Direct Integration of low-carbon and carbon-free fuels with Concentrated Solar Radiation

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Key drivers for hybridisation

**Potential for Firm Supply or continuous production**
- Particularly relevant to energy-intensive industrial processes

**Potential for increased capital utilisation**
- Shared infrastructure within CST plant
- Shared network infrastructure – grid and fuels

**Potential for increased efficiency**
- Reduced start-up and shut-down losses
- Reduced heat exchange area

Growing interests in hybrid solar thermal/combustion systems

- Combustion complements solar thermal energy/storage
- Potential to provide firm supply or continuous production (24/7)
- Reduce the need and/or cost of thermal storage
- Lower capital costs relative to combined solar-only plus combustion only

Hybrid Solar Receiver Combustor (HSRC)

- Direct hybridisation between a solar receiver and a combustor
- Single device
- Three modes of operation
  - Solar-only
  - Combustion-only
  - Mixed

HSRC - Concept

Stand-alone system

Integrated system

Magnitude of estimated benefits

**Technology Drivers**

**Reduced capital cost**
- Reduced infrastructure
- One system instead of two

**Reduced heat losses/thermal stress**
- Avoids thermal cycling, cooling
- Avoids need to start-up combustor

**Increased solar utilisation - harvesting of low-flux, intermittent solar resource**
- Useful contributions for shorter periods & lower fluxes

**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 $\sim 10\text{--}19\%$ (Lim et al., 2016)
- reduces fuel use and CO$_2$ by $\sim 10\text{--}20\%$ (Lim et al., 2016)
Solar Thermal Hybrid Combined Heat and Power
Target for Process Heat < 350°C

Thermal storage unit

Hybrid Boiler / Receiver

Pump (Compressor)

Turbine + Generator

Avoid dumping ~65% energy
Challenges

- Two different energy sources
- Different heat transfer mechanisms
- Design/optimisation
- Mixed-mode operation
- Effects of CSR on combustion process
- Avoid air ingress into and combustion product out of HSRC

Progress to date

- 2017: First demonstration with fossil fuels at lab-scale (TRL-4)
- No data for alternative fuels, sealing gas under development

Aims

- First-of-a-kind demonstration of HSRC fed with free-carbon fuels
  - Compare performance under different modes of operation
  - Advance current understanding of the mixed-mode
  - Data for models validation

Energy sources:
- H₂, Syngas (H₂/CO = 3/1 - 1/1)
- 5 kWₑₓ Xenon Arc Lamp (single)

Heat Transfer Fluid:
- Air
- Four coils

Combustion mode:
- MILD (low-NOₓ)

Annular arrangement
Laboratory-scale HSRC

Front-view

Side-view

During operation
Cases investigated

<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>10-20</td>
<td>H₂/CO = 1-∞</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>10-20</td>
<td>H₂/CO = 1-∞</td>
<td>4-8</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
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

Thermal efficiency:
- Mixed and combustion-only: considering heat recovering 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
\[ \eta_{\text{coil}} = \frac{q_{\text{abs}}}{P_{\text{in}}} \quad \eta_{\text{th}} = \frac{q_{\text{abs}} + q_{\text{rec,HX}}}{P_{\text{in}}} \]
Semi-uniform temperature and heat flux distribution → typical for MILD Combustion

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

Good Performance measured in all three modes

Thermal Efficiency

Key findings from demonstration

- Efficient operation in the three modes: $\eta_{th}$ up to 90%, $T_{HTF} > 750$ °C
- Low solar fluxes can be used to supplement combustion
- Convective losses through aperture < 50% of radiative (no wind)
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)

- 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>H₂</td>
<td>0.13</td>
<td>0.11</td>
<td>15.3</td>
</tr>
<tr>
<td>H₂/CO = 2/1v/v</td>
<td>0.24</td>
<td>0.2</td>
<td>16.7</td>
</tr>
</tbody>
</table>
Additional findings

- CSR has beneficial effects on the stability limits of the combustion process
- Mixed mode: Stable process in a wider range of operating conditions
Conclusions

**Technology**
- First demonstration of a 20 kW HSRC unit fed with alternative fuels
- Device can operate under 100% renewable
- Efficient operation in all three modes of operation
- Ultra-low NO\textsubscript{x} (< 20 ppm) and CO emission (< 10 ppm)

**Fundamentals**
- A single device can efficiently accommodate two different energy sources characterised by different heat transfer mechanisms
- Key features of the combustion process:
  - Not altered by interactions with CSR and heat/mass transfer with ambient
  - Mixed-mode: Net thermal gain from adding CSR relative to combustion-only
Laboratory-scale
- Assess performance at solar-to-fuel ratio up to 50%
- Assess performance under wind conditions (wind tunnel)
- Developing and testing of strategies to mitigate convective heat losses:
  - Fluidic seal
- Assess of other alternative fuels (e.g. NH$_3$)

Generation II
- New hybrid configurations which will be applicable to other receiver designs (e.g. billboard)
Thank you for the attention