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CFD and FEM study of hydrogen jet fire effect on tunnel structure

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Clean Hydrogen Partnership
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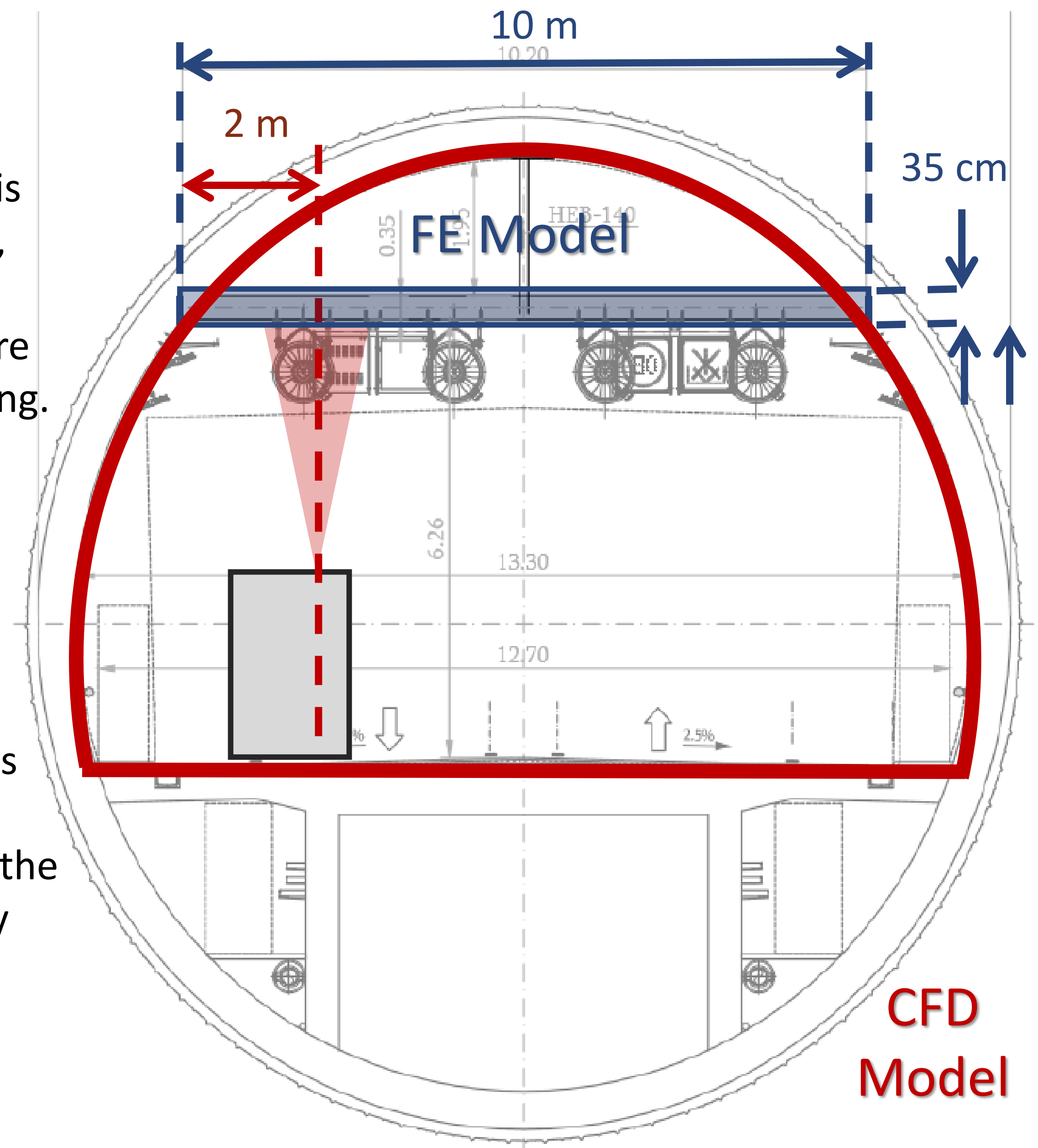
Introduction

Scenario and aim

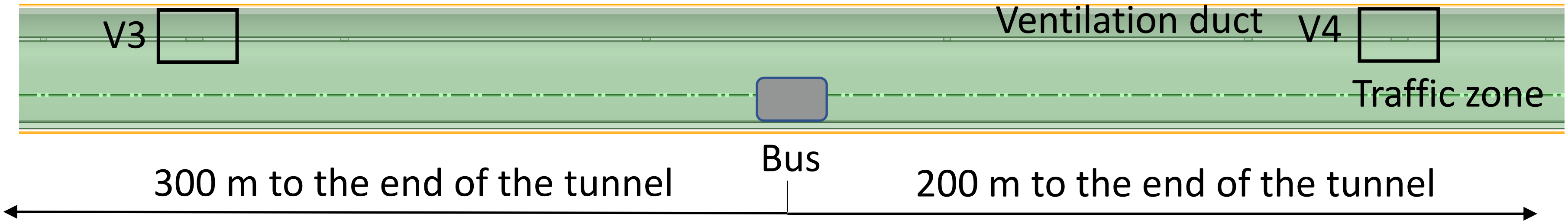
- **Scenario:** Hydrogen powered bus is involved in an incident in a tunnel, causing the TPRD on the storage tanks to open and produce a jet fire impinging on the tunnel false ceiling.
- **Aim**: Investigate whether the hydrogen fire may affect the integrity and stability of the slab:
  - *Occurrence of spalling*
  - *Structural resistance*
- **Method:** The CFD analysis provides the thermal load on the slab. The FEM transient thermal analysis of the 2D section of the slab impinged by the flame will provide info on the structural integrity of the slab.



