Solar Receiver Modeling
Central Receiver
• Introduction

• Tubular receiver

• Volumetric receiver

• Solid particle receiver

• Conclusion
Higher efficiency power cycles pursued to reduce LEC → High-temperature receivers

Challenges:

- Development of optimized geometric designs
- High temperature materials
- Heat-transfer fluids
- Maximize absorptance, minimize heat loss
- High reliability over thousands of thermal cycles
- Direct vs. indirect heating

No intermediate heat exchange → Ability to store the heat transfer media
Receiver thermal efficiency: $\eta_{th} = \frac{\alpha Q_{in} - Q_{loss}}{Q_{in}} = \alpha - \frac{\varepsilon F_{view} T_R^4 + f_{conv} h_{conv} (T_R - T_{amb})}{\eta_{field} E_{DNA}}$
Receiver thermal efficiency: 

\[
\eta_{th} = \frac{\alpha Q_{in} - Q_{loss}}{Q_{in}} = \alpha - \theta F_{view} T_R^4 + f_{conv} h_{conv}(T_R - T_{amb}) \eta_{field} E_{DNI} C
\]
Receiver thermal efficiency: \[ \eta_{th} = \frac{\alpha Q_{in} - Q_{loss}}{Q_{in}} = \alpha - \varepsilon \sigma F_{\text{view}} T_R^4 + f_{\text{conv}} h_{\text{conv}} (T_R - T_{amb}) \frac{\eta_{field} E_{DNI} C}{\eta_{f}} \]
Introduction

Tubular receiver

Volumetric receiver

Solid particle receiver

Cavity receiver
Solhyco (SOlar HYbrid power and COgeneration plant)

- Developed by DLR (Germany)
- Profiled multi-layer tube (Alloy/Copper/Alloy)

Temperature profile

Ref.: P. Heller, Solar-Hybrid Power and Cogeneration Plants, Final public report, 2011
Solhyco (SOLar HYbrid power and COgeneration plant)

- 40 metallic tubes of 2.5 meter length arranged in a cavity and connected in parallel
- Wire-coil insert to enhance the heat transfer
- Unpressurized quartz window implemented to reduce thermal radiation and convection losses

Ref.: P. Heller, Solar-Hybrid Power and Cogeneration Plants, Final public report, 2011
Model:
- FEMRAY (Finite Element Mesh Ray Tracing) to estimate the heat flux distribution
- Creation of a 3D-finite-element model (FEM)
- Absorber tubes and cavity considered, distributor and collector neglected
- Thermal heat transfer in the tubes: Nusselt-correlation
- Thermal radiation between tubes, walls and environment taken into account
- Convection losses neglected and cavity walls considered adiabatic
- Receiver designed for a pressure drop of 70 mbar in the tubes

Ref.: P. Heller, Solar-Hybrid Power and Cogeneration Plants, Final public report, 2011
PEGASE (Production of Electricity from GAs and Solar Energy)

- Developed by CNRS-PROMES (France)
- Manufacturing of the absorber module (50 x 200 x 400 mm) using HIP process to weld Copper and Incoloy
- Whole absorber: 1.2 m x 1.2 m, 16 modules (8 per stage)
- Cavity of 1 m deep
- Heliostat field not adapted to develop a conical cavity
- Absorber modules designed for a pressure drop of 150 mbar

Ref.: B. Grange, Modélisation et dimensionnement d’un récepteur solaire à air pressurisé pour le projet PEGASE, PhD, 2012
PEGASE (Production of Electricity from GAs and Solar Energy)

• Assessment of the heat flux distribution with SolTrace
• Analysis of the first impact of the concentrated sunlight
• Reflection and radiation calculated in the net radiation method
• Steady-state analytical model
• Finite element discretization of the receiver
• 3 temperatures for each element
• Heat transfer coefficient and pressure drop in the tubes correlated with experimental results
• Losses considered
  - Through aperture (convective and radiative)
  - Back of the cavity/absorber

Ref.: B. Grange, Modélisation et dimensionnement d’un récepteur solaire à air pressurisé pour le projet PEGASE, PhD, 2012
Methods to calculate the convective coefficient:

