THE UNIVERSITY of ADELAIDE

Hybrid Solar-MILD Combustion for Renewable Energy Generation

CRICOS PROVIDER 00123M

Bassam Dally
Alfonso Chinnici, Gus Nathan

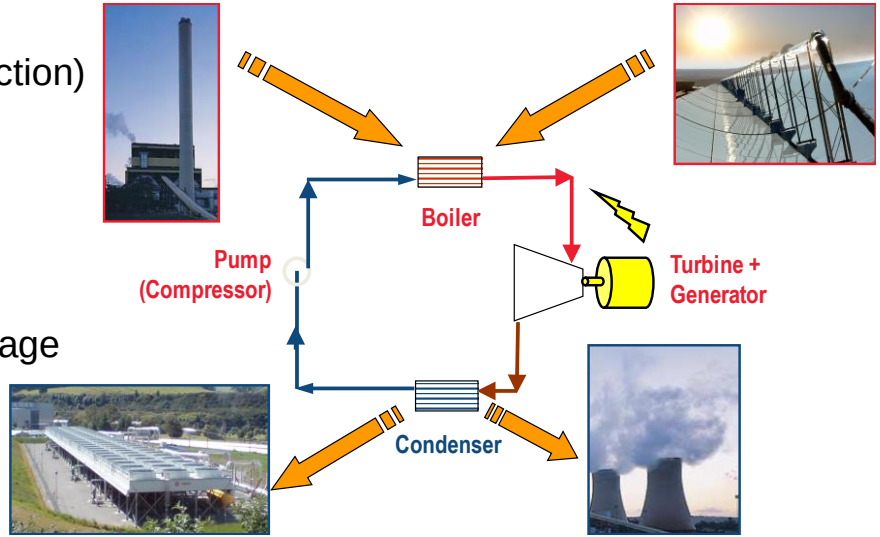
Background - Hybridisation

Growing interests in Concentrated Solar Thermal Technology

- Combustion presently provides for ≈80% of the traded energy in industrialised economies
- Need to decarbonise High-T processes is driving the development of technologies using alternative sources
- **Concentrated Solar Thermal:**
  - Source of High-T process heat (500-2000 ºC);
  - Several applications (heat, power, fuels production)
  - Synergies with combustion technology
  - Intermittent and variable radiation resource

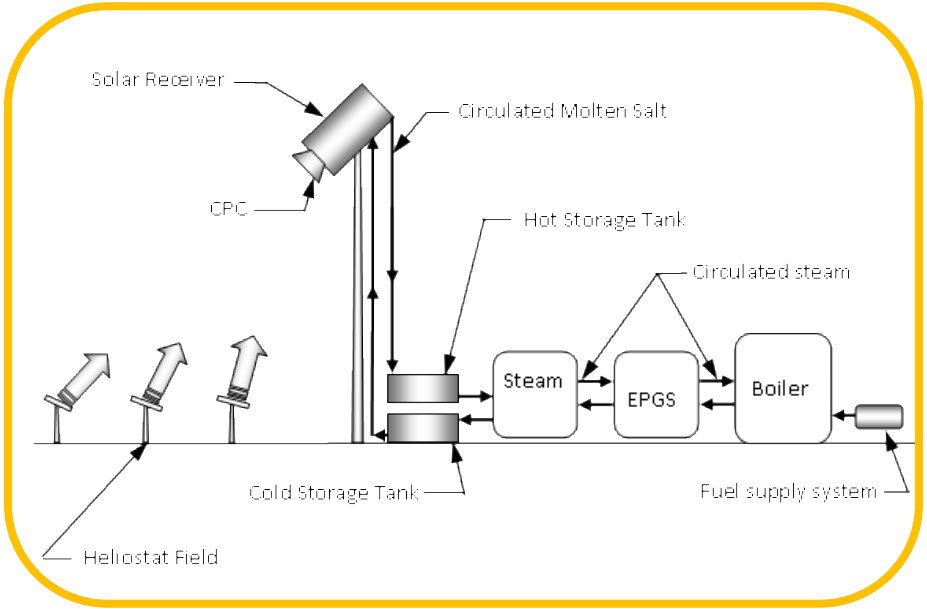
Hybrid solar thermal systems

- Potential to provide firm supply
- Combustion complements solar thermal energy/storage
- Lower capital costs relative to standalone systems

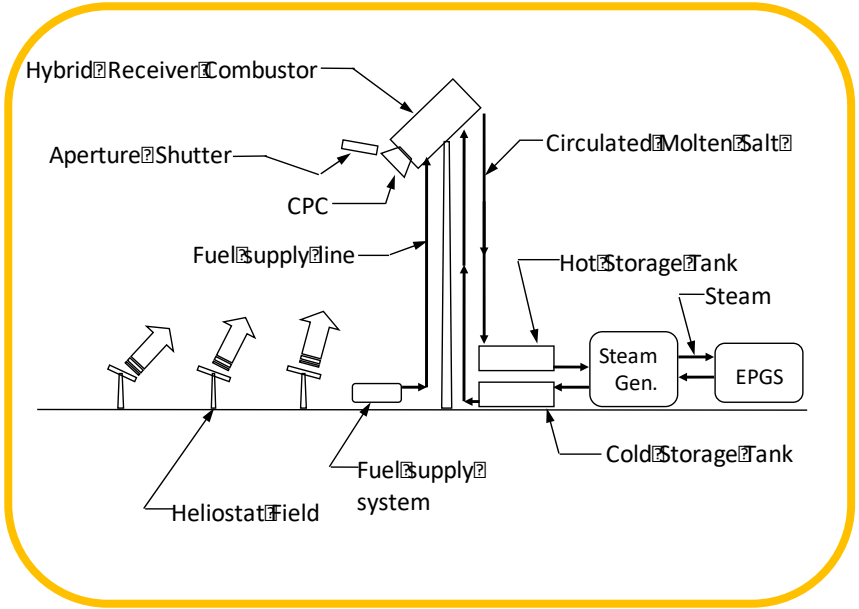


Hybridisation Concept for Solar Power Generation

Stand-alone System



Integrated System



Nathan et al., *Applied Energy* (2014).

HSRC - Technology

Hybrid Solar Receiver Combustor (HSRC)

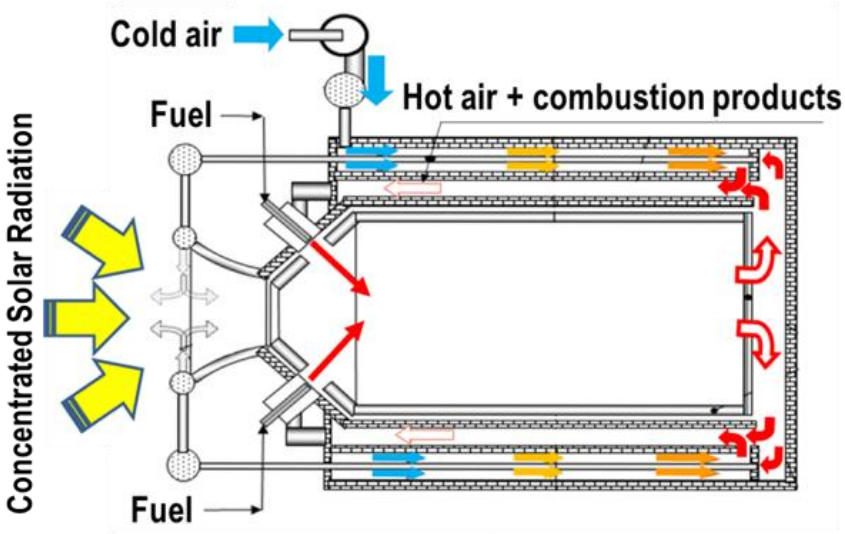
- **Direct hybridisation between a solar receiver and a combustor**

Three modes of operation

- Solar-only
- Combustion-only (conventional or MILD)
- Mixed mode (**poorly understood**)

MILD Combustion

- Ultra-low NO_x
- Potential for enhanced heat transfer
- Fuel flexibility and uniform heat flux distribution

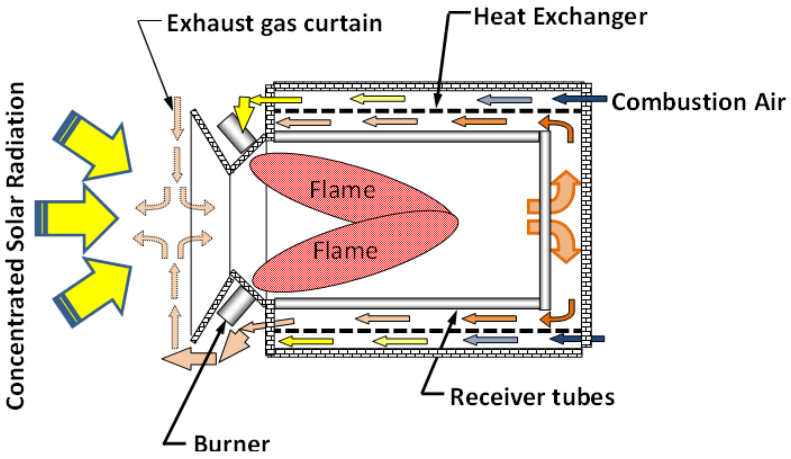


MILD Hybrid Solar Receiver Combustor

Nathan, Dally, Ashman, Steinfeld (2013). *PCT Patent App* #PCT/AU2013/000326

Magnitude of Estimated Benefits

Estimated benefits relative to ”equivalent” conventional hybrid



Different scales up to 30 MW_{th}

- reduces capital cost by ~ 21% (Lim et al., 2016)
- reduces LCOE by ~ 10-19% (Lim et al., 2016)
- reduces fuel use and CO_2 by ~ 10-20% (Lim et al., 2016)

Lim et al., *Applied Energy* (2016).

