WHEN TRUST MATTERS

Green Hydrogen Production: Mitigation Measures against Explosions

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UKELG 65th – 27th November 2025

Contents

Dilution Ventilation

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Introduction

- Green Hydrogen Production often makes uses of enclosures
- *Dilution ventilation* to prevent build-up of flammable gas
- Minimize recirculation and stagnant regions
- Considerable research and industry guidance
- Quantitative frameworks to evaluate performance
- Role for modelling tools (and *in-situ* measurements)
- Mostly based on natural gas
- Need to account for hydrogen and its increased reactivity
- Modelling tools also need to be tested for hydrogen

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Objectives

- Literature on ventilation (*performance-based approach)*
- Hydrogen-specific literature on ventilation
- Test an engineering CFD tool on hydrogen data
- Demonstrate use of the model to support design

Dilution Ventilation (natural gas)

- Large ("catastrophic") releases cannot be mitigated with dilution ventilation that is meant to protect from Small leaks
- ACH is not a suitable parameter to evaluate the effectiveness of the ventilation
- A measure of the flammable volume is more adequate
- The flammable volume correlates with the ratio "release rate/ ventilation rate" (and not with ACH)
- To evaluate ventilation, we need to define a release rate first! (0.25m^2 to 25mm^2)
- The research has produced the ISO-21789 standard (for GTs)
- The flammable volume generated by the leak should be less than 0.1% of the enclosure volume
- The performance of ventilation needs to be demonstrated with CFD and measurements
- This criterion has been tested for enclosures of 100m^3 and if V_f < 0.1%, P_{max}<10mbarg
- CFD performed well when compared to experiments where the wind conditions were "steady" but less well for highly unsteady wind conditions
- For large enclosures (>1,000m^3) ventilation needs to be complemented with enhancing Gas Detection
- Ventilation rate is not the only parameter to design for: the distribution of air-inlets and outlets is also key

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Guidance (general)

- API RP 505 – 2025 Edition (January 2025)
- EI 15 (2024)
- IEC 60079 – 10-1 (2020)
- ISO 21789:2022 (GTs, natural gas!)

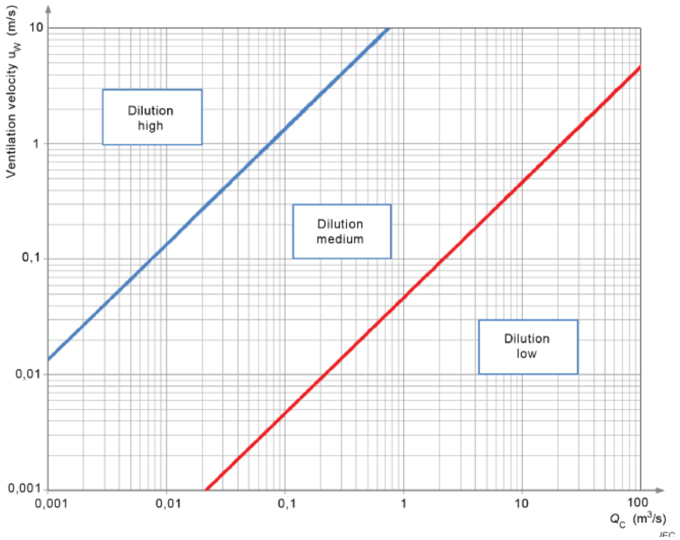
IEC: Ventilation Criterion

hole size (1-2 mm)

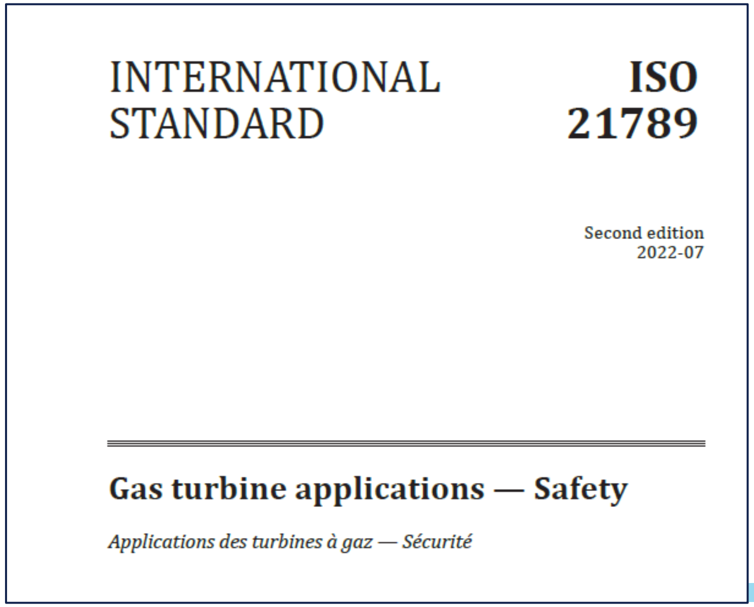
Table B.1 – Suggested hole cross sections for secondary grade of releases

Type of item	Item	Leak Considerations: Typical values for the conditions at which the release opening will not expand	Leak Considerations: Typical values for the conditions at which the release opening may expand, e.g. erosion	Leak Considerations: Typical values for the conditions at which the release opening may expand up to a severe failure, e.g. blow out
		S (mm²)	S (mm²)	S (mm²)
Sealing elements on fixed parts	Flanges with compressed fibre gasket or similar	≥ 0,025 up to 0,25	> 0,25 up to 2,5	(sector between two bolts) × (gasket thickness) usually ≥ 1 mm
	Flanges with spiral wound gasket or similar	0,025	0,25	(sector between two bolts) × (gasket thickness) usually ≥ 0,5 mm
	Ring type joint connections	0,1	0,25	0,5
	Small bore connections up to 50 mm[a]	≥ 0,025 up to 0,1	> 0,1 up to 0,25	1,0
Sealing elements on moving parts at low speed	Valve stem packings	0,25	2,5	To be defined according to Equipment Manufacturer's Data but not less than 2,5 mm² [d]
	Pressure relief valves[b]	0,1 × (orifice section)	NA	NA
Sealing elements on moving parts at high speed	Pumps and compressors[c]	NA	≥ 1 up to 5	To be defined according to Equipment Manufacturer's Data and/or Process Unit Configuration but not less than 5 mm² [d and e]

"degree of dilution"



ISO


INTERNATIONAL STANDARD

ISO 21789

Second edition 2022-07

Gas turbine applications — Safety

Applications des turbines à gaz — Sécurité

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Dilution Ventilation Research (hydrogen)

- Releases in non-ventilated enclosures. A characteristic stratification (in the vertical direction) with almost homogeneous concentration near the ceiling (InsHyde, HySea, Hy4Heat)
- Releases in naturally ventilated enclosures. Natural ventilation can be buoyancy-driven, wind-driven or a combination of both. Depending on speed and direction, wind can either “assist” or “oppose” the buoyancy. Recirculation regions can also disrupt the buoyancy-driven ventilation. Configurations with multiple vents at multiple locations of the enclosure are more effective (HSE UK, tests, HyIndoor)
- Releases in forced ventilated enclosures. Very few data, conflicting findings if not properly analysed

Author	Volume (m^3)	R (hydrogen/ventilation rate)	Effect (conc.)
Ekoto &al., 2012	45	3.5×10^{-1}	none
Lach &al., 2021	60	1.1×10^{-2}	modest
Kim & Hwang, 2024	1.3	8.7×10^{-4}	considerable

Guidance (hydrogen)

- NFPA 2: Hydrogen Technologies Code: *" ventilation should be at a rate not less than 0.3 $Nm^3/min/m^2$ of floor area… "*
- ISO/TR 15916: Basic Considerations for the Safety of Hydrogen Systems*: "Ventilation system should remove hydrogen from the confined space or at least keep its concentration below the appropriate lower flammability limit"*
- DNV-ST-J301: Electrolyser Systems*: "The level of dilution shall be sufficient to reduce the concentration of hydrogen to no greater than 1%, i.e. equivalent to 25% of the lower explosive limit".*

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Model Validation/Testing

Model Validation/Testing (FLACS)

- Source term (release rate, velocity, temperature, expanded diameter)
- Free jet structure (under-expanded jet)
- Dispersion in the enclosures (ventilation, obstacles, confinement, etc.)

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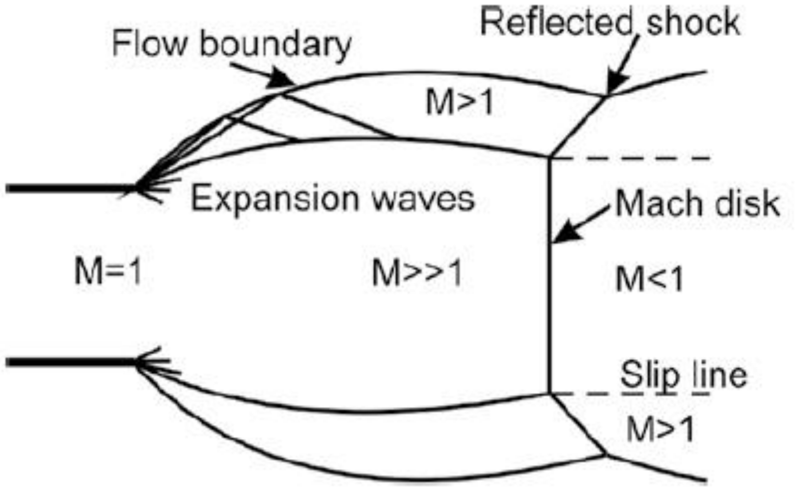
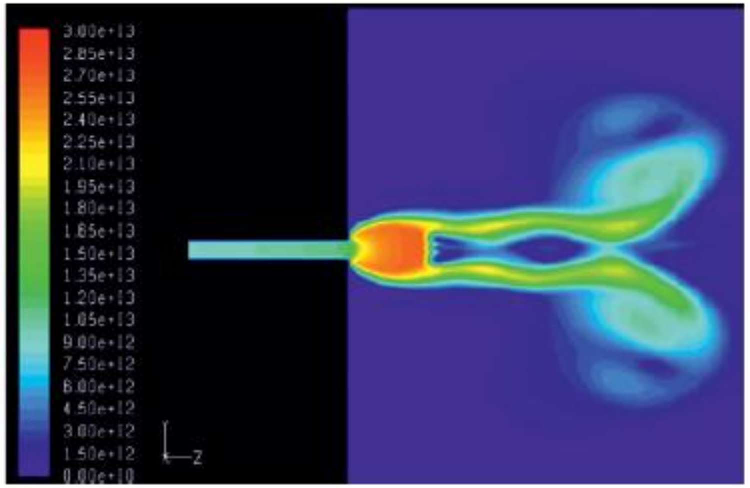
Source term





