Session 6: Accident Physics – Liquid / cryogenic behaviour

Chair: Phil Hooker; Contributors/Panelists: Simon Jallais (Air Liquide), Jennifer Wen (Warwick University), Ethan Hecht (Sandia), Bill Buttner (NREL)

Research Priorities Workshop – 26/27 September 2016, JRC IET Petten, Netherlands

The Focal Point on Integrated Research and Information for Hydrogen Safety

Liquid / cryogenic behaviour

Status at the time of previous workshop

- The complexities of liquid hydrogen puts different demands on the modelling of releases
- The quality and level of detail of available experimental data available in literature are insufficient to allow complete and accurate validation of CFD
- Criteria for model performance in other field (e.g. LNG) need to be revised for hydrogen because of the significant differences in its physical properties
- Analytical models have been developed but complete validation is missing

Liquid / cryogenic behaviour

Status at the time of previous workshop

- Liquid / cryogenic behaviour featured both in „Indoor“ and „Unintended release-Liquid“ categories in 2014
- „Indoor“ ranked 3rd with 13%
- „Unintended release-Liquid“ ranked 4th with 11%

Ref: “HySafe Priorities – ICHS 2015, Yokohama

Liquid / cryogenic behaviour

Status at the time of previous workshop

Topic	Number of Votes	% of Votes Received
Behavior and dispersion of cryogenic jets	23	24
Improve understanding of hydrogen behavior indoors	21	22
Simplified model development for indoor accidents and incidents	14	15
Passive ventilation approaches	9	9
Validation of pressure peaking phenomenon for releases in realistic enclosures like garages	8	8
Extinction of fire in a garage by water vapor generated during combustion of moderated release of hydrogen from TPRD in a garage	8	8
Further numerical investigation of fire regimes indoors by taking into account water condensation	8	8
Wind/vent modeling, two-vent model	5	5
Validated turbulent models	0	0
Effect of soft/acoustic absorbing walls/boundaries on flame acceleration and on DDT	0	0

“INDOOR”

Liquid / cryogenic behaviour

Status at the time of previous workshop

Topic	Number of Votes	% of Votes Received
Laboratory tests for behavior of liquid hydrogen release: pools, spreading, “ice” formation, evaporation and fires	23	21
Flashing liquid hydrogen jet releases	18	16
Explanation of why windy conditions during spills could create conditions for explosion of non-gaseous phase	16	15
Consequence modeling of liquid hydrogen release in congested areas	12	11
Boiling Liquid Expanding Vapor Explosion or Fireball (BLEVEs)	11	10
Carefully controlled cold hydrogen release data	11	10
Accurate state modeling implementation	7	6
Formation of liquid hydrogen/liquid oxygen mixes of hydrogen/hydride-air/water systems and behavior	7	6
Multi-phase flow models with velocity slip	5	5

“Unintended release – Liquid”

Liquid / cryogenic behaviour
Important differences: LH2 and other gases

Fluid

Oxygen

Nitrogen

Neon

Hydrogen

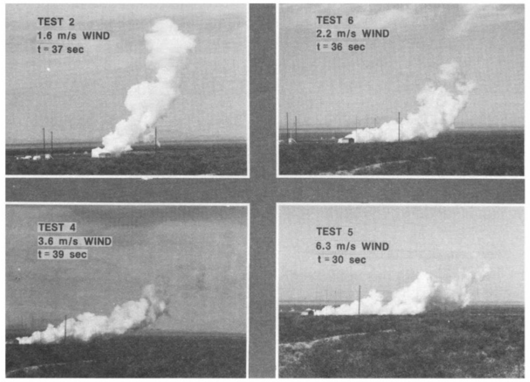
Helium

Cryogenic plumes/jets

Progress / Closed gaps

Large experiments have demonstrated condensation in plumes and ground cooling

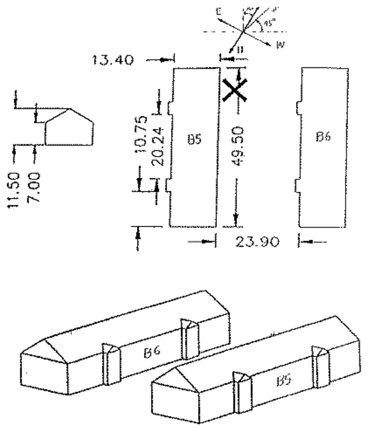
Rapid release of 1500 gal LH2 at NASA White Sands



- Quickly warms, become buoyant and mixes with air
- Prolonged spills cool ground and can travel further

Witcofski and Chirivella, IJHE, 1984

Large-scale releases (0.4 kg/s) at Battelle Ingnieurtechnik (BAM)

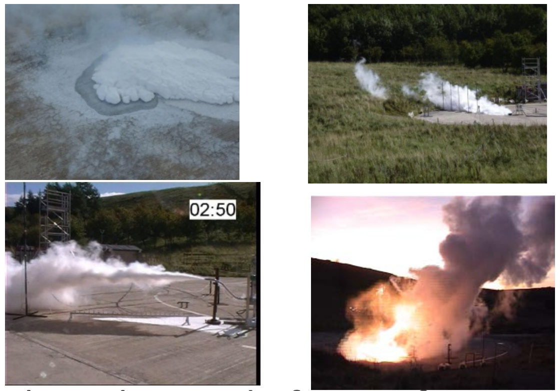


- Ignitable gas cloud significantly smaller than visible condensed water vapor cloud
- Little pooling observed
- Cooled ground significantly

