Thermal hazards from cryogenic hydrogen jet fires

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PRESLHY dissemination conference, 5-6 May 2021, online event

Pre-normative REsearch for Safe use of Liquid HYdrogen

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Introduction

- Jet flames originated by cryo-compressed ignited hydrogen releases can cause life-threatening conditions in their surroundings.
- Understanding of consequences of potential accidents with cryogenic hydrogen jet fires is fundamental to protect life and prevent property loss.
- Sandia National Laboratories (SNL) observed that, for a fixed mass flow rate, the decrease of release temperature causes (Panda and Hecht, 2016):
  - Longer flame length;
  - Higher radiative heat flux from a jet flame.
- The present study has the following objectives:
  - Development and validation of a CFD model to simulate flame length and radiative heat flux for cryogenic hydrogen jet fires;
  - Assessment of thermal hazard distances for vertical and horizontal cryogenic jet fires.

Validation experiments

- Nine experiments are used to validate the CFD model against:
  - Radiative heat flux measurements.
  - Flame length measurements.

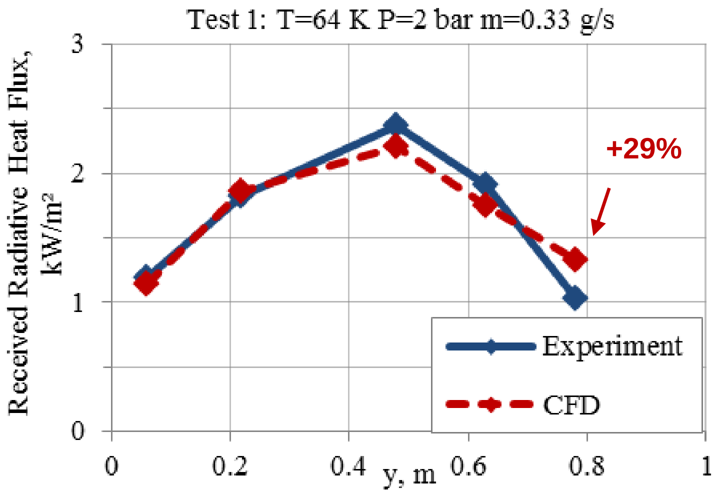
Validation experiments	**SNL tests**	**KIT tests**
Reference	Panda and Hecht (2016)	Breitung et al. (2009)
Direction	Vertical	Horizontal
Number of tests	5	4
Temperature (K)	48-82	80
Pressure ($\mathrm{bar_{abs}}$)	2-5	3-20
Nozzle diameter (mm)	1.25	2.0, 4.0
Mass flow rate (g/s)	0.33-0.64	3.3, 4.4

CFD model description

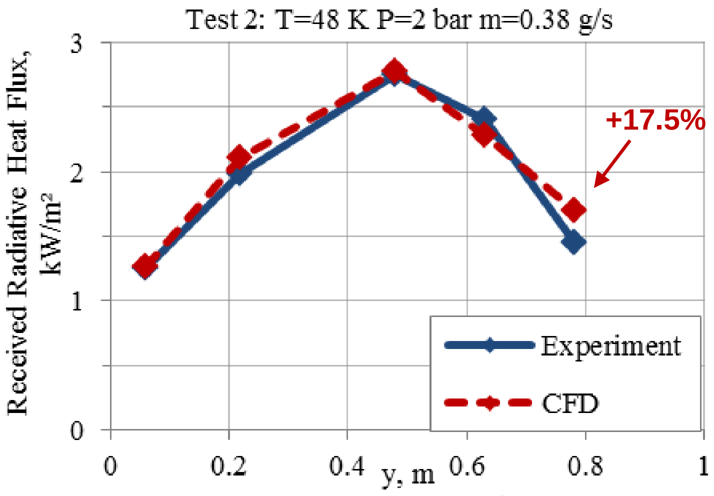
Turbulence	Reynolds Averaged Navier-Stokes (RANS) equations ❖ Realizable k-ε (Shih et al.,1995)
Combustion	Eddy Dissipation Concept (Magnussen, 1981) ❖ Peters and Rogg's (1993) mechanism with 9 species and 18-step chemical reactions
Radiation	Discrete Ordinates model (Murthy et al., 1998) ❖ 10x10 angular divisions, 3x3 pixels ❖ Water vapour is the only emitting/absorbing species with absorption coefficient defined according to Hubbard and Tien (1978)
Release modelling	Notional nozzle approach by Molkov et al. (2009)