- Clauing model
  - Power gained by the air slipping out of the cavity: \( P_a = \rho_{air} \cdot u_{air} \cdot S_{ouv} \cdot c_{p,air} \cdot (T_c - T_{amb}) \)
  - Convective heat loss power: \( P_c = h_{conv} \cdot S_{cav} \cdot (T_{rec} - T_{ref}) \)
  - Bayley correlation:
    \[
    Nu = 0.082 \cdot (Gr \cdot Pr)^{\frac{1}{2}} \cdot \left[ -0.9 + 2.4 \left( \frac{T_{rec}}{T_{amb}} \right) - 0.5 \left( \frac{T_{rec}}{T_{amb}} \right)^2 \right] \text{ with } T_c \text{ verifying } P_a = P_c
    \]

- Correlation of S. Paitoonsurikarn
  \[
  Nu_L = \frac{h_{conv} \cdot L_S}{\lambda_{air}} \quad Ra_L = \frac{g \cdot \beta_{air} \cdot (T_{rec} - T_{amb}) \cdot L_S^3}{\alpha_{air} \cdot \nu_{air}} \quad Pr = \frac{\mu_{air} \cdot c_{p,air}}{\lambda_{air}}
  \]
  \[
  L_S = \left| \sum_{i=1}^{3} a_i \cdot \cos(\theta + \theta_i)^b \cdot L_i \right|
  \]
  \[
  Nu_L = 0.0196 \cdot Ra_L^{0.41} \cdot Pr^{0.13}
  \]

Ref.: B. Grange, Modélisation et dimensionnement d’un récepteur solaire à air pressurisé pour le projet PEGASE, PhD, 2012
S. Paitoonsurikarn and K. Lovegrove (2011), Numerical investigation of natural convection loss from cavity receivers in solar dish applications, Transactions of the ASME 133(2)
PEGASE (Production of Electricity from GAs and Solar Energy)

- Radiosity balance

  - J. R. Howell law:

\[ \mathcal{G} = \frac{1}{2\pi} \left[ \frac{r^2}{(r^2 + a^2)^{3/2}} \tan^{-1} \left( \frac{r-a}{a \sqrt{r^2 + a^2}} \right) \right] \]

  - Net-radiation method (2 spectral bands):

\[ J^S_i = \rho^S_i \left( \varphi^{inc}_i + \sum_j F_{ij} \cdot J^S_j \right) \]

\[ J^{IR}_i = \epsilon_i \cdot \sigma_{bolz} \left( T_i^{rec} \right)^4 + \rho^S_i \cdot \left( \sum_j F_{ij} \cdot J^{IR}_j \right) \]

\[ P_{i, nette} = S_i \cdot \left( \varphi^{inc}_i + \sum_j F_{ij} \cdot J_j - J_i \right) \]
Tubular receiver

PEGASE (Production of Electricity from GAs and Solar Energy)

- Iterative method

  - Convective transfer in the tubes
    \[
    P_{i}^{\text{éch}} = h_{i}^{\text{glob}} \cdot S_{i} \cdot (T_{i}^{\text{réc}} - T_{i}^{\text{moy}}) \quad \rightarrow \quad T_{i}^{s} = T_{i}^{e} + \frac{P_{i}^{\text{éch}}}{m_{i}^{\text{air}} \cdot c_{p,\text{air}}}.
    \]

  - Residual power calculation
    \[
    P_{i}^{\text{rés}} = P_{i}^{\text{nette}} - \left( P_{i}^{\text{éch}} + P_{i}^{\text{perdue}} \right).
    \]

  - By introducing a time interval \( \Delta t \), the residual power is converted into heat in the metal
    \[
    T_{i,n+1}^{\text{réc}} = T_{i,n}^{\text{réc}} + \frac{P_{i}^{\text{rés}} \times \Delta t}{m_{i}^{\text{réc}} \cdot c_{p,\text{réc}}}.
    \]

  - Radiative balance in the infra-red spectral band with the new metal temperatures

