SAND2019-3384C

FLAME CHARACTERISTICS OF CRYOGENIC HYDROGEN RELEASES FROM HIGH-ASPECT RATIO NOZZLES

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11th U. S. National Combustion Meeting

Pasadena, California

March 27, 2019

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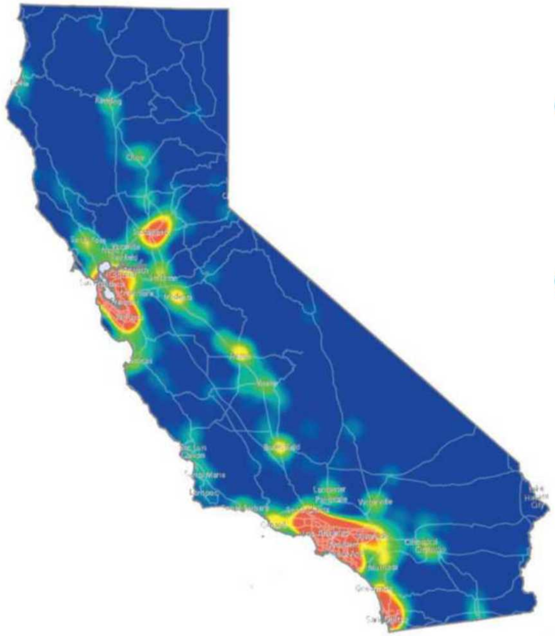
More than 5,000 FCEVs on California roadways

Numbers as of January 2019	Total
Fuel cell cars sold and leased	5899
Fuel cell buses in operation in California	25
Retail hydrogen stations open in California	39



- Clusters in big cities
- “Connectors” and “destination” stations across the state

By The Numbers https://cafcp.org/by_the_numbers

CaFCP Station Map Fuel Cell Revolution (July, 2018)

As FCEV fueling stations serve higher capacity, liquid hydrogen delivery and on-site storage is the likely technology

- For a similar vehicle/day capacity as gasoline, liquid H_2 tankers make sense
  - Underground gasoline stations tanks hold on the order of 10,000 gallons
  - Liquid H_2 tankers can hold up to approximately 4,000 kg
  - Compressed tube trailers hold approximately 300 kg
  - Lack of hydrogen pipelines where stations are needed
- High purity hydrogen needed for FCEVs
- Higher energy density of liquid hydrogen over compressed H_2 makes it more economically favorable for larger fueling stations

Linde's cryo pump fueling station system
https://www.youtube.com/watch?v=Pjh639S2dek

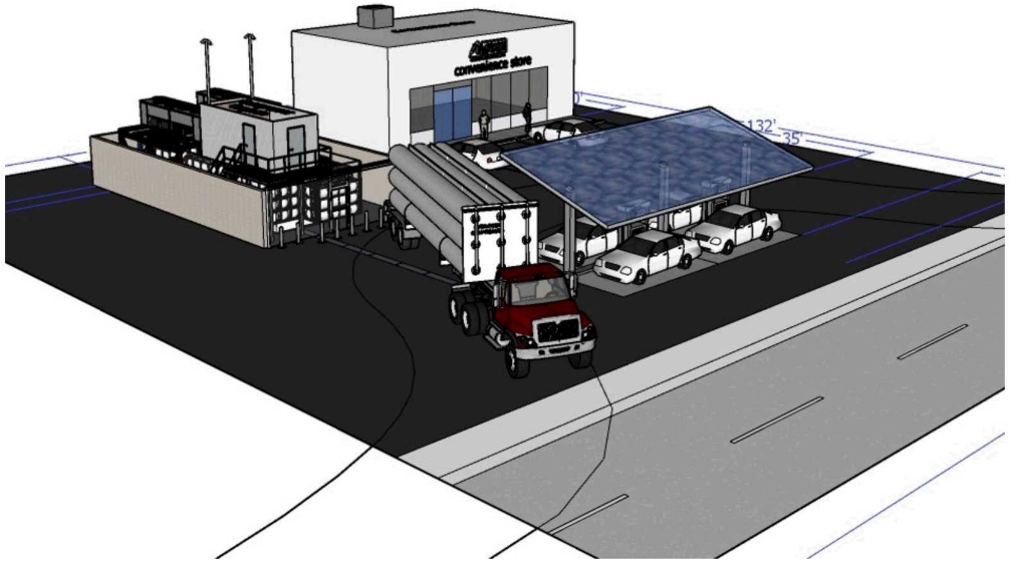
Current separation distances for liquid hydrogen systems are based on consensus rather than a comprehensive scientific basis

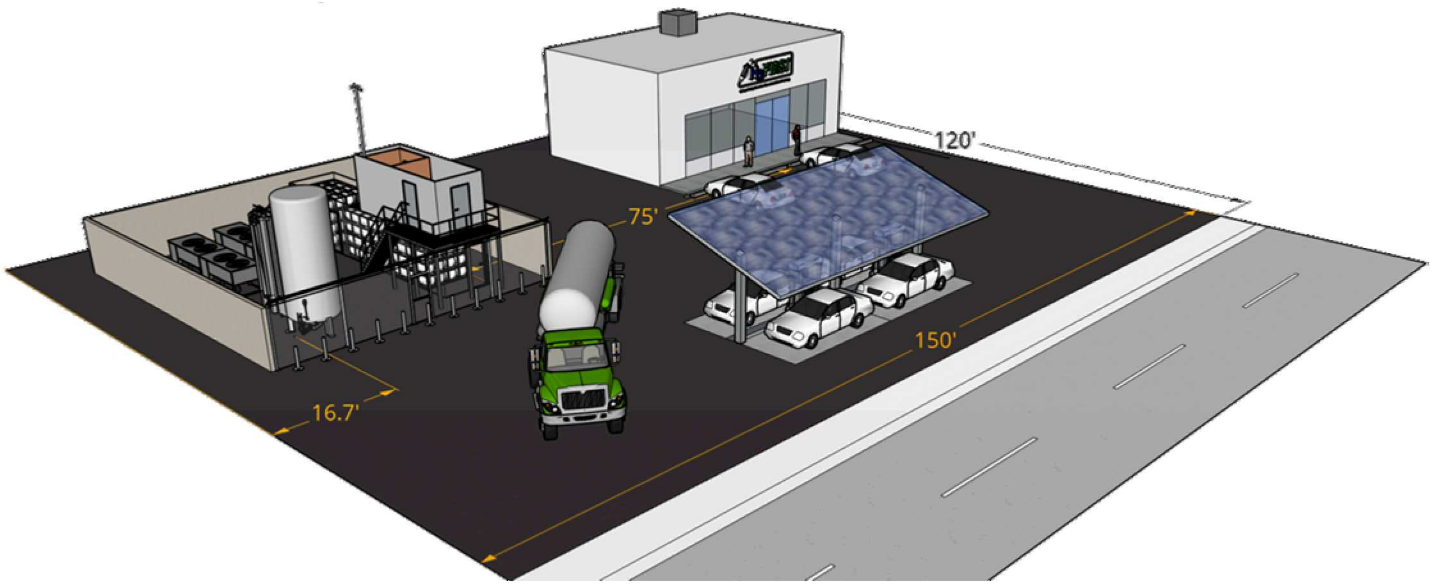
Compressed H_2 storage

- Previous work by this group led to science-based, reduced, gaseous H_2 separation distances

