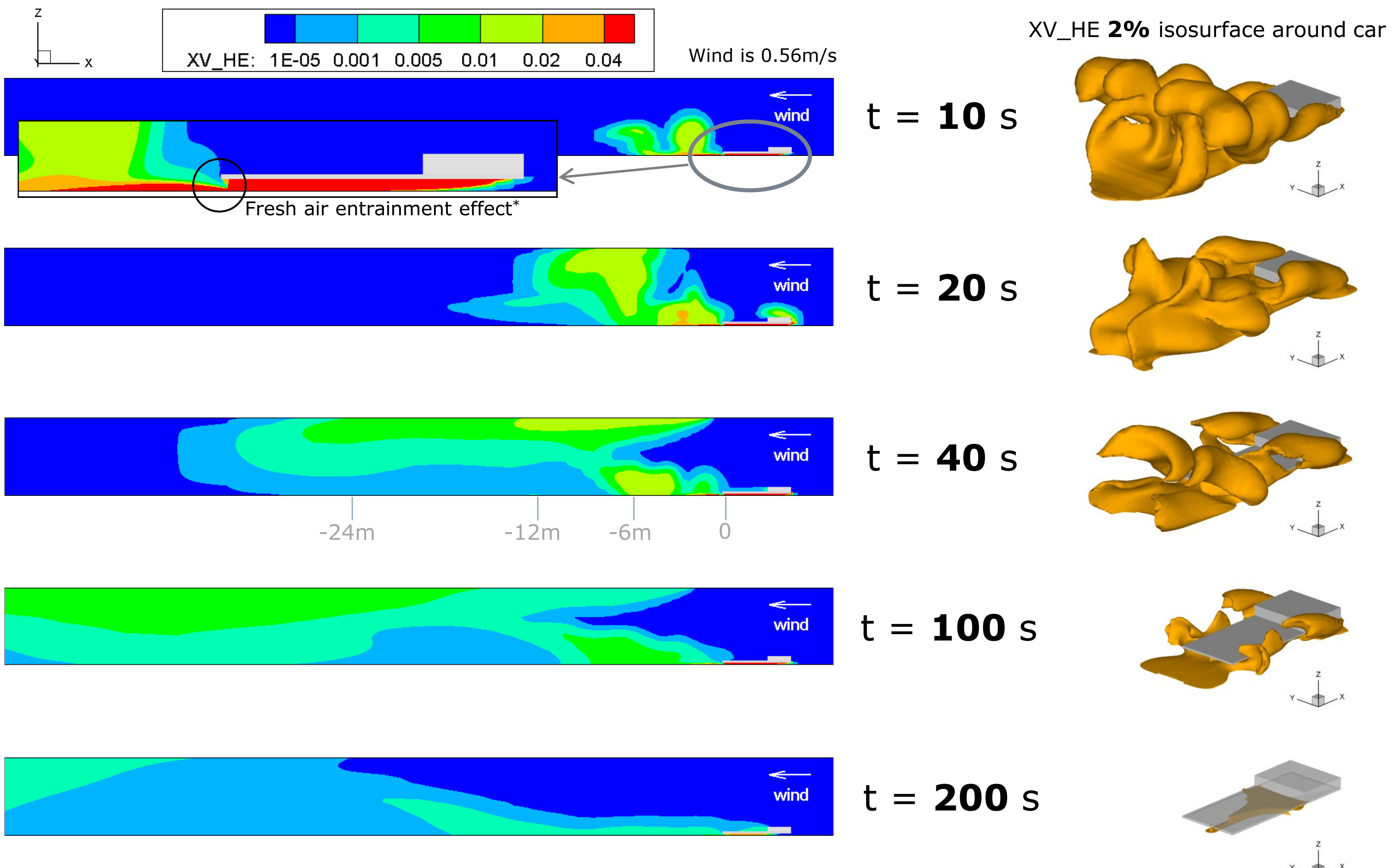
Sensors positions



upwards		**S1u**	**S2u**	**S3**	**S4u**	**S5**	**S6**	**S7**	**S8u**	**S9u**	**S10u**	**S11**	**S12**	**S13**	**S14u**	S15u	**S16u**	**S17u**	**S18**	**S19u**	**S20**	–	–
	X	23.9	23.9	23.9	11.9	11.9	5.92	5.92	5.92	5.92	5.92	2.01	-5.92	-5.92	-5.92	–	-5.92	-11.9	-11.9	-23.9	-23.9	–	–
	Y	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.12	-0.46	-0.54	0.00	0.00	0.00	-1.20	–	-0.50	0.00	0.00	0.00	0.00	–	–
	Z	4.72	4.86	4.98	4.87	4.97	4.67	4.83	4.83	4.96	4.96	1.03	4.71	4.83	4.83	–	4.96	4.89	5.06	4.87	5.01	–	–
downwards		**S1d**	**S2d**	**S3**	S4d	**S5**	**S6**	**S7**	S8d	**S9d**	**S10d**	**S11**	**S12**	**S13**	**S14d**	**S15d**	**S16d**	**S17d**	**S18**	**S19d**	**S20**	**S21d**	**S22d**
