Thermal Resistance Model for CSP Central Receivers

by Oelof de Meyer

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Qualifications  2010, B.Eng. (Mechatronics), Stellenbosch University  
2012, M.Sc. (Electrical Eng.), University of Cape Town

Work Experience  2011, Eskom : Control & Instrumentation
•   Matimba C&I Refurbishment,  
    2011/11 - 2012/06
•   Lead Discipline Engineer for:
  •   Eskom 100MW CSP Plant  
      2011/11 - present  
  •   Solar Augmentation  
      2013/10 - present  
  •   SERE Wind 100MW  
      2014/03 – present

Further Studies  2014, Eskom Power Plant Engineering Institute (EPPEI)  
•   PhD Program – Stellenbosch University
Concentrated Solar Power

Ivanpah, 337 MW

173,500 heliostats
140m tower
Introduction: Molten Salt Central Receiver
Operating Strategy and Philosophy optimisation for a 100 MW CSP Plant
PhD Research Topic (In Short)

- Power Purchase Agreement (PPA) initials “Operating Strategy”
  - Agreement between Independent Power Producer (IPP) and Utility / System Operator
- IPP design, build and optimise plant to adhere to PPA
- IPP business is *money*,
  - thus maximise power production
  - Minimise energy losses
  - Minimise O&M costs
  - = Max Revenue

For Example:
PPA = 75 MW between 4-10 pm
Thus storage of about 6 hours
Start/Stop turbine each day
Etc...
“Design Plant accordingly”

- What happens if you have a varying operating strategy?
  - “Flexible Plant required”
  - Optimisation of plant operation

Eskom is not an IPP
PhD Research Topic

Operating Strategy and Philosophy optimisation for a 100 MW CSP Plant

Operating Philosophy (Process Plant) relationship Operating Strategy (SA Grid)

Plant Model

System Operator

Solar Field & Weather Data

*Done: Sep 2014

Receiver Model

*Done: Jan 2015

Thermal Energy Storage

*Done: June 2015

Power Block

Grid
Receiver Thermal Resistance Model

\[ \dot{Q}_{\text{in}} = \dot{Q}_{\text{rad(\text{ext})}} + \dot{Q}_{\text{field}(1 - \rho)} + \dot{Q}_{\text{ref}} \]

\[ T_{\text{surr}} \quad R_{\text{rad(\text{ext})}} \quad T_{\text{field}} \quad R_{\text{field}(1 - \rho)} \quad T_{\text{ref}} \quad \dot{Q}_{\text{in}} \]

\[ T_{\text{s}} = R_{\text{cond(t)}} \quad T_{t} = R_{\text{conv(in)}} \quad T_{m} = \Delta y \]

\[ T_{o} \quad T_{i} \]

\[ \eta_{\text{tube}} \quad \rho_{\text{tube}} \]
Model Capabilities

Solar Field & Weather Data
- TMY Data
  - Ambient Temperature
  - Wind speed
  - DNI etc.

DELSOL3
12x10 Receiver Flux Map

Evaluate:
- Aiming Strategy used
- Receiver design/materials
- Tube strain per panel, O&M

Temperatures:
- Inner tube
- Receiver surface
- HTF outlet temperature

Receiver Efficiency
- Receiver heat losses
- HTF thermal energy gained
- HTF mass flow rate

Evaluate:
- Receiver design/materials
- Pressure drop across receiver
How does the model work?

Receiver design & configuration:
- Height: 19.24 m
- Diameter: 16.32 m
- Panels: 16
- Tube diameter: 50 mm
- Tube thickness: 1.5 mm

Flow regime:
- 2x flows with cross over halfway
- HTF enters from South panel
- HTF exit through North panel

Step 1:
Determine HTF mass flow rate in flow regimes by determining:
- Heat loss per panel
- Heat gained per panel

*Initial surface temperature guess values required*
How does the model work?