Schmidtchen et al., Cryogenics, 1994

Statharas et al., J. Haz. Mat., 200

Experiments at the Health and Safety Lab (HSL) in the UK observed condensed oxygen and nitrogen



- Pooling observed after surface cooled
- Releases at sufficient height evaporate before reaching ground
- Solid deposit ignited in one test (trapped H_2 in solid O_2)

Royle and Willoughby, Proc. Safety and Env. Protection, 2011

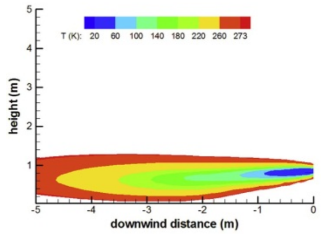
Royle and Willoughby, Health and Safety Executive, 2014

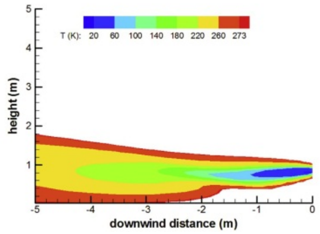
Hall, Health and Safety Executive, 2014

Cryogenic plumes/jets
Progress / Closed gaps

Simulations have had limited success (and limited data)

ADREA-HF has been used to simulate HSL work

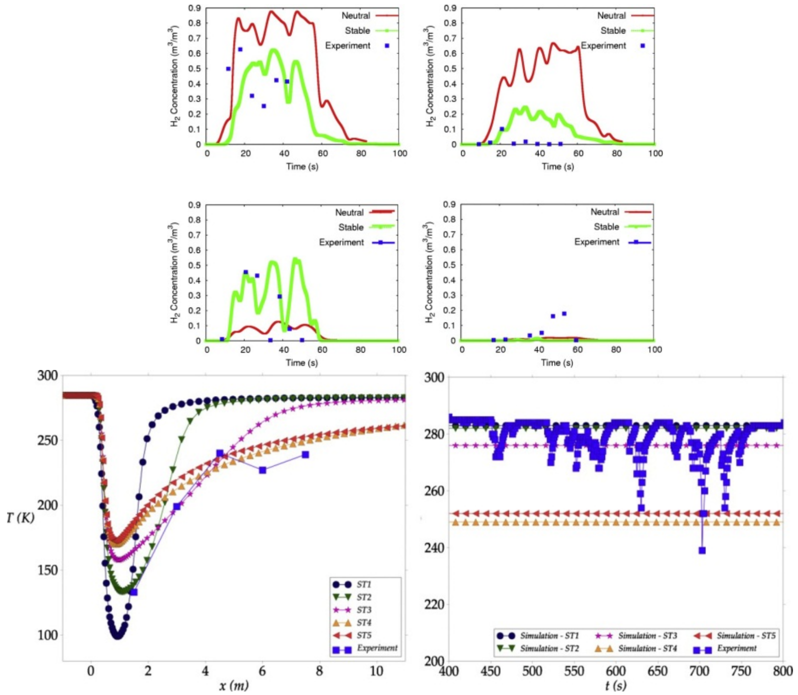




- needed to account for humidity and slip between vapor and non-vapor phases

Giannissi et al. IJHE 2014

The HSL, BAM and NASA liquid hydrogen release experiments were modeled using FLACS



- Shallow water equations for pooling
- Assume gas/liquid phases in local thermal and kinematic equilibrium

Middha, Ichard, Arntzen, IJHE 2011

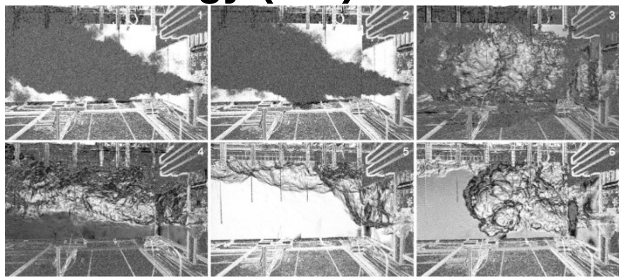
Ichard et al. IJHE 2012

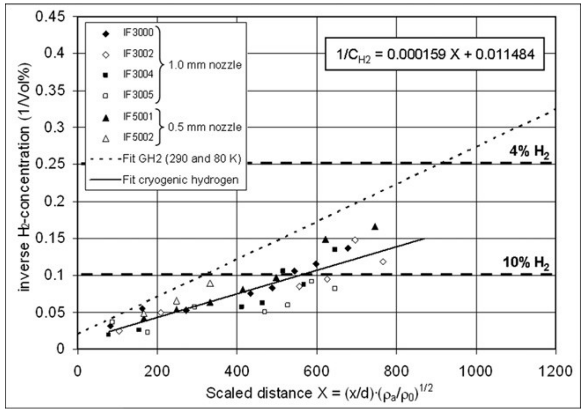
Cryogenic plumes/jets

Progress / Closed gaps

Smaller experiments with more boundary condition control are more appropriate for validation

Experiments at Karlsrhue Institute of Technology (KIT)