	X	1.32	1.32	23.9	–	11.9	5.92	5.92	–	0.00	-0.32	2.01	-5.92	-5.92	-1.69	-3.82	4.37	-0.07	-11.9	-0.07	-23.9	5.86	5.86
	Y	0.00	0.00	0.00	–	0.00	0.00	0.00	–	-2.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.16	0.00	-1.16	0.00	0.00	-0.95
	Z	0.03	0.20	4.98	–	4.97	4.67	4.83	–	0.41	0.25	1.02	4.71	4.83	0.27	0.26	0.03	0.41	5.06	0.03	5.01	0.41	0.41

Test 12 CFD results (downwards release)



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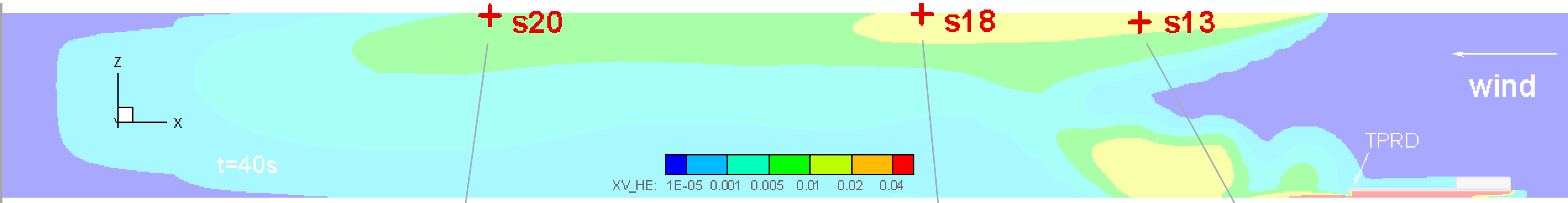
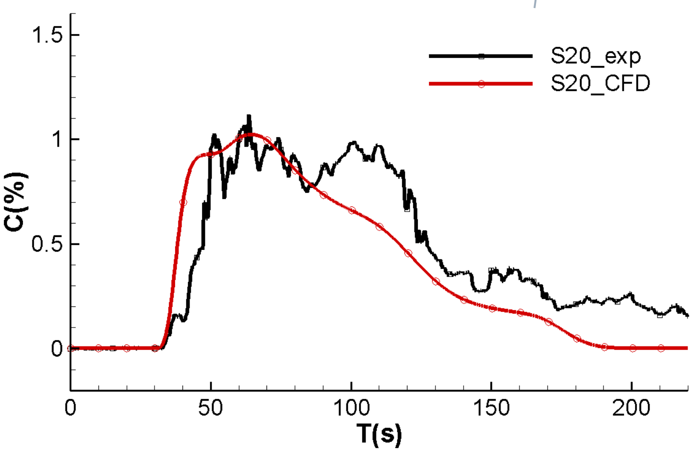
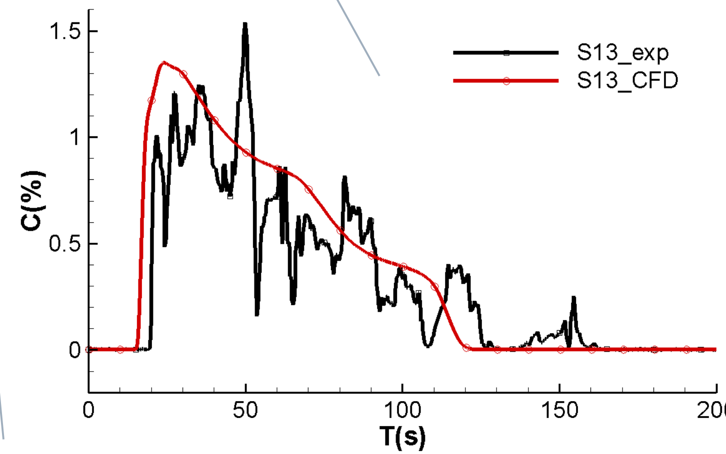
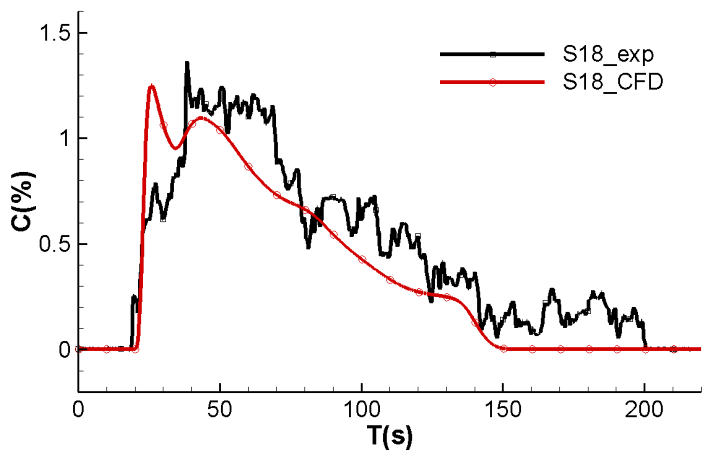
Test 12 CFD results vs. measurements