Several approaches:

- Birch et al., 1984
- Ewan & Modie, 1986
- Schefer et al., 2007
- Molkov et al., 2009

- Sonic velocity at the “notional nozzle” exit seems to work better
- Birch (subsonic) also OK (tends to overestimate concentrations)
- Use Real Gas equation of state for pressure above 100barg (Abel-Nobel EoS)

Pressure (barg)	Z
15.7	1.01
157	1.1
786	1.5

$$PV = ZRT$$

Free under-expanded hydrogen jets

At least three reasons to study free under-expanded H_2 jets:

- They provide good, controlled data to validate the CFD tool
- The initial air entrainment is key to define the concentration profiles and is NOT affected by the ventilation ("momentum dominated region")
- The jet generated shear turbulence is sufficient to produce strong overpressures upon ignition (differently from common HCs)

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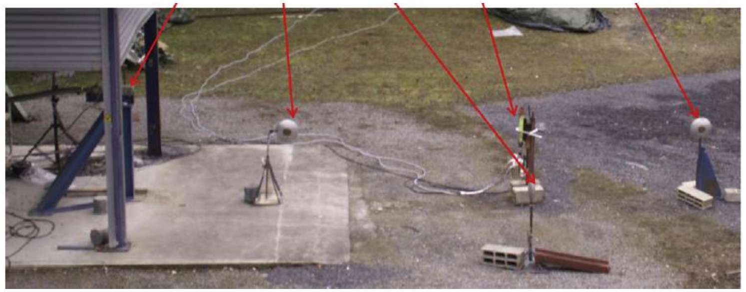
Free hydrogen jets: Data

	P0 (barg)	T0 (degC)	D0 (m)	Release rate (kg/s	z(m)	direction
Roberts &al., 2006	94	13	0.004	0.07	1.5	Horizontal
Daubech &al., 2015	40	10	0.012	0.25	1.5	Horizontal
Tanaka &al., 2007	400	10	0.008	1	1	Horizontal

Roberts & al., 0.07 kg/s

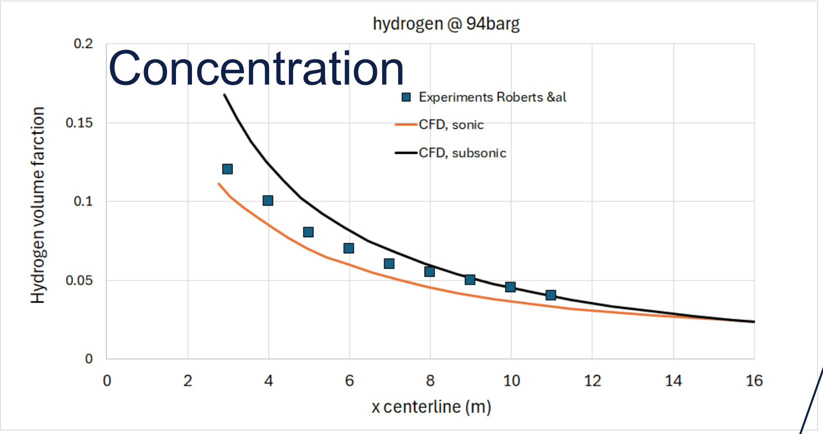
Daubech & al., 0.25 kg/s

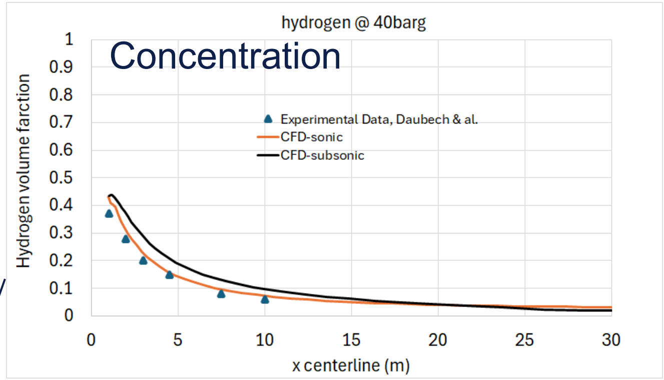


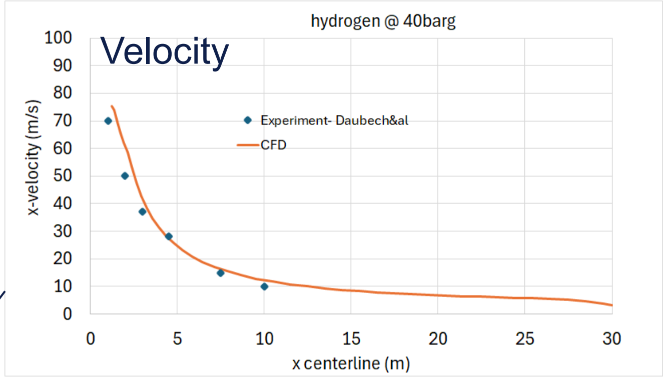
Tanaka & al., 1 kg/s

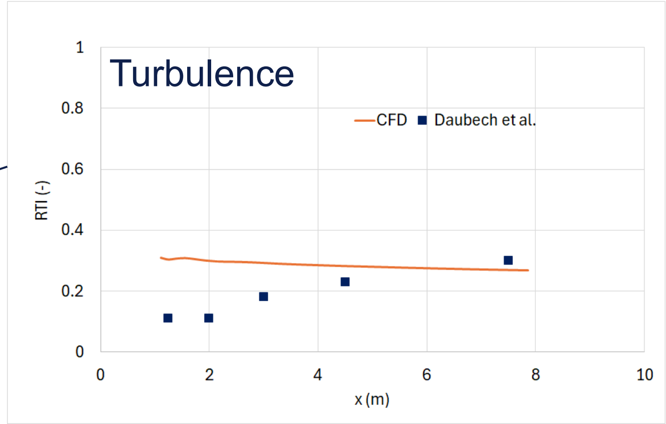
Free hydrogen jets: Model Performance

Roberts &al.

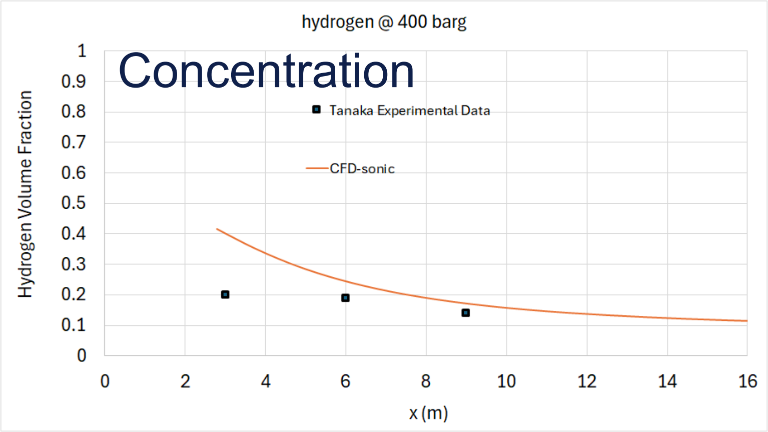








Tanaka & al.



Daubech & al.

Hydrogen Releases in Enclosures: Data

Test ID	Authors
1	Lacome &al., 2007-INERIS
2	Lacome &al., 2007-INERIS
3	Lucas & al., 2020- HySea
4	Lucas & al., 2020-HySea
5	Lowesmith &al., 2009- NaturalHy-DNV Spadeadam
6	Tanaka&al., 2010 - DNV Spadeadam
7	Tanaka&al., 2010 - DNV Spadeadam
8	Lach&al, 2021
9	Lach&al, 2021
10	Lach&al, 2021
11	Lach&al, 2021
12	Lach&al, 2021
13	Lach&al, 2021

- Non-ventilated, natural and forced
- Pressure range: atm - 400 bar
- Release rates: 0.2 g/s – 1 kg/s
- Release: diffuse and jet
- Outflow velocities: subsonic and sonic
- Froude Number: 10^2 to 10^7