Validation against SNL tests

The CFD model was validated against 5 tests performed at SNL (Cirrone et al., 2019). Experimental radiative heat flux was predicted with ±15% accuracy; only exceptions are given at the 5th sensor in 2 tests.



V_{hood} = 7.0 m/s



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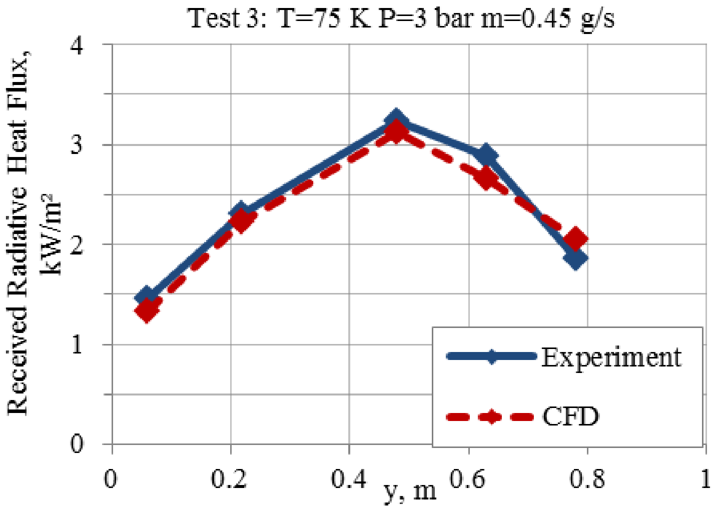

