Model Tools for Solar Tower Receiver Systems

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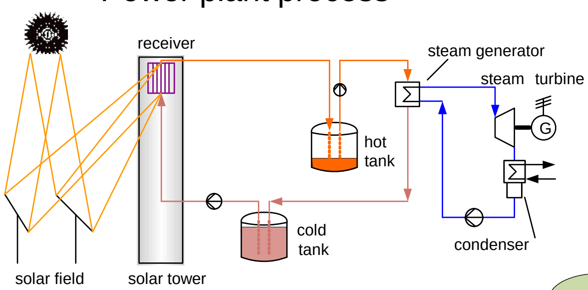
CRS Receiver Simulation: Overview

Levels of Simulation

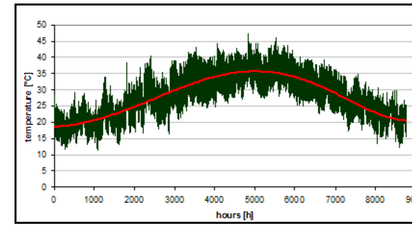
- **System level**
  - layout
  - simplified receiver models (also costs)
    (receiver characteristic => as map or correlation)
  - **=> Annual Performance**
- **Pre-design**
  - definition of basic receiver design
- **Detailed design**
  - detailed analysis of
    - solar flux distribution
    - temperature distribution
    - Stresses / lifetime assessment
  - **=> Design Values**

