'Joint workshop Combustion & Sprays SIGs’

Special interest Group Meeting – London, Tuesday 9th April, 2019

Experimental and Numerical Evaluation of Pressurized, Lean Hydrogen-Air Flame Stability with Carbon Dioxide Diluent

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Presentation Outline

- Background and Previous Hydrogen Studies
    - Hydrogen Projects in the UK
    - Hydrogen GTs & GTRC Hydrogen Studies
- Experimental and Numerical Study of Lean Premixed, Preheated, and Pressurized H_2-CO_2 Swirl Flames
    - Introduction
    - Experimental Setup and Diagnostics
    - Experimental Results
        - CH_4-air vs. H_2-CO_2-air Flame Stability
        - H_2-CO_2 Flame Stability with Varying Fuel CO_2 %
        - Pressure Effects on H_2-CO_2 Lean Blowoff (LBO)
- Conclusions and Future Work

Hydrogen Projects in the UK

- **UK Government Clean Growth Strategy**
  - £20M funding announced May 2018 for H_2 technology development
- **H21 Project – Northern Gas Networks et al.**
  - Convert homes and businesses from natural gas to 100% hydrogen, starting in 2028
- **HyNet Northwest – Cadent et al.**
  - Start with 20% H_2 blending into natural gas (HyDeploy) at Keele University
- **Hy4Heat – Arup et al.**
  - H_2 heating for homes, business, and industry
  - GTRC involved with WP6 – Industrial Appliances and WP7 – Safety Assessment

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- **Do OCGTs/CCGTs have a role to play in these hydrogen systems?**
  - 2018 HyNet Project Report: “The extent and ease to which industry can be converted varies across the different applications. Whilst there appear to be no insurmountable technical barriers to converting existing kilns, furnaces and particularly boilers to **high hydrogen**, reaching such levels **in gas turbines and engines is a far greater challenge**.”