  - Iterative loop: the thermal balance is reached when \( T_{i,n+1}^{\text{réc}} - T_{i,n}^{\text{réc}} < \text{critère} \)

Ref.: B. Grange, Modélisation et dimensionnement d’un récepteur solaire à air pressurisé pour le projet PEGASE, PhD, 2012
PEGASE (Production of Electricity from GAs and Solar Energy)

➢ Results of ray-tracing software SolTrace

Ref.: B. Grange, Modélisation et dimensionnement d’un récepteur solaire à air pressurisé pour le projet PEGASE, PhD, 2012
Tubular receiver

PEGASE (Production of Electricity from GAs and Solar Energy)

- Results of the analytical model

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</table>

Ref.: B. Grange, Modélisation et dimensionnement d’un récepteur solaire à air pressurisé pour le projet PEGASE, PhD, 2012
PEGASE (Production of Electricity from GAs and Solar Energy)

- Current study
  - Increasing the number of tube’s row in the depth of the module absorber to decrease the pressure drop
  - Enhance the air alimentation in the module
    - Numerical simulation (FLUENT) using UDF for heat transfer and pressure drop in the tubes

- Perspective
  - Comparing simulated results with experimental data (module absorber and whole receiver)

Ref.: B. Grange, Modélisation et dimensionnement d’un récepteur solaire à air pressurisé pour le projet PEGASE, PhD, 2012
The main goals for the optimization of the volumetric receiver concept are:

• Achievement of high heat transfer coefficients to ensure small temperature differences between gas and absorber

• Low manufacturing costs in comparison to other receiver types (e.g. nitrate salt or sodium receiver)

• Minimize the emissive losses by having a temperature distribution of the absorber rising from the entrance region of the solar radiation to the inner region of the volumetric receiver

Under development since the 1980s

Porous structure irradiated by concentrated sunlight

Two types: open-loop (no pressurization) and closed-loop (pressurization)

Volumetric receiver

DIAPR (Directly Irradiated Annular Pressurized Receiver)

- Developed by Weizmann Institute (Israel)

- Volumetric cavity receiver

- Array of Pin-Fins, constructed with elongated heat transfer elements (Porcupine ‘quills’), implanted in a base plate

- Quills are made of ceramic tubes or rods and the base is made of a relatively soft ceramic insulation board

- Orientation of the pins is designed to match the mean direction of the incoming radiation

- Spacing between them is determined so that the desired radiative flux penetration into the depth of the absorber is obtained

DIAPR (Directly Irradiated Annular Pressurized Receiver)

Computational code includes:

- Models for hydrodynamics, heat convection and radiation transfer in the Porcupine
- Coupling of the inner receiver continuum models to a statistical (Monte-Carlo) treatment of the external radiation field
- Incorporation of the model within the numerical code PHOENICS

Volumetric receiver

Pressurized air receiver of ETH (Switzerland)

• Annular reticulate porous ceramic (RPC) bounded by two concentric cylinders

• CPC at the aperture to boost the solar concentration ratio and reduce the aperture size and reradiation losses

• Absorbed heat is transferred by conduction, radiation, and convection to the pressurized air flowing across the RPC

• Outer cylinder is made of nonporous insulating material and is surrounded by a metallic shell to maintain the inner pressure of 10 bar.

Volumetric receiver

Pressurized air receiver of ETH (Switzerland)

• 2D axisymmetric steady-state heat transfer model

• Radiative transfer is modeled by employing three different approaches: the Rosseland approximation, the P1 approximation, and the collision-based Monte Carlo method

• Finite volume technique applied

Solid phase:
\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r k_s \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k_s \frac{\partial T}{\partial z} \right) - s h (T_s - T_f) + q_r = 0
\]

Fluid phase:
\[
\rho v_c \frac{\partial T_f}{\partial z} = s h (T_s - T_f)
\]

solved iteratively using Gaussian elimination implemented in MATLAB

http://www.mathworks.fr/fr/help/symbolic/mupad_ref/linalg-gausselim.html

radiative source distributions (from Rosseland, P1 or MC) calculated at each iteration