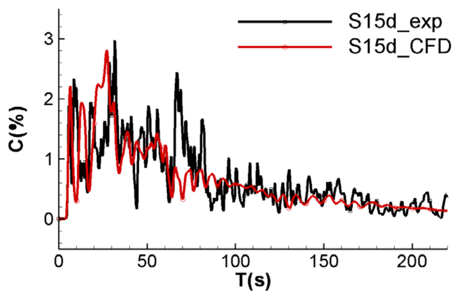
Ceiling sensors

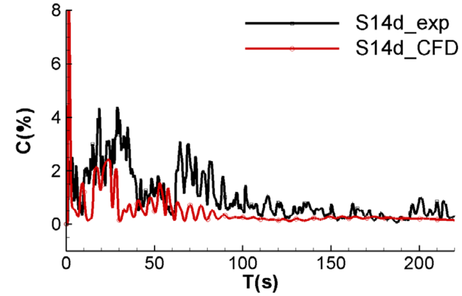


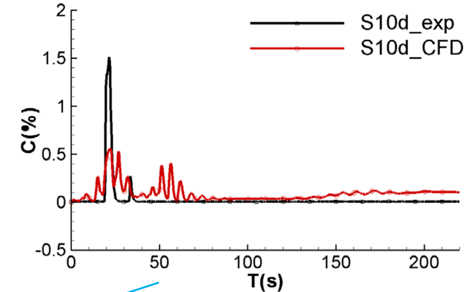
→ Upwind ceiling sensors have zero values

Test 12 CFD results vs. measurements

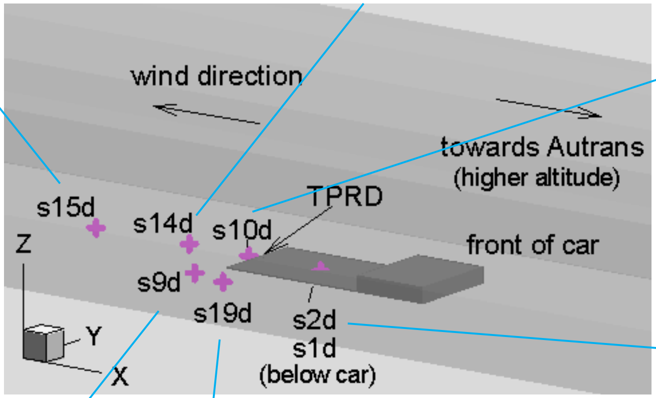
Behind-car sensors



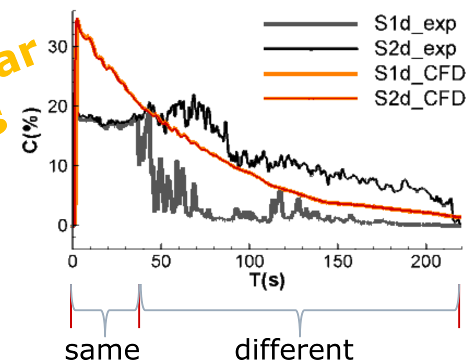




	S1d	S2d	S9d	S10d	S14d	S15d	S19d
X	1.32	1.32	0.00	-0.32	-1.69	-3.82	-0.07
Y	0.00	0.00	-2.14	0.00	0.00	0.00	-1.16
Z	0.03	0.20	0.41	0.25	0.27	0.26	0.03