HM Government

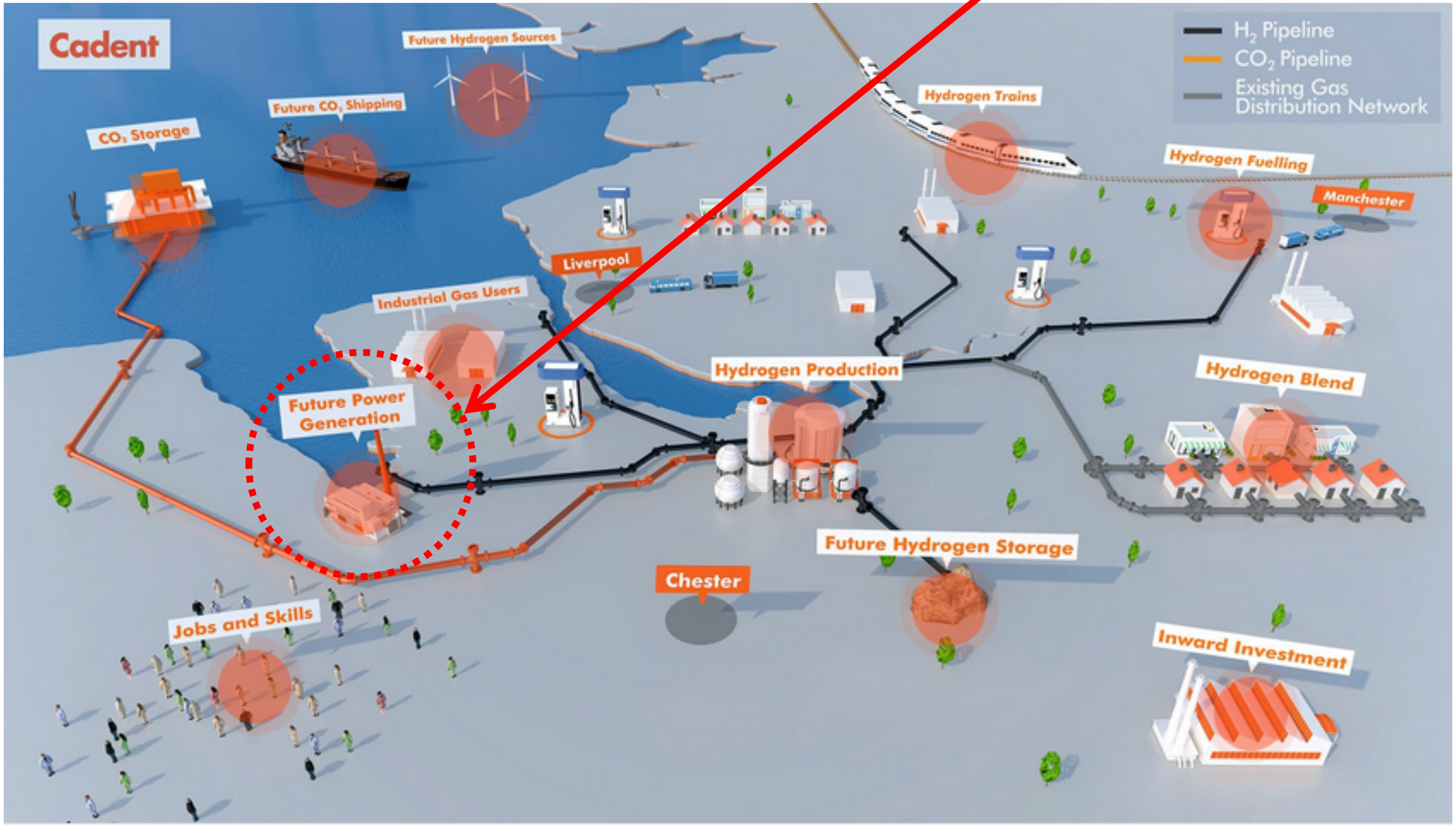
H21

HyNet

Hy4Heat

HyNet

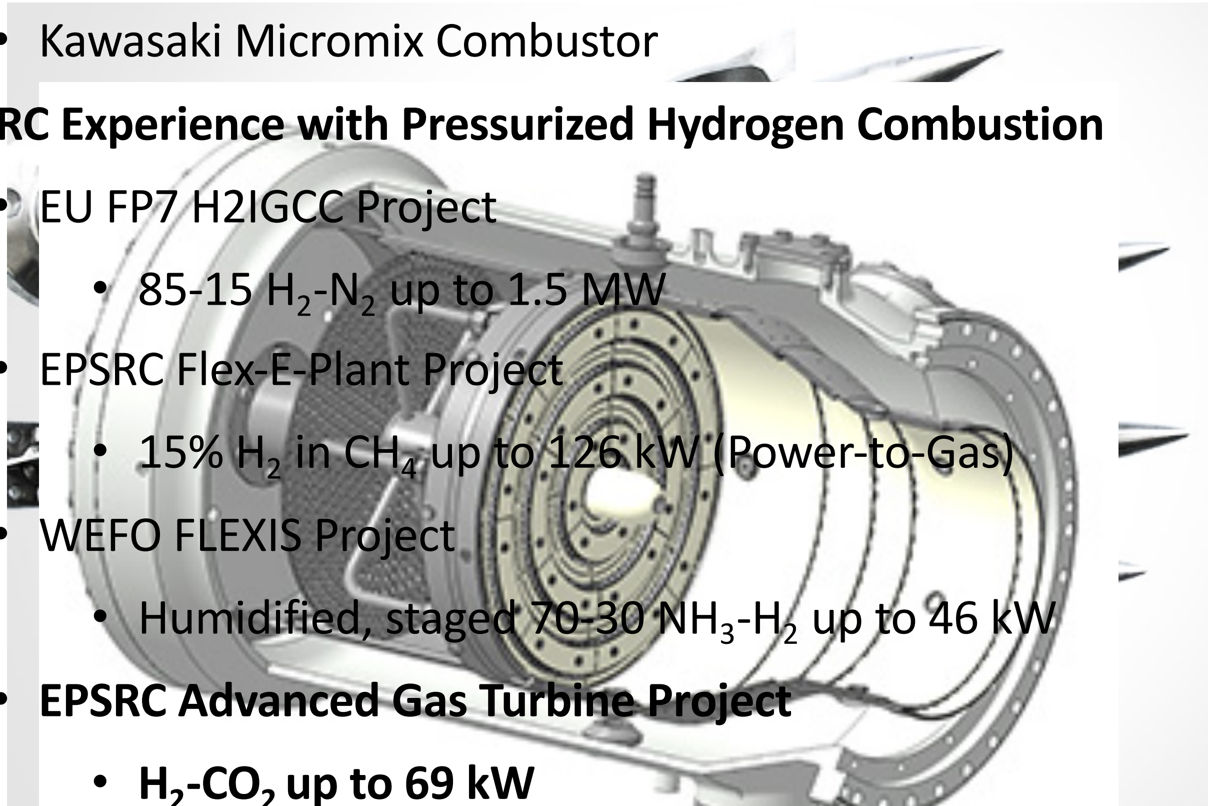
New H_2-fuelled OCGTs/CCGTs? What about existing GTs?