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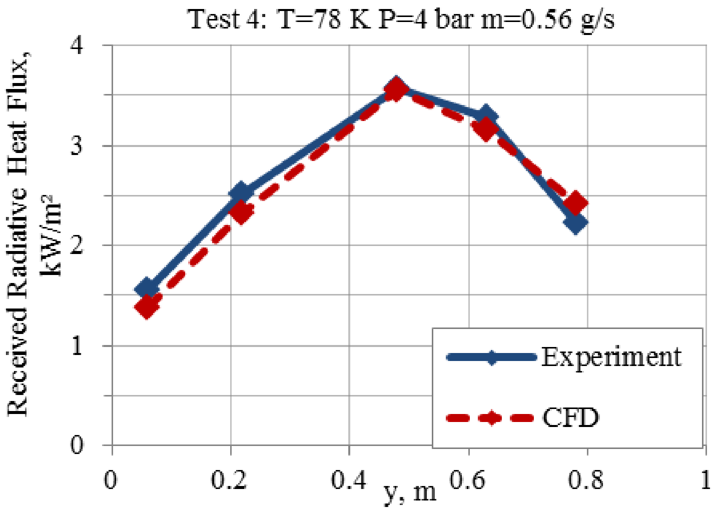
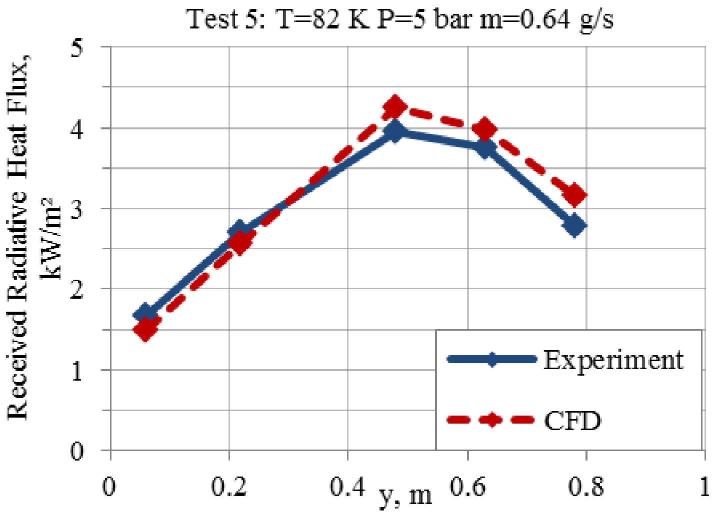
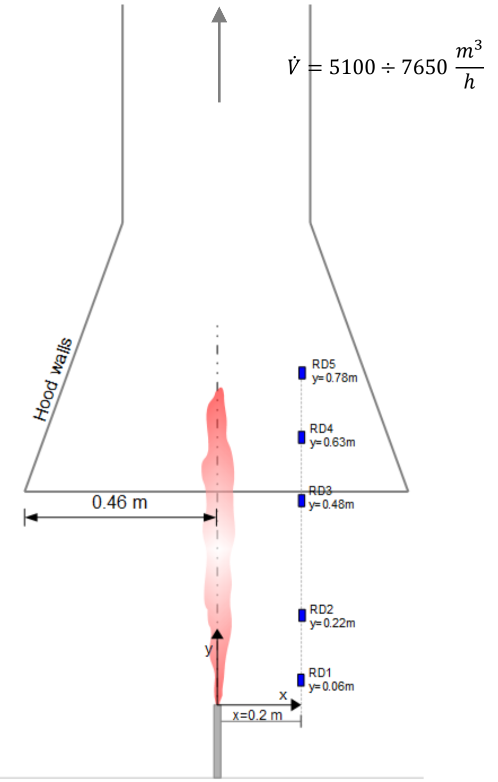