Hydrogen jet fire in a tunnel

Details of a scenario

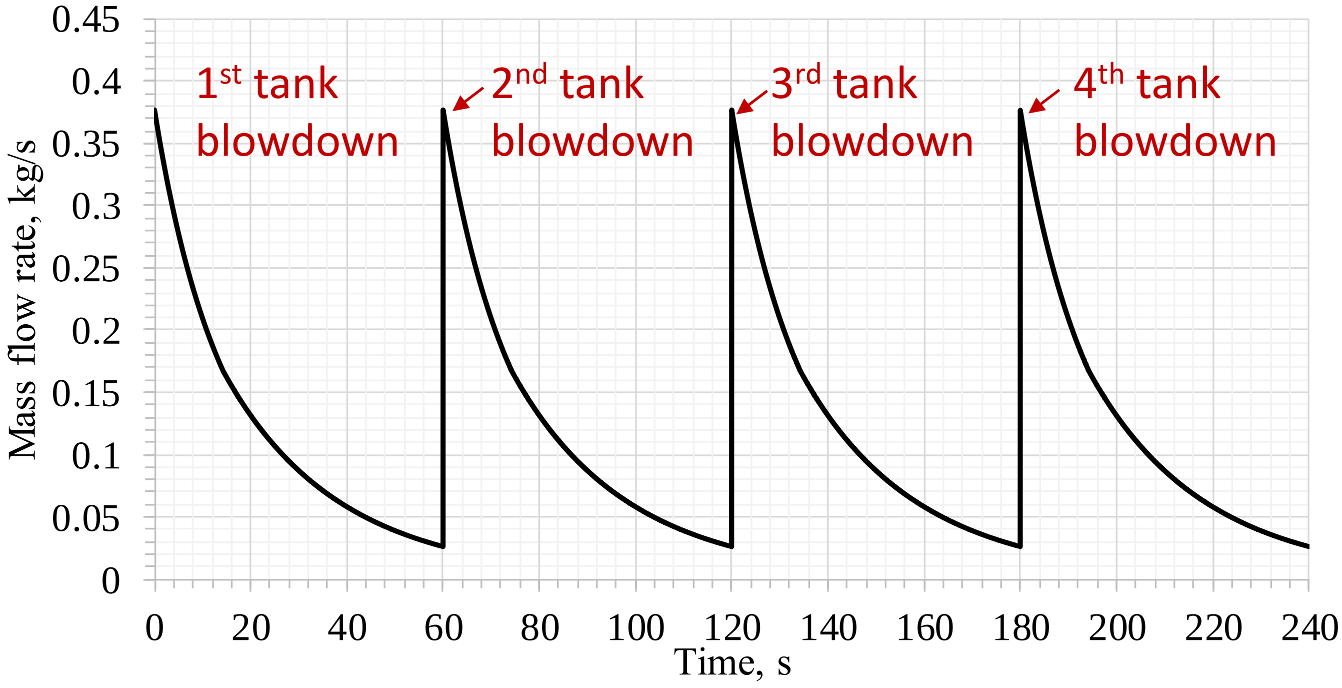
- The study considers a hydrogen powered bus with 4 storage tanks with volume 322 L and NWP of 350 bar.
- TPRD has diameter of 5 mm and is directed upwards.
- A 500 m long tunnel is considered for the study.
- The fresh air injection openings are all closed.
- Five extraction vents (1.8x1.4m) are placed each 100 m along the tunnel. The ventilation system is not active for the release duration.



Tank blowdown dynamics

Problem formulation

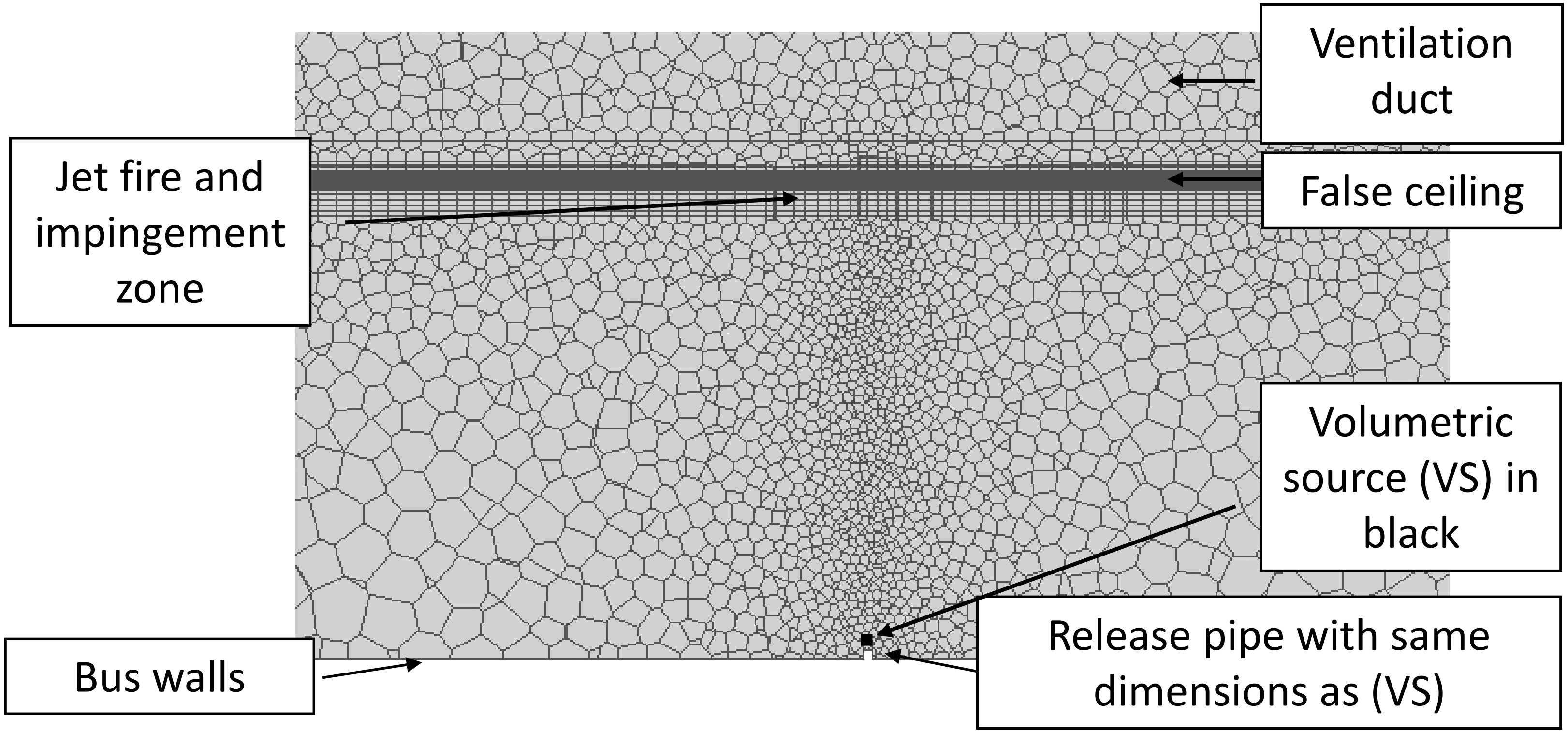
- The Ulster notional nozzle approach is applied to simulate the under-expanded jet properties dynamics during the tank blowdown through implementation of a **volumetric source**.
- The four tanks open in sequence every 60 s.