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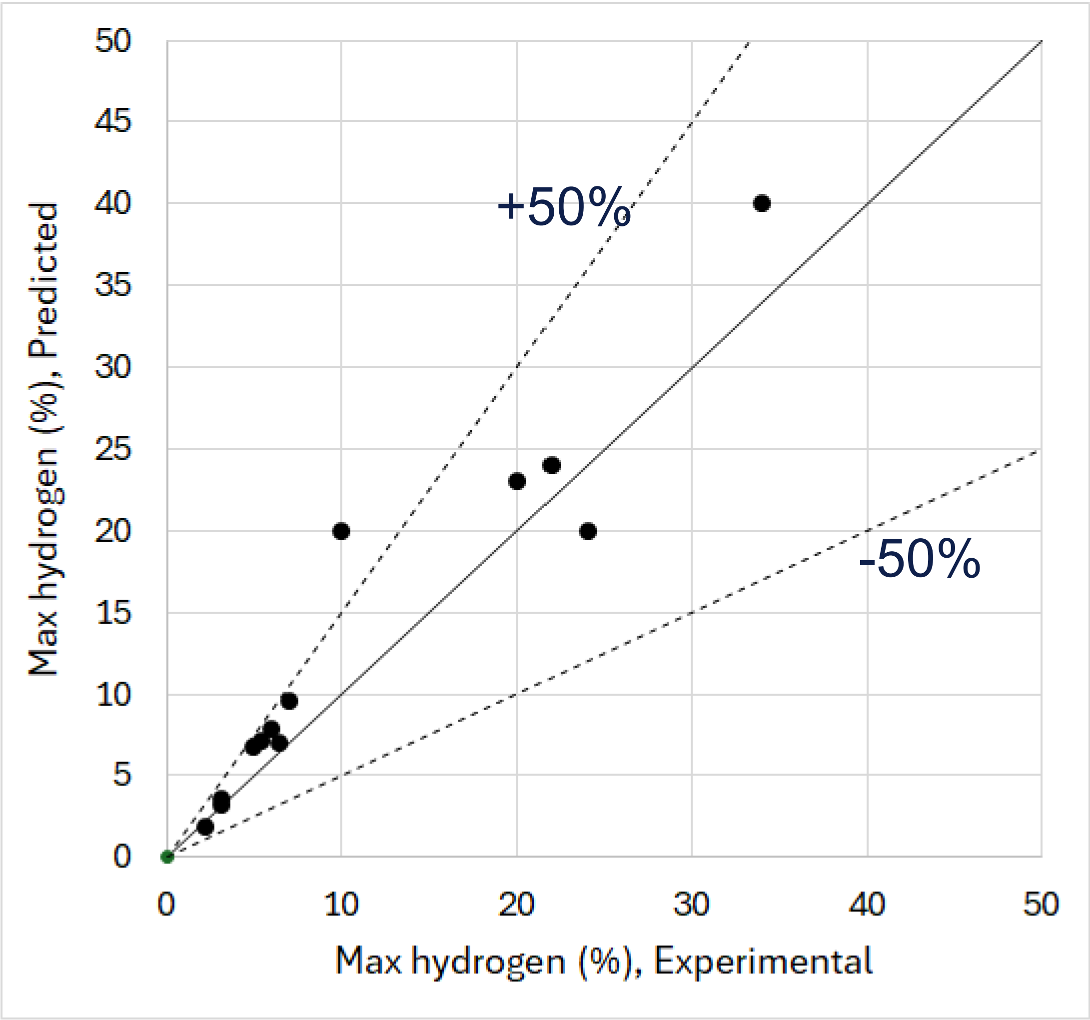
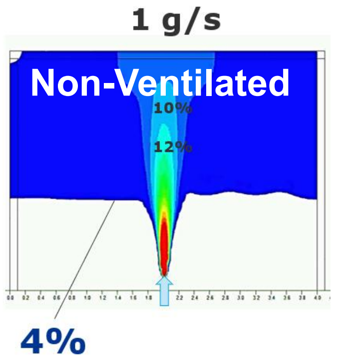
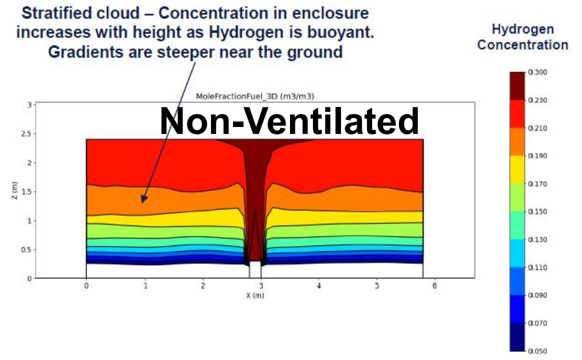
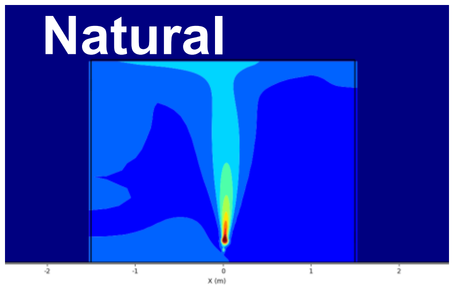
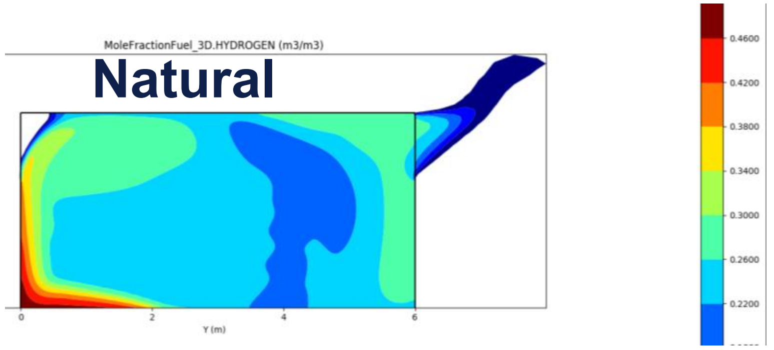
Model Performance: Max Concentration

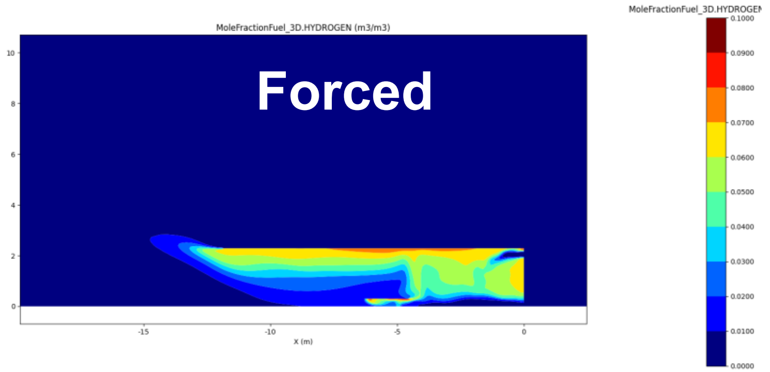




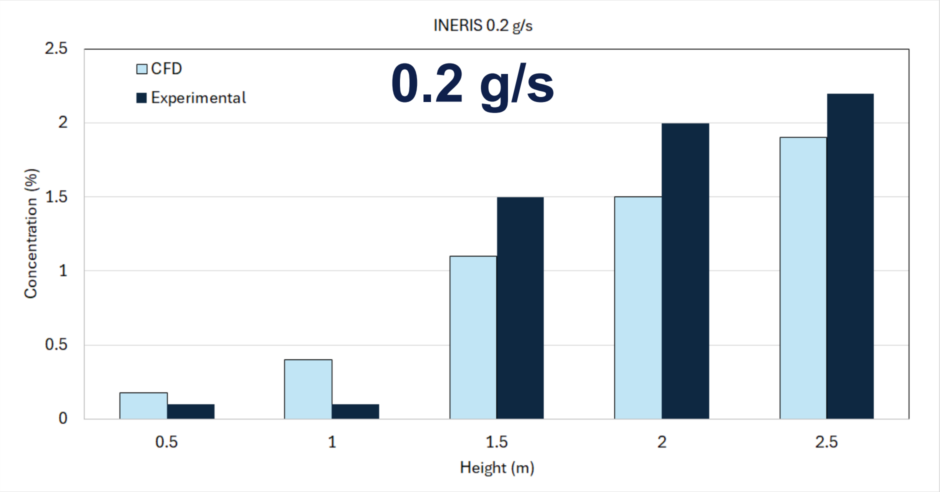


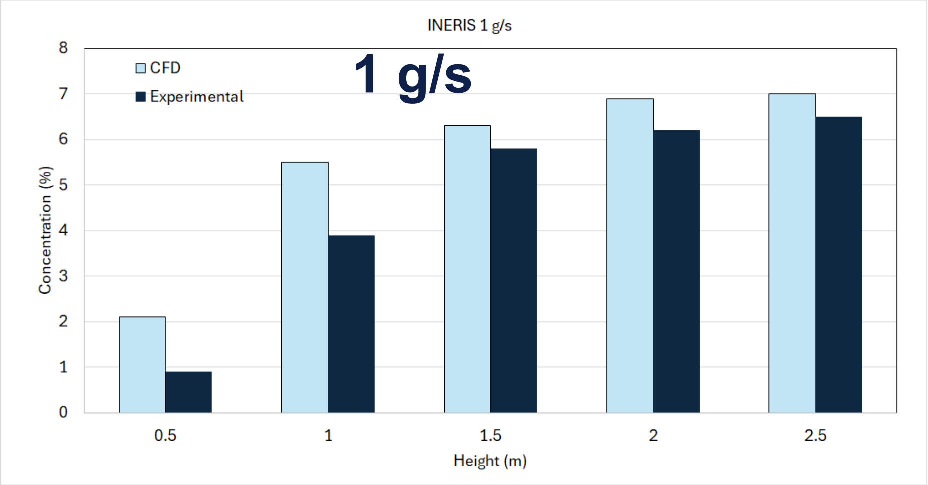


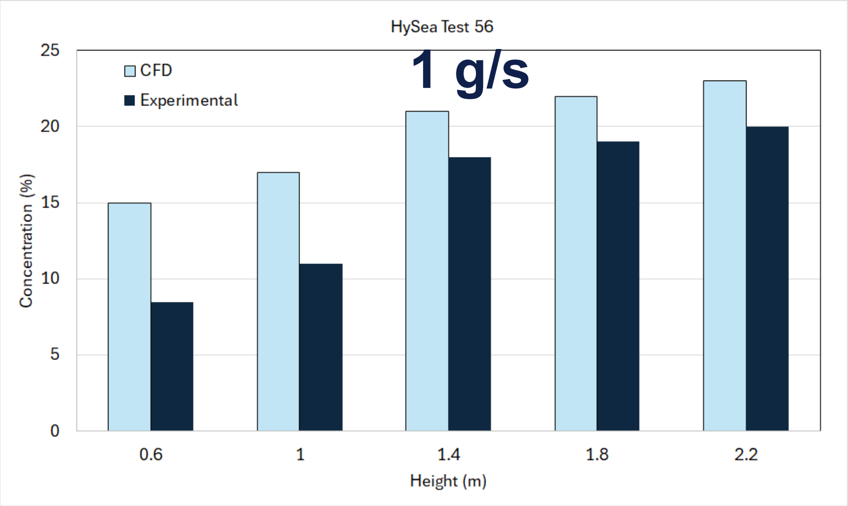


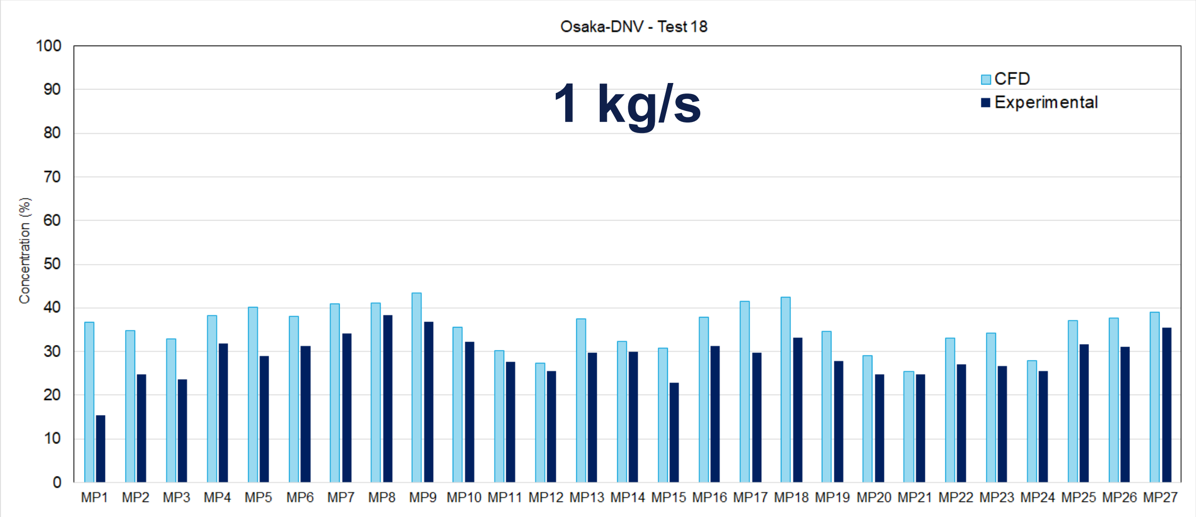


Model Performance: Stratification









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Support to Design: Case Study

