ETN Hydrogen Combustion Subgroup:
Hydrogen Combustion Position Paper

AGM & Workshop Meeting, 17th March 2021

Proposed Remit and Aims

- REMIT
  - To review the current state of the art of the combustion of natural gas/hydrogen mixtures with a particular focus on the impact of hydrogen concentration on NOx emissions and other key combustion characteristics
- AIM
  - To produce a position paper on the subject that could be used to
    - Inform and influence the EC and other relevant authorities regarding appropriate future changes to legislation and strategy relating to gas turbine utilisation of natural gas/hydrogen blends up to 100% hydrogen
    - Recommend particular areas for future research

Approach

- The group should determine:
  - Whether it can be claimed that there are fundamental reasons that mean that adding hydrogen to natural gas will always increase NOx emissions
  - Whether it can be claimed that there are reasons that adding hydrogen to natural gas will tend to increase NOx emissions
  - Other impacts of hydrogen addition: such as flashback, blow-off and acoustics
  - At what hydrogen concentration these impacts become significant.
  - The impact of the range of hydrogen content
  - Whether significant development efforts will be required to mitigate problems

- This evaluation would then be used to produce the position paper with appropriate recommendations for emissions legislation, future hydrogen gas turbine strategy and appropriate areas for further research.

Position paper: “Addressing the Combustion Challenges of Hydrogen Addition to Natural Gas” (Overview)

1. Introduction
2. Review of impact of hydrogen in natural gas on combustion behaviour
    2.1. Fundamentals
    2.2. Impact of fundamentals on flame characteristics
3. Practical considerations
    3.1. Positive impacts and advantages of adding hydrogen
    3.2. Adverse impacts of adding hydrogen
    3.3. Development efforts required to mitigate adverse impacts
    3.4. Modelling challenges, reduction of kinetics and turbulence
4. Recommendations
    4.1. Funding areas
    4.2. Emission targets
5. Conclusions

What's covered: details of Section 2

2. Review of impact of hydrogen in natural gas on combustion behaviour
2.1. Fundamentals
  - 2.1.1. Chemical kinetics and **relevant physical properties**
  - 2.1.2. Adiabatic flame temperature
  - 2.1.3. **Fuel placement**
  - 2.1.4. **Air /fuel mixing**
  - 2.1.5. **Flame speed**
  - 2.1.6. Ignition delay time

2.2. Impact of fundamentals on flame characteristics
  - 2.2.1. **Flame shape and position**
  - 2.2.2. **Residence time distribution**
  - 2.2.3. **Flashback**
  - 2.2.4. **Combustion acoustics (dynamics, pulsations, humming etc)**
  - 2.2.5. Lean blow-out and CO emissions
  - 2.2.6. NOx emissions

- Work is well underway on all sub-sections (except 2.1.6.)
- Brief reviews of the items in **bold** has been given in the last H2 working group meeting

Physical Properties: Hydrogen vs Methane

- Significant difference in properties between methane (natural gas) and hydrogen
- Blending hydrogen into natural gas will progressively change mixture properties

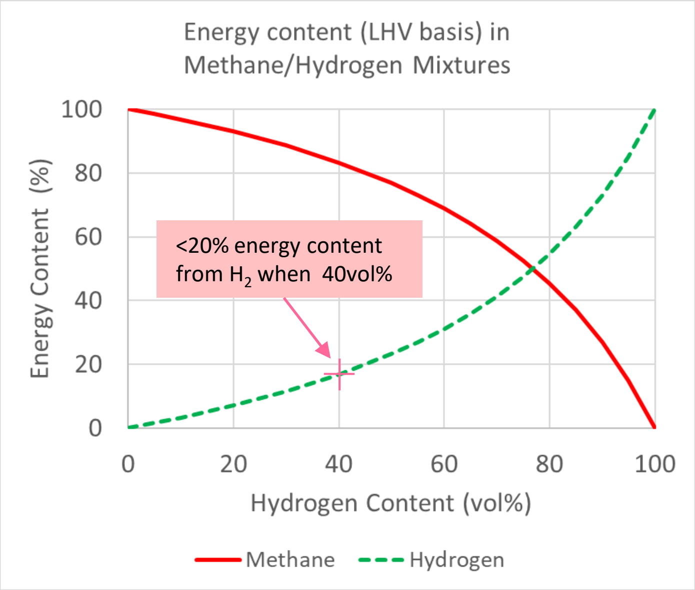


Table 1. Thermophysical and chemical properties of hydrogen [26,28].