Source: https://hynet.co.uk/

Hydrogen Gas Turbines and GTRC Studies

- **New hydrogen GT combustors are currently under development by OEMs, often requiring new geometries/injection methods**
  - Mitsubishi Hydrogen Injector
  - Kawasaki Micromix Combustor
- **GTRC Experience with Pressurized Hydrogen Combustion**
  - EU FP7 H2IGCC Project
    - 85-15 H_2-N_2 up to 1.5 MW
  - EPSRC Flex-E-Plant Project
    - 15% H_2 in CH_4 up to 126 kW (Power-to-Gas)
  - WEFO FLEXIS Project
    - Humidified, staged 70-30 NH_3-H_2 up to 46 kW
  - **EPSRC Advanced Gas Turbine Project**
    - **H_2-CO_2 up to 69 kW**



Source: https://www.mhps.com/special/hydrogen/article_1/index.html
http://global.kawasaki.com/en/corp/rd/technologies/energyb.html

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Cronfa Datblygu Rhanbarthol Ewrop
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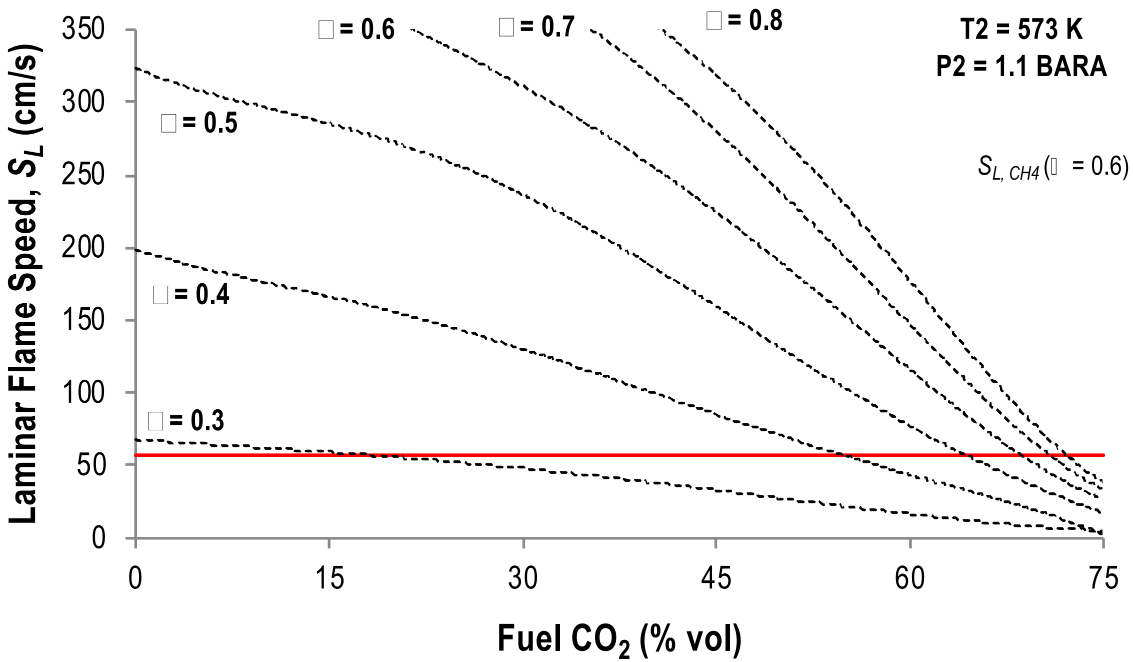
Experimental and Numerical Study of Lean Premixed, Preheated, and Pressurized H_2-CO_2 Swirl Flames

- If H_2 is produced in the future via steam-methane reforming (SMR) with CCUS, could these two unique vectors (H_2-CO_2) replace natural gas as fuel in existing lean, premixed (LPM) GTs without costly modification or will these assets be stranded around the UK?
- Possible advantages of CO_2 dilution in LPM, swirl-stabilized H_2 flames?
    - Availability from the CCUS process – cost-effective
    - Control NOx emissions – limit flame temperatures
    - Prevent flashback – reduce H_2 flame speed
    - Increase stability over operating range – control heat release fluctuations
    - Limit thermodiffusive effects of H_2 – control flame stretch effects under highly-turbulent conditions

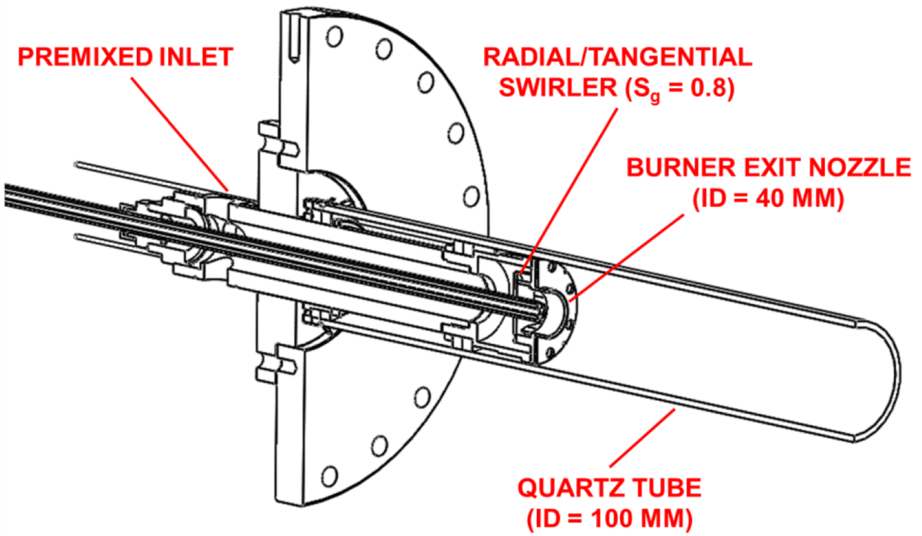
Preliminary Study:

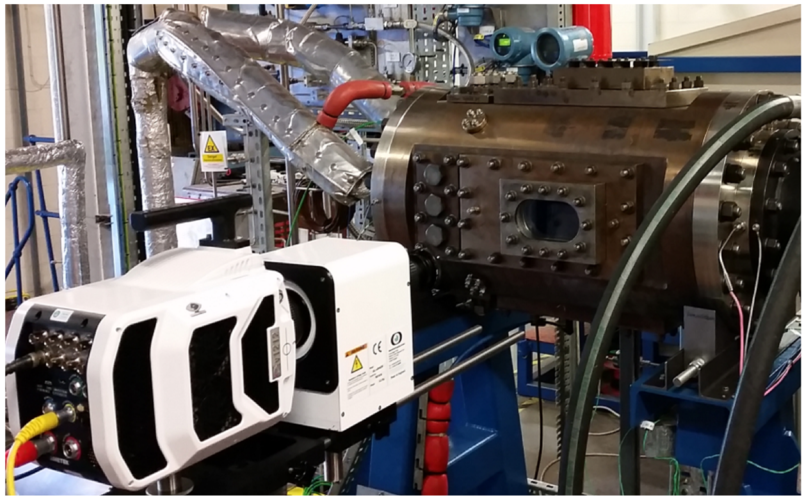
- CHEMKIN modelling of H_2-CO_2 laminar flame speed at 573 K and 1.1 bara (Li et al. Mechanism).
- Compare with a stable CH_4 condition (φ = 0.6) in GTRC's High-Pressure Generic Swirl Buner (Mk. II), HPGSB-2, using GRI-Mech.
- Successfully used S_L/u scaling to identify H_2-CO_2 lighting condition.



Experimental Setup and Diagnostics

- Fully **premixed**, **preheated** (T2 = 573 K ± 5 K), **pressurized** (25 kW/bar) combustion in generic swirl burner (Sg = 0.8) in high-pressure optical chamber.
- First, compare CH_4-air and H_2-CO_2-air flames at P2 = 1.1 bara using:
  - High-speed OH* chemiluminescence (4 kHz, 10 µs gate), Phantom V1212 High-Speed Camera with SIL High-Speed Image Intensifier
  - In-burner dynamic pressure measurement (4 kHz).
- A single lean equivalence ratio (φ = 0.25) is selected to investigate the influence of P2 on lean H_2-CO_2-air flame stability and lean blowoff (LBO) behavior.





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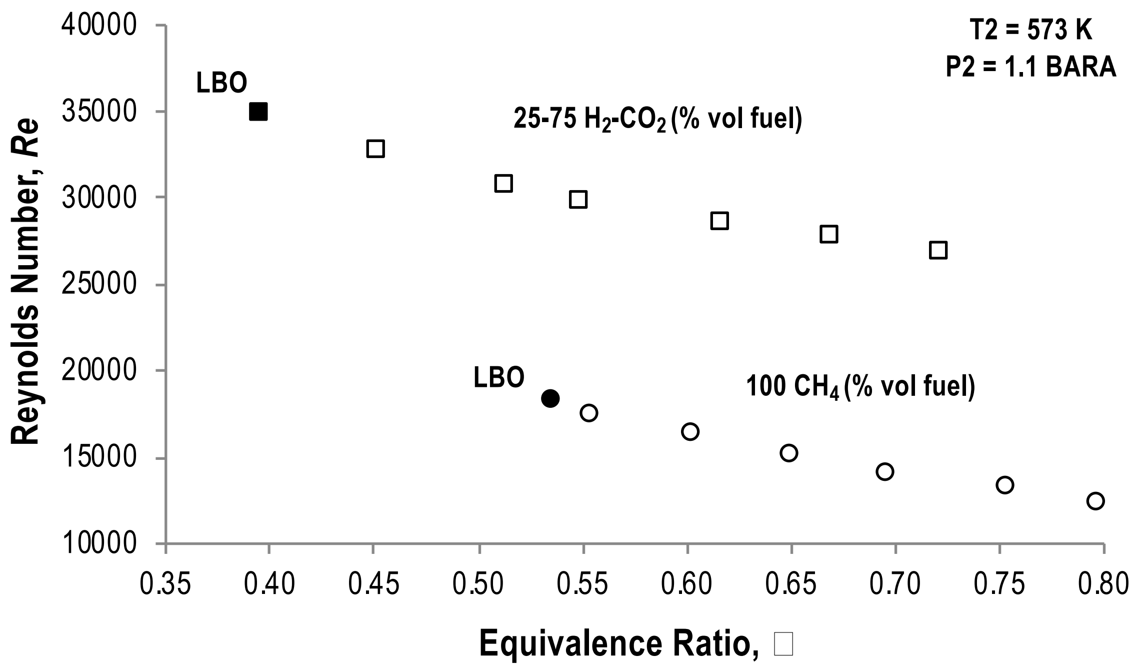
Results - CH_4-air vs. H_2-CO_2-air Flame Stability

