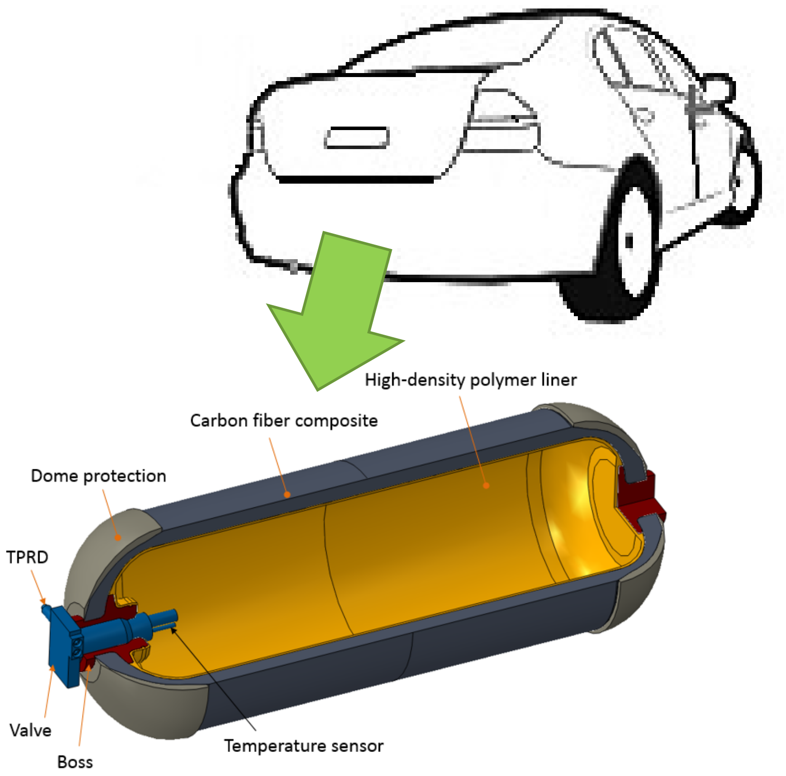
DE LA RECHERCHE À L’INDUSTRIE

HYDROGEN JET FIRES IN A FULL-SCALE ROAD TUNNEL: EXPERIMENTAL RESULTS

- **Overview**
  - Hydrogen jet-fires description
- **Experiment setup**
- **Test matrix**
- **Test sequence – Results**
  - Blowdown characterization
  - Reference jet-fire (200 bar, 2 mm, UP)
  - Effect of tank pressure for a 2 mm jet-fire
  - Effect of release location for a 2 mm jet fire
  - Coupling Fire/jet-fire for a 2 mm upward jet-fire
- **Conclusions and recommendations**

- **HFC EVs are eco-friendly alternatives to internal combustion engine vehicles but are powered by pressurized hydrogen gas**
- **Challenges arise in confined spaces, such as tunnels and underground car parks, as risks increase in these spaces compared to open atmospheres**
- **Critical need for validated hazard and risk assessment tools.**
- **Safety measures include thermally activated pressure relief valve (TPRD) to prevent catastrophic rupture and with it the study of:**
  - Potential accidents with conventional gasoline vehicles
  - Downward and upward gas discharges
  - Various release diameters



TPRD = Thermally Activated Pressure Relief Device
Credit: Process Modeling Group, Nuclear Engineering Division. Argonne National Laboratory (ANL)

Campaign 1:

- 50 liters type II tanks
- Pressure: 20 MPa

Campaign 2:

- 78 liters type IV tanks
- Pressure: 70 MPa

- A flat plate simulating a vehicle was employed.
- Investigated downward and upward gas discharges for rollover scenarios.
- Downward discharge orientation varied from normal to a 45° rearward inclination.
- First campaign under a concrete vault; second campaign under a rocky vault.
- Additional tests included a propane fire simulating a hydrocarbon vehicle fire for interaction analysis.

Research Focus

- The paper reports results from the second campaign.
- Key Parameters Measured:
  - Hydrogen jet-fire size evolution
  - Radiated heat fluxes
  - Temperature of hot gases released in the tunnel.

Engineering Model Comparisons

- Comparisons with classical correlations from open field tests.
- Assessment of the applicability of these correlations.
- Conclusions drawn regarding their suitability.

These tests are based on the geometrical characteristics of the flame like:

- Length
- Width
- Shape
- Temperature in the hot gases
- Radiative fluxes

For the length the Molkov correlation is used:

$$\frac{L_F}{D} = 805\left(\frac{\rho_N}{\rho_\infty} Ma_N^3\right)^{0.47}$$

L_F : Length of the flame
D: TPRD diameter
ρ : density
Ma: Mach number
N for the nozzle
∞ to the atmosphere.

Figure 1. Jet fire

Experiment setup

Tunnel

- Horse-shoe geometry
- Length: ~502 m
- Slope: 3.6%
- Sections:
  - Flat concrete ceiling arch
  - Raw limestone rocks

