SH$_2$IFT WP-3: Gaseous Hydrogen Jet Fires

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Gexcon Software

SH$_2$IFT

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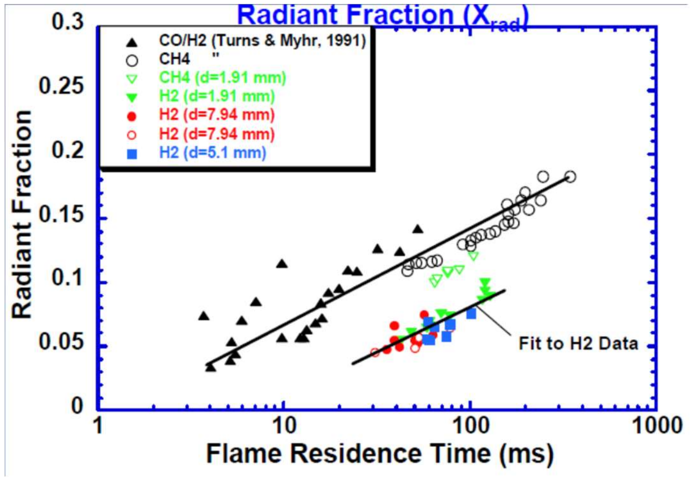
Organization of Presentation

- Introduction
- GH2 Fire modelling - Knowledge Gaps.
- GH2 Fire - Validation database.
- Parametric Study & Model improvements
- Validation: SH2IFT GH2 jet fires.
- Conclusions

Introduction - Hydrogen Fires

- Consequences that are much more severe as compared to hydrocarbons:
  - Wide flammable range (between 4% and 75% in air)
  - Low ignition energy
  - Burns quickly
  - Almost invisible

- Help to reduce the risk of using the GH2:
  - much lighter than air (very strong buoyancy quickly remove the gas in an unconfined situation.)
  - **Low radiant heat**
  - Radiative properties (absence of CO2 and SOOT)



SH2IFT WP3 - Work Plan

- The main objective of WP-3 is to fill knowledge gaps about fire safety of GH_2 transport and use and improve established risk and consequence modelling tools for GH_2-related scenarios, in close collaboration with task 2.1 (RFR GH_2 Jet fire experiments).
  - Task 3.1 – Gaps in theoretical approximations used in risk and consequence modelling
  - Task 3.2 – Validation of consequence modelling tools
  - Task 3.3 – Improved risk and consequence models

GH2 Fire modelling - Knowledge Gaps.

- **Constitution of a validation matrix for CFD simulations (validation against experimental data and inter-comparison), including turbulence modelling, combustion models, and mesh sensitivity issues.**
- Transient solution for under-expanded jet fire lift-off.
- Under-expanded plane jet flame length.
- Impinging jet fires and heat transfer to structural elements, storage vessels, etc.
- **Radiation hazard from jet fires & Thermal loads to inside structures**
- **Radiation effects at various distances, including CFD and engineering methods.**
- Simulation of fireballs, their cooling down and movement dynamics, especially for large clouds, where cooling occurs mainly by radiation.
- Effect of impinging jets on hazard distances.
- Models for large scale H2 jet fires, including under transient conditions of decreasing notional nozzle diameter and temperature during a blowdown.

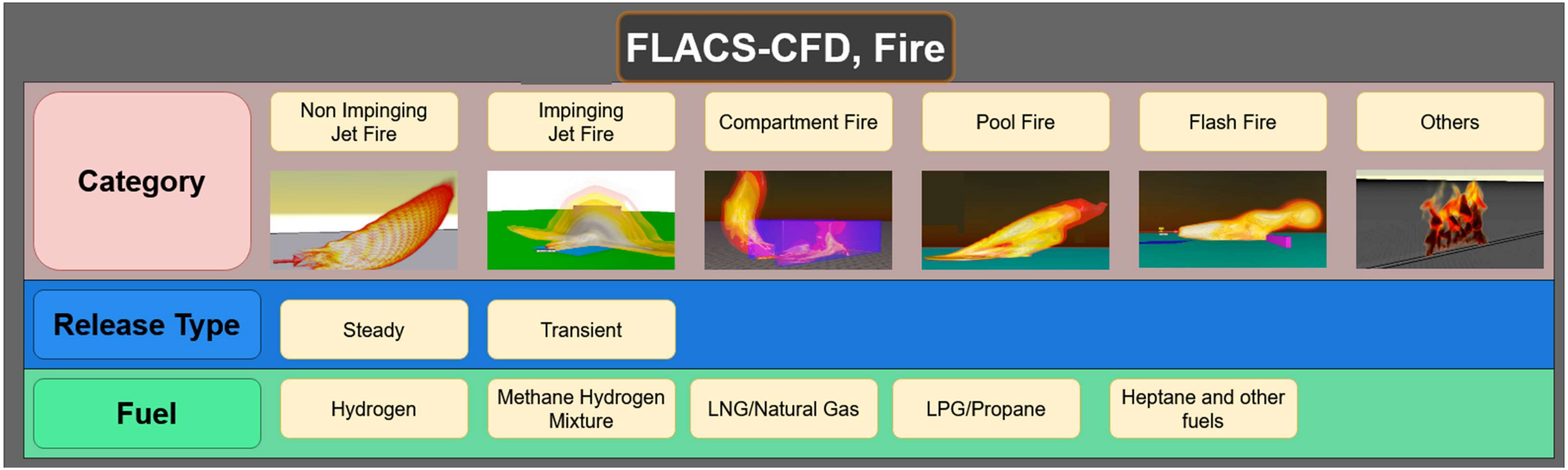
Consequence Modelling Tools

- Gexcon FLACS-CFD.
- Gexcon EFFECTS.
- Shell FRED.
- Sandia HyRAM

FLACS-Fire Validation Database

FLACS-Fire: Validation Database

- Gexcon software has developed a model evaluation protocol and a well-defined system for running validation simulations and extracting data.
- categorization and coverage :



FLACS-Fire: Validation Database

Coverage	Non Impinging Jet Fire	Impinging Jet Fire	Compartment Fire	Pool Fire	Flash Fire	Others
Hydrogen	Campaign = 4 Simulations = 26	Campaign = 4 Simulations = 65				
Methane Hydrogen Mixture	Campaign = 2 Simulations = 24					
LNG/Natural Gas	Campaign = 1 Simulations = 28		Campaign = 1 Simulations = 3	Campaign = 3 Simulations = 9		
LPG/Propane		Campaign = 1 Simulations = 14	Campaign = 1 Simulations = 6		Campaign = 1 Simulations = 42	
Heptane and other fuels				Campaign = 1 Simulations = 3		

Total Campaigns	19
Simulations (comprises of number of test cases per campaign and grids used per test)	223

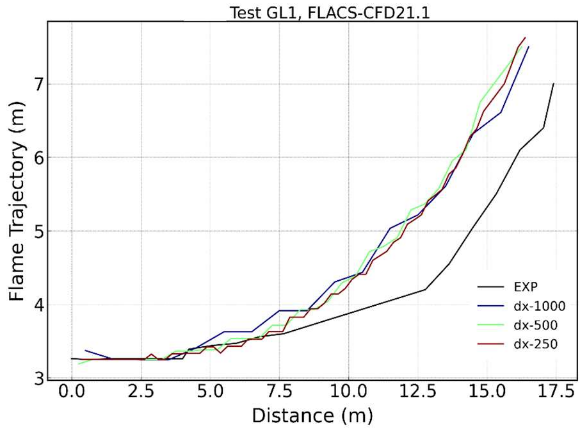
Steady leak jet fire cases

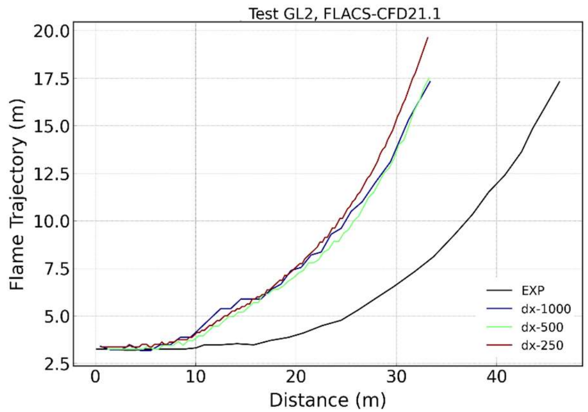
- GL Hydrogen Jet Fire
- SANDIA Cryogenic Hydrogen Jet Fire
- NaturalHy Jet Fire

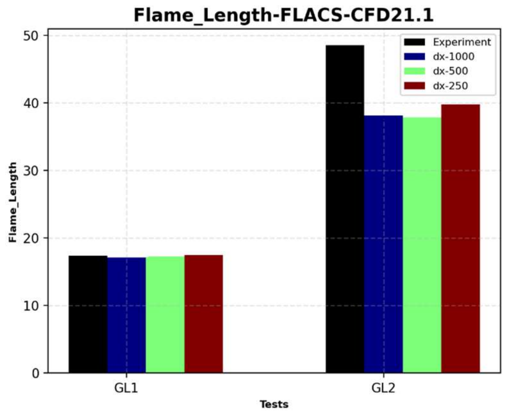
GL Hydrogen Jet Fire

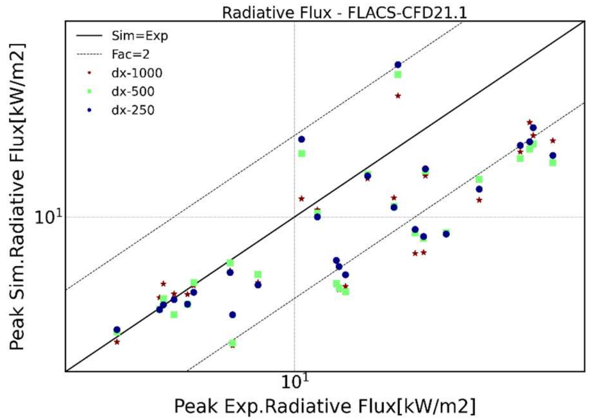
- Steady release rate
- Two test cases
- 3 grids used:
  - 250, 500 and 1000mm in core domain
  - with refinement around leak
  - Followed by stretching towards boundary

Flame	d_j[mm]	$\dot{m}$ [kg/s]	p_0 [barg]	T_0 [K]	RH [%]	T_{amb} [K]	p_{amb} [bar]	u_{wind} [m/s]	φ_{wind} [°]	L_{vis} [m] (rms)
1	20.9	1.0	59.8	308.7	94.3	280	1.022	2.84	68.5	17.4 (1.1)
2	52.5	7.4	62.1	287.8	94.5	280	1.011	0.83	34.0	45.9 (2.5)

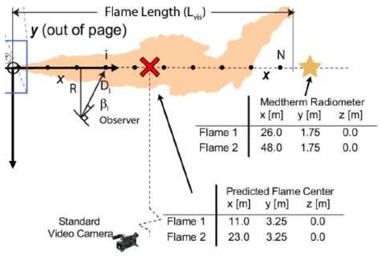








Comparison with Simplified models



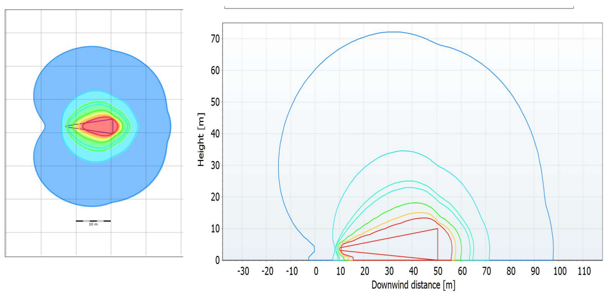
Total Flame length (in meter) experiment vs simulation

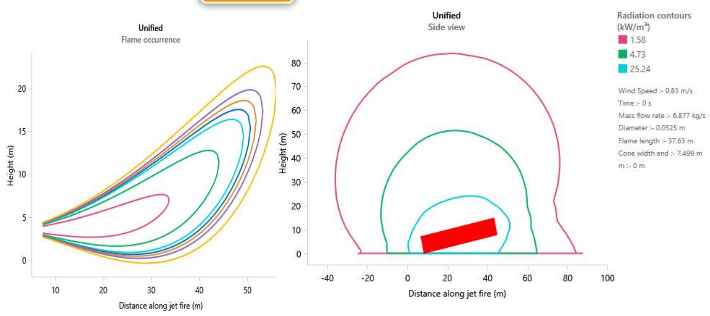
Case	Measurement	FLACS	EFFECTS	FRED	HyRAM
Flame 1	17.4	19.3	16.7	19.6	20.3*
Flame 2	45.9	41.6	50.3	45.1	48.9*

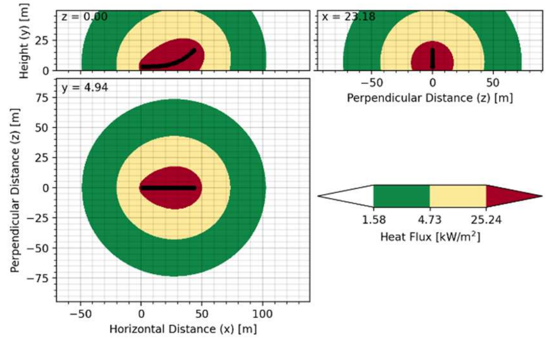
Heat flux (in kW/m^2) experiment vs simulation

Case	Measurement	FLACS	EFFECTS	FRED	HyRAM
Flame 1	4.7	4.9	5.1	4.1	6.1*
Flame 2	23.9	9.1	45.6	13.6	26.3*

* With zero wind speed



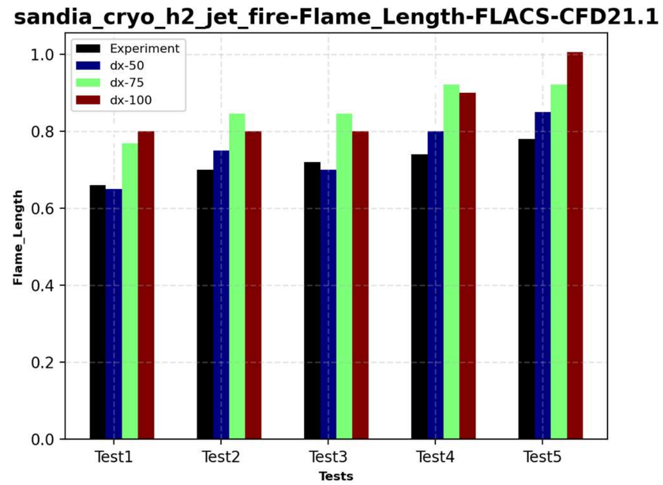


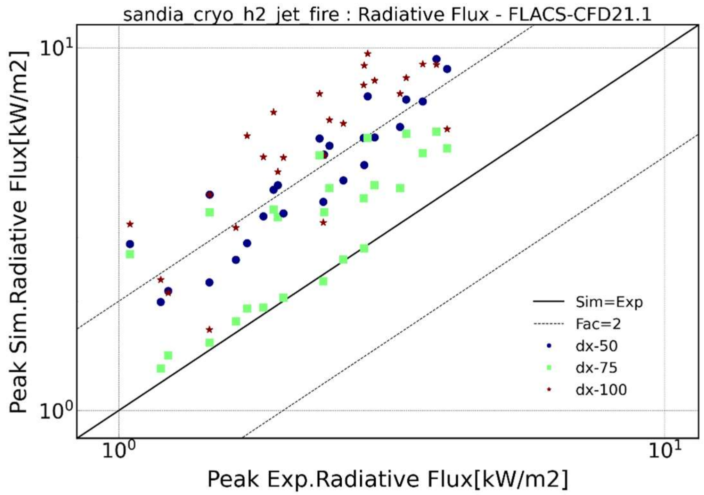


SANDIA cryogenic hydrogen jet fires

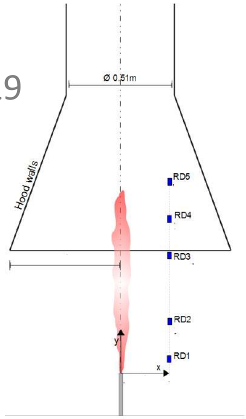
- Steady release rate
- 5 test cases
- 3 grids used:
  - 100, 75 and 50mm in core domain
  - with refinement around leak
  - Followed by stretching towards boundary

Test No.	Mass flow rate, g/s	Temperature, K	Pressure, bar abs
1	0.33	64	2
2	0.38	48	2
3	0.45	75	3
4	0.56	78	4
5	0.64	82	5