Liquid H_2 storage

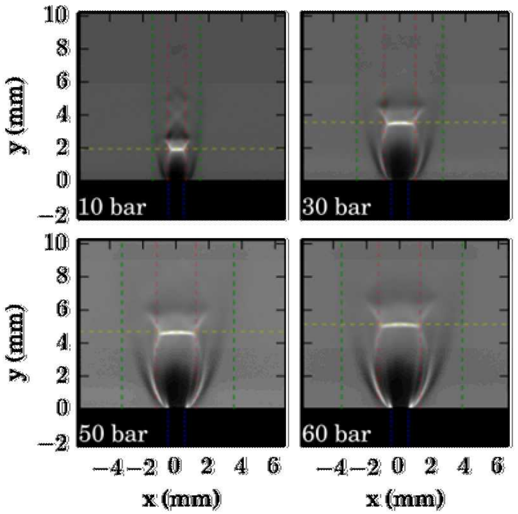
- Even with credits for insulation and fire-rated barrier wall 75 ft. offset to building intakes and parking make footprint large





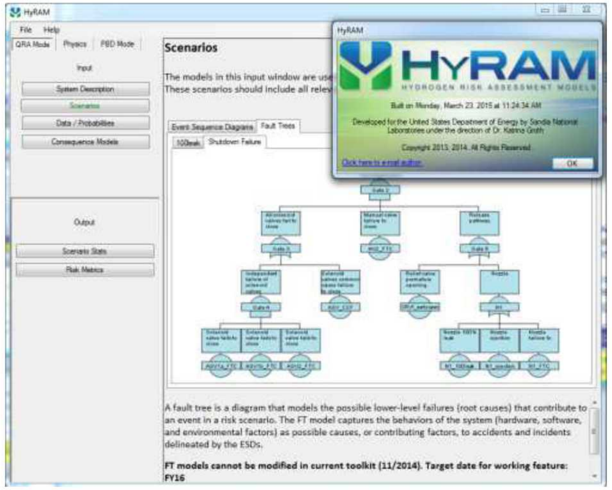
Sandia H_2 Safety Codes and Standards research includes coordinated activities that facilitate deployment of hydrogen technologies

H_2 behavior R&D



Develop and validate scientific models to accurately predict hazards and harm from liquid releases, flames

QRA methods, tools R&D



Develop integrated algorithms for conducting QRA (Quantitative Risk Assessment) for H_2 facilities and vehicles

Apply R&D to RCS

Apply QRA and behavior models to real problems in infrastructure and emerging technology

Enabling methods, data & tools for H_2 safety

Realistic leaks are more likely to be from high aspect ratio cracks for which limited data exist

- Buoyancy controlled slot flames studies have shown that flame length depends on heat release rate ($L_F/W \sim \dot{Q}^n$) or Froude number ($L_F/W \sim Fr^n$)
- Momentum controlled flame study by Mogi & Horiguchi have reported that flame length decreases with increasing aspect ratio.
- Recent work by Gao *et al.* have reported higher non-dimensional flame length for slot flames relative to releases from round nozzles

