Fuel flexibility under MILD combustion conditions

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THE UNIVERSITY of ADELAIDE

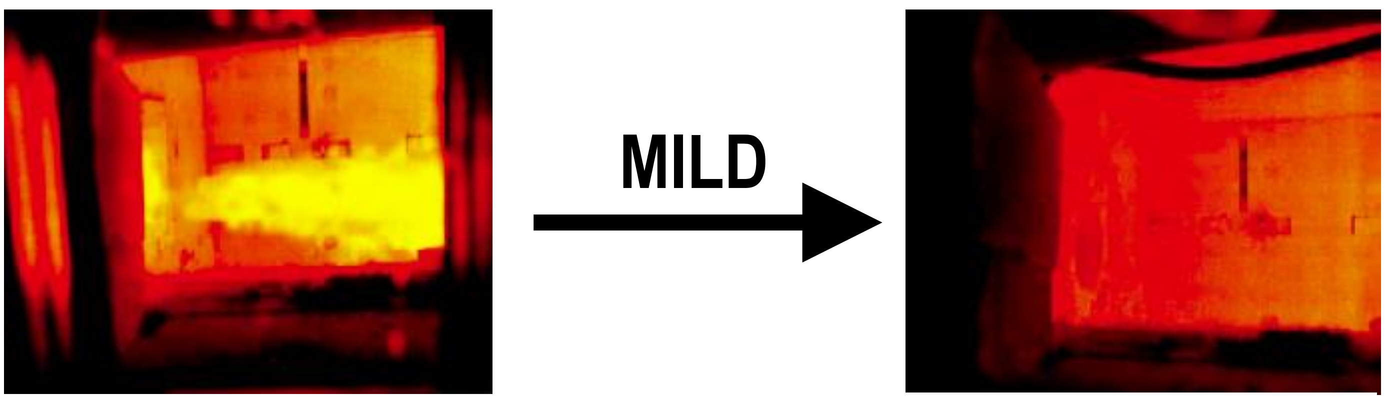
Overview

- MILD combustion
- JHC burner
- Flame stabilisation
- Fuel flexibility
- Pressurised combustion
- Conclusions

2–6 December 2019
Australian Conference on Laser Diagnostics
Australian Combustion Symposium

What is MILD combustion?

- Moderate or Intense Low oxygen Dilution (MILD)
  - Fuel and oxidant burnt under strong recirculation of exhaust gases
- Local conditions around the reaction zone:
  - Very low oxygen concentration (<6% O_2 c.f. 21%)
    - Reduce peak temperature → Low NOx
  - High initial reactant temperature (>T_{si} to allow reaction)
    - Improved stability

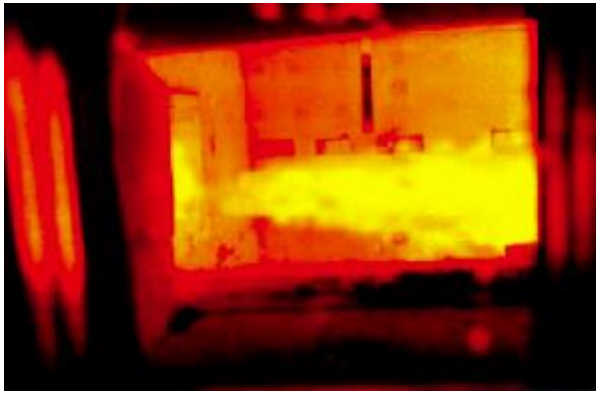


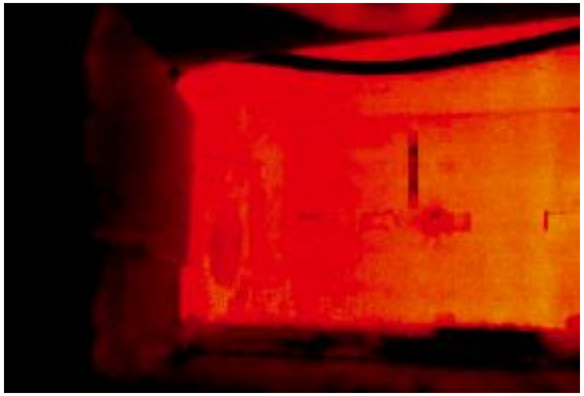
~21% O_2 ~3% O_2

Characteristics of MILD combustion

- **30% increase in thermal efficiency**
- **90% reduction in NOx emissions**
- **Almost complete elimination of soot**

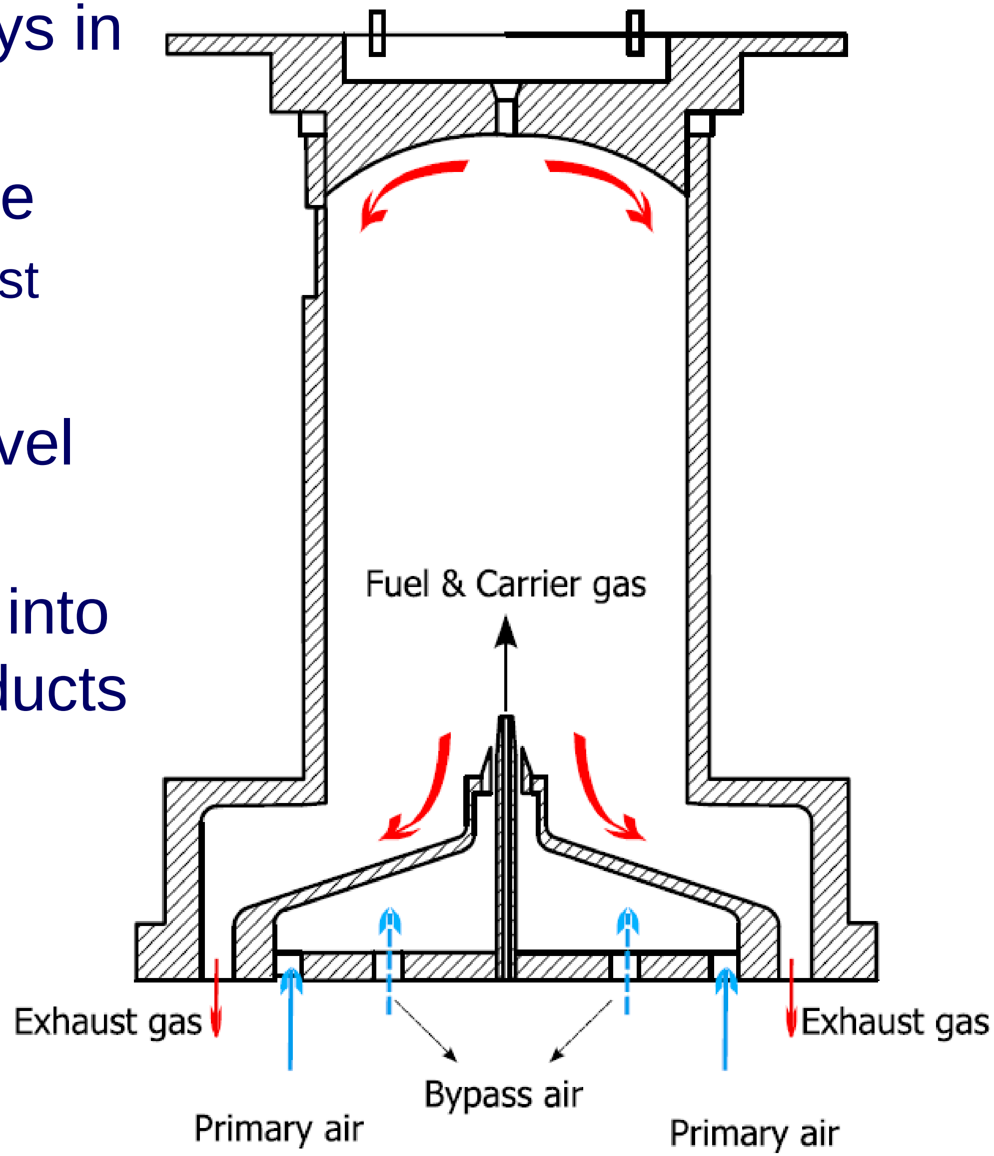
- (Can) result in no visible flame
  - Also known as flameless oxidation (FLOX®), high-temperature air combustion, colourless combustion, …
- Distributed reaction zone
  - Uniform thermal field
  - Reduced peak flame temperatures (thus reduced NOx)





Achieving MILD combustion

- Achieved many different ways in industrial furnaces
- e.g. self-recuperative furnace
  - Heat and products from exhaust
  - Coupled system
- Not ideal for fundamental-level parametric investigations
- Basic process is fuel issues into hot and vitiated oxygen products



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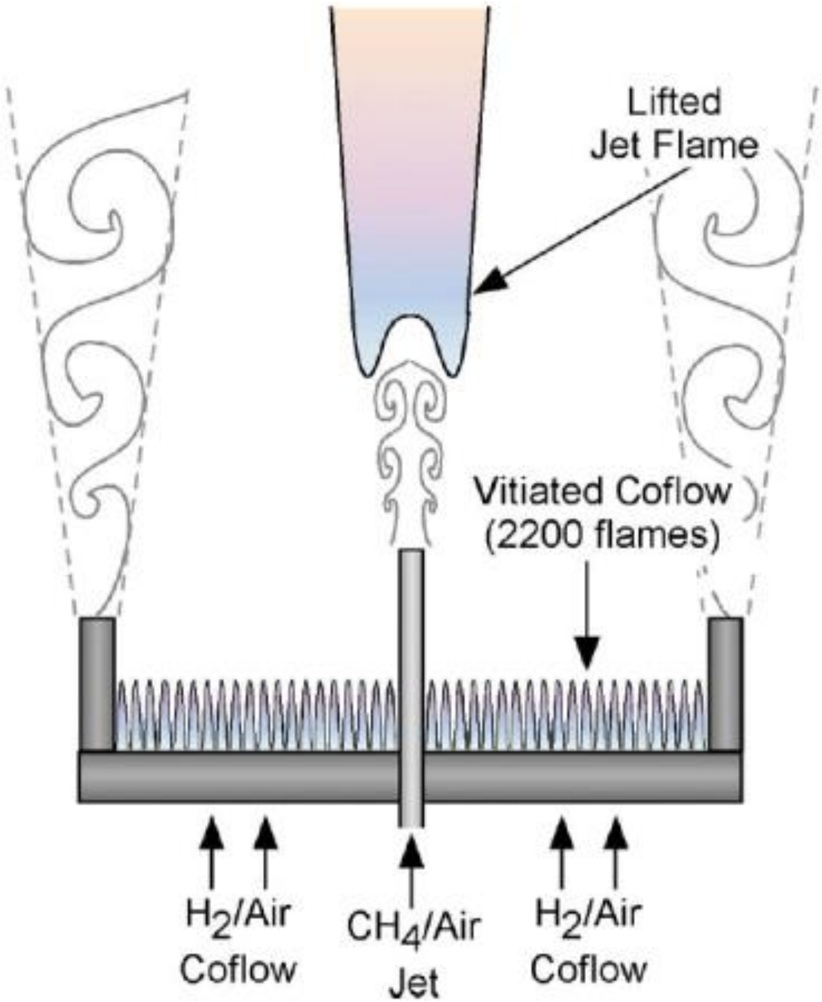
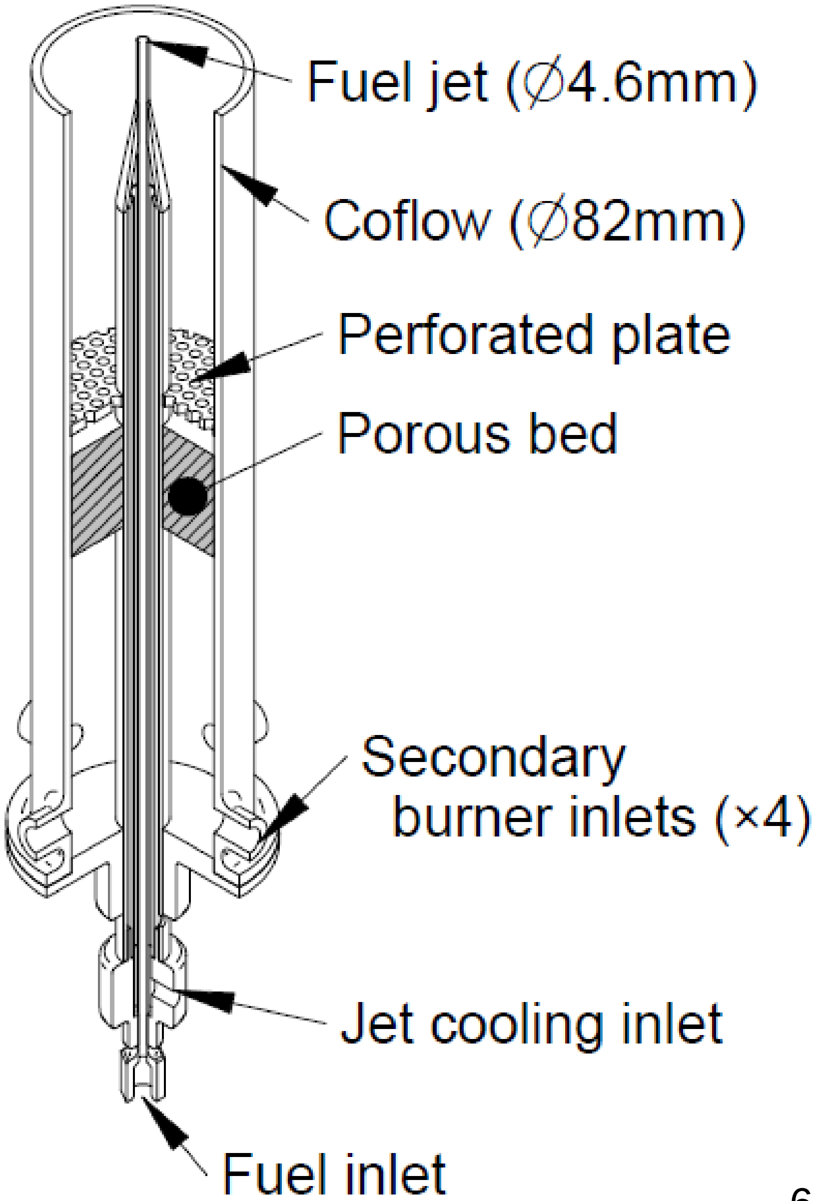
  - "Cabra" burner
  - Auto-ignitive flames
  - Coincidentally, developed at the same time as the JHC burner