V_{hood} = 10.5 m/s

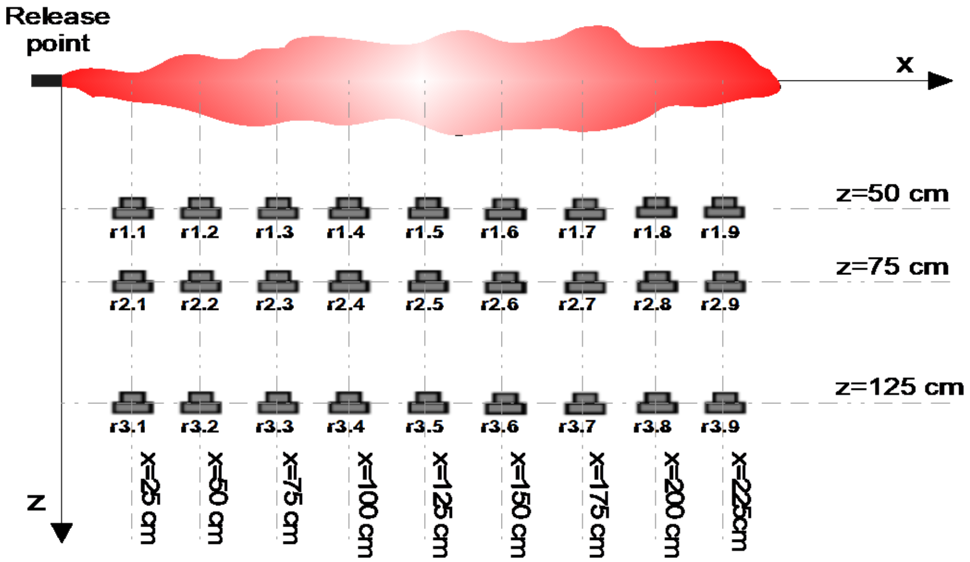


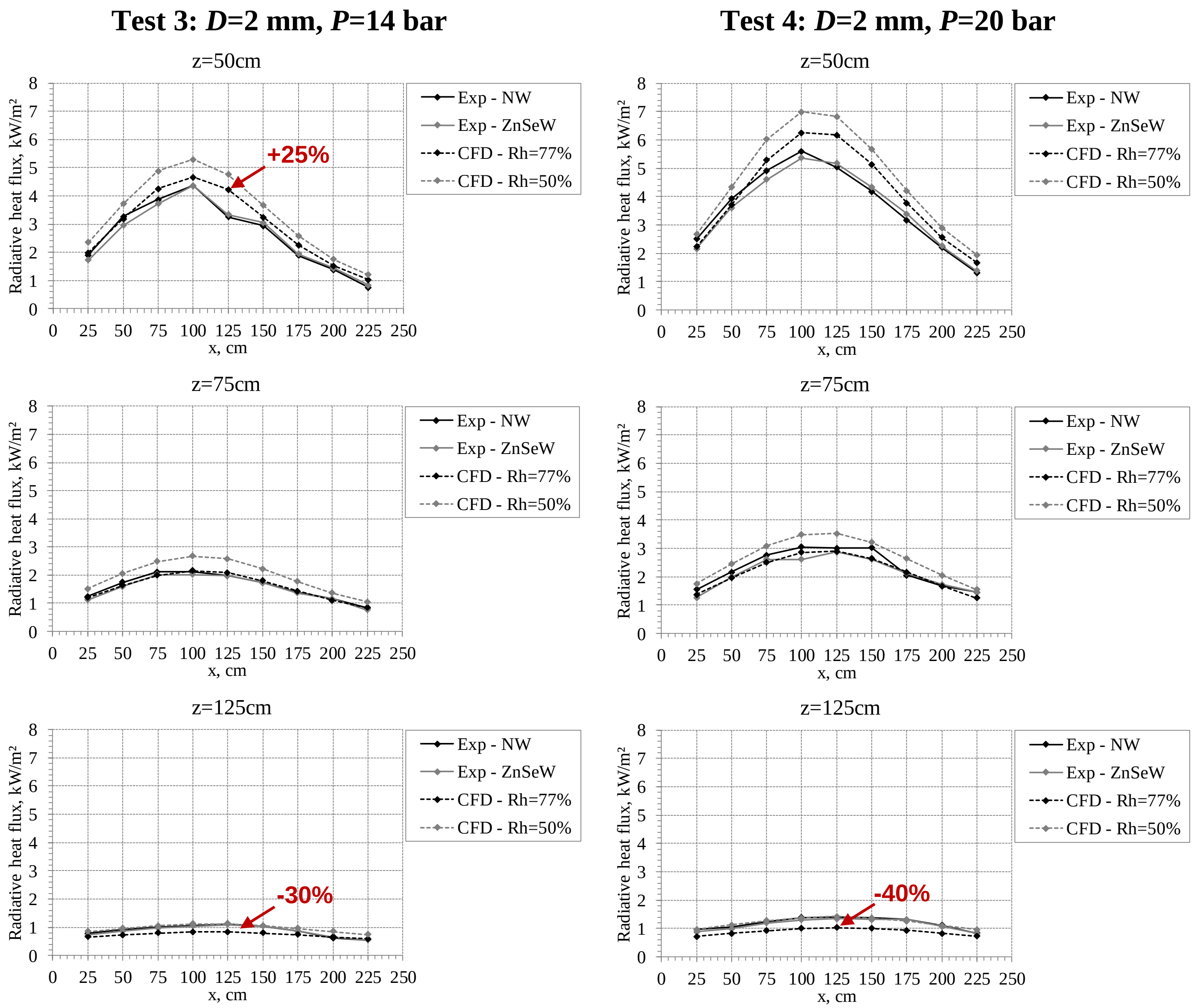
V_{hood} = 10.5 m/s



Radiometers (RD) location

Validation against KIT tests (1/2)





Test 3, Rh=77%: prediction accuracy is within 10%, with few exceptions at z=50 cm and z=125cm.