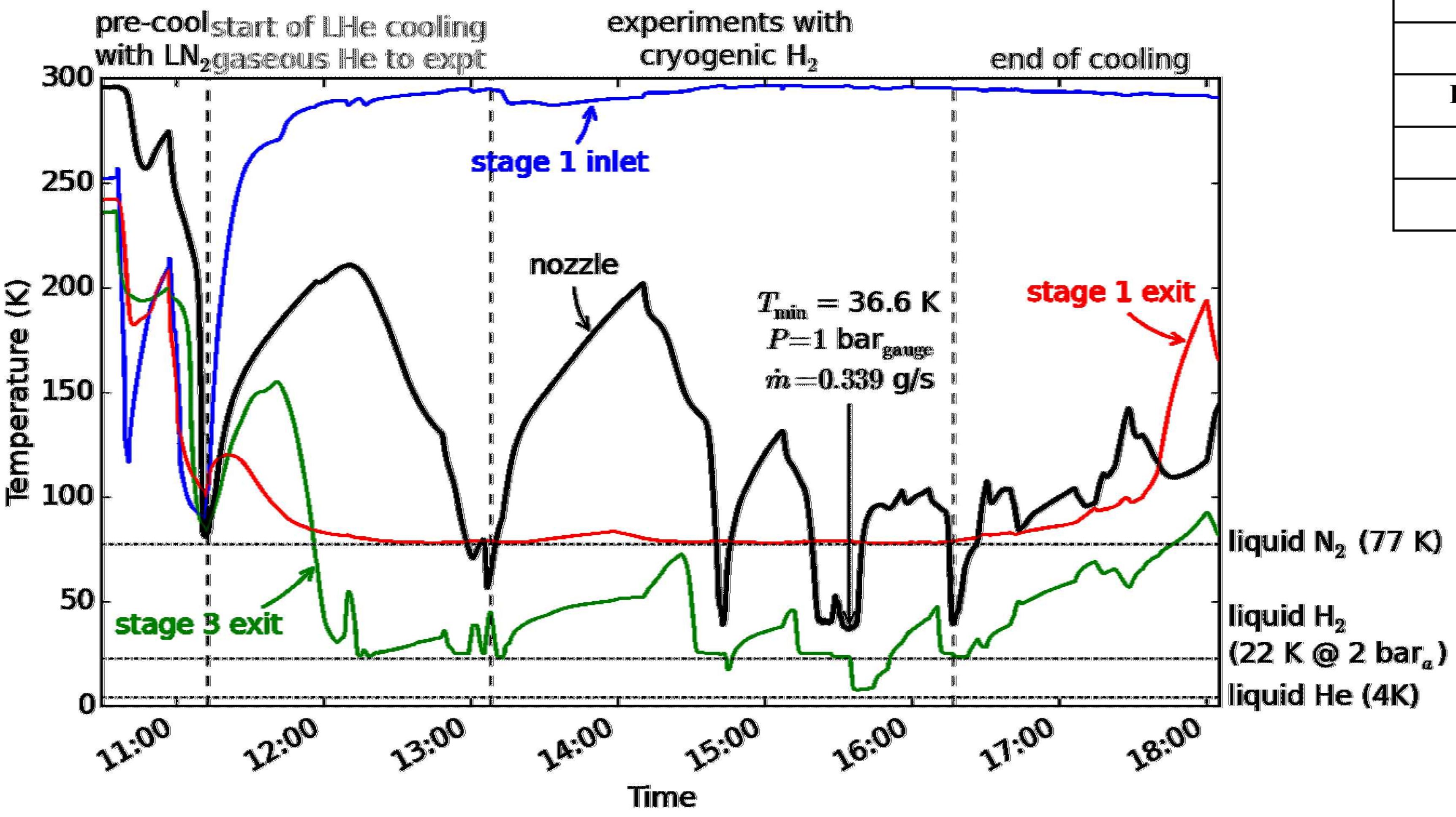
Objectives of the present study

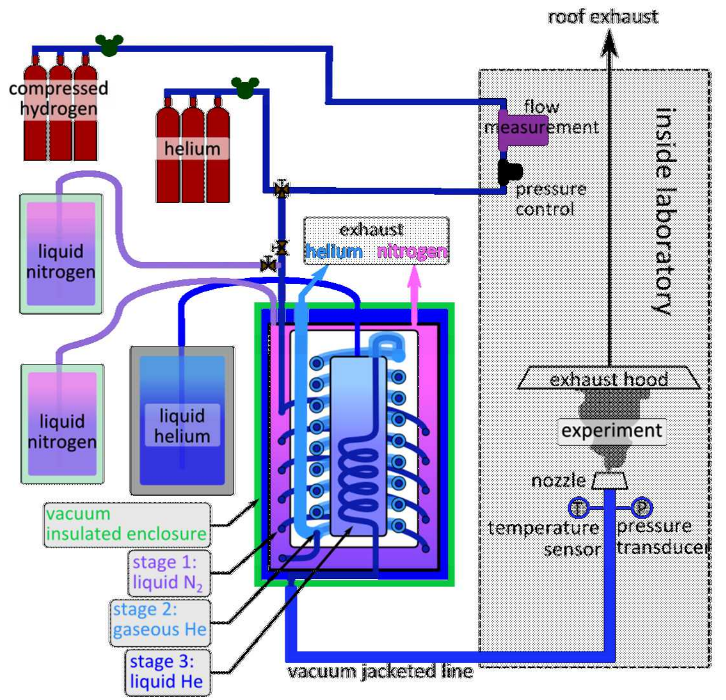
- Examine the reported observations for high aspect ratio nozzles at relevant cryogenic conditions
- Compare the flame characteristics to those of cryogenic hydrogen releases from round nozzle

For development of science-based safety codes and standards, it is important to identify the worst-case scenario and use the worst-case as a conservative approach.

We are releasing cryogenic hydrogen in the laboratory to study its flame properties

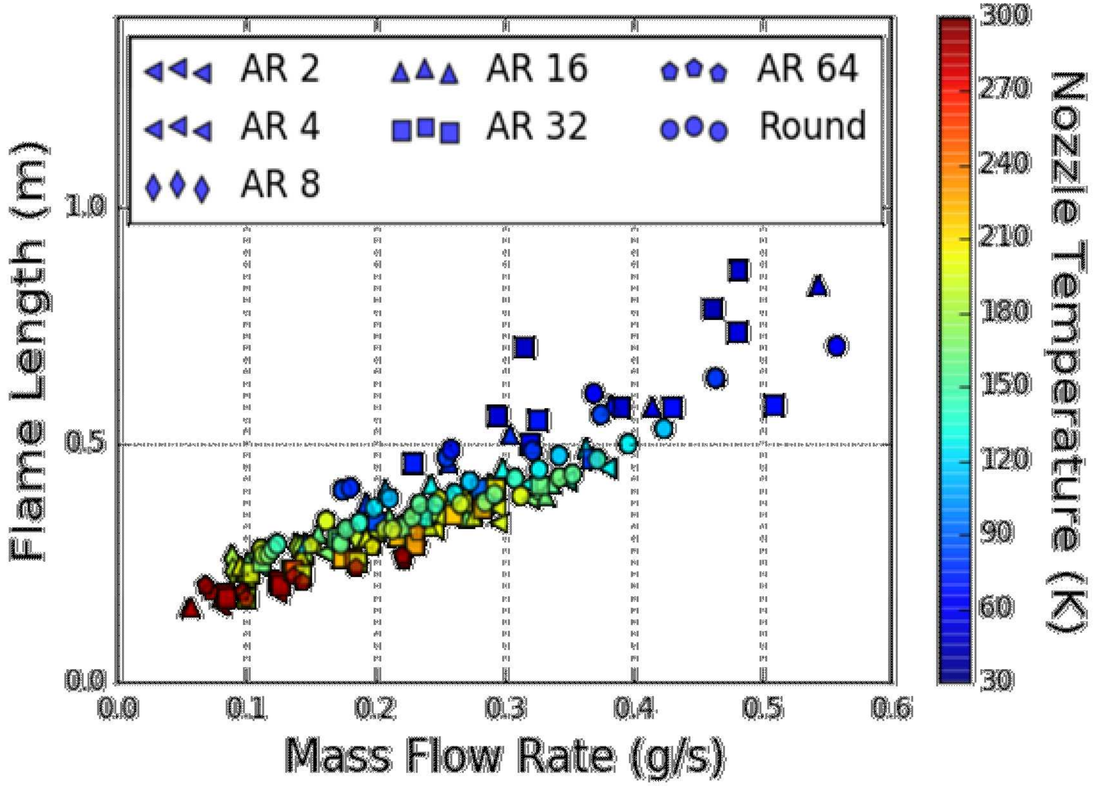
Experimental Parameter	Range
Pressure (bar_{abs})	2.0 – 6.0
Temperature (K)	37 - 295
H_2 mass flow rate (g/s)	0.054 – 0.544
Rectangular Nozzles	A.R : 2,4,8,16,32,64
Circular Nozzle	D : 1 mm