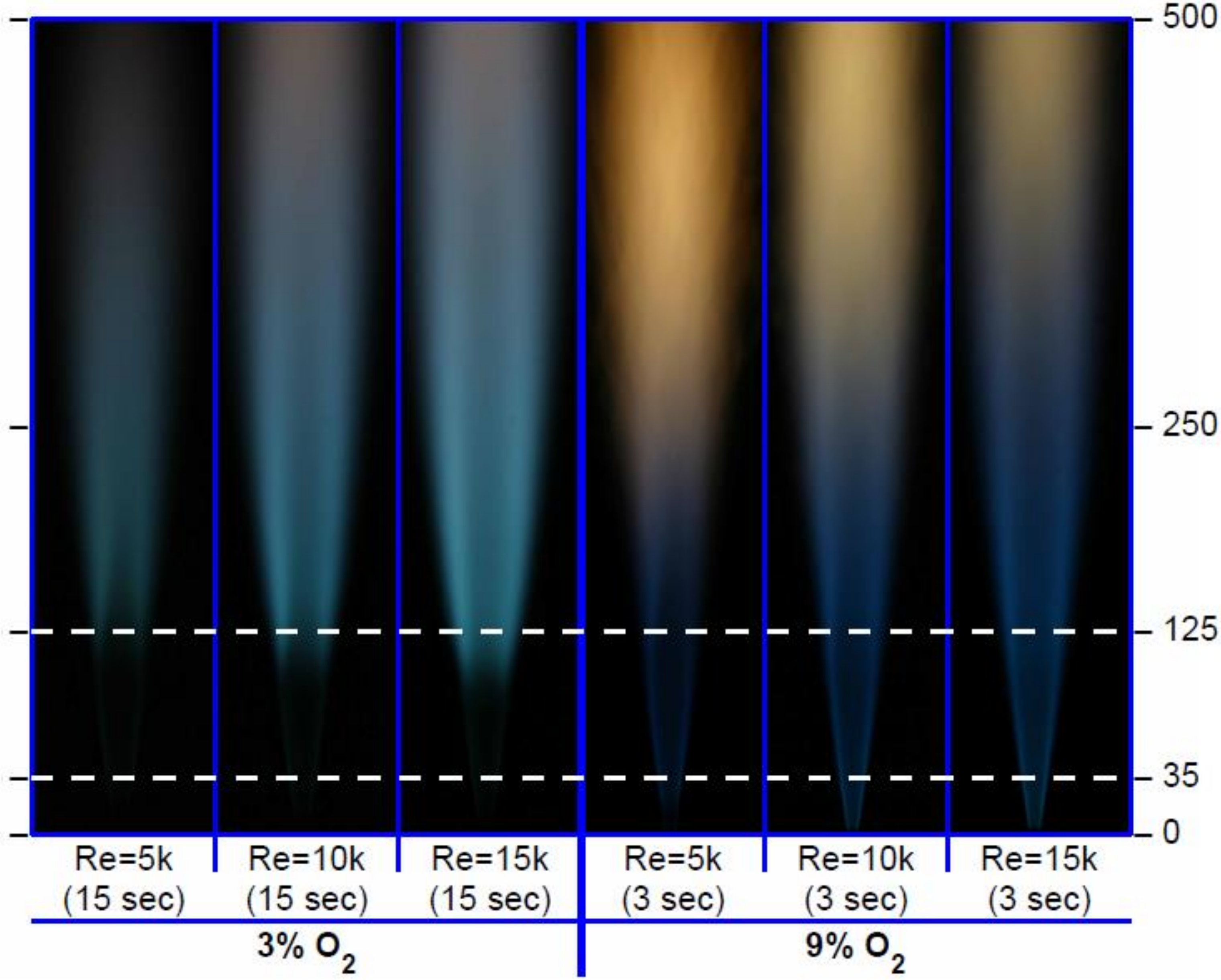
Cabra et al. (2002) Proc Combust Inst

Jet in hot coflow (JHC) burner

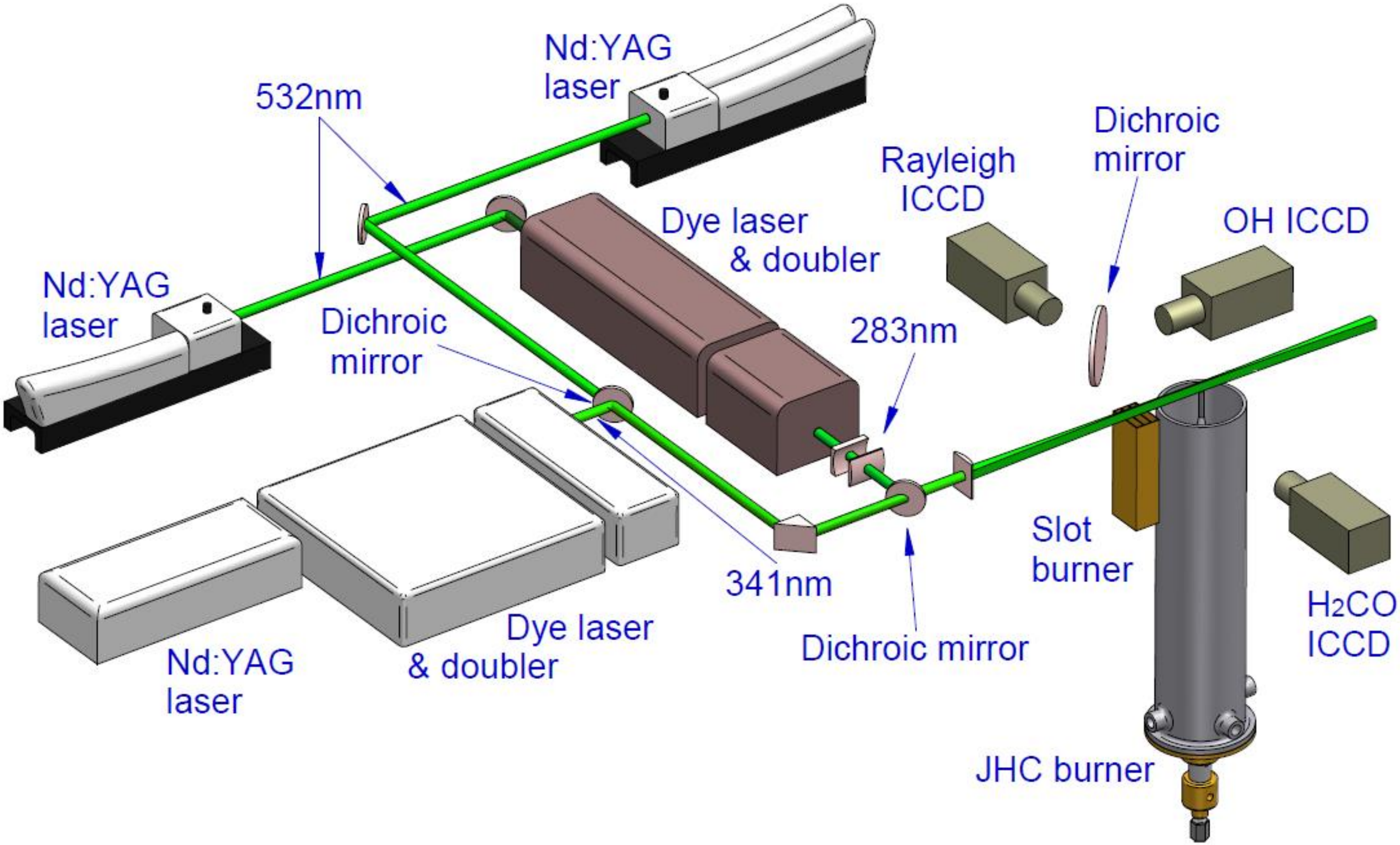
- Jet issues into coflow of hot products from secondary burner
- Jet and coflow independent
- Coflow temperature and oxygen controlled independently
- First reported by Dally in 2002
  - Proc. Combust. Inst. 29.
  - Medwell (Adelaide)
  - Roekaerts (Delft)
  - Blunck (Oregon)
  - …
- Variants
  - Jet and coflow diameter
  - Secondary burner design
- Research burner