Test 4, Rh=77%: prediction accuracy is within 20%, with exceptions of sensors at z=125cm.

Test 3 and 4, Rh=50%: predictions overlap with experiments at z=125cm.

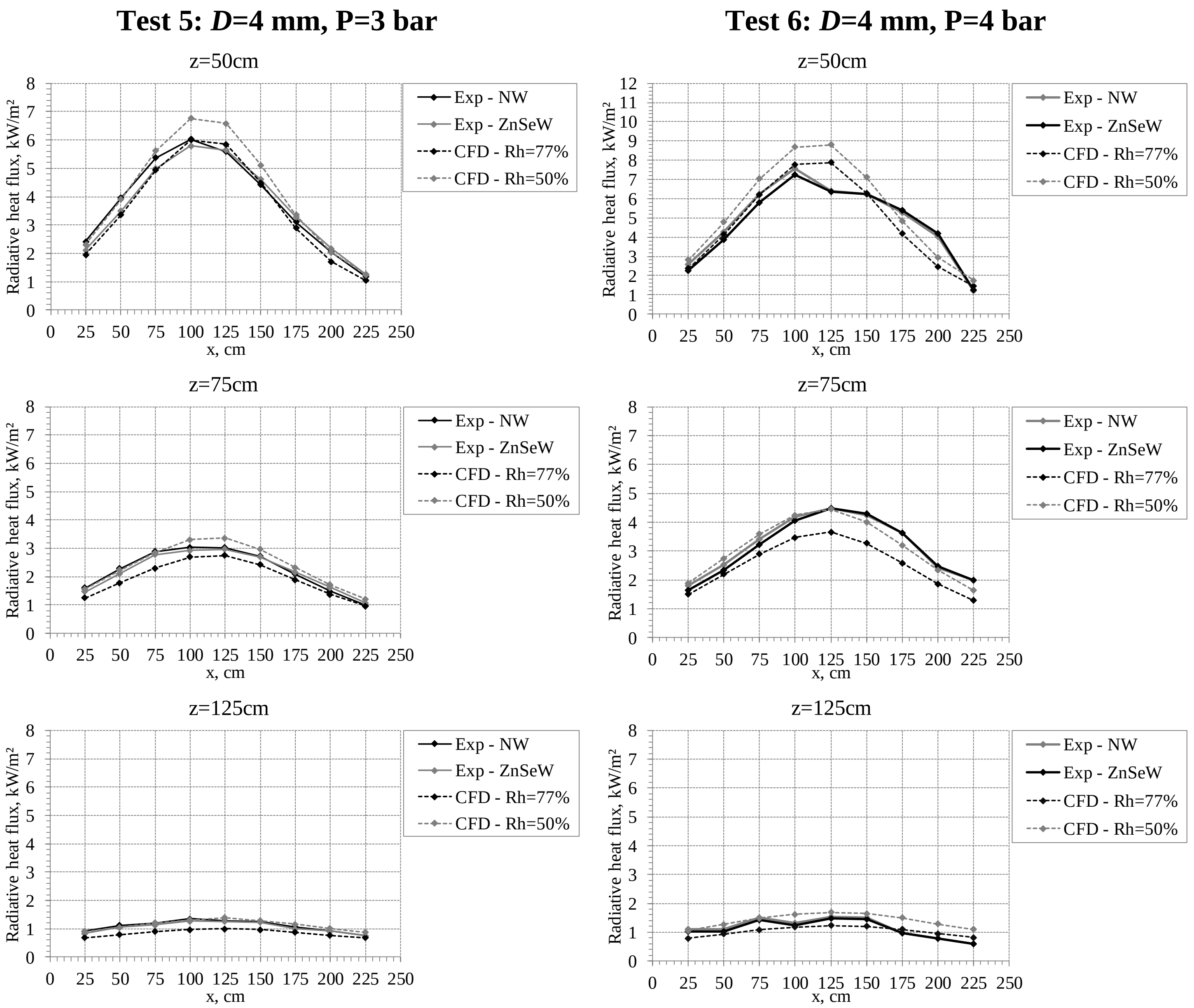
Validation against KIT tests (2/2)

Test 5, Rh=77%: prediction accuracy is within 10%, for sensors at z=50 cm. Measurements at z=125cm are underpredicted (up to -40%).