CFD model and numerical domain

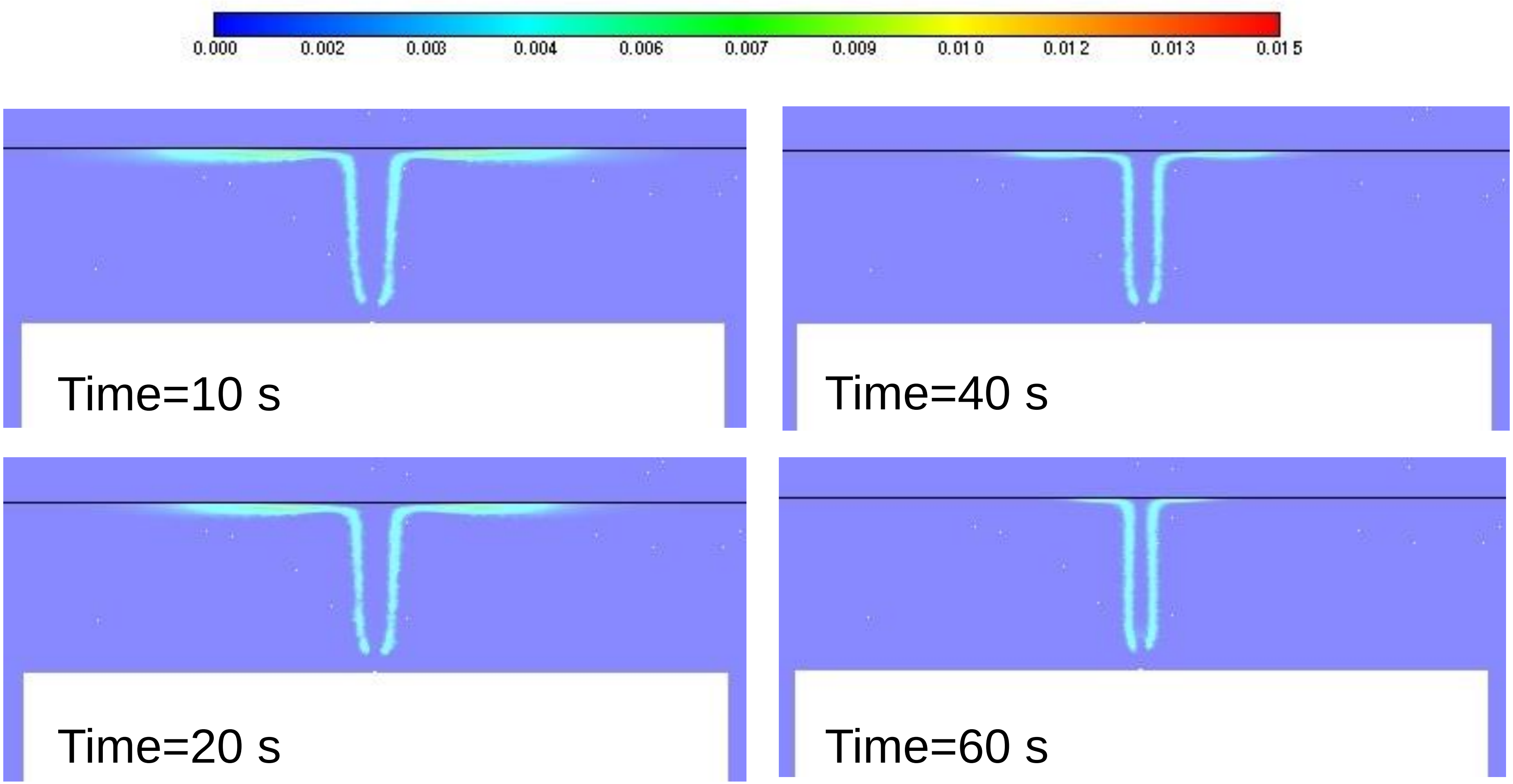
Description and details

- RANS approach is used for turbulence modelling.
- Eddy dissipation concept for combustion modelling.
- Discrete ordinates model for radiation.
- The numerical domain includes the entire 500 m long tunnel