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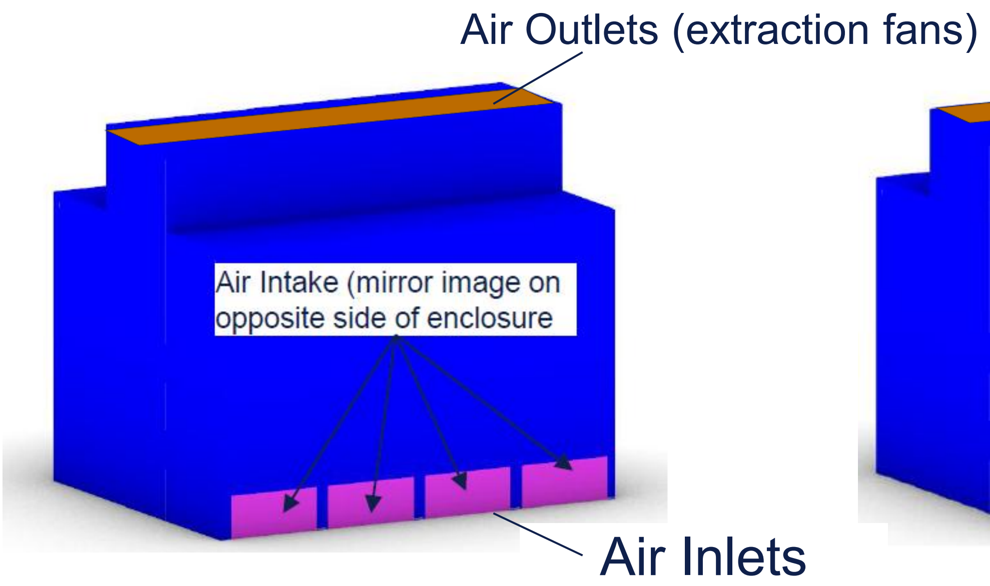
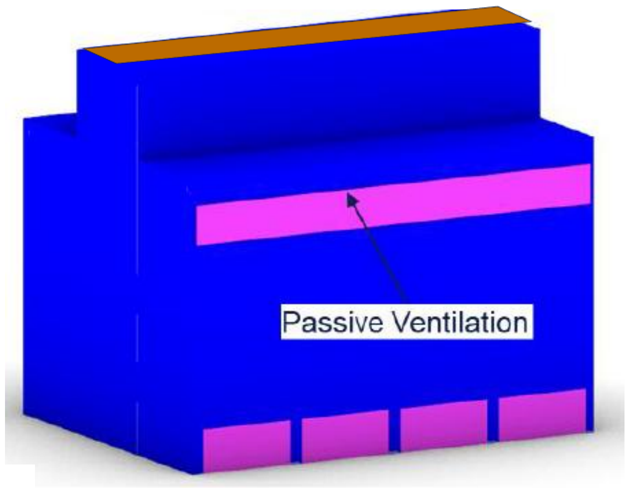
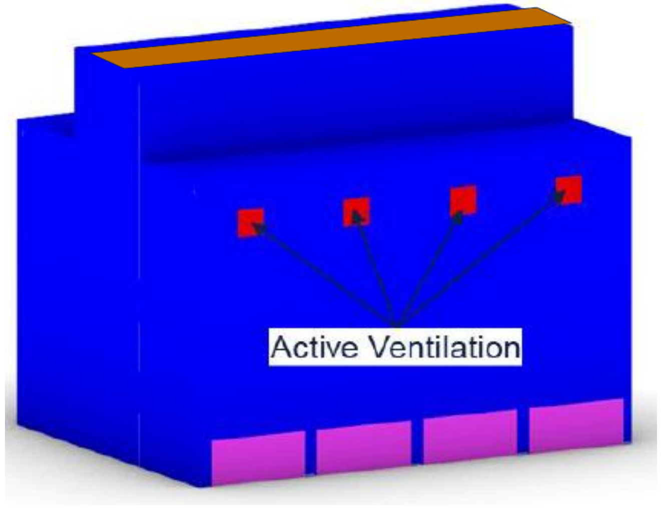
Case Study: Configurations

Five different ventilation configurations were studied with CFD for a compressor shelter (5,000 m^3)







Air extracts at the roof;

Air inlets at floor;

3 Ventilation Air Rates: 50, 100, 200 kg/s (30, 60 and 120 ACH)

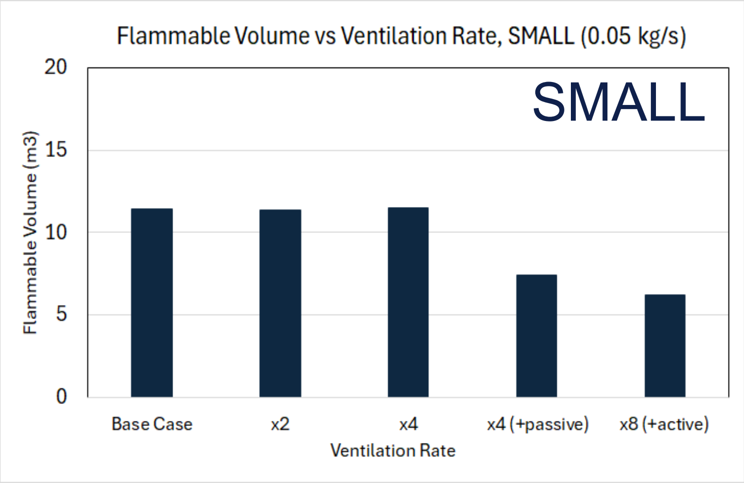
+ Side Wall Openings (passive)

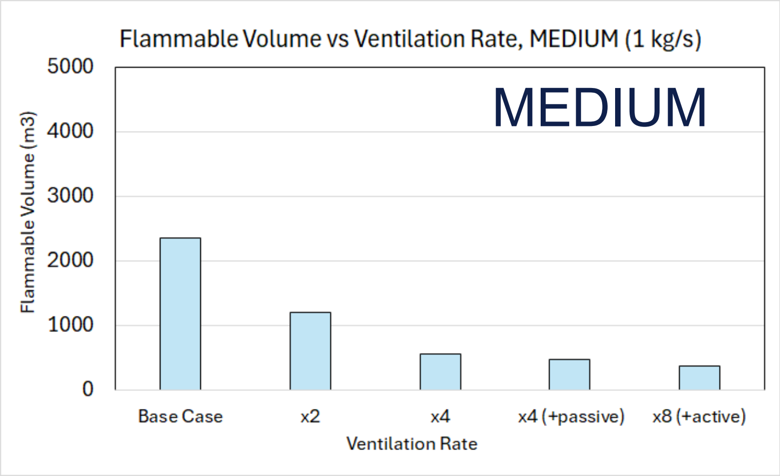
1 Ventilation Air Rate: 200 kg/s (120 ACH)

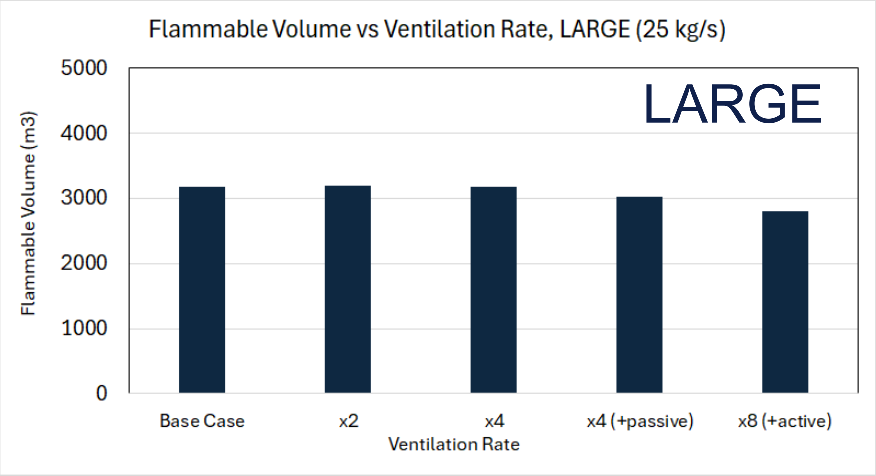
+ Side Wall Openings (active)

1 Ventilation Air Rate: 400 kg/s (240 ACH)

Case Study: Flammable Volume





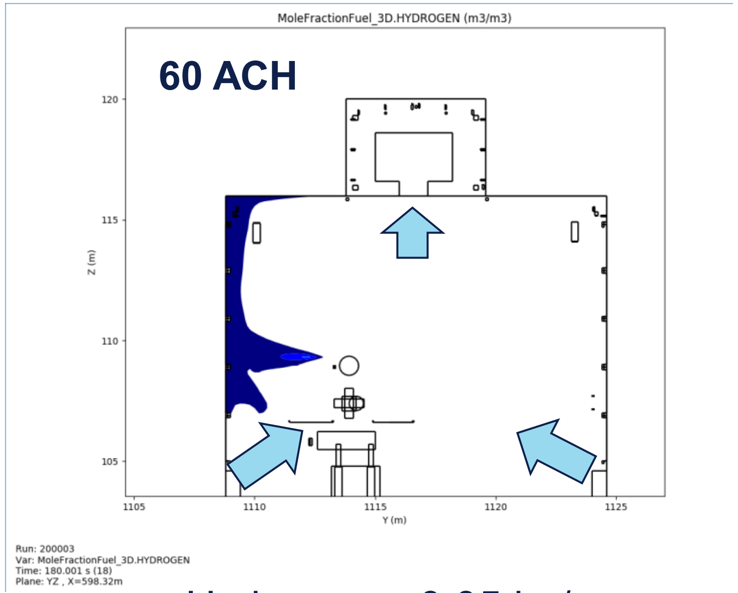


- Considerable reduction of flammable volume for the Small by adding side openings (50% reduction). In any case the Small releases generate filling fraction of order 0.1%
- Considerable reduction for the Medium by doubling the air ventilation rate (50% reduction). One order of magnitude reduction by an eightfold increase of the ventilation rate
- Modest reduction for the Large (even for an eightfold increase of air rate).
- Max filling fractions: 0.2%, 47% and 64% respectively for S, M and L
- Note that SMALL was calculated for 5mm; if 1 mm was considered, $V_{f,max} = 1m^3 = 0.01$ %