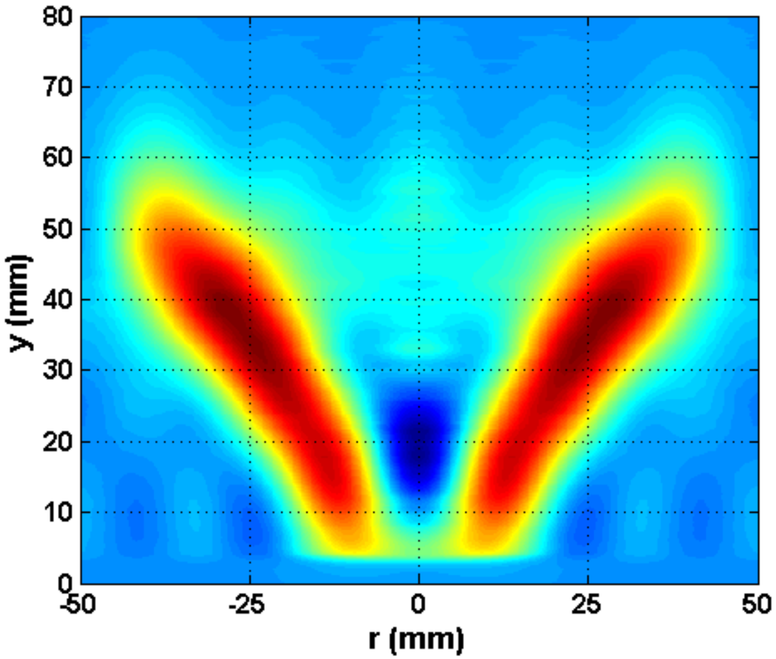
- Stable operating curve comparison of 100% CH_4 and 25-75% H_2-CO_2 swirl flames at 25 kW, 1.1 bara



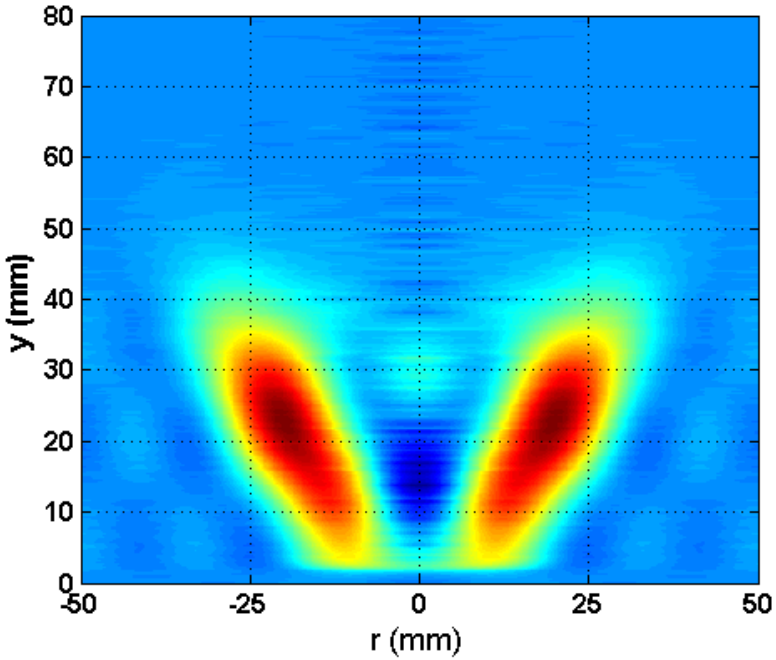
- The use of H_2 reduces the lean blowoff (LBO) equivalence ratio and requires stabilization at higher *Re*. Up to 40% vol CO_2 in the premixed reactants at φ > 0.70 is achieved (limited only by CO_2 delivery).