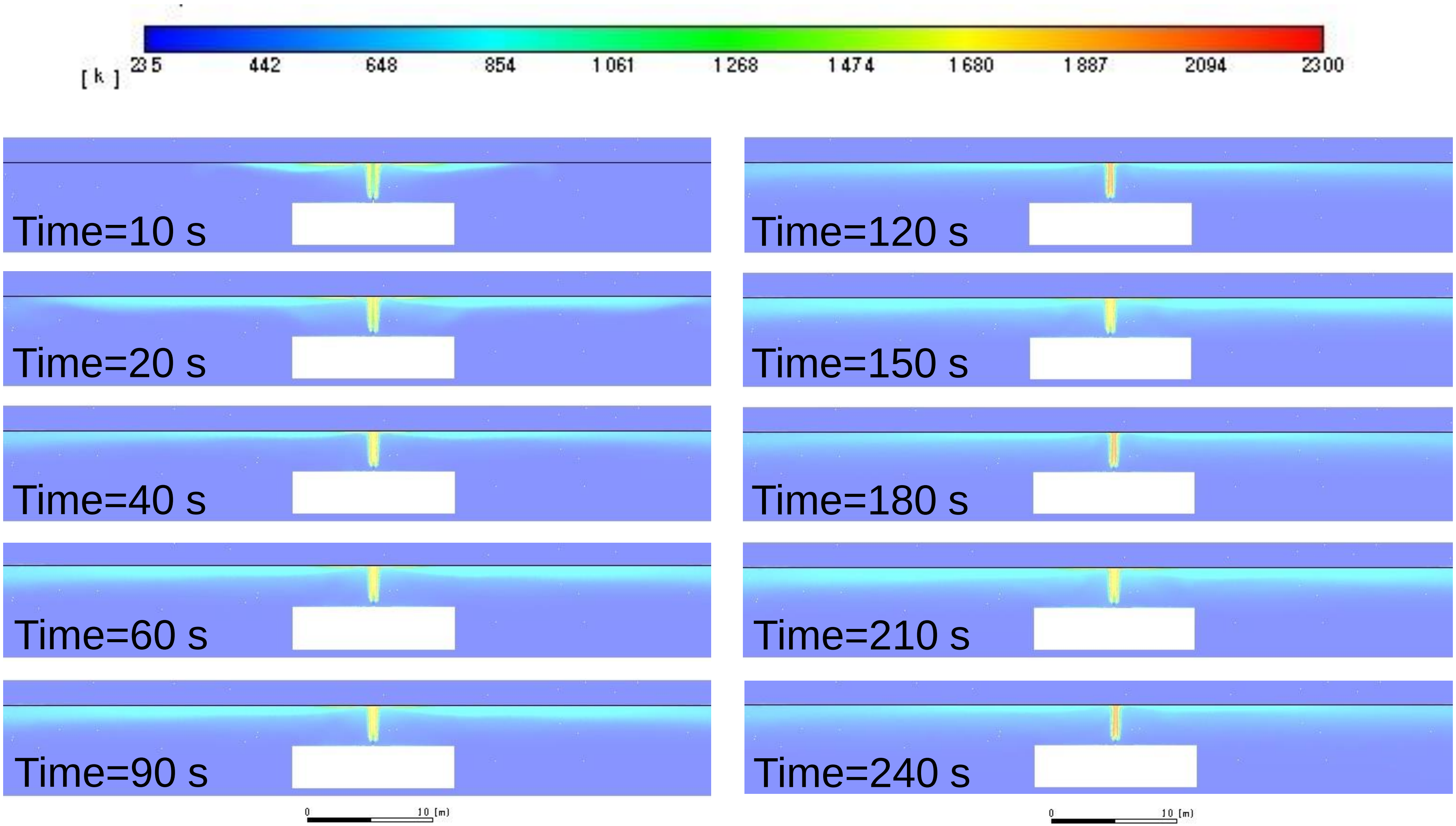
OH mole fraction dynamics

CFD simulation results



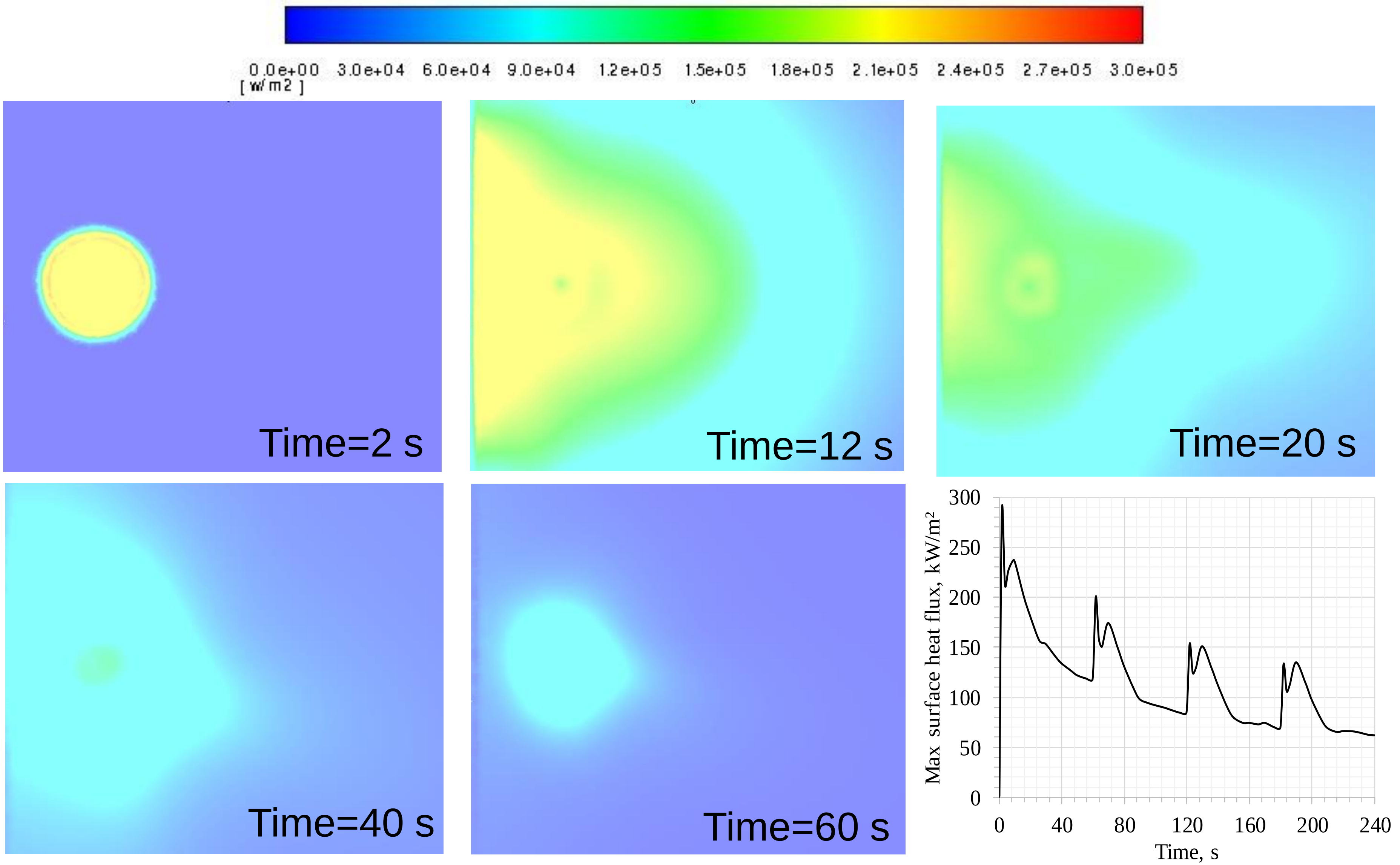
Temperature dynamics