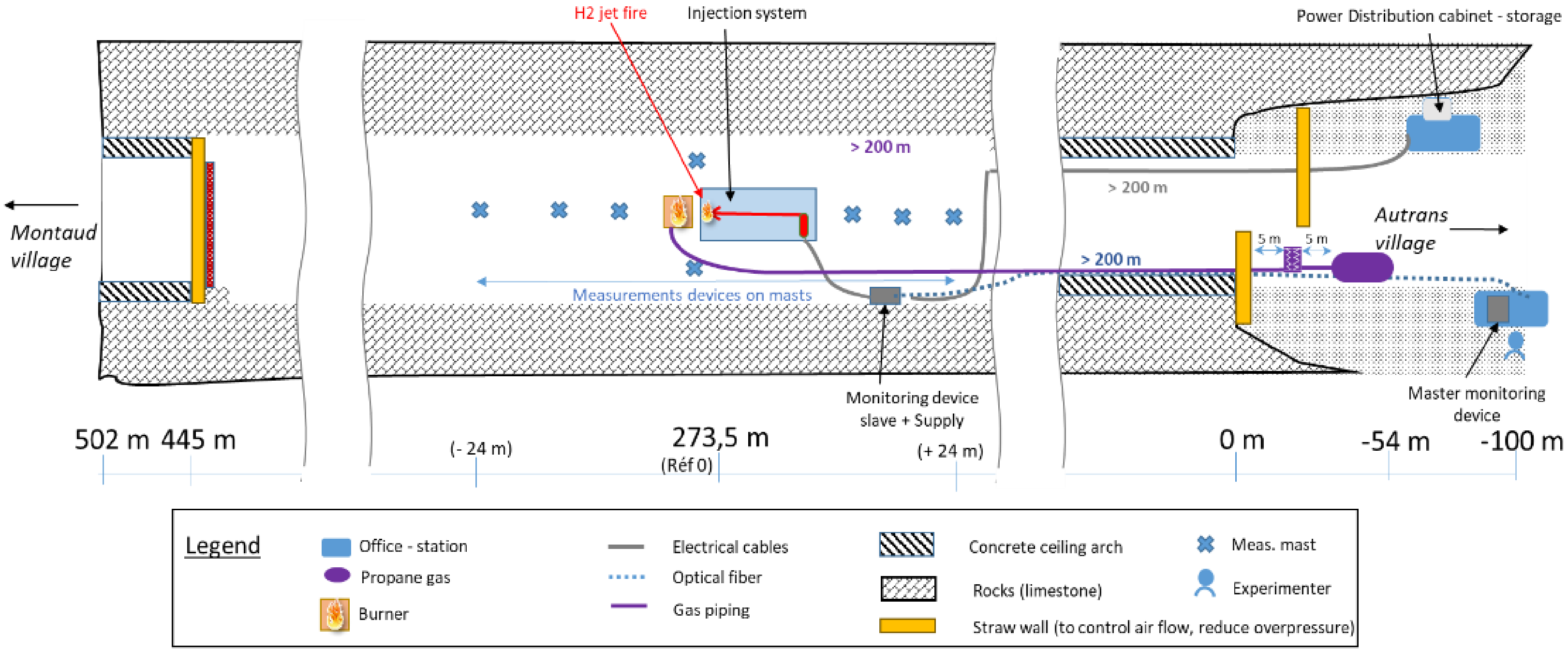


Figure 2. General sketch of the 2021 jet/fire and fire/jet-fire interaction tests

Instrumentation

- Data Acquisition Frequency: 100 Hz
- Monitored parameters:
  - Tank and Pipes: Relative pressures and gas temperature (P0, T0, P1, T1, P2, P2bis, T2)
  - Tunnel: heat fluxes around chassis, hydrogen concentration (Xe and He), temperatures (Tk), Oxygen (Ox), CO2, wind (convection).