Property	Hydrogen	Methane
Specific gravity at NTP [1]	0.07	0.55
Lower calorific value by mass (MJ/kg)	119.93	50.02
Lower calorific value by volume at NTP (MJ/m^3)	10.05	33.36
Flammability limits in air (by volume)	4 to 75	5.3 to 15
Minimum ignition energy in air (mJ)	0.02	0.29
Autoignition temperature (K)	858	813
Maximum adiabatic flame Temperature in air at NTP [1,2] (K)	2376	2223
Maximum laminar flame speed in air at NTP [1,2] (cm/s)	306	37.6
Thermal diffusivity at NTP [1,2] (mm^2/s)	153.26	23.69
Momentum diffusivity at NTP [1,2] (mm^2/s)	105.77	16.81
Mass diffusivity in air at NTP [1,2] (mm^2/s)	78.79	23.98

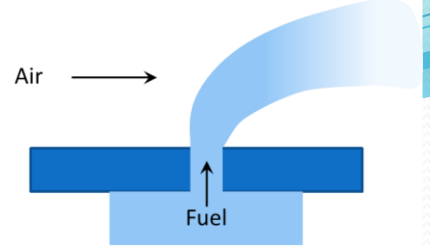
[1] NTP = Normal Temperature and Pressure, i.e., 20 °C and 101.325 kPa. [2] Computed for this article using Cantera [29] with GRI-Mech 3.0 thermal and transport properties [30].

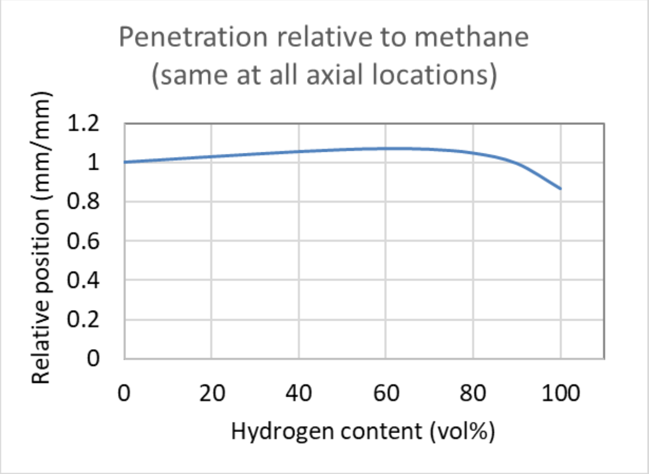
Table from: Beita, J.; Talibi, M.; Sadasivuni, S.; Balachandran, R. Thermoacoustic Instability Considerations for High Hydrogen Combustion in Lean Premixed Gas Turbine Combustors: A Review, Hydrogen 2021, 2, 33–57. https://doi.org/10.3390/hydrogen2010003

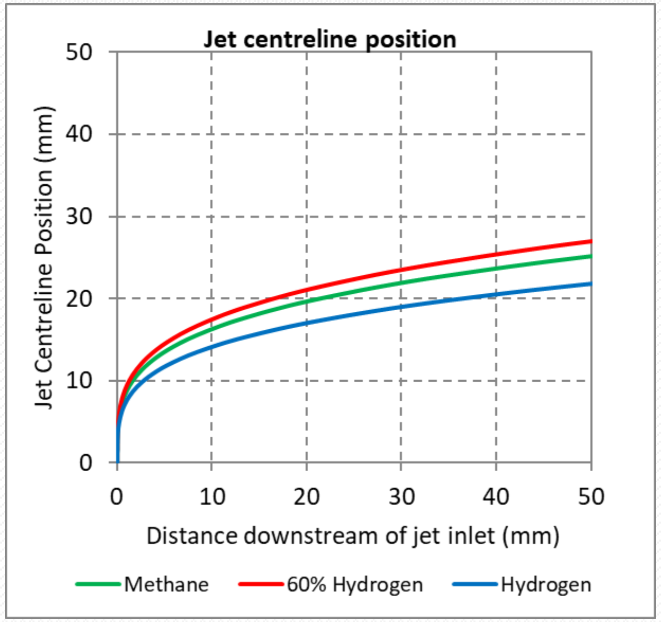
Fuel Placement: Effect of adding H_2 to NG