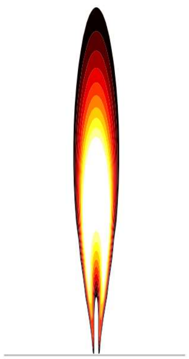




Cirrone et al. 2019



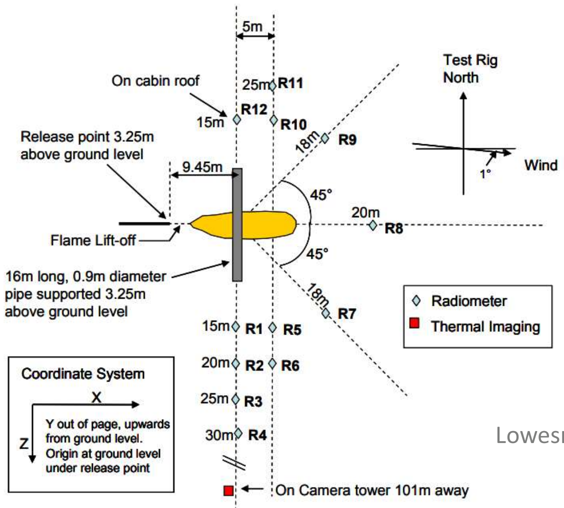
Experiment Setup



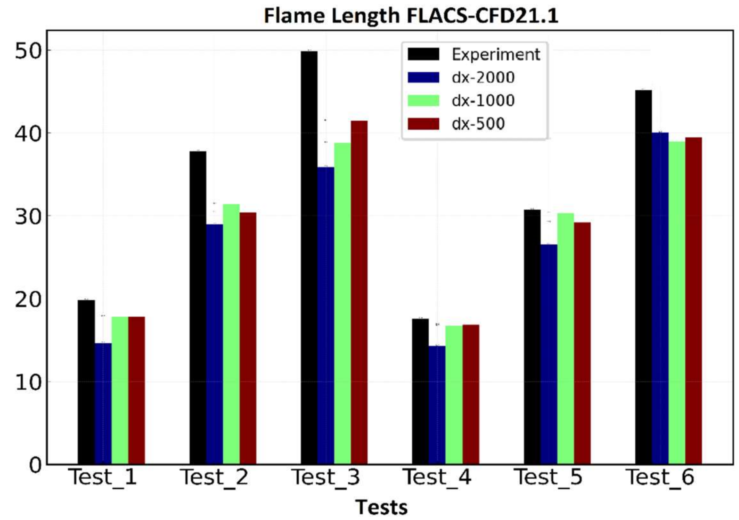
FLACS-CFD

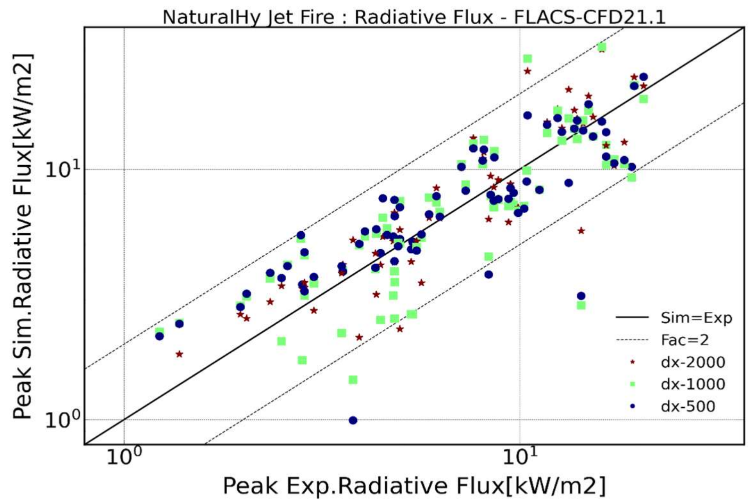
NaturalHy Jet Fire

- High pressure jet releases representing punctures in above ground plant or pipework
- The distances to the radiometers from the flame and the pipe target varied between tests
- Total six tests:
  - Tests 1 to 3 with natural gas
  - Tests 4 to 6 with 75% natural gas/25% hydrogen mixture
  - The orifice size, 20mm, 35mm and 50mm
  - Reservoir pressure, 60 bar for all the tests

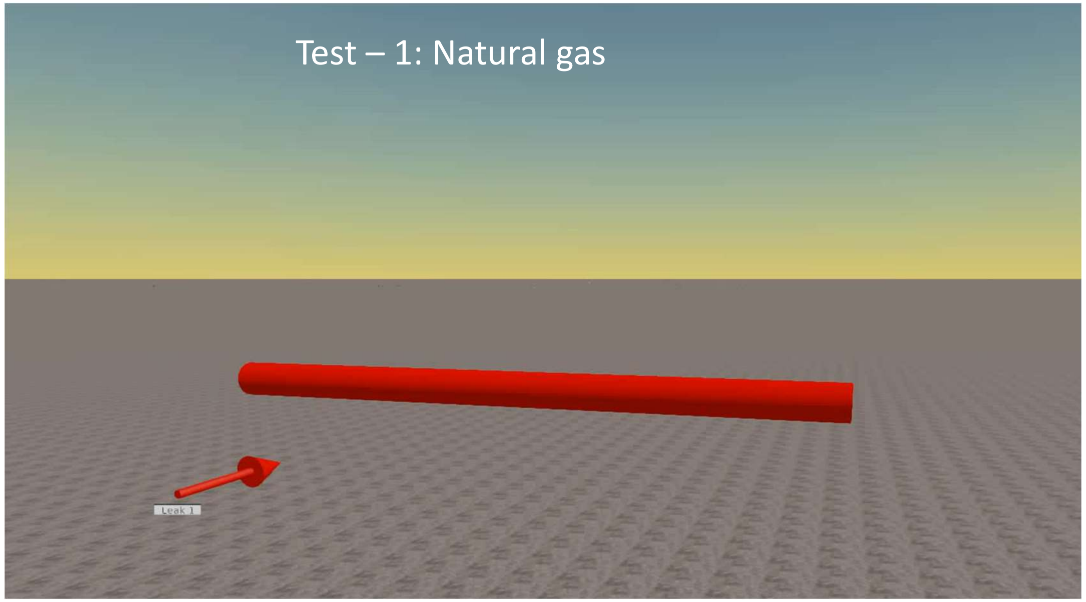


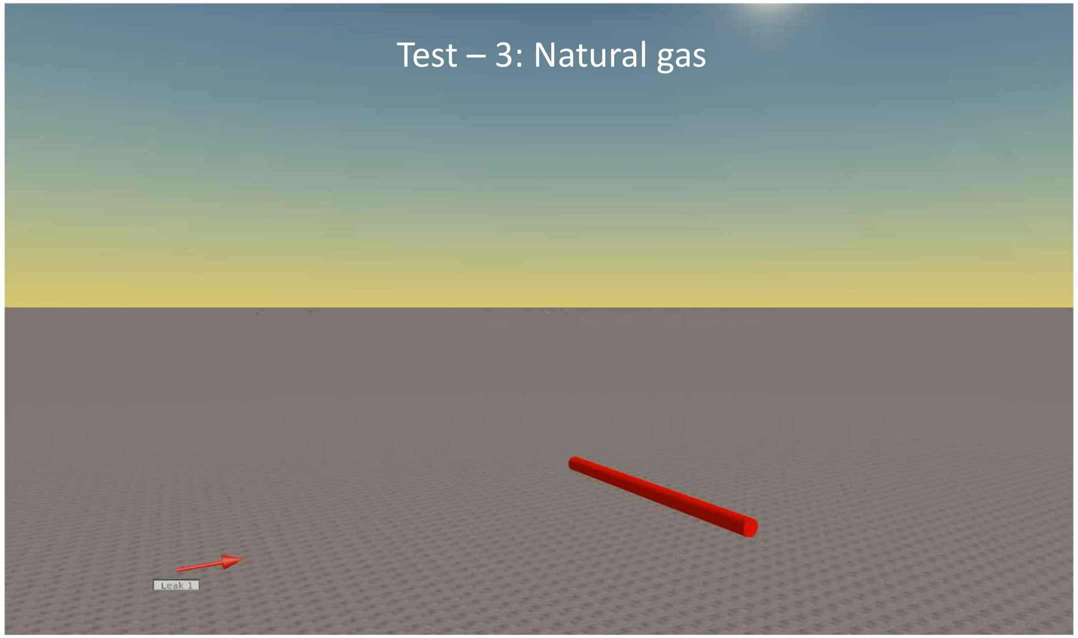
Lowesmith and Hankinson, 2012





Results:



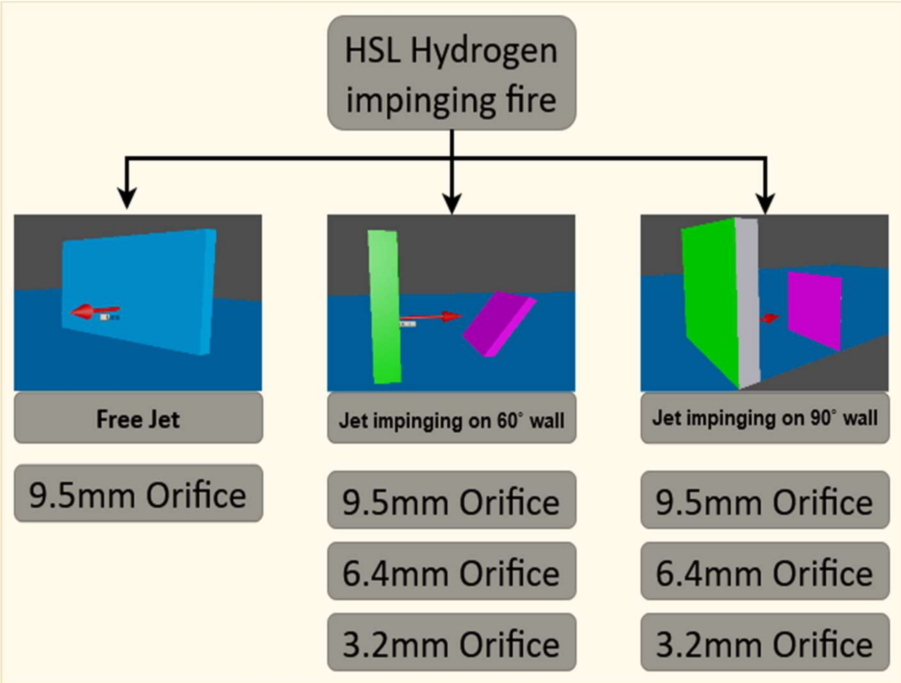


Transient jet fire cases

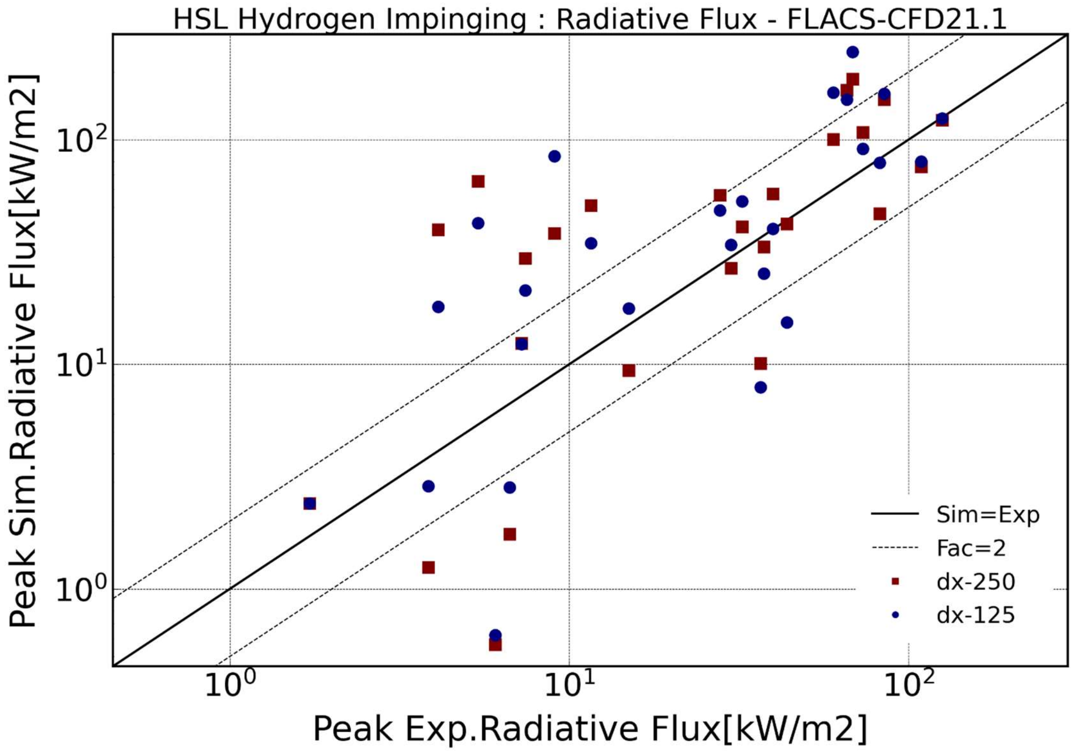
- HSL Hydrogen Jet Fires
- NaturalHy Pipe Rupture
- SRI Large Releases Jet Fire
- INERIS Hydrogen Jet Fires
- SH2IFT Hydrogen Jet Fires

HSL Hydrogen impinging fire

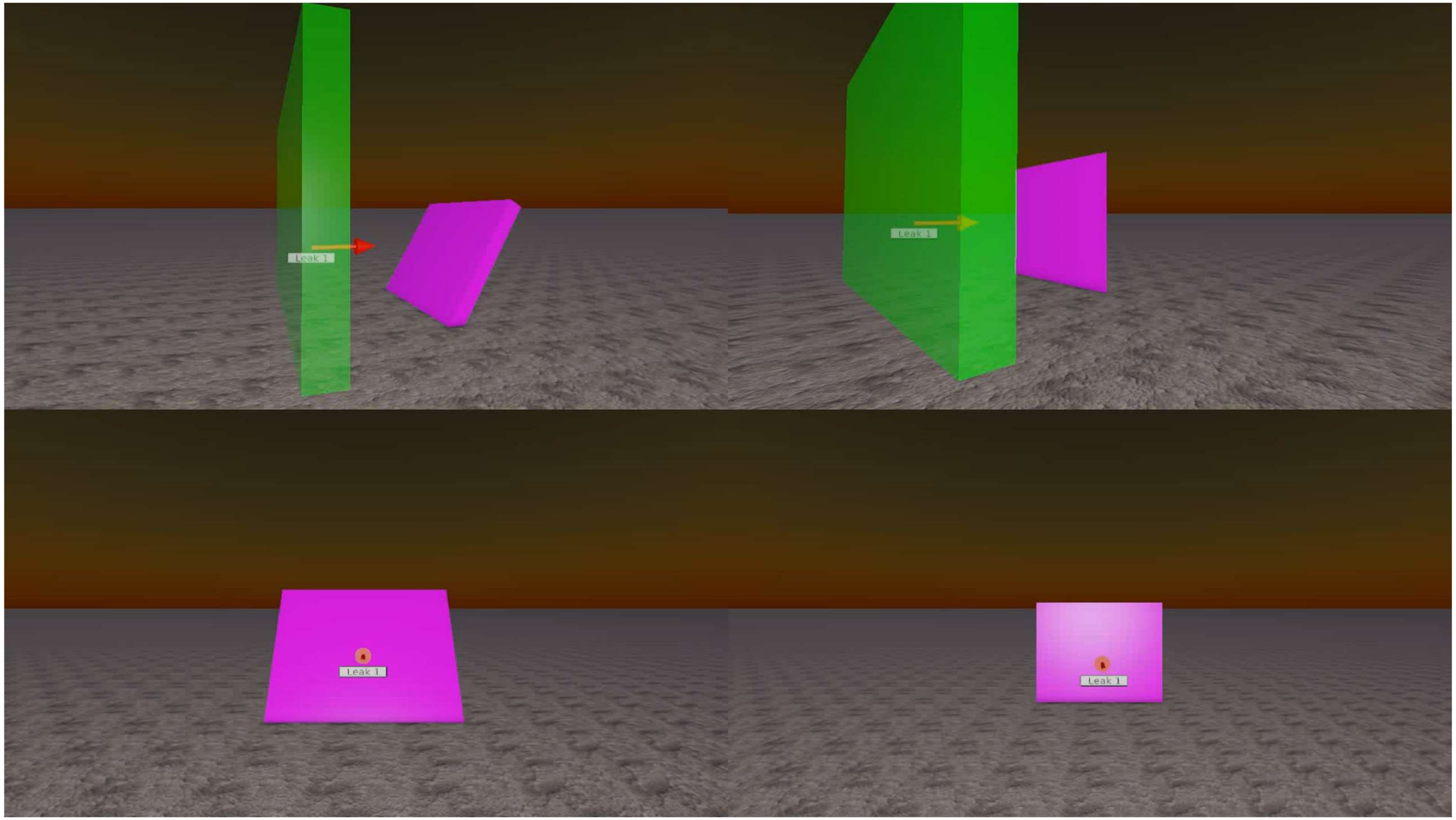
Willoughby, et al. 2009



Transient Release Rate



Results:

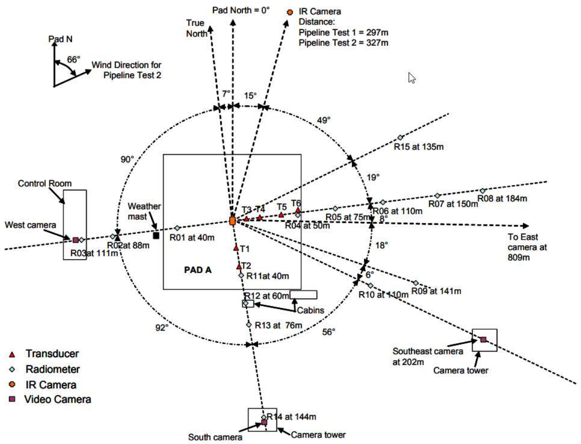


60° Inclined wall

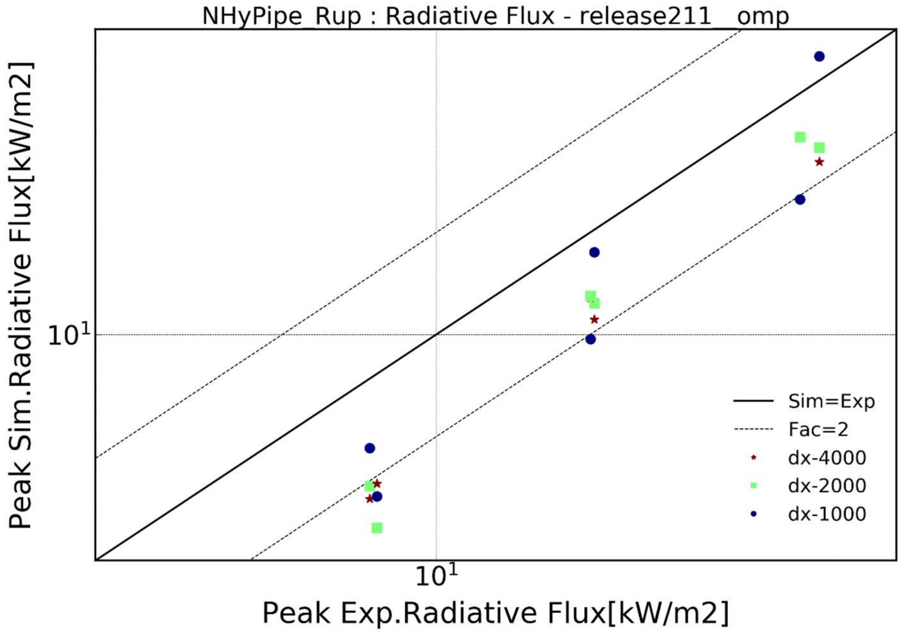
90° Inclined wall

NaturalHy Pipe Rupture

- Pipeline Diameter = 150mm
- The pipe was failed catastrophically by removing a 1.67m section using shaped high explosive charges, allowing gas to discharge from both ends of the severed pipe at gauge pressure of 70 bar
- Two tests
  - Test 1: 75% natural gas & 25% hydrogen mixture
  - Test 2: natural gas



Lowesmith and Hankinson, 2013



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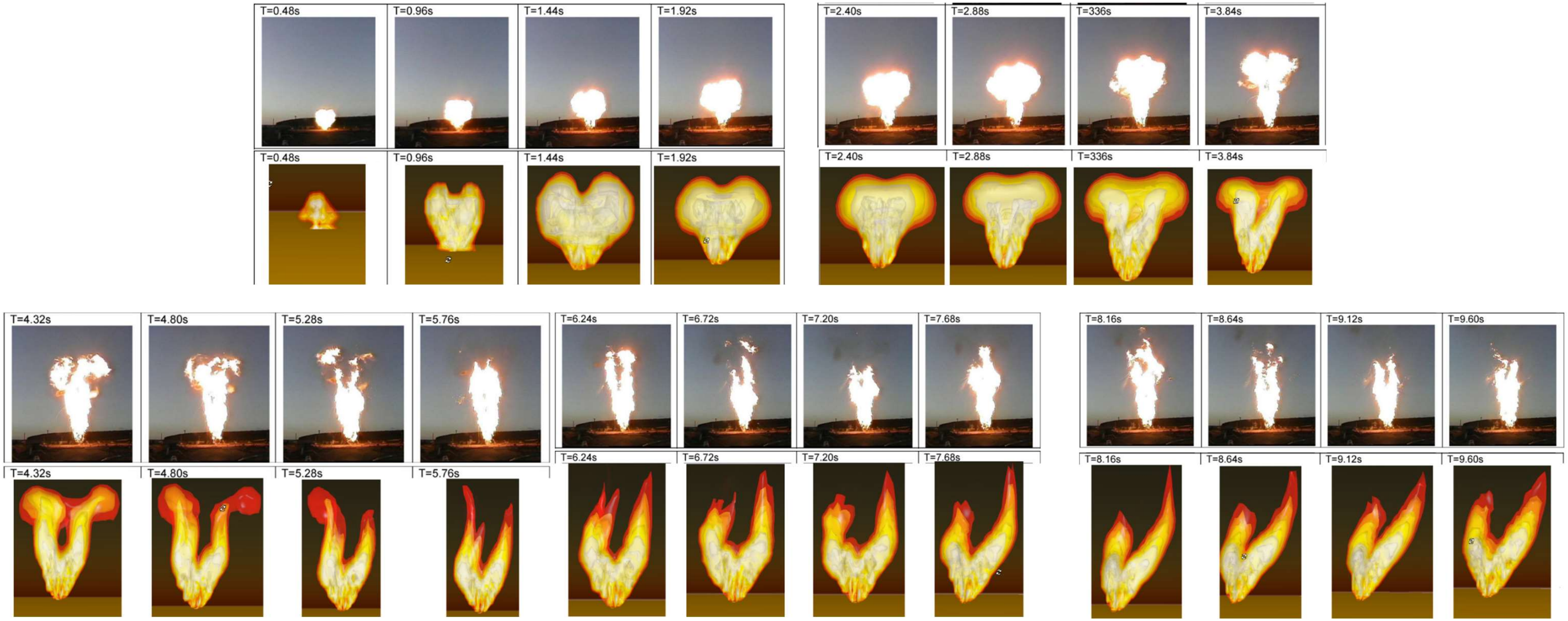
Pipe Rupture Test - 1 : 75% natural gas & 25% hydrogen mixture



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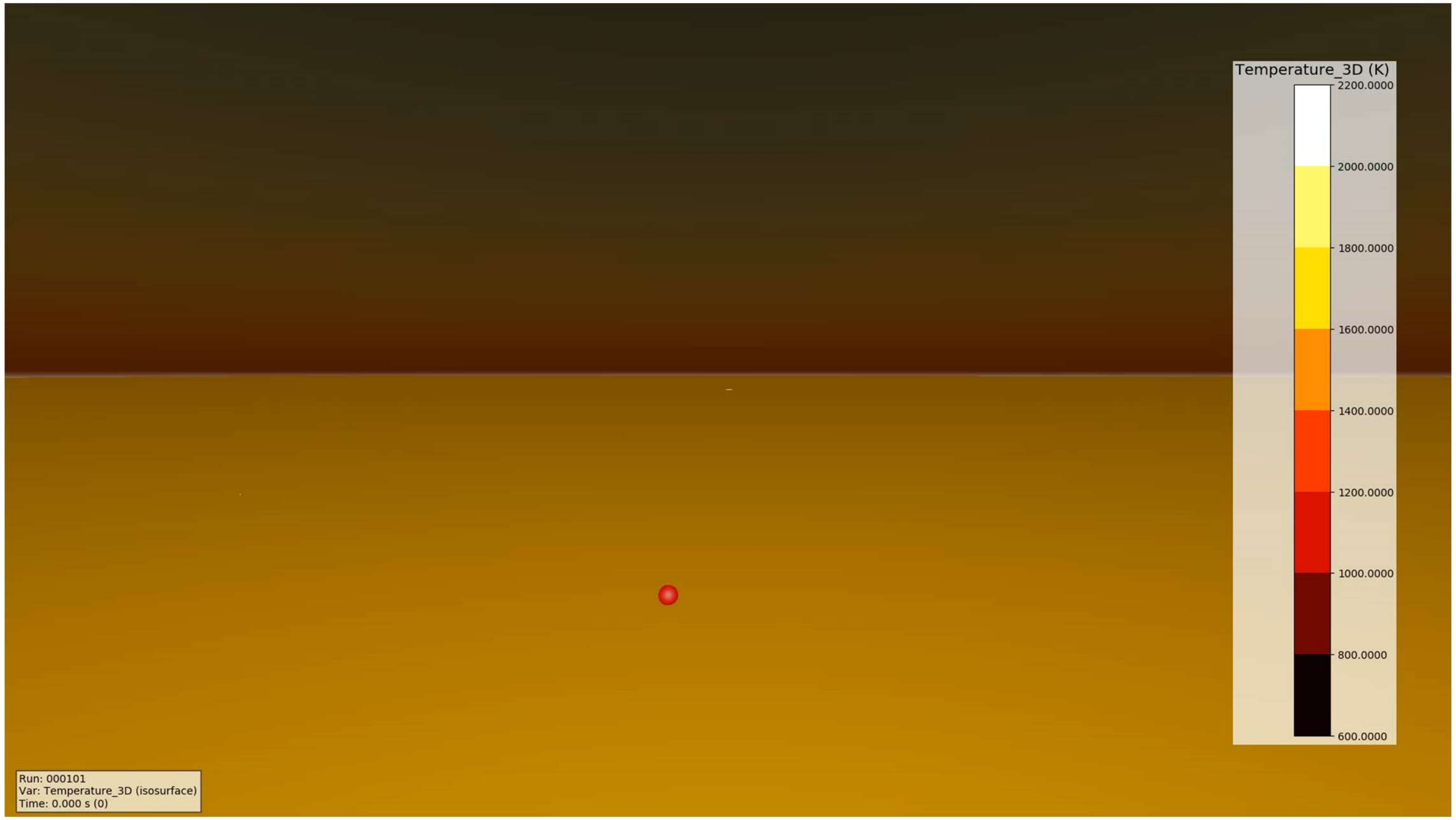

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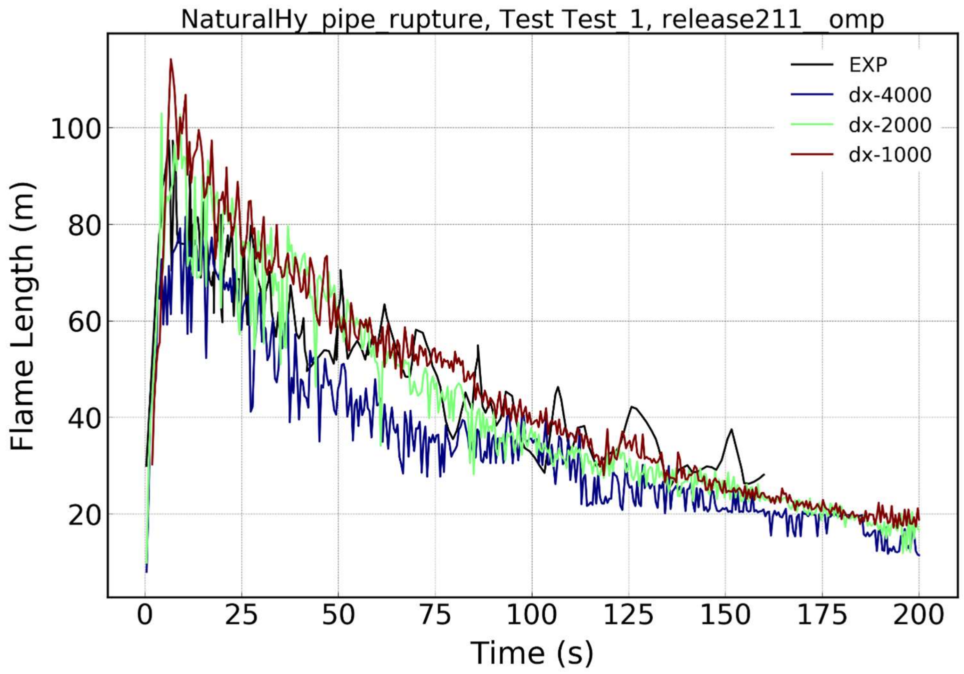
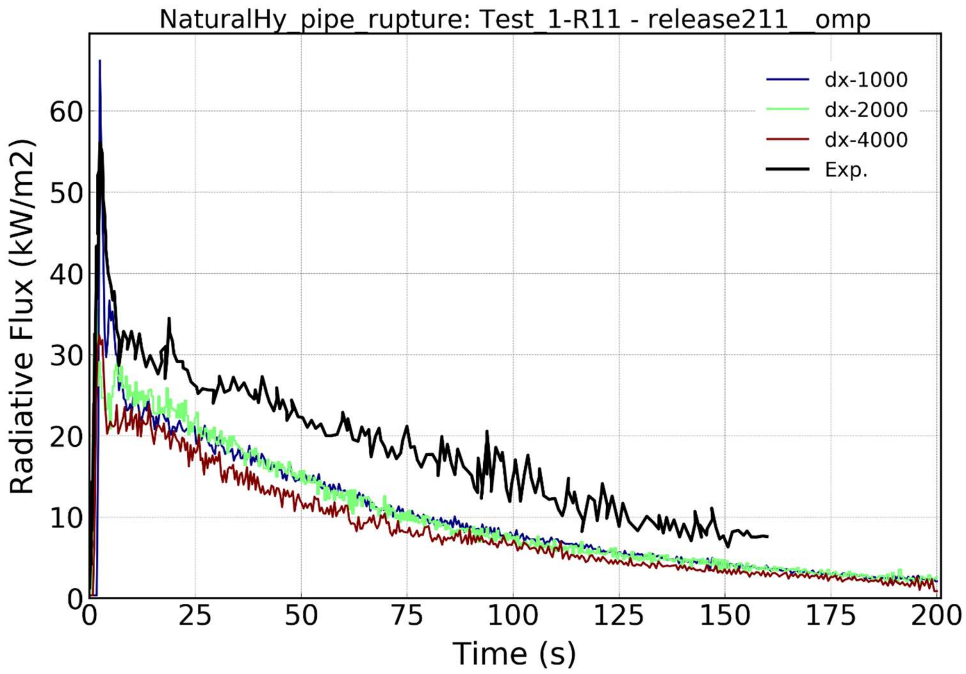
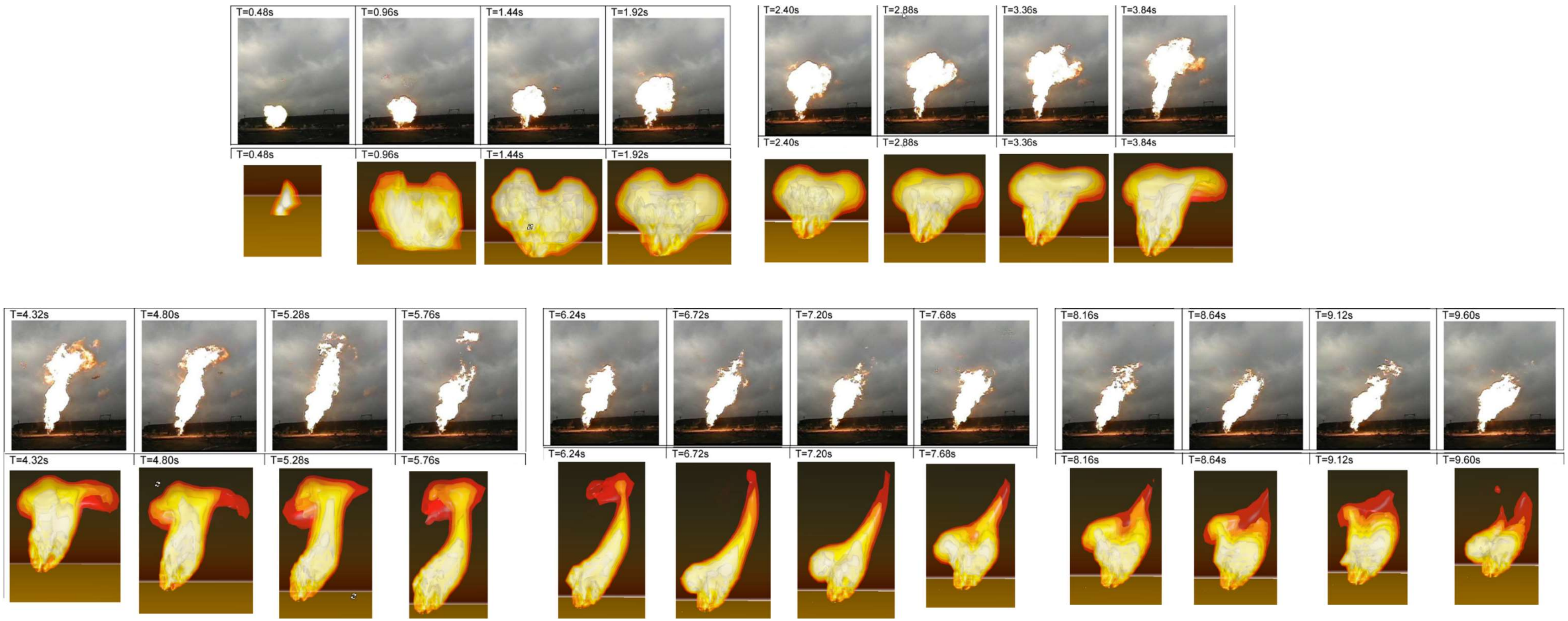
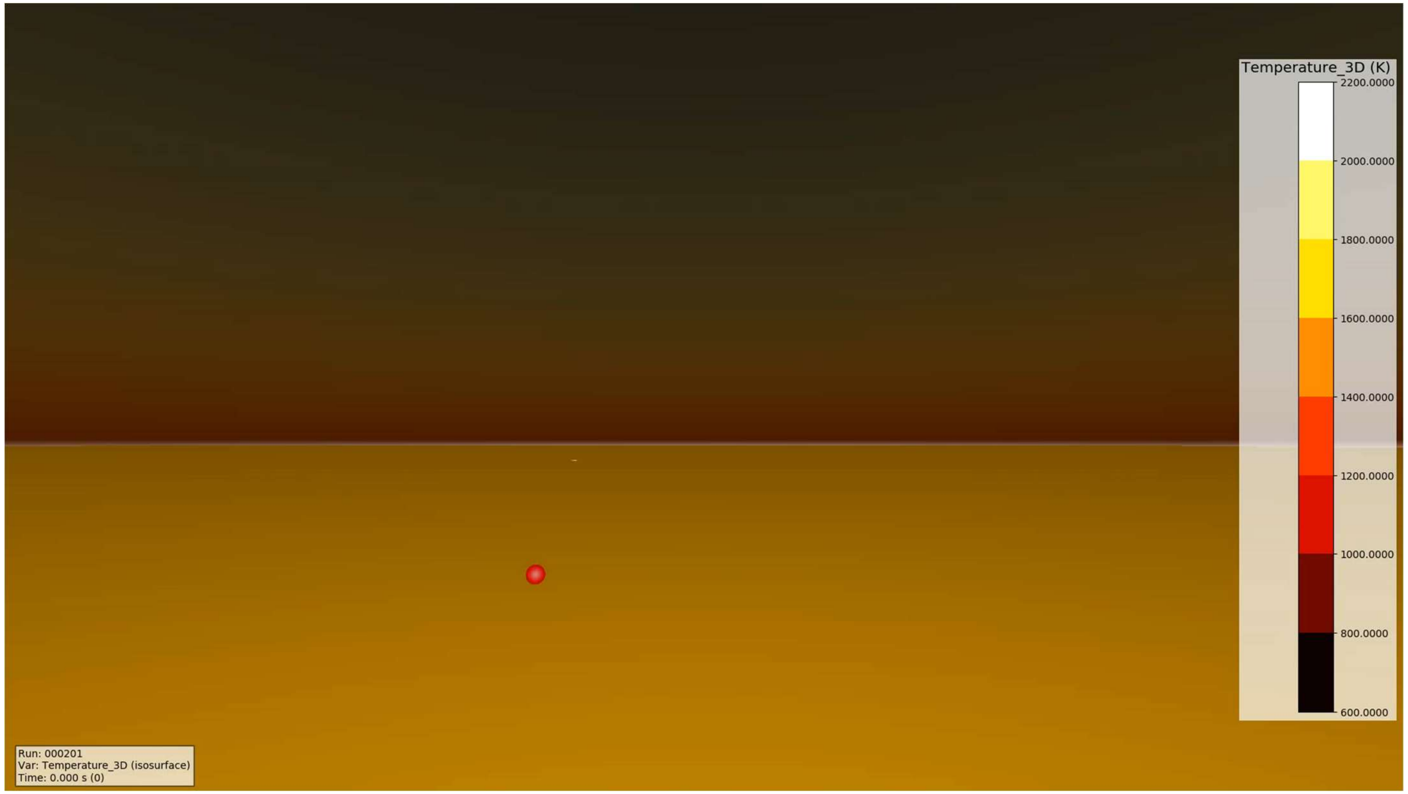