Experiment setup

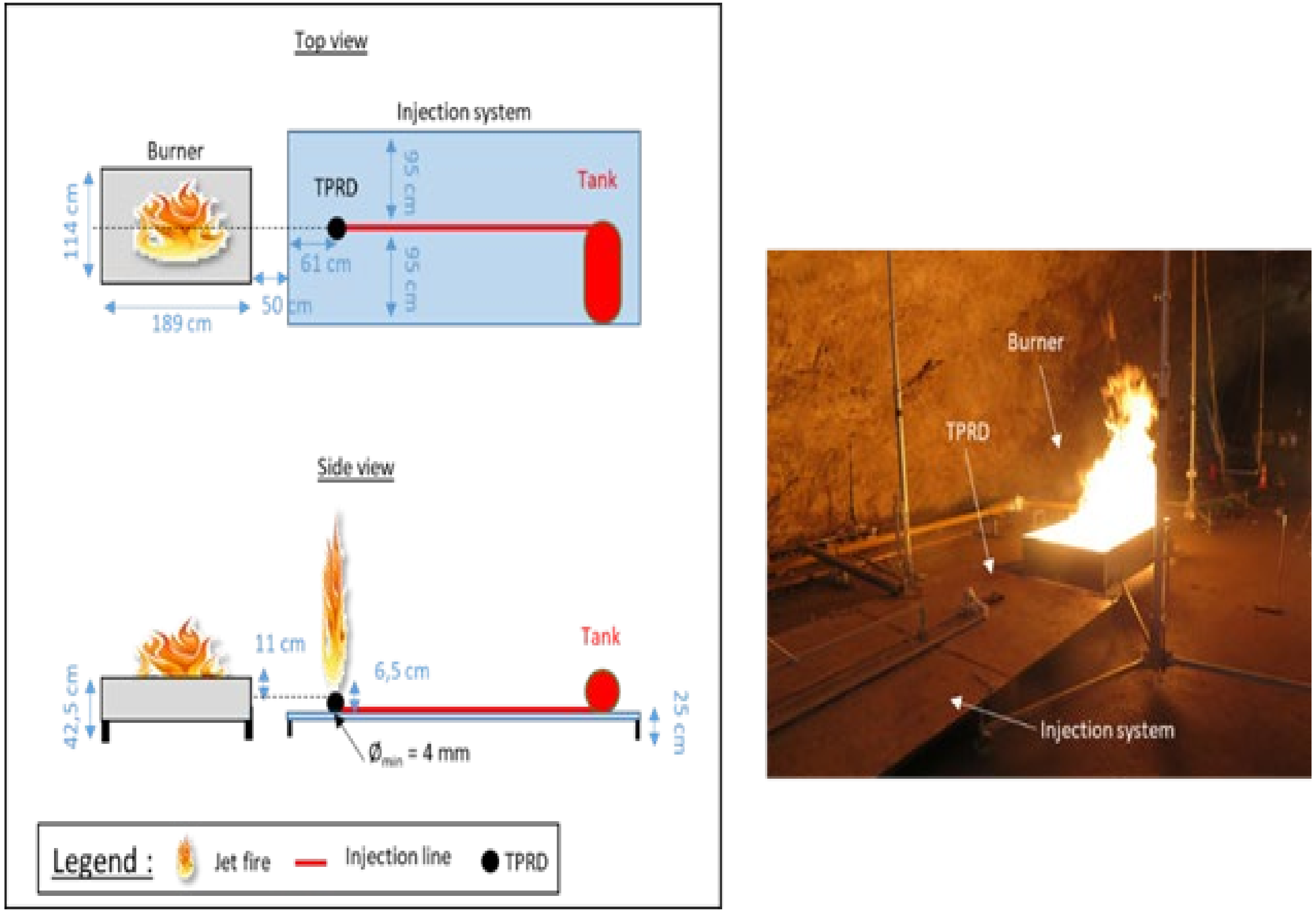


Figure 3. Position of the burner in the tunnel

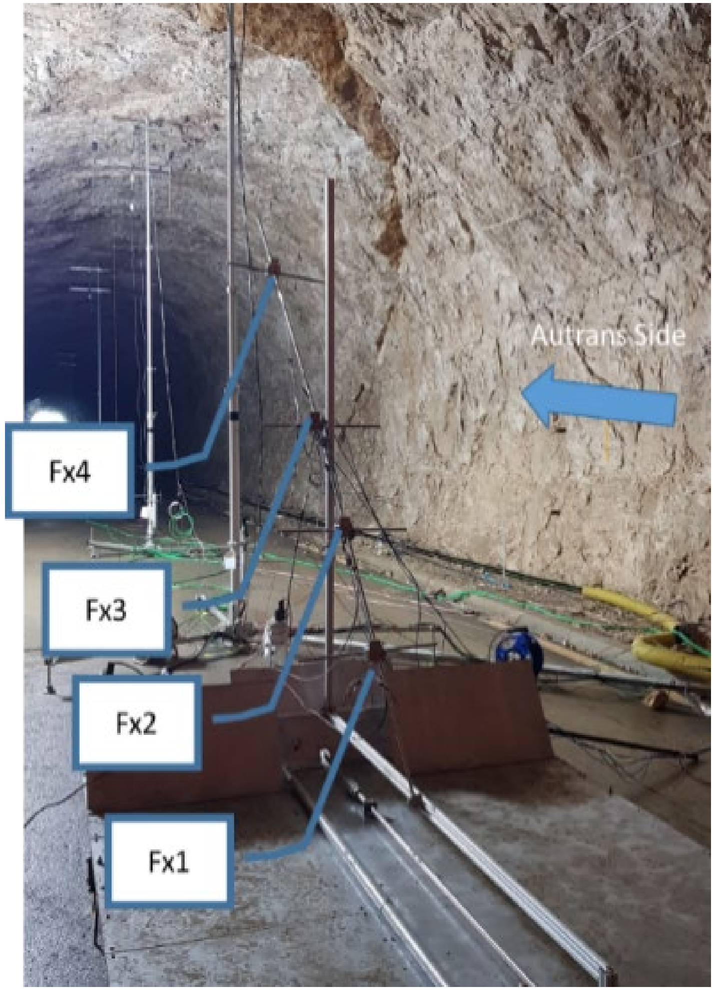


Figure 4. Radiative heat flux sensors in 2021 test series – structure with 4 staggered sensors

Jet-fire and Fire/Jet-fire interaction test matrix 2021

Type of test	Nb of test	Volume (liter)	Pressure (MPa)	Configuration	Ø TPRD (mm)	C_d	Max Flowrate (g/s)	Test number
H2 jet fire	5	50 type II	17.7	UP	2	0.75	25	n°21-09
		78 Type IV	59.8	UP	2	0.75	68	n°21-10
			63.5	DW 45°	2	0.78	72	n°21-12
			66.3	DW 45°	1	0.93	28	n°21-13
			66.7	DW 90°	2	0.85	77	n°21-18
Burner	1	-	-	-	-	-	-	n°21-14
H2 jet fire + burner	1	78 Type IV	66.1	UP	2	0.78	73	n°21-15

Test sequence - Results

Two methods were used:

- **The mass balance method (MBM):**
  - T1-P0 or T1-P1 determines gas density (ρgas) using Abel-Noble equation.
  - Mass of gas in the tank calculated as density times tank volume (Vtank).
  - Mass flow rate (QMBM) computed via 1st derivative of mass balance method during blowdown.

$$m_{gas} = \rho_{gas}(T,P)V_{tank} \qquad Q_{MBM} = \frac{\Delta m_{gas}}{\Delta t}$$

- **The sonic nozzle method (SNM):**
  - T2-P2 or T2-P2bis used.
  - "Barré de Saint Venant" theoretical model computes sonic regime mass flow (QSNM) at TPRD exit (if pressure > critical).
  - Method doesn't consider nozzle geometry and surface roughness.
  - Correction applied via discharge coefficient (Cd).

$$Q_{SNM} = C_d\left(\frac{\pi D^2}{4}\right)\sqrt{\frac{2\gamma r \rho_N^2 T_2}{(\gamma-1)+2(1-b\rho_N)^2}} \qquad \left(\frac{\rho_2}{1-b\rho_2}\right)^{\gamma} = \left(\frac{\rho_N}{1-b\rho_N}\right)^{\gamma}\left[1+\frac{\gamma-1}{2(1-b\rho_N)^2}\right]^{\gamma/(\gamma-1)}$$