System Simulation: Workflow for Solar Towers
Annual Yield Calculation

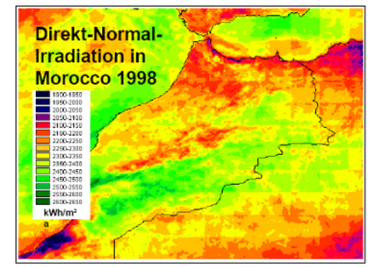
Power plant process

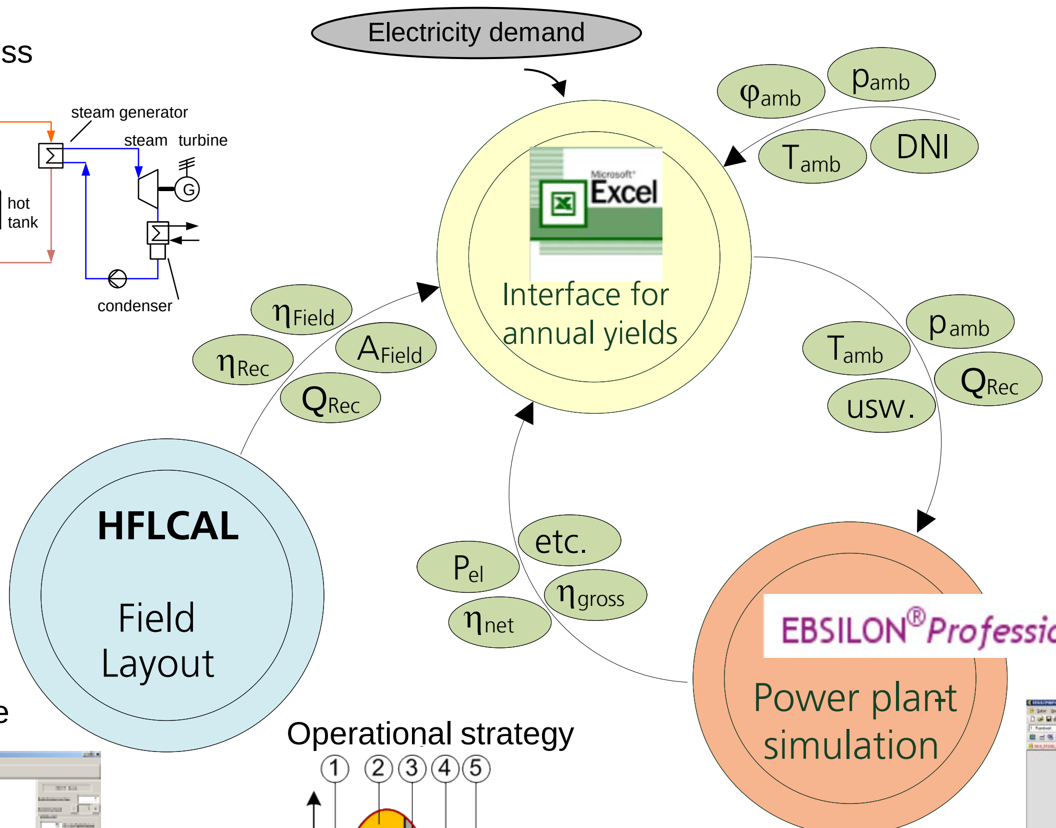


Climate data

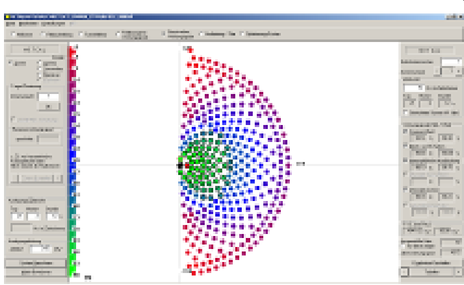


Solar resource data

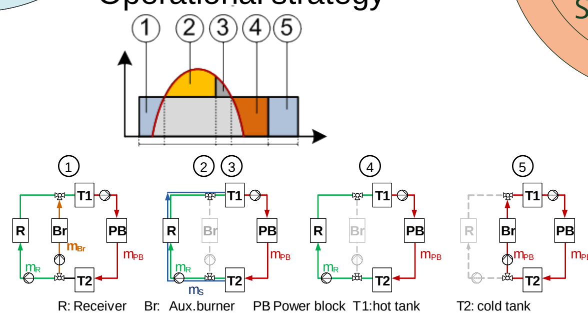


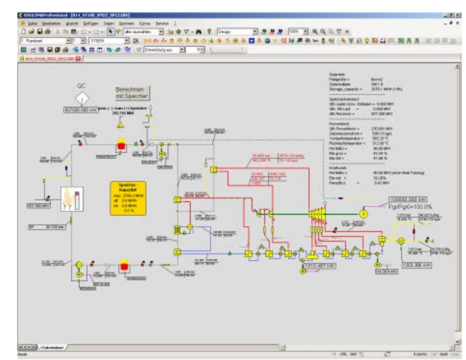


Solar field performance



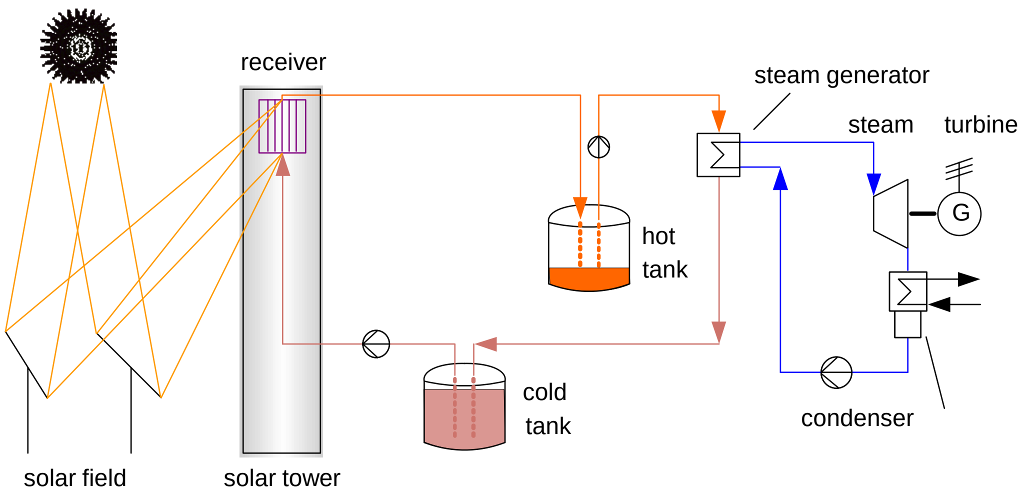
Operational strategy





System Simulation: CSP System Modelling

- Heliostatfield
- Tower with receiver
- HTF loop
- Thermal storage
- Power block



- Total power of CSP power plant

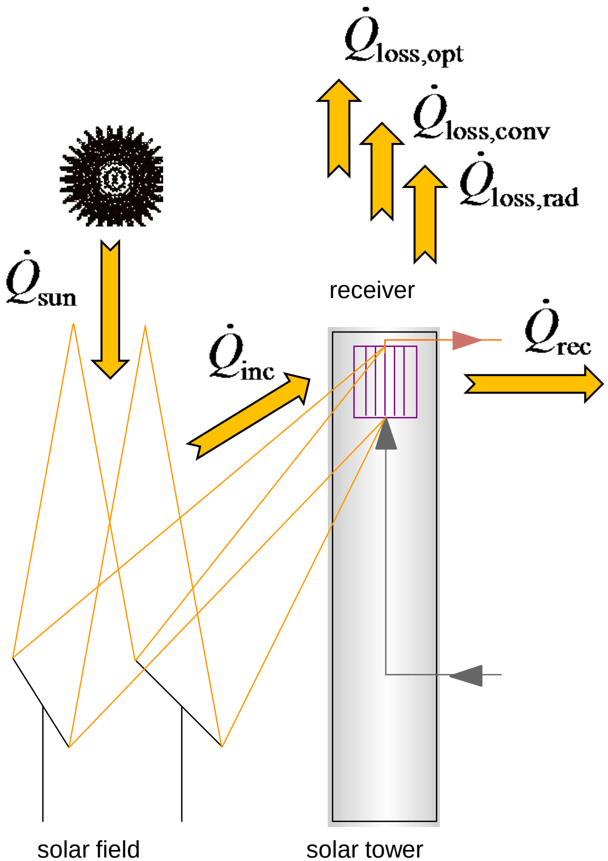
$$P_{sys,el} = DNI \cdot A_{SF} \cdot \eta_{SF} \cdot \eta_{\mathrm{Rec}} \cdot \eta_{HTF} \cdot \eta_{TES} \cdot \eta_{PB}$$

→ Every single sub-component is important!