Results - CH_4-air vs. H_2-CO_2-air Flame Stability

- Abel-transformed OH* chemiluminescence at 25 kW, 1.1 bara, φ = 0.60 (Note, from 2000 images (t = 0.5 s), false colormap scaled to each image maximum)



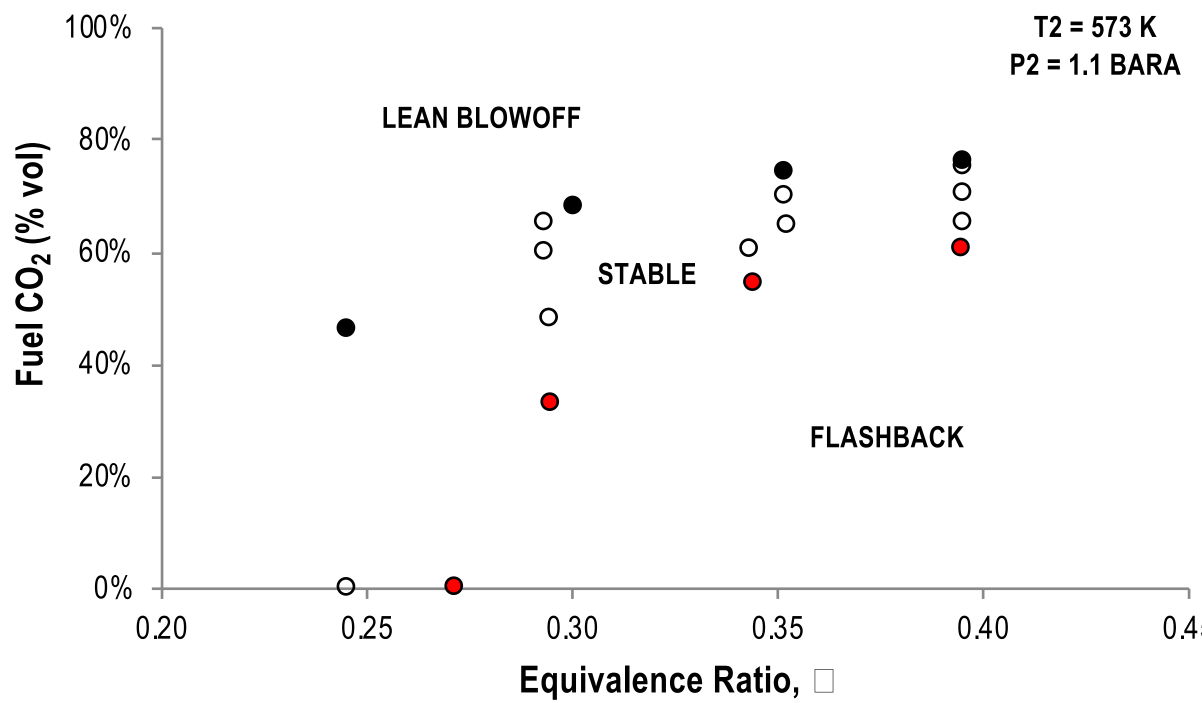
CH_4-air
u = ~16 m/s
Re = ~18000



25-75 H_2-CO_2-air
u = ~60 m/s
Re = ~30000

$$\frac{q'_{RMS}(H_2/CO_2)}{q'_{RMS}(CH_4)} = \sim 9\%$$

Results - H_2-CO_2 Flame Stability with Varying Fuel CO_2 %

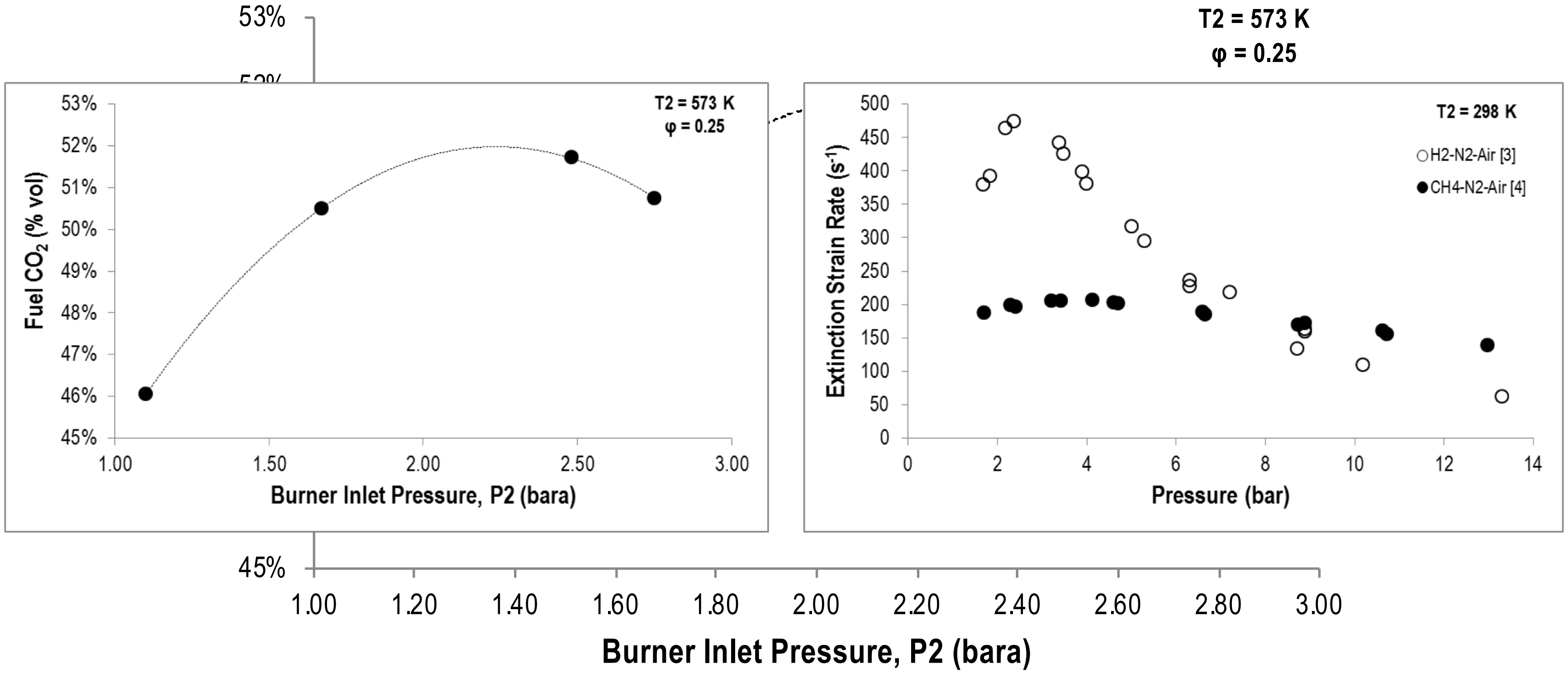


- For increasing φ, the achievable CO_2 dilution increases, but the stable operational range reduces.