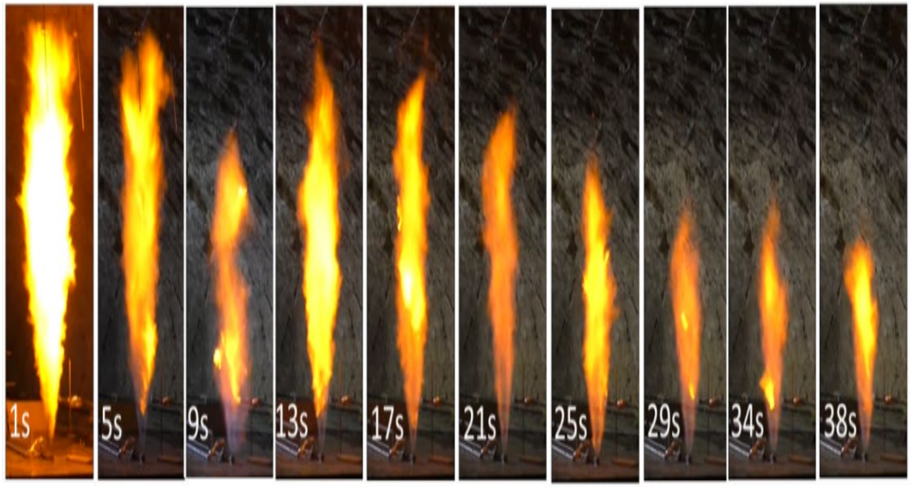


Figure 5. Test 21-09 Morphology of the jet-fire

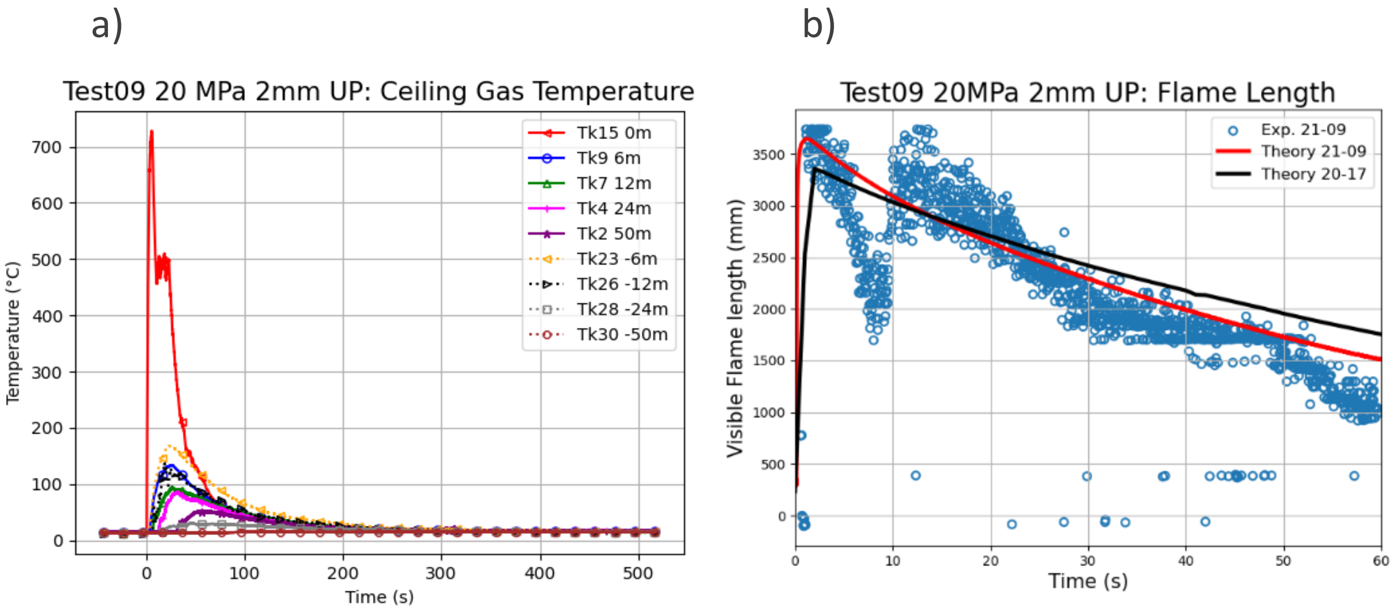


Figure 6. Test 21-09 a) Comparison of visible flame length with theoretical predictions in an open environment, b) hot gas temperature close to the ceiling

Test 21-09 Details:

- Type II cylinder at 200 bar pressure.
- 2 mm orifice.
- Vertical orientation.
- Objective: Confirm 2020 results (test n°20-17) under similar conditions, with different tunnel location.

Maximum flux measured at 2m from flame center:

- 2021 - 3.0 kW/m² > 2020 - 2.5 kW/m²
- Both reached 1 kW/m² after 40 seconds
- Predicted values from radiant source method [10] closely match measurements.

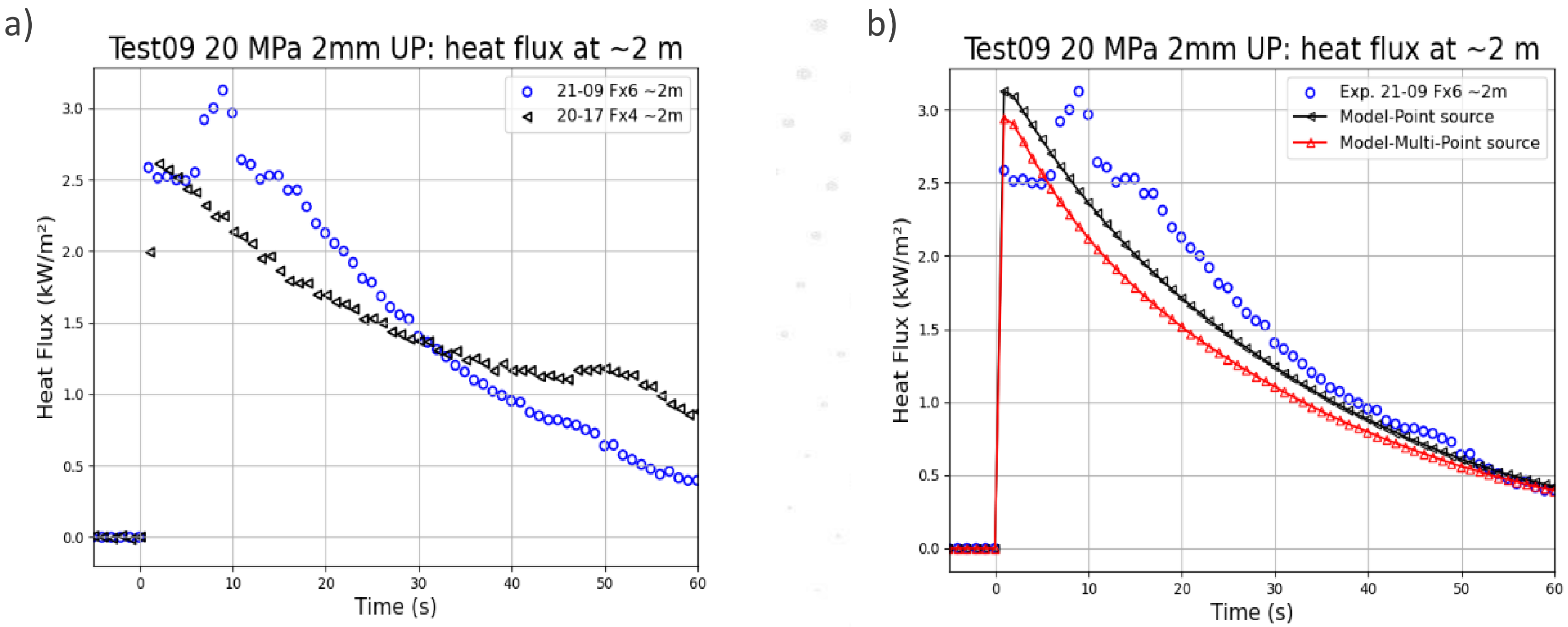


Figure 7. Test 21-09: a) Measured Radiated heat flux, b) Radiated heat flux computed by the point and multi-point source theory

Effect of tank pressure for a 2 mm jet-fire

Gas Temperatures:

- Flame tip: 1000°C
- Safe distance for ventilation systems: ~6m (at ~300°C)
- 12m from flame: ~200°C