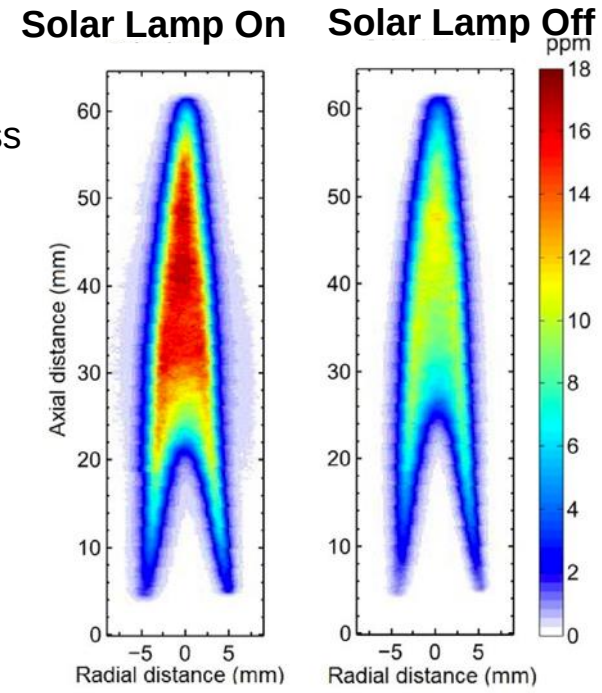
Previous Works and Knowledge Gap

Previous investigations

- Data limited to laminar flames
- CSR significantly influences the evolution of the combustion process
- Increase in the peak soot volume fraction by up to 250%
- Length and width of the flame not significantly affected
- Soot inception translated upstream
- Overall soot volume increased by 55%

Limited understanding

- **No data in practical combustion systems (e.g. furnaces)**
- **Lack of data on the effect of external radiation on:**
  - **Wall temperature**
  - **Reaction structure**
  - **MILD stability**
- **Lack of data on the effects of air ingress on MILD stability**
- **Lack of data on the suitability of solar fuels to HSRC**



Measured mean soot volume fraction in a laminar ethylene flame

Dong et al., *Combustion and Flame* (2016), Medwell et al., *Combustion and Flame* (2014)

Gaps and aims

Gaps & challenges

- **Different modes → Different contributions from radiation and convection → design challenge**
- **Mixed-mode of operation is poorly understood**
  - Maximizing thermal efficiency?
  - Avoid air ingress into and combustion products out of HSRC (heat/mass transfer through the aperture)
  - Effects of CSR on combustion process not known
- Only few works on comparison of heat transfer mechanisms and performance in MILD vs conventional
- Limited data on MILD Combustion of alternative, renewable fuels (e.g. hydrogen-based fuels)

Aims

- **First-of-a-kind experimental demonstration of HSRC technology**
  - Compare performance under different modes of operation
  - Advance current understanding of the mixed-mode
  - Effects of CSR on stability and performance of MILD combustion
  - Effects of hydrogen addition on stability and performance of MILD combustion of NG and LPG
  - Comparison of performance between MILD and conventional combustion

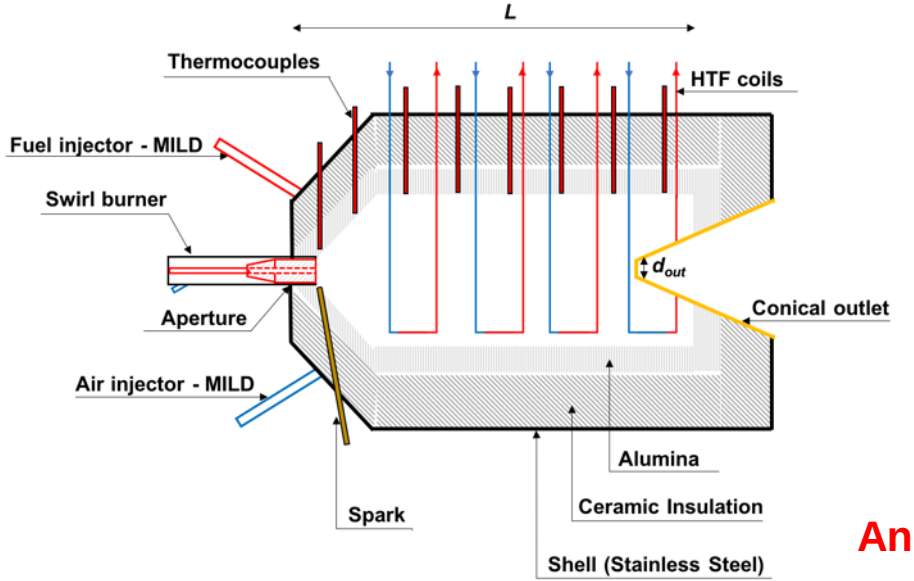
Laboratory-scale (20 kW) HSRC

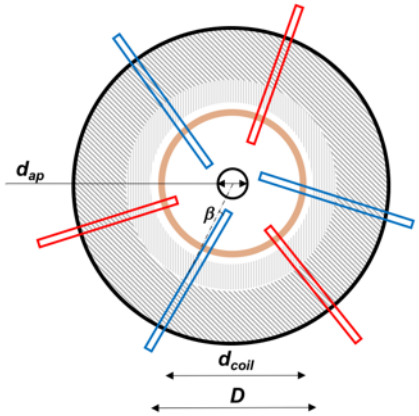
Energy sources:

- **NG** (CH_4 = 92% v/v), **LPG** (C_3H_8 = 97%), **H_2**, **NG/H_2** and **LPG/H_2** blends, and **H2/CO (1/X).**
- **5 kW_{el} Xenon Arc Lamp (single)**

Heat Transfer Fluid:

- Air
- Four coils



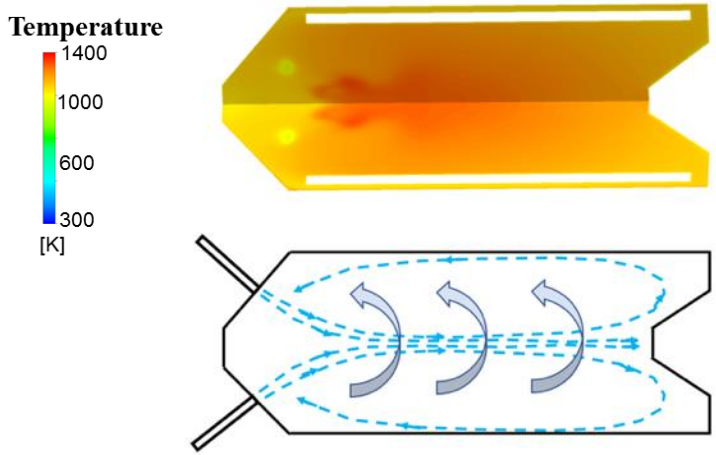


Annular arrangement

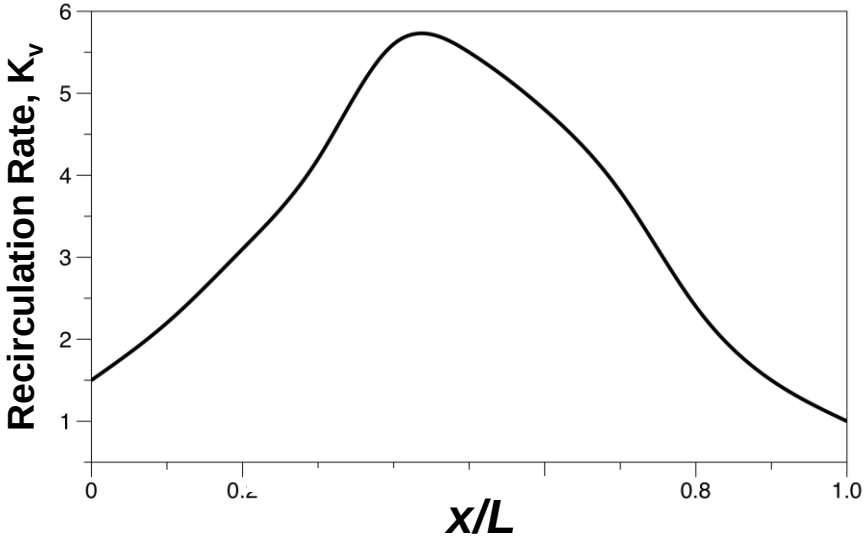
Laboratory-scale (20 kW) HSRC

Design:

- Use of CFD to identify suitable configurations
  - Maximize recirculation rate (enhance heat transfer), establish MILD Combustion (K_v = 6-7)
  - Use of multiple-inclined-interacting jets



Calculated thermal and flow fields (MILD)



Calculated recirculation rate K_v

Heat Transfer Analysis

Measured quantities (transient and steady-state conditions):

- Axial temperatures – alumina lining (10 points - N-TC)
- Outlet Temperature HTF, Heat flux distribution coils (4 points – N-TC)
- Average Temperature outer shell (36 points - infrared thermometer)
- Gas emissions and residual oxygen in exhaust (TESTO analyser)

Energy balance:

- The balance is closed – all terms measured or estimated for the three modes

Potential thermal efficiency:

- Mixed and combustion-only: considering heat recovering (80%) from exhaust

Energy Balance $Q_{solar,in} + Q_{fuel,in} = Q_{abs} + Q_{conv} + Q_{rad} + Q_{cond}$

Efficiencies $\eta_{coil} = Q_{abs}/P_{in}$ $\eta_{pot,th} = Q_{abs} + Q_{rec,HX}/P_{in}$

Case Study I

Mode	Energy input, *kW*	Fuel Type	Equivalence ratio	Solar/combustion ratio, %	HTF flow rate, *slpm*
Combustion-only	10-20	**NG, LPG, H_2, NG/H_2, LPG/H_2**	0.8-1	0	150-1000
Solar-only	0.8	/	/	100	
Mixed	10-20	**NG, LPG, H_2, NG/H_2, LPG/H_2**	0.8-1	6.6-8	

Combustion-only and mixed-mode:

- Heat from exhaust is not recovered
- MILD Combustion: high-speed air jets ($80 < v_{air} < 120$ m/s, $50 < J_{air}/J_{fuel} < 200$)

Solar-only:

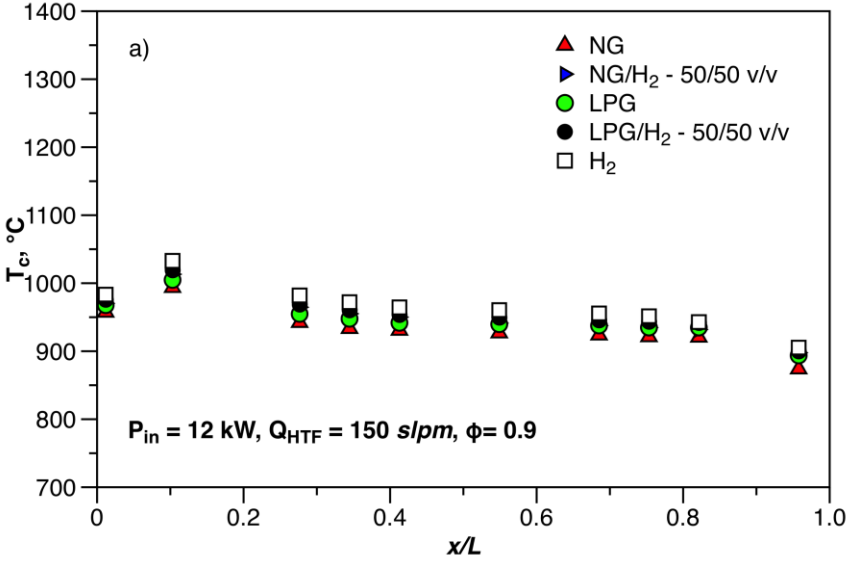
- No secondary concentrator and/or window employed
- Conical outlet close by a ceramic plug to reduce losses

All modes:

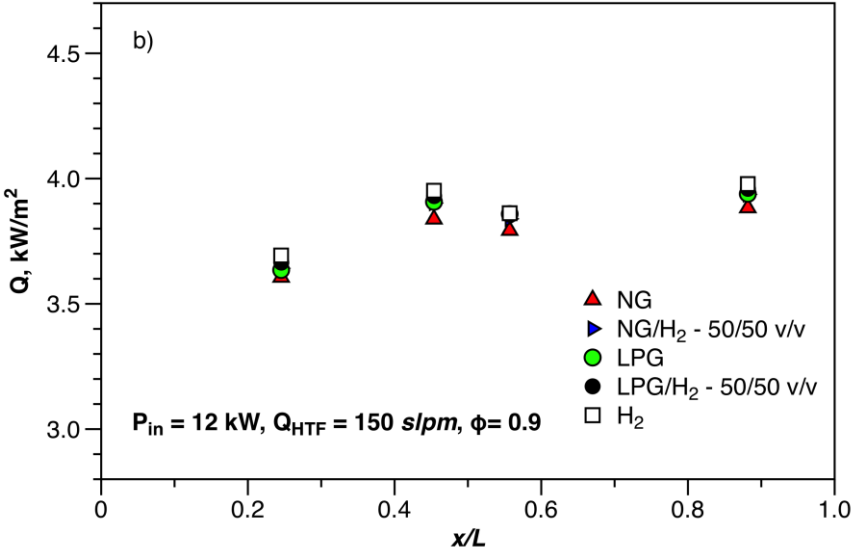
- Horizontal position

Combustion-only (MILD)

Wall Temperature – alumina lining



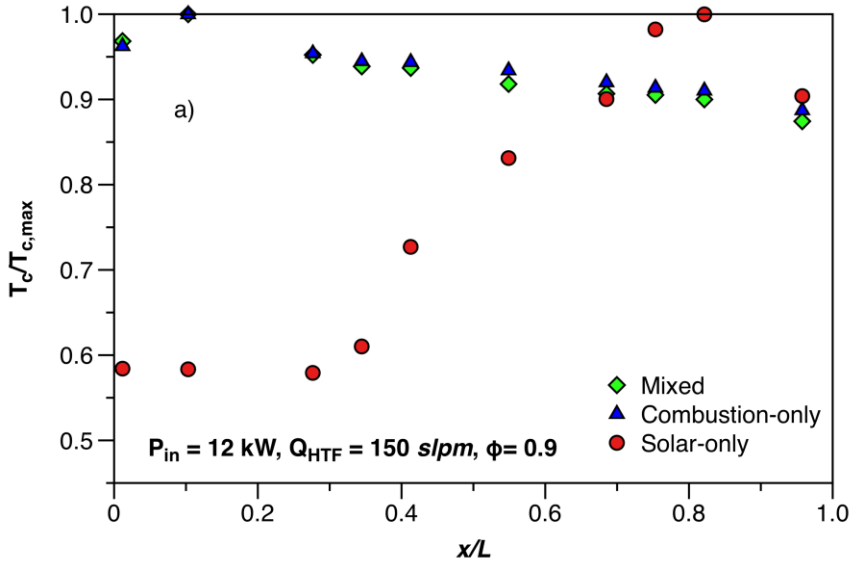
Heat flux on HTF coils



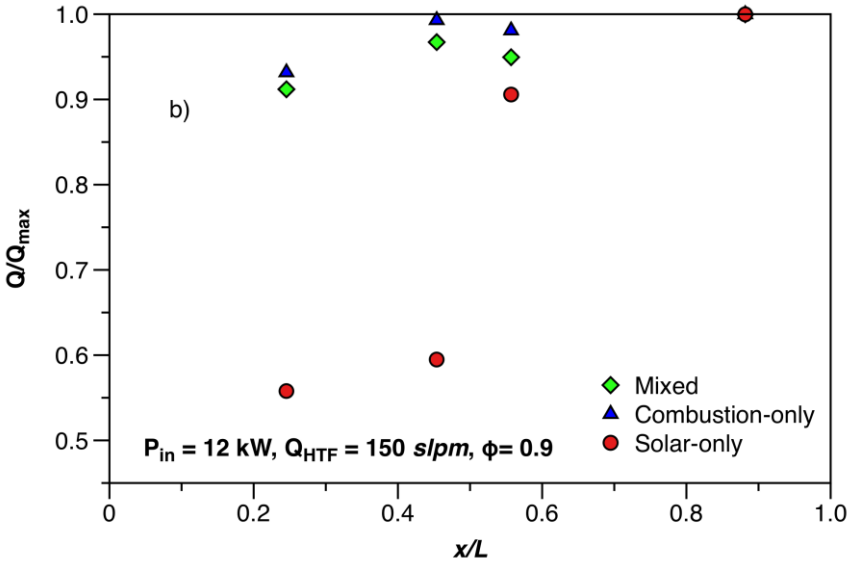
- Uniform temperature and heat flux distribution → typical of MILD Combustion

Comparison with solar-only and mixed mode

Normalised wall Temperature - alumina



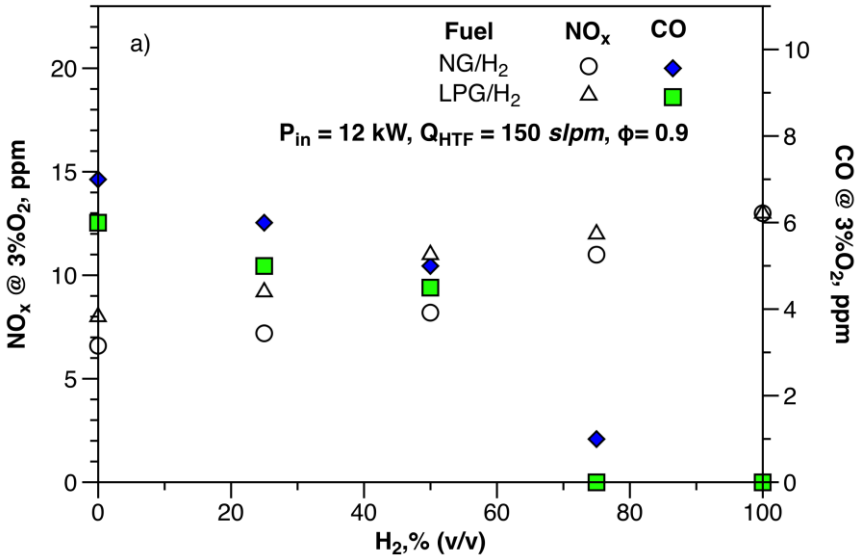
Normalised heat flux on HTF coils



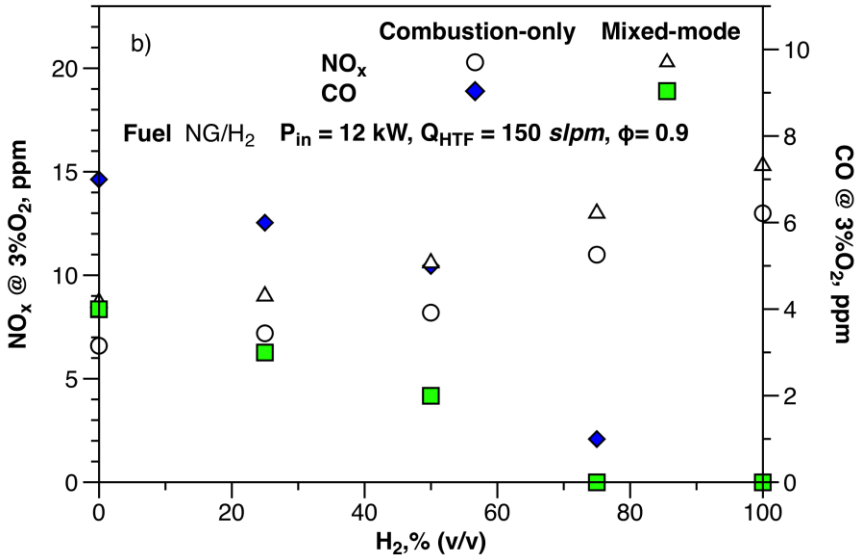
- Mixed-mode: key features of the MILD combustion process are preserved
- Different modes → Different trend in the axial distribution of heat flux on coils

Emissions (MILD, Mixed mode)

Combustion-only (MILD)