- Most often systems are economically optimized (LCOE minimum)

$$LCOE = \frac{\text{total annual cost}}{\int_{t_0}^{t_{end}} P_{sys,el}\, dt} \, [EUR/kWh]$$

System Simulation: Thermodynamic analysis of receiver



receiver efficiency:

$$\eta_{rec} = \dot{Q}_{\text{rec}} / \dot{Q}_{\text{inc}}$$

$\dot{Q}_{rec}$: thermal power from receiver [W]

$\dot{Q}_{inc}$: incident power on receiver [W]

incident power on receiver aperture area:

$$\dot{Q}_{\text{inc}} = DNI \, \rho_{\text{refl}} \, A_{\text{refl}} \, \eta_{\text{Field}}(\gamma_S, \alpha_S)$$

ρ_{refl} : average reflectivity [-]

A_{refl} : heliostat field aperture area [m2]

η_{field} : solar field optical efficiency [-]

γ_S : sun azimuth [°]

α_S : sun elevation [°]

power from receiver to HTF:

$$\dot{Q}_{\text{rec}} = \dot{m}(h_{\text{out}} - h_{\text{in}})$$

$$\dot{Q}_{\text{rec}} = \dot{Q}_{\text{inc}} - \dot{Q}_{\text{loss}}$$

$\dot{m}$: mass flow HTF [kg/s]

h_{out} / h_{in} : inlet/ outlet enthalpie [kJ/kg]

losses of receiver :

$$\dot{Q}_{\text{loss}} = \dot{Q}_{\text{loss,opt}} + \dot{Q}_{\text{loss,conv}} + \dot{Q}_{\text{loss,rad}}$$

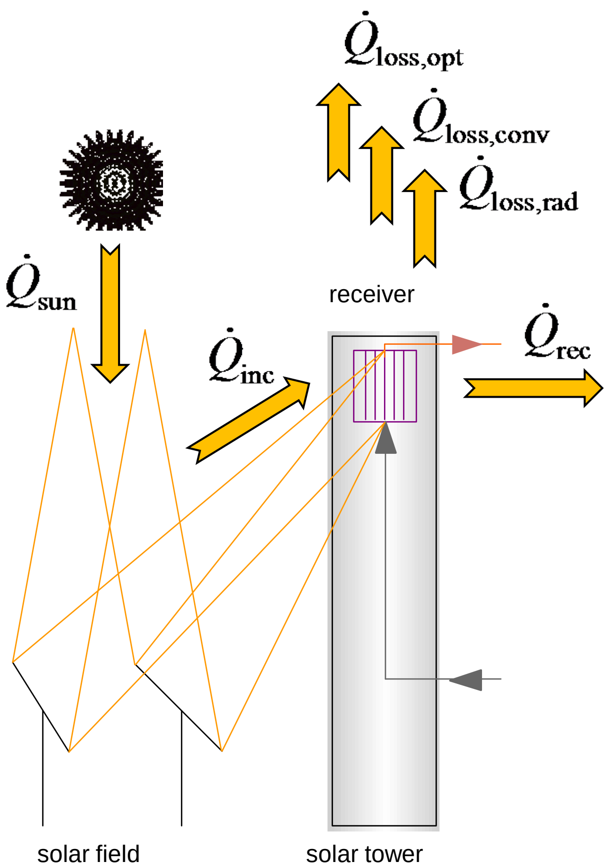
$\dot{Q}_{\text{loss,opt}}$: optical losses [W]

$\dot{Q}_{\text{loss,conv}}$: convective losses [W]

$\dot{Q}_{\text{loss,rad}}$: radiation losses [W]

Note: optical losses do not depend on the receiver temperature whereas convective and radiation heat losses do

System Simulation: Thermodynamic analysis of receiver



<u>optical losses:</u>

$$\dot{Q}_{loss,\,opt} = \dot{Q}_{inc}\left(1-\eta_{opt}\right)$$

η_{opt} : optical efficiency receiver [-]

<u>convective losses:</u>

a) option “constant heat losses” :

$$\dot{Q}_{loss,\,conv} = \dot{q}_{loss}\;A_{rec}$$

$\dot{q}_{loss}$: constant area specific heat loss [W/m^2]

A_{rec} : receiver aperture area [m^2]

b) option “heat transfer coefficient ” :

$$\dot{Q}_{loss,\,conv} = \alpha\left(T_{rec} - T_{amb}\right)A_{rec}$$

α : constant heat transfer coefficient [W/m^{2}K]

T_{rec} : mean receiver temperature [°C]

T_{rec} : ambient temperature [°C]

$$T_{rec} = T_{in} + k\left(T_{out} - T_{in}\right) + \Delta T_{wall,des}\,\frac{\dot{Q}_{inc}}{\dot{Q}_{inc,des}}$$

α : constant heat transfer coefficient [W/m^{2}K]

k : weighting factor, e.g. 0.5 [-]

(used to define any representative temperature between inlet/ outlet)

$\Delta T_{wall,des}$: Over-temperature of receiver wall outer surface [K]