Configuration	ACH
Base Case	30
x2	60
x4	120
x8	240

Case Study: Distribution of Inlets/Outlets

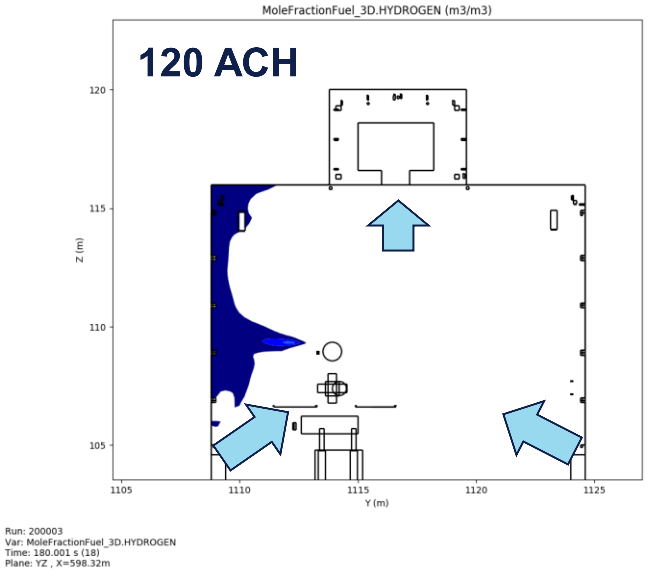
Hydrogen concentration (LFL-UFL)



Hydrogen = 0.05 kg/s

No side openings

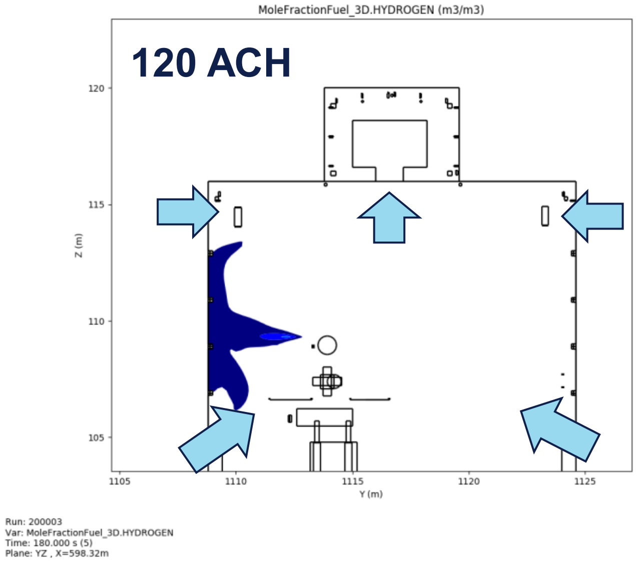
Hydrogen concentration (LFL-UFL)

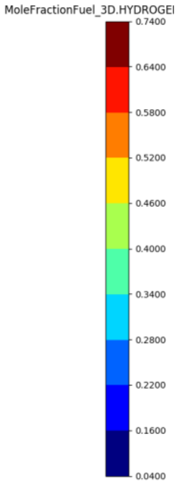


Hydrogen = 0.05 kg/s

No side openings

Hydrogen concentration (LFL-UFL)





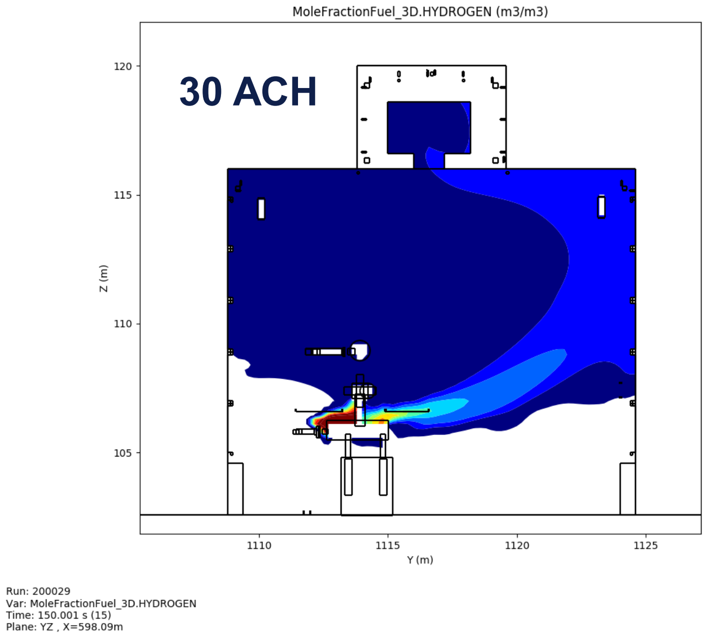
Hydrogen = 0.05 kg/s

Side openings

- Side openings promote dilution of stagnant pockets
- In some conditions, ventilation rate alone is not enough, and distribution of inlets/outlets is more effective

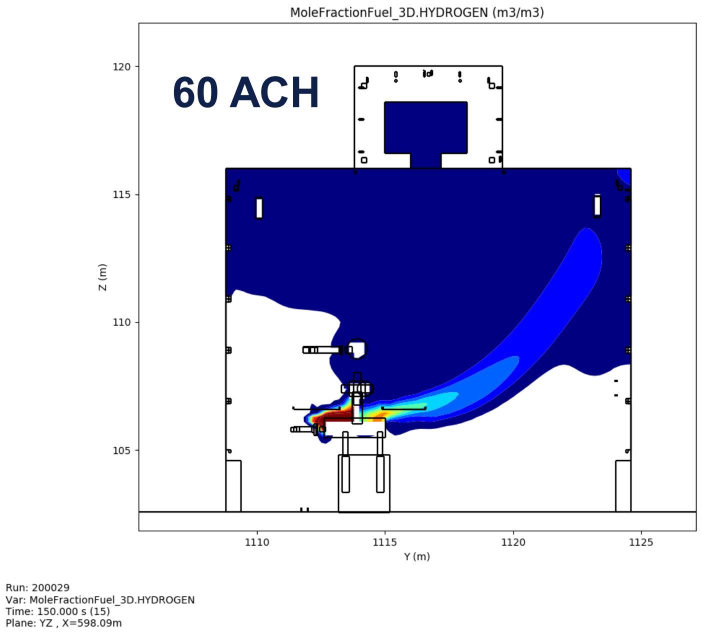
Case Study: Increasing Air Rate

Hydrogen concentration (LFL-UFL)



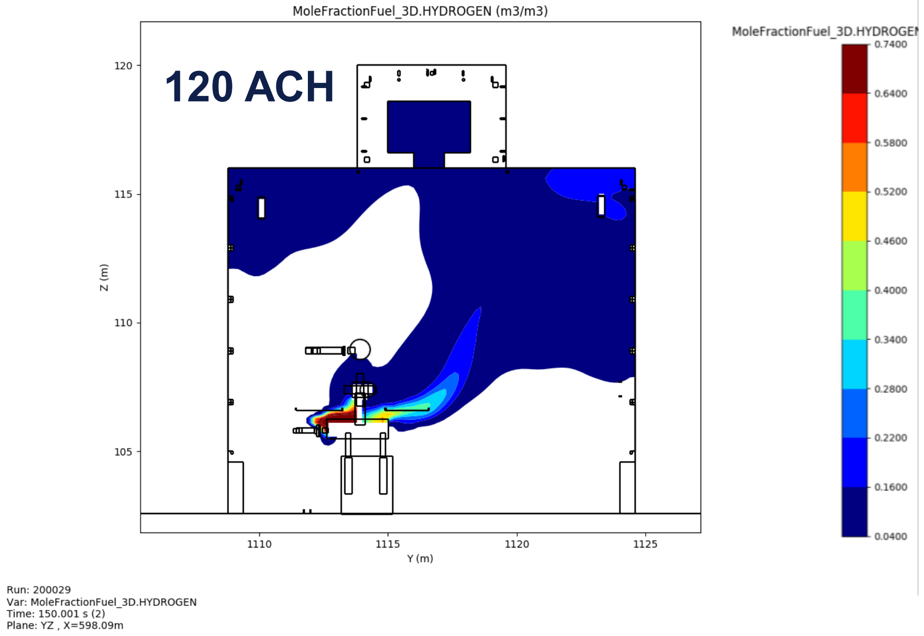
Hydrogen=1 kg/s

Hydrogen concentration (LFL-UFL)



Hydrogen=1 kg/s

Hydrogen concentration (LFL-UFL)



Hydrogen=1 kg/s

- Increasing air rate promote dilution of regions where gas has lost momentum and can clear significant part of the enclosure

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Support to Design: Remarks

- Ventilation has good potential to dilute flammable gas for S and M releases.
- The ventilation rate is not the only design parameter: distribution of air inlets and outlets is also key
- Even when dilution is good (S and M), ventilation alone cannot eliminate the flammable hazard (especially for high-pressures typical of a compressor room).
- It needs to be complemented with all the other mitigation measures: control of ignition sources, gas detection and automatic isolation, explosion relief venting, etc.
- Ventilation is not a substitute of good design (i.e., selection of material, minimization of the inventories, minimization of the size of the piping/connection etc.)

Conclusions

Conclusions

- Current guidance for the design of ventilation systems handling hydrogen is lacking or not fully quantitative
- CFD engineering tools can reproduce experimental trends - of systems handling hydrogen - in a wide range of conditions. Hence, they can be a valuable support for the design of ventilation
- A mix of modelling, full-scale testing - when possible - and a good look at the past is the best recipe to support design.