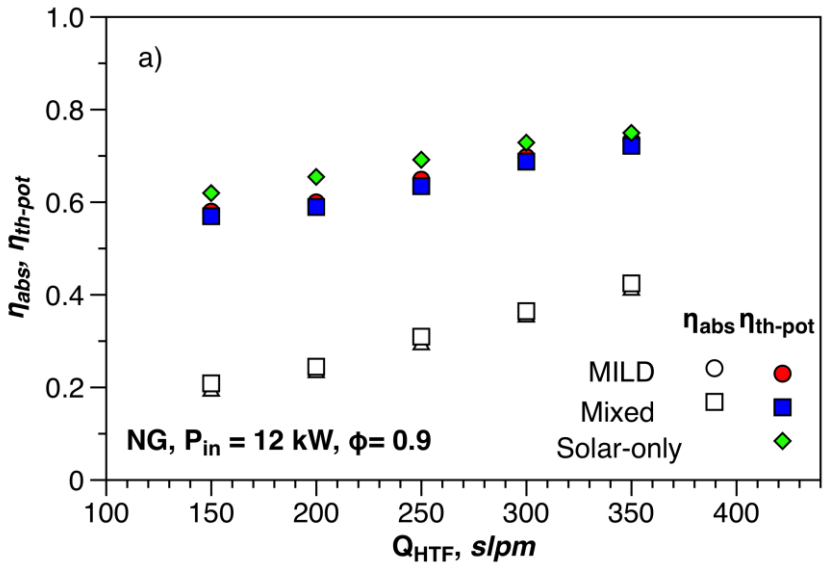
Comparison with Mixed mode



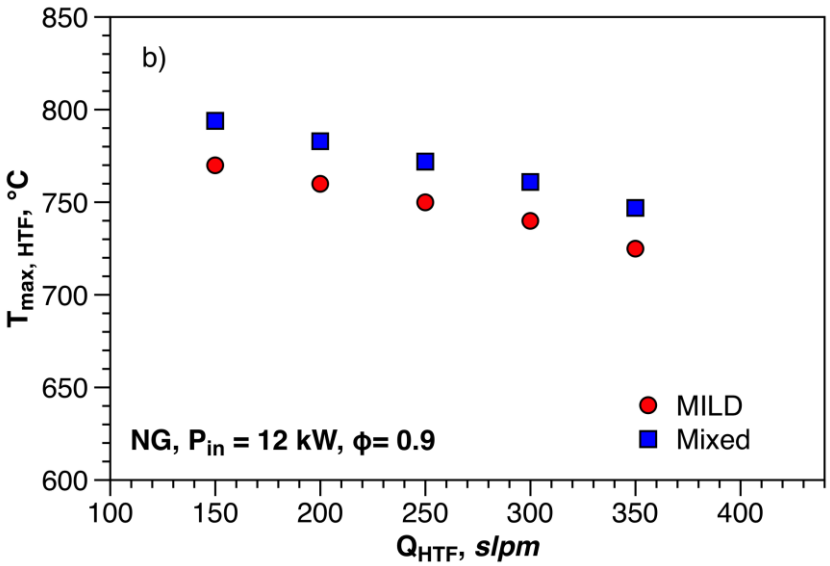
- Ultra-low NOx (< 20 ppm) and CO (< 50 ppm) through MILD Combustion
- Mixed-mode: key features of the MILD combustion process are preserved

Thermal Performance

Coil and Thermal Efficiencies



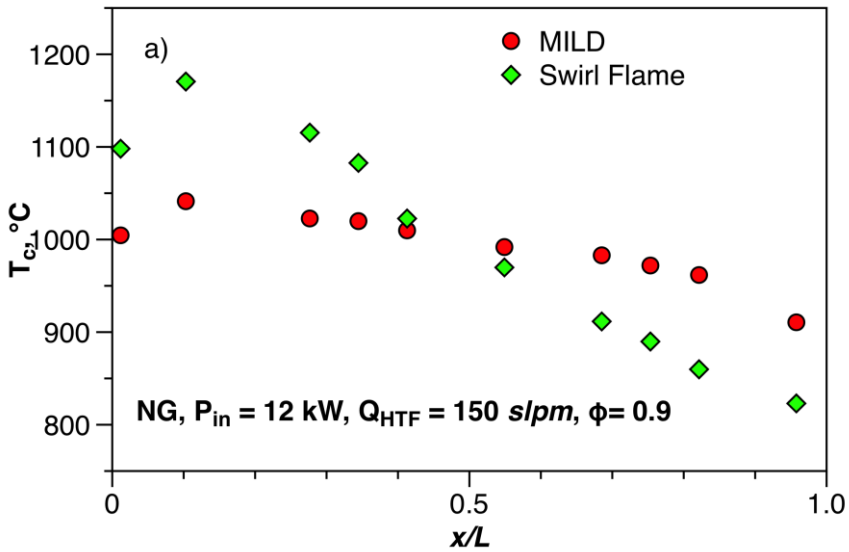
Maximum HTF Temperature



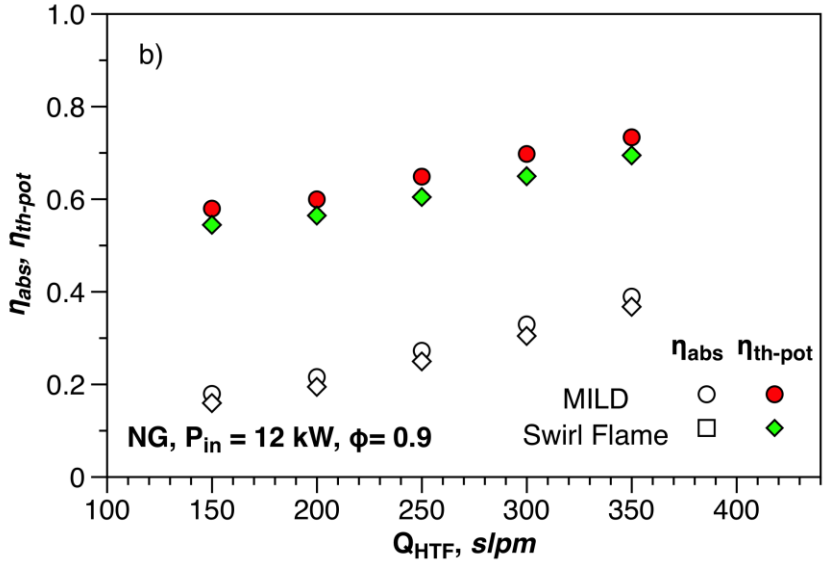
- Efficient operation in all three modes with maximum HTF temperature ≈800 ºC
- Mixed-mode: Higher $T_{max,HTF}$ and η_{coils} compared with combustion-only
- Mixed-mode: $\eta_{pot,th}$ slightly smaller than that of combustion-only (≈1.5%) but ≈15% fuel consumption reduction

Thermal Performance – MILD vs Conventional

Wall Temperature – alumina lining

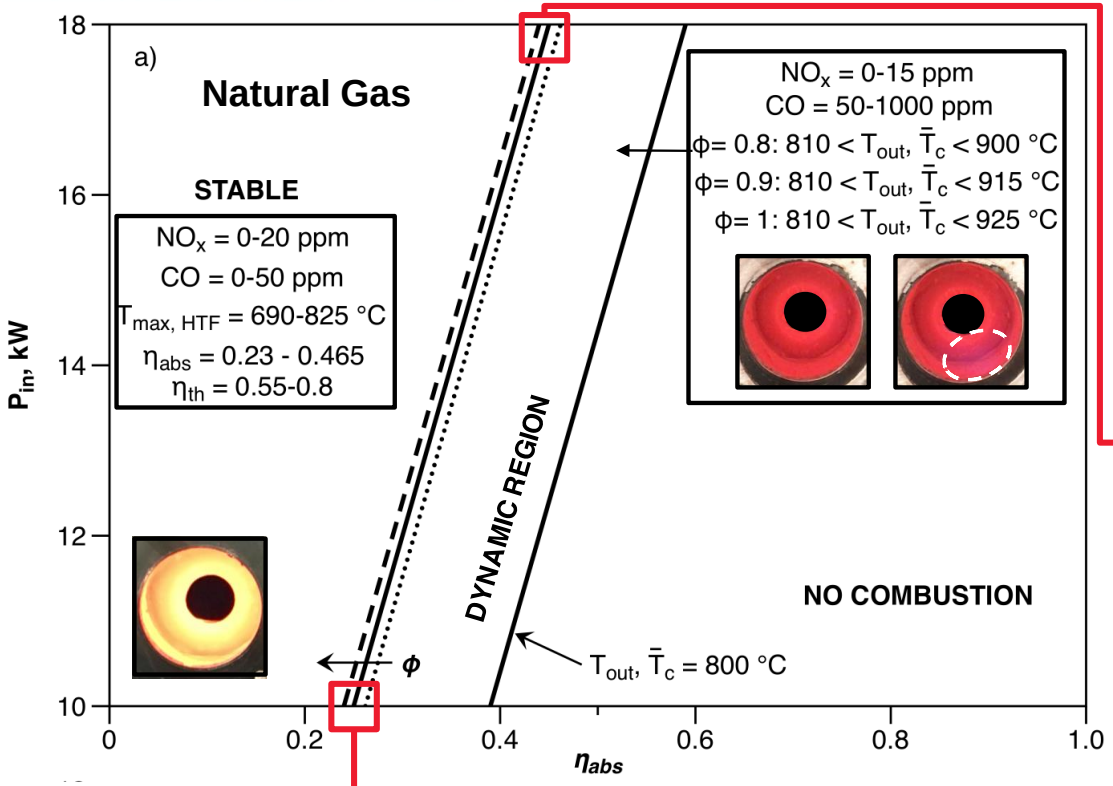


Coil and Thermal Efficiencies



- MILD vs Conventional combustion (non-premixed swirl flame):
  - Higher thermal performance (up to 5%) and NO_x reduction (≈85%)
  - Lower radiative-to-convective heat transfer rate ratio (CFD analysis)

Stability Limits (MILD)