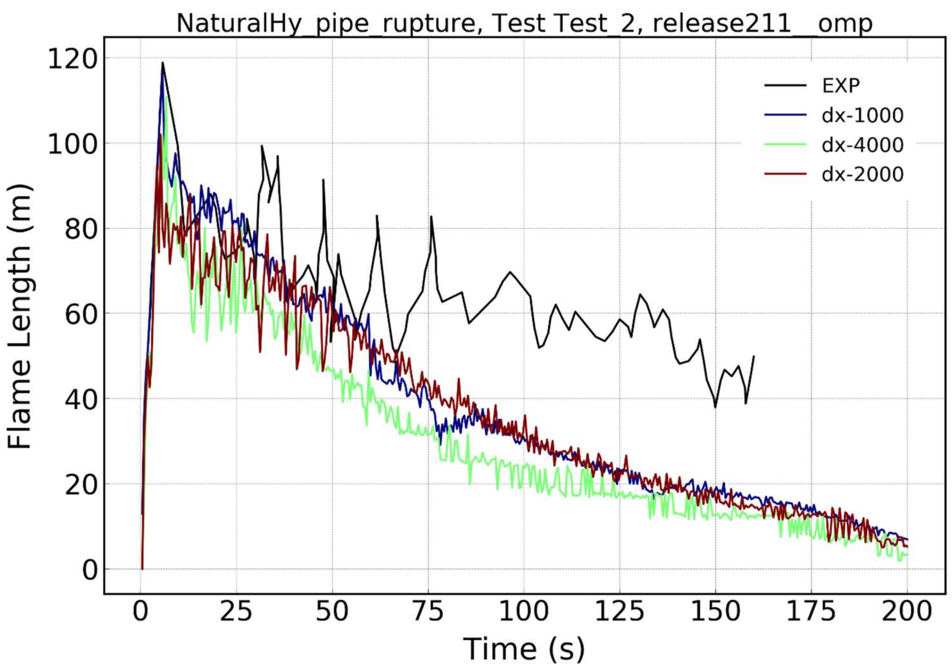
Pipe Rupture Test – 2: Natural gas

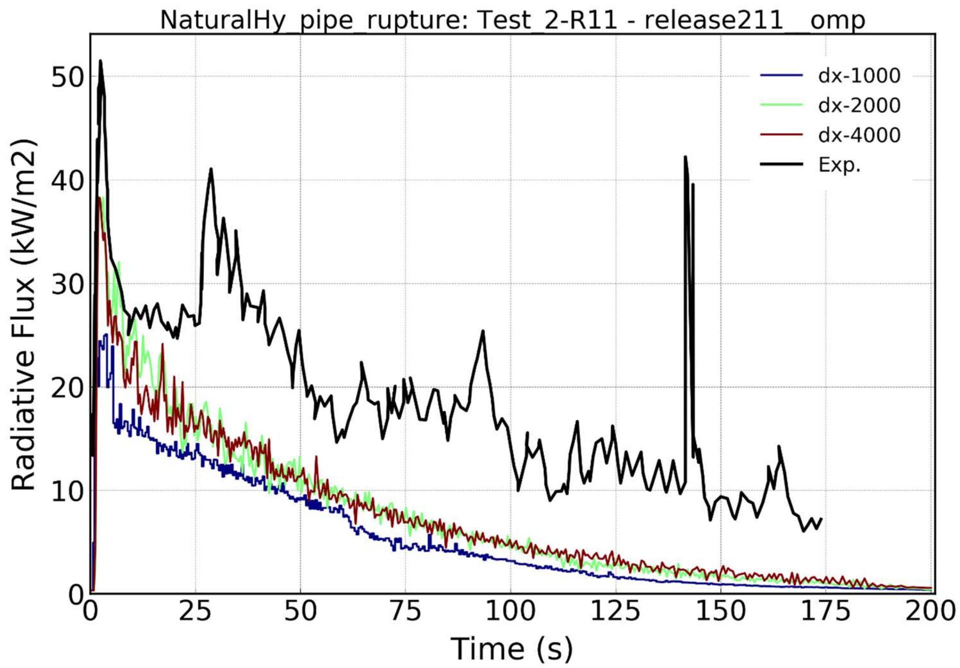


Pipe Rupture Test – 2: Natural gas

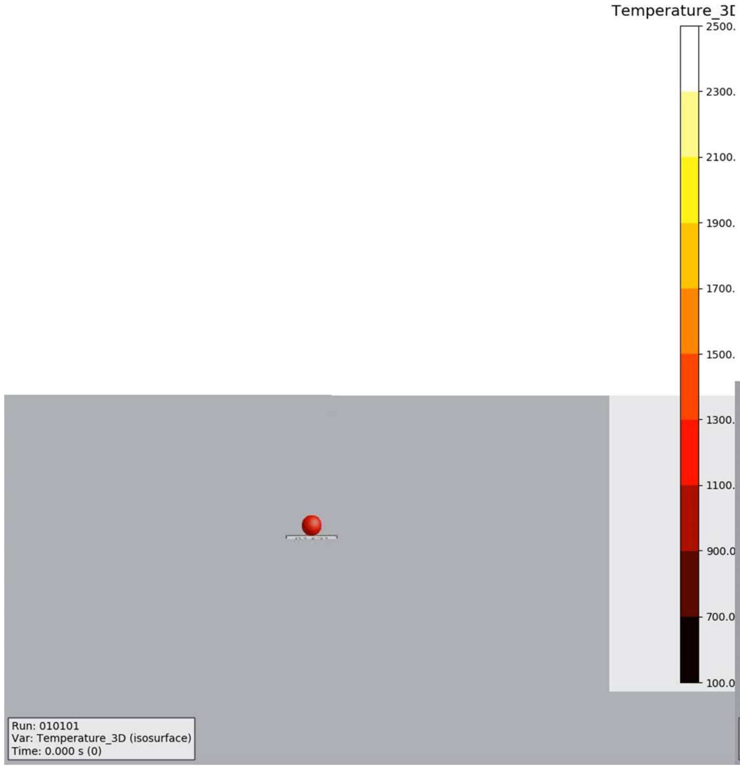


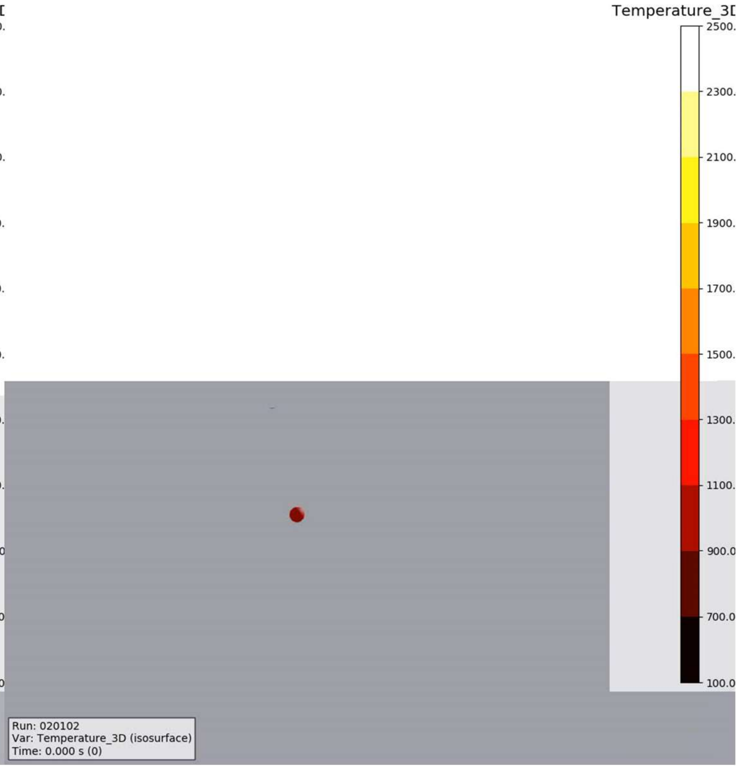
Pipe Rupture Test – 2: Natural gas





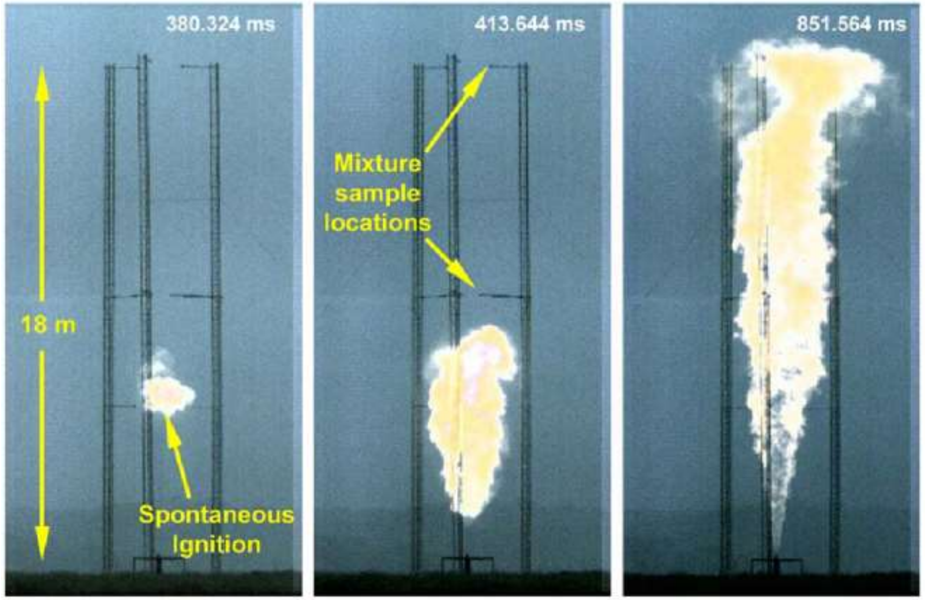
Pipe Rupture cases comparison



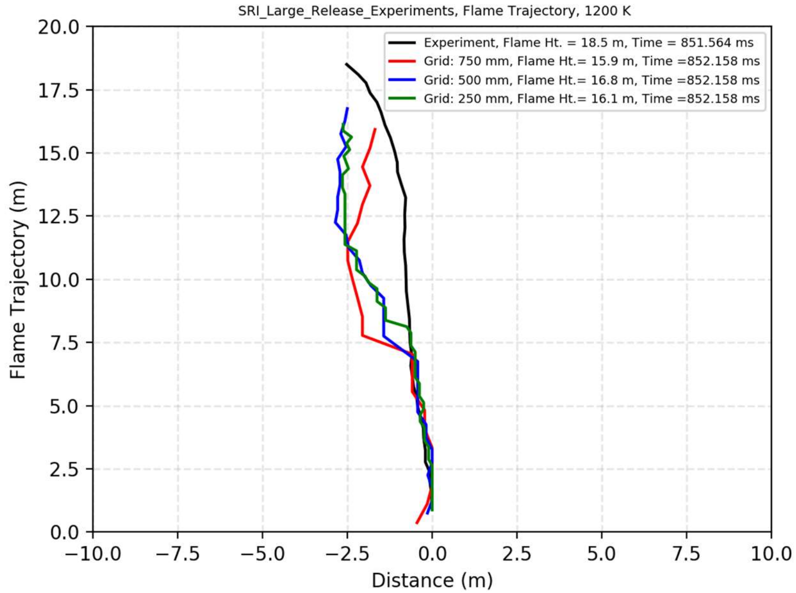


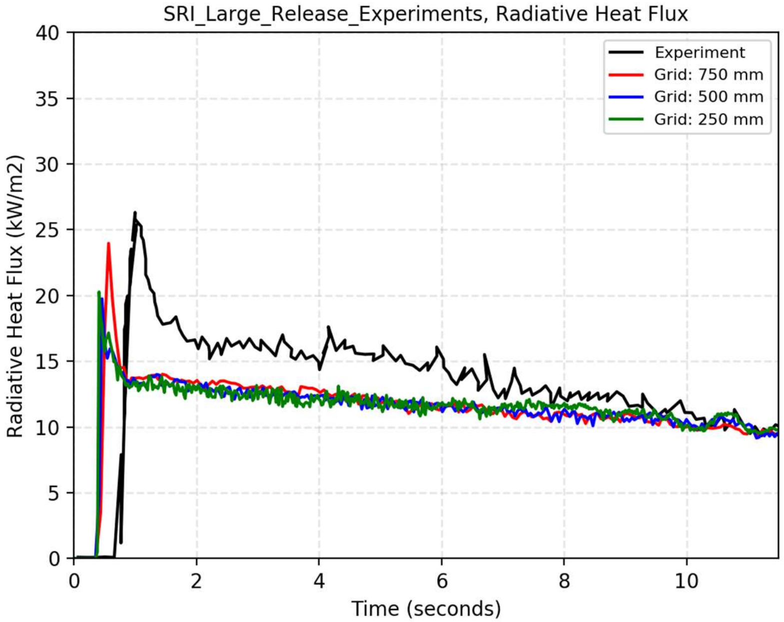
SRI Large Release

- A facility was built to study the release and ignition of large quantities of hydrogen (27 kg and 54 kg released in 30seconds) that might result from catastrophic failure of a storage container
- Transient release
- 3 grids used, 250, 500 and 750mm in core domain
- with refinement around leak, followed by stretching towards boundary