- Volumetric heating value reduces and so a increased volume of mixture needed for same energy content. The density also changes.
- Impacts the way in which the fuel enters the combustor and is mixed with air. The extent of this effect will depend on the combustor design.
- Many combustors use jet in cross flow →used as an example

- Holdeman* correlation used to indicate jet penetration as hydrogen content increases
  - Initially jet over-penetrates; increases to ~7% greater penetration at ~60vol% hydrogen
  - Then reduces regaining original position at ~90vol% hydrogen
  - Further increases cause under-penetration reaching ~13% less penetration at 100% hydrogen

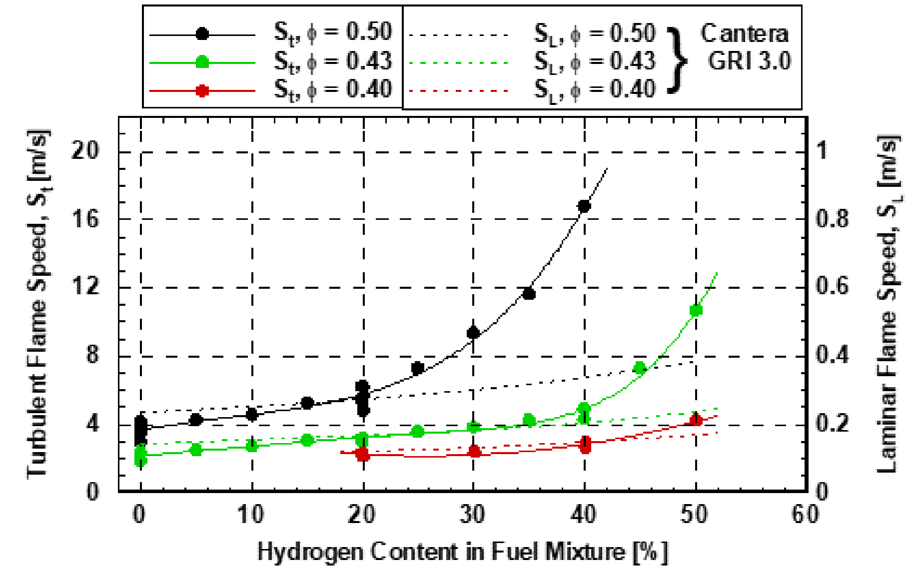




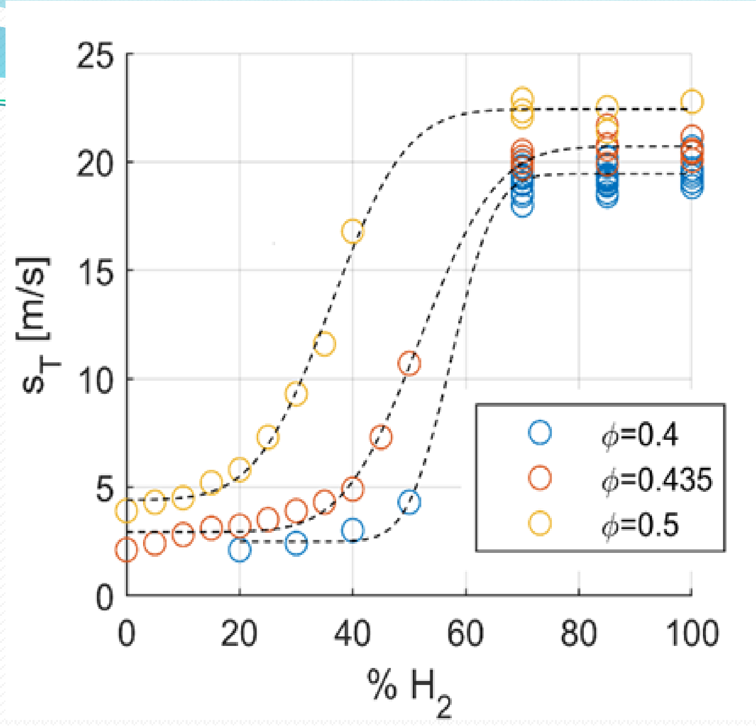


* James D Holdeman, Correlation for Temperature Profiles in the Plane of Symmetry Downstream of a Jet Injected to a Crossflow, NASA Technical Note: NASA TN D-6966, 1972

Flame Speed



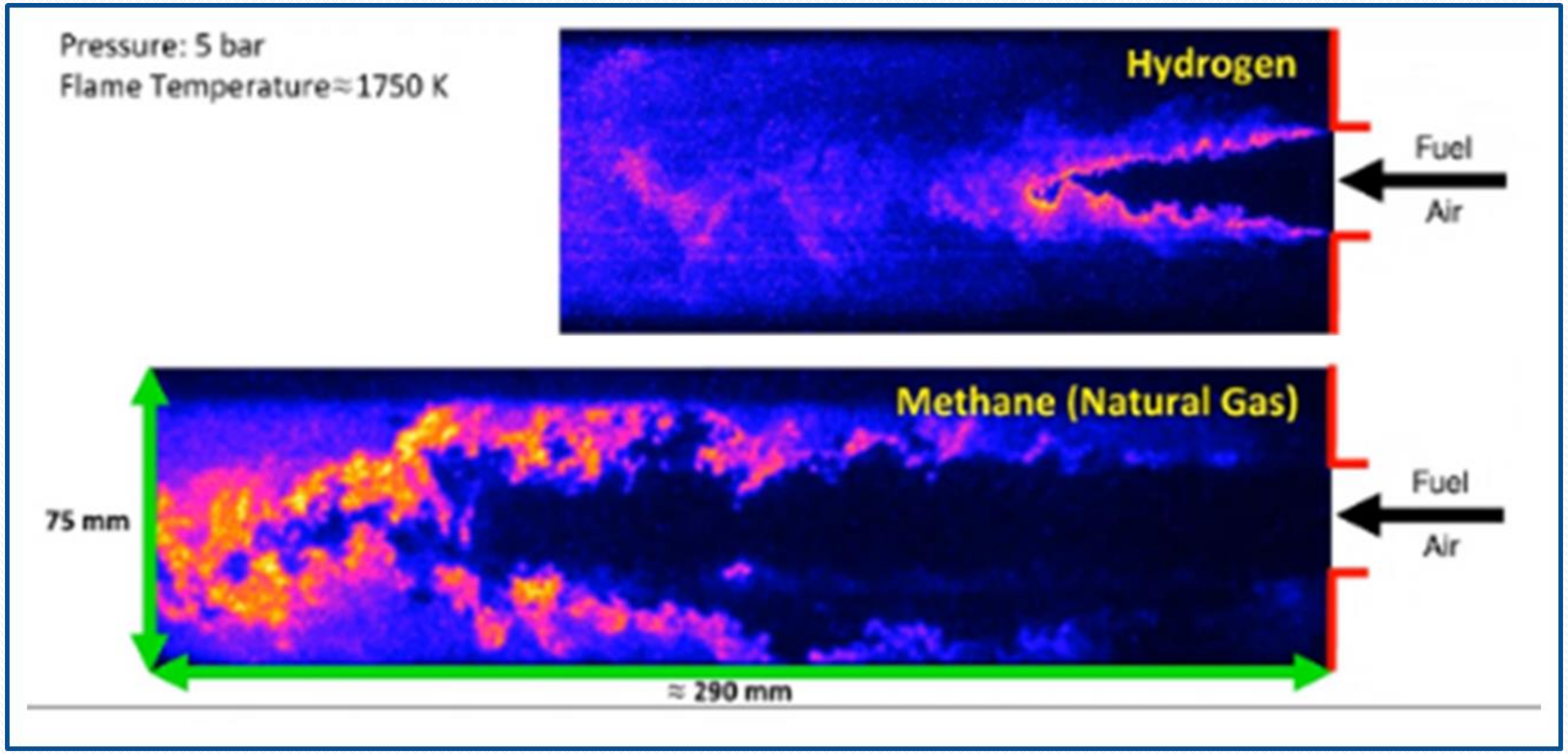
Turbulent flame speed data for CH4/H2 fuel gas mixtures (low/medium H2 content) [31].