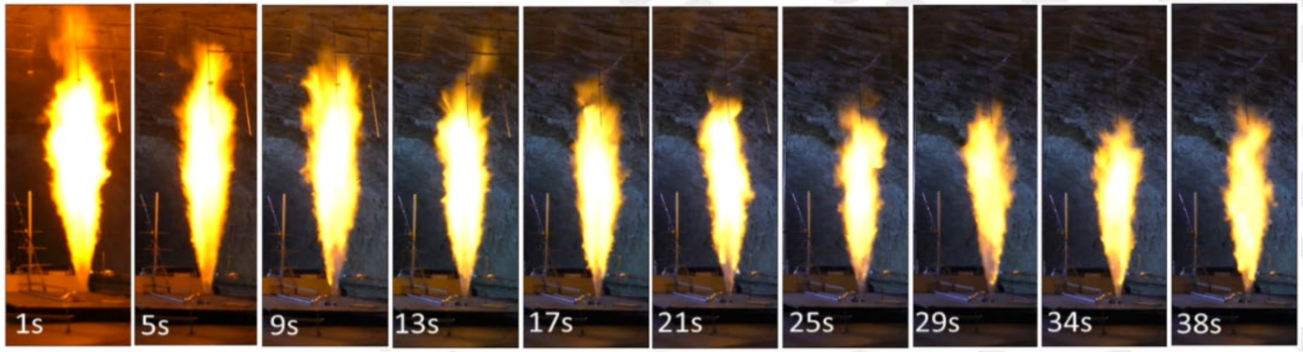
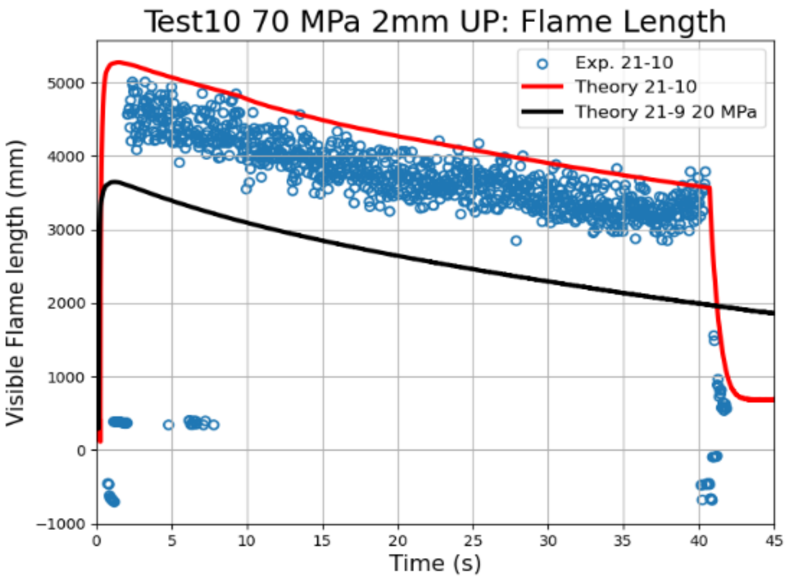


Figure 8. Test 21-10 Morphology of the jet-fire

a)



b)

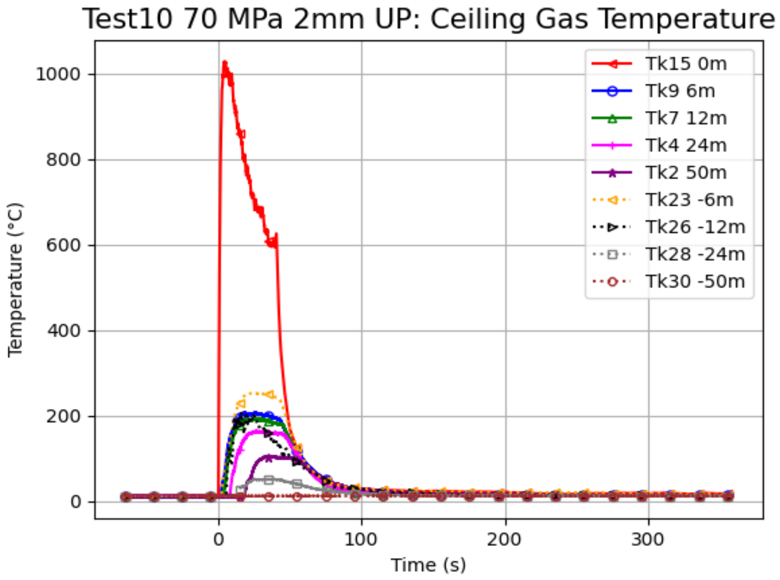


Figure 9. Test 21-10 a) Visible flame length with comparison to theory in open environment, b) hot gas temperature close to the ceiling

Effect of tank pressure for a 2 mm jet-fire

Radiated heat fluxes approximately 0.5 kW/m² higher than 20 MPa jet-fire measurements.

Predicted value by the point or multi-point source methods aligned with measurements at Fx4 and Fx5

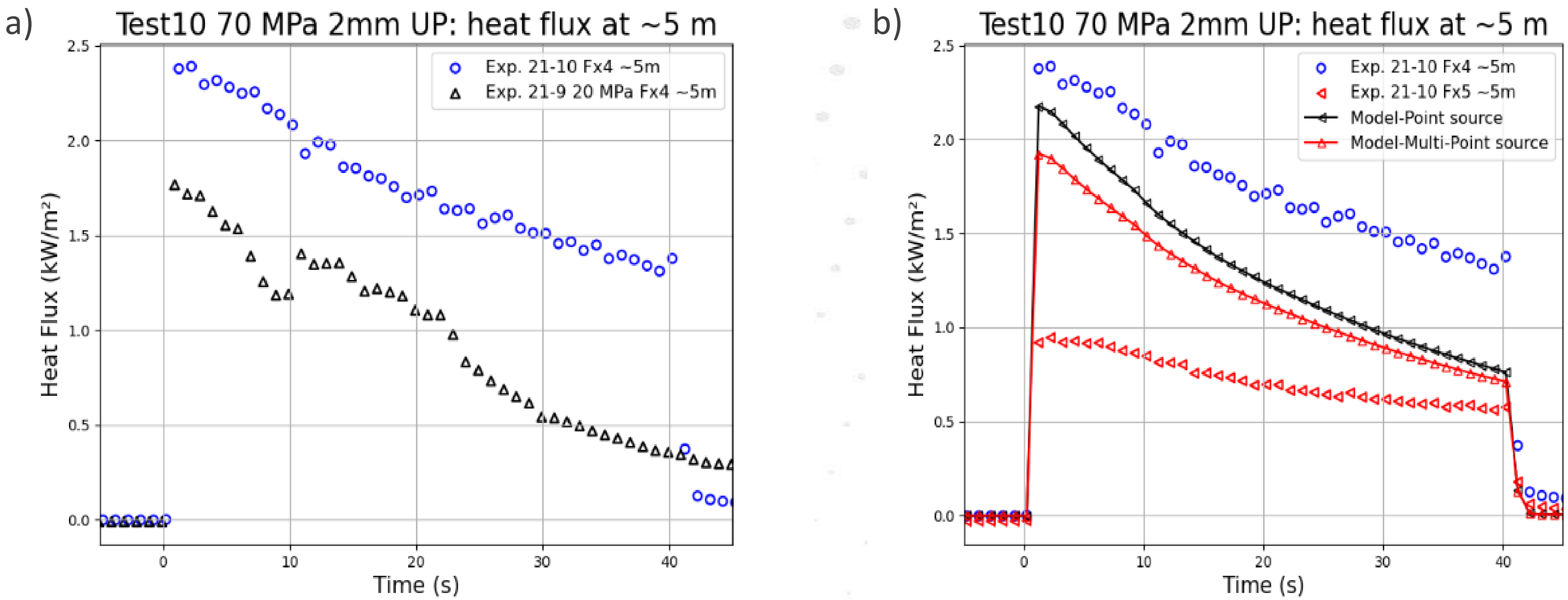


Figure 10. Test 21-10: a) Measured Radiated heat flux, b) Radiated heat flux computed by the point-and multi-point source theory