Groethe et al. 2007





INERIS Hydrogen Jet Fire

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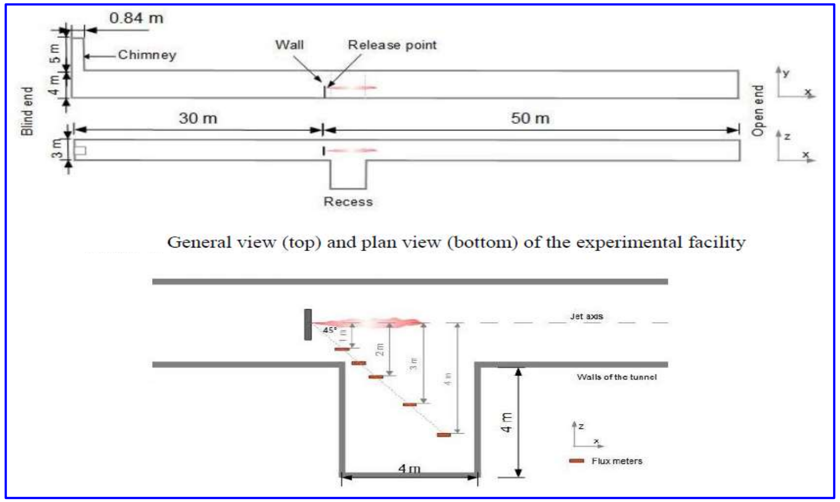
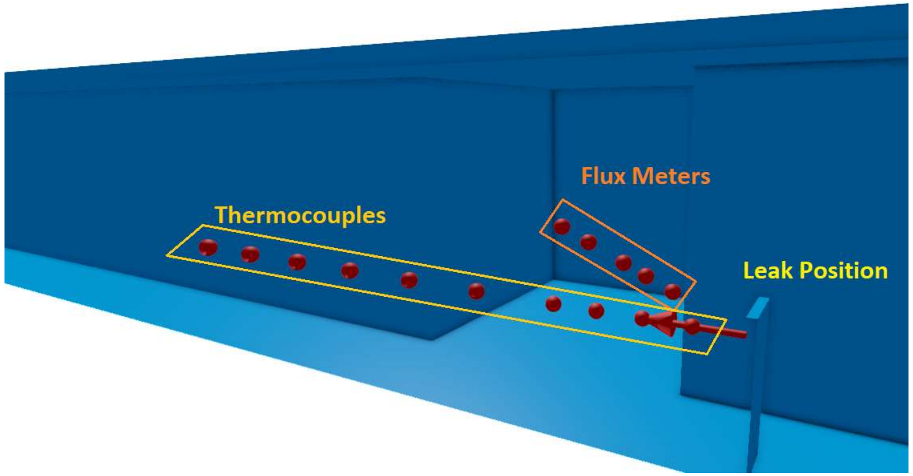
- Tank blowdown of high-pressure hydrogen reservoir (from 90MPa down) through orifices ranging from 1 to 3mm has been studied
- The jets were ignited, and the flame geometry and radiative properties were investigated
- This work was performed within the frame of French nation project DRIVE and E.U. sponsored programme HyPER.
- Transient release
- 2 grids used: 250, 500mm in core domain
- with refinement around leak, followed by stretching towards boundary

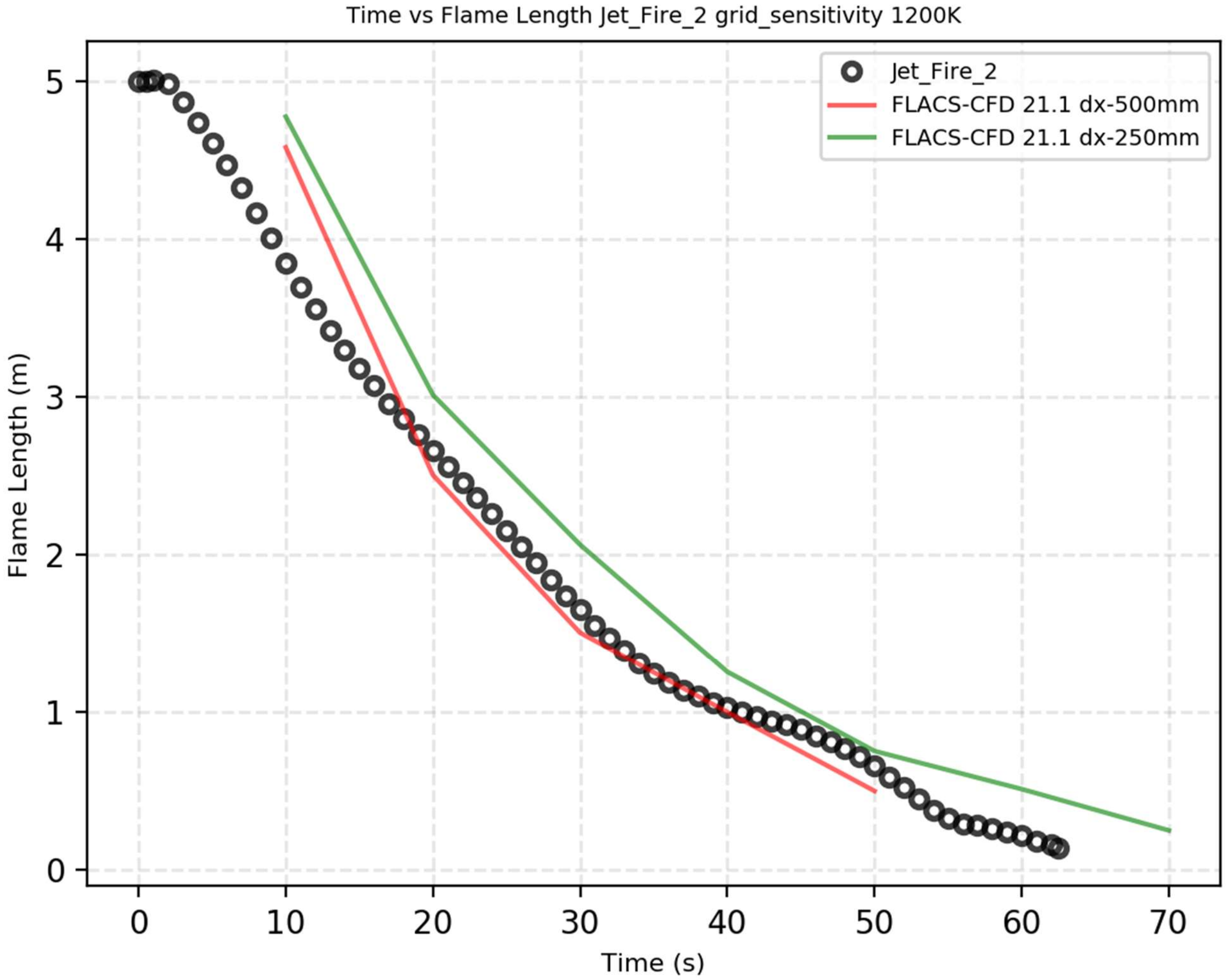


General view (top) and plan view (bottom) of the experimental facility

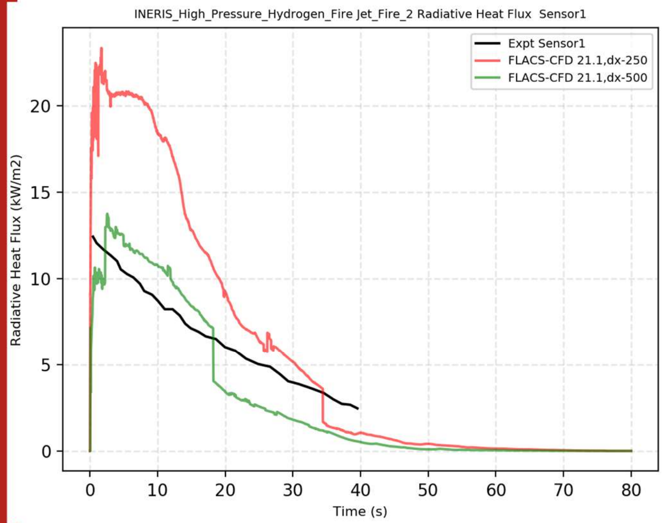
Studer et al.2009

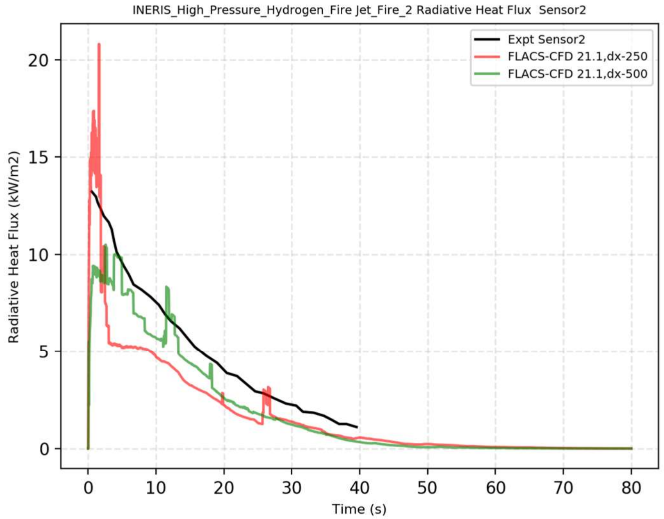


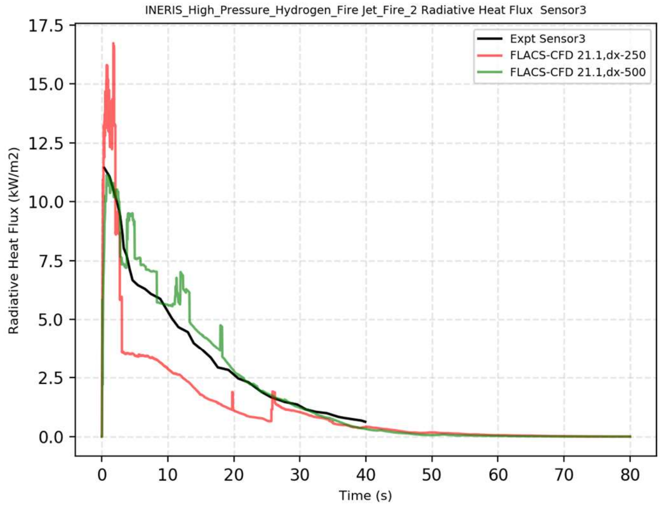
INERIS Hydrogen Jet Fire

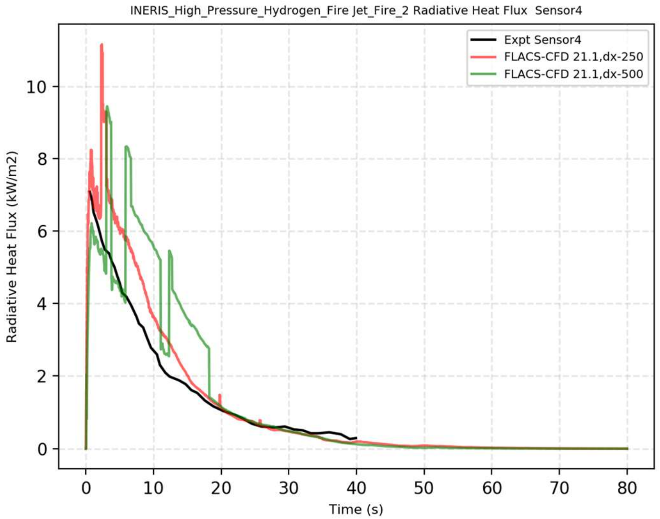


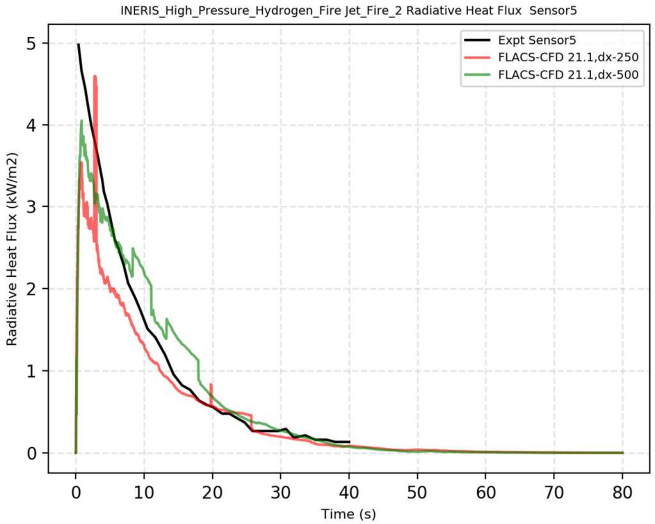
INERIS Hydrogen Jet Fire







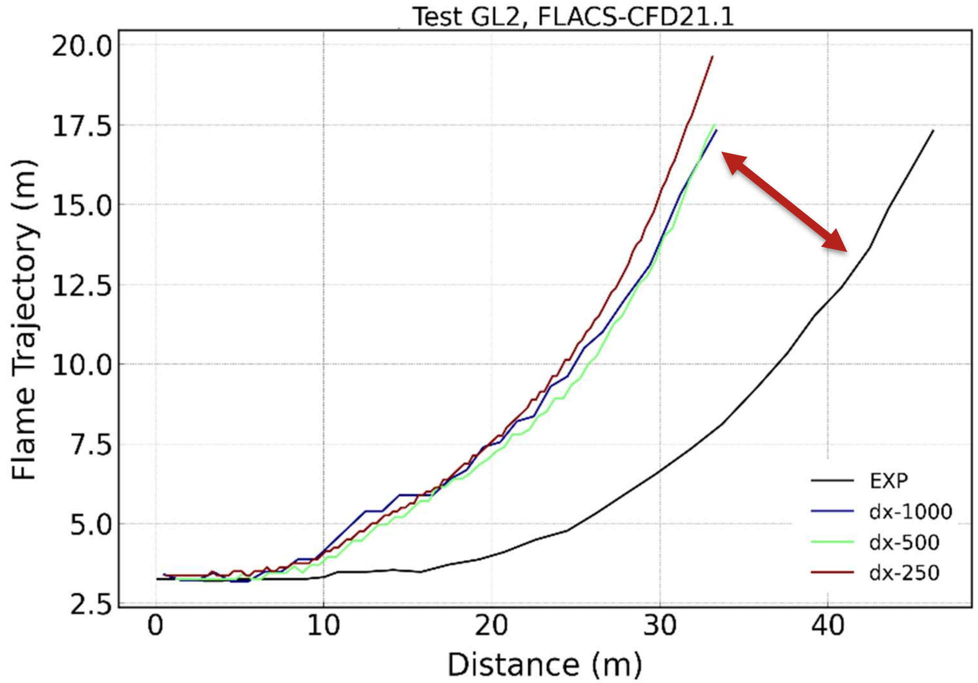




Parametric Studies

Horizontal Jet Fires

- FLACS-Fire simulations for large horizontal non-impinging jet fires shown to be dominated by significantly more buoyancy forces on the end part of the flame, causing the flame to bend off and rise up earlier compared to the experimental flame.



Flame to bend off and rise up much earlier compared to the experiments

Parametric Studies

- Important to understanding effect of following parameters
  - Pseudo source leak models (FLACS Jet utility Vs Ewan-Moodie)
  - Flame lift-off
  - Alter the turbulence decay - Increased momentum of the flame (second constant in k-ε, i.e. $\mathbf{C_2\varepsilon}$)
- Effect of Leak models & Flame-Liftoff model are extensively studied;
- The default turbulence coefficients can be varied to alter the turbulence decay (Hassel, 1997). This is especially the case for flames that involve hydrogen, due to the buoyancy and higher diffusivity of the chemical.

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GL Hydrogen Jet Fire

- Steady release rate
- 2 grids used:
  - 500 and 1000mm in core domain
  - with refinement around leak
  - Followed by stretching towards boundary

Flame	d_j[mm]	$\dot{m}$ [kg/s]	p_0 [barg]	T_0 [K]	RH [%]	T_{amb} [K]	p_{amb} [bar]	u_{wind} [m/s]	φ_{wind} [°]	L_{vis} [m] (rms)
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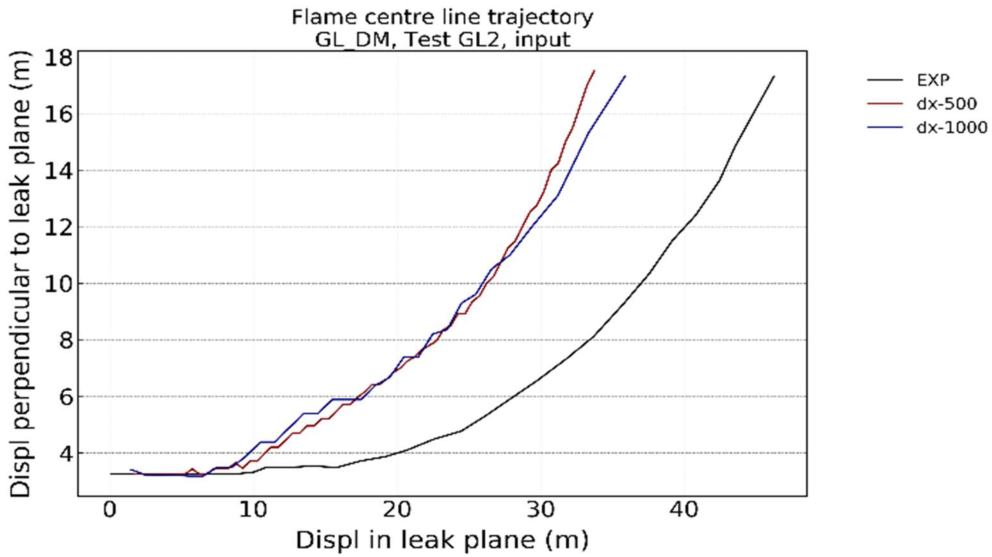
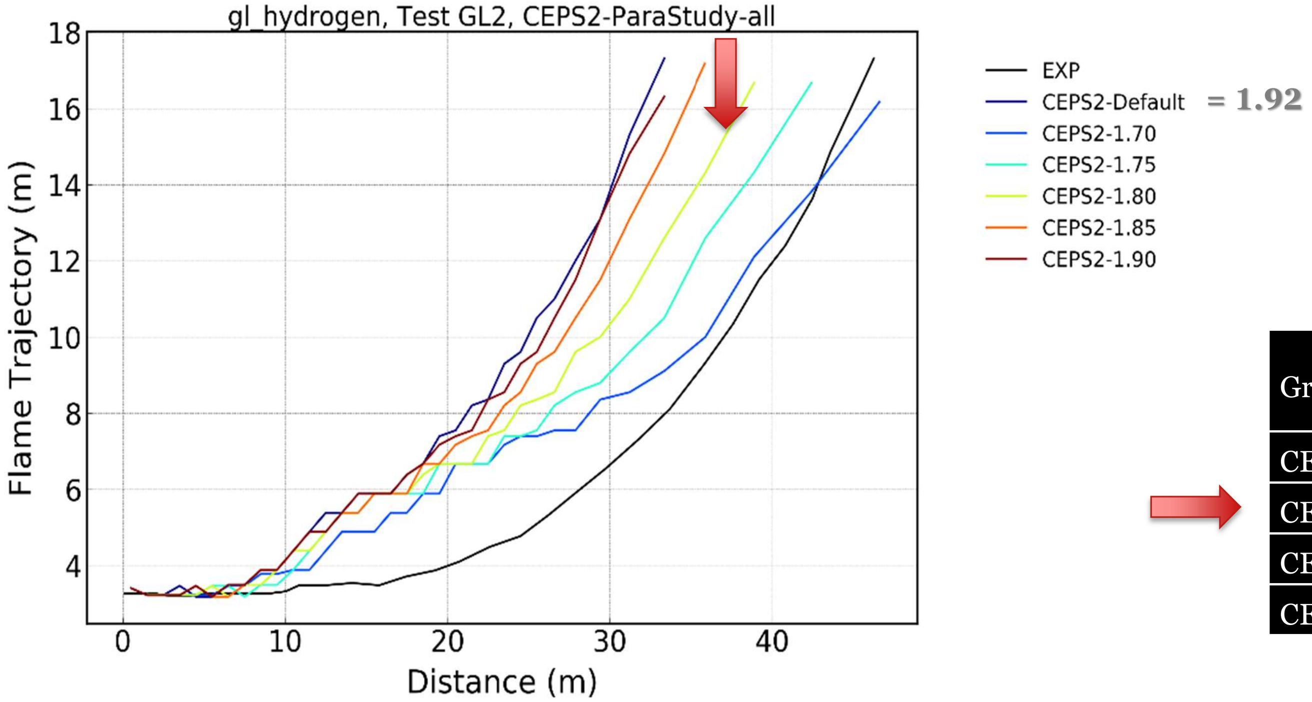