$\dot{Q}_{inc,des}$: design incident power [W]

<u>radiation losses:</u>

$$\dot{Q}_{loss,\,rad} = \varepsilon\,\sigma\left(\left(T_{rec}+273.15K\right)^4 - \left(T_{amb}+273.15K\right)^4\right)A_{rec}$$

ε : emissivity [-] σ : Stefan Boltzmann constant [W/m^{2}K^4]

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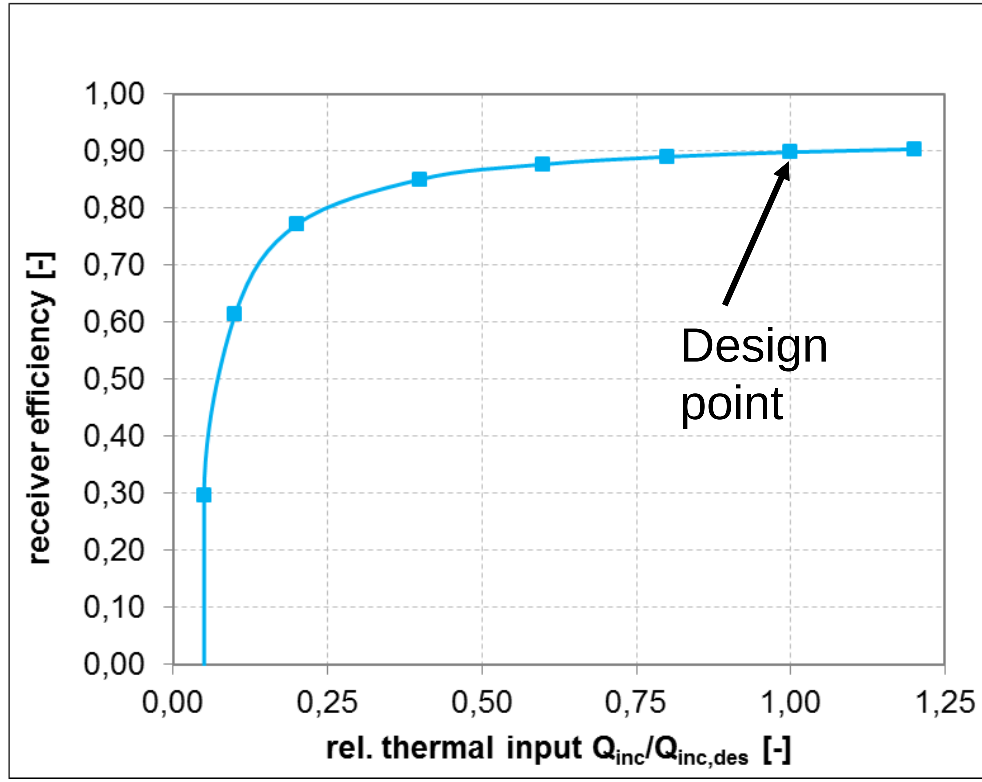
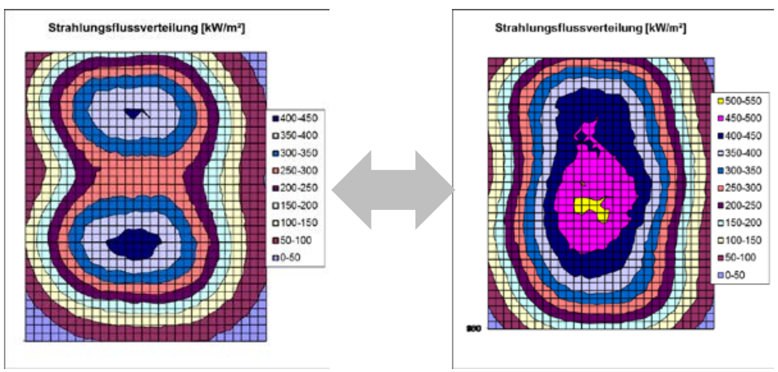
System Simulation: Thermodynamic analysis of receiver

On system level different approaches for receiver modeling can be used:

- simplified receiver models (as shown before)
- receiver characteristic, as map or correlation (if available => detail simulation)