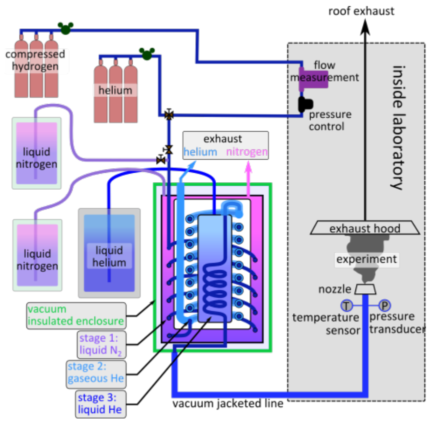


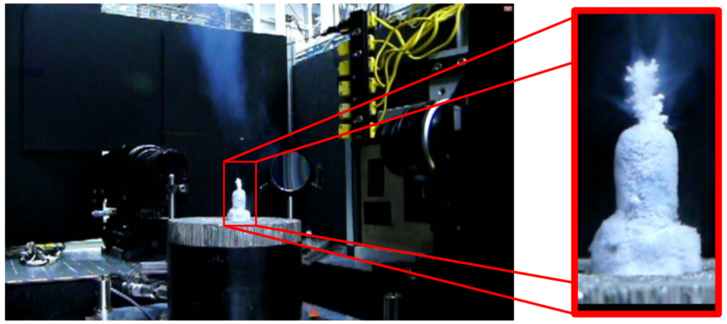
- Discrete temperature and sampling locations
- Concentration decay less rapid than for gaseous hydrogen

Friedrich et al. IJHE 2012

Xiao et al, IJHE 2011

Experiments at Sandia National Labs





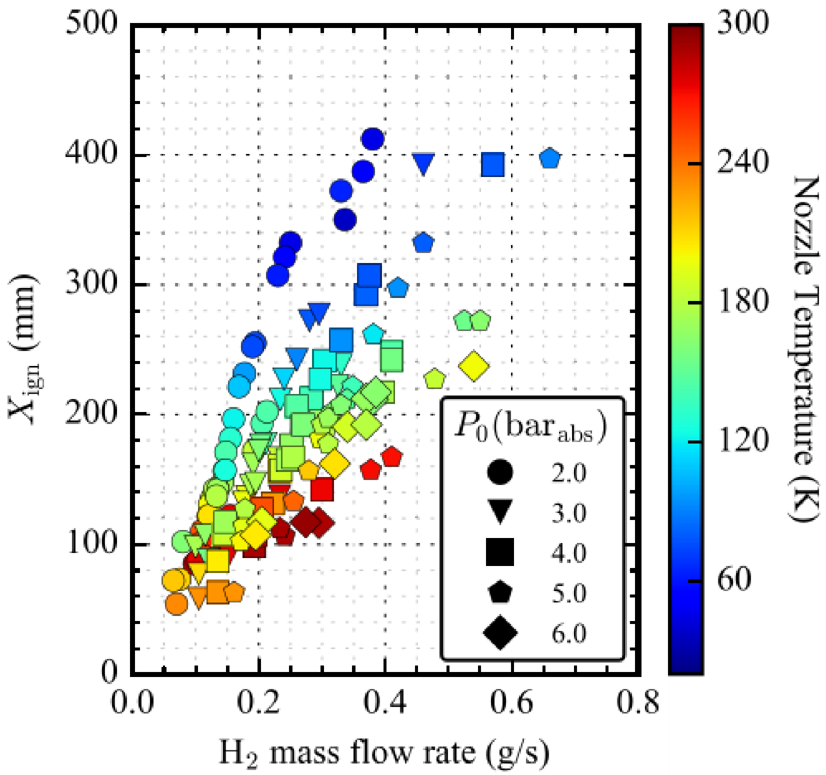
- (Air, moisture?) icing around Liq. H_2 Jet Column
- Performed ignition and radiation study on cold H2
- Working to implement filtered Rayleigh for measuring concentration field

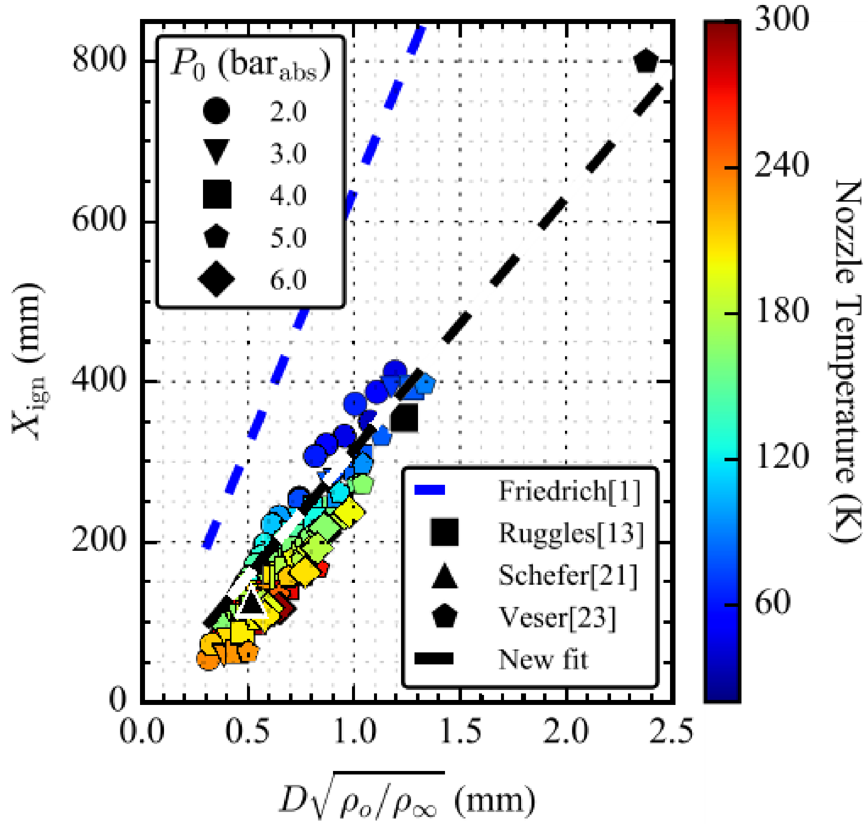
Panda and Hecht, IJHE 2016

Cryogenic plumes/jets

Progress / Closed gaps

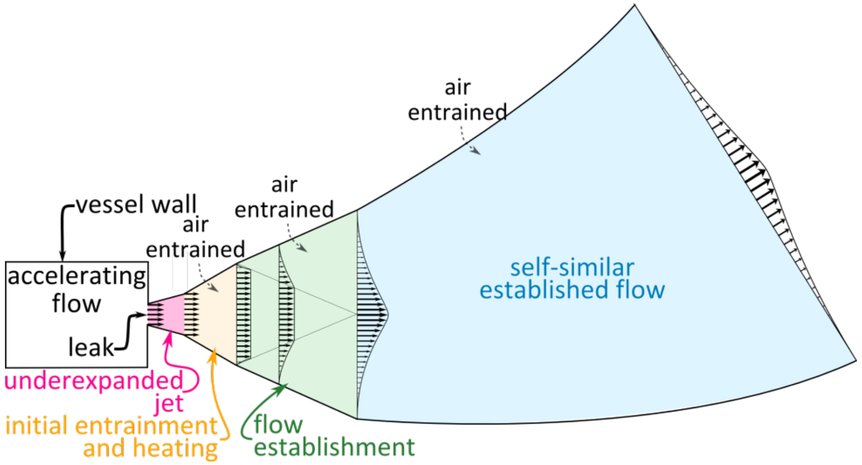
- Distance to flammable limits determined experimentally and correlations obtained (Panda 2016):



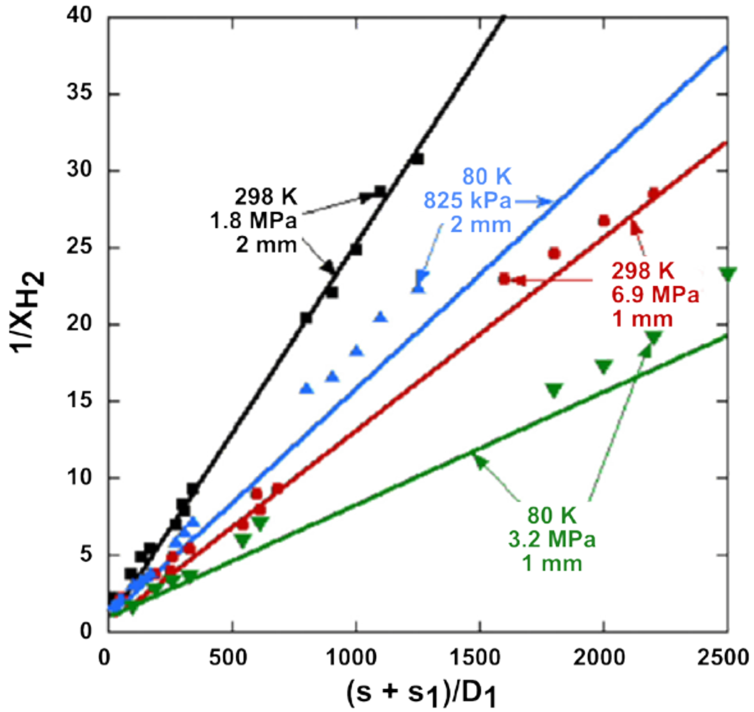


Cryogenic plumes/jets
Progress / Closed gaps

- A cold dispersion model exists (for incorporation into HyRAM), but requires further validation data (Hecht 2016)



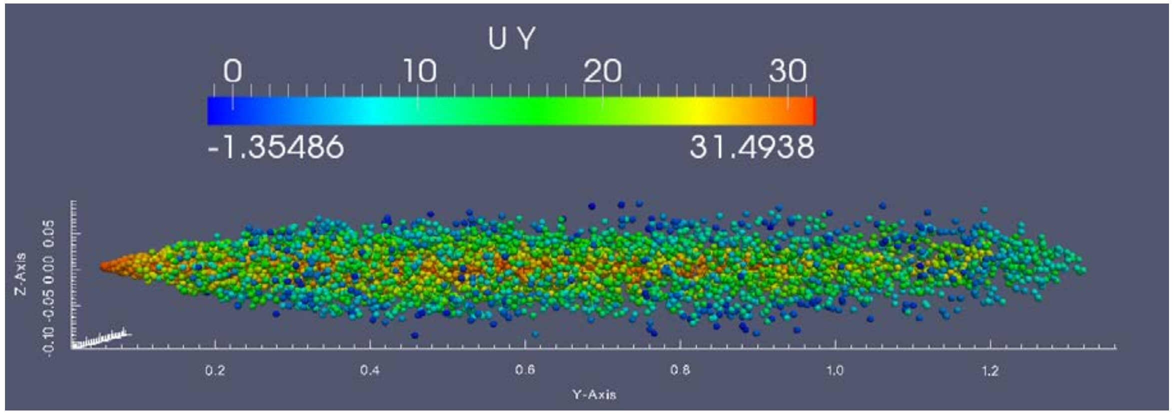
- No air or moisture condensation considered
- Overpredicts centerline concentration for 80 K release