Grid Size, mm	Flame Length, m	
	FLACS-CFD	Experiment
100	38.6	45.9
50	41.6	

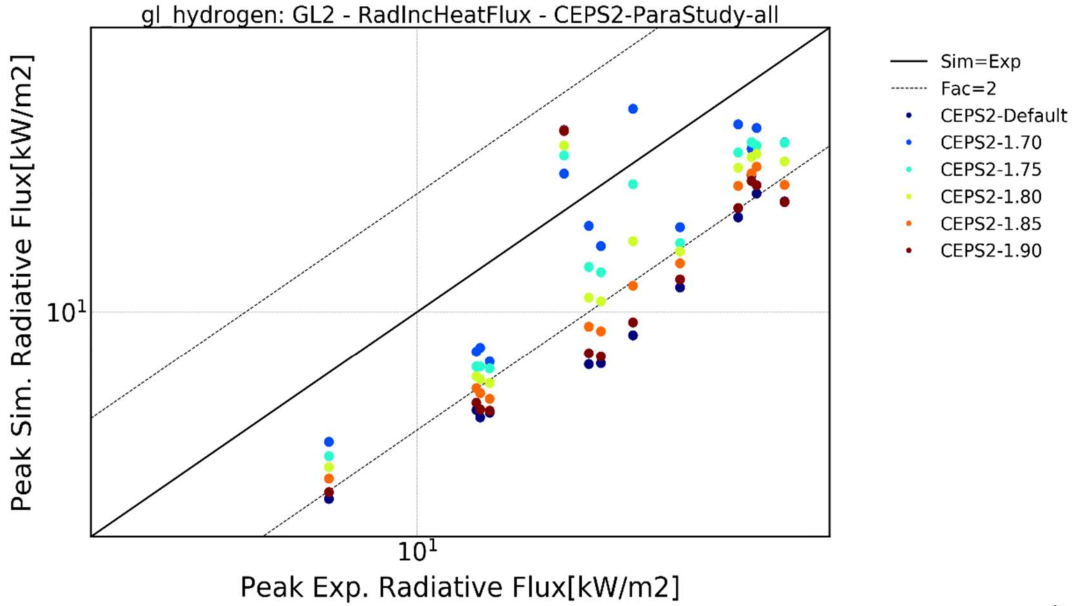
Effect of C2ε on Flame length and trajectory

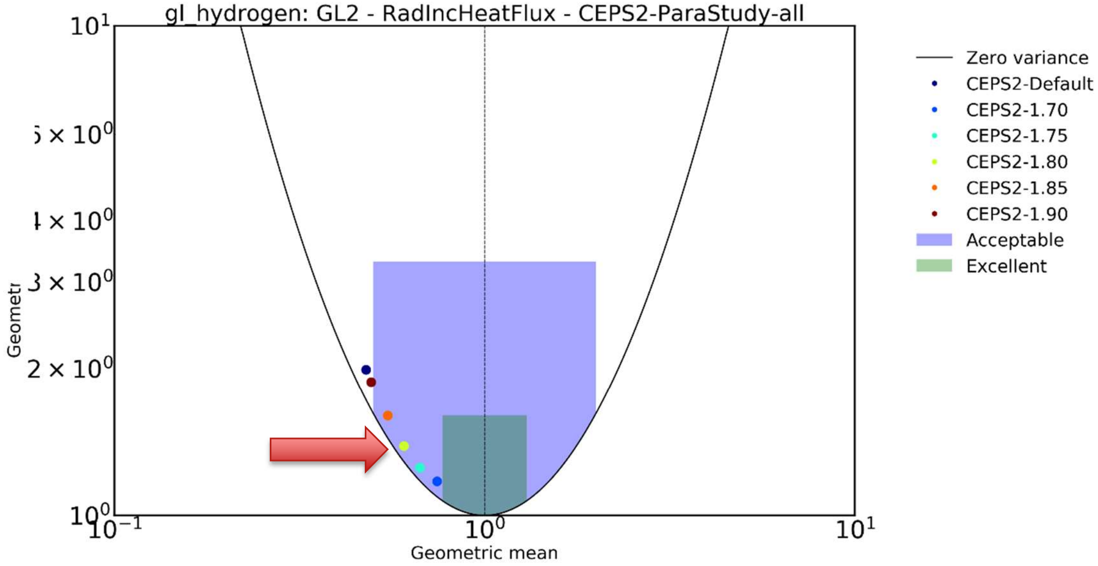
- Lowering of the coefficient value increases the momentum domination in the initial jet development, while buoyancy forces strengthen as centerline velocities decrease; observations that qualitatively agree with experimental observation.



Grid Size, mm	Flame Length, m	
	FLACS-CFD	Experiment
CEPS2-1.92	41.6	45.9
CEPS2-1.80	50.9	
CEPS2-1.70	62.5	
CEPS2-1.60	74.6	

Radiative Heat Flux Vs Measurement



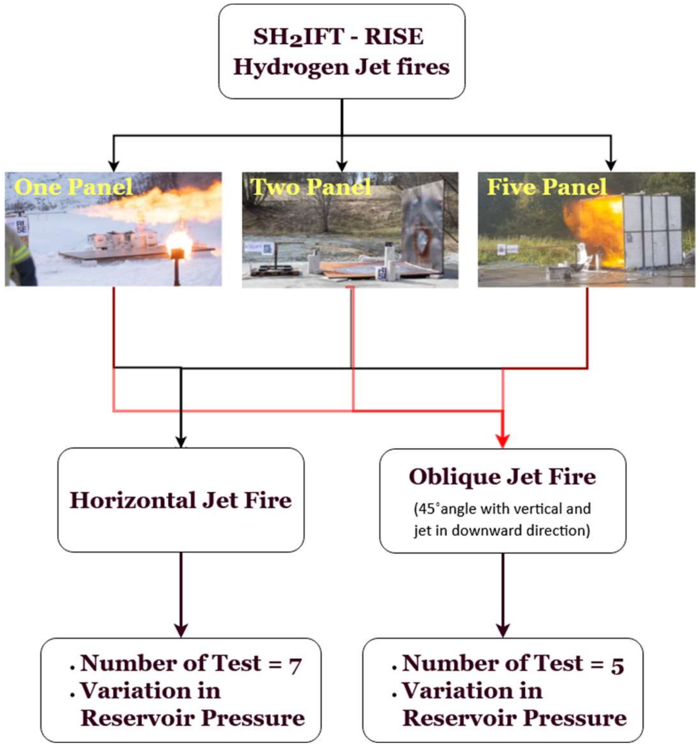


SH2IFT Experiments

SH2IFT Jet Fire experiments

- Objective: To quantify the severity of a fire involving a GH2 tank from a vehicle inside an enclosed space with a focus on the thermal exposure on the surfaces that enclose the fire and are impinged directly by the jet flame.
- The hydrogen jet is a transient blowdown from a 250-litre reservoir at initial pressure around 285 bar through a jet nozzle with diameter 6 mm.
- The duration of the jet releases was approximately 2 minutes.
- The thermal exposure to the inside of this enclosure is measured using the steel walls of the enclosure as plate thermometers.

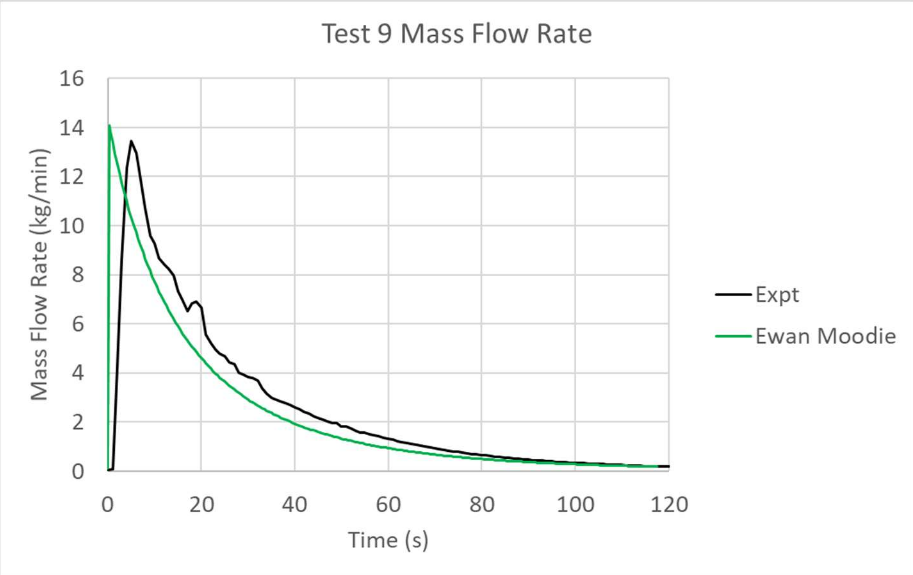
Sub Categories	Value
Fuel	Hydrogen
Scale	Large
Release Type	Vessel blowdown
Source Type	Jet
Jet Orientation	Horizontal and 45° downwards
Release Rate	Transient
Storage Condition	Gas

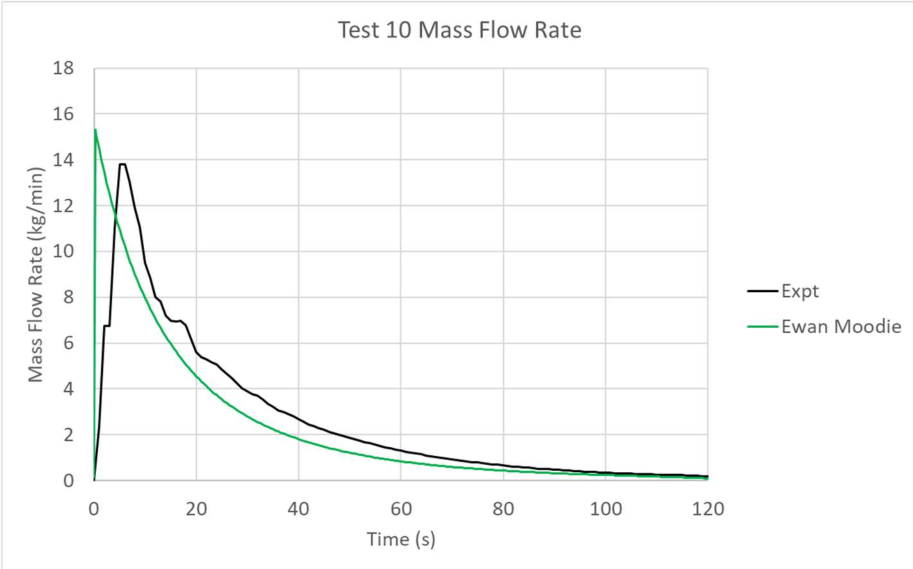


Tank blowdown

- Computed using Leak wizard in FLACS-CFD21.1
- Leak is modelled using Ewan Moodie pseudo source model

FLACS-CFD21.1





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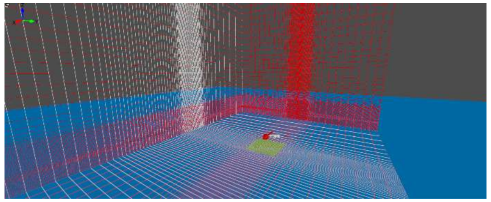
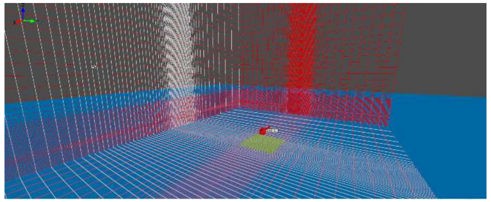
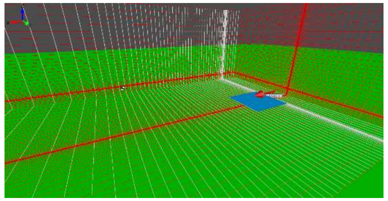
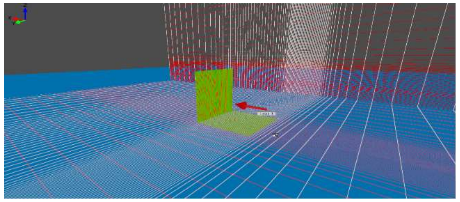
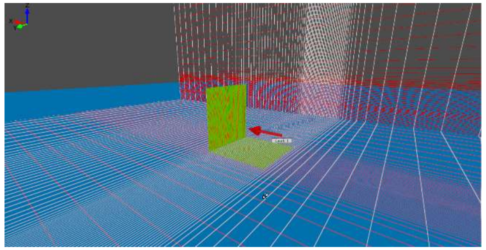
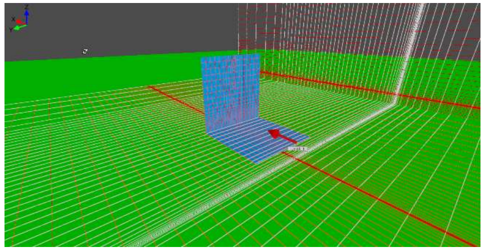
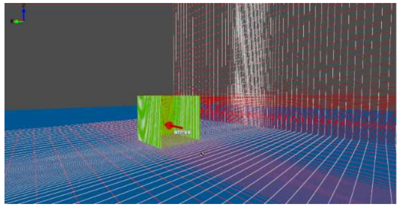
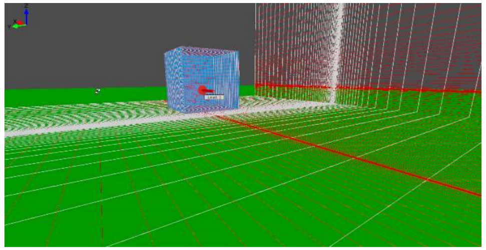
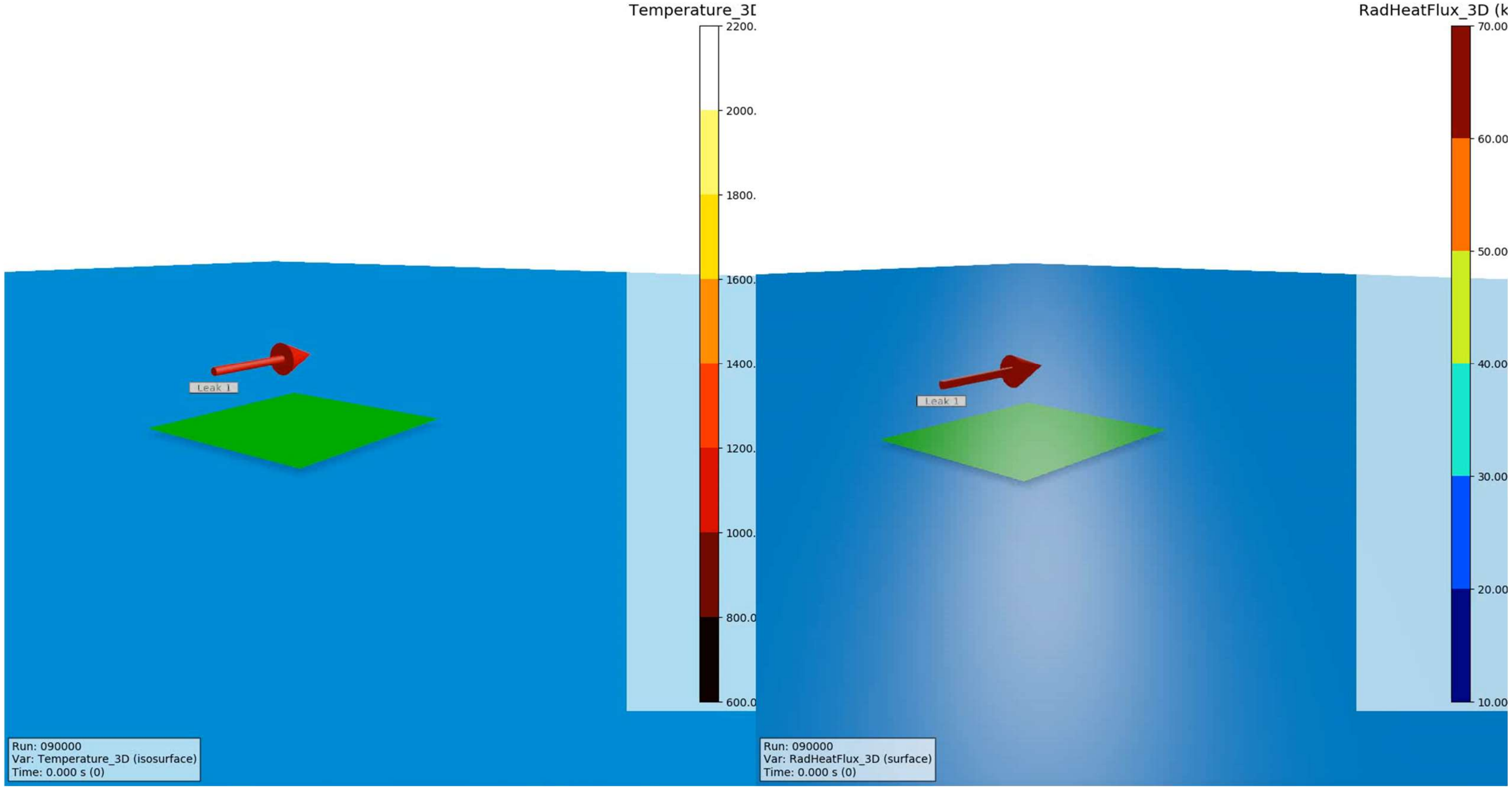
FLACS Setup & Grid Size used

