Simulation of a demonstration high temperature liquid sodium receiver with Heliosim

Daniel Potter, Jin-Soo Kim and Robbie McNaughton
Presentation overview

1. Background
2. Experimental facility
3. Receiver design
4. Physical modelling
5. Results
6. Conclusions
Background

The ASTRI Integrated Test Facility program

- A high temperature liquid sodium loop with an on-sun receiver is to be installed and operated at the CSIRO’s ‘Solar Field 2’ experimental CST facility in Newcastle
- ANU and the CSIRO have developed a number of conceptual designs for the demonstration receiver, one of which has been selected for fabrication, installation and operation in 2020
- The demonstration receiver will have sodium inlet and outlet temperatures of 520 and 740 °C, respectively, and a nominal thermal capacity of 700 kW/m²
- The focus of this paper is the computational simulation of an early conceptual receiver design with CSIRO’s Heliosim software, considering various levels of geometric complexity
Background

Previous work

Optimised Design of a 1 MWt Liquid Sodium Central Receiver System

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Figure 1: The objective function workflow implemented in previous work for optimisation of a 1 MW<sub>th</sub> sodium receiver and heliostat field (Potter et al., 2015).
Background

Previous work

Figure 2: Surface mesh, absorbed solar flux and surface temperature distribution for a 1 MW$_{th}$ sodium receiver (Potter et al., 2015).
Background

Present work

- Include cylindrical geometry of heat transfer pipes in the receiver surface mesh used for both the solar flux and heat transfer simulations

(a) Liovic et al. (2014)

(b) Martinek et al. (2012)

Figure 3: Relevant prior art — simulation of solar reactors with ANSYS Fluent.
Experimental facility

‘Solar Field 2’ at CSIRO Newcastle

Figure 4: Photograph taken in 2011 of the ‘Solar Field 2’ experimental CST facility at CSIRO Energy in Newcastle, Australia.
Figure 5: Heliostat seating plan for ‘Solar Field 2’, with facet focal lengths ($f$) indicated. Heliostats used for the design point simulations considered in the present work are outlined in black. ‘$\times$’ denotes the likely location of sodium receiver aperture centroid.
### Experimental facility

#### Heliostats

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>396</td>
</tr>
<tr>
<td>Actuation</td>
<td>Tilt-roll</td>
</tr>
<tr>
<td>Facet width × height (m)</td>
<td>1.85 × 2.44</td>
</tr>
<tr>
<td>Facet focal length variants (m)</td>
<td>27, 35, 44, 50, 55</td>
</tr>
<tr>
<td>Nominal facet slope error (mrad)</td>
<td>1.4</td>
</tr>
<tr>
<td>Nominal tracking error (mrad)</td>
<td>1.0</td>
</tr>
<tr>
<td>Nominal facet solar specular reflectivity</td>
<td>0.9</td>
</tr>
<tr>
<td>Nominal focal point (m)</td>
<td>(0,0,26.8)</td>
</tr>
<tr>
<td>Likely location of sodium receiver aperture centroid</td>
<td>(-2.35, 0.23, 28.03)</td>
</tr>
</tbody>
</table>

Table 1: Heliostat parameters for the ‘Solar Field 2’ experimental CSP facility.
Figure 6: 3D rendering of a preliminary conceptual design for the ‘Mark I’ sodium receiver.
Receiver

3D visualisations in Heliosim

Figure 7: View of facility from the south-west.
Receiver

3D visualisations in Heliosim

Figure 8: View of facility from the west.
Receiver

3D visualisations in Heliosim

Figure 9: View of receiver and tower platform from the control room.
Receiver

3D visualisations in Heliosim

Figure 10: View of receiver from the control room.
Receiver

3D visualisations in Heliosim

Figure 11: View of receiver from the control room (shielding removed).
Figure 12: View of receiver from the control room (shielding and insulation removed).
Receiver

3D visualisations in Heliosim

Figure 13: View of heat transfer pipes from above (shielding and insulation removed).
Receiver

3D visualisations in Heliosim

Figure 14: View of heat transfer pipes through the aperture (shielding and insulation removed).
Figure 15: View of heat transfer pipes through the aperture (shielding and insulation removed, no rays).
Receiver

Dimensions

Figure 16: Drawings of a preliminary conceptual design for the ‘Mark I’ sodium receiver with key dimensions.
Figure 17: Diagrams of the flow path arrangement for a preliminary conceptual design of the ‘Mark I’ sodium receiver.
## Receiver

### Heat transfer pipes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe outer diameter (mm)</td>
<td>25.4</td>
</tr>
<tr>
<td>Pipe wall thickness (mm)</td>
<td>1.65</td>
</tr>
<tr>
<td>Pipe separation (mm)</td>
<td>2.5</td>
</tr>
<tr>
<td>Irradiated length of each pipe (m)</td>
<td>1.6</td>
</tr>
<tr>
<td>Pipe material</td>
<td>Seamless Inconel 625</td>
</tr>
<tr>
<td>Pipe coating</td>
<td>Pyromark 2500</td>
</tr>
<tr>
<td>Pipe count per module (0,1,2)</td>
<td>13, 12, 11</td>
</tr>
</tbody>
</table>