Test 5, Rh=50%: predictions improve at z=75cm, and overlap with experiments at z=125cm.

Test 6, Rh=77%: underestimation of experimental measurements beyond x=100 cm. This is consistent with the underprediction of flame length.

Test	5	6
Experiment, m	1.62	2.08
CFD 1300 K, m	1.72	1.86
CFD 1500 K, m	1.57	1.70



Hazard distances by temperature

- A jet fire leads to the production of hot currents harmful to people. Molkov (2012) correlated the temperature distribution along a jet fire trajectory from experiments to the distance normalised by the flame length in order to derive hazard distances for people.

Harm level (LaChance et al., 2011)	Hazard distances	
	Vertical jet fires	Horizontal jet fires*
“No-harm”: 70°C for any exposure duration	x=3.5L_f	x=2.2L_f
“Pain”: 115°C for 5 minutes exposure	x =3L_f	x =2.1L_f
“Fatality”: 309°C, third-degree burns for 20 s exposure	x =2L_f	x =1.75L_f

*along the flame tilting axis

- The buoyancy of combustion products reduces the “no harm” distance from x=3.5L_f for vertical jet fires to x=2.2L_f for horizontal jet fires.

- Conclusions and change of multiplier in hazard distance between vertical and horizontal jet are valid for these particular experiments.

Hazard distances by thermal radiation

Horizontal jet fires under investigation

Thermal radiation emitted by the jet fire in its surroundings:

- "No-harm" distance (1.6 kW/m^2) along the horizontal jet fire direction corresponds to x=3.2L_f, which is larger than hazard distance by temperature "no-harm" criteria.
- "First-degree burns" hazard distance (4.0 kW/m^2) along the jet fire direction corresponds to x=2.1L_f.
- "First-degree burns" hazard distance (4.0 kW/m^2) on the side of the horizontal jet fire is about 3.5 times shorter than hazard distance in axial direction.
- "No-harm" distance on the sides of the horizontal jet fires resulted > 2.7 m (domain size).

The thermal dose calculates the harm level as a function of exposure duration and incident thermal radiation:

$$TD = \int_0^t I(t)^{4/3}\, dt$$

- The thermal dose is a valuable tool to assess the feasibility of short-term activities and emergency operations.
- Firefighters can stand without harm as close as 0.71 m to the jet fire axis for a time < 168 s.

Conclusions

- The CFD model for simulation of thermal hazards from cryogenic hydrogen jet fires is validated against experiments with release temperatures in the range 48-82 K and pressures up to 20 bar.
- The buoyancy of combustion products reduces the “no harm” distance by temperature from $x=3.5L_f$ for vertical jet fires to $x=2.2L_f$ for investigated horizontal jet fires.
- For horizontal jet fires, thermal radiation leads to longer “no-harm” distances in the direction of the jet (x=3.2L_f) compared to hazard distance defined by temperature.
- Harmful distances on the side of the investigated horizontal jets were calculated to be longer than the domain size, i.e. 2.7 m in the radial direction to the jet.
- The thermal dose is a useful parameter to define hazard distances for emergency personnel.
- A throughout assessment of thermal hazards and associated distances from a hydrogen jet fire should combine the analysis of temperature, thermal radiation and thermal dose, as these are found to be complementary to each other.

Acknowledgement

The PRESLHY project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under the grant agreement No 779613.

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

European Commission | Horizon 2020 European Union funding for Research & Innovation

Thank you for your attention