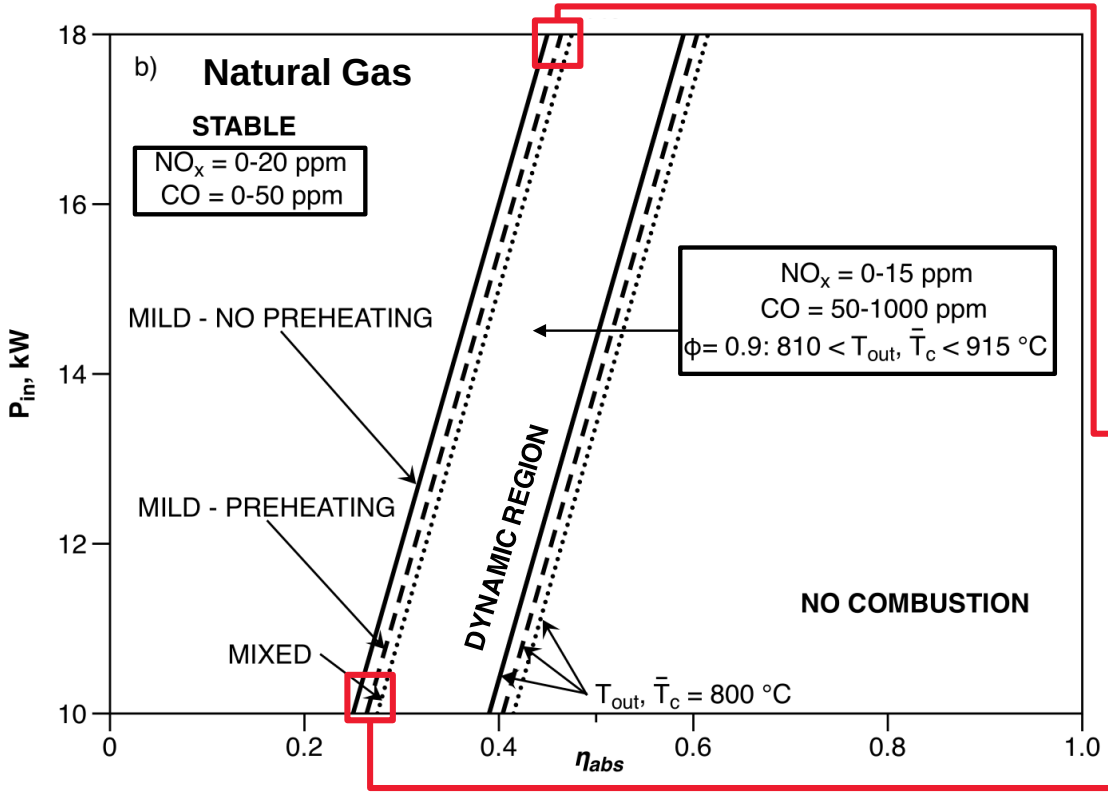


Dynamic Region

- Intermittent appearance of a flame
- Temporal oscillations of T, species
- Observed in other MILD devices

- **Stable operation for:**
  - **η_{abs} up to ≈ 24% (P_{in} = 12 kW)**
  - **η_{abs} up to ≈ 42% (P_{in} = 18 kW)**

Stability Limits, MILD vs Mixed



Mixed Mode

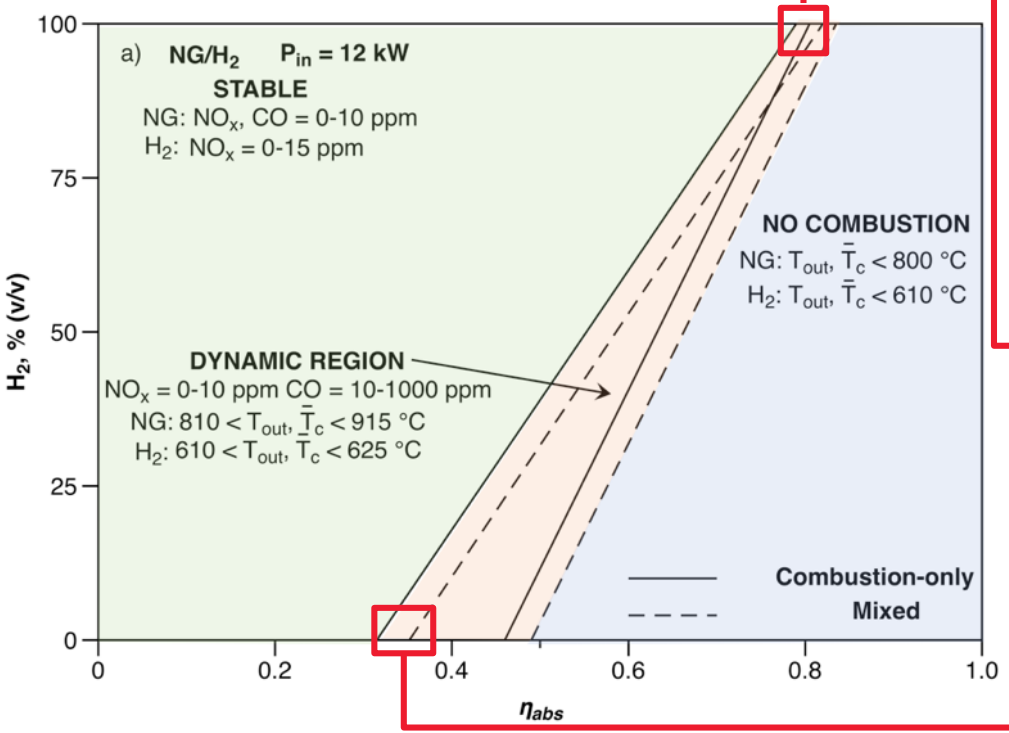
- Dynamic region still observed but shifts towards higher values of heat extracted
- **Stable operation for a wider range of conditions**

- **Stable operation (Mixed) for:**
  - **η_{abs} up to ≈ 28% (P_{in} = 12 kW)**
  - **η_{abs} up to ≈ 47% (P_{in} = 18 kW)**

Case Study I

Stability Limits - Effect of Hydrogen addition (MILD and Mixed)

NG/H_2 Blends (P_{in} = 12 kW)



MILD and Mixed Modes

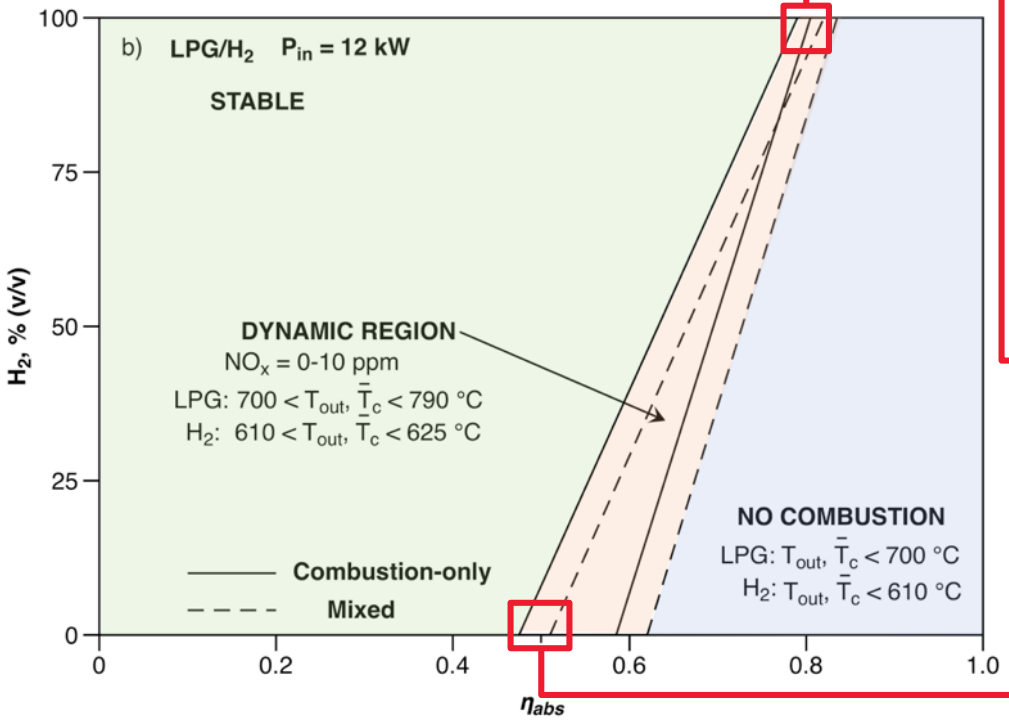
- Dynamic region still observed (also for 100% H_2)
- H_2 addition → instabilities shift towards higher values of heat extracted (approx. linear trend with H_2 %)

- **Stable operation (MILD) for:**
  - **η_{abs} up to ≈ 24% (H_2 = 0 %)**
  - **η_{abs} up to ≈ 78% (H_2 = 100 %)**

- **Stable operation (Mixed) for:**
  - **η_{abs} up to ≈ 28% (H_2 = 0 %)**
  - **η_{abs} up to ≈ 81% (H_2 = 100 %)**

Stability Limits - Effect of Hydrogen addition (MILD and Mixed)

LPG/H_2 Blends (P_{in} = 12 kW)



LPG vs NG

- Wider range of stable operations
- Dynamic region still observed (but 'smaller')

Effects of CSR and H_2

- Similar to NG and NG/H_2 blends

- **Stable operation (MILD) for:**
  - **η_{abs} up to ≈ 46% (H_2 = 0 %)**
  - **η_{abs} up to ≈ 78% (H_2 = 100 %)**

- **Stable operation (Mixed) for:**
  - **η_{abs} up to ≈ 50% (H_2 = 0 %)**
  - **η_{abs} up to ≈ 81% (H_2 = 100 %)**

Case Study II

Mode	Energy input, *kW*	Fuel, v/v	Solar-to-Comb ratio, %	HTF flow rate, *slpm*
Combustion-only	12	**H_2/CO = 1, 2, 3 & ∞**	0	150-1000
Solar-only	0.8	**/**	100	150-1000
Mixed	12	**H_2/CO = 1, 2, 3 & ∞**	7	150-1000

Combustion-only and mixed-mode:

- No air preheating (i.e. heat from exhaust is not recovered)
- Use of MILD Combustion (state-of-the-art technology giving distributed volumetric reaction and low-NOx), equivalence ratio = 0.9

Solar-only:

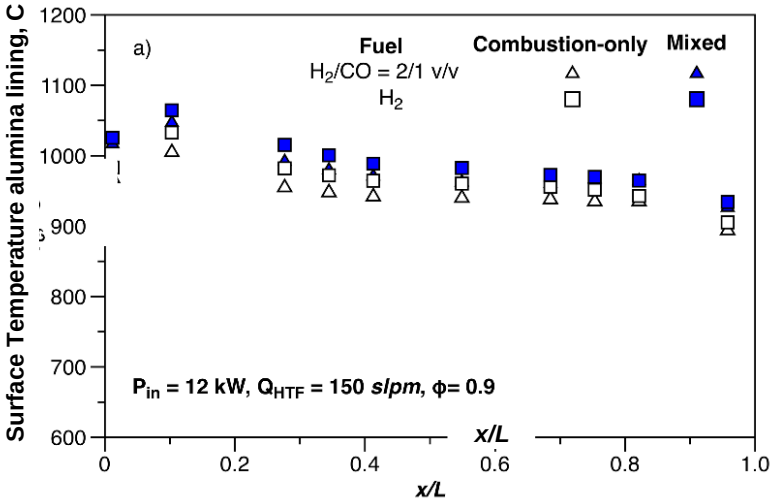
- No secondary concentrator and/or window employed
- Conical outlet close by a ceramic plug to reduce losses