Effect of release location for a 2 mm jet fire

TPRD oriented downward at 45° towards the rear of the vehicle

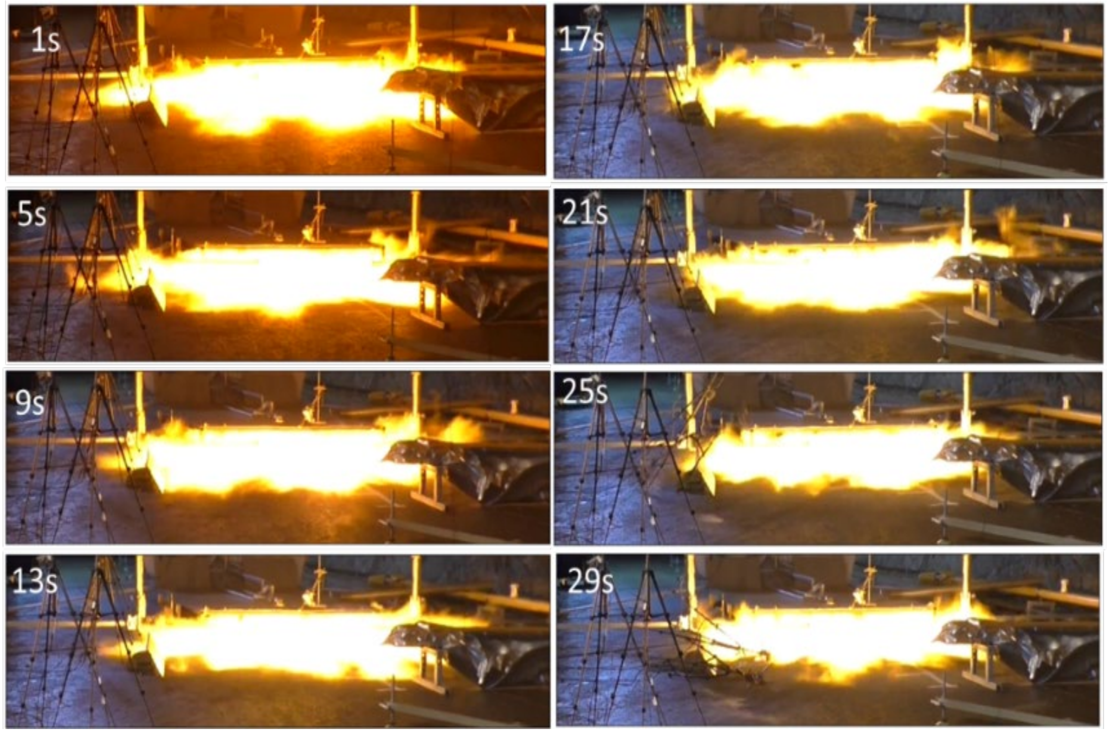


Figure 11. Test 21-12 2 mm DW 45°: Jet-fire morphology viewed from the rear side.

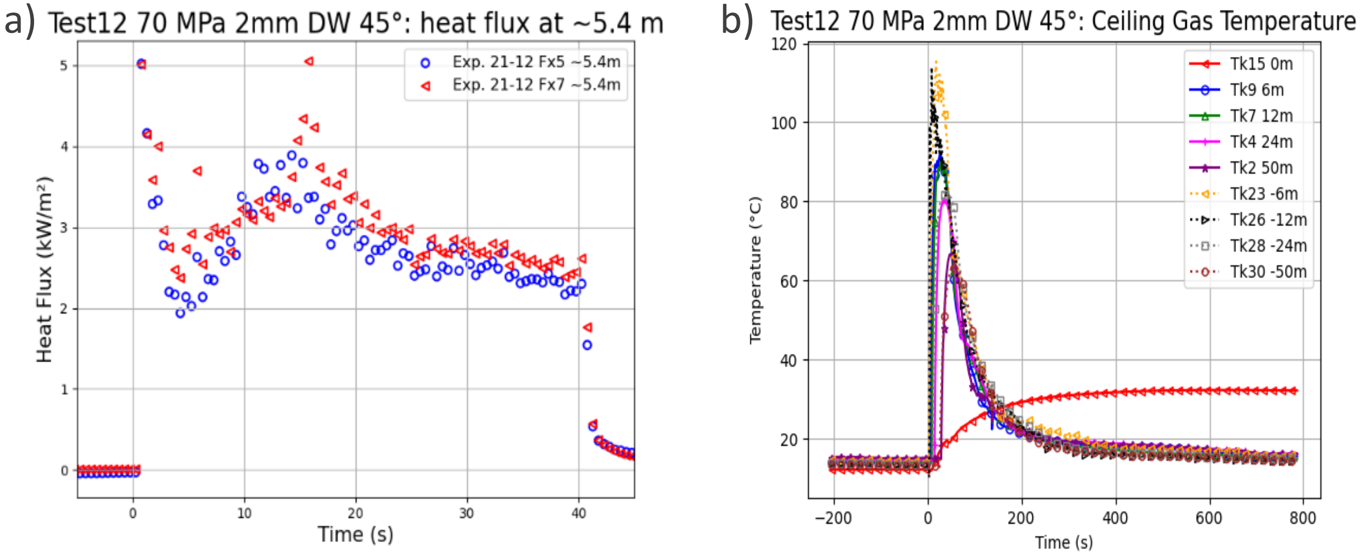


Figure 12. Test 21-12: a) Measured Radiated heat flux, b) Gas temperature along the ceiling.

Radiometer Measurements

- On chassis, far from flame (~1 kW/m²).
- Fx5 and Fx7 near flame, both at 5.4 m.
- Orientation less significant; heat flux reaches burn threshold.
- Unusual signal shapes with two peaks

Hot Gas Temperatures

- Near tunnel ceiling: Below 100°C.