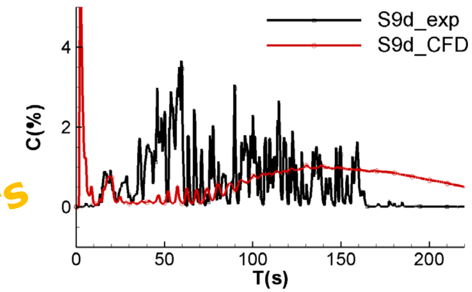


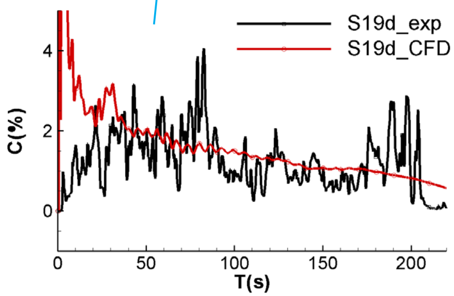
Below-car sensors



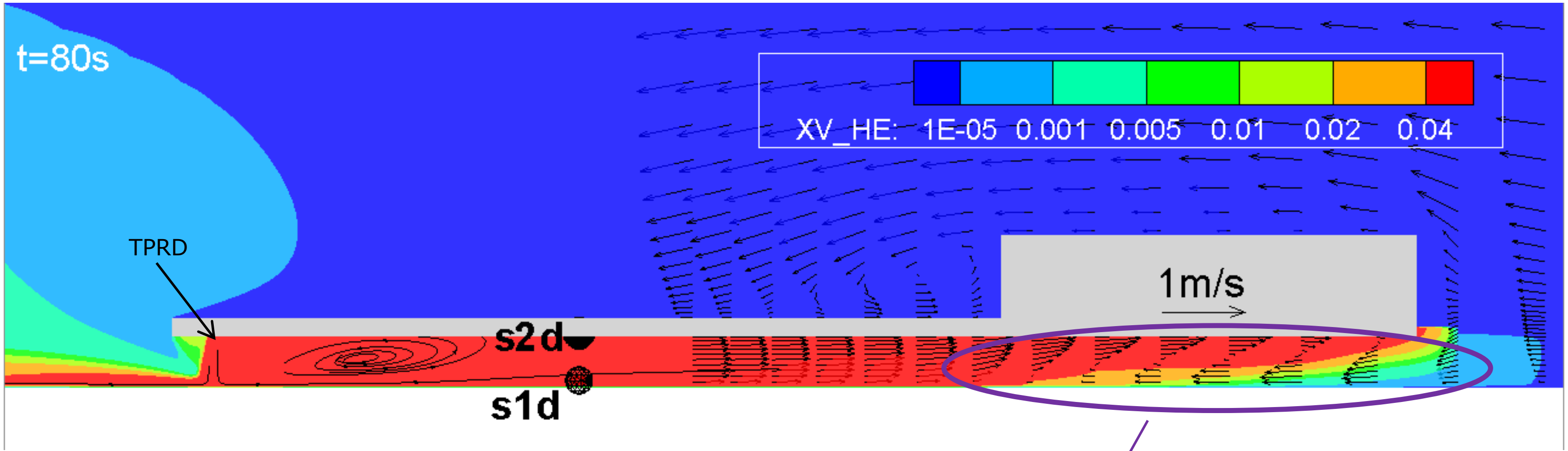
Exp. values of s1, s2 same till 37 s and then different. ***WHY?***