All modes:

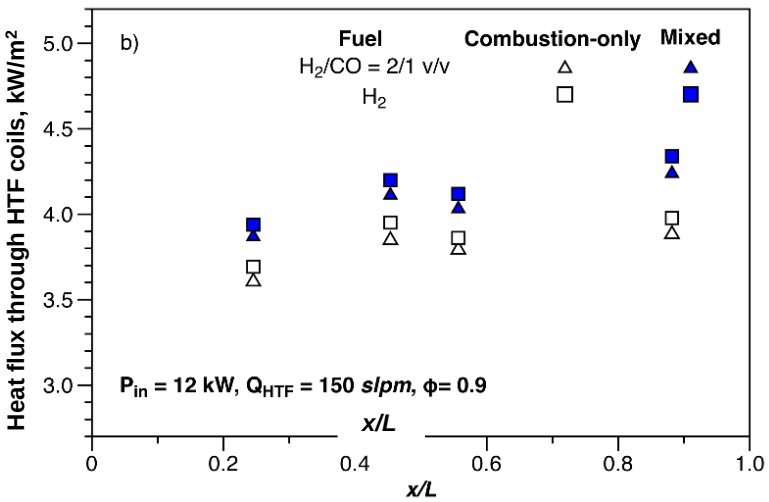
- Horizontal position

Combustion-only vs Mixed

Wall Temperature – alumina lining

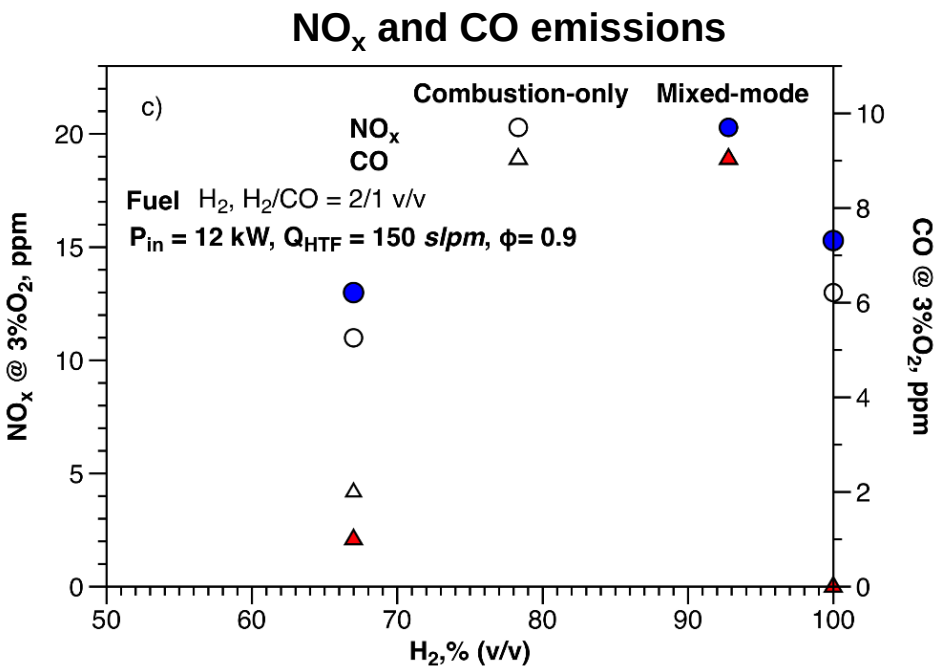


Heat flux on HTF coils



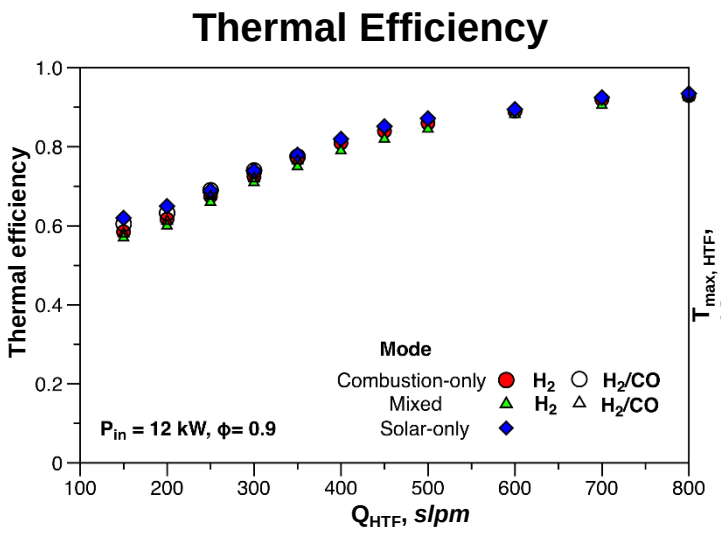
- Semi-uniform temperature and heat flux distribution → typical for MILD Combustion
- Mixed-mode: key features of the MILD combustion process are preserved

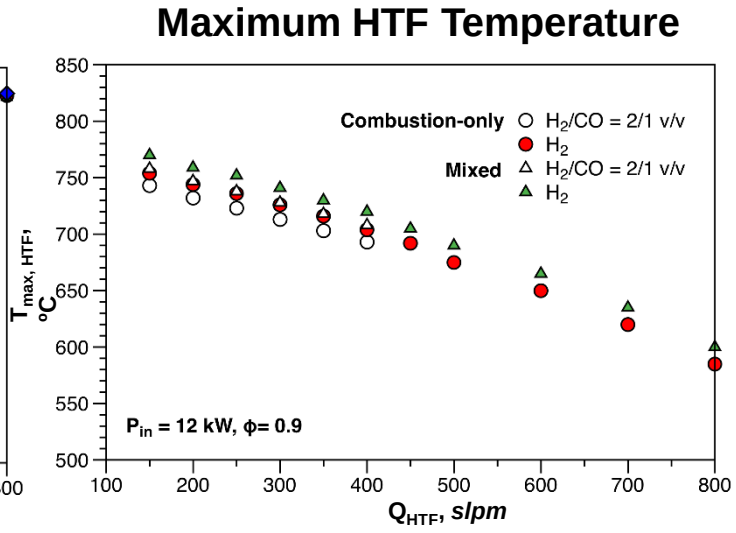
Combustion-only vs Mixed



- Ultra-low NO_x (< 20 ppm) and CO (< 10 ppm) through MILD Combustion
- Mixed-mode: key features of the MILD combustion process are preserved

Thermal performance

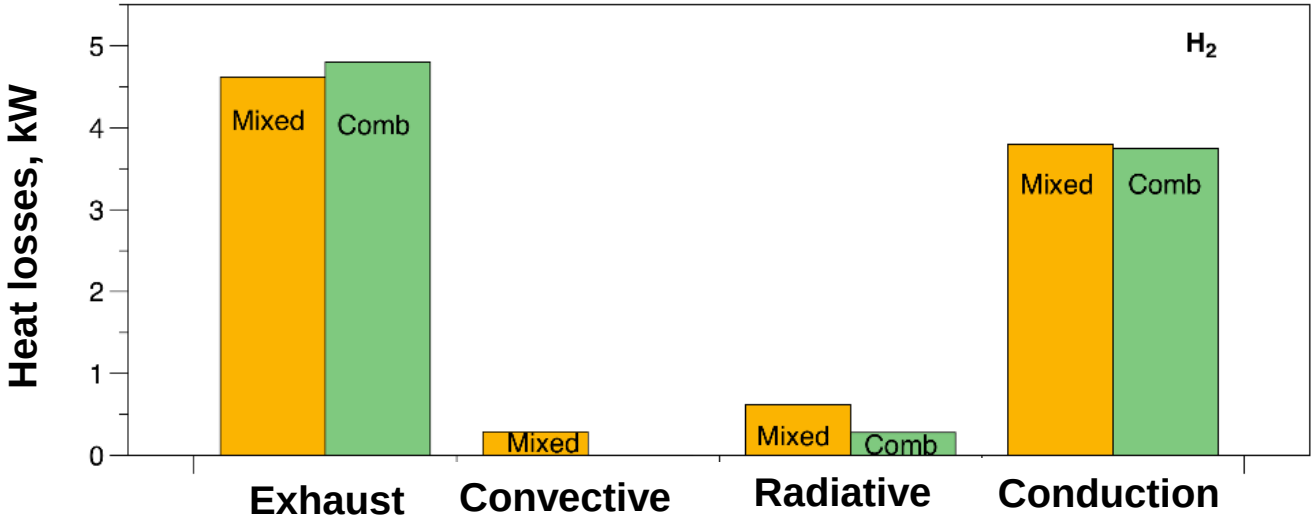




Key findings from demonstration

- Efficient operation in the three modes: **η_{th} up to 90%, T_{HTF} > 750 ºC**
- Low solar fluxes can be used to supplement combustion

Heat losses and specific fuel consumption



- Mixed mode vs Combustion
  - Slight additional convective and re-radiation heat losses (<12% of total)
  - Ambient air entrained into device is small (<2% of combustion air)
  - Convective losses through aperture <50% of radiative (no wind)

Heat losses and specific fuel consumption

Specific Fuel Consumption (*SFC*)

sfc, kg/kWh	Combustion	Mixed	%
H_2	0.13	0.11	**15.3**
H_2/CO = 2/1v/v	0.24	0.2	**16.7**

- Mixed mode vs Combustion
  - Net thermal gain
  - ***SFC* reduced by ≈ 15-17%**