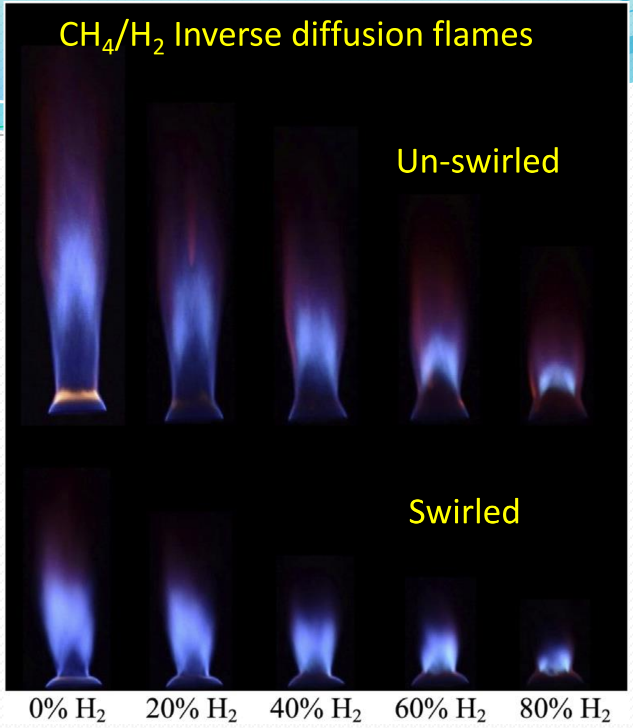


Turbulent flame speed data for H2-rich fuel gas mixtures (combined from original data sets [5, 31]; data for H2-rich (70-100 %vol) flames scaled for turbulence)

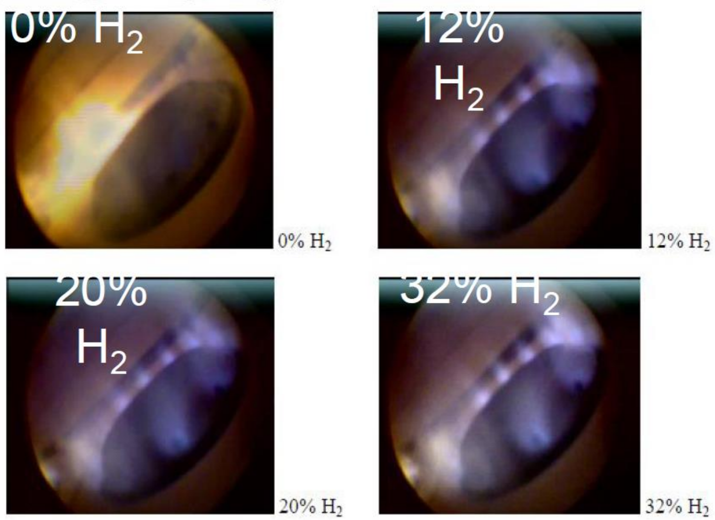
- Only modest influence of H_2 on flame speed up to a particular value depending on ϕ
- Then rapid change to higher value dominated by H_2 properties
- Transition appears sooner at higher ϕ (mixture quality plays a significant(?) role)
- The “constant” flame speed at high H_2 does not imply identical flame behaviour, other effects make designing for high H_2 (above ~70%) particularly challenging