side sensors

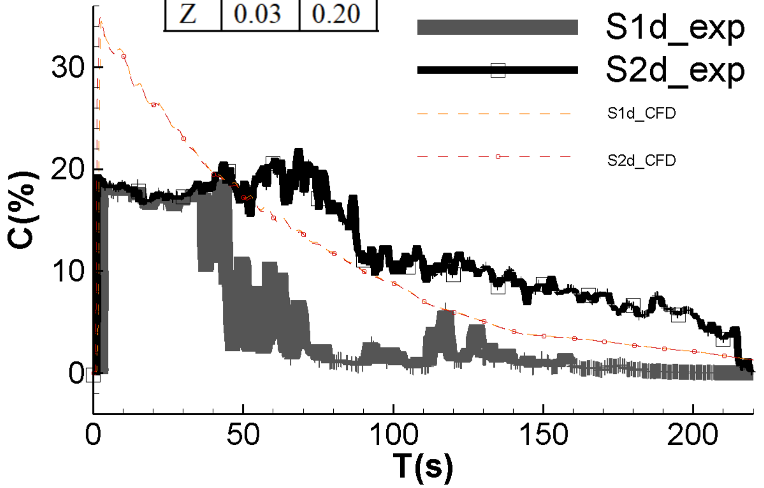




Test 12 CFD results



	S1d	S2d
X	1.32	1.32
Y	0.00	0.00
Z	0.03	0.20



'Street-level backflow effect'*: Air enters from front of car at the level just above the street (reducing the concentrations close to the street), until it collides with the below-chassis helium recirculations due to the jet.
This explains the exp. timeseries of s1, s2 that are initially the same and then different.