Flames in JHC burner

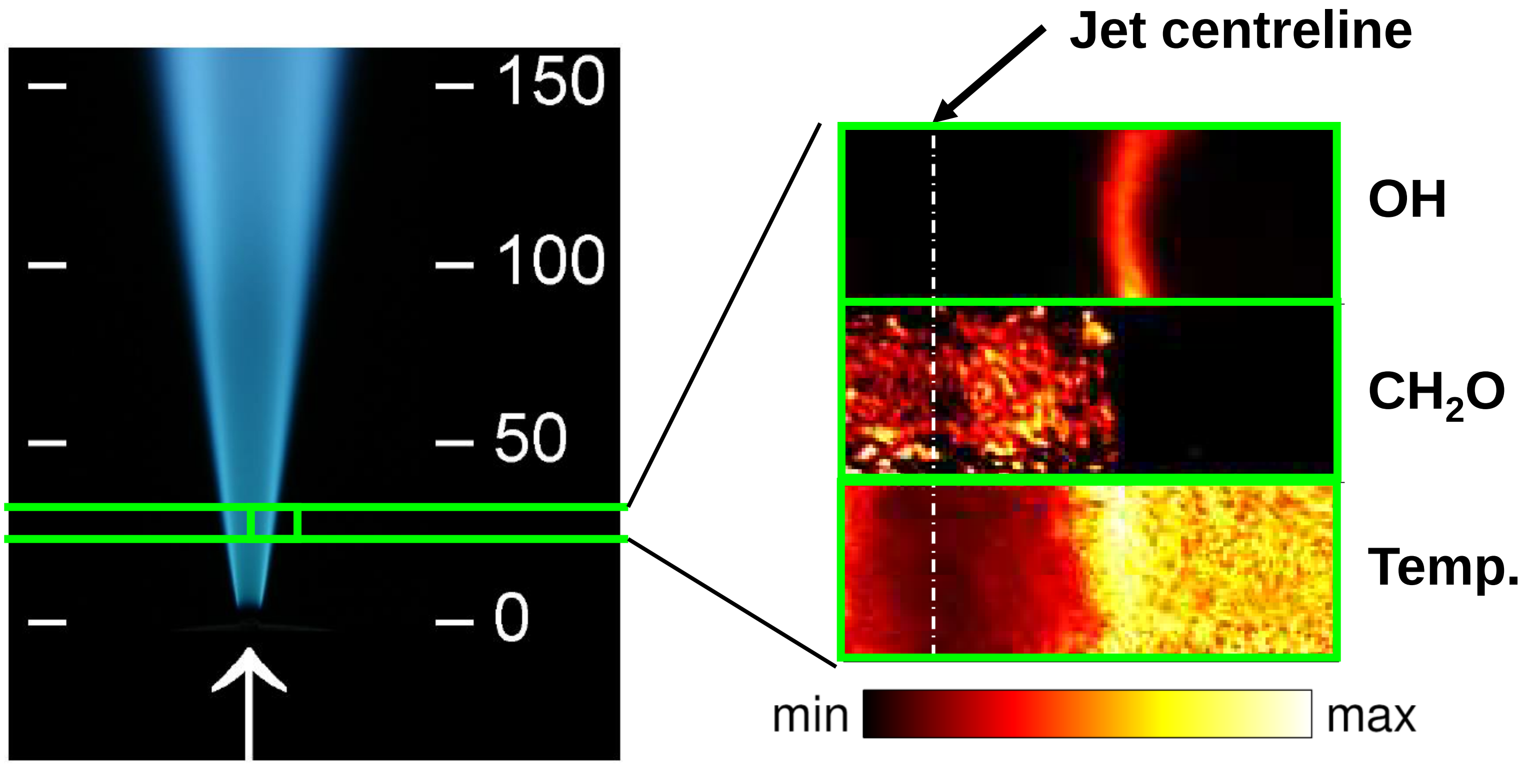


Example laser diagnostic setup in JHC burner



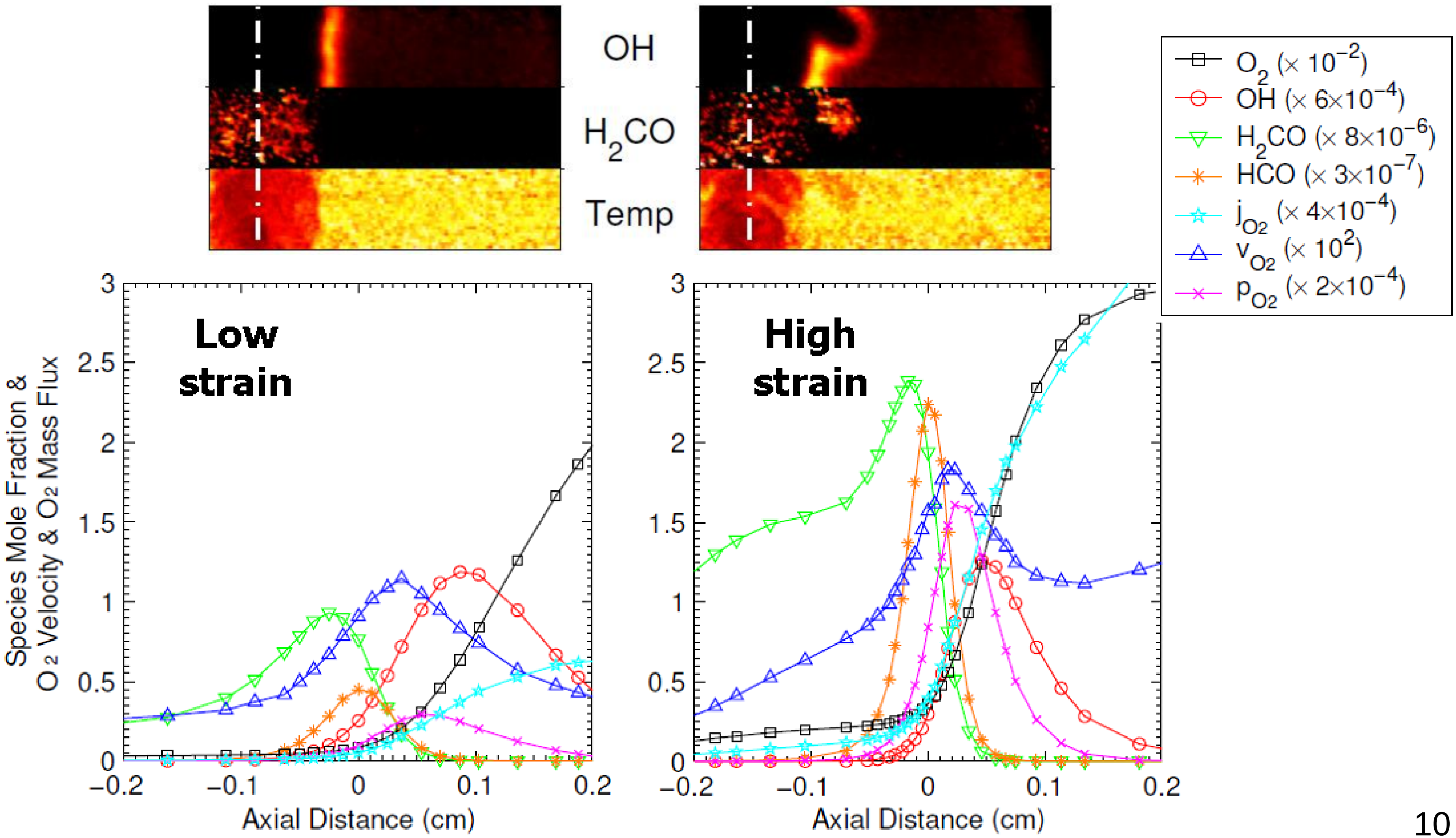
Laser-based imaging in JHC burner

- Example images



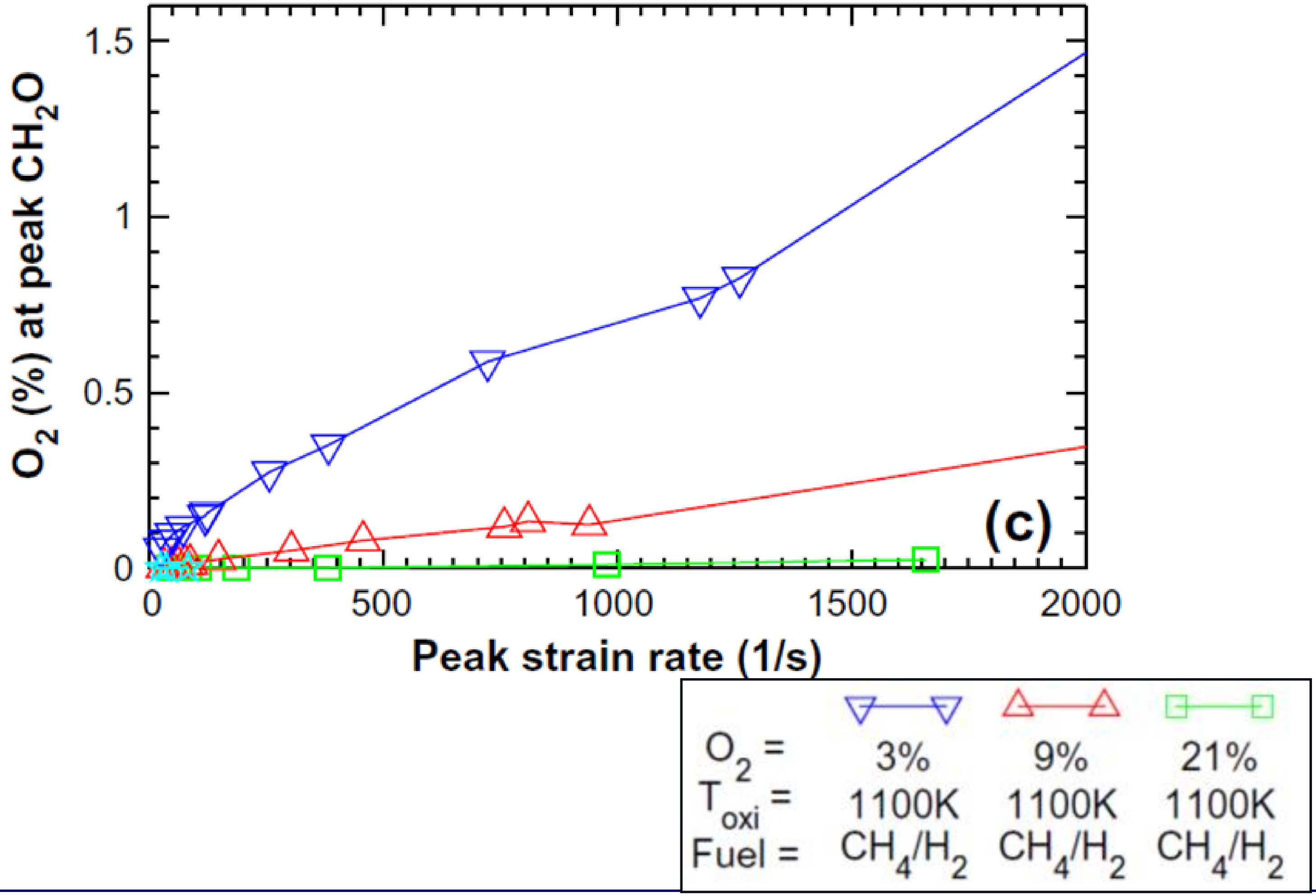
Reaction zone weakening and O_2 penetration

- Localised reaction zone weakening can occur
  - Transport of oxygen across the reaction zone leads to more CH_2O



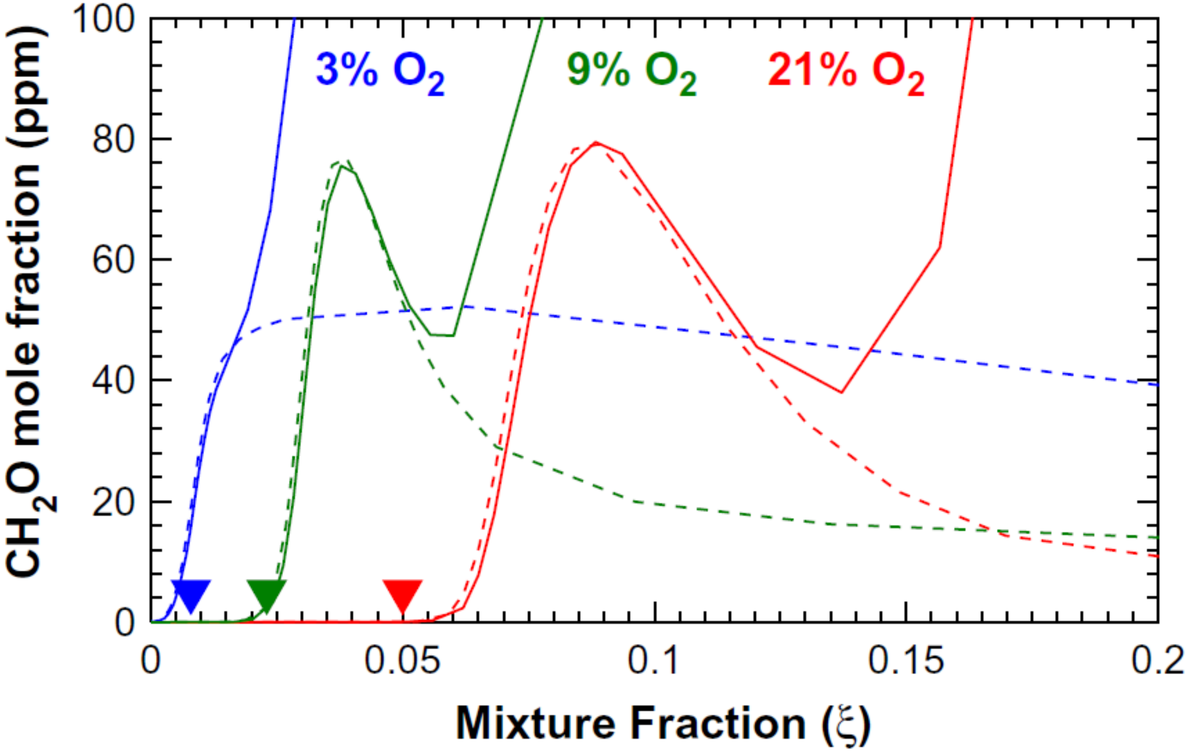
Oxygen (O_2) penetration and formaldehyde (CH_2O)

- Despite low oxygen levels, concentration of O_2 on fuel-rich side up to 50% of the level in the oxidant
  - These flames become very stable and difficult to blow-off



Effects of formaldehyde

- Formaldehyde stabilises the flame
  - Laminar flame calculations show CH_2O increases with strain rate
  - Artificially adding CH_2O to the fuel stream reduces the lift-off height of flames
    - Most effective at low O_2 levels