Flame shape and position





Hydrogen % by volume



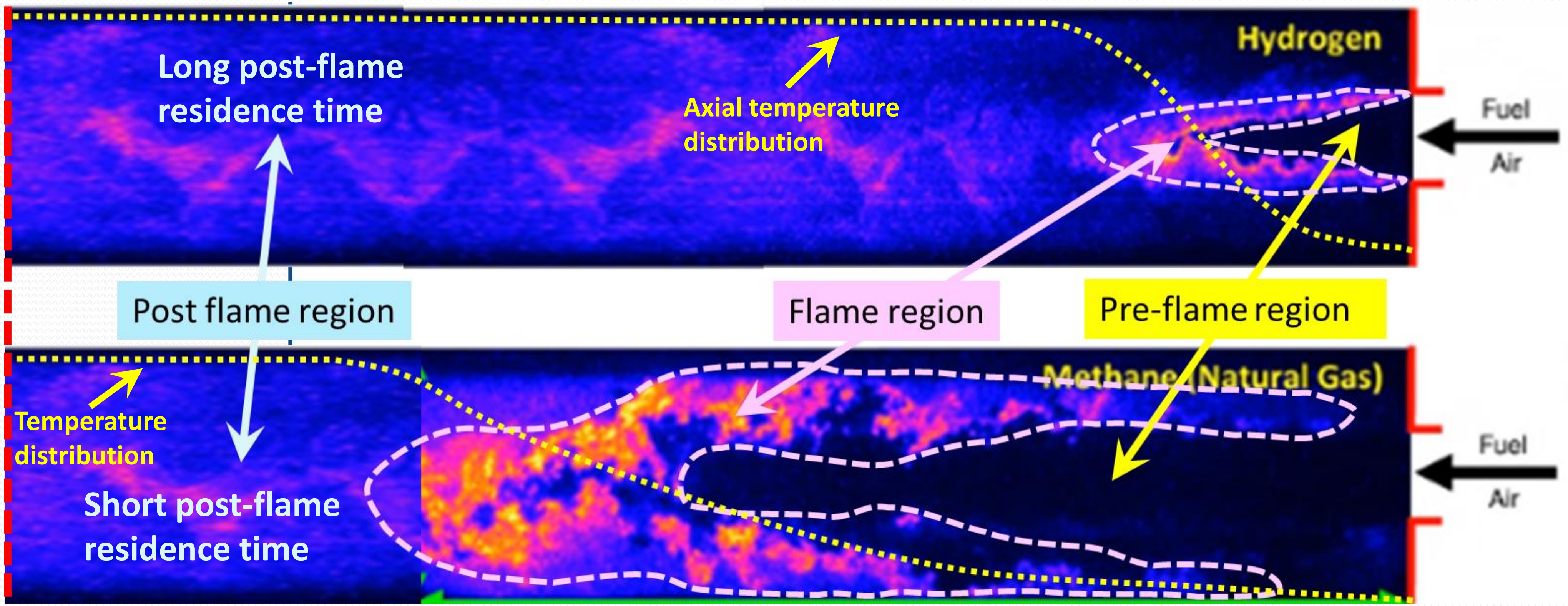
Siemens burner on engine*

- Hydrogen addition results in shorter flame and thinner flame front
- Holds across wide range of flame types
- Effects seen (already) at modest hydrogen content

* Siemens image from: Applying simulation and additive manufacturing to the development of next generation of hydrogen combustion, Jenny Larfeldt: downloaded from@ https://www.international-bc-online.org/wp-content/uploads/2018/04/2_-Hydrogen_cofiring_Larfeldt_13april2018.pdf