“We see further by standing on the shoulders of giants”, Isaac Newton, 1675

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Thank You

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Geometry of the jet as a function of Froude Number

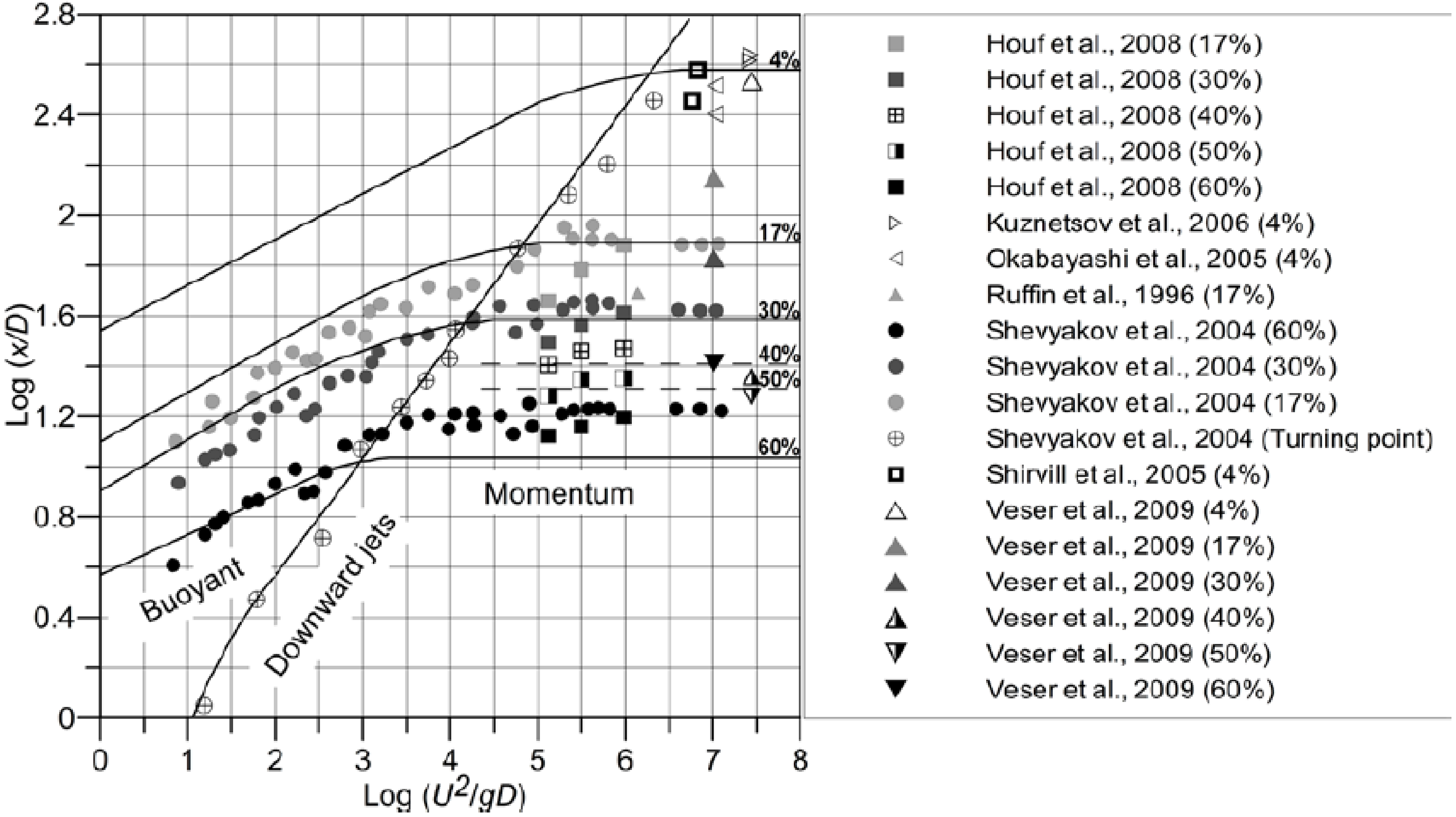
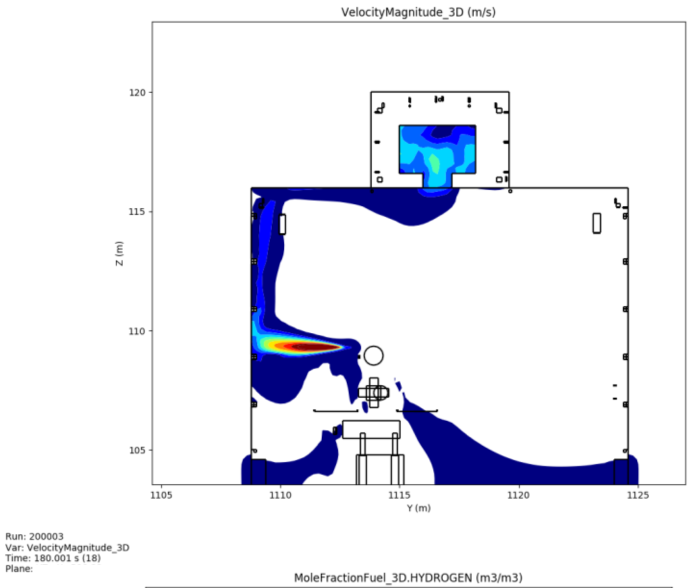
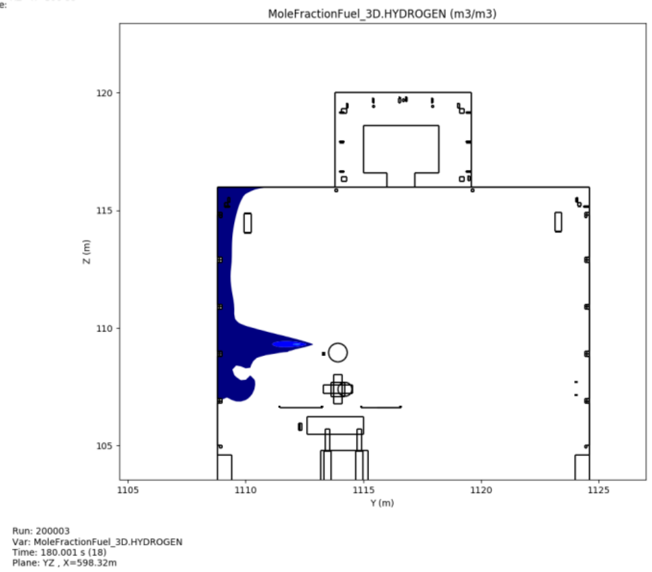


Figure 5–8. The dependence of the distance to nozzle diameter ratio for particular concentration of hydrogen in air on the Froude number.