Table 2: Key heat transfer pipe parameters for the CSIRO ‘Mark I’ sodium receiver.
Physical modelling
Receiver geometry and meshing

Figure 18: Visualisations of the receiver meshes for the simple and detailed models. The meshes have been clipped by the vertical symmetry plane to show the cavity interior.
Physical modelling
Receiver geometry and meshing

Figure 19: Visualisations of the receiver meshes for the simple and detailed models. The meshes have been clipped by the vertical symmetry plane to show the cavity interior.
Physical modelling

Heliostat optics

Simulated using Heliosim’s GPU accelerated ray tracing model:

- Rays are cast from the primary reflection surfaces (i.e. heliostat facets)
- Incident direction, mirror intercept location and mirror surface normal direction calculated via Monte Carlo sampling of CDFs using the function inversion method
- Progressive deposition of absorbed energy on intercepted surfaces (i.e. energy partitioning)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun shape</td>
<td>Buie model (Buie et al., 2003)</td>
</tr>
<tr>
<td>Circumsolar ratio</td>
<td>0.02</td>
</tr>
<tr>
<td>Atmospheric attenuation</td>
<td>DELSOL3 23 km visibility model (Kistler, 1986)</td>
</tr>
<tr>
<td>Effective heliostat facet slope error (mrad)</td>
<td>1.72</td>
</tr>
<tr>
<td>Rays cast per heliostat (simple, detailed)</td>
<td>$10^5, 10^6$</td>
</tr>
<tr>
<td>Maximum surface interactions per ray</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3: Parameters for ray tracing simulation of the heliostat optics.
Physical modelling

Receiver heat transfer

- System of nonlinear equations is formed by the set of flux balances for each facet, where surface temperature is the independent variable.
- System is solved via Newton iterations:
  1. Steady state flux balance is calculated for each surface mesh facet
  2. Jacobian matrix is analytically calculated
  3. Jacobian matrix is inverted using the Armadillo linear algebra library (Sanderson and Curtin, 2016) with OpenBLAS backend (shared memory parallelisation)
  4. Surface temperature solution is updated via the Newton increment

Despite parallelisation, matrix inversion (Step 3) is by far the most computationally intensive part.
Physical modelling

Receiver heat transfer — pipes

\[ \sum_{j \neq i} N_s f_j,i \frac{A_j}{A_i} \epsilon_{t,j} \sigma T_{w,j}^4 + \left( 1 - \sum_{j \neq i} N_s f_j,i \right) \epsilon_{t,i} \sigma T_a \]

Absorbed thermal radiation

Absorbed solar radiation

\[ q_{s,i} \]

Convective cooling by ambient air

\[ \alpha_{a,i} \left( T_{w,i} - T_a \right) \]

Emitted thermal radiation

\[ \epsilon_{t,i} \sigma T_{w,i}^4 \]

Heat transfer fluid @ \( T_{f,i} \)

Radial conduction through wall to fluid

\[ \frac{k_{w,i} (T_{w,i} - T_{f,i})}{r_0 \ln \left( \frac{r_0}{r_i} \right) + r_0 \frac{k_{w,i}}{\epsilon_{f,i}}} \]

Figure 20: Illustration of terms included in the flux balance for each surface mesh facet.
Physical modelling

Receiver heat transfer — insulated surfaces

\[ \sum_{j \neq i} N_s f_{j,i} A_i \epsilon_{t,j} \sigma T_{w,j}^4 + \left( 1 - \sum_{j \neq i} N_s f_{j,i} \right) \epsilon_{t,i} \sigma T_a \]

Absorbed thermal radiation

Ambient air @ \( T_a \)

Convective cooling by ambient air

Absorbed solar radiation

\( q_{s,i} \)

Emitted thermal radiation

\( \epsilon_{t,i} \sigma T_{w,i}^4 \)

Insulation or casing wall outer surface @ \( T_{w,i} \)

Conduction through wall

\( k_w \frac{T_{w,a} - T_{w,i}}{t_w} \)

Adjacent wall @ \( T_{w,a} \)

Region of wall represented by projection of surface facet

Figure 21: Illustration of terms included in the flux balance for each surface mesh facet.
Physical modelling

Receiver heat transfer

Table 4: Input parameters for the receiver flux balance equations.

<table>
<thead>
<tr>
<th>Part</th>
<th>Pipes</th>
<th>Insulation</th>
<th>Casing</th>
<th>Shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Iconel 625</td>
<td>Isowool</td>
<td>Zincalume</td>
<td>253MA</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>1.65</td>
<td>400</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Solar reflectance</td>
<td>0.06</td>
<td>0.7</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Thermal emittance</td>
<td>0.85</td>
<td>0.5</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Thermal conductivity (W/m/K)</td>
<td>$5.53 + 1.43 \times 10^{-2}T + 4.19 \times 10^{-7}T^2$</td>
<td>0.25</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Ambient convection coefficient (W/m²/K)</td>
<td>10 (6.37)²</td>
<td>10 (0)²</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

* Value in parentheses is for the front half of the cylindrical pipes in the detailed model.
* Value in parentheses is for the insulation behind the pipes in the detailed model.