CFD simulation results



Thermal load on tunnel structure

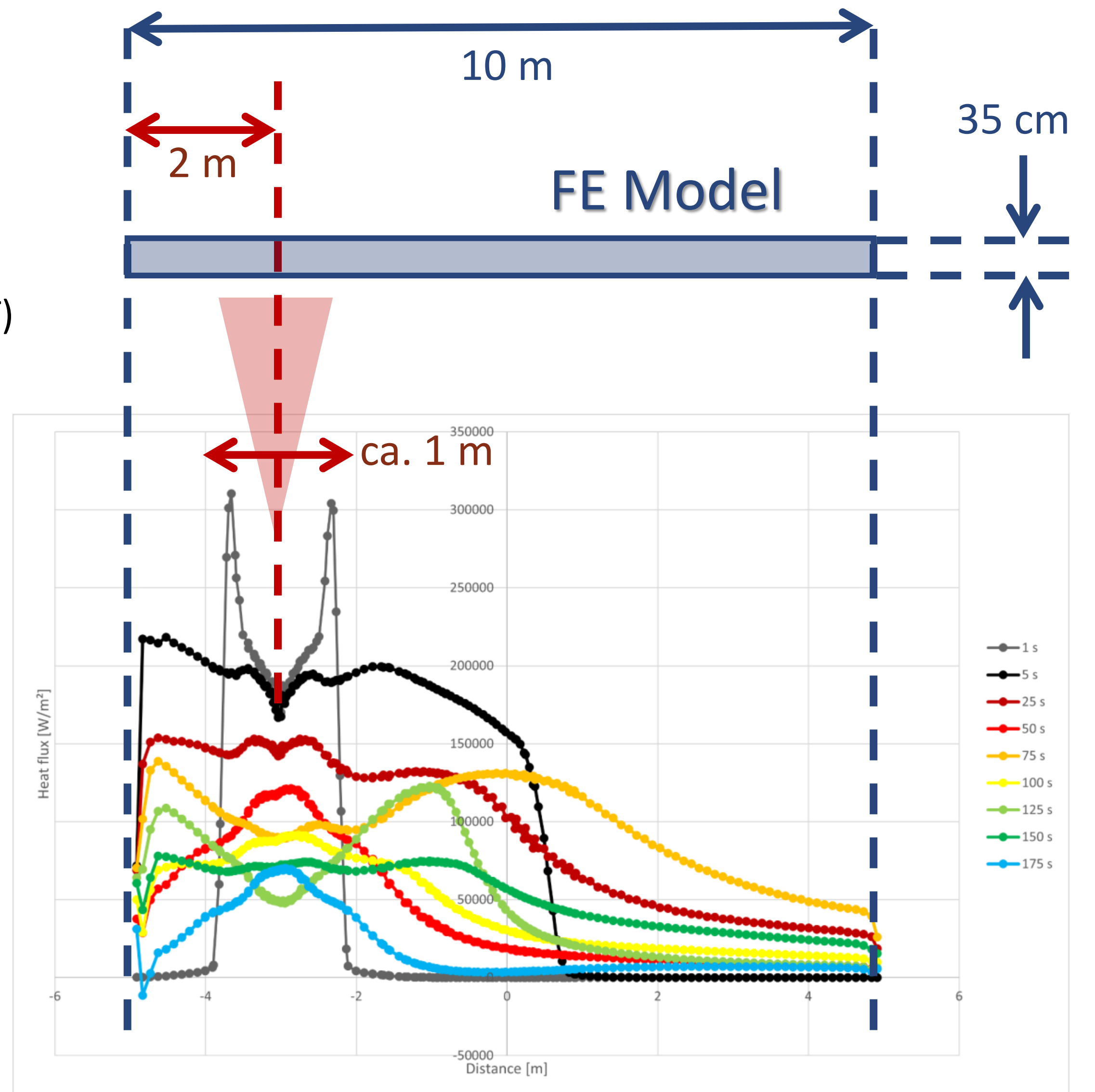
Total surface heat flux on false ceiling



