Hybrid Solar-MILD Combustion for Renewable Energy Generation

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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 °C);
  - 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).
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
Estimated benefits relative to "equivalent" conventional hybrid

Different scales up to $30 \text{ MW}_{th}$
- 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)
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
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
Energy sources:
- NG (CH₄ = 92% v/v), LPG (C₃H₈ = 97%), H₂, NG/H₂ and LPG/H₂ blends, and H₂/CO (1/X).
- 5 kWₑₑ Xenon Arc Lamp (single)

Heat Transfer Fluid:
- Air
- Four coils

Annular arrangement
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)
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
\[ Q_{\text{solar, in}} + Q_{\text{fuel, in}} = Q_{\text{abs}} + Q_{\text{conv}} + Q_{\text{rad}} + Q_{\text{cond}} \]

Efficiencies
\[ \eta_{\text{coil}} = \frac{Q_{\text{abs}}}{P_{\text{in}}} \]
\[ \eta_{\text{pot,th}} = \frac{Q_{\text{abs}} + Q_{\text{rec,HX}}}{P_{\text{in}}} \]
| Mode                | Energy input, kW | Fuel Type         | Equivalence ratio | Solar/combustion ratio, % | HTF flow rate, slpm |
|---------------------|------------------|-------------------|-------------------|--------------------------|---------------------|
| Combustion-only     | 10-20            | NG, LPG, H₂, NG/H₂, LPG/H₂ | 0.8-1             | 0                        | 150-1000            |
| Solar-only          | 0.8              | /                 | /                 | 100                      |                     |
| Mixed               | 10-20            | NG, LPG, H₂, NG/H₂, LPG/H₂ | 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
Uniform temperature and heat flux distribution → typical of MILD Combustion
Mixed-mode: key features of the MILD combustion process are preserved
Different modes → Different trend in the axial distribution of heat flux on coils

Case Study I
Ultra-low NOx (< 20 ppm) and CO (< 50 ppm) through MILD Combustion

Mixed-mode: key features of the MILD combustion process are preserved

Case Study I
Efficient operation in all three modes with maximum HTF temperature $\approx 800 ^\circ C$

- Mixed-mode: Higher $T_{\text{max, HTF}}$ and $\eta_{\text{coils}}$ compared with combustion-only
- Mixed-mode: $\eta_{\text{pot,th}}$ slightly smaller than that of combustion-only ($\approx 1.5\%$) but $\approx 15\%$ fuel consumption reduction

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**Case Study I**

NG, $P_{\text{in}} = 12\ kW$, $\phi = 0.9$
MILD vs Conventional combustion (non-premixed swirl flame):

- Higher thermal performance (up to 5%) and NO\textsubscript{x} reduction (≈85%)
- Lower radiative-to-convective heat transfer rate ratio (CFD analysis)
Stability Limits (MILD)

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

Dynamic Region

- Stable operation for:
  - $\eta_{\text{abs}}$ up to $\approx 24\%$ ($P_{\text{in}} = 12\ kW$)
  - $\eta_{\text{abs}}$ up to $\approx 42\%$ ($P_{\text{in}} = 18\ kW$)
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

Natural Gas
- Stable operation (Mixed) for:
  - $\eta_{abs}$ up to $\approx 28\%$ ($P_{in} = 12\ kW$)
  - $\eta_{abs}$ up to $\approx 47\%$ ($P_{in} = 18\ kW$)
Stability Limits - Effect of Hydrogen addition (MILD and Mixed)

NG/H₂ Blends (P_in = 12 kW)

MILD and Mixed Modes

- Dynamic region still observed (also for 100% H₂)
- H₂ addition → instabilities shift towards higher values of heat extracted (approx. linear trend with H₂ %)

Stable operation (MILD) for:
- η_abs up to ≈ 24% (H₂ = 0 %)
- η_abs up to ≈ 78% (H₂ = 100 %)

Stable operation (Mixed) for:
- η_abs up to ≈ 28% (H₂ = 0 %)
- η_abs up to ≈ 81% (H₂ = 100 %)
Stability Limits - Effect of Hydrogen addition (MILD and Mixed)

LPG/H₂ Blends (P_in = 12 kW)

LPG vs NG
- Wider range of stable operations
- Dynamic region still observed (but ‘smaller’)