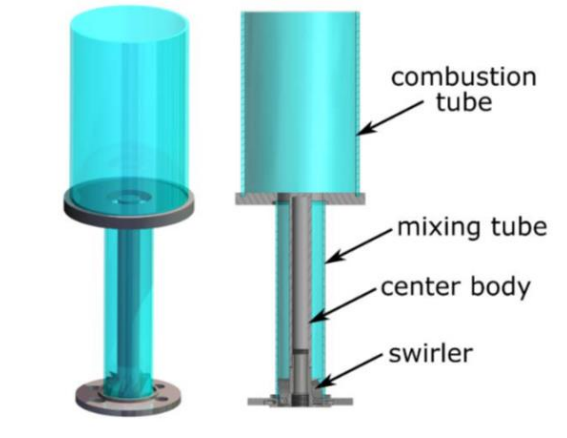
Residence time distribution

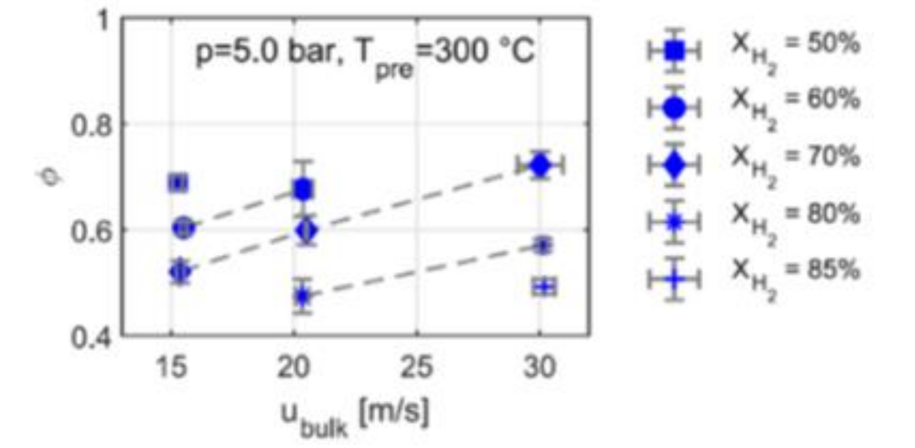
End of hot combustion zone



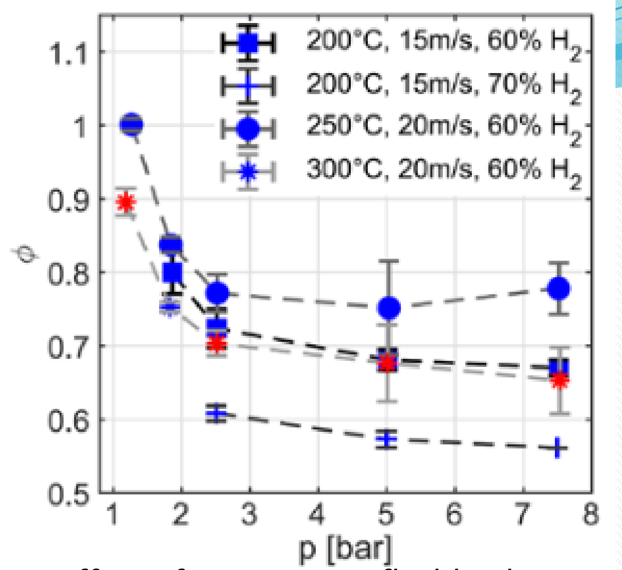
- Flame size and shape determine the distribution of sizes of pre-flame, flame and post-flame zones and thus residence times
  - Impact on NOx (longer post flame residence time → increased NOx.)
  - Impact on thermoacoustics (flame and pre-flame residence times affect phase matching)