TPRD oriented downward at 90° towards the road

a)

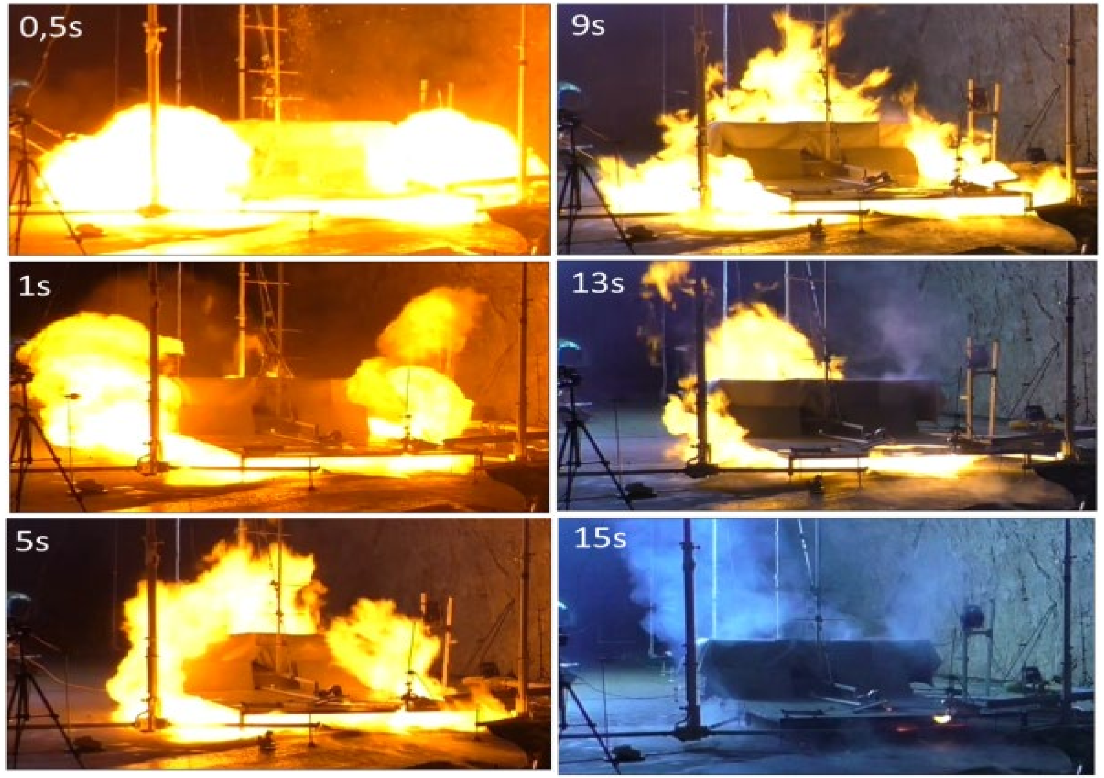
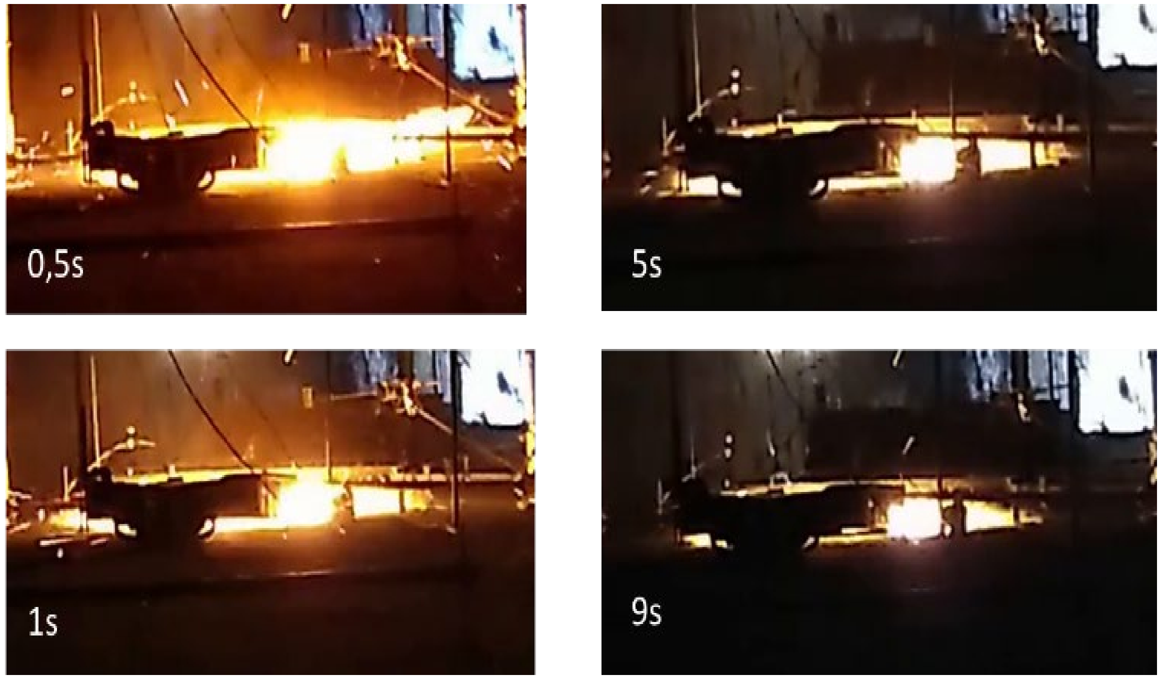


Figure 13. a) Test 21-18 2 mm DW 90°: Jet-fire shape viewed from the rear side, b) Test n°20-22 2 mm DW 90°: Jet-fire morphology viewed from the rear side.

- Delay the ignition noted
- Initial radiative heat fluxes (up to 20 kW/m²) high due to fireball.
- Temperature peak (150°C) at +6 m, corresponding to vehicle front.
- Flame shape comparison (test 21-18 vs. test n°20-22, 20 MPa) - significant modification in flame extent.

b)