**Step 2:**
Use HTF mass flow rate to determine temperature rise in HTF

**Step 3:**
Use bulk fluid temperature to determine:
- Inner tube temperature
- Outer tube temperature (surface)
- Corresponding heat loss
  - Radiation, convection

*Steady state model requires iterations due to initial surface temperature guess values*
Results

Temperature Distribution in Receiver Panels for Flow Regime 1

- Flux Map kW/m²: DAY 81 HOUR 12
- Surface Temperature °C: DAY 81 HOUR 12
- Tube temperature °C: DAY 81 HOUR 12

- Receiver Height
- Panel Number

- Surface Temperature Distribution
- Inner Tube Temperature
- Heat Transfer Fluid (Molten Salt)
Morning, Mid-day and Afternoon – Case Studies

Flux Map kW/m²: DAY 272 HOUR 7

Flux Map kW/m²: DAY 272 HOUR 12

Flux Map kW/m²: DAY 272 HOUR 17

Ts [°C]: DAY 272 HOUR 7

Ts [°C]: DAY 272 HOUR 12

Ts [°C]: DAY 272 HOUR 17
You may think... Yes, results are nice and pretty, but surely someone developed this model already?!

Yes!

Similar models are being developed to analyse
- Receiver design
- Receiver material
- Pressure drop calculations
- Tube-strain of panels
- Etc...

- My overall research requires a model with the level of similar to results on a basic design.

- The model will be assigned some intelligence during the operating philosophy optimisation phase

- My model is not a “black box”
  • Know what is going in and out – verified!
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Summary

- Model provide methodology used to obtain
  - HTF mass flow rate through receiver
  - Surface temperature distribution
  - Inner tube temperature distribution
  - Heat losses
  - Receiver Efficiency
  - Result of Heliostat field aiming strategy
  - Corresponding receiver pressure drop
  - Tube-strain per panel can be obtained
What is next?
### Heliostat Field & Flux Maps – DONE!!

**Heliostat Aiming Strategy**

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<th>SIGAZ= Foundation motion</th>
<th>SIGSX= Mirror waviness</th>
<th>SIGSY= Panel alignment error</th>
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<tr>
<td><strong>SIGAZ= 0</strong></td>
<td>7.48</td>
<td>271</td>
<td>280</td>
<td>441</td>
<td>622</td>
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<tr>
<td><strong>SIGSX= 0</strong></td>
<td>5.34</td>
<td>365</td>
<td>394</td>
<td>597</td>
<td>826</td>
</tr>
<tr>
<td><strong>SIGSY= 0</strong></td>
<td>3.21</td>
<td>314</td>
<td>362</td>
<td>558</td>
<td>819</td>
</tr>
<tr>
<td><strong>SIGTX= 0</strong></td>
<td>1.07</td>
<td>277</td>
<td>328</td>
<td>481</td>
<td>750</td>
</tr>
<tr>
<td><strong>SIGTY= 0</strong></td>
<td>-1.07</td>
<td>278</td>
<td>330</td>
<td>485</td>
<td>755</td>
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<tr>
<td><strong>#_Heli= 8965</strong></td>
<td>-3.21</td>
<td>319</td>
<td>369</td>
<td>565</td>
<td>829</td>
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<tr>
<td><strong>SIGEL= 0</strong></td>
<td>-9.62</td>
<td>60</td>
<td>56</td>
<td>102</td>
<td>156</td>
</tr>
</tbody>
</table>

**GrossP= 651.72 MWT**

Area= 9.13 m²

GrossPM= 660.35 MWT

-1.32%

NetP= 87.59 Mwe

---

**Heliostat Error (Ideal)**

<table>
<thead>
<tr>
<th>DAY</th>
<th>HOUR</th>
<th>COSINE</th>
<th>SHADOW</th>
<th>BLOCK</th>
<th>AIR ATT</th>
<th>SPILLAGE</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81.00</td>
<td>0.00</td>
<td>0.83</td>
<td>1.00</td>
<td>0.98</td>
<td>0.92</td>
<td>0.99</td>
</tr>
</tbody>
</table>