CFD/FEM integration

Input data

- <u>Quantities</u>:
  - Given: Heat flux (HF)
  - Given: Gas temp. at interface (GT)
  - Derived: Adiabatic surface temp. (AST)
- <u>Space discretization</u>:
  168 nodes along the slab width
  (ca. every 6 cm on average)
- <u>Time discretization</u>: 1 s
- <u>Duration</u>:
  Release: 4 x 60 s = 240 s
  CFD analysis: 279 s
  (linear cooling of additional 60 s assumed for interface gas temperature)



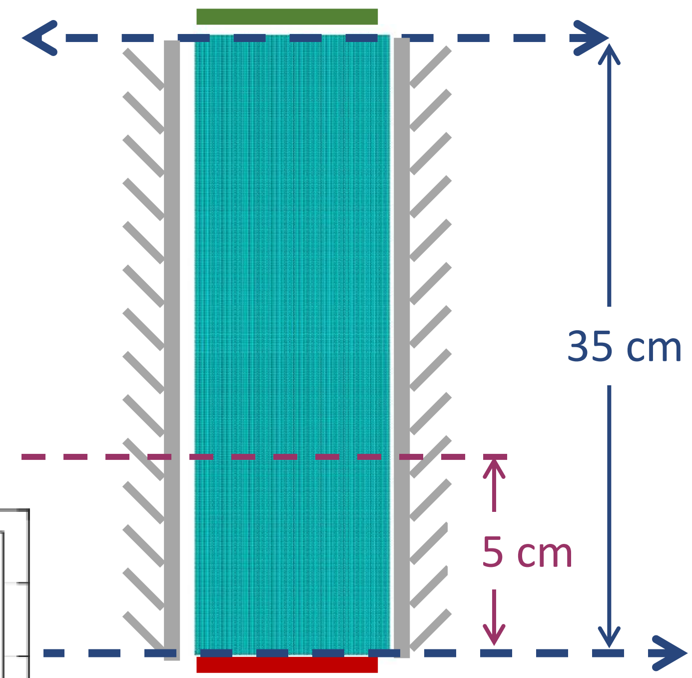
Heat flux vs. distance

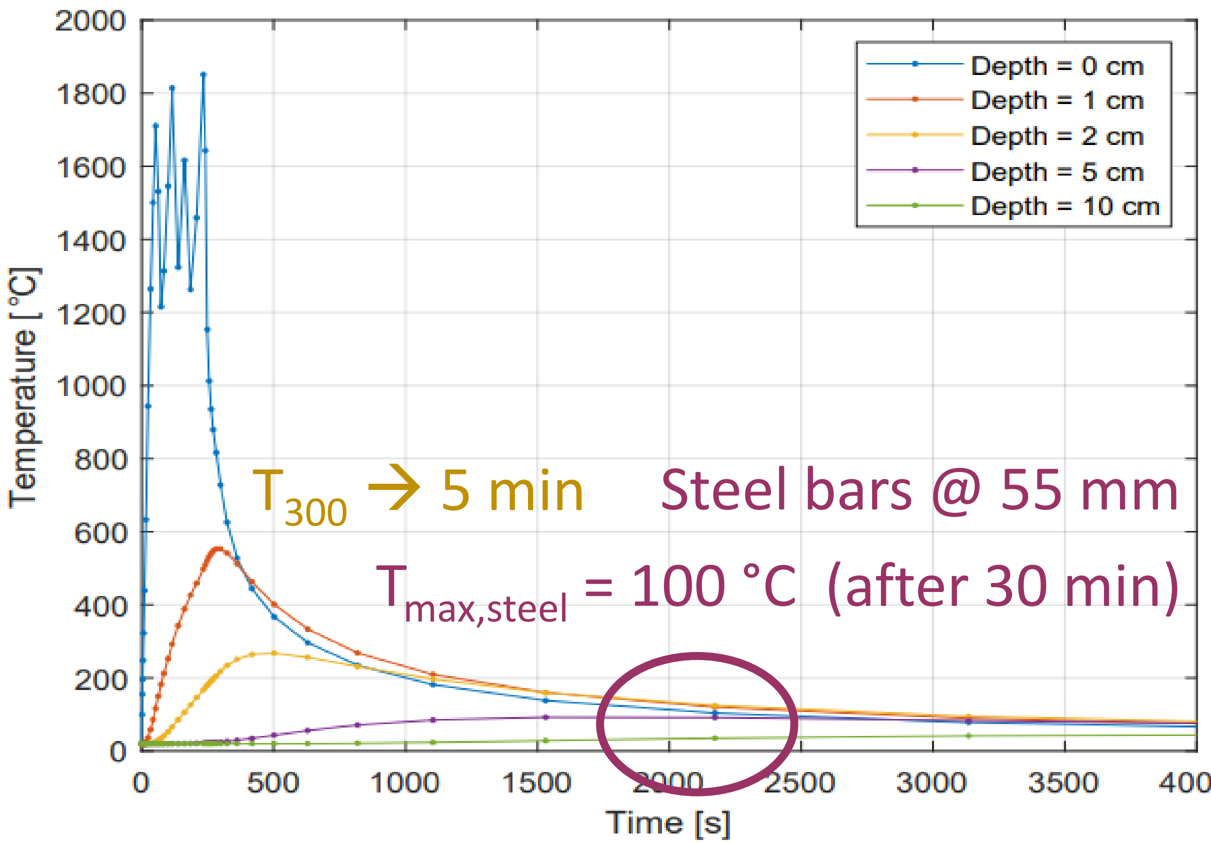
Temperature dynamics

Preliminary (slice) FE Model

Simplified slice model:

conservative estimate of the peak temperatures



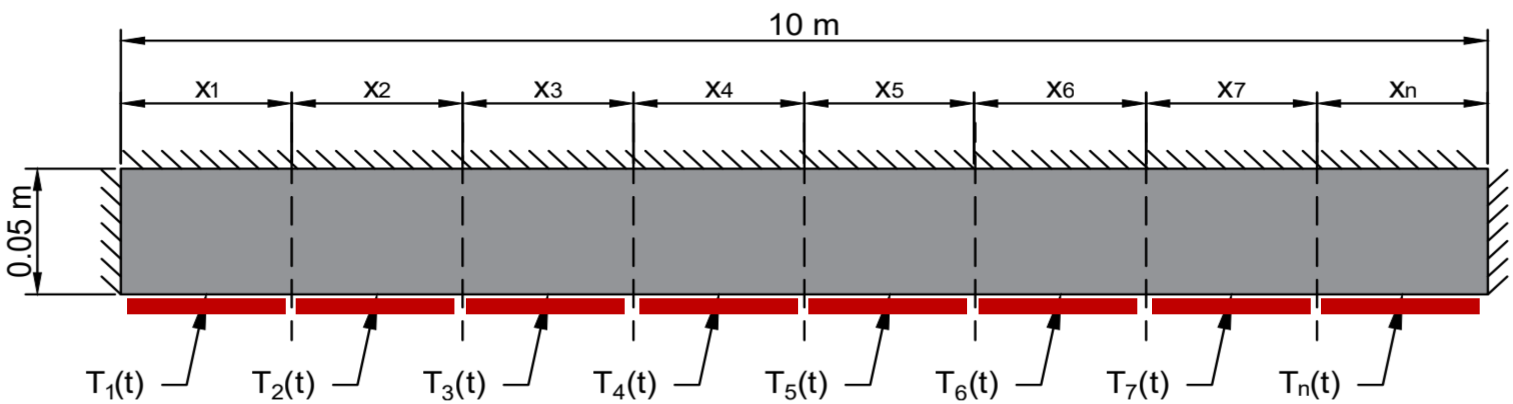


>10 cm: T = 20°C ca. (height)

5-10 cm: T < 100°C (bars)

CFD/FEM integration

Advanced FE Model



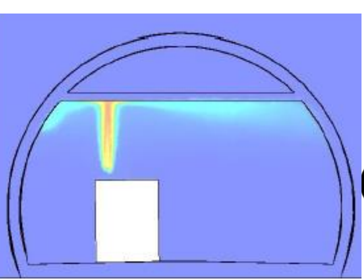
n = 168

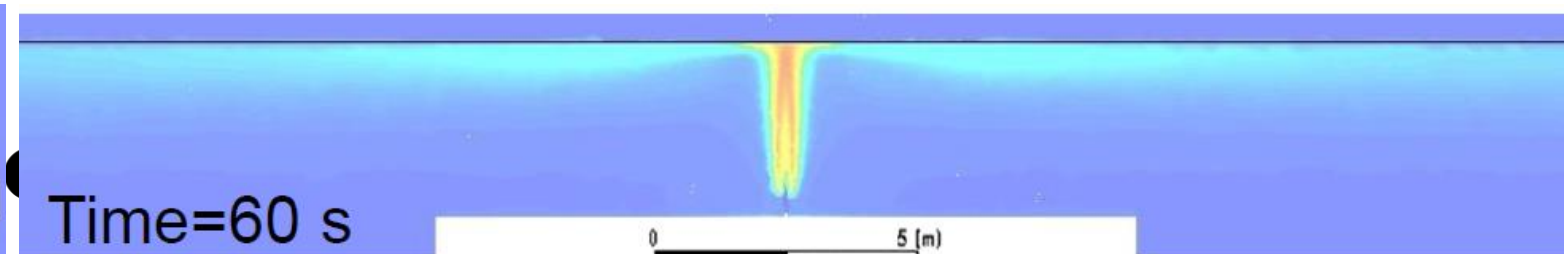
vertical mesh 0.5 mm

FE Model

CFD		FE
3D tunnel	SPACE	2D element (or part)
Polyhedric, coarser (cm)	MESH	Regular, finer (mm)
Duration of flame	TIME	Penetration time

CFD Model





Temperature at the end of fire

Advanced FE Model results

Spalling occurrence

- Heating rate > 20-30°C/min

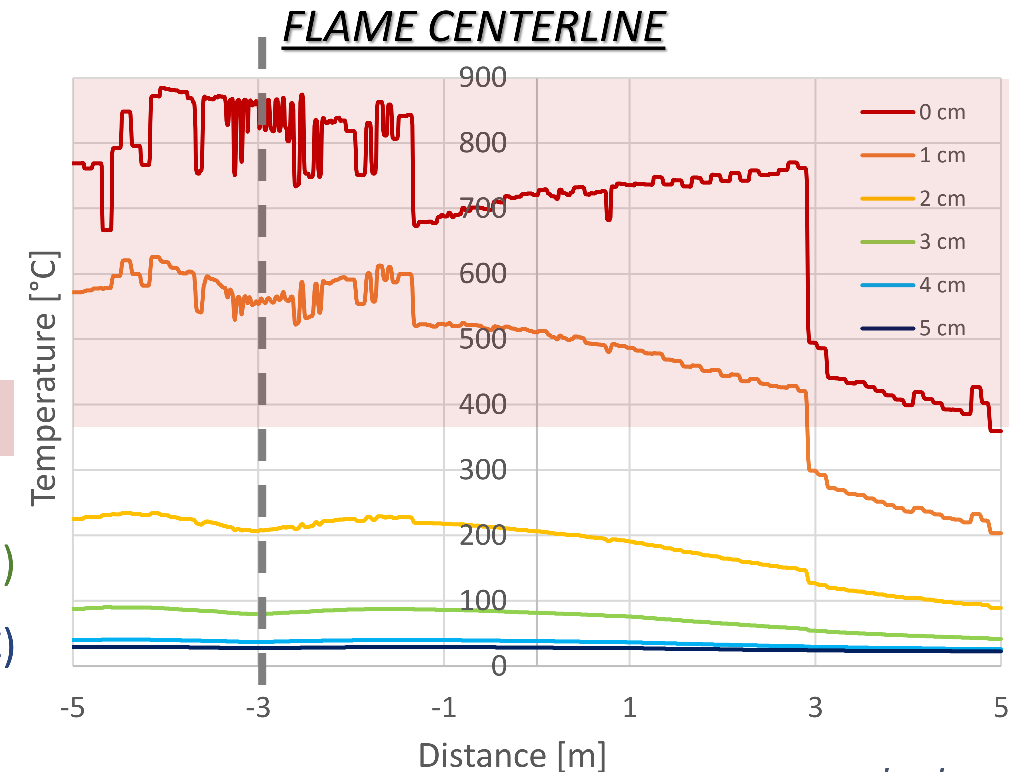
  (normal concrete)