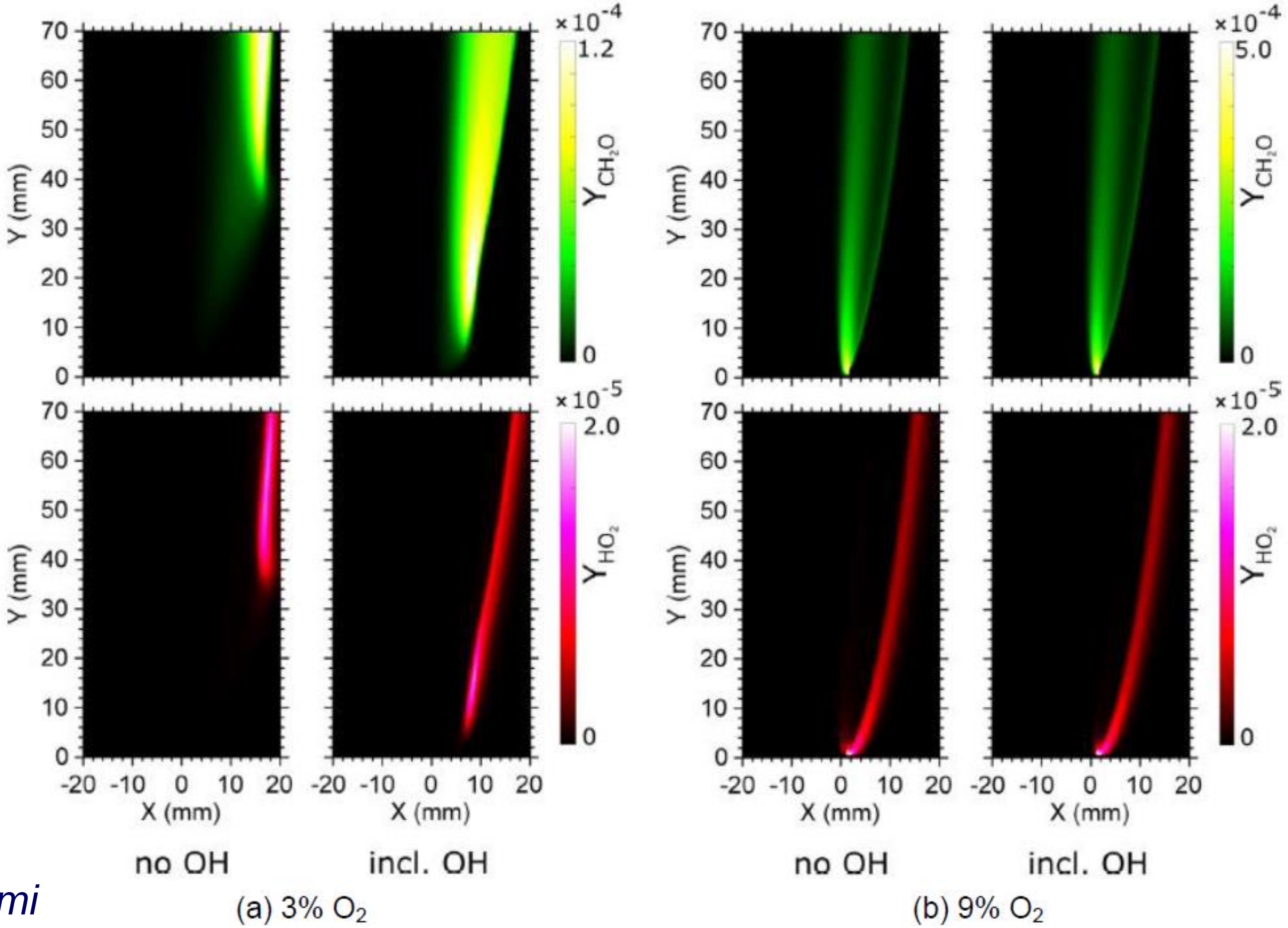


No CH_2O | With CH_2O

Collaboration with David Blunck

Role of intermediates: laminar nonpremixed flame

- Impact of equilibrium OH in the hot oxidiser
  - Little effect on autoignitive triple-flames, critical for MILD combustion



With Polimi

Role of intermediates: ignition delay time

- Compare calculated ignition delays (max dT/dt) for some of the experimental cases
  - Different assumed oxidant stream composition
  - Significant role of minor species

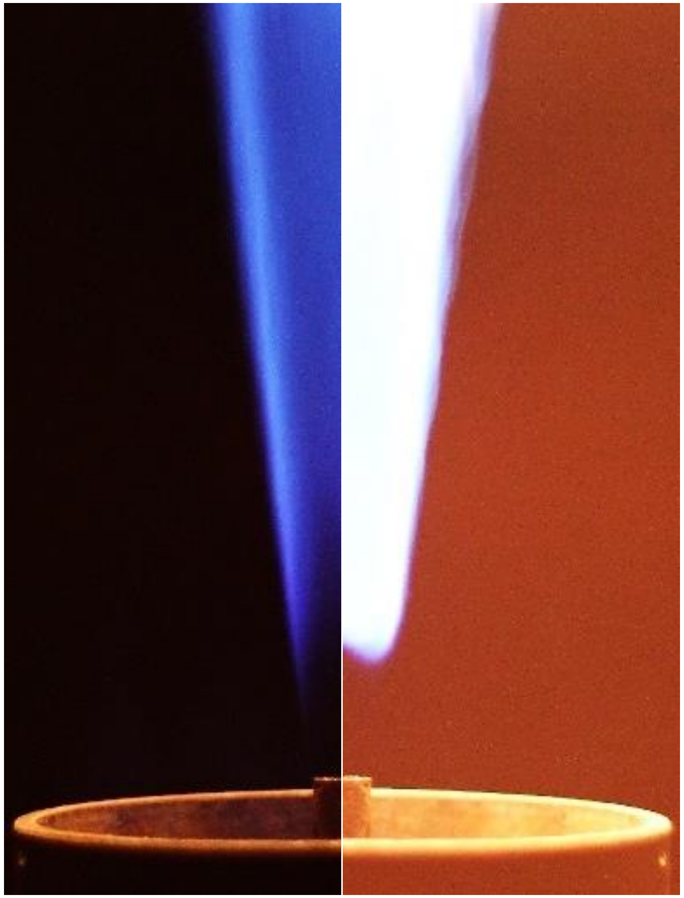
Flame	O_2 / N_2	O_2 / N_2 / CO_2 / H_2O	Full equil (inc. OH)
Cabra (2002) H_2/N_2	0.28ms	0.34ms	0.2ms
Cabra (2005) CH_4/air	6.8ms	7.5ms	6.2ms
Oldenhof (2011) DNG-I	0.69ms	0.73ms	0.67ms
Oldenhof (2011) DNG-V	1.27ms	1.38ms	1.29ms
Medwell (2008) 3% C_2H_4	6.2ms	4.8ms	0.69ms
Medwell (2008) 9% C_2H_4	5.0ms	5.3ms	0.84ms

Collaboration with Vish Katta

Flame stabilisation

- Lots of work on flame liftoff and structure of flame base
  - Many unusual trends observed ➔ explanations from chemistry
  - One example…

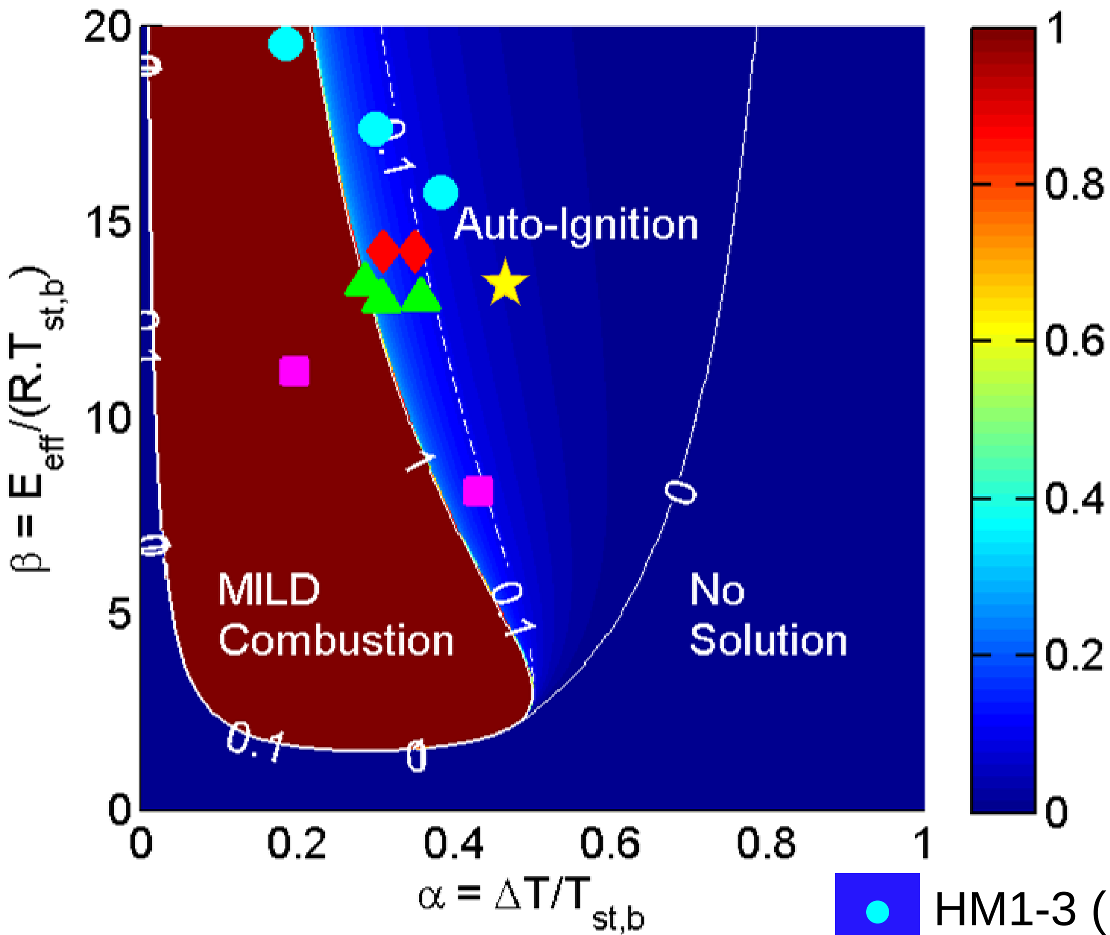
3% O_2 9% O_2



- Liftoff height vs O_2 level
- Shape of flame base
- MILD vs non-MILD
  … definitions

Ethanol/Ethylene
Re_{jet}=10k, 1400K coflow

Terminology and regimes – separate topic



θ_{ai} - normalised autoignition temperature

α - heat release parameter

β - normalised 1-step activation energy

- HM1-3 (Dally *et al.* 2002)
- C_2H_4 flames (Medwell *et al.* 2008)
- DJHC-I,-V (Oldenhof *et al.* 2010)
- F1, 4, 7 (Arndt *et al.* 2013)
- CH_4/air (Cabra *et al.* 2005)

Collaboration with Matthias Ihme

Operating conditions affect regime

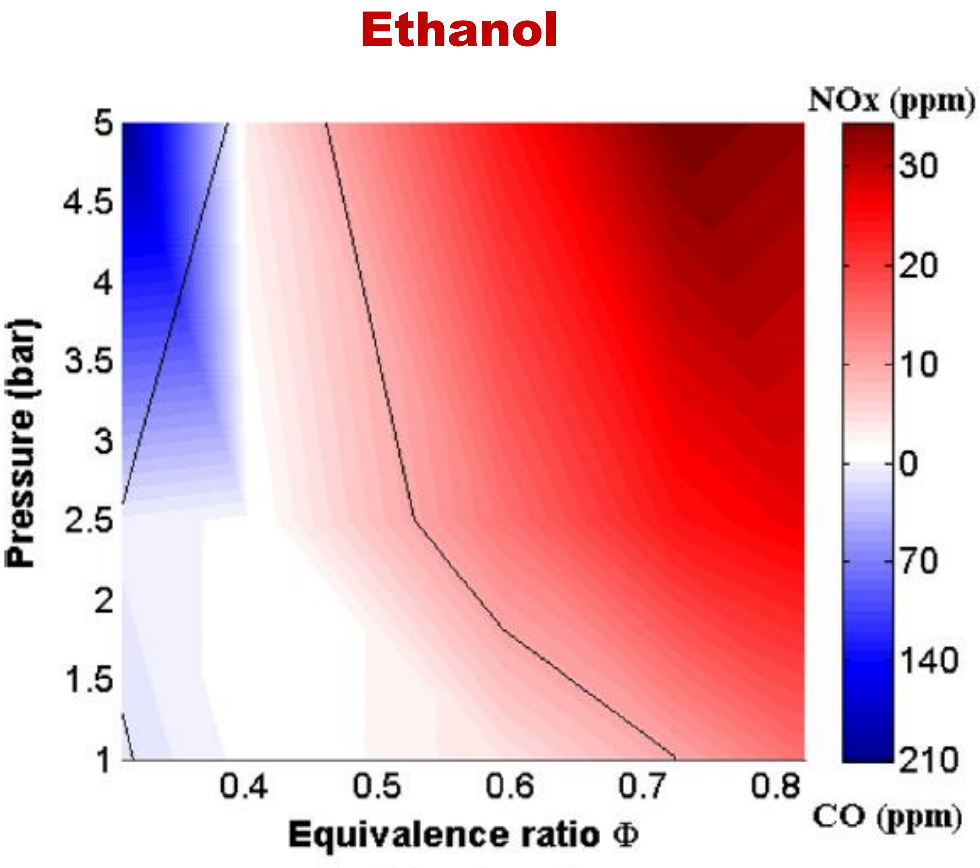
- Investigated various fuels/mixture in JHC burner (>200 cases)
- Recent and unpublished parametric study:
  - Coflow temperature: 1100, 1250, 1300, 1400, 1500, 1600 K
  - Coflow oxygen level: 3, 4, 5, 6, 9, 11%
  - Coflow velocity: Two cases
  - Coflow C/H ratio: Two cases
  - Jet Reynolds number: 1k, 5k, 10k, 20k, 30k
  - Fuel: CH_4, C_2H_4, Ethanol, Acetone, n-heptane, DME
  - Admixture: Air, Nitrogen, $H_{2,}$ C_2H_4
  - Admixture ratio (Φ): 5.3, 6.9, 9.8, 15.5

- Was motivated by results in a high-pressure MILD chamber
  - Intention of collaboration with Heinz Pitsch was to move beyond JHC
  - Fundamental-level parametric study to complement pressurised results

