Design and Construction of a 700kW High-Temperature Sodium Receiver

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Overview

- ASTRI program
- Concept design
- Structural integrity analysis
- Detailed design
- Construction
- Conclusions

Sneak preview: sodium receiver design (top left), completed prototype (top right), position of the receiver on the tower with the sodium loop (bottom left) and CSIRO Heliostat tower 2 where the receiver will be mounted (bottom right)
ASTRI program

- Australian Solar Thermal Research Institute (ASTRI): developing high-temperature CSP technologies to complement development of the supercritical CO₂ Brayton cycle
- Two pathways: liquid sodium and solid particles
- A strong focus on demonstration for the final year of the ASTRI program (2023)
Concept design

- Operating temperature range was set to match the Gen3 CSP Liquids Project at 520-740°C

Design criteria

- Successful operation and integration of a 700kW\textsubscript{th} sodium cavity receiver
- A design that is simple, scalable, and durable, supporting the objective of lowering the cost of CSP
- Validate receiver performance models using experimental data
- Increase understanding of receiver design interfaces with system balance of plant
- Demonstrate a receiver efficiency greater than 86%
Concept design development

Stage 1: concept generation and down-selection
(Coventry et al., APSRC 2019)
- Simplicity and scale up feasibility were key differentiators favouring the CSIRO-led design
- Consensus that the ANU-led design offered significant performance advantage

Stage 2: performance modelling including ray tracing and heat transfer modelling in CSIRO’s Heliosim software
(Potter et al., APSRC 2019)
- Shifted to a vertical tube-bank design (safety, mounting)

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver tube outer diameter</td>
<td>mm</td>
<td>25.4</td>
</tr>
<tr>
<td>Receiver tube separation</td>
<td>mm</td>
<td>0.7</td>
</tr>
<tr>
<td>Receiver tube count per tube bank</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Tube banks per flow path</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Flow paths</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Relative azimuth angle between adjacent tube banks</td>
<td>degrees</td>
<td>12</td>
</tr>
<tr>
<td>Irradiated length per pipe</td>
<td>mm</td>
<td>1300</td>
</tr>
</tbody>
</table>

ANU-led cylindrical cavity receiver
CSIRO-led tilted panel cavity receiver

Heliosim 3D surface model, with predicted absorbed solar flux at design point.
### Design point conditions and performance

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNI (W/m²)</td>
<td>W/m²</td>
<td>900</td>
</tr>
<tr>
<td>Installed heliostats (CSIRO Field 2)</td>
<td></td>
<td>396</td>
</tr>
<tr>
<td>Available heliostats</td>
<td></td>
<td>235</td>
</tr>
<tr>
<td>Utilised heliostats</td>
<td></td>
<td>235</td>
</tr>
<tr>
<td>Power through aperture</td>
<td>kW</td>
<td>782</td>
</tr>
<tr>
<td>Spillage loss</td>
<td>kW</td>
<td>38.5</td>
</tr>
<tr>
<td>Receiver solar reflection loss</td>
<td>kW</td>
<td>16.5</td>
</tr>
<tr>
<td>Receiver thermal radiation loss</td>
<td>kW</td>
<td>33.1</td>
</tr>
<tr>
<td>Receiver convection loss</td>
<td>kW</td>
<td>15.5</td>
</tr>
<tr>
<td>Receiver conduction loss</td>
<td>kW</td>
<td>6.4</td>
</tr>
<tr>
<td>HTF thermal output</td>
<td>kW</td>
<td>711</td>
</tr>
<tr>
<td>Aperture interception efficiency</td>
<td>%</td>
<td>95.3</td>
</tr>
<tr>
<td>Receiver efficiency</td>
<td>%</td>
<td>90.9</td>
</tr>
<tr>
<td>Combined interception and receiver efficiency</td>
<td>%</td>
<td>86.6</td>
</tr>
<tr>
<td>East flow path average mass flow rate per pipe</td>
<td>kg/s</td>
<td>0.183</td>
</tr>
<tr>
<td>West flow path average mass flow rate per pipe</td>
<td>kg/s</td>
<td>0.183</td>
</tr>
<tr>
<td>East flow path peak fraction of allowable net flux</td>
<td></td>
<td>0.955</td>
</tr>
<tr>
<td>West flow path peak fraction of allowable net flux</td>
<td></td>
<td>0.934</td>
</tr>
<tr>
<td>Peak insulation behind pipes surface temperature</td>
<td>°C</td>
<td>806</td>
</tr>
<tr>
<td>Peak shield surface temperature</td>
<td>°C</td>
<td>1116</td>
</tr>
<tr>
<td>Peak insulation surface temperature</td>
<td>°C</td>
<td>928</td>
</tr>
<tr>
<td>Peak pipes back surface temperature</td>
<td>°C</td>
<td>748</td>
</tr>
<tr>
<td>Peak pipes front surface temperature</td>
<td>°C</td>
<td>789</td>
</tr>
<tr>
<td>Peak average pipe wall temperature</td>
<td>°C</td>
<td>743</td>
</tr>
<tr>
<td>Peak temperature disparity across pipes in a single panel</td>
<td>°C</td>
<td>13.9</td>
</tr>
<tr>
<td>Peak sodium outlet temperature disparity</td>
<td>°C</td>
<td>16.8</td>
</tr>
<tr>
<td>Peak sodium temperature</td>
<td>°C</td>
<td>748</td>
</tr>
</tbody>
</table>
Structural integrity analysis