- At $\varphi < 0.3$, pure H_2-air flames were stabilized, however burner exhaust temperatures were insufficient (< 1100 K), suggesting a future increase in 25 kW/bar scaling.

Experimental and Numerical Evaluation of Pressurized, Lean Hydrogen-Air Flame Stability with Carbon Dioxide Diluent

Results - Pressure Effects on H_2-CO_2 Lean Blowoff (LBO)

- Scale all flow rates with pressure (25 kW/bar) to maintain exit nozzle velocity and drive burner to LBO.



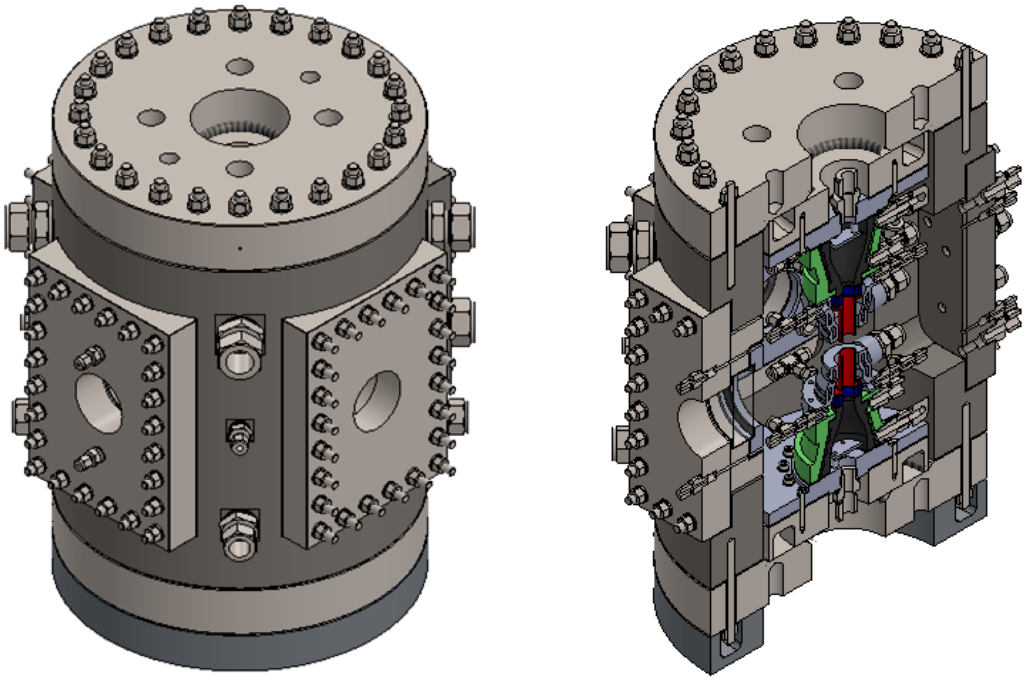
- With increasing pressure, the CO_2 dilution level at LBO is nonmonotonic.
- This suggests a relationship with the extinction strain rate due to high turbulence (similar relationship identified by Niemann et al.).