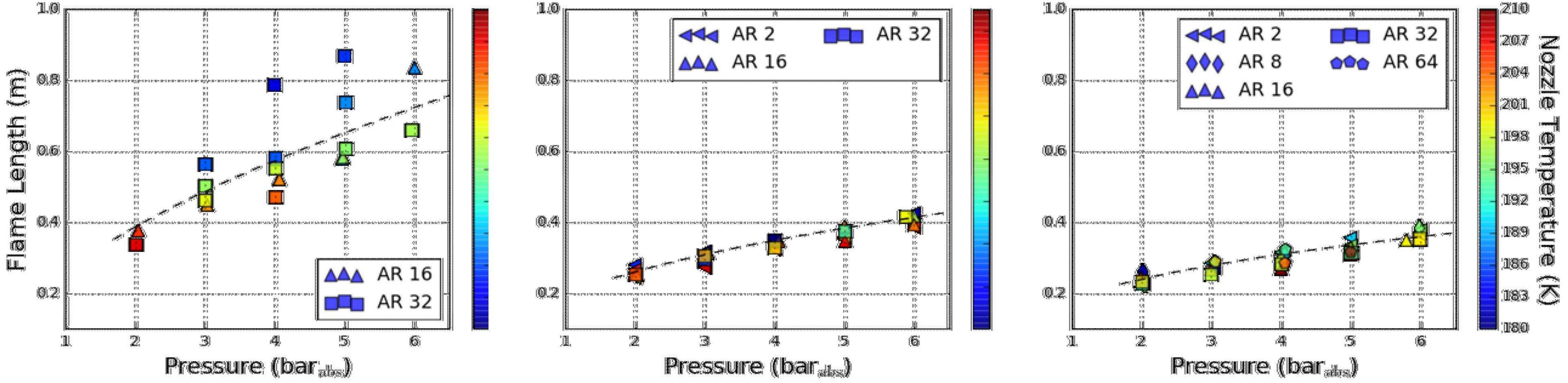
Flame length increases with hydrogen mass flow rate

- Visible flame images were captured by a commercial Panasonic Lumix camera with an exposure time of 200 ms
- Flame length : Distance from the nozzle exit along the axis where the intensity drops to 10 % of the maximum intensity level of that image.
- Visible flame length has a linear trend with mass flow rate
- For a fixed mass flow rate, the flame length is higher for colder jet releases



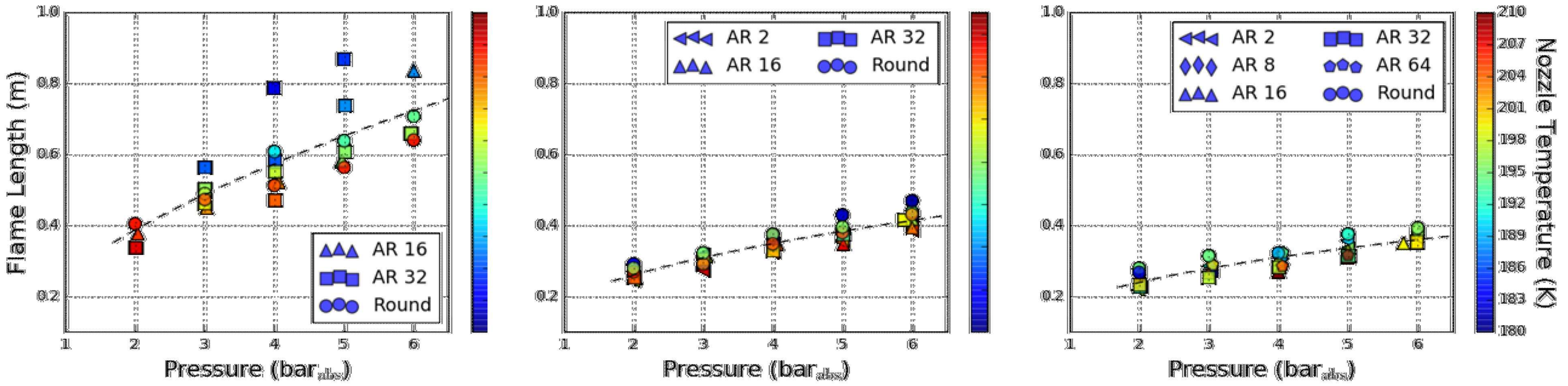
Flame length is affected by release pressure and temperature

- Mass flow rate through the nozzle is governed by release pressure and temperature
- Flame length increases with release pressure at identical nozzle temperatures
- Aspect ratio does not have a large impact on flame length



Flame length is not affected by nozzle geometry

- Mass flow rate through the nozzle is governed by release pressure and temperature
- Flame length increases with release pressure at identical nozzle temperatures
- Aspect ratio does not have a large impact on flame length
- Round nozzle has a very similar flame height relative to slit nozzles



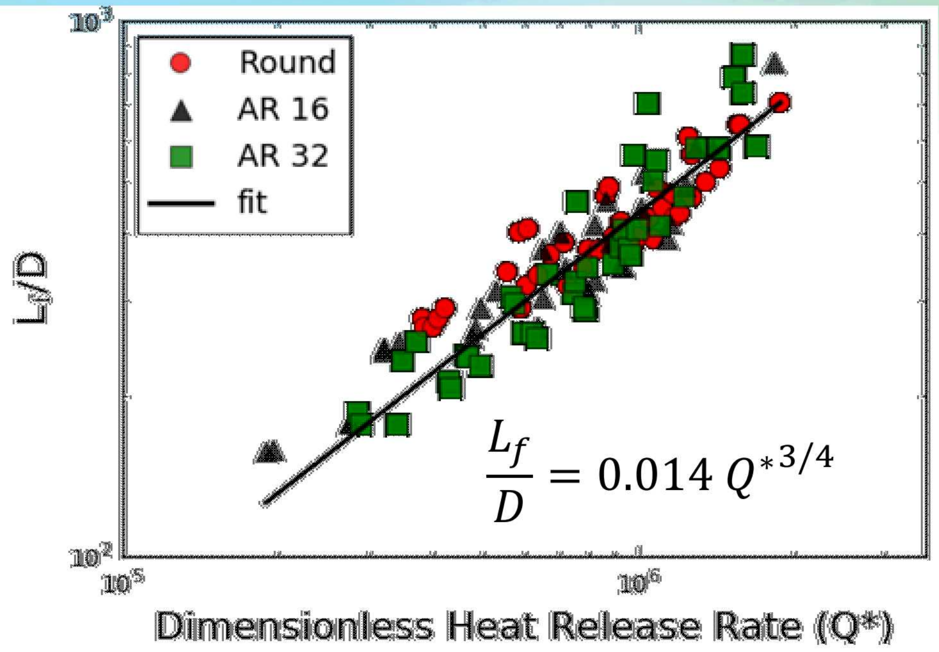
Variation of flame length as a function of heat release rate