Obviously *at CFD the backflow did not reach until sensors 1, 2*, while at the experiment it did
(possibly because the jet recirculations were stronger at CFD?)

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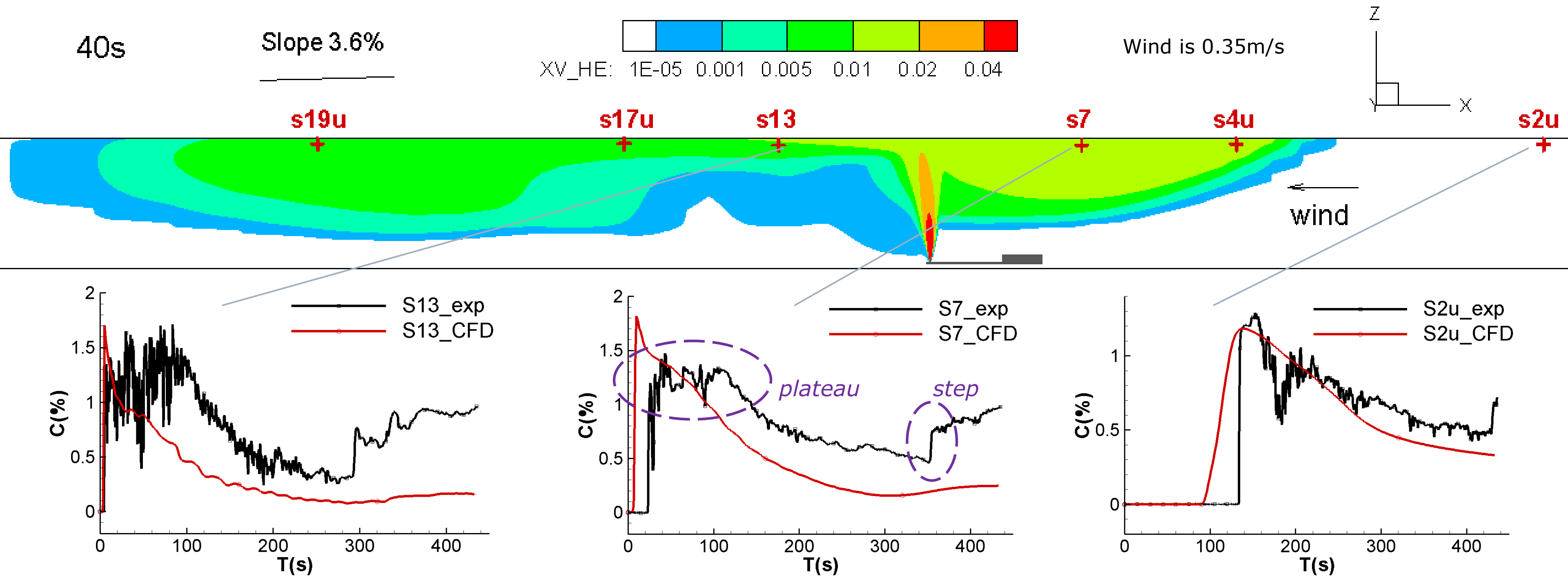
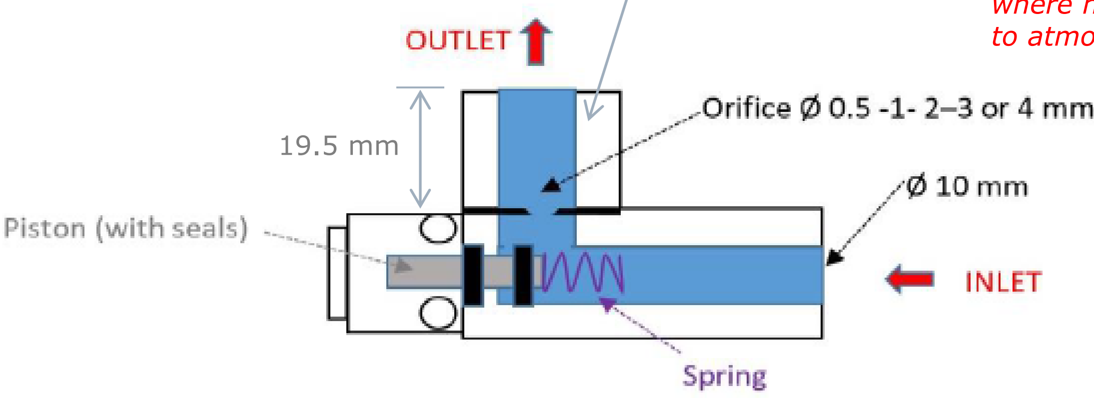
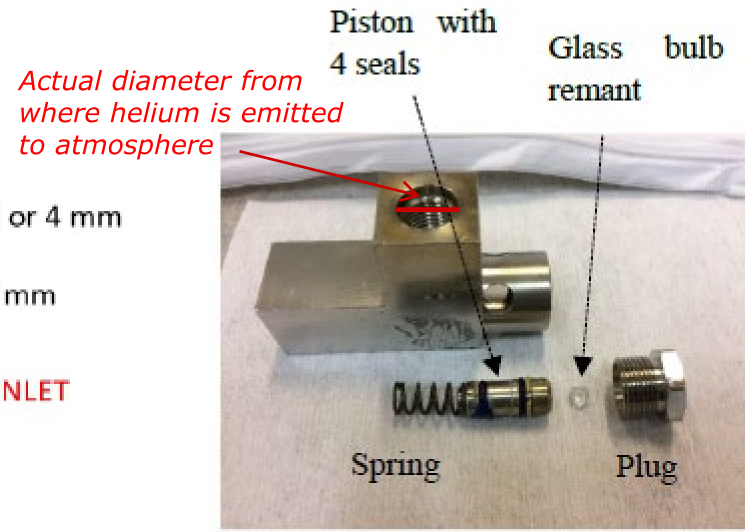
Test 3 CFD results (upwards release)