Horizontal Jet	
Grid Size used, m	Name
0.300	dx-300
0.200	dx-200
0.100	dx-100

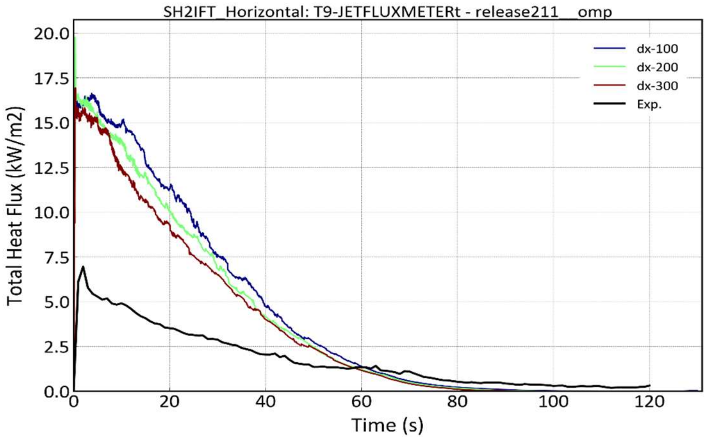
Oblique Jet	
Grid Size used, m	Name
0.200	dx-200
0.100	dx-100

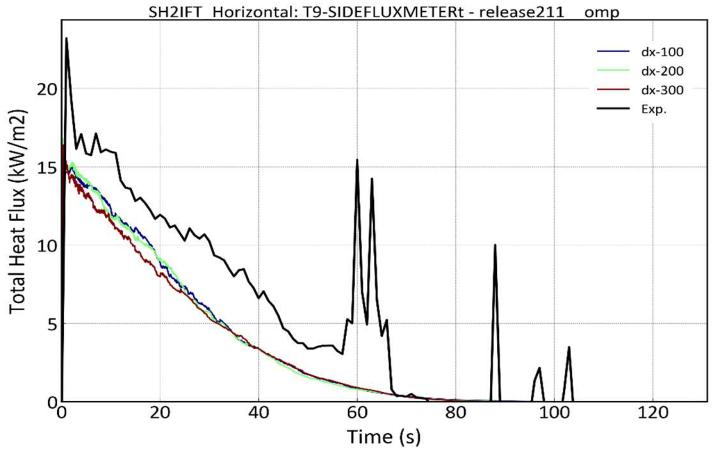









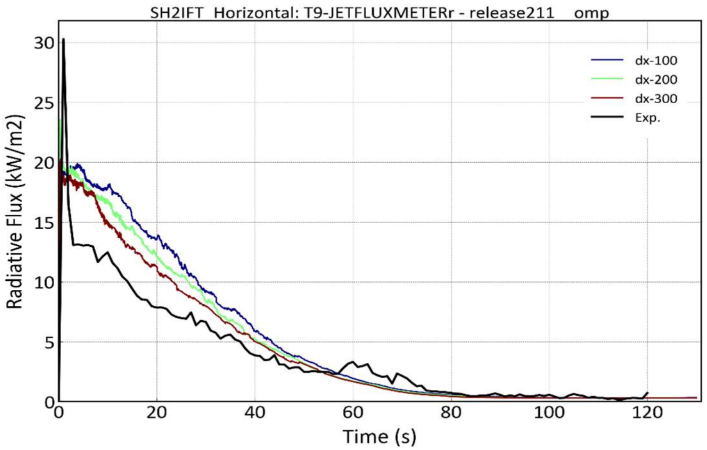
Results for Test T9 (J90-1p)

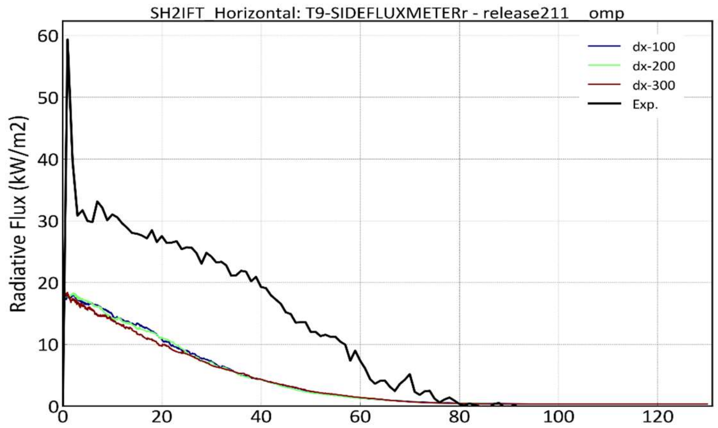


Results for Test T9 (J90-1p)

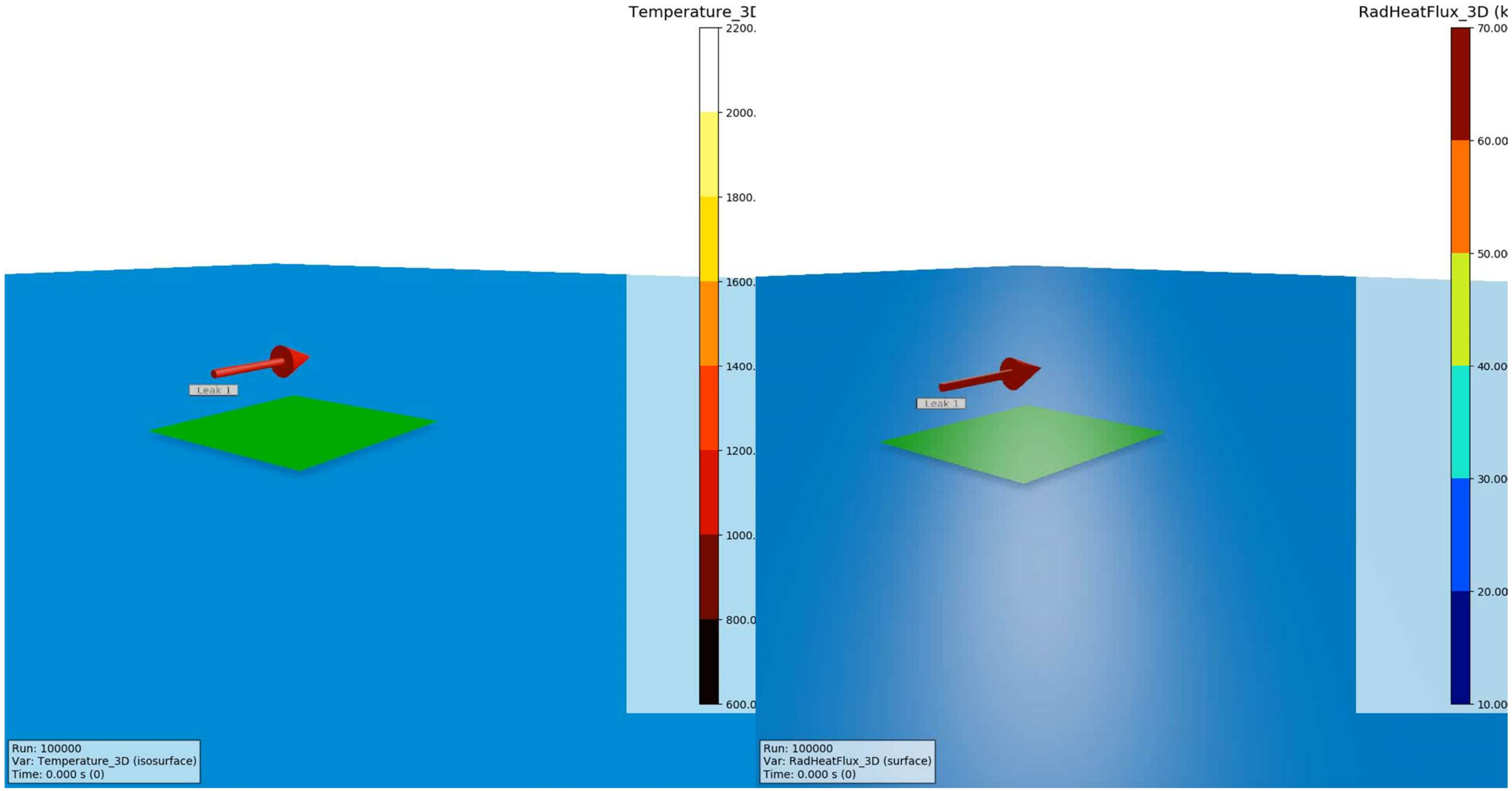




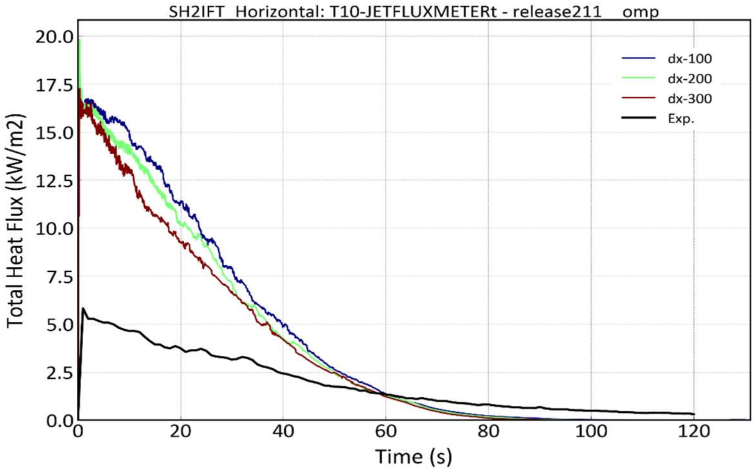


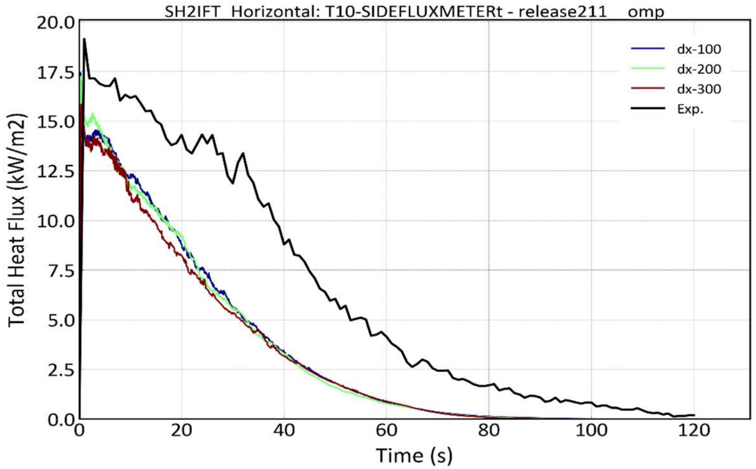


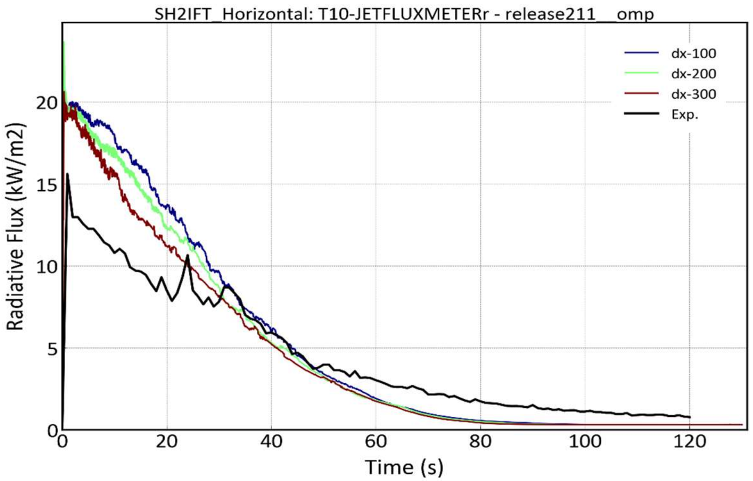
Results for Test T10 (J90-1p)

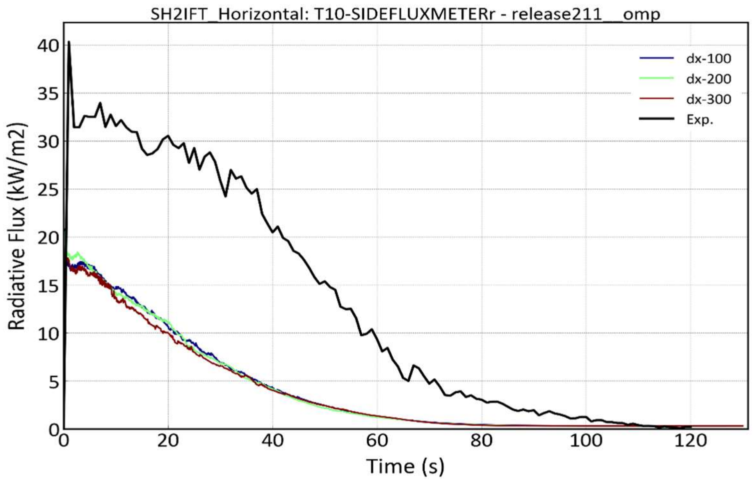


Results for Test T10 (J90-1p)