Case Study III

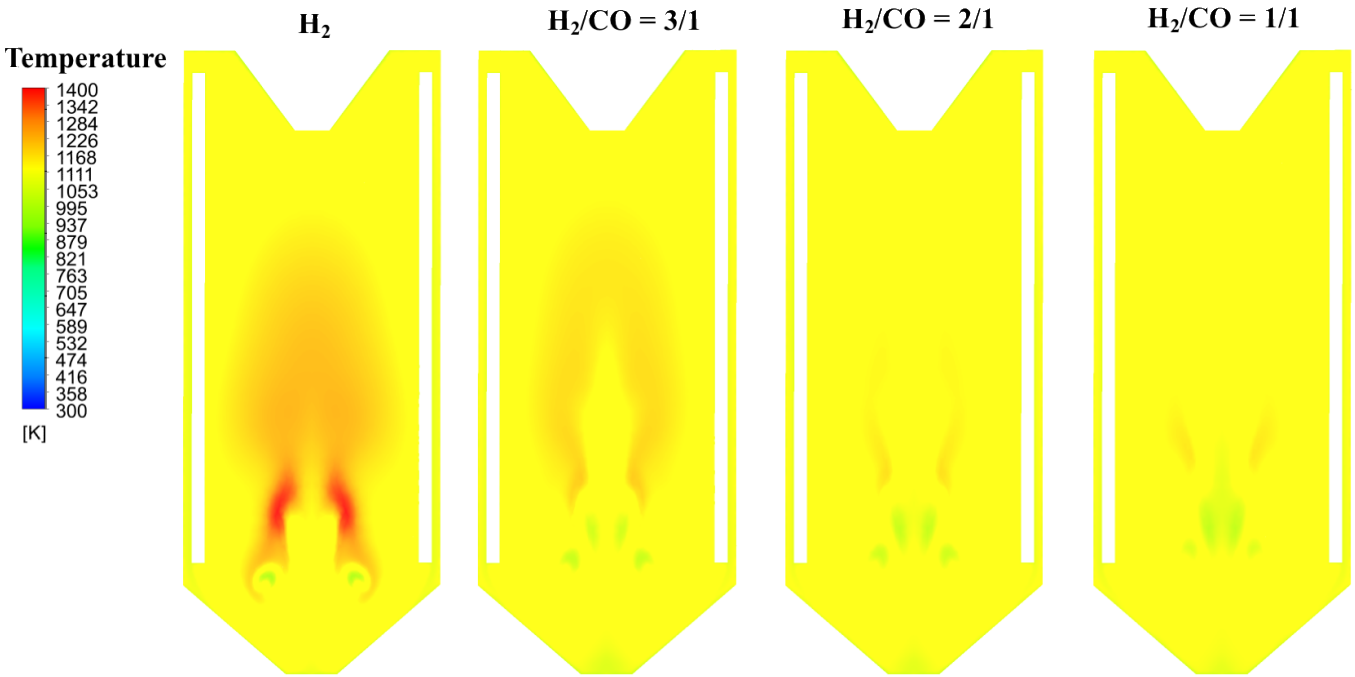
Mode	Energy input, *kW*	Fuel Type	Equivalence ratio	Solar/combustion ratio, %	HTF flow rate, *slpm*
Combustion-only	10-20	**H_2, H2/CO, NH3**	0.8-1	0	150-1000

K-epsilon realisable + EDC + detailed chemistry + DO and WSGGM for radiation + 2nd order discretisation + SIMPLE

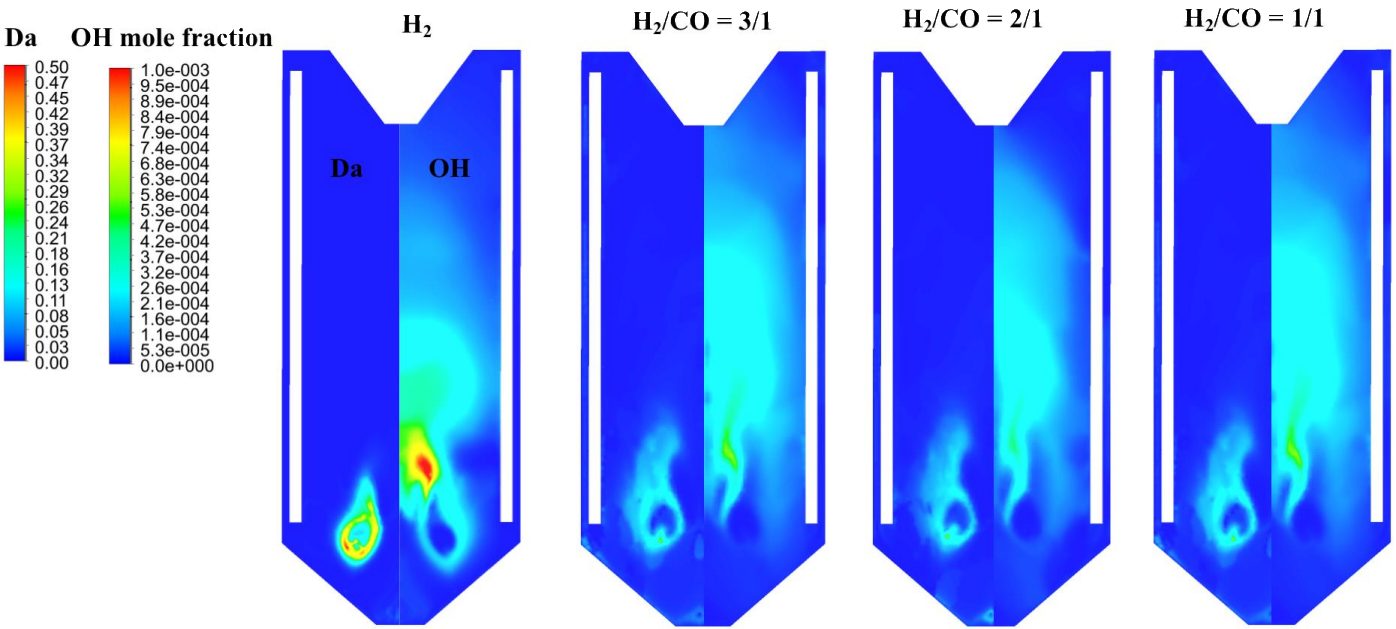
AMMONIA MECHANISM Xiao et al (2016) Cardiff mechanism → reduced from Konnov, consisting of 31 species and 243 reactions

H2/CO MECHANISM: PoliMI mechanism → 14 species and 33 reactions

Computed Temperature Distribution along the Periodic Plane



Computed Da and OH Distribution along the Periodic Plane



Heat Transfer Analyses in HSRC

Fuel	$\dot{Q}_{abs,rad}$, kW	$\dot{Q}_{abs,rad}/\dot{Q}_{abs,con}$	a_g, m^{-1}	R_e	$h_{c,RT}$, W/m^2K
H_2	1.97	2.25	0.62	193	36.3
H_2/CO v/v = 3/1	1.76	2	0.69	187	36.1
H_2/CO v/v = 2/1	1.72	1.9	0.71	185	36.0
H_2/CO v/v = 1/1	1.64	1.84	0.72	183	35.9

a_g - mean values of the absorption coefficient, **R_e** - normalised emissive source term

Exp and Numerical Study … (Chinnici et al., MCS 2019, submitted)

Heat Transfer Analyses in HSRC

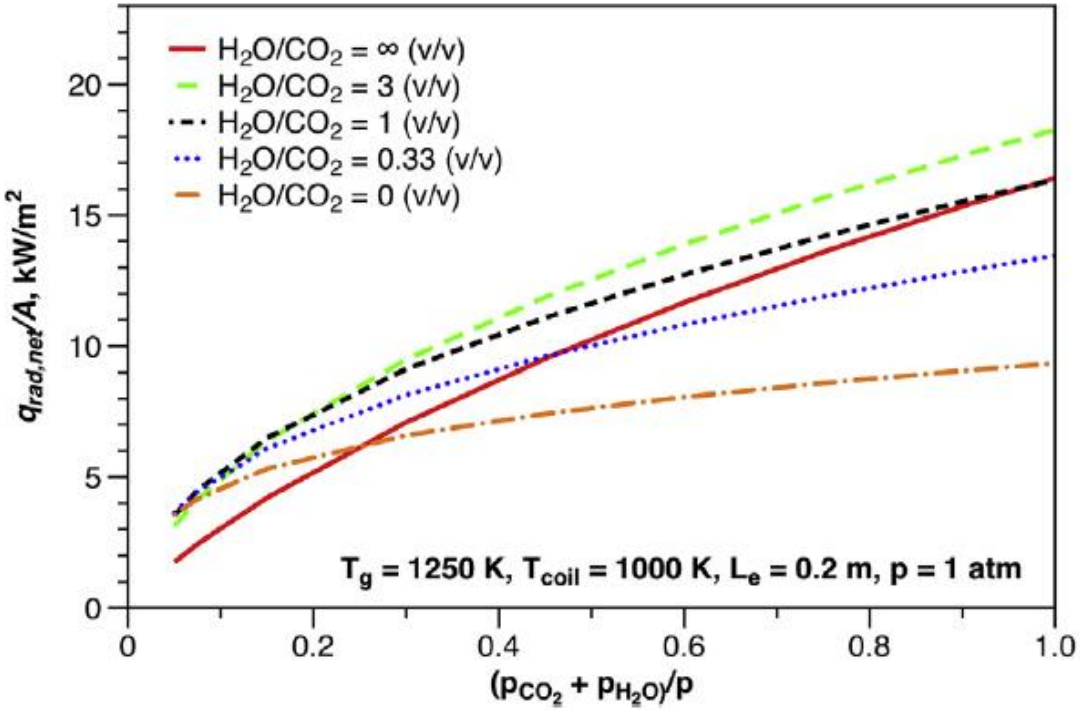
Table 4 – Measured values of the heat losses (kW) for combustion-only and mixed operations, and for different fuels (with $Q_{HTF} = 150$ *slpm*). For mixed operations, the values of $\dot{Q}_{ex}$ presented here include $\dot{Q}_{conv}$. The difference (kW) between the nominal power input and the sum of the measured values of the heat collected through the HX ($\dot{Q}_{abs}$) and the specific losses ($\dot{Q}_{losses}$) is also shown (absolute value).