typical receiver characteristic



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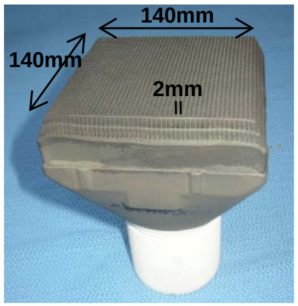
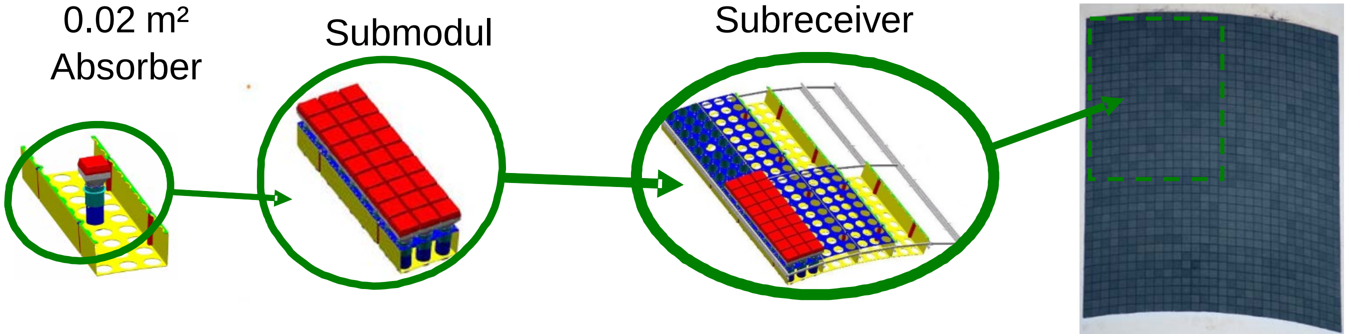
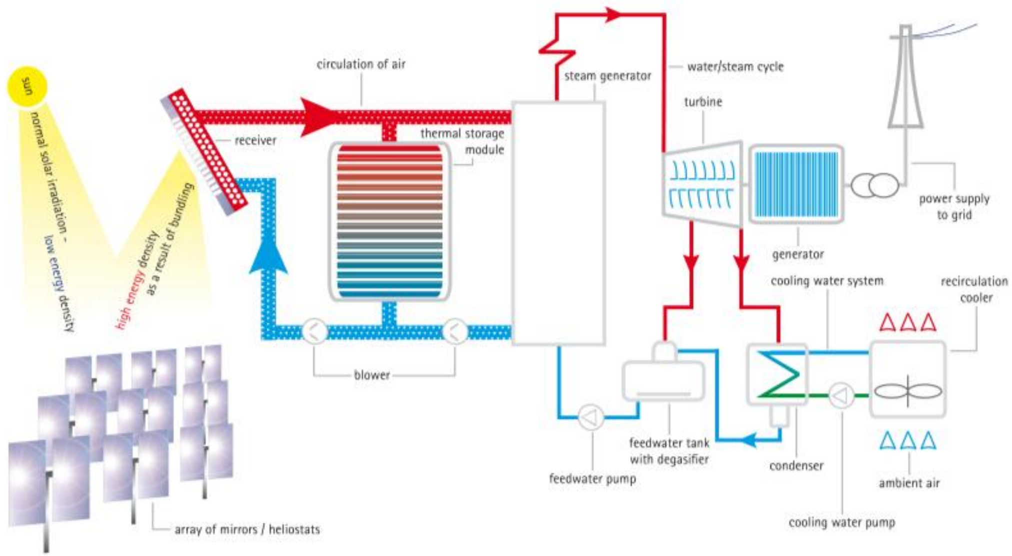
Detail Design: Open Volumetric Receiver







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Detail Design: Open Volumetric Receiver

Simulation of Volumetric Absorber Structures

homogenous approach

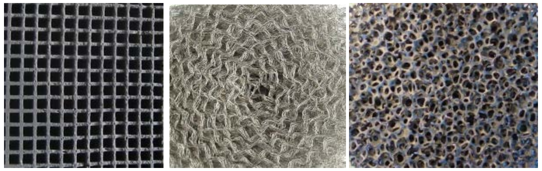
$$(1-Po)\cdot\lambda\cdot\frac{d^2T_w}{dz^2}-\alpha A_v\cdot(T_w-T_f) = \frac{dI}{dz};$$

$$\rho c_p v\frac{dT_f}{dz}-\alpha A_v\cdot(T_w-T_f) = 0;$$

heat transfer: $\alpha A_v = \frac{\mathrm{Nu}A_v\cdot\lambda}{d}; \quad \mathrm{Nu}A_v \propto \mathrm{Re}^m$

radiation: absorption and scattering coefficients for discrete directions

approach valid for different kinds of porous structures
➔ suitable for comparison of different materials

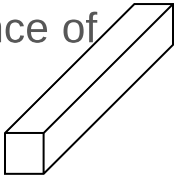


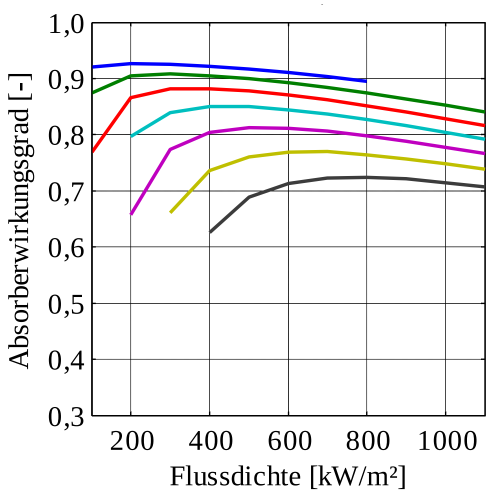
channel model

heat transfer: standard Nu - correlations

radiation: terminated ray tracing

calculate performance of defined honeycomb structures



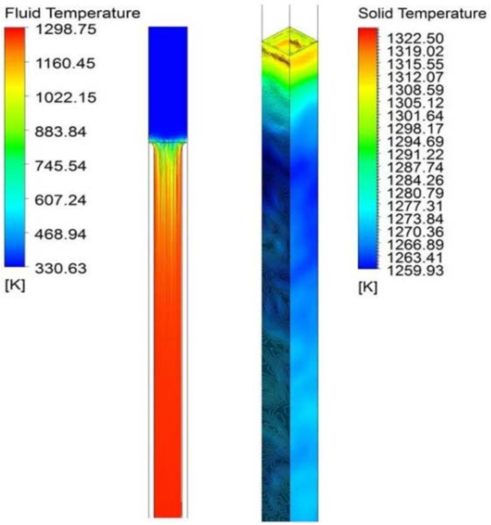


FEM

heat & mom. transfer: Navier - Stokes Equ.