Conclusions

- From CHEMKIN modelling, nearly 70% vol CO_2 in the fuel is required for a reduction in S_L to equivalent CH_4-air values (at $\varphi = 0.6$), while only 30% vol CO_2 in the fuel is required for an equivalent reduction in AFT, impacted by the increased heat capacity of CO_2.
- Fully premixed, lean H_2-air flames were successfully stabilized in a swirl burner with sufficient levels of CO_2 dilution (up to 75% vol fuel / 40% vol premix) and turbulence ($Re_{H2} \approx 2*Re_{CH4}$).
- Fully premixed, **pure** H_2-air flames were successfully stabilized at low equivalence ratios ($\varphi < 0.3$) with sufficiently high burner exit nozzle velocity.
- Maximum levels of CO_2 dilution in H_2-air flames near LBO exhibit a non-monotonic influence of pressure, suggesting that thermodiffusive effects dominate under these highly stretched conditions, in agreement with the work of Niemann et al.

Future Work

- Mode decomposition for high-speed OH* chemiluminescence images
- Operation with higher CO_2 mass flow at higher φ to achieve representative GT combustor exit temperatures, evaluate NOx/CO emissions
- Operation at higher pressures to further evaluate LBO behavior
- Development of a pressurized counterflow burner system for fundamental study of H_2-CO_2-air extinction behavior.



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Thank you!

Any questions?

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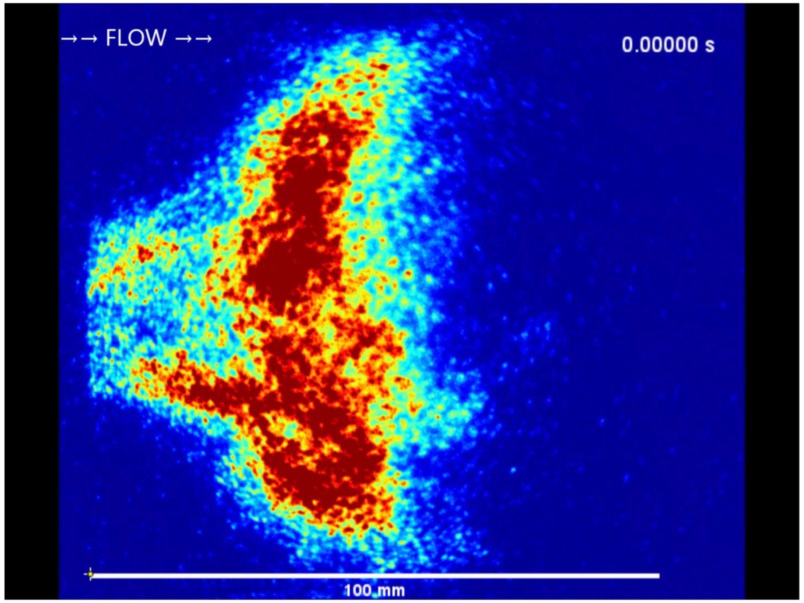
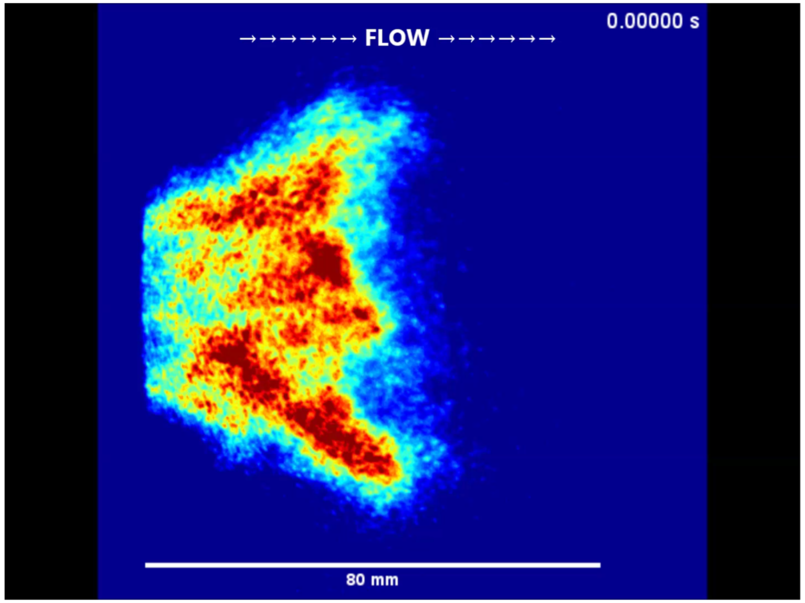
Results – LBO and Flashback Instabilities – CH_4-air (High-Speed OH* Chemiluminescence at 4000 Hz)



LBO Instability



FB Instability

- LBO instability characterized by bulk extinction and re-ignition events (7.8 Hz) at φ =0.51
- FB instability characterized by heat release fluctuations coupling with longitudinal combustor mode (~400 Hz) at φ =0.83