Fuel	Mode	$\dot{Q}_{ex}$	$\dot{Q}_{conv}$	$\dot{Q}_{rad}$	$\dot{Q}_{cond}$	$\lvert P_{in} - \dot{Q}_{losses} - \dot{Q}_{abs} \rvert$
NG	Combustion-only	5.8	N/A	0.15	3.2	0.2
NG	Mixed	5.65	0.22	0.45	3.25	0.1
LPG	Combustion-only	5.5	N/A	0.18	3.3	0.25
LPG	Mixed	5.2	0.25	0.5	3.32	0.14
H_2	Combustion-only	4.8	N/A	0.28	3.75	0.2
H_2	Mixed	4.62	0.29	0.62	3.8	0.1

P_{in}=12 kW, HTF = 150 SLPM

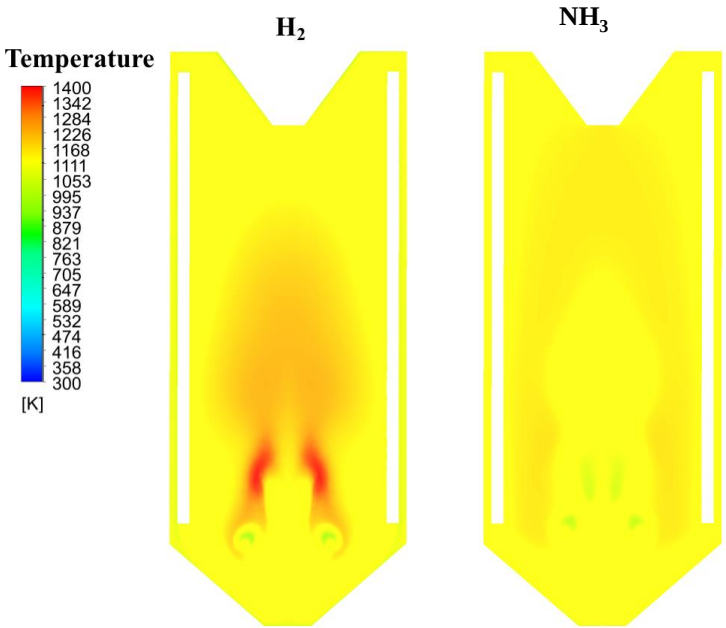
Combined Solar Energy ..(Chinnici et al., IJHE 2018, 43, 20086-200100)

Heat Transfer Analyses

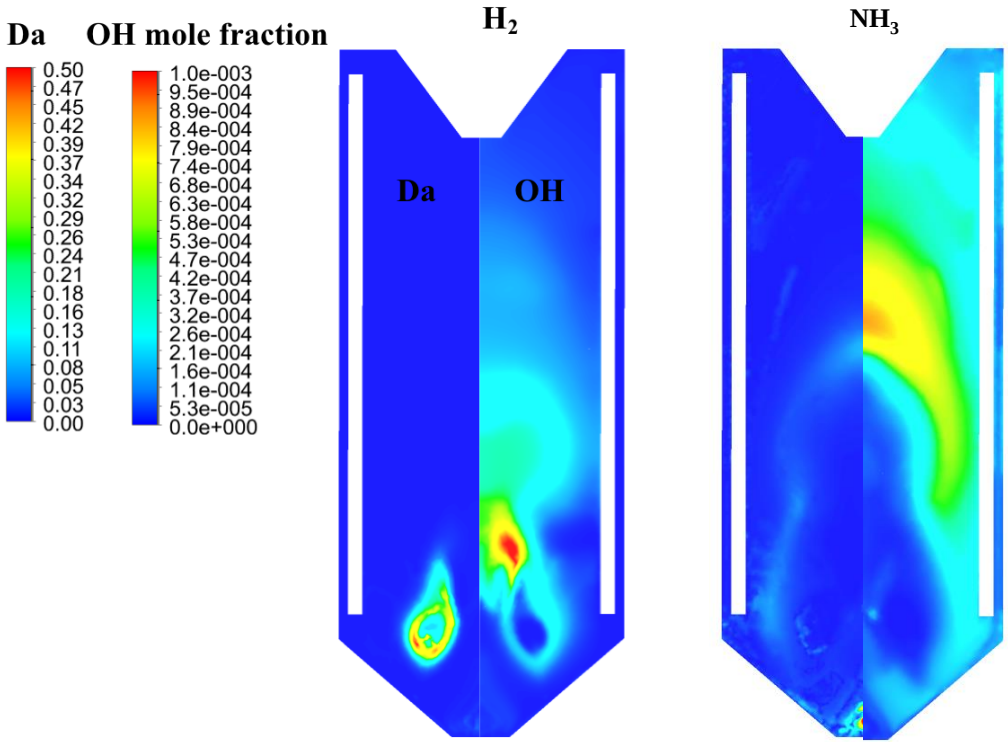


Radiation Heat Transfer rate - Gray gas model (Chinnici et al., IJHE 2018)

H2 and NH3 under MILD Conditions

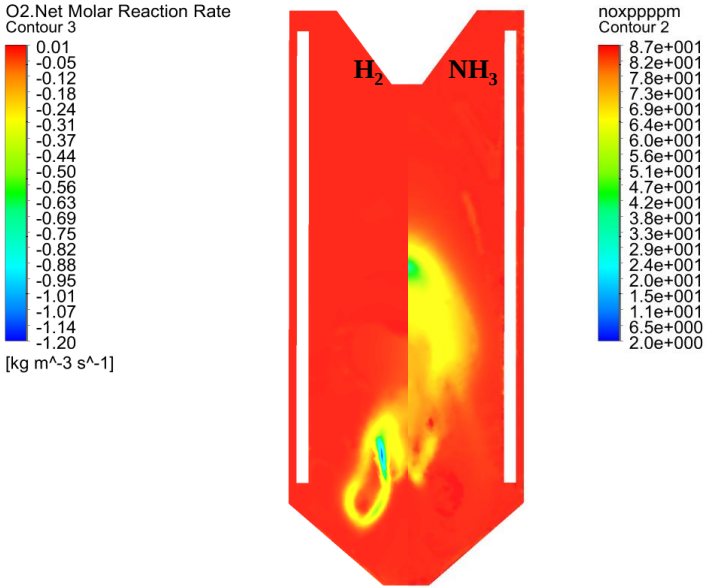


Distribution of Da and OH for H2 and NH3 under MILD Conditions

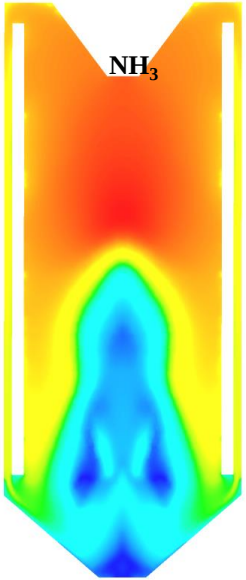


Reaction Rate and NO for H2 and NH3 under MILD Conditions

Net reaction rate of O2 along periodic plane



NO formation



Key outcomes for HSRC

- MILD combustion successful stabilised for H_2, Syngas and NH3
- It is found that Da < 1, low NO_x and uniform Temperature
- **For Syngas**
  - CO acts as a 'diluent' in comparison with H_2 case.
  - A decrease in H_2/CO leads to:
    - Decrease of max Da number, mean gas temperature and reaction rates;
    - Broaden the reaction zone and shifts it closer to the outlet section.
- **For Ammonia**
  - Decrease of max Da number, mean gas temperature and reaction rates;
  - Broaden the reaction zone and shifts it closer to the outlet section
  - Emission**18 ppmv NH3, 87 ppmv NOx @3%O2**
- **NOx Source**
  - **For NH3**: 72% fuel-NOx, 18% N2O intermediate, 8% prompt, 2% thermal
  - **For H2**: 75% N2O, 20% prompt, 5% thermal

Key outcomes for HSRC - I

- MILD combustion successful stabilised for H_2, Syngas and NH3
- It is found that Da < 1, low NO_x and uniform Temperature
- **For Syngas**
  - CO acts as a 'diluent' in comparison with H_2 case.
  - A decrease in H_2/CO leads to:
    - Decrease of max Da number, mean gas temperature and reaction rates;
    - Broaden the reaction zone and shifts it closer to the outlet section.
- **For Ammonia**
  - Decrease of max Da number, mean gas temperature and reaction rates;
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  - Emission**18 ppmv NH3, 87 ppmv NOx @3%O2**
- **NOx Source**
  - **For NH3**: 72% fuel-NOx, 18% N2O intermediate, 8% prompt, 2% thermal
  - **For H2**: 75% N2O, 20% prompt, 5% thermal

Key outcomes for HSRC - II

- **Radiative-to-convective heat transfer rate ratio** → 1.2 for MILD (55% Radiation, 45% Convection), 2.3 for conventional combustion (70% Radiation, 30% Convection)
- CFD: both global and semi-detailed mechanisms, EDC for turbulence-chemistry interaction

- **Experimental maps**: more than 50 data points for each fuel type, power input and mode of operation
  - 12 kW case and $\phi = 0.9$
    - 100% NG: instabilities start at T_{cavity} = 915ºC
    - 100% LPG: instabilities start at T_{cavity} = 790ºC
    - 100% H2: instabilities start at T_{cavity} = 615ºC
  - CFD analysis
    - 100% H2 case: higher radiative heat transfer rate and thermal performance in comparison with 100% LPG or 100% NG → up to 12% higher radiative heat transfer (due to higher T), despite a lower value of the emissivity (approx. 5% less than LPG and NG)

- **Hydrogen Fuel**
  - T_{coil} = 610 C when operated with 100% H_2 and 80% of heat extracted (MILD)

Conclusions

Technology

- **First unit built and demonstrated at TRL-4 (12 kW)**
- Efficient operation in all three modes of operation
- Flexibility to the fuel composition. It can operate with 100% renewable energy if fuel is generated from renewable sources (H2, Syngas, NH3)
- Ultra-low NO_x (< 20 ppm) and CO emission (< 50 ppm) in both MILD and mixed modes

Fundamentals

- A single device can efficiently accommodate two different energy sources characterised by different heat transfer mechanisms
- Stability and key features of the MILD process → not altered by interactions with CSR and heat/mass transfer with ambient (through the aperture)
- Stability limits of MILD combustion → improve by adding CSR (up to 15%) and/or H_2 to the fuel (up to 40%)
- Mixed-mode: Net thermal gain from adding CSR relative to combustion-only (up to 5% increase in η_{abs})
- Different modes → different trend in the axial distribution of heat flux on coils

Acknowledgments

FCT COMBUSTION

VastSolar

THE UNIVERSITY of ADELAIDE

ARC AUSTRALIAN RESEARCH COUNCIL

Thank you for the attention