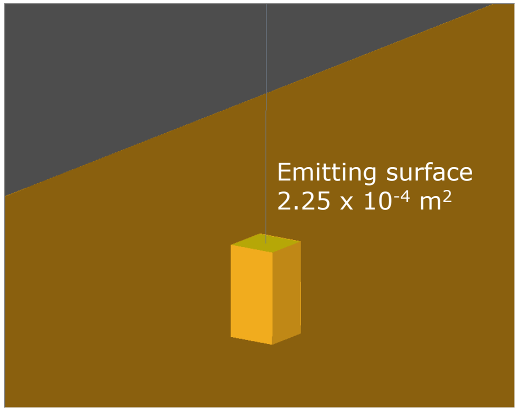
- CFD mainly underestimates the concentrations. Also the 'plateaus' and the 'steps', present at most experimental sensors, are not captured
- Special case: balance between **low** wind speed and buoyancy
- A dozen of sensitivity tests revealed that *low source speed* could partly explain the 'strange' measurements → focus on the source

- Actual TPRD had a ‘nozzle’ of ~20 mm after the 2 mm orifice

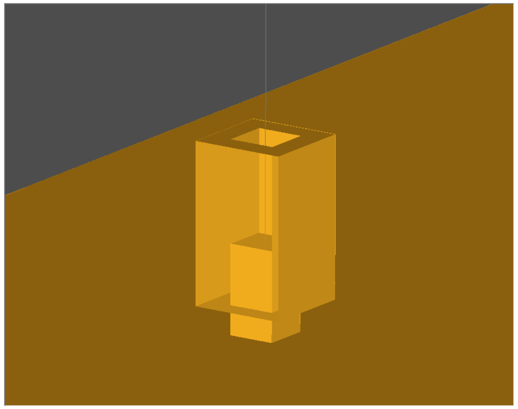




- New draft CFD simulation with new geometry of TPRD area

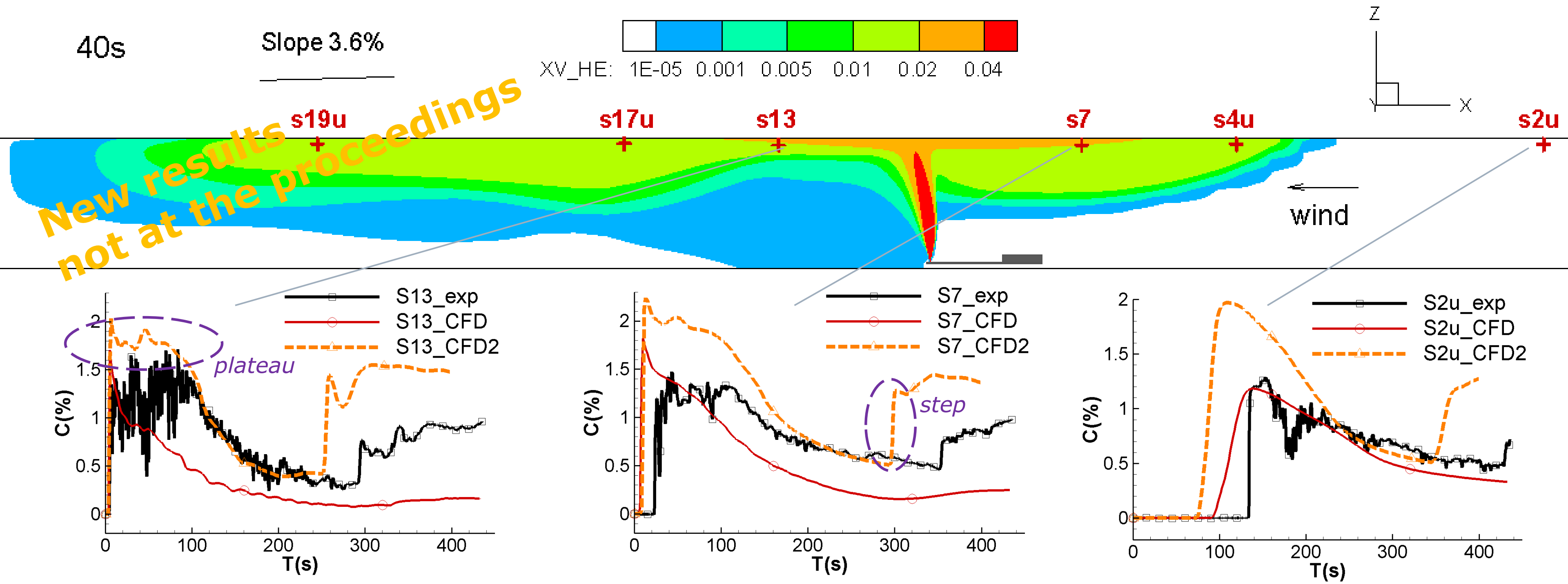


Old TPRD geometry



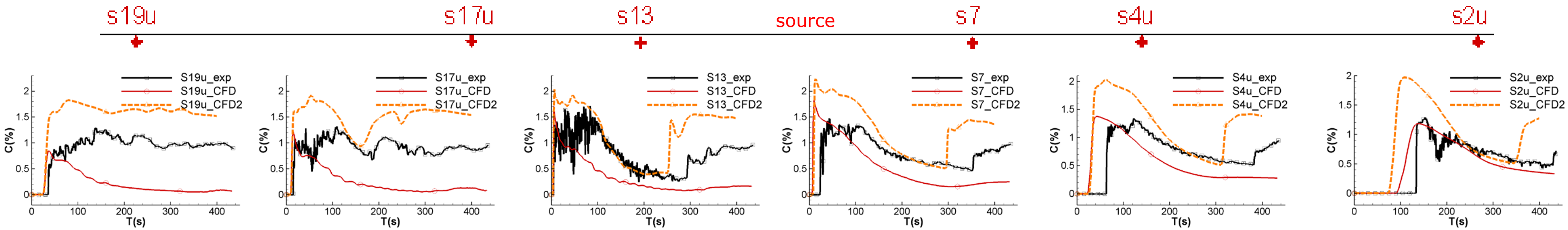
New TPRD geometry

Test 3 CFD results (draft new results)