**GrossP= 658.42 MWT**

Area= 9.13 m²

GrossPM= 660.75 MWT

-0.85%

NetP= 88.54 Mwe

---

**Heliostat Error (Ideal)**

<table>
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<th>BLOCK</th>
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<td>1.00</td>
<td>0.98</td>
<td>0.92</td>
<td>0.99</td>
</tr>
</tbody>
</table>

**GrossP= 668.40 MWT**

Area= 9.13 m²

GrossPM= 668.62 MWT

-1.40%

NetP= 88.68 Mwe

---

**Heliostat Error (Ideal)**

<table>
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<th>SHADOW</th>
<th>BLOCK</th>
<th>AIR ATT</th>
<th>SPILLAGE</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81.00</td>
<td>0.00</td>
<td>0.79</td>
<td>1.00</td>
<td>0.98</td>
<td>0.92</td>
<td>0.86</td>
</tr>
</tbody>
</table>

**GrossP= 669.33 MWT**

Area= 9.13 m²

GrossPM= 670.75 MWT

-1.73%

NetP= 88.71 Mwe

---

**Heliostat Error (Ideal)**

<table>
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<tr>
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<th>BLOCK</th>
<th>AIR ATT</th>
<th>SPILLAGE</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81.00</td>
<td>0.00</td>
<td>0.86</td>
<td>1.00</td>
<td>0.98</td>
<td>0.92</td>
<td>0.86</td>
</tr>
</tbody>
</table>
Receiver Model – DONE!!

Temperature Distribution in Receiver Panels for Flow Regime 1

\[ \dot{Q}_{\text{rad(xy)}} = \frac{(T_s - T_{\text{surr}})}{R_{\text{rad(ext)}}} \]

\[ \dot{Q}_{\text{conv(xy)}} = \frac{(T_s - T_{\text{amb}})}{R_{\text{conv(ext)}}} \]
Power Block Model – DONE!!!

**Diagram Details**

- **Pressure (bar)**: 120.00, 21.79, 21.79, 10.94, 4.87, 1.86, 0.58, 0.1363
- **Temperature (°C)**: 541.36, 306.89, 543.45, 442.99, 334.20, 221.67, 109.47, 52.00
- **Enthalpy**:
  - 3459
  - 3035
  - 3583
  - 3355
  - 3198
  - 2015
  - 2760
  - 2585

**Diagram Components**

- **Power Flow Diagram**
  - HTF_m: 540.35 [kPa]
  - HTF_T: 595.00 [°C]
  - Reheater: HTF_RH: 456.20 [°C], HTF_T2: 308.50 [°C], PT_T: 543.45 [°C], HTF_m_Rh: 236.00
  - Superheater: HTF_SH: 455.98 [°C], HTF_T1: 541.36 [°C], HTF_m_SH: 310.35
  - Boiler: HTF_m_BC: 339.78 [°C], FW_T1B: 324.68 [°C]
  - Pro-Heater: HTF_P1H: 288.43 [°C], FW_T1T: 323.07 [°C]
  - Total Work (W_Total): 101.54 MW
  - Steam_mon: 77.22

**Additional Details**

- **Heat Transfer**
  - AU: 474
  - AU_ref: 574
  - Q_SH: 51.3 [kW]
  - Q_B: 79.1 [kW]
  - Q_DH: 30.0 [kW]
  - Q_TOT: 203.2 [kW]
  - Q_TOT_sys: 213.059

**Temperature-Heat Transfer Diagrams**

- **HP FWH 2: TQ Diagram**
- **HP FWH 1: TQ Diagram**
- **LP FWH 2: TQ Diagram**
- **LP FWH 1: TQ Diagram**

**Diagram Legends**

- **Bled Steam**
- **Feedwater**
- **Series1**
- **Series2**
- **Bled + Flash Steam**
- **Feedwater**
Operating Philosophy

System Operator

Plant Status

Weather Conditions

Field

Receiver

Hot Tank

Steam Generator

Turbine Generator

Cold Tank
Thank you..
Questions