Xiao et al, IJHE, 2011
Houf & Winters, IJHE, 2013

Cryogenic plumes/jets
Progress / Closed gaps

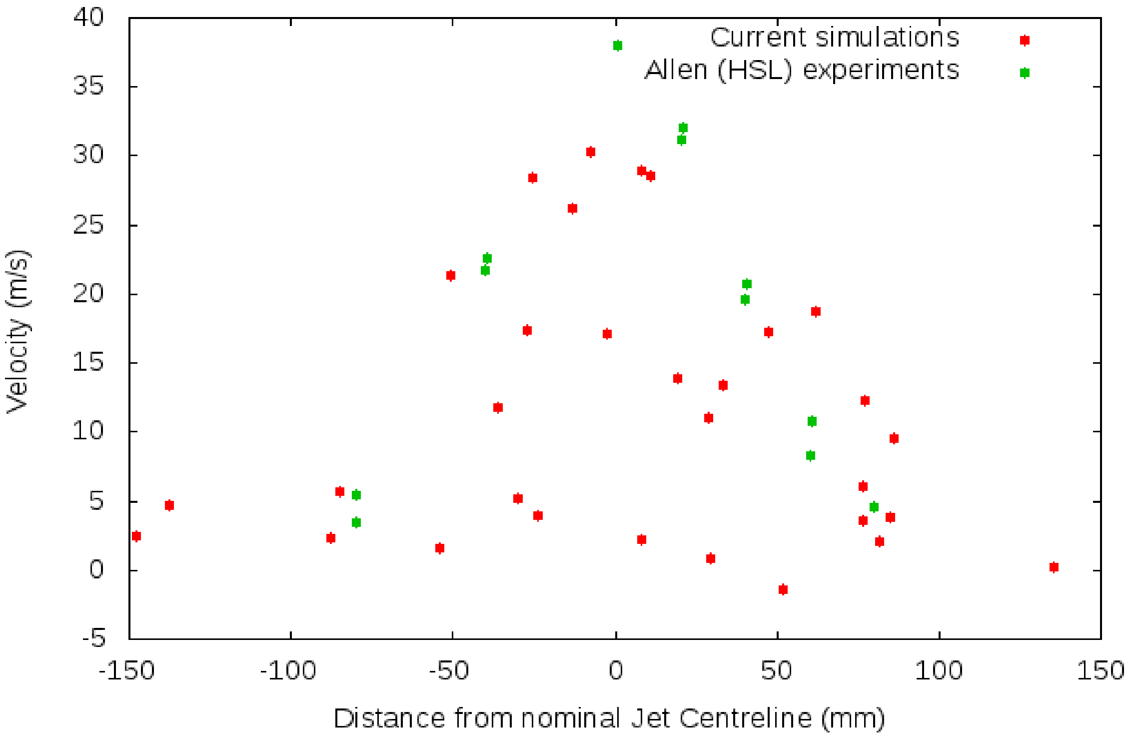
University Warwick developing SprayFoam for flashing LNG jets within OpenFOAM

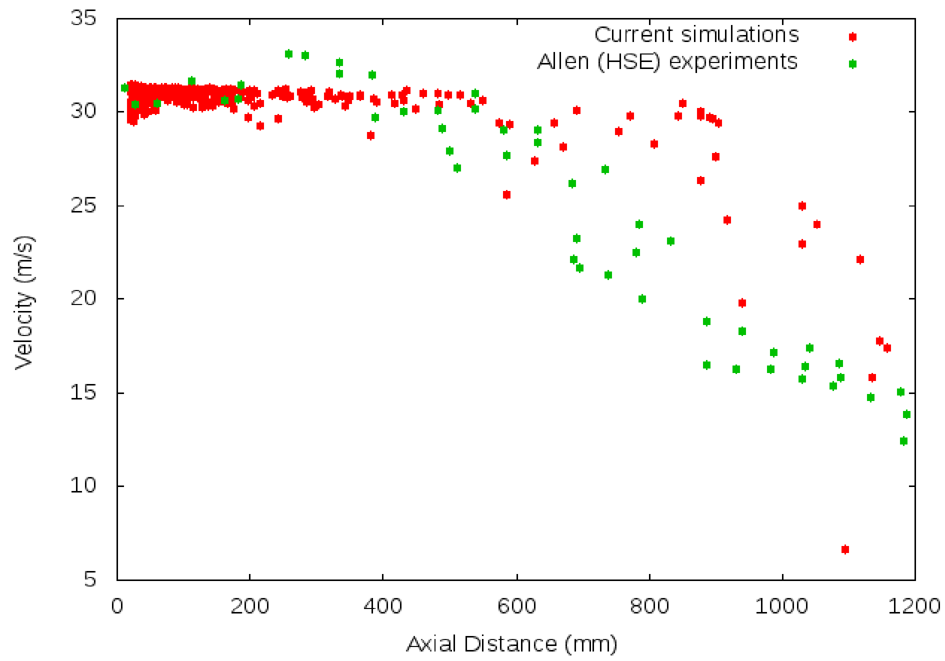


Cryogenic plumes/jets
Progress / Closed gaps

University Warwick developing SprayFoam for flashing LNG jets within OpenFOAM; some validation with LPG jets