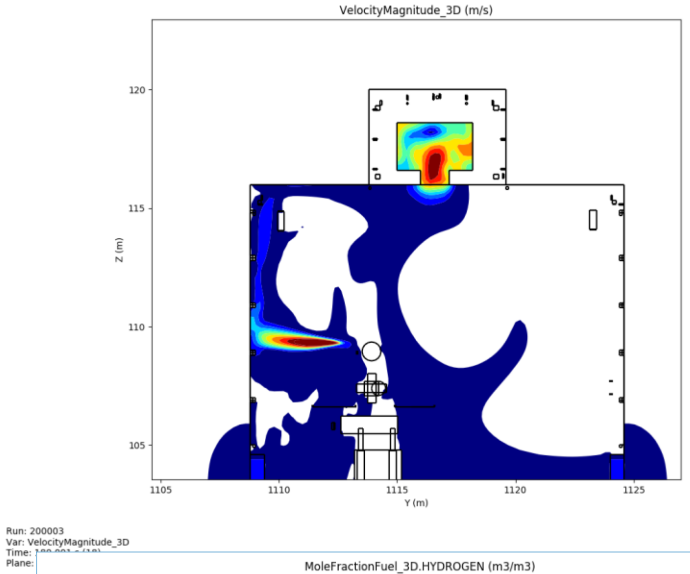
Small

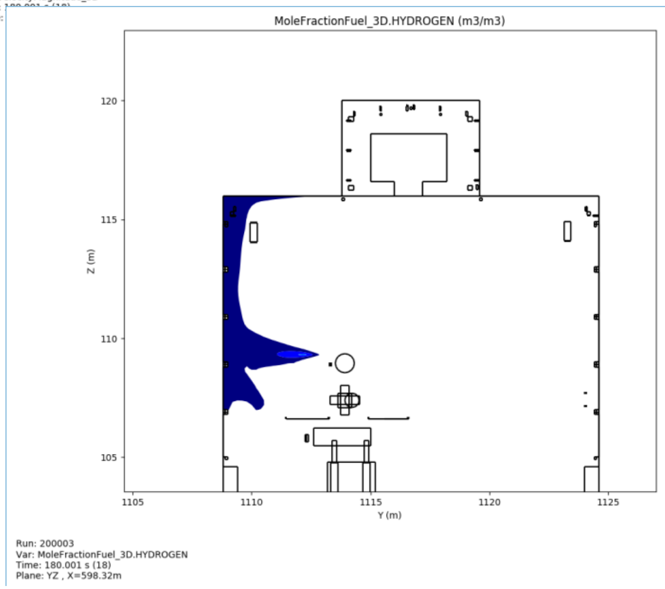
50 kg/s



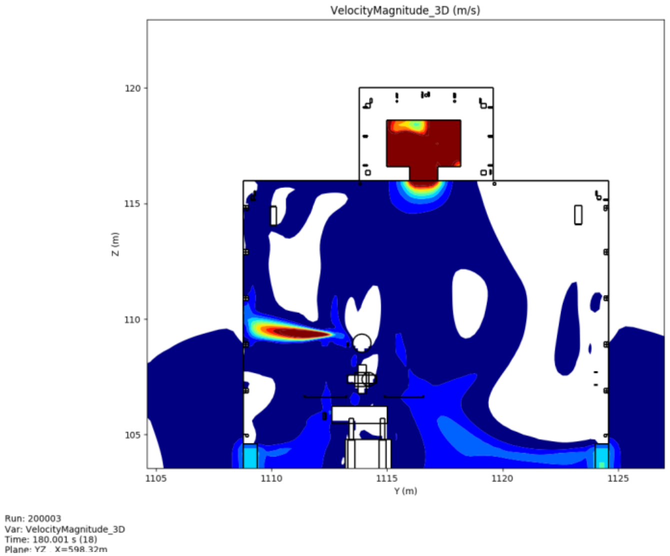


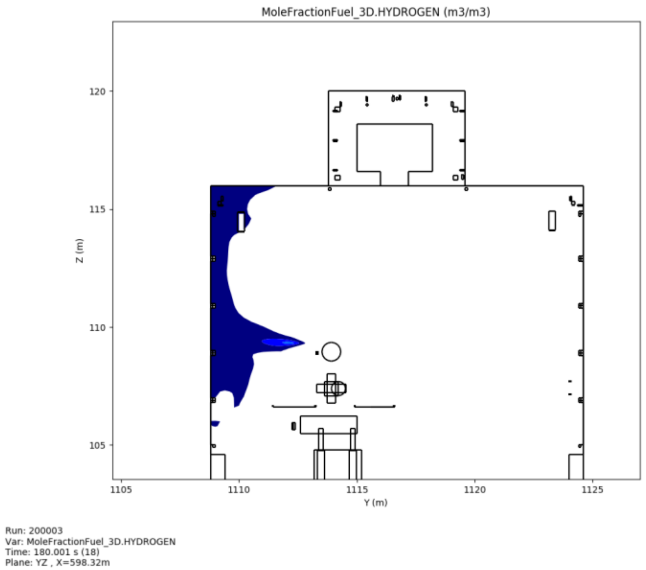
100 kg/s





200 kg/s

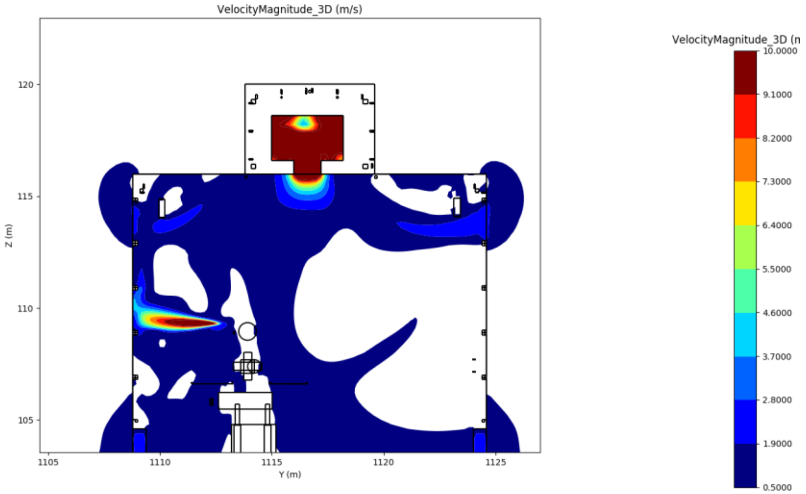




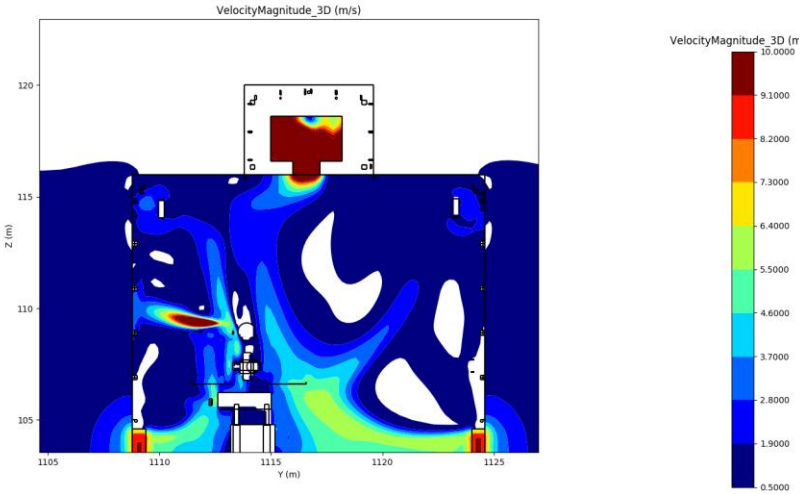
Small

200 kg/s, additional side openings (passive)

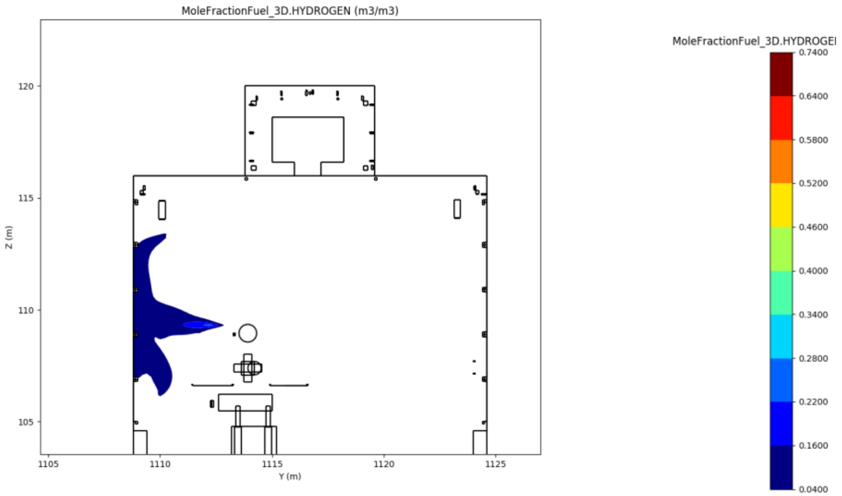
400 kg/s, additional side openings (active, forcing air ir



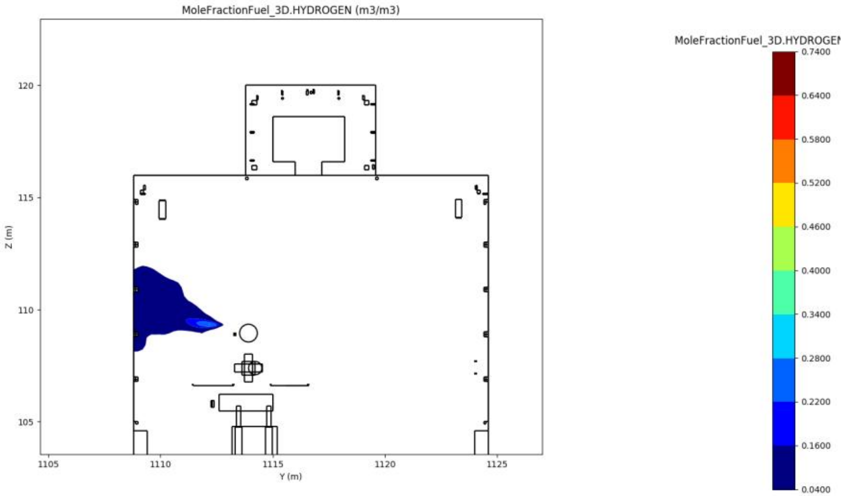
Run: 200003
Var: VelocityMagnitude_3D
Time: 180.000 s (5)
Plane: YZ , X=598.32m



Run: 200003
Var: VelocityMagnitude_3D
Time: 180.001 s (5)
Plane: YZ , X=598.32m



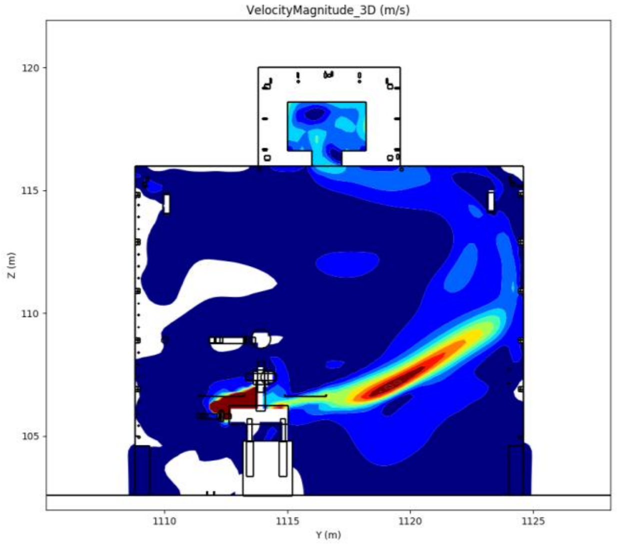
Run: 200003
Var: MoleFractionFuel_3D.HYDROGEN
Time: 180.000 s (5)
Plane: YZ , X=598.32m

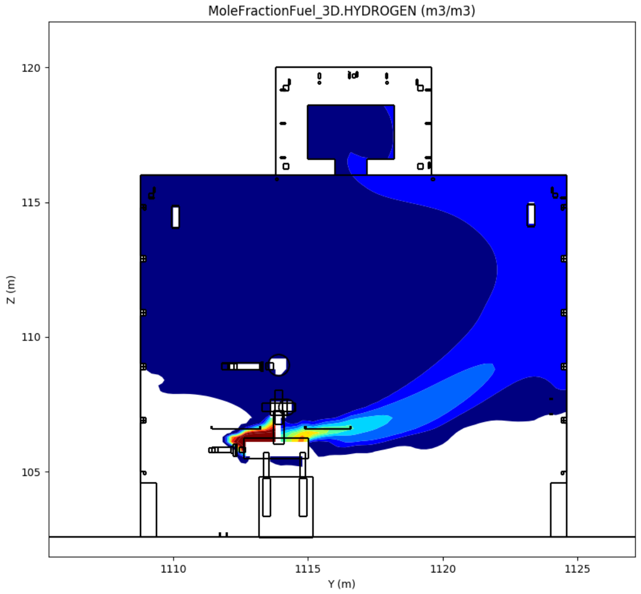


Run: 200003
Var: MoleFractionFuel_3D.HYDROGEN
Time: 180.001 s (5)
Plane: YZ , X=598.32m