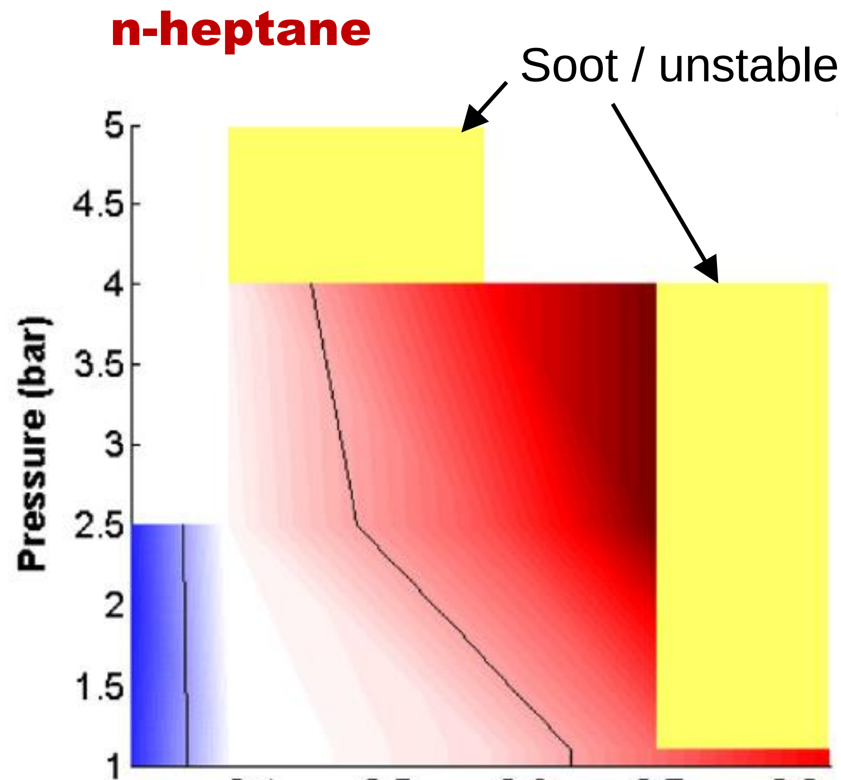
    ➔ went back to JHC to better understand these trends…

MILD combustion at pressure

- Operational range becomes narrower at higher pressure



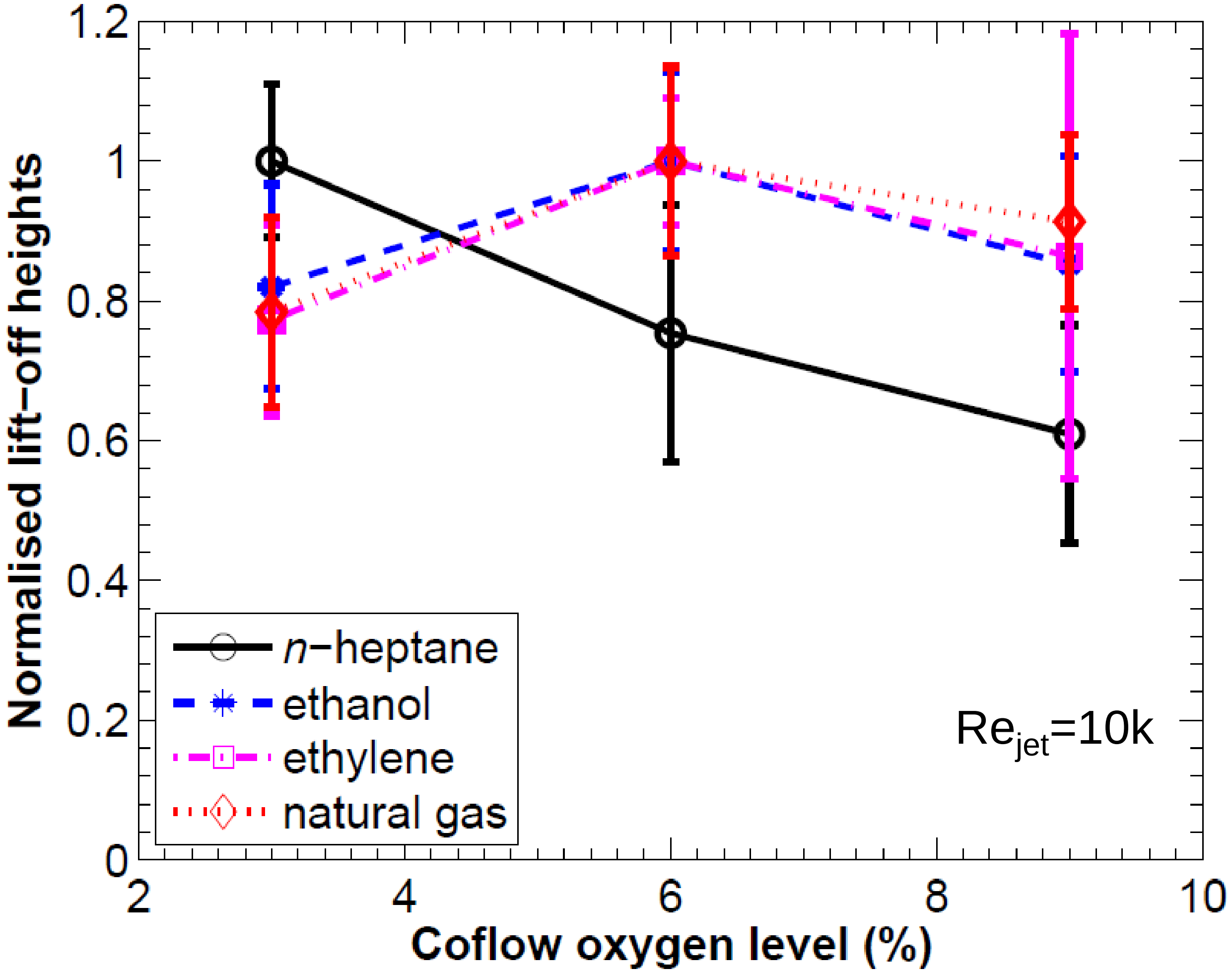
(a) ethanol



(c) n-heptane

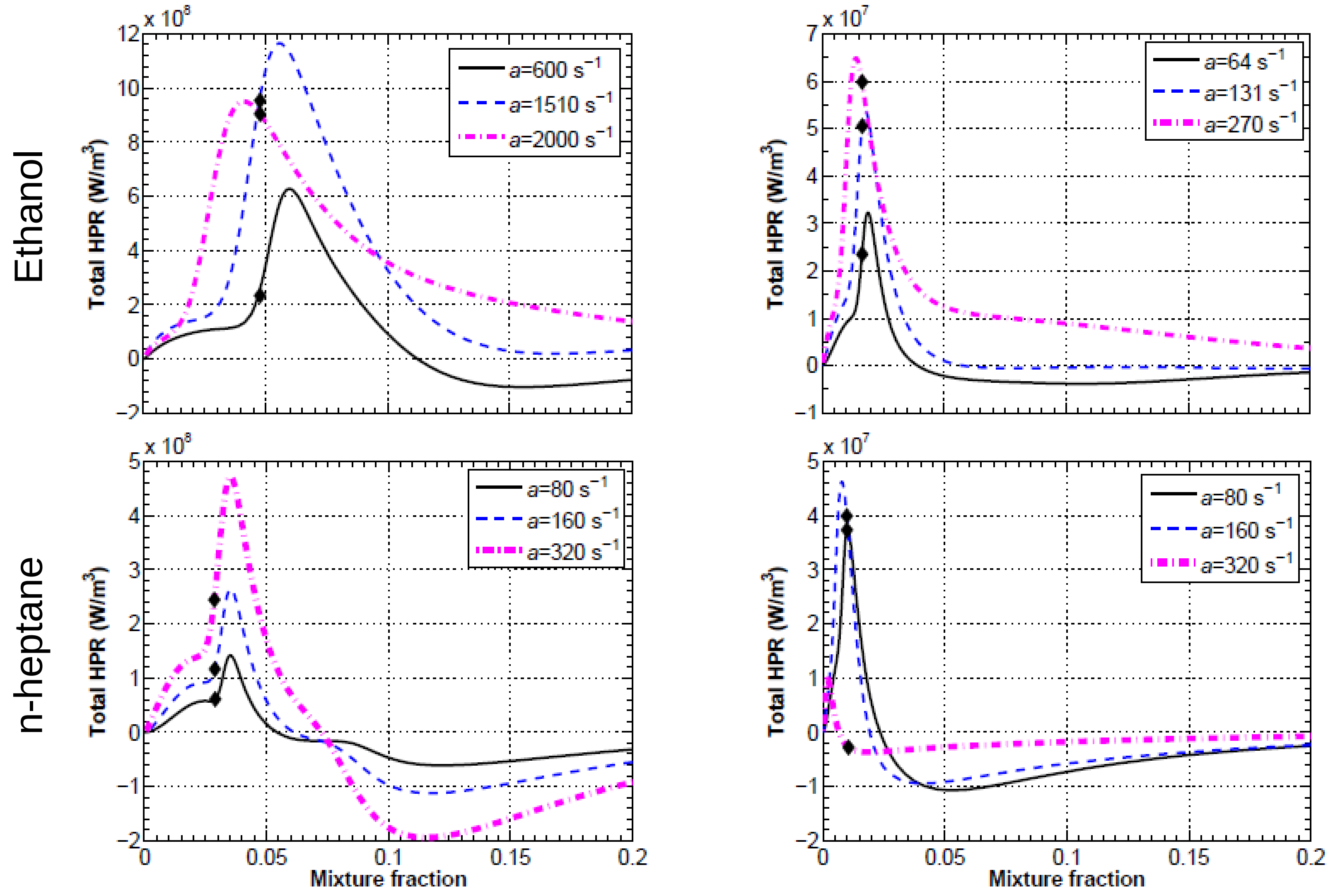
Alternative fuels – JHC burner

- Heptane behaves differently to previously-tested fuels
  - Collaboration with Heinz Pitsch



Fuel behaviour – JHC burner

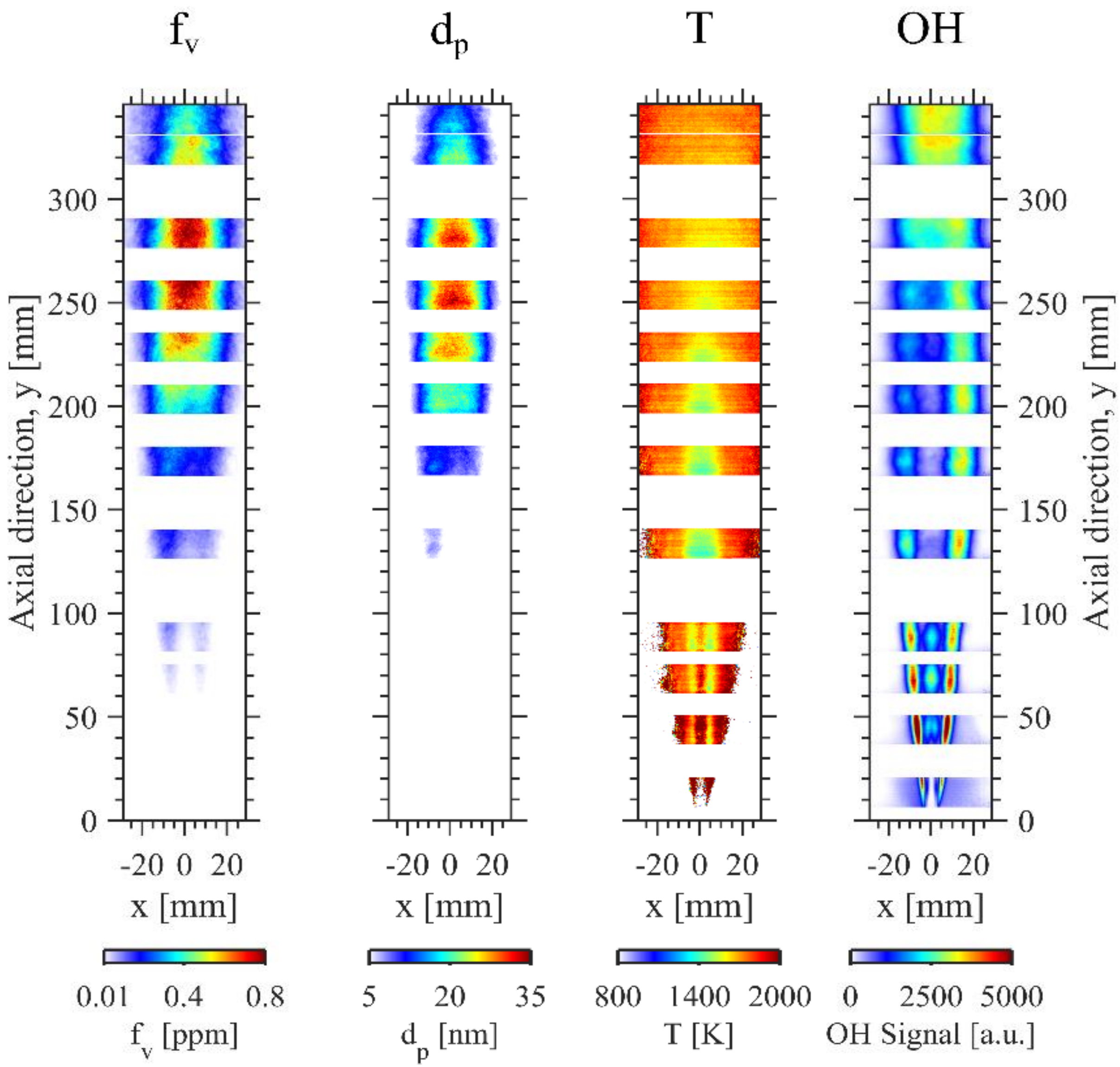
- One criteria for MILD is a lack of negative heat release