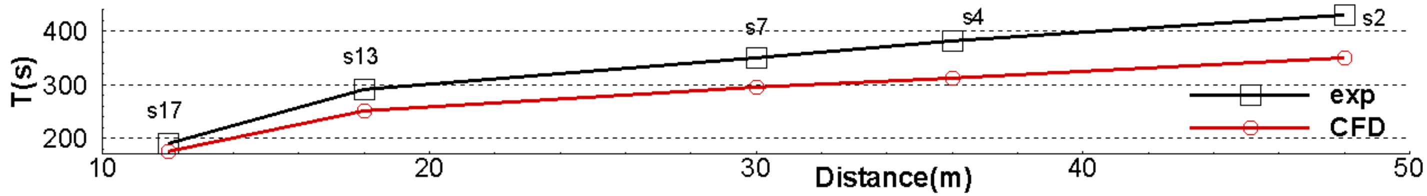


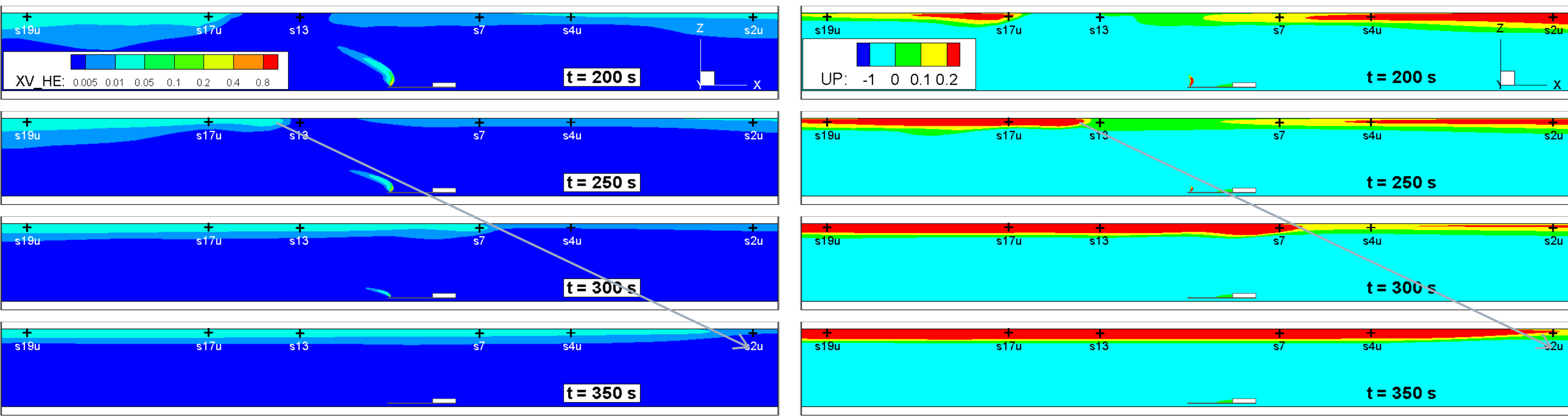
- New results: Contours are different and the jet is more tilted
  - Velocities of jet outside the TPRD are (much) smaller
- **New results** with orange (CFD2): **'plateaus' and 'steps' are present**
  - Possible explanation of overestimation: bigger final TPRD area than the experimental one => lower velocities => higher concentrations

Test 3 CFD results (‘steps’ explained)



Arrival time of ‘step’ vs. horiz. distance from sensor 19 →





High helium gathering at the ceiling at the left of sensor 17 at about 150s-200s. Due to high buoyancy there (and to reduced-speed tilted jet), the particular ‘pack’ (cloud) of helium starts moving towards the right, against the wind. This thin cloud just below the ceiling passes consecutively from all sensors, creating the ‘steps’.

Conclusions

- ADREA-HF: good predictive capabilities of the experimental results
  - Can be used in hydrogen dispersion studies in sloped tunnels
- CFD can help in the design of experiments and in parametric studies
- CFD can help in the interpretation of experimental facts
  - “Street-level backflow” explained ‘strange’ values of sensors 1,2 in test 12
  - ‘Steps’ at timeseries of concentrations in test 3 were explained
- TPRD geometry should be taken into account in more detail
  - This way ‘plateaus’ and ‘steps’ of timeseries were predicted in test 3
- Velocity measurement(s) inside the source-to-ceiling jet may be valuable
- **Phenomena happening inside and close to actual TPRDs should be further examined (theoretically, experimentally and numerically)**

Ευχαριστώ! (Thank you)

Questions ???

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FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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