Pressurized air receiver of ETH (Switzerland)

- Results of the model

Radiative source term within the RPC in the radial direction (at z=0.008 m)

P1 used for further calculations because:
- significant savings in computation times
- improved accuracy

Pressurized air receiver of ETH (Switzerland)

- Results of the model

- Power inputs in kW (solid lines)
- Constant mass flow rates in g/s (dotted lines)
- Reference case indicated by the star

For the reference case, $\eta_{\text{thermal}} \sim 68\%$

Pressurized air receiver of ETH (Switzerland)

- Results of the model – Parameter study

\[ \Delta P = \frac{P - P_{\text{ref}}}{P_{\text{ref}}} \]

- Largest effect is observed for the cavity’s radius and length
- Since \( q_{\text{solar}} \) is kept constant, a smaller radius implies higher solar concentration ratios and reduces the reradiation losses
- Optimum length results from a tradeoff between capturing efficiently the concentrated solar radiation while keeping the highest temperature at the back of the cavity
- Further increase in thermal efficiency may be achieved by decreasing the RPC’s thickness and increasing the INS’s thickness, but at the expense of increasing the thermal inertia of the system, which results in longer startups

Developed by DLR (Germany)

Secondary concentrator and a pressurized volumetric receiver unit (concave fused silica window)

Ceramic foam absorber installed on ceramic mounting structure

Rib geometry was selected to lower the amount of ceramic structures

12 rib segments held together by two clamping rings

Critical point: pressurized window

Development of active window cooling based on air jets blowing towards the window to reach air outlet temperature above 800°C

Ref.: European Commission (2005), SOLGATE – Solar hybrid gas turbine electric power system, Final publishable report, EUR 21615, pp. 47
REFOS (Solgate project)

- Radiative heat transfer between the absorber, semi-transparent window, and ambient modeled by applying the enclosure method (zone method)


Assumptions:

- Radiation spectrum modeled by discretization in different wavelength bands

- Geometry discretized into many different zones, each zone is assigned individual spectral properties

- To account for transversal heat flux inside the glass volume, the concept of effective thermal conductivity is applied

- Temperature, incident and outgoing flux density distributions assumed to be homogeneous over each zone

- Surfaces possess diffuse radiative characteristics
REFOS (Solgate project)

- Net radiation method applied
- Configuration factors of different zones are determined by a ray-tracing algorithm
- Four wavelength bands were used to model the spectral properties of fused silica

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda_{i-1}$ in $\mu$m</th>
<th>$\lambda_i$ in $\mu$m</th>
<th>$T_{\Delta\lambda}$</th>
<th>$R_{\Delta\lambda}$</th>
<th>$A_{\Delta\lambda}$</th>
<th>Radiant power fraction* in %</th>
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<td>0.131</td>
<td>0.055</td>
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<td>8–4</td>
</tr>
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</table>

*Approximate values for receiver operation between 800°C and 1200°C.

Simulated  Measured

Good agreement

Solugas project = Solhyco + Solgate

- 10 modular panels to keep the overall stresses as low as possible and increase the lifetime expectation

- Honeycomb of several ceramic volumetric receiver individually equipped with pressurized quartz windows to get around the thermo-mechanical constraints

Ref.: M. Quero, Solugas – Future solar hybrid technology
• Indirect heating

• Solid particles fed from the top of the receiver

• Air jet may be added on the top of the aperture to separate hot air within the receiver and cold air out of the receiver

• Aerodynamic behavior of particles is impacted by the wind, the air jet flow, the air flow inside the receiver induced by the falling of particles, and the temperature difference

• Thermal interactions that need to be investigated are:
  - particle-particle radiation
  - particle-wall radiation
  - particle-air convection
  - air-wall convection

Air flow inside the receiver influenced by drag forces and buoyant convective heat transfer in the vicinity of the particles.

Particle volume fraction found to be less than 0.1 % collisions neglected.

Two-way coupled Euler-Lagrange method (exchange of heat and momentum between the gas phase and the solid phase) used to simulate the gas-particle flow.