Spalling depth

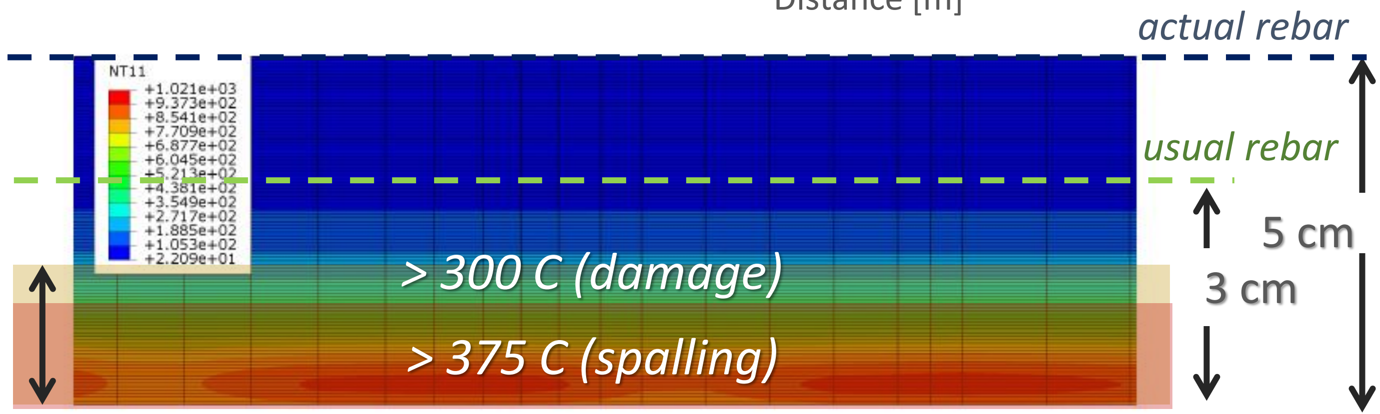
- Theory: 375 °C (critical steam point)

$T_{@3cm}$ = 87 °C (T_{max} ≈ 200 °C)

T_{steel} = 28 °C (T_{max} ≈ 100 °C)

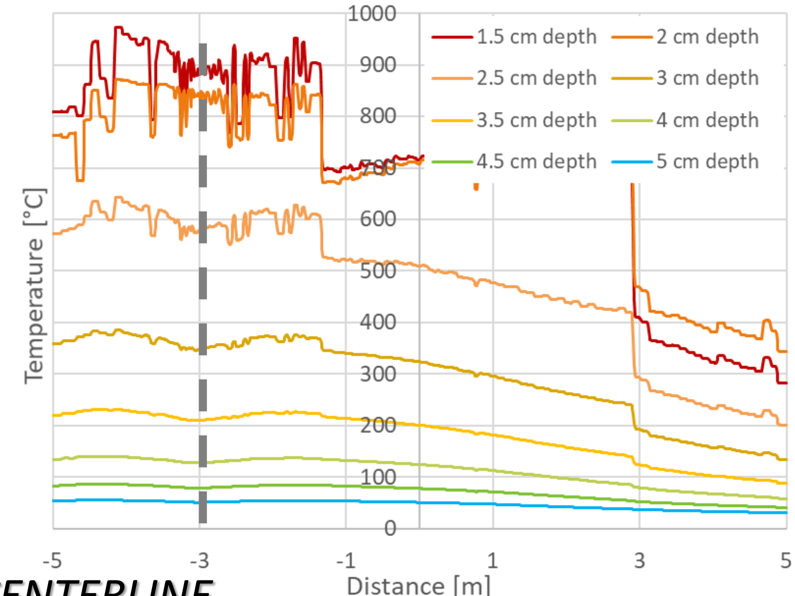


a segment of the whole model is shown here



Temperature at the end of fire
Conservative assessment

- A bottom layer of 1.5 cm concrete is removed from the model (temperature criterion 375°C).
- Temperature of the actual steel bars (5 cm → now 3.5 cm) increases from 28°C to 55°C, but is still very low at the end of fire and not expected to reach critical temperature (400 °C) at peak (ca. 6 min, according to simplified model).
- Temperature of steel bars at usual 3 cm (now 1.5 cm) increases from 87°C to 385°C. This may exceed 400 °C at peak, thus causing a reduction of the bar strength.



FLAME CENTERLINE

Conclusions and recommendations

- CFD modelling is recommended as a reliable tool to assess the hazardous conditions given by transient hydrogen jet fires impinging on tunnel structures.
- CFD/FEM integration provides a comprehensive assessment of the tunnel structure response to the hydrogen jet fire.

Spalling

- Spalling of outer concrete may occur (1.5 cm layer according to temperature criterion of 375°C), due to very high heating rate.

Structural resistance

USE LARGE REBAR COVER

- No significant reduction of the slab resistance is expected, also in the case of spalling, as the temperature at 5 cm stays well below 400°C.
- A slab with a lower (more common) rebar cover of 3 cm would also resist the hydrogen fire, if no spalling occur, but may experience a decrement of the capacity in case of spalling (as the steel temperatures gets above 400°C).
- Joined effect of a hydrogen jet fire and a longer vehicle fire could strongly affect spalling, reduce the slab resistance and its failure is possible.

AVOID SPALLING

Acknowledgements

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