Coupling Fire/jet-fire for a 2 mm upward jet-fire

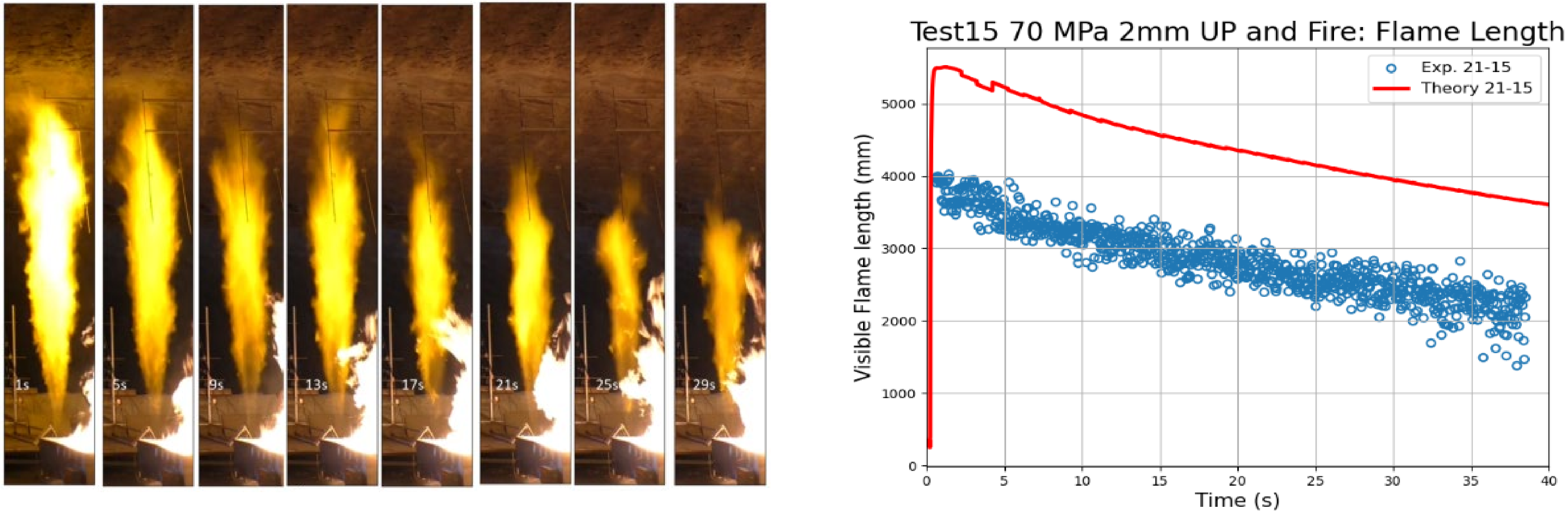


Figure 16. Test 21-15: a) Jet-fire morphology viewed from the rear side, b) Visible flame length with comparison to theory in open environment.

- **Jet-fire consistently below tunnel vault, diminishing steadily.**
- **Flame height below theoretical prediction and values measured without fire.**
- **Inconclusive findings regarding burner's effect on the fire from videos and measurements.**
- **Possible jet fire length reduction due to air cross-flow from air entrainment into the burner.**

Coupling Fire/jet-fire for a 2 mm upward jet-fire

- **Radiometers indicate increased radiative flux in presence of jet-fire.**
- **Net radiative effect not just a superposition; 50% amplification measured regardless of sensor position due to steam.**
- **Temperature of hot gases near vault shows jet-fire effect: Values up to 250°C toward Autrans at +24 m.**
- **Fire HRR: ~1.5 MW; Jet-fire produced 9-2.5 MW during blowdown.**

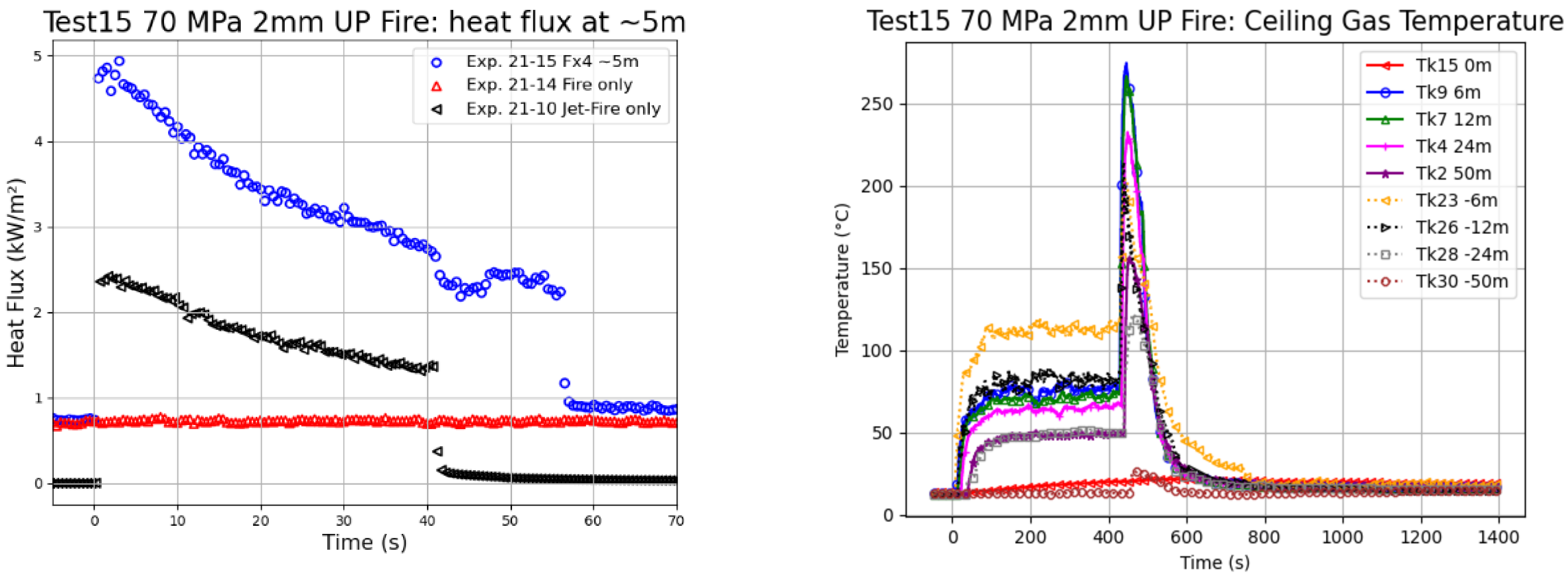


Figure 17. Test 21-15: a) Measured Radiated heat flux, b) Gas temperature along the ceiling

Conclusions

Conclusions

- Experiments show that jet-fires up to 2 mm in release diameter have a small impact on the tunnel (height above 5 m).
- Smaller release diameters, like 1 mm, are preferred as they reduce jet-fire extent but prolong its duration, posing a risk of igniting an asphalted road. Nozzle diameter is thus a critical parameter.
- Flame length for vertical jet-fire can be predicted by correlations developed for open environment if the height under the vault is sufficient to develop it.
- Downward jet-fires at a 45° rearward orientation extend up to 3.5 m with a 2 mm diameter. This orientation reduces hazard distances for people and structure damage compared to perpendicular releases
- Hot gas cloud (T>300°C) is monitored close to the ceiling of the tunnel in the case of 2 mm release with a car fire (1 MW/m²).
- This car fire set-up prior the orifice opening lower the extent of the jet-fire and amplify the radiated flux.

Thanks for your attention!

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