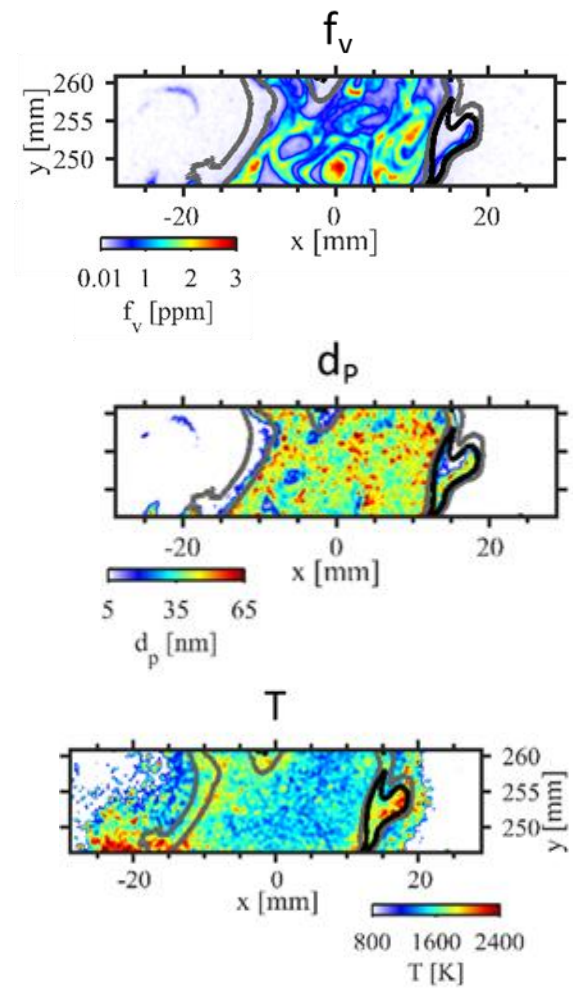


(a) 9% O_2 (b) 3% O_2

Sooting behaviour – JHC burner

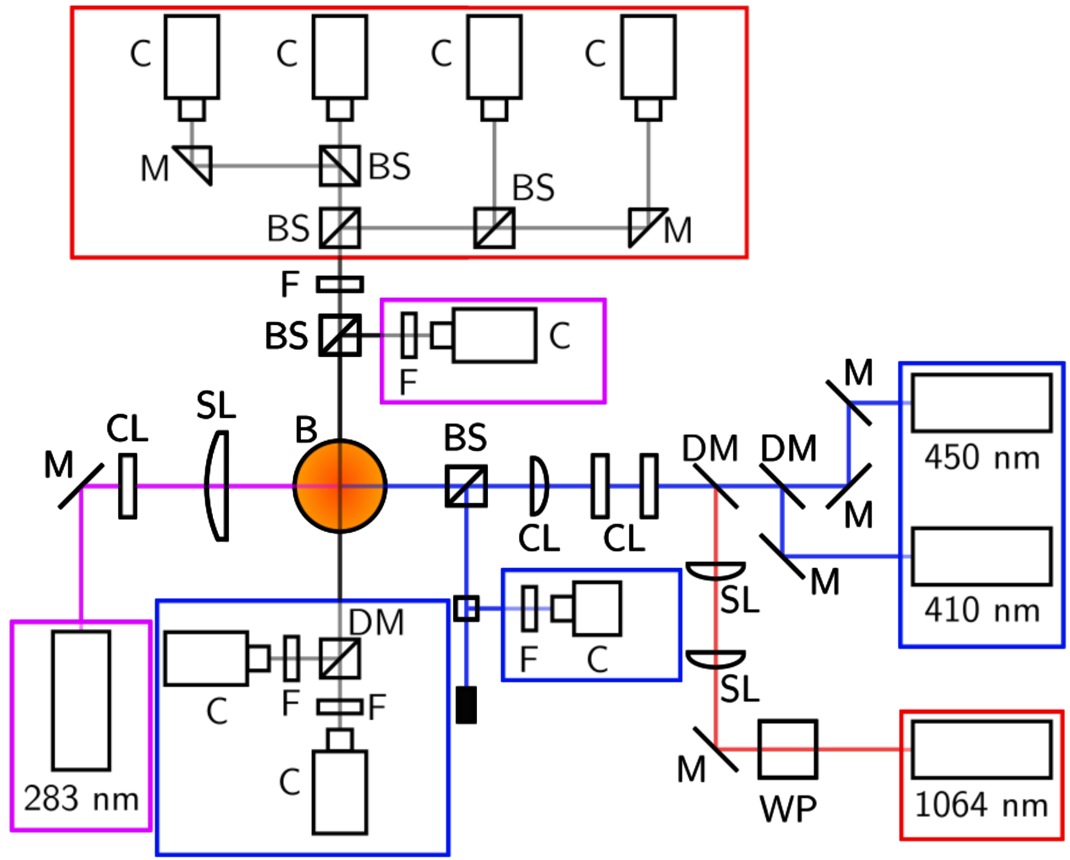
- Toluene flame





NTLAF and LII — temperature and soot

- Reaction zone ➔ OH-PLIF (283nm)
- Temperature ➔ NTLAF (410 & 450nm)
- Soot volume fraction ➔ LII (1064nm)
- Primary particle size ➔ TiRe-LII (1064nm)
- Velocity field ➔ PIV
  - Usually simultaneous with OH-LIF only (other combinations possible)



Future fuels

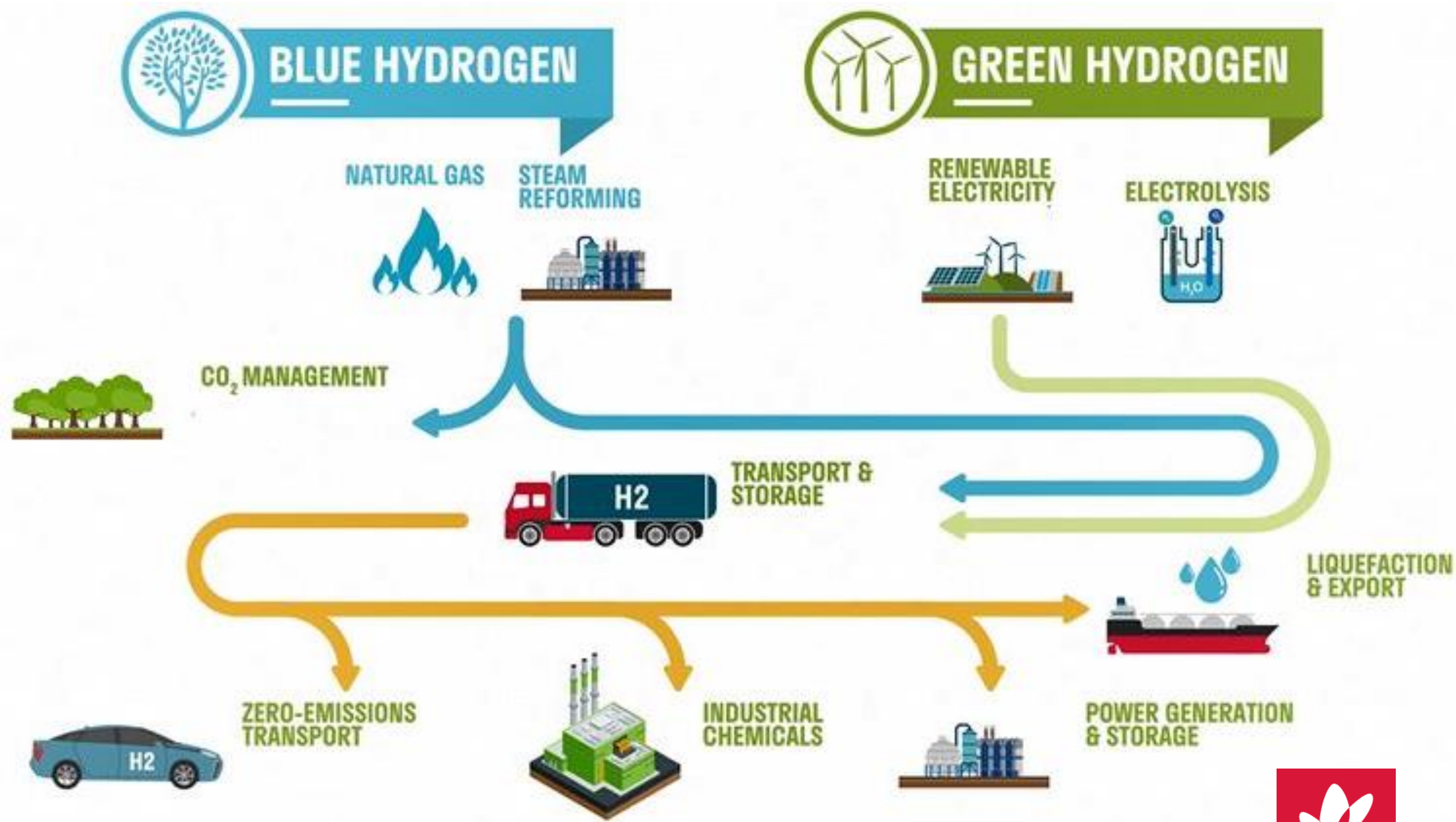
- Future fuels
  - Hydrogen and ammonia
  - Biofuels (ethanol, biodiesel, etc.)
  - Syngas (can be solar-aided)

Production is a separate body of work

- Fuel switching and fuel flexibility
  - Burner designs based on good science ➔ laser diagnostics
  - Flame stability and NOx reduction ➔ MILD combustion
- Essential to:
  - Meet carbon emission targets
  - Maintain competitive advantage
  - Cost effective
  - Develop new combustion concepts that maintain/improve efficiency
    - Rotational detonation engines
    - Inter-turbine burners
  - Fuel flexibility

Hydrogen – Australia

- Australia has plenty of capacity to produce hydrogen…



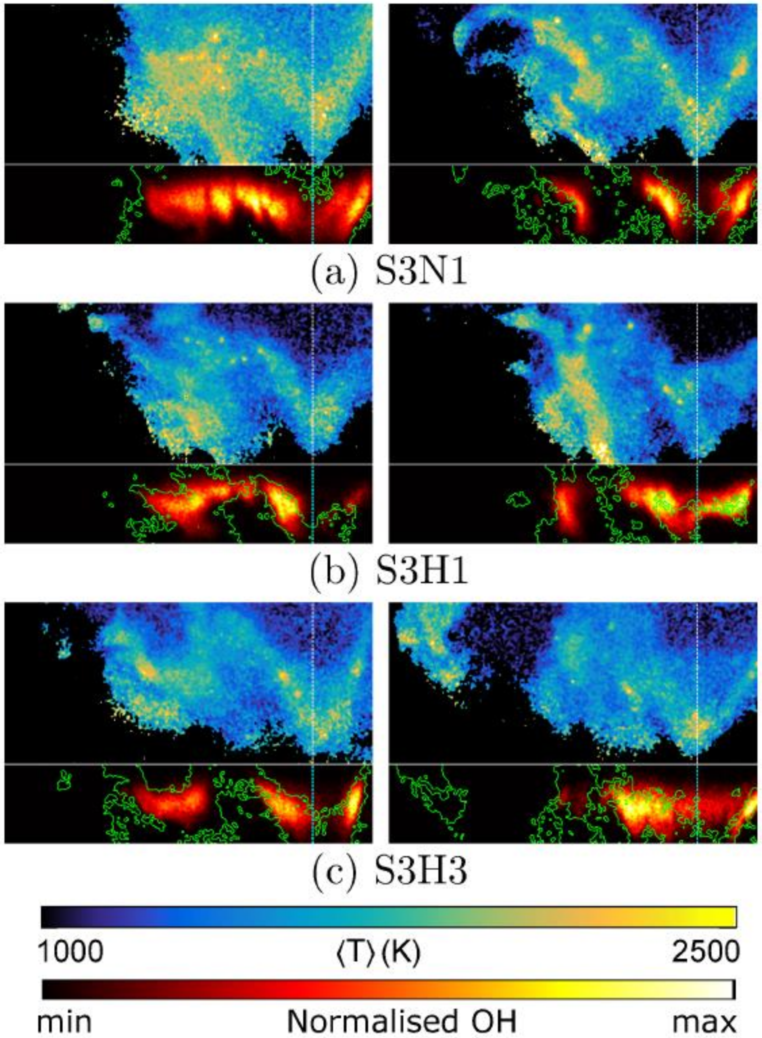
Woodside

Fuel blending – Australia

- Government developing a Hydrogen Strategy and Roadmap
  - Plus, Future Fuels Cooperative Research Centre (Australia-wide group)
- Trialling adding H_2 to the natural gas distribution network
  - Hydrogen Park of South Australia (in Adelaide's southern suburbs)
    - Australian Gas Infrastructure Group (AGIG) and State Government
  - Plan to blend up around 10% H_2 into the network
    - Primarily domestic use in neighbouring area
    - Wider-scale roll out and industrial applications on horizon
  - Similar schemes
    - Project H2GO (Jemena, NSW)
    - Clean Energy Innovation Hub (ATCO, WA)
    - H21 (Leeds, UK) → 100% H_2
- Technical and regulatory barriers
  - Effects on composition, network materials, appliances, consumer acceptance, and risk and safety ➔ especially for blends…