radiation: FE - radiation exchance

study temperature and flow details inside regular porous structures



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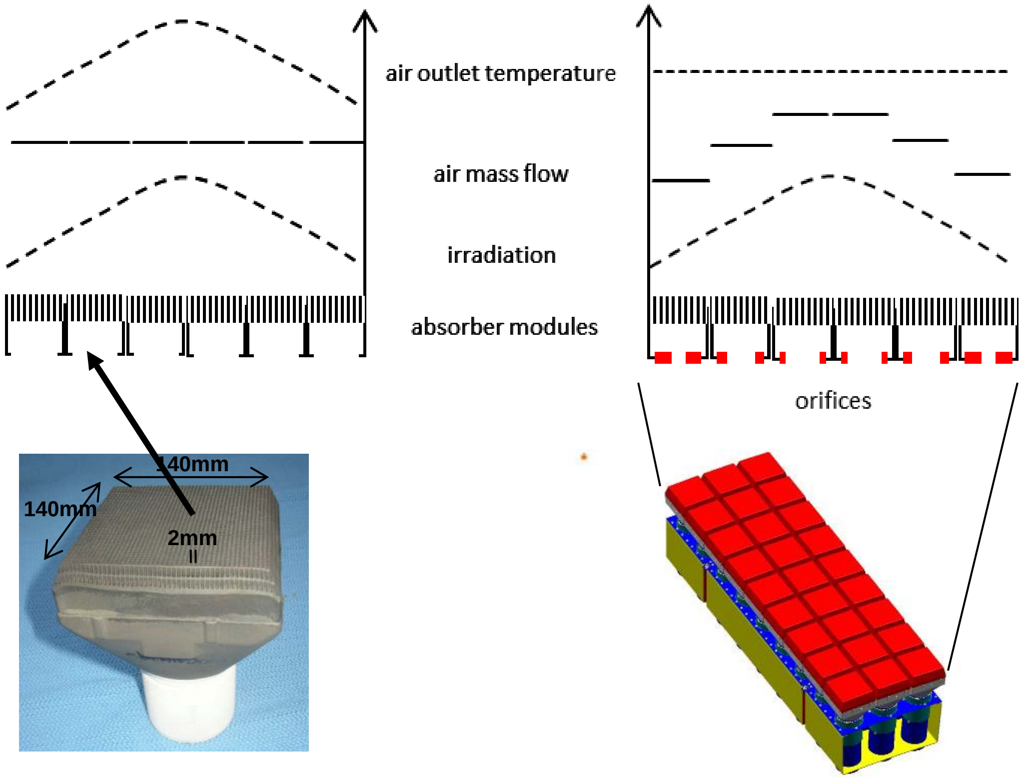
Detail Design: Open Volumetric Receiver