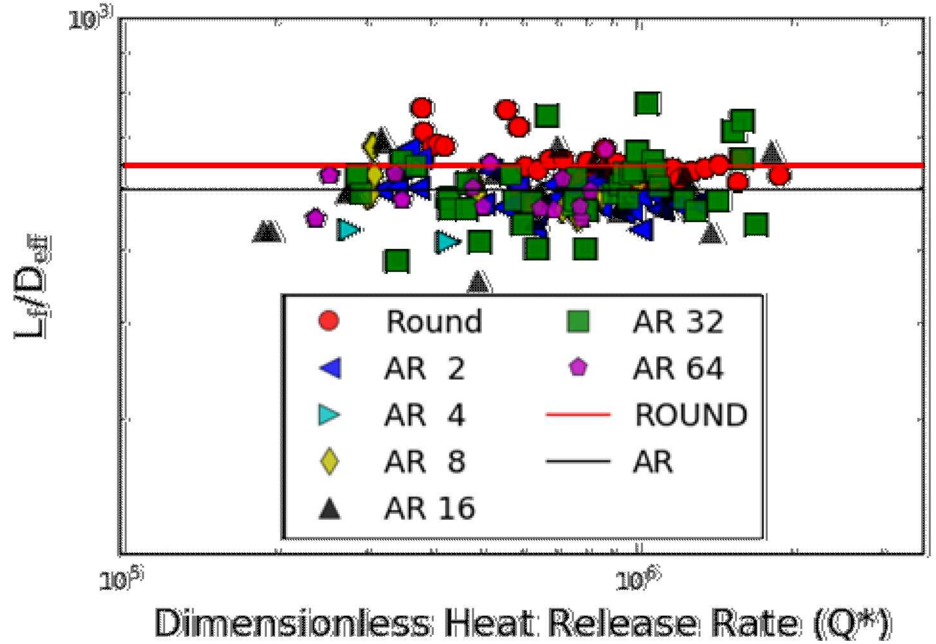
Previously developed correlations:

$$\frac{L_f}{D} = f\left(Q^* = \frac{\dot{Q}}{\rho_\infty C_p T_\infty \sqrt{gD} D^2}\right)$$

Governing Length Scale : Equivalent Nozzle Diameter (D)

- For momentum dominated flames, non-dimensional flame length is independent of Q^* (MaCaffrey, 1988)





- Using effective diameter improves the variation
$$D_{eff} = D(\rho_{NOZ}/\rho_\infty)^{0.5}$$
- Still large scatter of current data around 630 (Round Nozzles) and 598 (Rectangular Nozzles)

Jet Reynolds number provides a better fit to the flame length data

Previously developed correlation for hydrogen flames from round nozzles:

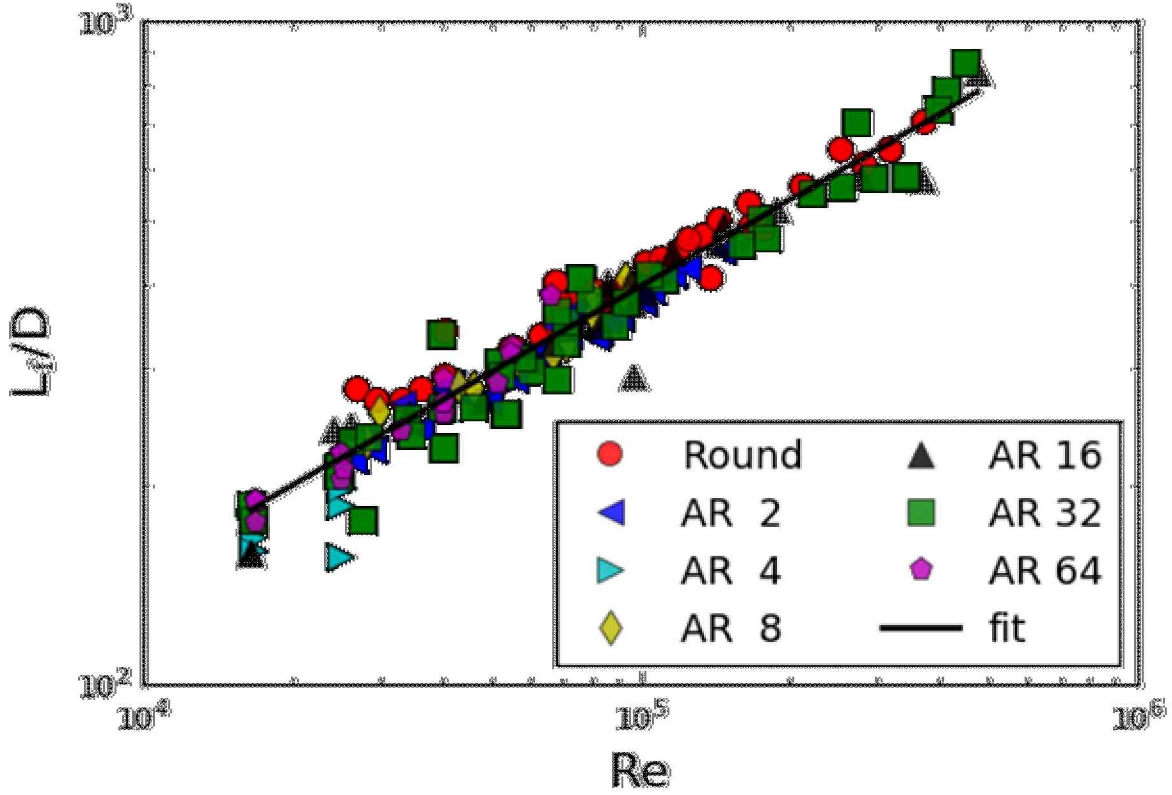
$$L_F = f\left[(\dot{m}D)^{1/2}\sqrt{\frac{4}{\pi\mu_N}}\right]$$ (Molkov & Saffers, 2013)