Flashback





Equivalence ratio ϕ at which flashback occurred versus the bulk flow velocity

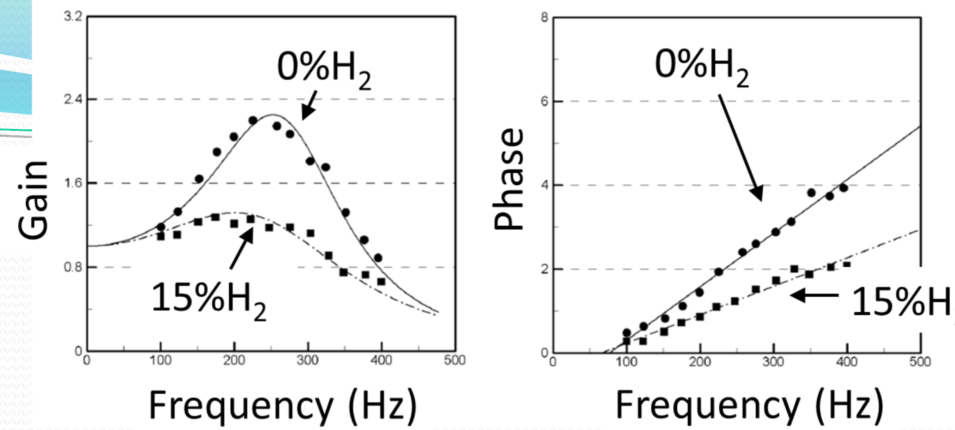


Effect of pressure on flashback limits

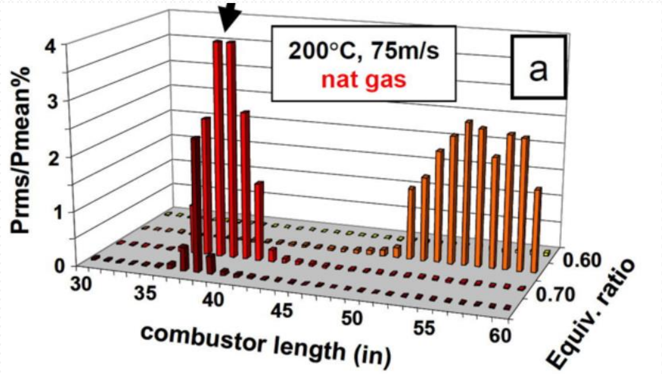
- Boundary layer flashback most significant mechanism for high hydrogen
- Up to 80% H_2 an increase in bulk flow velocity provides a reasonable improvement in flashback margin
- Influence of wall temperature significant
- Pressure has only limited effect above ~2bar

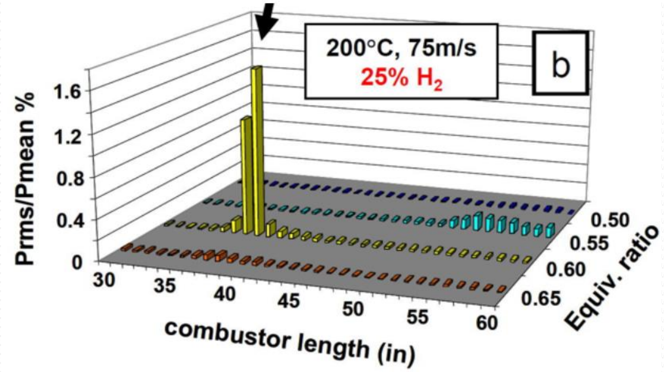
Combustion acoustics

- Hydrogen addition affects flame shape and position and thus acoustic response
- Hydrogen enrichment is likely to favour higher frequency instabilities
- Hydrogen addition can result in mode switching impacting instability control strategies
- Hydrogen-enrichment has the potential to increase the propensity for combustion dynamics-induced flashback.
- Pure hydrogen injection in minute quantities, may have potential for suppressing combustion instabilities.
- Hydrogen enrichment may shift regions of thermoacoustic instabilities to lower equivalence ratios/flame temperatures.



Impact of hydrogen addition of Flame Transfer Function from Kim (see*)





Stability maps for variable length LPM combustor from Figura et al (see*)

* Figures adapted from : Beita, J.; Talibi, M.; Sadasivuni, S.; Balachandran, R. Thermoacoustic Instability Considerations for High Hydrogen Combustion in Lean Premixed Gas Turbine Combustors: A Review, Hydrogen 2021, 2, 33–57. https://doi.org/10.3390/hydrogen2010003

Progress

- Significant progress has been made on:
  - Data gathering
  - First drafts of subsections relating to:
    - 2.1 Fundamentals
    - 2.2 Impact of fundamentals on flame characteristics

Next steps:

- Produce consolidated document from draft subsections
- Evaluate content of consolidated document to determine content for
  - 3 Practical considerations
  - 4 Recommendations

Thank You:
Do you have any suggestions