Layout & Operation of Modular Air Receivers

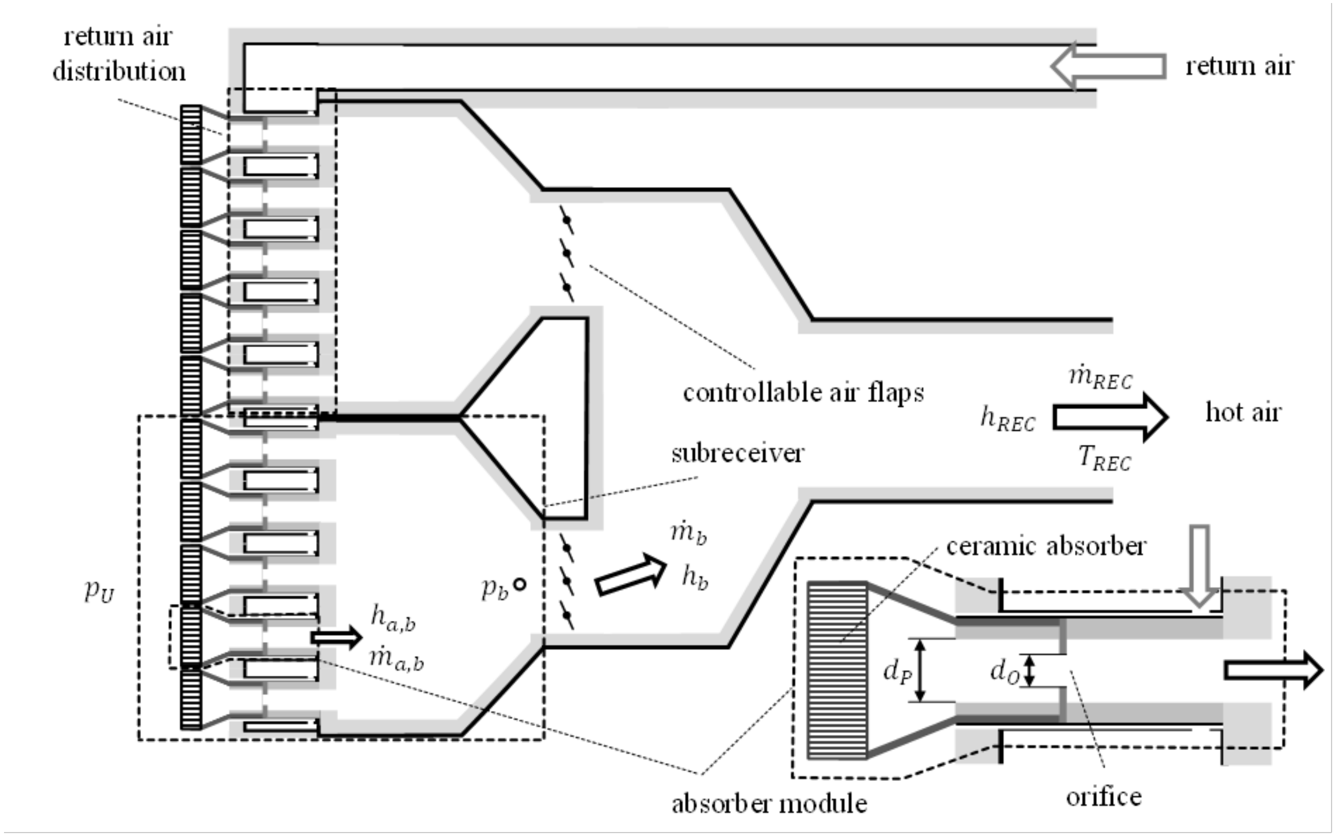
parallel flow trough absorber modules ➔ adapt flow to flux distribution



Detail Design: Open Volumetric Receiver

Layout & Operation of Modular Air Receivers

parallel flow trough absorber modules ➔ adapt flow to flux distribution



step 1:

layout of fixed orifice diameter for design flux distribution

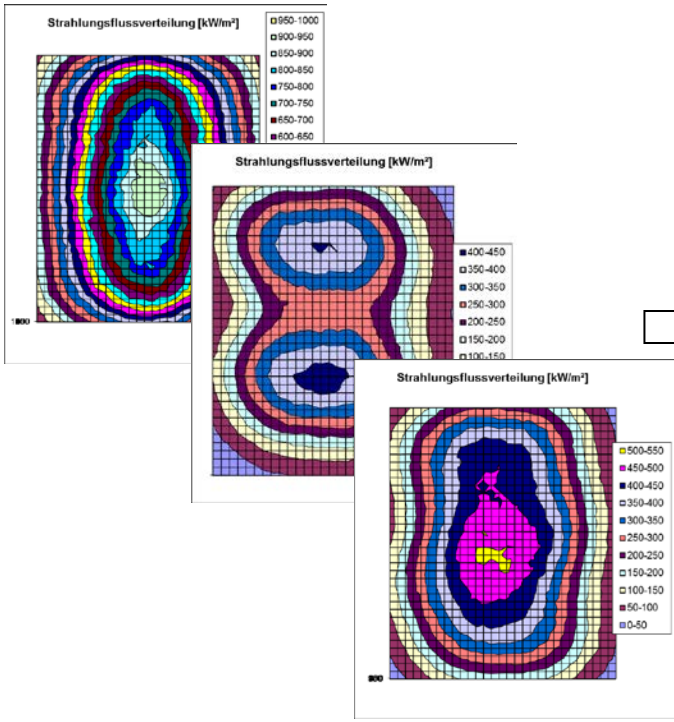
step 2:

variation of flow through subreceivers during operation to adapt to changing flux profile