Lateral Axial velocity profile at 300 mm





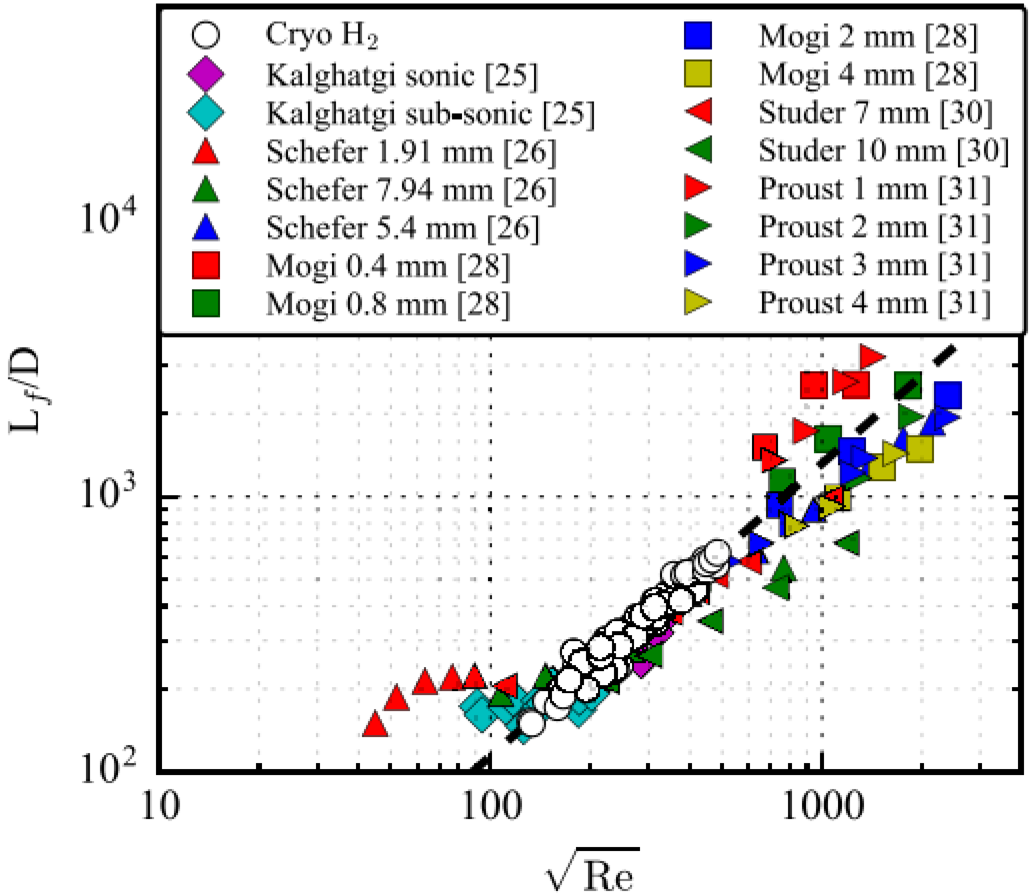
Cryogenic plumes/jets

Progress / Closed gaps

- Engineering models are good enough (?) for LH_2 Jet fires (very similar to GH_2 jet fires)
  - Limited radiation levels, but higher than gaseous release (Panda 2016)
  - SNL, UU, …approaches could be used

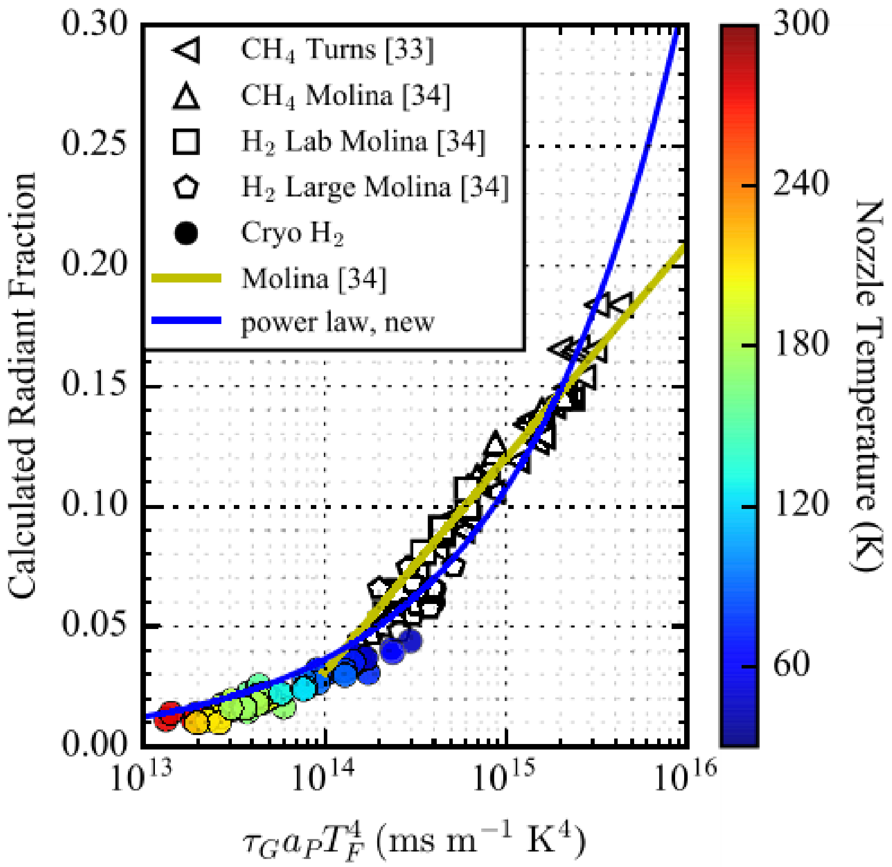
Cryogenic plumes/jets

Progress / Closed gaps



For Cryo, viscosity important so $L_f = f(Dm)^{0.5}$ not sufficient (Panda 2016)