Effects of CSR and H₂
- Similar to NG and NG/H₂ blends

Stable operation (MILD) for:
- η_abs up to ≈ 46% (H₂ = 0 %)
- η_abs up to ≈ 78% (H₂ = 100 %)

Stable operation (Mixed) for:
- η_abs up to ≈ 50% (H₂ = 0 %)
- η_abs up to ≈ 81% (H₂ = 100 %)
## Case Study II

| Mode               | Energy input, \( kW \) | Fuel, v/v          | Solar-to-Comb ratio, \( \% \) | HTF flow rate, \( slpm \) |
|--------------------|------------------------|--------------------|-------------------------------|--------------------------|
| Combustion-only    | 12                     | \( \text{H}_2/\text{CO} = 1, 2, 3 \& \infty \) | 0                             | 150-1000                 |
| Solar-only         | 0.8                    | /                  | 100                           | 150-1000                 |
| Mixed              | 12                     | \( \text{H}_2/\text{CO} = 1, 2, 3 \& \infty \) | 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

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

Case Study II
Ultra-low NO$_x$ (< 20 ppm) and CO (< 10 ppm) through MILD Combustion

Mixed-mode: key features of the MILD combustion process are preserved

**Case Study II**
Thermal performance

Key findings from demonstration

- Efficient operation in the three modes: $\eta_{th}$ up to 90%, $T_{HTF} > 750 \degree C$
- 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)

Case Study II
## Specific Fuel Consumption (SFC)

| sfc, kg/kWh | Combustion | Mixed | %   |
|-------------|------------|-------|-----|
| $H_2$       | 0.13       | 0.11  | 15.3|
| $H_2/CO = 2/1\text{v/v}$ | 0.24       | 0.2   | 16.7|

- Mixed mode vs Combustion
  - Net thermal gain
  - *SFC* reduced by $\approx 15\text{-}17\%$
| Mode                  | Energy input, kW | Fuel Type          | Equivalence ratio | Solar/combustion ratio, % | HTF flow rate, slpm |
|----------------------|------------------|--------------------|-------------------|--------------------------|---------------------|
| Combustion-only      | 10-20            | H₂, H₂/CO, NH₃     | 0.8-1             | 0                        | 150-1000            |

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

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

**H₂/CO MECHANISM:** PoliMI mechanism $\rightarrow$ 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$^2$K |
|-----------------------|-------------------------|--------------------------------------|-----------------|-------|---------------------|
| 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 $Q_{ex}$ presented here include $Q_{conv}$. The difference (kW) between the nominal power input and the sum of the measured values of the heat collected through the HX ($Q_{abs}$) and the specific losses ($Q_{losses}$) is also shown (absolute value).

| Fuel | Mode           | $\dot{Q}_{ex}$ | $\dot{Q}_{conv}$ | $\dot{Q}_{rad}$ | $\dot{Q}_{cond}$ | $|P_{in} - \dot{Q}_{losses} - \dot{Q}_{abs}|$ |
|------|----------------|----------------|------------------|-----------------|-----------------|------------------------------------------|
| 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
Net reaction rate of O2 along periodic plane

NO formation

H2, NH3
Key outcomes for HSRC

- MILD combustion successful stabilised for H₂, Syngas and NH₃
- It is found that Da < 1, low NOₓ and uniform Temperature

For Syngas
- CO acts as a ‘diluent’ in comparison with H₂ case.
- A decrease in H₂/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 H₂, Syngas and NH₃
- It is found that Da < 1, low NOₓ and uniform Temperature
- **For Syngas**
  - CO acts as a ‘diluent’ in comparison with H₂ case.
  - A decrease in H₂/CO leads to:
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- **For Ammonia**
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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 $T_{\text{cavity}} = 915^\circ\text{C}$
  - 100% LPG: instabilities start at $T_{\text{cavity}} = 790^\circ\text{C}$
  - 100% H2: instabilities start at $T_{\text{cavity}} = 615^\circ\text{C}$

- **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**
  - $T_{\text{coll}} = 610^\circ\text{C}$ when operated with 100% $H_2$ and 80% of heat extracted (MILD)
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 $\eta_{abs}$)
- Different modes → different trend in the axial distribution of heat flux on coils
Thank you for the attention