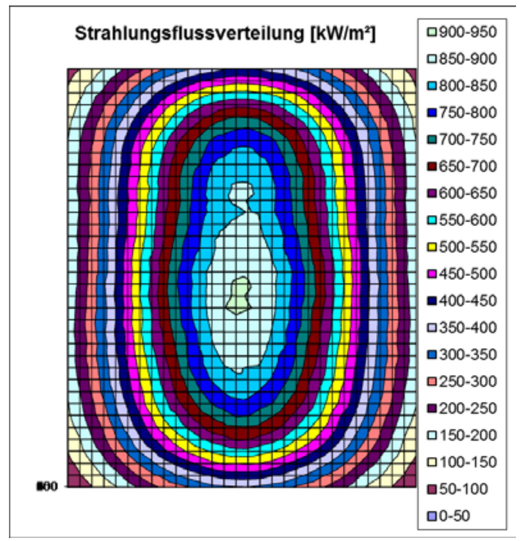
Detail Design: Open Volumetric Receiver

Layout & Operation of Modular Air Receivers

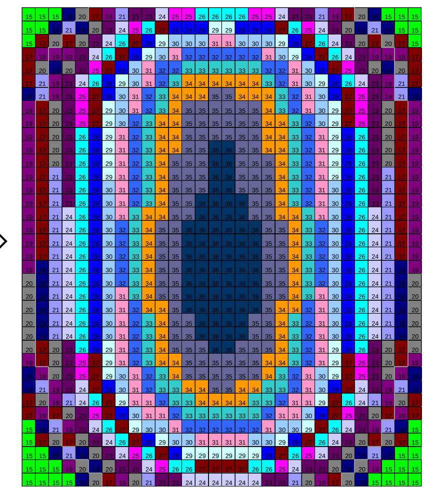
example: layout of mass flow distribution for Solar Tower Jülich



ray tracing: calculate flux distribution for different sun angles



create artificial design flux distribution for receiver layout (weighted superposition of real flux distributions)

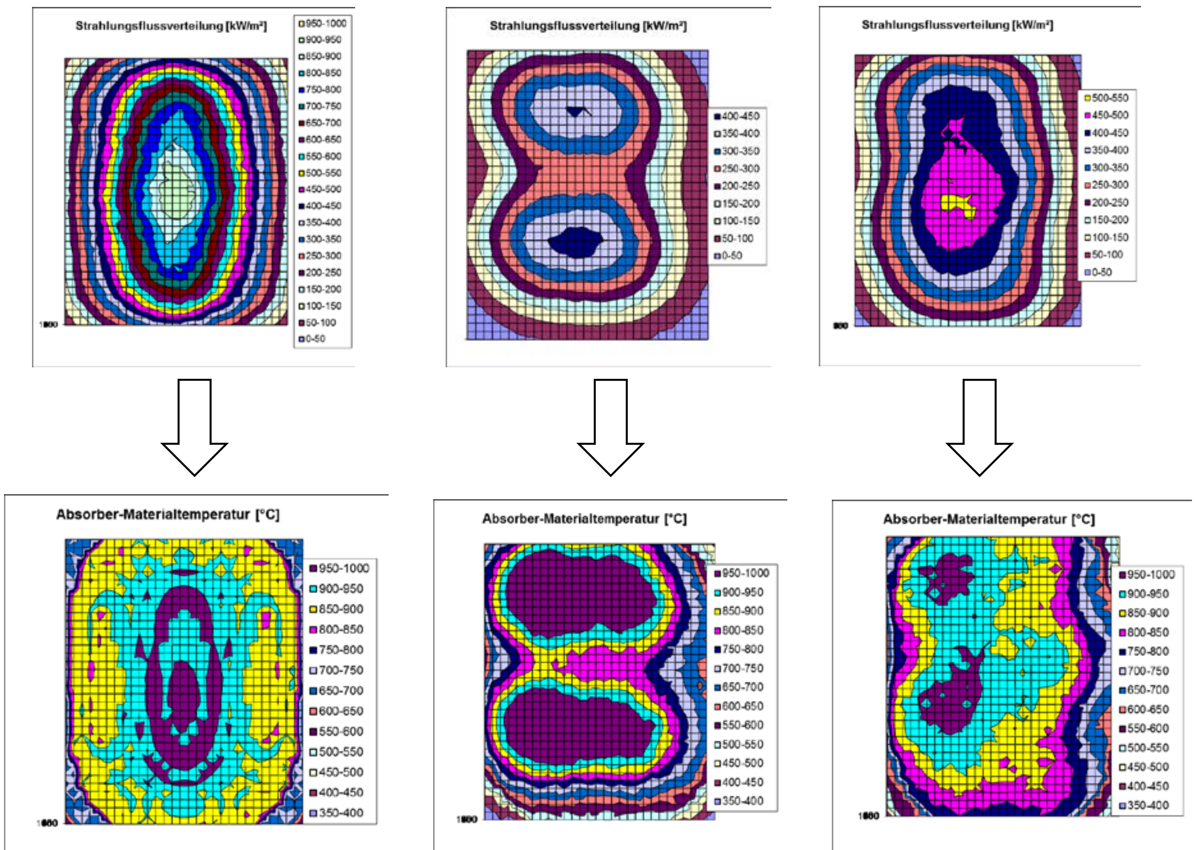


calculate fixed orifice size distribution

Detail Design: Open Volumetric Receiver

Layout & Operation of Modular Air Receivers

example: layout of mass flow distribution for Solar Tower Jülich



calculation of maximum material temperatures for real flux distributions

Setup of a characteristic map for the system simulation

DLR

Conclusion

- **System Simulation**
  - aims for **determination of the design** point with the highest annual yield and the lowest LCOE (operation strategies)
  - **must be fast** to enable an optimization of a set of different plant configurations on a yearly base (storage sizes, power block designs, hybrid modes…)
  - models the components as simple as possible/acceptable due to the demanded accuracy (correlations, characteristic maps,…)

- **Detail Simulation**
  - aims **the real design** values for each component
  - and the **detection of constrains**, critical operation modes and life time estimation
  - **checks possible improvements** and new design approaches

Thank you for your attention!