Medium

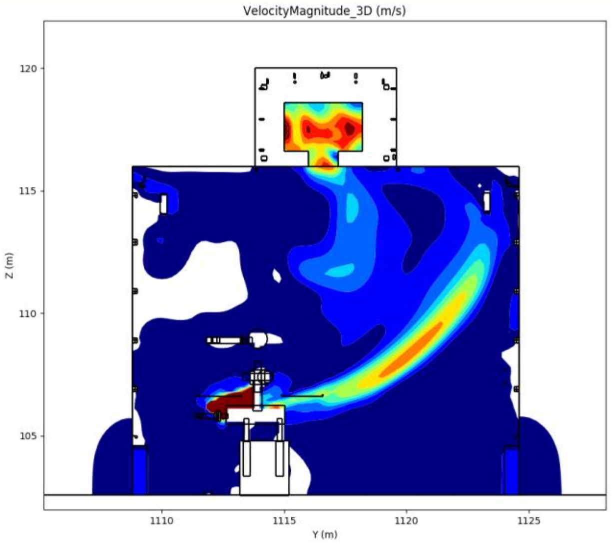
50 kg/s

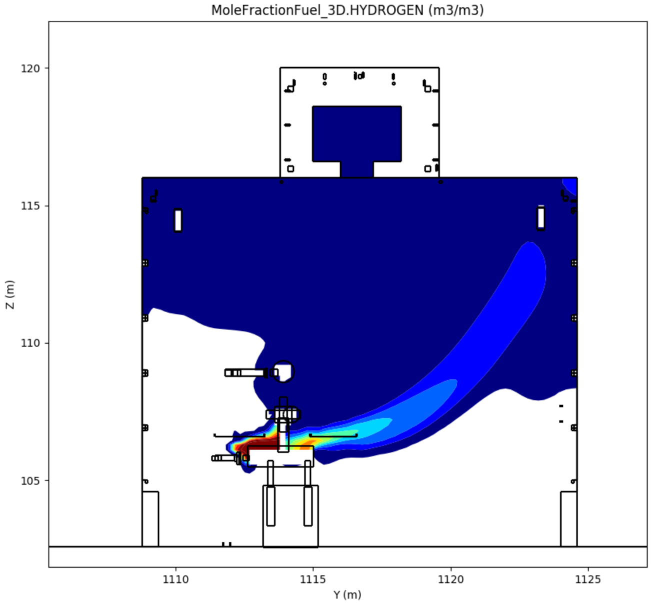




Run: 200029
Var: MoleFractionFuel_3D.HYDROGEN
Time: 150.001 s (15)
Plane: YZ , X=598.09m

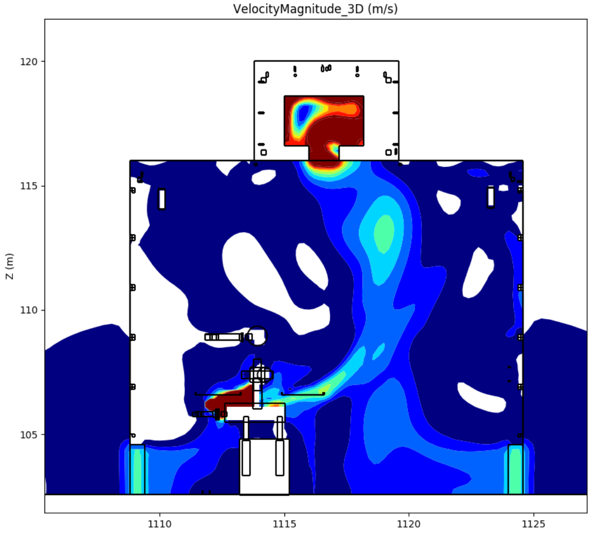
100 kg/s

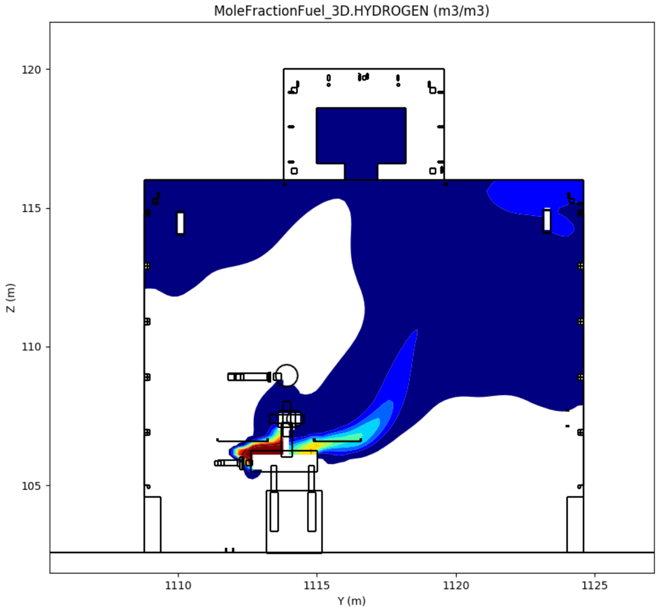




Run: 200029
Var: MoleFractionFuel_3D.HYDROGEN
Time: 150.000 s (15)
Plane: YZ , X=598.09m

200 kg/s

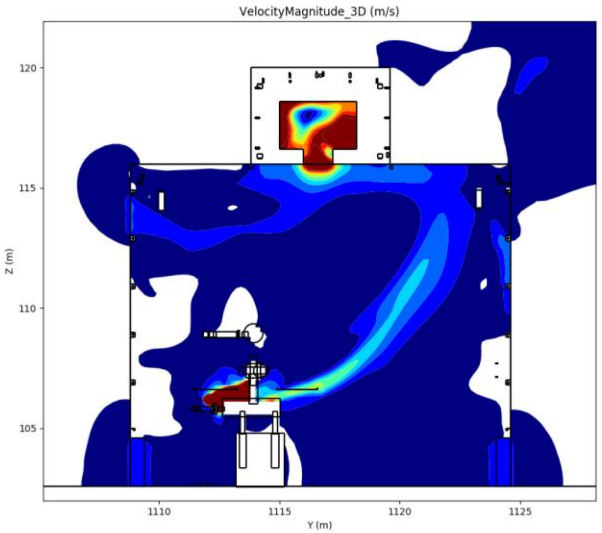


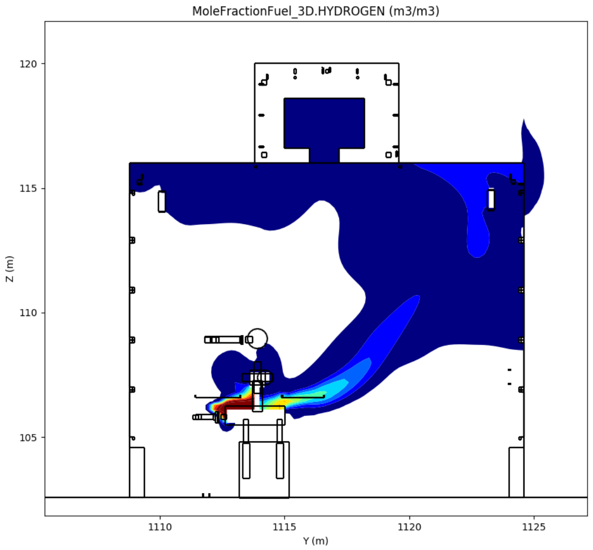


Run: 200029
Var: MoleFractionFuel_3D.HYDROGEN
Time: 150.001 s (2)
Plane: YZ , X=598.09m

Medium

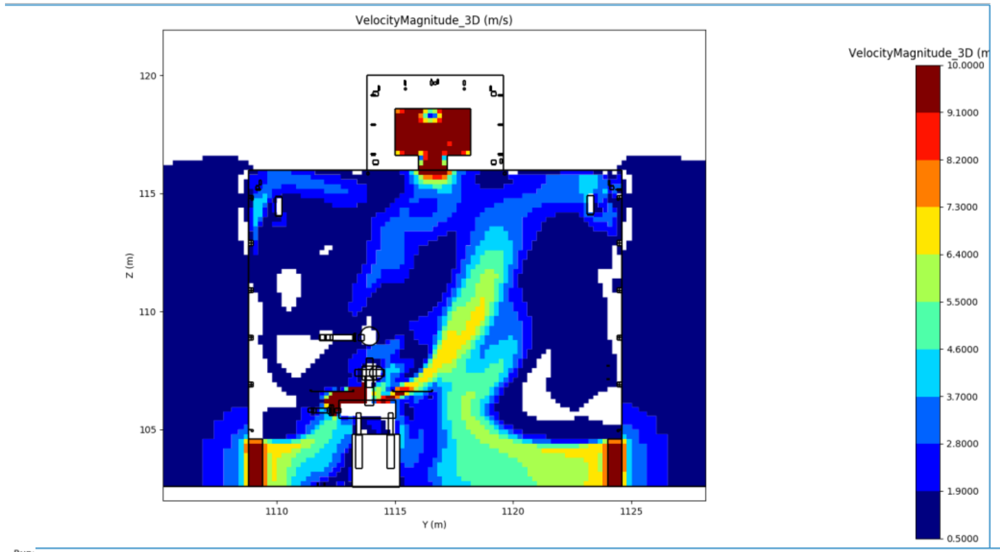
200 kg/s, additional side openings (passive)

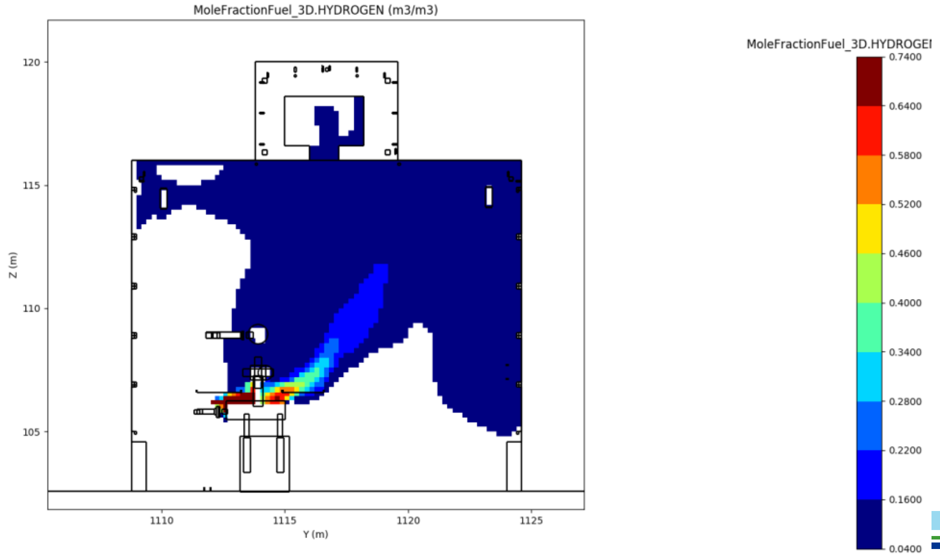




Run: 200029
Var: MoleFractionFuel_3D.HYDROGEN
Time: 150.001 s (2)
Plane: YZ , X=598.09m

400 kg/s, additional side openings (active, forcing air ir





Run: 200029
Var: MoleFractionFuel_3D.HYDROGEN
Time: 150.001 s (2)
Plane: YZ , X=598.09m

Extraction Fans at the Roof