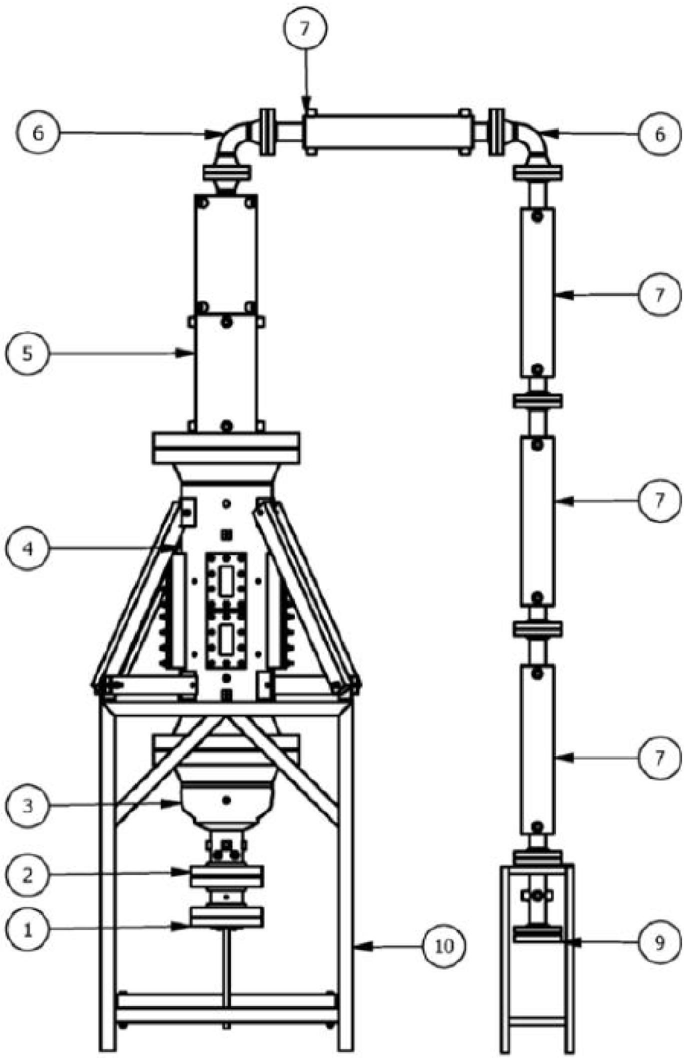
Hydrogen and dual-fuelling fuels

- OEM gas turbines already offer dual-fuel options
  - Just one example, Siemens SGT-800: 60% H_2 (vol.)
- Always new things to try…
  - Heptane spray + NG or H_2
    - Collaboration with Nondas Mastorakos
  - Complements other fuel blends in JHC
  - Effects of pressure…

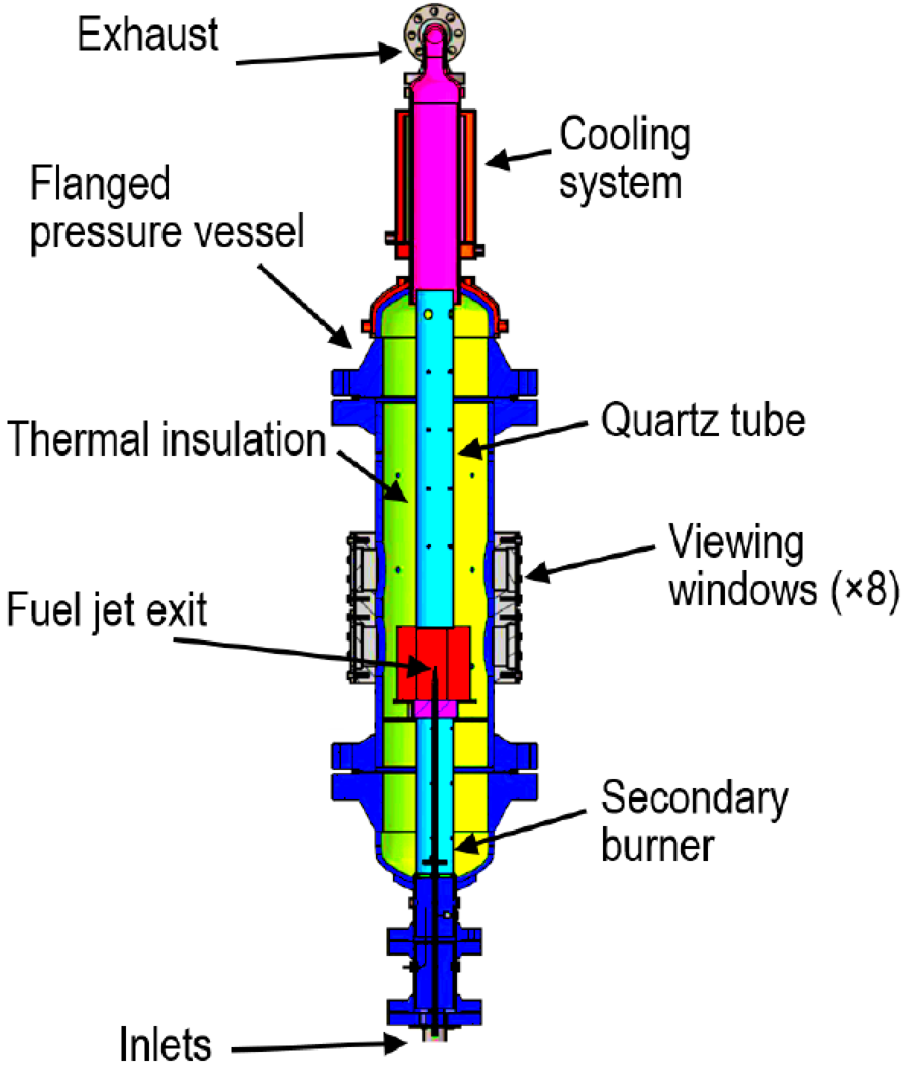


Confined and pressurised JHC (CP-JHC)

- JHC configuration in a thermally-insulated pressure vessel



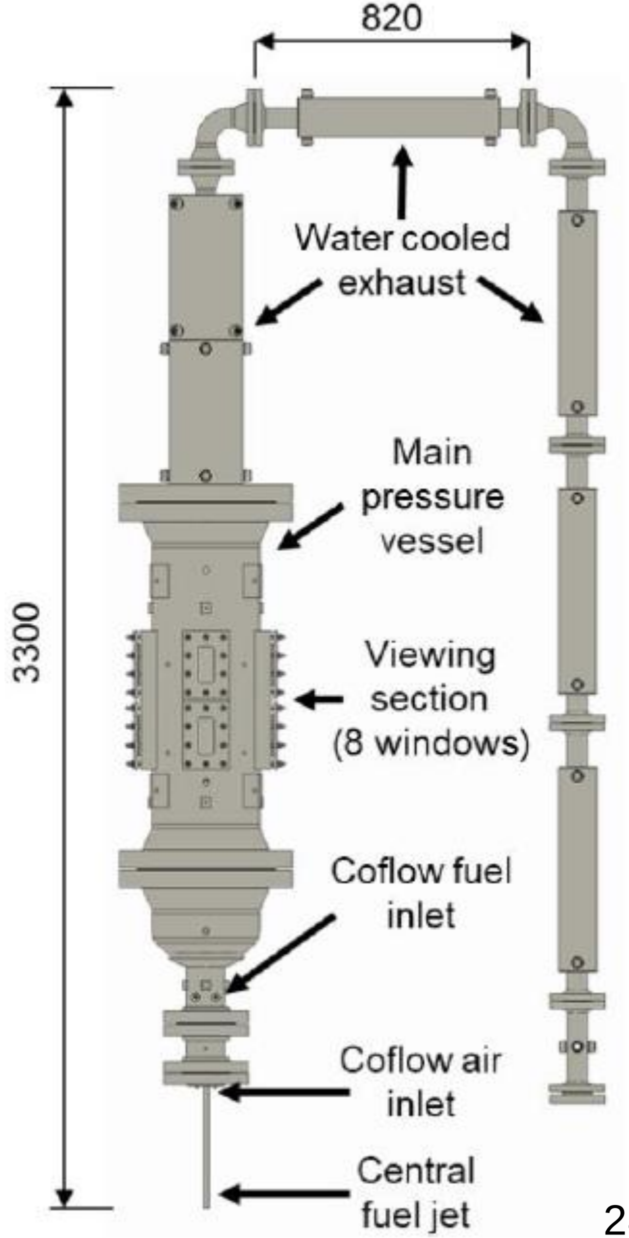
(a) Assembled view



(b) Sectioned view

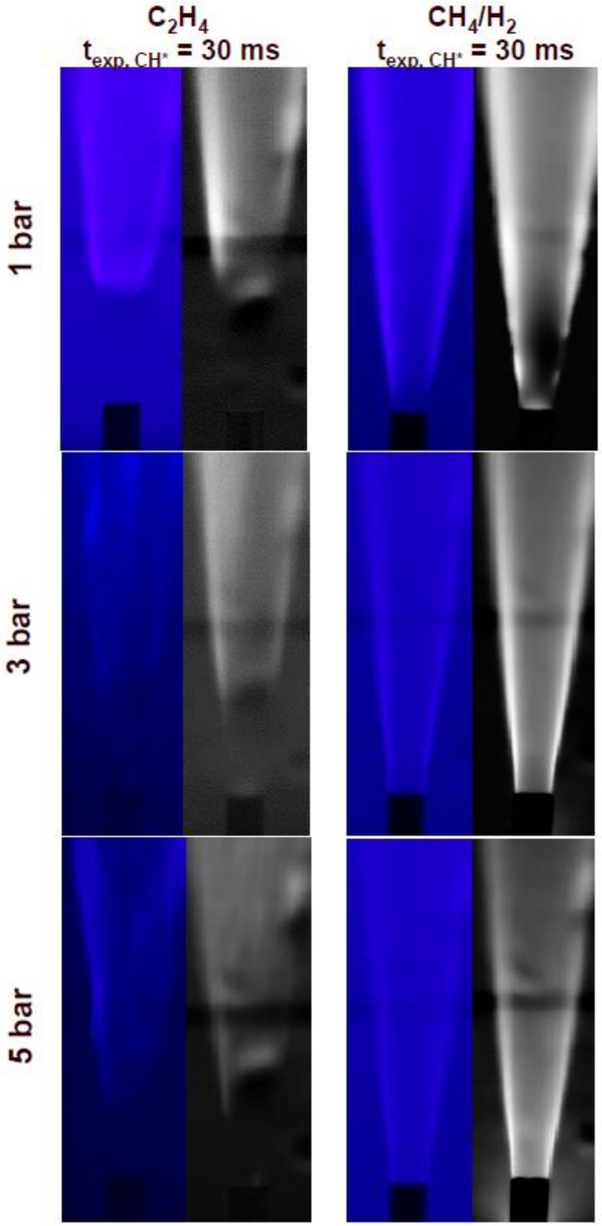
Confined and pressurised JHC (CP-JHC)

- Steady-state pressure to 10 bar
  - Commissioned to 5 bar so far
- Internal temperatures to 1975 K
  - Water cooled central jet and exhaust
  - Thermally insulated
- Optical access through 8 windows
  - 48 mm × 107 mm each
  - Quartz and sapphire for UV transparency
- Remotely operated
  - Multiple-redundant safety systems
- Modular design: currently jet in coflow
  - Jet in cross flow
  - Sprays