Taking into consideration the variation of viscosity due to temperature leads to:

$$L_F = f[D, Re]$$

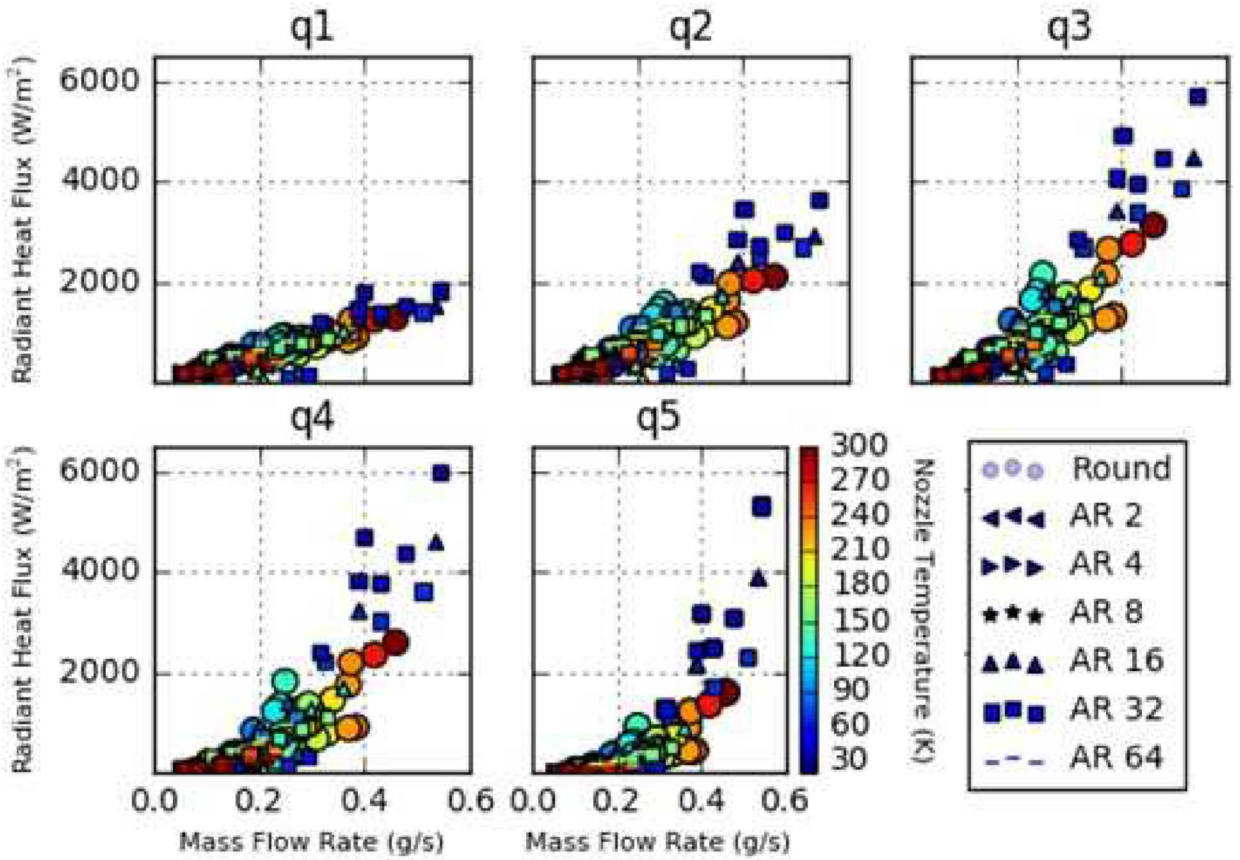
Best fit equation which collapses all the data:

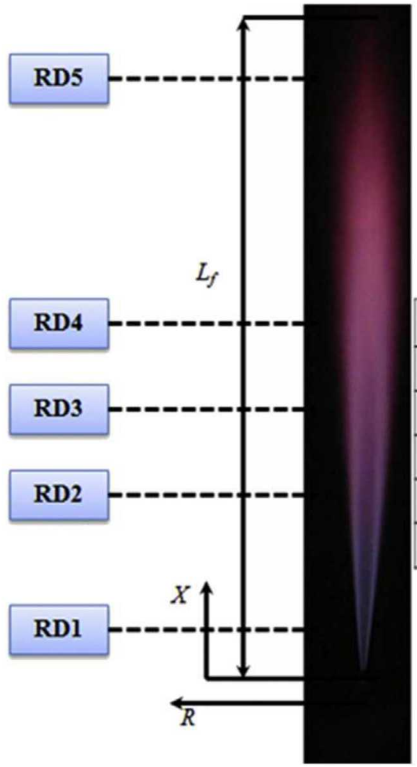
$$\frac{L_F}{D} = 2.8\, Re^{0.43}$$



Radiative heat flux increases with mass flow rate

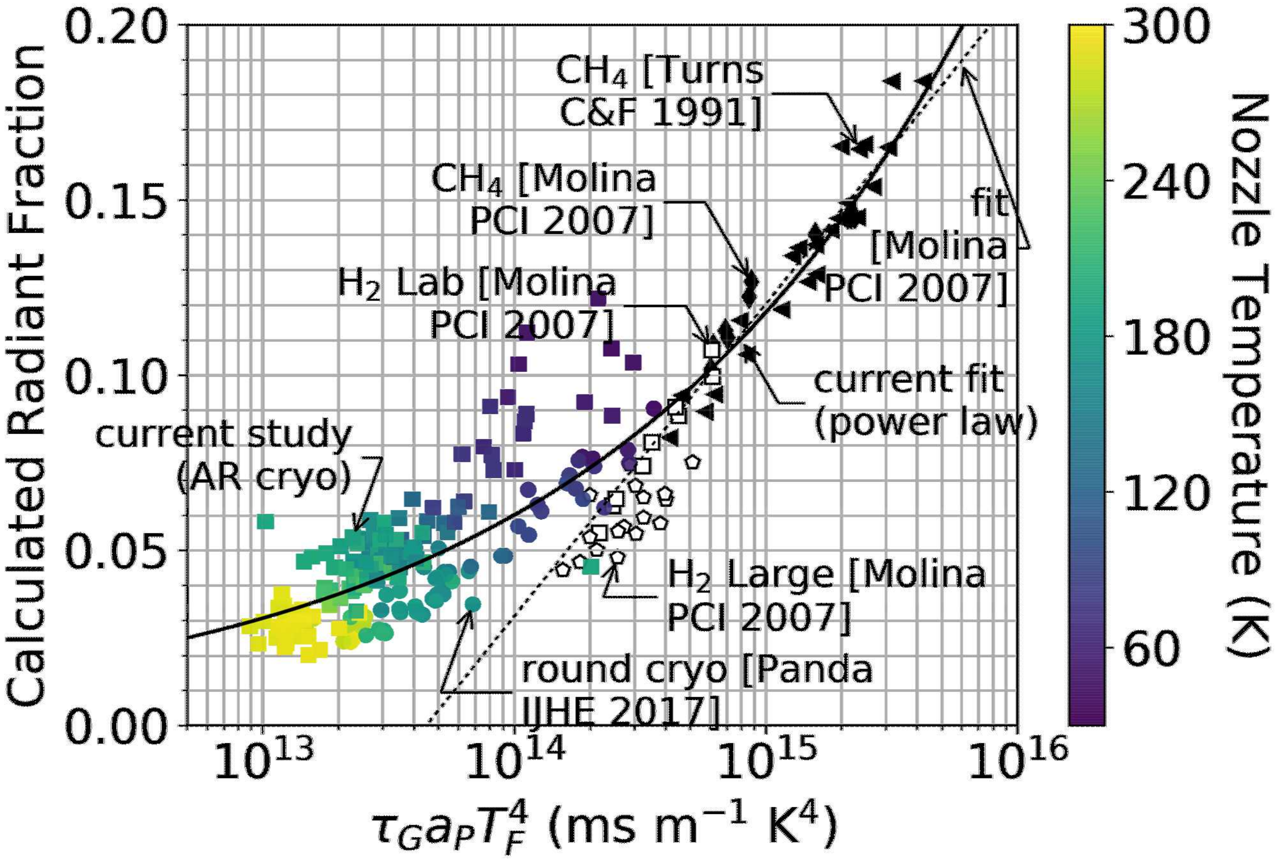
- Radiative power was measured by five wide-angle Medtherm Model 64P-1-22 Schmidt-Boelter thermopile detectors, each with a 150º view angle
- For a fixed mass flow rate of hydrogen, the radiative heat flux is higher for colder jet releases.