**Stage 1 design screening:** used a reduced 2D generalised plane strain analytical model (Logie et al., Solar Energy, 2018)

**Stage 2 design development:** detailed 3D Finite Element Analysis (FEA) evaluation
- Primary stresses (internal pressure, dead weight)
- Secondary stresses: due to thermal expansion under live loads

Peak allowable net flux for UNS N06625 for a mass flow of 0.18 kg s⁻¹.

Design tensile strength ($f$-values) for Alloy 625
• Highest flux is 0.76 MWm\(^{-2}\) (corresponding to bulk sodium temp 555°C, max surface temp 668°C)
• Tube bends significantly reduce equivalent stress
Detailed design

The receiver consists of:

- Tube banks
- Receiver frame and cladding
- Panel mounting system (on spring hangers)
- Instrumentation (thermocouples)
- Mechanical door
- Spill tray
- Interconnecting piping, including fill and drain lines and valves
- Heat tracing
- Insulation.

3D model of the sodium receiver showing a section view through the centre of the receiver, with the door removed to show the aperture.
Detailed design

- Designed to Australian Standard AS1210 2010 Class 1
- Operating pressure 200 kPa (gauge)
- Creep design life is 1000 h and number of design thermal cycles is 500,
- The design low cycle temperature is 300°C
- Total sodium volume 85 L.
- Post weld heat treatment not required
- Top headers were supported via a dummy leg, supported by spring hangers
- Tube bends allow deflection, stress relief, weld access
- Interconnecting pipe allows for thermal expansion mismatch
- Drain and fill lines also allow gravity drain in case of incident, with sodium returning to the drain tank
Detailed design

- The mechanical door closes when not in use, standby, or automatically in the event of tube failure
- Seals and water shedding features prevent water ingress even in driving rain
- A drip tray at the base can contain the entire inventory of sodium
- In the event of tube failure, smoke is vented to the scrubber system
- The tubes are painted with Pyromark 2500
- Instrumentation includes 67 thermocouples on the back of the panels, and on other piping
- Insulated with SiO$_2$-CaO-MgO (Superwool Plus) blanket
- Heat tracing on all pipework except the receiver tubes themselves
Construction

- The receiver tubes were bent and welded to the headers to form the tube banks by MCM Manufacturing.
- The receiver enclosure and door were fabricated by Performance Engineering Group, who also mounted the tube banks, and welded on the interconnecting pipework and valves.

The sodium receiver in various stages of construction showing (top) the completed tube banks and (bottom) the tube banks welded to the interconnecting piping.
Construction

Challenges

• The Alloy 625 material was not a simple material to weld. Weld rectification work was required for many of the welds in order to pass the NDT requirements.
• Sourcing of Alloy 625 grade 2 in the small quantities required for the prototype.
Conclusions

- Fabrication of the sodium receiver was completed in July 2022
- The receiver is designed to interface with a new sodium loop at CSIRO Newcastle
- On-sun testing expected to commence in mid 2023
- Commercial prospects for a high-temperature sodium pathway were assessed in the Gen3 CSP Liquid Pathways project, yielding promising LCOE of 58 USD/MWh (Source: Turchi et al., 2021)
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