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

- Solar Receiver
- CPC
- Circulated Molten Salt
- Hot Storage Tank
- Circulated Steam
- Steam
- EPGS
- Boiler
- Fuel supply system
- Cold Storage Tank
- Heliostat Field

Integrated System

- Hybrid Receiver Combustor
- Aperture Shutter
- CPC
- Circulated Molten Salt
- Fuel supply line
- Hot Storage Tank
- Steam
- EPGS
- Steam Gen.
- Fuel supply system
- Cold Storage Tank
- Heliostat Field
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\textsubscript{x}
- Potential for enhanced heat transfer
- Fuel flexibility and uniform heat flux distribution
Magnitude of Estimated Benefits

Estimated benefits relative to "equivalent" conventional hybrid

Different scales up to $30\, MW_{th}$

- reduces capital cost by $\sim 21\%$ (Lim et al., 2016)
- reduces LCOE by $\sim 10-19\%$ (Lim et al., 2016)
- reduces fuel use and CO$_2$ by $\sim 10-20\%$ (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 ($\text{CH}_4 = 92\%$ v/v), LPG ($\text{C}_3\text{H}_8 = 97\%$), $\text{H}_2$, NG/$\text{H}_2$ and LPG/$\text{H}_2$ blends, and H2/CO (1/X).
- 5 kW$_{el}$ 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

[Diagram showing calculated thermal and flow fields (MILD)]

Laboratory-scale (20 kW) HSRC
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
\[ \eta_{\text{coil}} = \frac{Q_{\text{abs}}}{P_{\text{in}}} \quad \eta_{\text{pot,th}} = \frac{Q_{\text{abs}} + Q_{\text{rec,HX}}}{P_{\text{in}}} \]
<table>
<thead>
<tr>
<th>Mode</th>
<th>Energy input, $kW$</th>
<th>Fuel Type</th>
<th>Equivalence ratio</th>
<th>Solar/combustion ratio, %</th>
<th>HTF flow rate, slpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion-only</td>
<td>10-20</td>
<td>NG, LPG, $H_2$, NG/$H_2$, LPG/$H_2$</td>
<td>0.8-1</td>
<td>0</td>
<td>150-1000</td>
</tr>
<tr>
<td>Solar-only</td>
<td>0.8</td>
<td>/</td>
<td>/</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Mixed</td>
<td>10-20</td>
<td>NG, LPG, $H_2$, NG/$H_2$, LPG/$H_2$</td>
<td>0.8-1</td>
<td>6.6-8</td>
<td></td>
</tr>
</tbody>
</table>

**Combustion-only and mixed-mode:**
- Heat from exhaust is not recovered
- MILD Combustion: high-speed air jets ($80 < \nu_{air} < 120$ 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
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

- 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
Coil and Thermal Efficiencies

- Efficient operation in all three modes with maximum HTF temperature ≈800 °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 (≈1.5%) but ≈15% fuel consumption reduction

Maximum HTF Temperature

Case Study I
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)

Dynamic Region

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

Case Study I
**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:
  - $\eta_{\text{abs}}$ up to $\approx 28\%$ ($P_{\text{in}} = 12$ kW)
  - $\eta_{\text{abs}}$ up to $\approx 47\%$ ($P_{\text{in}} = 18$ kW)

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**Case Study I**
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 %)

Case Study I
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

<table>
<thead>
<tr>
<th>Mode</th>
<th>Energy input, kW</th>
<th>Fuel, v/v</th>
<th>Solar-to-Comb ratio, %</th>
<th>HTF flow rate, slpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion-only</td>
<td>12</td>
<td>$\text{H}_2/\text{CO} = 1, 2, 3 &amp; \infty$</td>
<td>0</td>
<td>150-1000</td>
</tr>
<tr>
<td>Solar-only</td>
<td>0.8</td>
<td>/</td>
<td>100</td>
<td>150-1000</td>
</tr>
<tr>
<td>Mixed</td>
<td>12</td>
<td>$\text{H}_2/\text{CO} = 1, 2, 3 &amp; \infty$</td>
<td>7</td>
<td>150-1000</td>
</tr>
</tbody>
</table>