Radiometer	Location (in m)
RD1	0.064
RD2	0.22
RD3	0.32
RD4	0.42
RD5	0.65

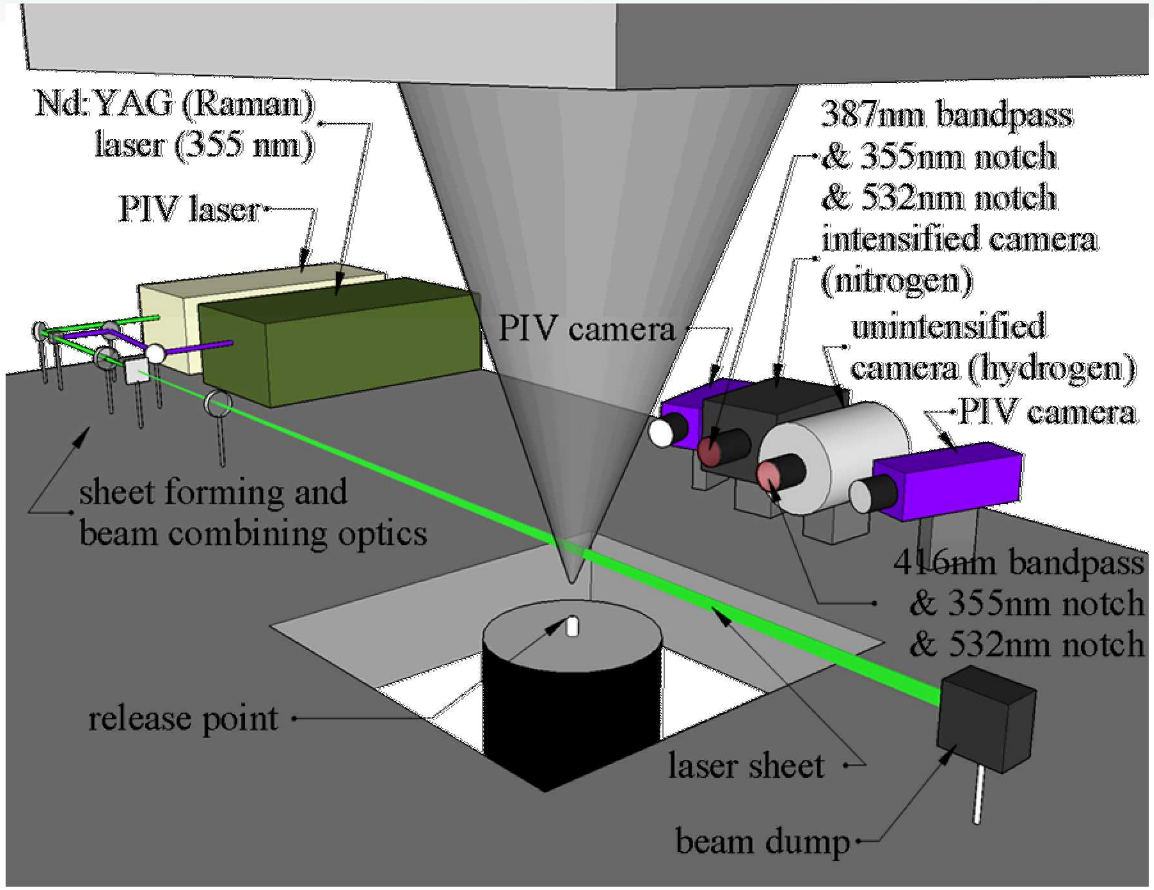
Radiative Fraction



- Radiant fraction for H_2 flames lower than hydrocarbon flames
- Radiant fraction slightly higher for non-circular cryogenic releases
- Power law correlation fits all data, considering noise on measurements
- Power law results in radiant fraction of zero for residence time of zero

Future work: Concentration measurements for cryogenic hydrogen releases

- Concentration and velocity decay rate depends on nozzle geometry
- Mapping the flammable envelope will enable in understanding the physics responsible for observed flame length variation
- Planar Raman Imaging and PIV has been set up to measure concentration and velocity field
- Condensed, entrained moisture acts as particles for stereo-PIV



Summary

- Cryogenic under-expanded hydrogen jet flames have been investigated over a range of temperature (38 – 295 K), pressure (2-6 bar_{abs}) , rectangular nozzles (aspect ratio 2 -64) and round nozzle of identical cross sectional area
- Flames from the rectangular nozzles have similar flame lengths as round nozzles
- Aspect ratio does not have a large impact on flame length
- Hydrogen jet flame length (normalized by equivalent diameter) is strongly dependent on jet Reynolds number
- For a fixed mass flow rate of hydrogen, the radiative heat flux is higher for colder jet releases which can be attributed to lower choked velocity of the colder hydrogen source which increases the flame residence time
- Radiant fraction for rectangular nozzles similar to round nozzles, and data for all fuels (warm and cryogenic) can be collapsed onto a single correlation