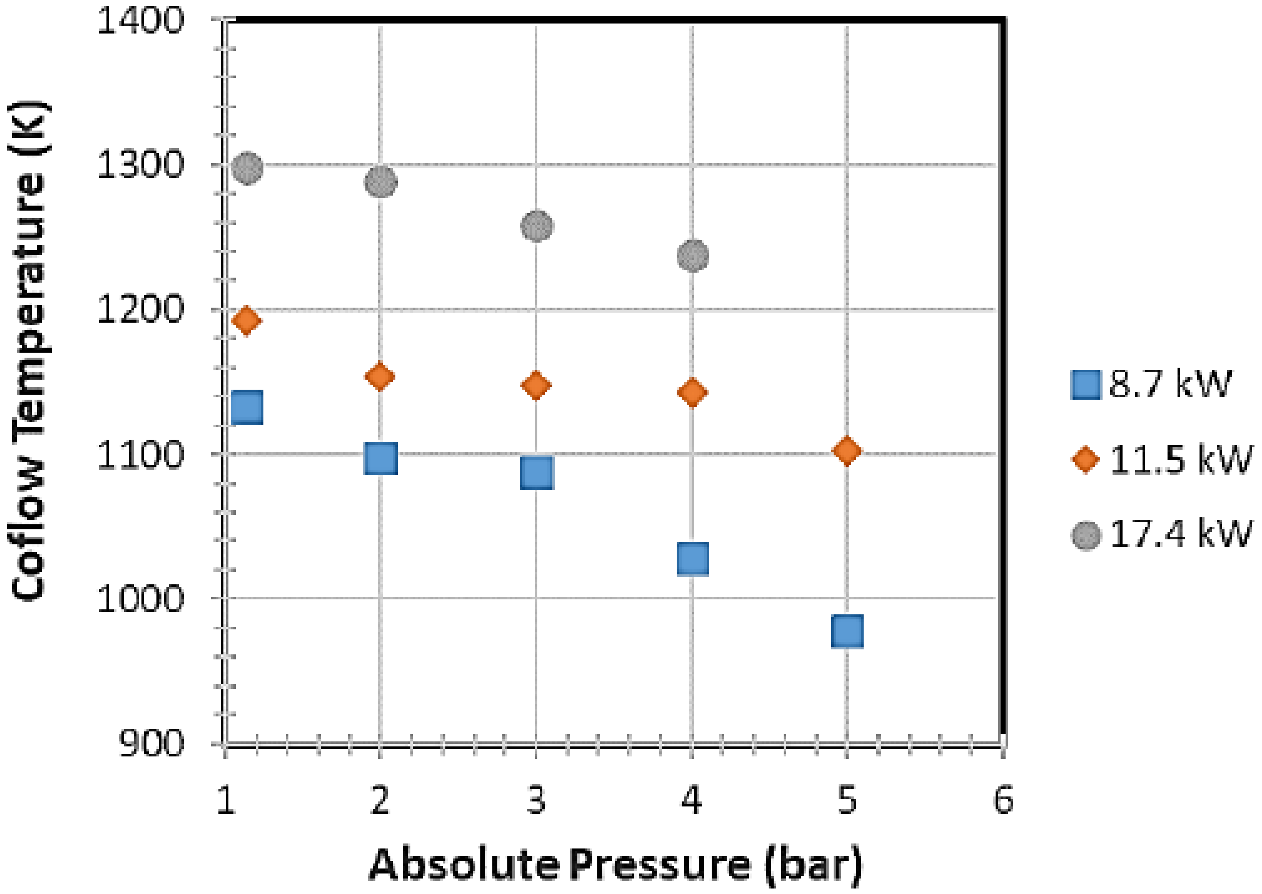
CP-JHC preliminary results

- Natural gas / H_2 / C_2H_4
- Chemiluminescence and photos



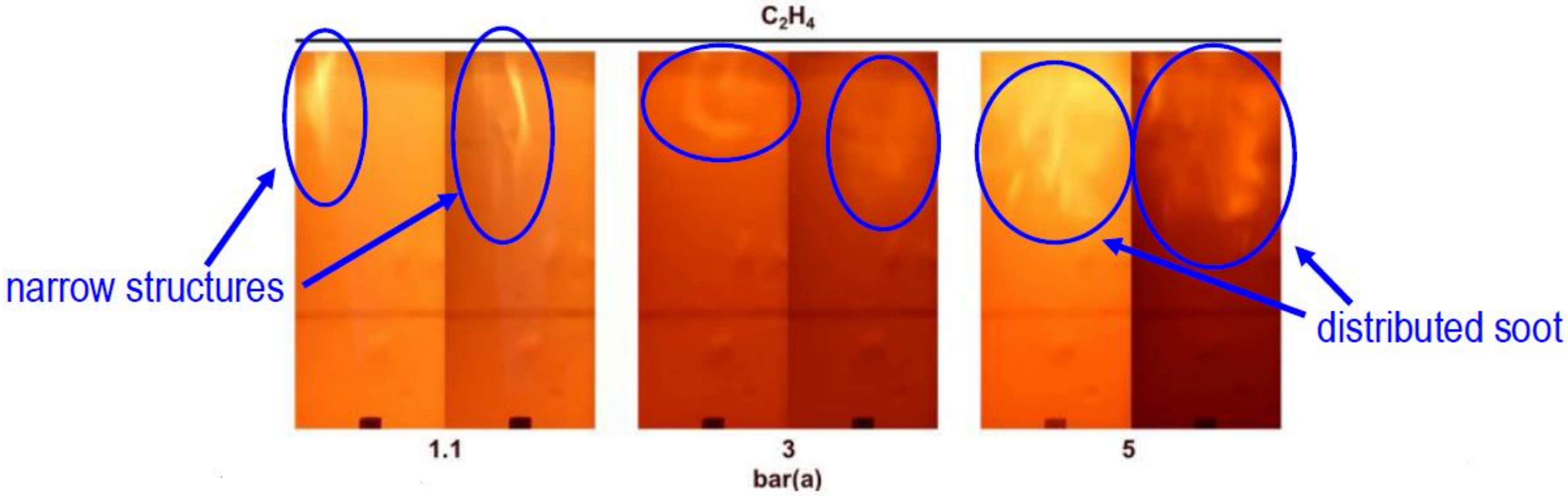
CP-JHC preliminary results

- Coflow characterisation
  - Duplicate previous conditions
  - Natural gas / H_2 coflow



CP-JHC preliminary results

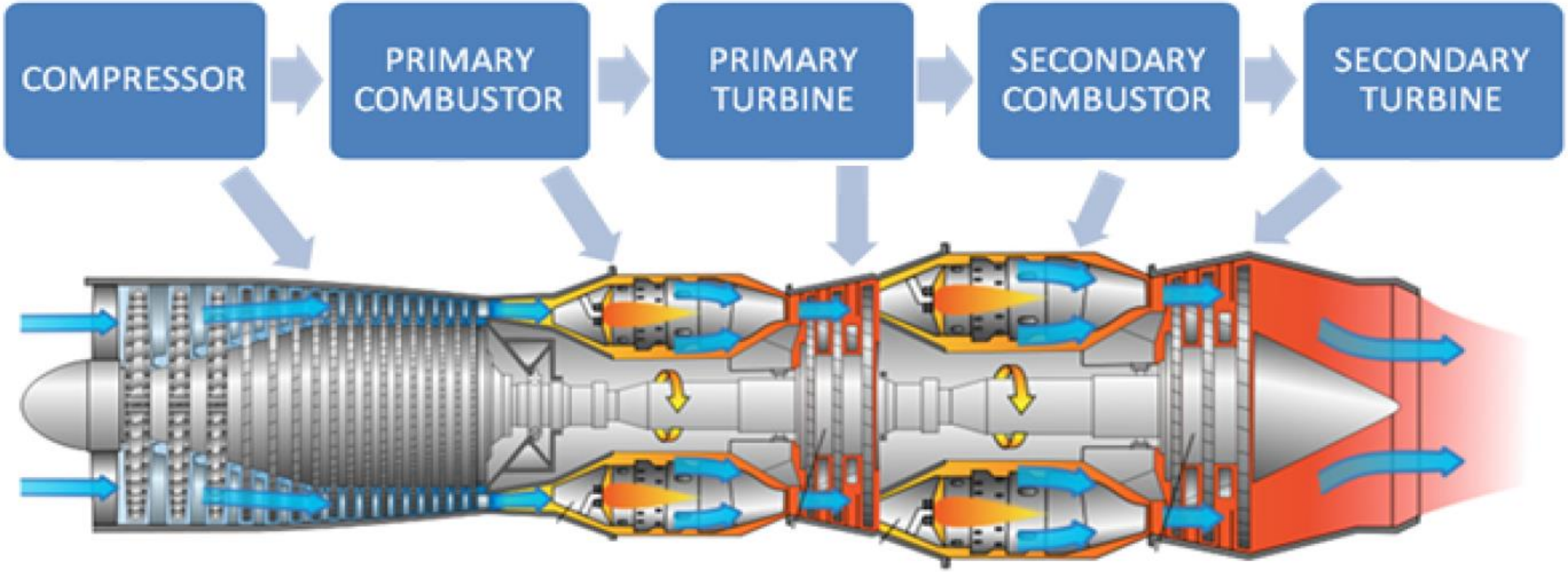
- Ethylene sooting flames
- Turbulent jet: Re_{jet}=10k



- Huge amount of work to do, but back to the motivation…

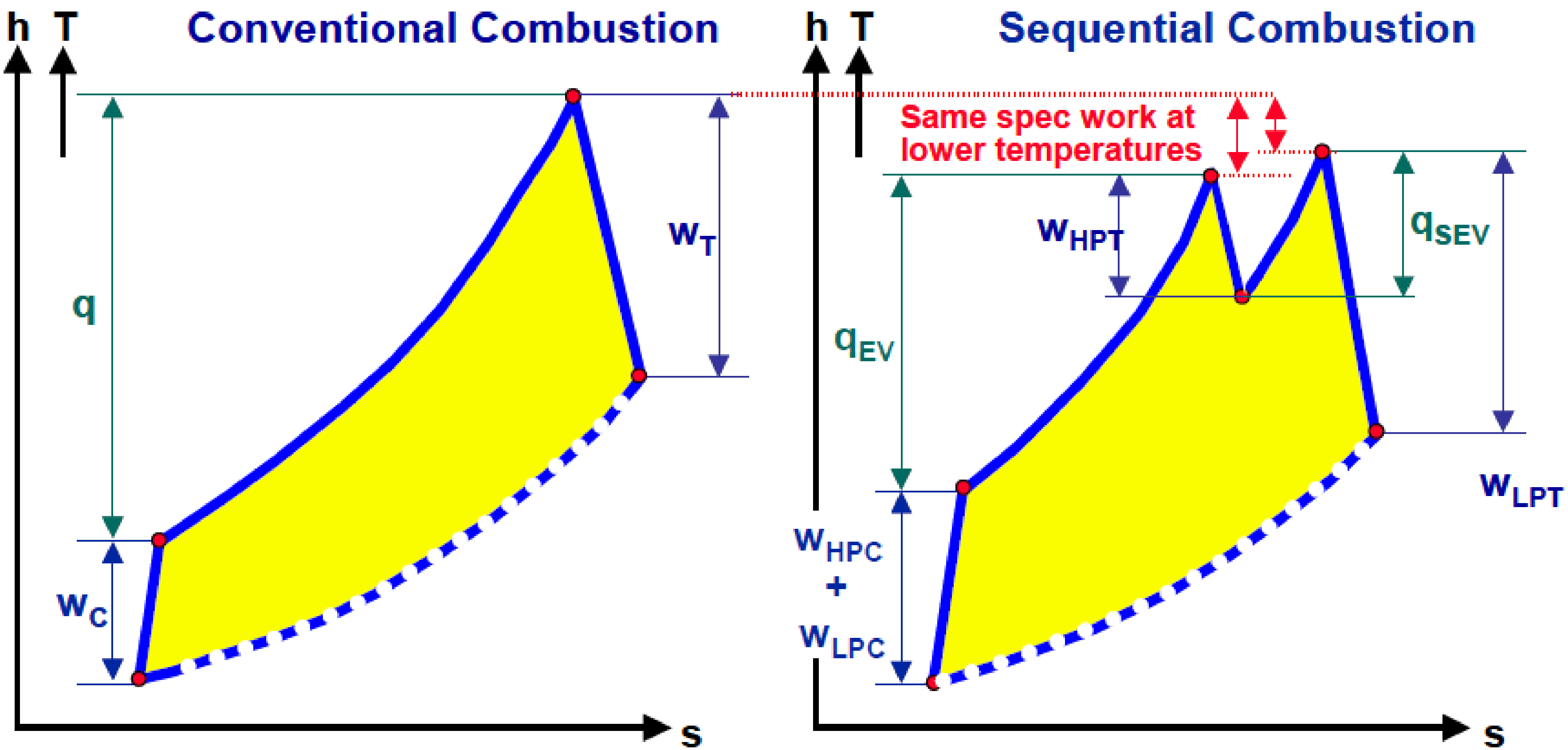
Sequential combustion

- JHC = fuel issues into hot and vitiated coflow
- Addition of fuel into combustion products…
  - Sequential combustion gas turbine (ABB/Alstom/GE/Ansaldo)
  - Inter-turbine burner (AFRL)
  - Reheat combustors



Sequential combustion

- Benefits of MILD (low NOx, low peak temperature, etc.)
- Wide range of turn-down ratios
- Fuel flexibility



Döbbeling et al (2007) J Gas Turb Power

Sequential combustion

- Sequential combustion / inter-turbine burners available
- Extending operation into the MILD regime not explored
  - Reburn mechanisms, especially NOx
- MILD combustion in gas turbines widely touted
  - Many attempts to adapt furnace burners
  - Sequential combustion mimics the JHC configuration
  - More work needed…
    - Power density
    - Stability
    - Emissions
    - Thermoacoustics
    - Fuel flexibility
    - etc.

Conclusions

- MILD combustion is good for several applications
  - Need to know more to apply to other systems
- JHC burner is a good test bench configuration
  - Provided much clearer understanding of stabilisation mechanisms
  - Role of intermediates
  - Definition of MILD is open for debate
  - Need to know how "MILD" changes with operating conditions
- Can apply lots of laser diagnostics
  - Continued room for improvement in new and existing techniques
- Future fuels and fuel flexibility are important
  - Develop new combustion technologies and approaches
  - MILD combustion a good candidate for facilitating future advancements
  - Need to know more

Acknowledgements

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