**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 $\rightarrow$ typical for MILD Combustion
- Mixed-mode: key features of the MILD combustion process are preserved
Ultra-low NO\textsubscript{x} (< 20 ppm) and CO (< 10 ppm) through MILD Combustion

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

Key findings from demonstration

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

<table>
<thead>
<tr>
<th>sfc, kg/kWh</th>
<th>Combustion</th>
<th>Mixed</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2$</td>
<td>0.13</td>
<td>0.11</td>
<td>15.3</td>
</tr>
<tr>
<td>$H_2/CO = 2/1\text{v/v}$</td>
<td>0.24</td>
<td>0.2</td>
<td>16.7</td>
</tr>
</tbody>
</table>

- Mixed mode vs Combustion
  - Net thermal gain
  - $SFC$ reduced by $\approx 15$-$17\%$
### Case Study III

<table>
<thead>
<tr>
<th>Mode</th>
<th>Energy input, $kW$</th>
<th>Fuel Type</th>
<th>Equivalence ratio</th>
<th>Solar/combustion ratio, %</th>
<th>HTF flow rate, $slpm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion-only</td>
<td>10-20</td>
<td>$H_2$, $H_2/CO$, $NH_3$</td>
<td>0.8-1</td>
<td>0</td>
<td>150-1000</td>
</tr>
</tbody>
</table>

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

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

$a_g$ - 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).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Mode</th>
<th>$Q_{ex}$</th>
<th>$Q_{conv}$</th>
<th>$Q_{rad}$</th>
<th>$Q_{cond}$</th>
<th>$P_{in} - Q_{losses} - Q_{abs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG</td>
<td>Combustion-only</td>
<td>5.8</td>
<td>N/A</td>
<td>0.15</td>
<td>3.2</td>
<td>0.2</td>
</tr>
<tr>
<td>NG</td>
<td>Mixed</td>
<td>5.65</td>
<td>0.22</td>
<td>0.45</td>
<td>3.25</td>
<td>0.1</td>
</tr>
<tr>
<td>LPG</td>
<td>Combustion-only</td>
<td>5.5</td>
<td>N/A</td>
<td>0.18</td>
<td>3.3</td>
<td>0.25</td>
</tr>
<tr>
<td>LPG</td>
<td>Mixed</td>
<td>5.2</td>
<td>0.25</td>
<td>0.5</td>
<td>3.32</td>
<td>0.14</td>
</tr>
<tr>
<td>H$_2$</td>
<td>Combustion-only</td>
<td>4.8</td>
<td>N/A</td>
<td>0.28</td>
<td>3.75</td>
<td>0.2</td>
</tr>
<tr>
<td>H$_2$</td>
<td>Mixed</td>
<td>4.62</td>
<td>0.29</td>
<td>0.62</td>
<td>3.8</td>
<td>0.1</td>
</tr>
</tbody>
</table>

$P_{in}=12$ 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

Reaction Rate and NO for H2 and NH3 under MILD Conditions
Key outcomes for HSRC

- MILD combustion successful stabilised for H\textsubscript{2}, Syngas and NH\textsubscript{3}
- It is found that Da < 1, low NO\textsubscript{x} and uniform Temperature
- **For Syngas**
  - CO acts as a ‘diluent’ in comparison with H\textsubscript{2} case.
  - A decrease in H\textsubscript{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 NH\textsubscript{3}, 87 ppmv NO\textsubscript{x} @3\%O\textsubscript{2}**
- **NO\textsubscript{x} Source**
  - **For NH\textsubscript{3}:** 72% fuel-NO\textsubscript{x}, 18% N2O intermediate, 8% prompt, 2% thermal
  - **For H\textsubscript{2}:** 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:
    - 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 - 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 $T_{cavity} = 915\,^\circ C$
    - 100% LPG: instabilities start at $T_{cavity} = 790\,^\circ C$
    - 100% H2: instabilities start at $T_{cavity} = 615\,^\circ C$
- **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**
  - $T_{coll} = 610\,^\circ C$ 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 NOx (< 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 H2 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