Cryogenic plumes/jets
Progress / Closed gaps



Cryo radiant fraction appears to follow same trend as ambient releases (Panda 2016)

Cryogenic plumes/jets
Working topics

❑ **Empirical Profiling of Cold Hydrogen Releases to support theoretical modelling and Codes (NREL and partners)**

• **LH2 routinely released (delivery protocol): 50 to 70 Kg**
– Primarily gas but may contain droplets
– Unknown temperature and gas profile
– Typically vented out of a 7 to 10 meter stack
– Duration approximately 1 hour

• **NFPA 2 Hydrogen Storage Task Group concerns regarding behavior of plumes during LH2 release**
– Does the plume drop below the release point?
– How does the cold release interact with ambient O_2 / N_2?
– Can dispersion models account for the actual physical phenomenon occurring during a hydrogen venting event?
– Does the visible cloud stream adequately indicate H2 plume?

• **Empirical profiling of H2 Plume during venting**

• **Key Partners:**
– The Linde Group, FP2Fire
– National Labs (LLNL, SNL, NREL)

Cryogenic plumes/jets
Working topics

- **Empirical Profiling of Cold Hydrogen Releases to support theoretical modelling and Codes (NREL and partners)**

•– Develop method for spatial and temporal profiling of plume during venting
– Tool for general understanding of LH2 dispersion
– Results fed back directly to NFPA 2
– Support scientific basis for setback distances
– Develop prototype Analyzer for general temperature and chemical screening
– Integrate empirical measurements with theoretical modelling
– Field demonstration to get initial profiles
– Adapt Analyzer for enhanced capabilities to meet requirements as identified by team and application
– Multiple deployments in coordination with industrial partner under various ambients (T, wind, RH)

Cryogenic plumes/jets
New gaps or directions

- Source term prediction
  - Mass release - Liquid outflow along long pipes
  - Jets : Droplets / Spray / Rain-out ….

- Do we know enough about indoor behaviour?

- Dispersion of massive releases : a heavy gas becoming a light gas !
  - No clear CFD validation for complex obstructed industrial environments, various of weather conditions (wind speed atmospheric stability class)
  - Zero wind conditions, gravity currents, little dispersion? Could conditions arise as for hydrocarbons at Buncefield, Jaipur etc? (Atkinson 2016)
  - Unconfined/partially confined vapour cloud explosions of cold, dense hydrogen?

Cryogenic plumes/jets
New gaps or directions

Findings of EU “Susana” modelling project (2016):

Cryogenic compressed releases:

- More research is required in modelling the two phase chocked releases, problems with estimation of the mass flow rate.
- Evaluation and comparison of the performance of the different Equation of States (EOS) in the two phase chocked flow approaches, in order to estimate the mass flow rate at the nozzle.
- A proper correlation for accurately calculating the specific heat capacity of hydrogen at low temperatures and high pressures should be further investigated and incorporated into CFD codes.
- Studies on humidity and air condensation during cryogenic compressed releases should be undertaken in order to inform modelling of these phenomena.

Cryogenic plumes/jets

New gaps or directions

Findings of EU “Susana” modelling project (2016):

Liquid hydrogen releases can be identified in the following subjects:

- Further development of pool spreading and evaporation models, coupled with vapour dispersion.
- Comparison between the models that solve the liquid pool separately and the models that do not solve the pool separately.
- Research should be directed at improving the modelling of ground heat flux in cases where a liquid pool is formed- for both solid and liquid (usually water) substrates.
- The radiative heat transfer and its contribution to the total heat transfer from the air and ground to the cold cloud should also be studied.
- The source modelling is another key parameter that needs further research (isenthalpic vs isentropic) to estimate the flashed vapour fraction.
- Study regarding turbulence intensity at the source.
- Humidity and air condensation phenomena need further exploration (effect on vapor dispersion and heat flux).
- Study effect of non-ideal behaviour of hydrogen on CFD predictions in liquid releases.
- Proper correlation for specific heat capacity of hydrogen at low temperatures required.
- Finally, it is essential to carry out additional experiments under more controlled conditions, in which all the above key parameters will be measured.