Acknowledgements

- Funding support from:
  - United States Department of Energy, Energy Efficiency &Renewable Energy, Fuel Cell Technologies Office, Safety, Codes, and Standards subprogram managed by Laura Hill
  - Industry support including the OEM Group at the California Fuel Cell Partnership, Linde, and Shell
- Team members:
  - Anthony McDaniel (behaviors), Rad Bozinoski (modeling), Myra Blaylock (CFD), Jon Zimmerman (H_2 program manager), Chris San Marchi (materials/metal interactions with H2), Chris LaFleur (Risk, Codes & Standards), John Reynolds (HyRAM), Nalini Menon (polymer interactions with H2), Alice Muna (Risk)
  - Previous researchers including: Pratikash Panda, Katrina Groth, Isaac Ekoto, Adam Ruggles, Bob Schefer, Bill Houf, Greg Evans, Bill Winters

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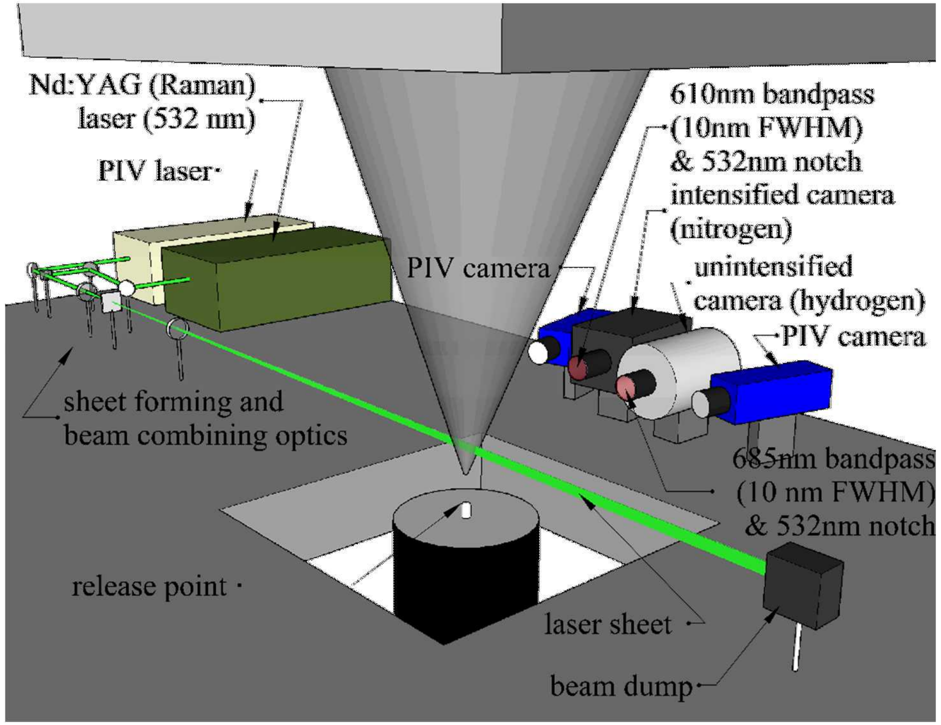
H2FC Hydrogen and Fuel Cells Program

Thank you

Additional Slides

Planar Raman imaging and particle imaging velocimetry off of the condensed moisture are used to measure all model parameters in 2D

- Previous lab approach of Planar Rayleigh imaging had signal overwhelmed by Mie scattering off of condensed entrained moisture in jet
- Filtered Rayleigh had insufficient Mie scattering light suppression (OD≈3)
- Raman scattering enables higher optical density filters to remove unwanted Mie scatter
  - 10 nm FWHM bandpass filters at wavelengths of interest
  - OD of 12 @ all wavelengths
  - OD of 18 @ 532 nm
- Condensed, entrained moisture acts as particles for stereo-PIV

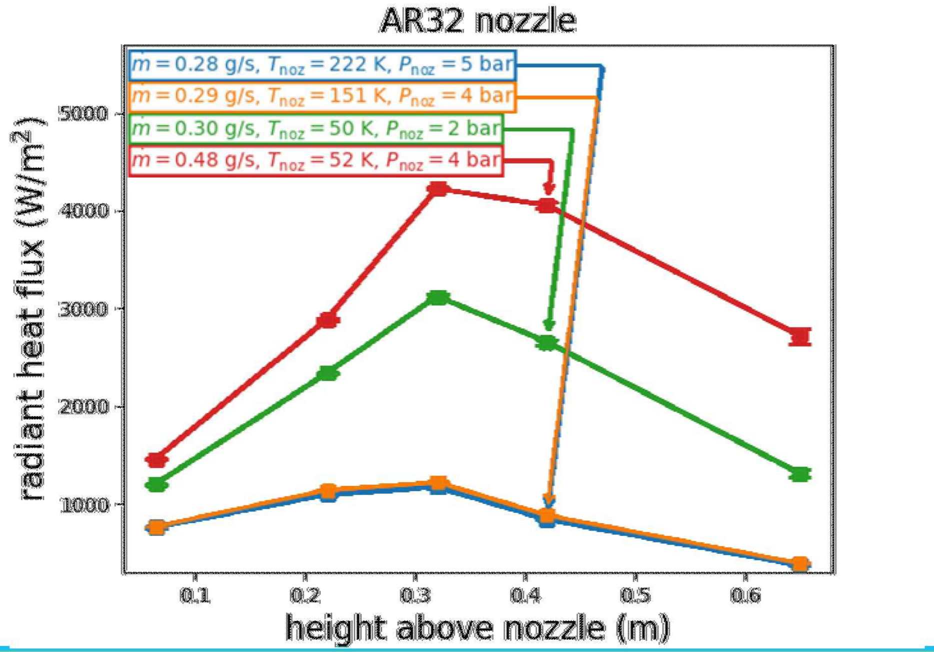


Independent model parameters:

- ✓ T - temperature
- ✓ x - mole fraction
- ✓ v - velocity
- ✓ B - halfwidth (velocity, concentration, temperature)

Heat flux measurements at cryogenic temperatures

- Aspect ratio does not have a large impact on flame length
- Cryogenic temperatures increase mass flow through nozzles
- For an equivalent mass flux, heat flux increases at cryogenic temperatures



➢ Variations in hazards due to temperature are important to understand for QRA of cryogenic systems