- Following Cagnoli et al. (2019), convection for rear half of pipes and insulation behind the pipes is set to zero and a correction factor of $\frac{2}{\pi}$ is applied for the front half of pipes.
- For the simple model, the rear half of the pipes is assumed adiabatic.
Results
Design point conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>Equinox</td>
</tr>
<tr>
<td>Time</td>
<td>Solar noon</td>
</tr>
<tr>
<td>Solar elevation angle (°)</td>
<td>56.9</td>
</tr>
<tr>
<td>Solar azimuth angle (°)</td>
<td>0</td>
</tr>
<tr>
<td>Direct normal irradiance (W/m²)</td>
<td>900</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 5: Design point solar and ambient conditions.
Results

Heliostat field utilisation

Figure 22: Heliostat utilisation for the Equinox design point with a DNI of 900 W/m².
Results

Absorbed solar flux distributions

Figure 23: Distribution of solar flux on the pipe modules from the design point simulations.
## Results

### Performance summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power through aperture (kW)</td>
<td>Simple</td>
<td>798.9</td>
<td>798.4</td>
</tr>
<tr>
<td></td>
<td>Detailed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spillage loss (kW)</td>
<td></td>
<td>26.0</td>
<td>26.1</td>
</tr>
<tr>
<td>Receiver solar reflection loss (kW)</td>
<td></td>
<td>14.9</td>
<td>13.1</td>
</tr>
<tr>
<td>Receiver thermal radiation loss (kW)</td>
<td></td>
<td>28.9</td>
<td>27.2</td>
</tr>
<tr>
<td>Receiver convection loss (kW)</td>
<td></td>
<td>47.9</td>
<td>45.8</td>
</tr>
<tr>
<td>Receiver conduction loss (kW)</td>
<td></td>
<td>5.2</td>
<td>6.7</td>
</tr>
<tr>
<td>HTF thermal output (kw)</td>
<td>Simple</td>
<td>702.0</td>
<td>705.6</td>
</tr>
<tr>
<td></td>
<td>Detailed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aperture interception efficiency (%)</td>
<td></td>
<td>96.84</td>
<td>96.83</td>
</tr>
<tr>
<td>Receiver efficiency (%)</td>
<td></td>
<td>87.88</td>
<td>88.37</td>
</tr>
<tr>
<td>Combined interception and receiver efficiency (%)</td>
<td></td>
<td>85.10</td>
<td>85.57</td>
</tr>
<tr>
<td>East flow path average mass flow rate per pipe (kg/s)</td>
<td>Simple</td>
<td>0.100</td>
<td>0.100</td>
</tr>
<tr>
<td></td>
<td>Detailed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>West flow path average mass flow rate per pipe (kg/s)</td>
<td></td>
<td>0.112</td>
<td>0.113</td>
</tr>
<tr>
<td>East flow path peak net flux (kW/m²)</td>
<td></td>
<td>706.0</td>
<td>721.7</td>
</tr>
<tr>
<td>West flow path peak net flux (kW/m²)</td>
<td></td>
<td>728.6</td>
<td>753.2</td>
</tr>
</tbody>
</table>

Table 6: Summary of results for design point simulations.
Results

Flow path profiles

Figure 24: Comparison of eastern flow path profiles for the simple and detailed model. Net flux is the heat conducted radially through the pipe wall to the fluid. For the detailed model, the maximum net flux is used for axial location.
Discussion

Net flux

Figure 25: Circumferential distributions for the middle-most pipes of the modules in the eastern flow path.
Discussion

Grid resolution

Figure 26: Resource usage and calculated result as a function of cell count in the receiver mesh for the simple model (●) and detailed model (—●—).
Conclusion
Findings from present work

- Representing pipe modules as flat surfaces provides a rapid (a few minutes) and reasonably accurate (to within 0.5 %) means of estimating receiver thermal output.
- However, net flux through the pipe wall can be significantly underestimated (up to 7 %).
- The detailed model should therefore be preferred, especially when the design is limited by thermally induced stress and incident irradiance is not normal to the pipe crown.
- However, the current approach to simulating the receiver heat transfer is not scalable to high resolution meshes.
Conclusion

Future work

Possible options for improving the computational performance of the detailed model:

1. Encoding a more accurate estimation of the Jacobian matrix so that the number of iterations (and therefore wall time) to convergence is reduced,
2. Using a Jacobian-free nonlinear solver such as the Newton-Krylov method to significantly reduce the memory requirement, or
3. Simulating the complete conjugate heating problem with a finite volume framework such as OpenFOAM.
Acknowledgements

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References


Thank You

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