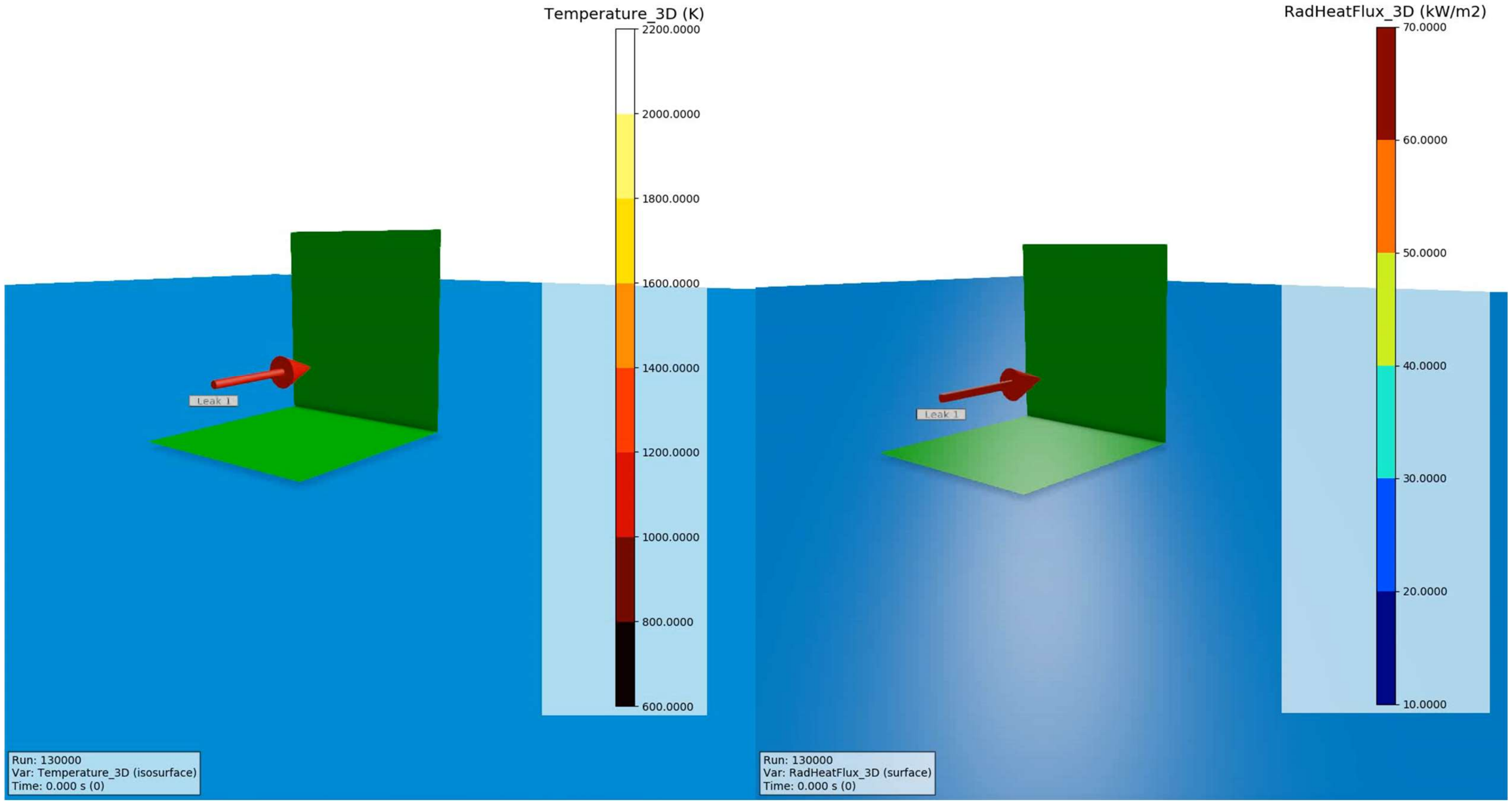




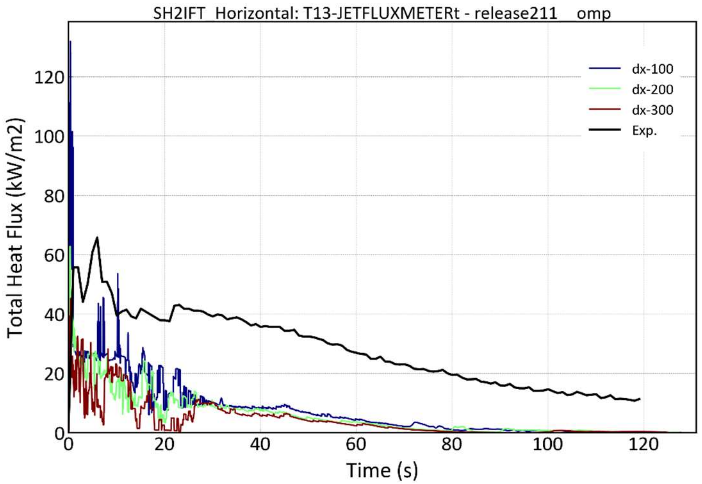


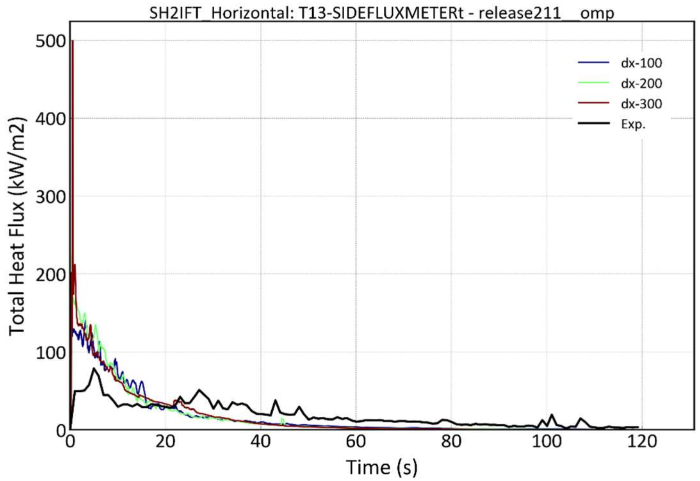


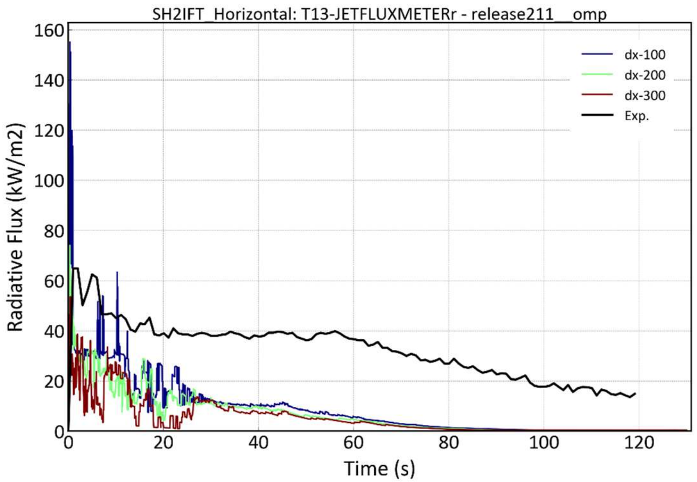
Results for Test T13 (J90-2p)

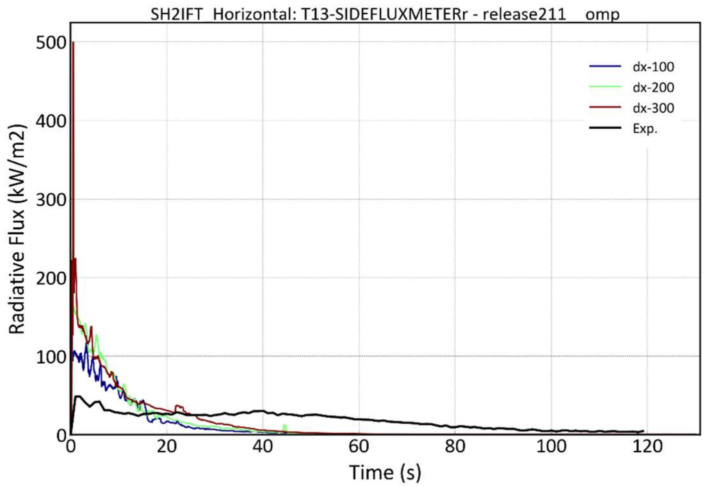


Results for Test T13 (J90-2p)

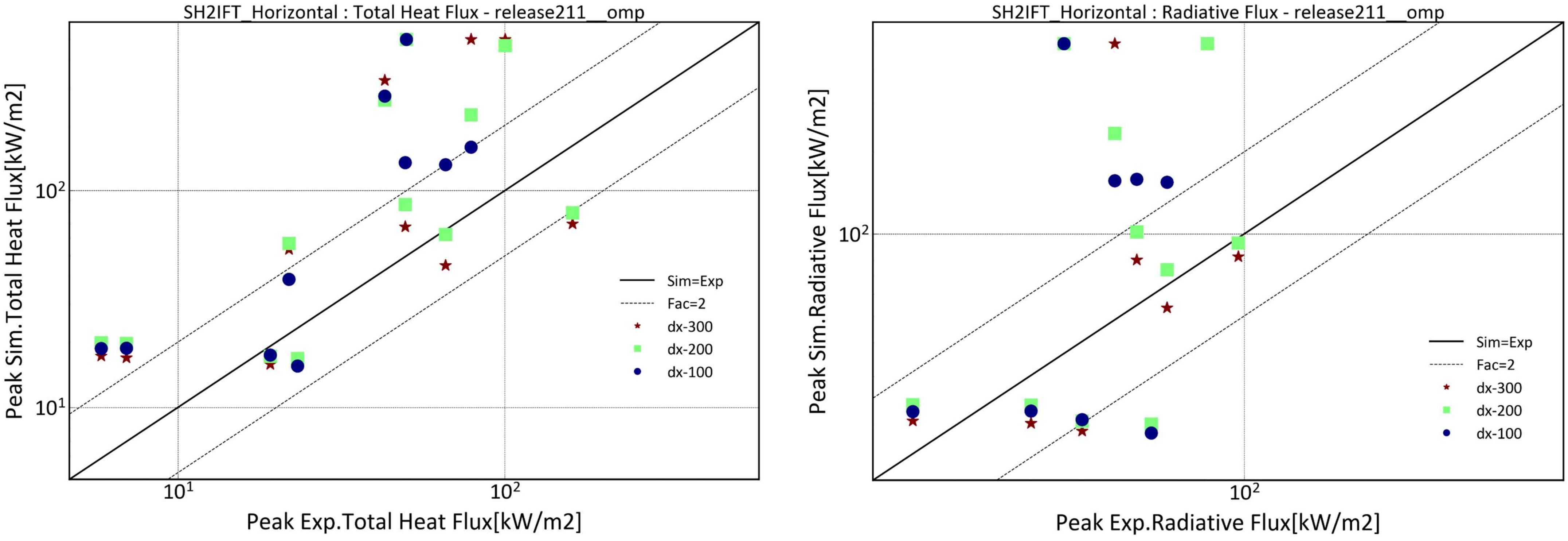








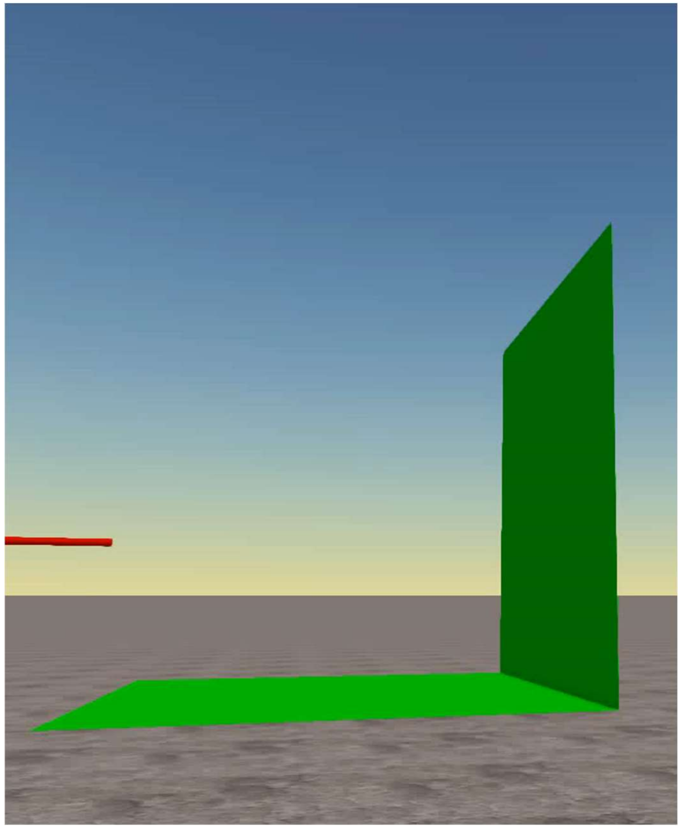
Results All Horizontal Jet Fire Tests

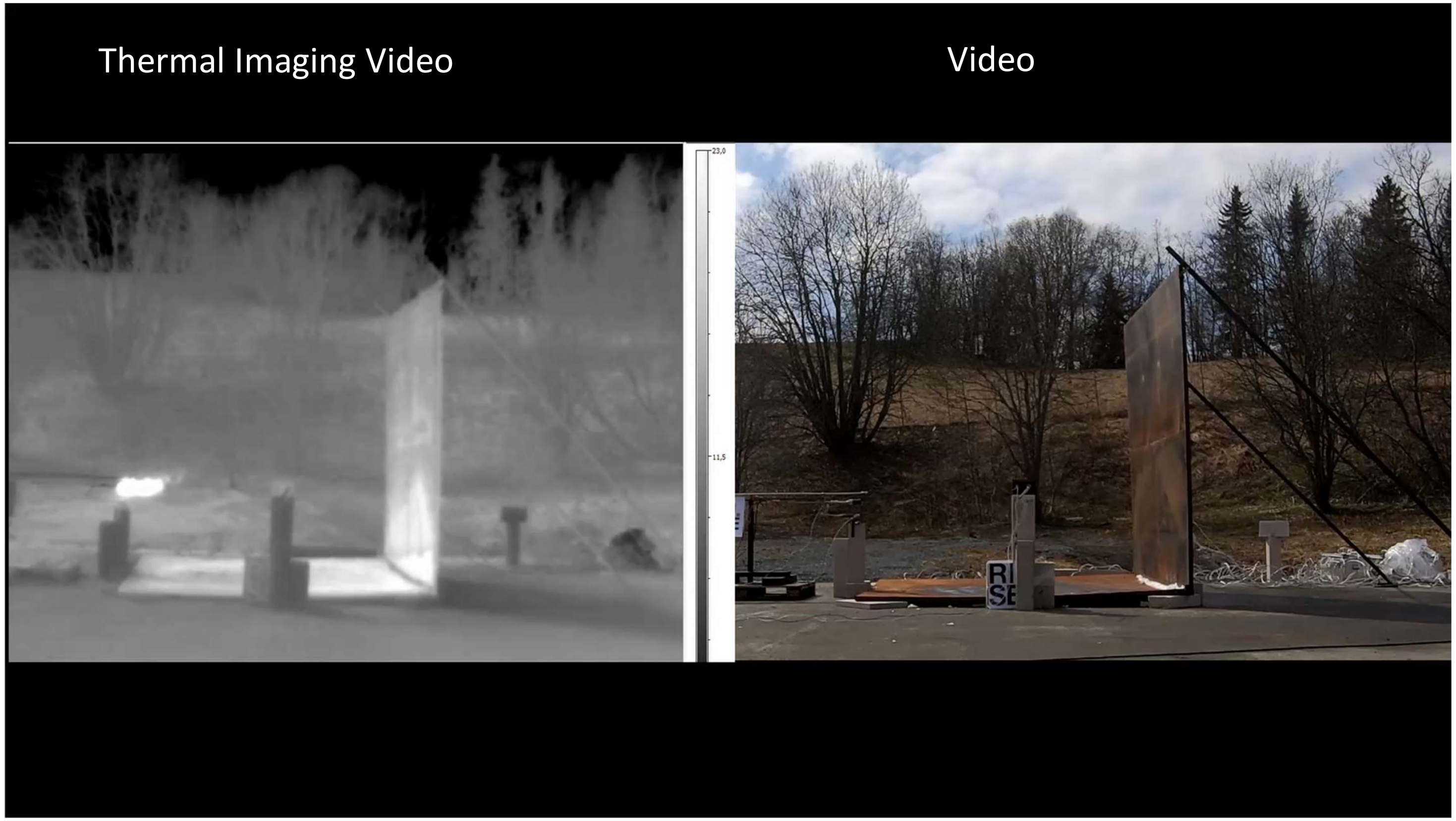


Test T13 – Video – Simulation Vs Experiment

FLACS-CFD Simulation

SH$_2$IFT Experiment





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Conclusions

- A database is essential for organizing knowledge related to validation.
- A detailed FLACS-Fire validation database for gaseous hydrogen jet fire with several example cases.
- FLACS simulations compared to SH_2IFT experiments (SH2IFT WP2.1).
- Added SH_2IFT cases to FLACS validation database.
- The resulting database is invaluable for software testing and validation, parameter optimization, estimation of uncertainties in simulation results, training, documentation, and marketing.
- Compared simulations against experimental data, FLACS perform well for flame length and flame trajectory
- Flame shape, flame length and Radiative heat fluxes from small to medium-scale hydrogen jet flames (< 20 m) from FLACS simulations compare favorably to measurements.

Conclusions

- FLACS-CFD overpredicts the buoyancy effect at the far end of the very large-scale hydrogen jet fires.
- The proposed turbulence constants allows for a possible route to improve the model. However, not implemented as impacts overall model performance.
- $C_2\varepsilon$ parameter, improved considered cases but not overall model performance when applied to wider validation dataset.

“Gexcon Makes The World A Safer Place”

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Deiveegan Muthusamy

Deiveegan.Muthusamy@gexcon.com

Thank you

FLACS-Fire

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Pre-Processing – CASD

- Solid model
- Mesh Generation
- Porosity calculator

- Solver settings
- Material properties
- Boundary conditions
- Initial conditions

Post Processing
Flowvis5, Python API

- Flame visualization
- Heat flux on surface, MPs
- ..

Solver

Equations solved on mesh

- Transport Equations
  - Mass: Species mass fraction
  - Momentum
  - Energy
- Equation of state
- Supporting physical Models

Other Physical models

- Turbulence: standard k-Ɛ
- Wall Functions, initial & boundary conditions
- Leak models,
- Pool Models
- Entrainment, pseudo-source models
- Equilibrium, thermodynamics, ..

Fire specific Physical models

- Non-Premixed combustion: **Eddy Dissipation Concept (EDC)**, Mixed Is Burnt (MIB)
- Premixed combustion: Beta-3 combustion model
- Automatic combustion regime marker (Fire switch)
- Simple heat conduction model
- Pool Fire
- Soot models: **Oxidation-Formation soot model (FOX)**, Fixed Conversion
- Radiation: **Hybrid Discrete Transfer Model (DTM) & Far-field radiation**
- Radiative properties: **Danish-Coupled-WSGGM**, ..