Liquid release behaviour
Progress / Closed gaps

- Liquid release behaviour “other”
  - Multi-phase accumulations and explosion potential
  - Pool fires
  - BLEVE

Liquid release behaviour

Progress / Closed gaps

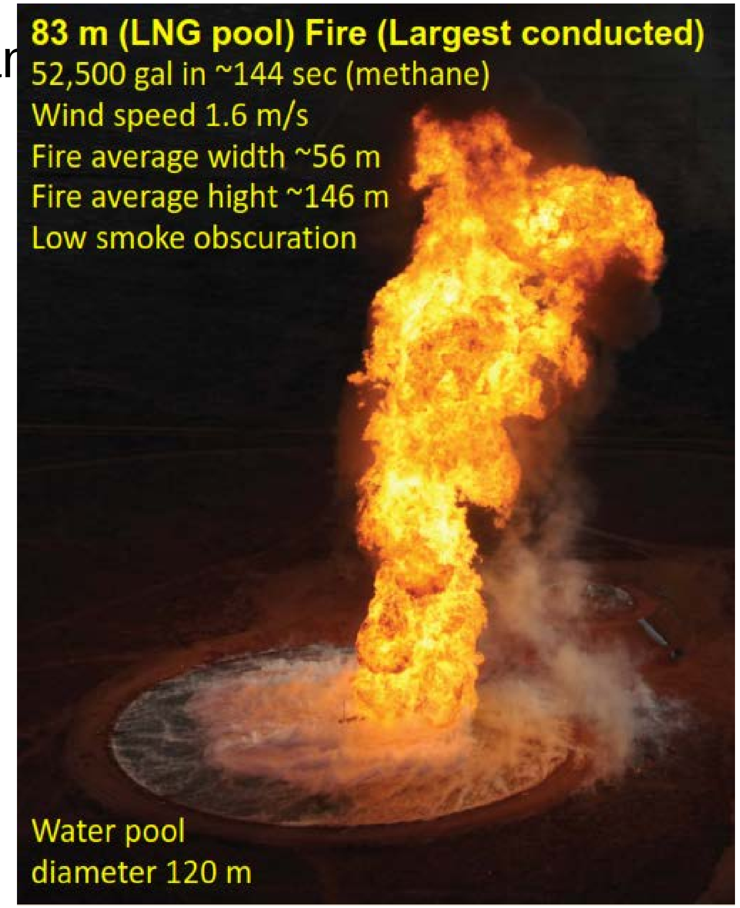
- Multi-phase accumulations with explosion potential
- Basic understanding of phenomenon known for some time (Perlee 1964):
  - LH2 can condense and freeze oxygen
  - The resultant mixture can be made to detonate (yield by weight > TNT)
  - The sonic velocities in hydrogen and solid oxygen phases are similar
- Explosion of ignited LH2 / solid air mixture at HSL (not driven by impact) (Hall 2013)
  - However, no further progress in really understanding required conditions to occur
  - Or the consequences

Liquid release behaviour

Progress / Closed gaps

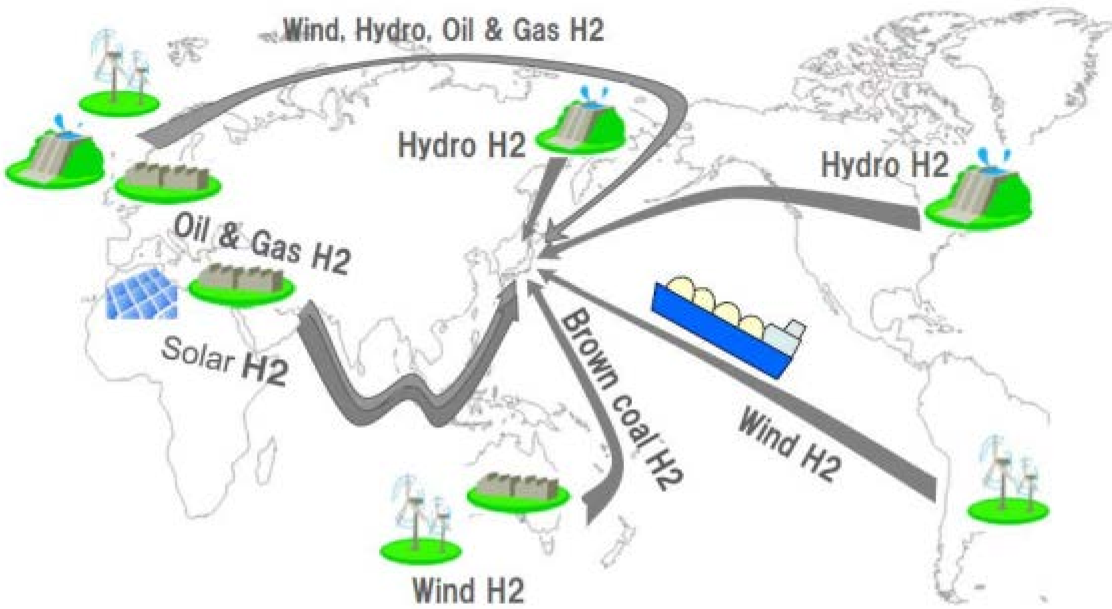
- LH_2 Pool fires
  - Radiation levels lower than HC pool fires
  - Existing engineering models could be used
  - Limited pool size by in-draft ? (as LNG? – Blar

- Rapid Phase Transition (LH_2 spillage on water)
  - Model developed for LNG could be adapted



Liquid release behaviour
Progress / Closed gaps

- BLEVE of LH_2 vessels
  - Existing engineering models could be used?
  - Time of resistance of an insulated vessel in a fire ?
    - Large LH2 ships? (of concern for LNG – Havens 2016)



Liquid release behaviour
Working topics

- Not much known about ??????

Liquid release behaviour
New gaps or directions

- Behavior in complex environments (eg, Ports)

Liquid / cryogenic behaviour
Summary

Source terms;
obstacles;
zero wind

Dispersion indoor

Dispersion outside

Jet-fire

Solids / explosion

Pool fires; Land/sea

BLEVE/ fire resistance

Need to define variables and what is of practical importance

Large-scale data

Are tanks designed for appropriate conditions?