Turbulent flow expected for typical operating conditions of the receiver.

Realizable k-ε model adapted for closing the turbulent Navier-Stokes equation system.

Force balance equates the particle inertia with the forces acting on the particle:

\[
\frac{du_{p,i}}{dt} = \frac{18\mu}{\rho_p d_p^2} \frac{C_D \text{Re}_p}{24} \left(u_i - u_{p,i}\right) + \frac{g_i(\rho_p - \rho)}{\rho_p}
\]

With \(\text{Re}_p = \frac{\rho d_p |u_{p,i} - u|}{\mu}\)

And \(C_D = \frac{24}{\text{Re}_p} \left(1 + 0.15 \text{Re}_p^{2/3}\right)\)


Chen H, Chen Y, Hsieh HT, Siegel N. Computational fluid dynamics modeling of gas-particle flow within a solid-particle solar receiver. JSEE 2007; 129:160-70

Solid Particle Receiver of SNL (Albuquerque, USA)

- Improvement of the modeling

  - Solar ray-tracing algorithm in FLUENT is used to predict the solar illumination energy on the walls

  - Small “solar patch” is applied in the middle of the aperture to simulate the concentrated solar irradiation from the heliostat field entering the receiver via the discrete ordinates radiation model

  - The magnitude of the solar irradiation (W/m²) applied to the solar patch is calculated using the estimated input power for each test

  - Heat conduction is simulated within the walls of the cavity

  - Convective heat loss to the ambient is simulated assuming a heat transfer coefficient of 5 W/m².K

  - Ambient temperature at the aperture boundary has no significant changes

  - For each on-sun test, converged solution was achieved for the continuity, velocity, energy, turbulence, and discrete-ordinates intensity residuals

Solid Particle Receiver of SNL (Albuquerque, USA)

- Unheated test/simulated results

Solid Particle Receiver of SNL (Albuquerque, USA)

- On-sun simulated results

- Wall incident radiation
- Particle curtain temperature
- Gas flow velocity

Solid particle receiver

Solid Particle Receiver of SNL (Albuquerque, USA)

- On-sun simulated results

- As the particle mass flow rate increases, the radiative heat loss decreases because more particles are available to absorb the input power (greater particle curtain opacity)

- In general, for a given mass flow rate, the relative amount of convective heat loss decreases as the incident power level increases. The amount of convective heat loss at similar power levels does not appear to change with mass flow rate

• Measured increase in particle temperature is within the range of simulated values for all tests

• Increased temperature rise at low flow rates comes at the expense of absorption efficiency

Solid Particle Receiver of SNL (Albuquerque, USA)

- On-sun test/simulated results

- Measured wall temperatures were still increasing during the duration of the test

- Trend in the transient temperature distribution is similar to the simulated steady-state wall temperature distribution

Solid Particle Receiver of SNL (Albuquerque, USA)

➢ Conclusion

• This model allows a good estimation of the prototype’s performance

• It is now being used to parametrically evaluate design modifications to the prototype receiver and provide design input

➢ Milestones to prove the general feasibility

• Particle exit temperature in excess of 900°C ➔ Optimize the design

• Receiver efficiency in excess of 70%

• Rigorous analysis of the impact of ambient wind on curtain stability in an open cavity and the demonstration of strategies to mitigate this issue

• Demonstration of the physical stability of the particles

Maximize the heat transfer while minimizing heat losses and pressure drop

For basic tubular geometry, existing Nusselt-Correlations (e.g. Colburn) for heat transfer and correlations for pressure drop

For complex tubular geometry, development of a correlation for heat transfer and pressure drop

Possible analytical model, fast computation time

**Tubular pressurized air receiver**

- Study the internal structure to enhance the heat transfer
- Cool down the quartz window to reduce the thermo-mechanical constraints
- Numerical model often essential, long computation time

**Volumetric pressurized air receiver**

- Complex modeling (hydrodynamic, heat transfer, particle behavior…)
- Several milestones must be achieved to prove the general feasibility of this concept
Thank you for your attention

Main References:

