Particle receiver and system development at DLR: status and perspectives

SolarPACES, International Particle Technology Working Group Workshop, Riyadh, Saudi Arabia

April 19 – 20, 2017

Miriam Ebert and Reiner Buck

DLR, Germany

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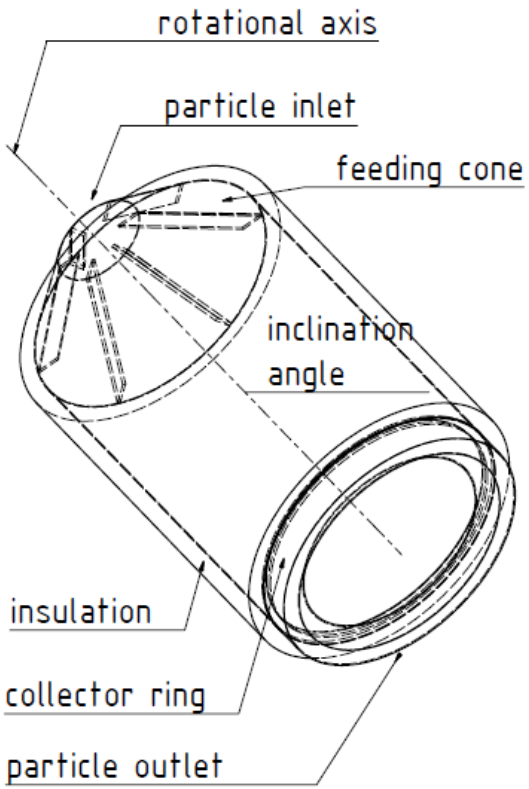
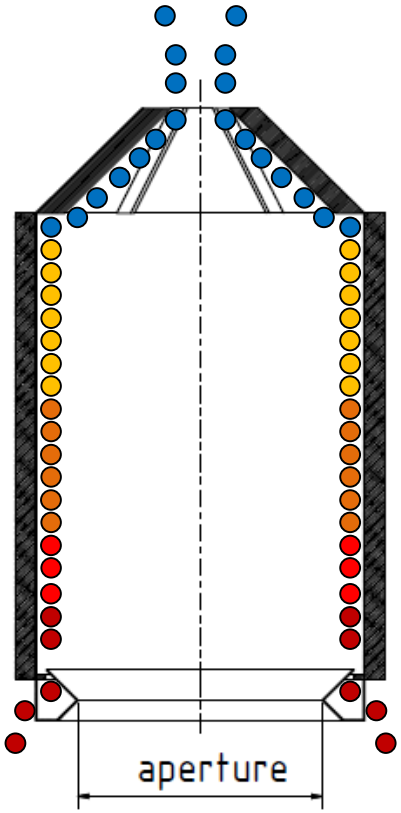
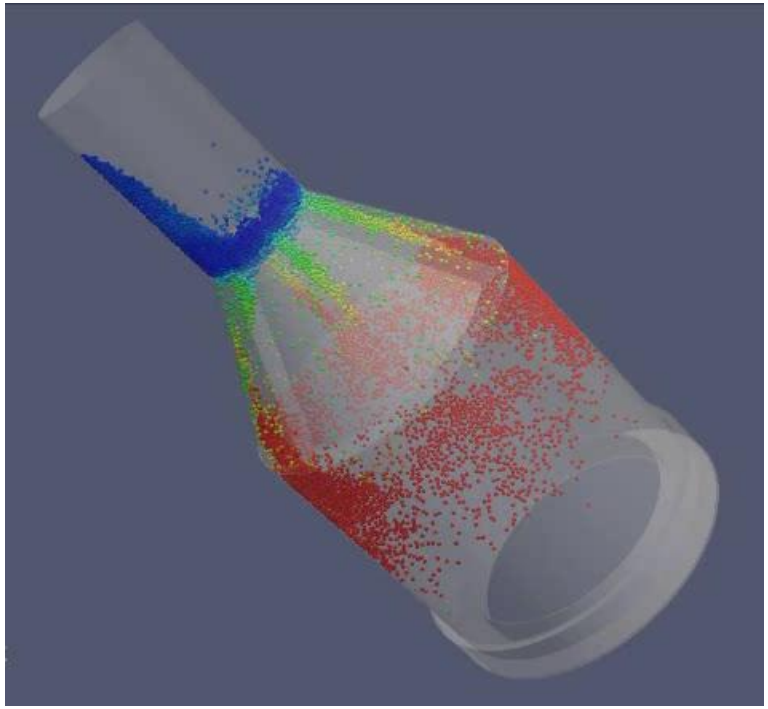
INTRODUCTION – Centrifugal Particle Receiver (CentRec)

- How CentRec Works







THEORY – Numerical Receiver Model PhD Wei Wu

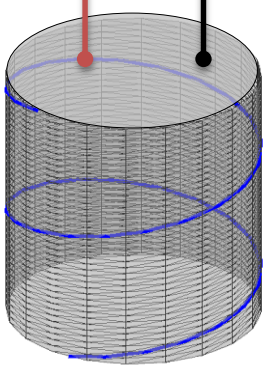
- Numerical receiver model based on FEM simulations and validated by experiments
- Receiver efficiency > 85% predicted at 900°C particle outlet temperature for input heat flux of 1 MW/m²

Fluid element

Particle mass flow
- empirical data, depending on rotation speed

Particle trajectory
- Calculated based on measured values

Inlet temperature



Surface element

Heat flux boundary
- heat flux distribution from solar field using raytracing tool, including reflection losses

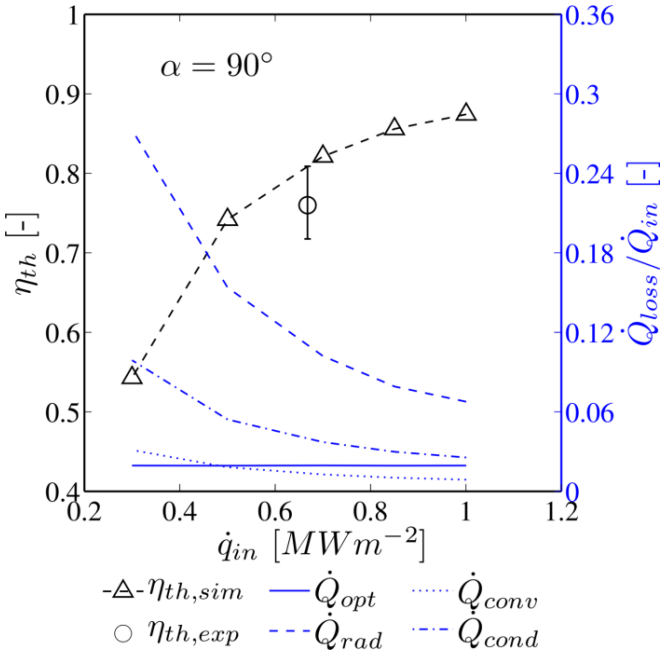
Heat transfer
- from surface into fluid element
- absorbtion by particle
- conduction losses through the wall

Radiosity calculation

$$H_i - (1-\epsilon_i)\sum_{j=1}^{n} F_{ij} H_j = \epsilon_i \sigma T_i^4$$

Convection losses
- Nu number by analytical correlation

Output
- Outlet temperature fluid element / particles
- Receiver efficiency: $\eta = \frac{Q_{out}}{Q_{in}}$



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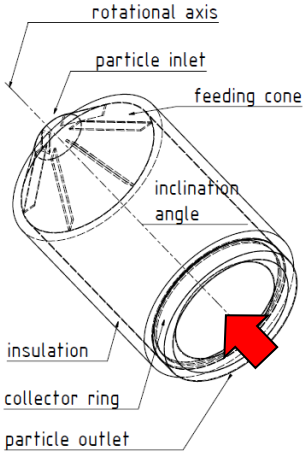
THEORY – Granular flow
PhD David Trebing



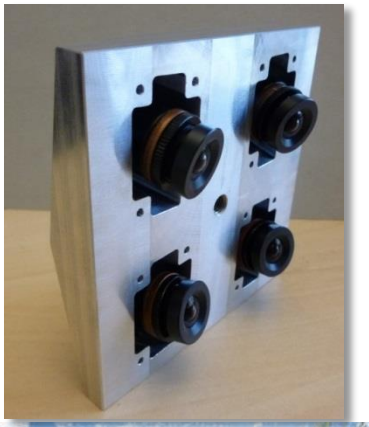
Gravity vs. acceleration due to circumferential force

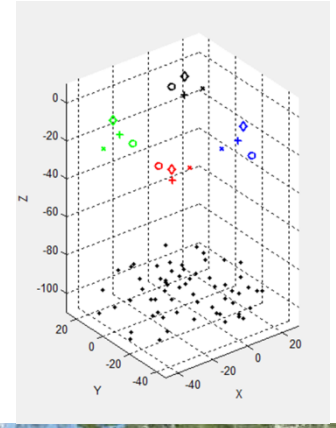
- angle of inclination $\theta_{\mathrm{rec}} = \theta_{\mathrm{rec}}(\alpha, r, \omega, \Omega)$
  - Inclination of rotation axis α
  - Radius r
  - Angular velocity ω
  - Angular position on circumference of receiver Ω

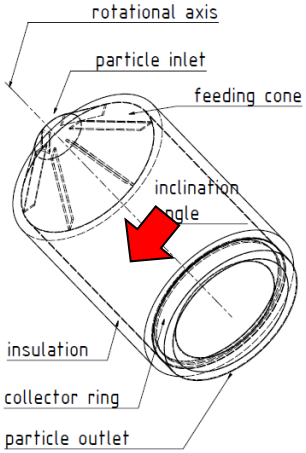
Camera position and view

Granular flow with inclination of rotation axis 45°

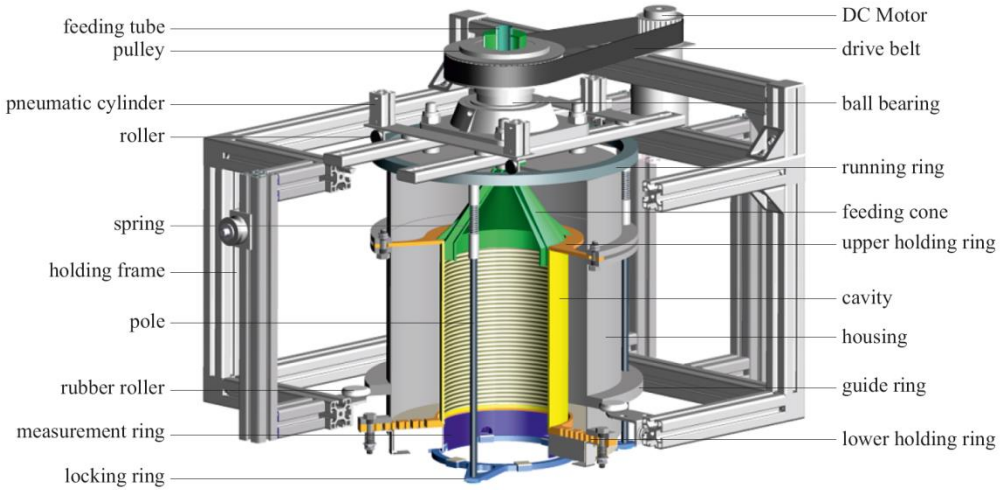
- Total film height
- Surface velocity

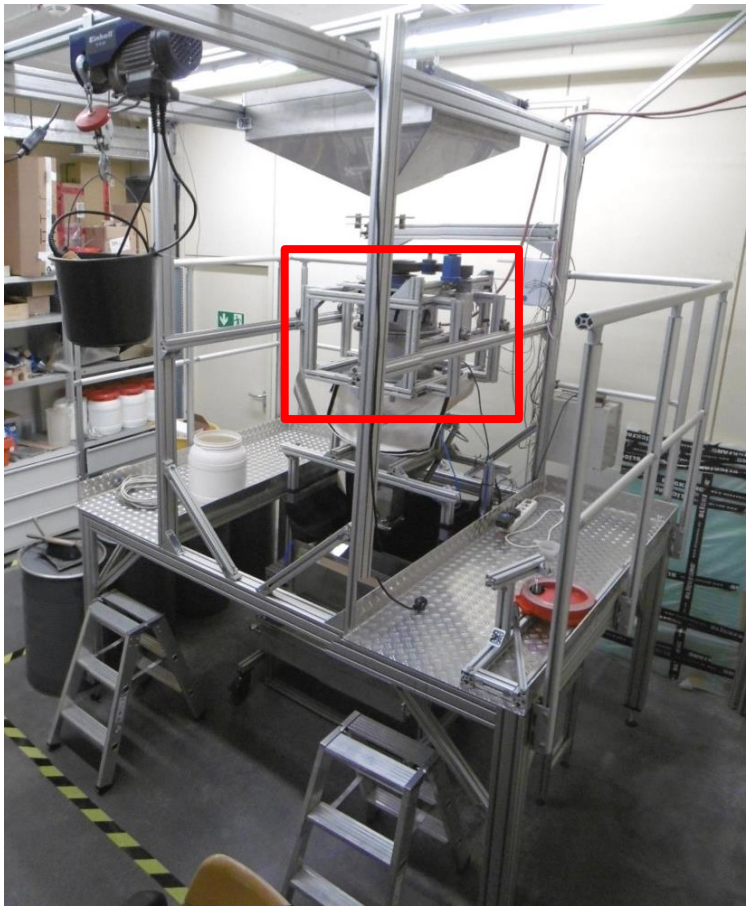






PROTOTYPE AND EXPERIMENTS – Prototype in Laboratory Scale 15 kW_{th} “CentRec15” PhD Wei Wu

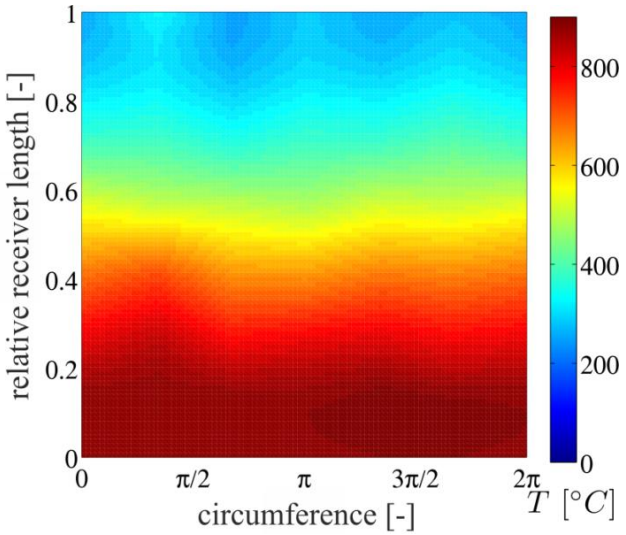


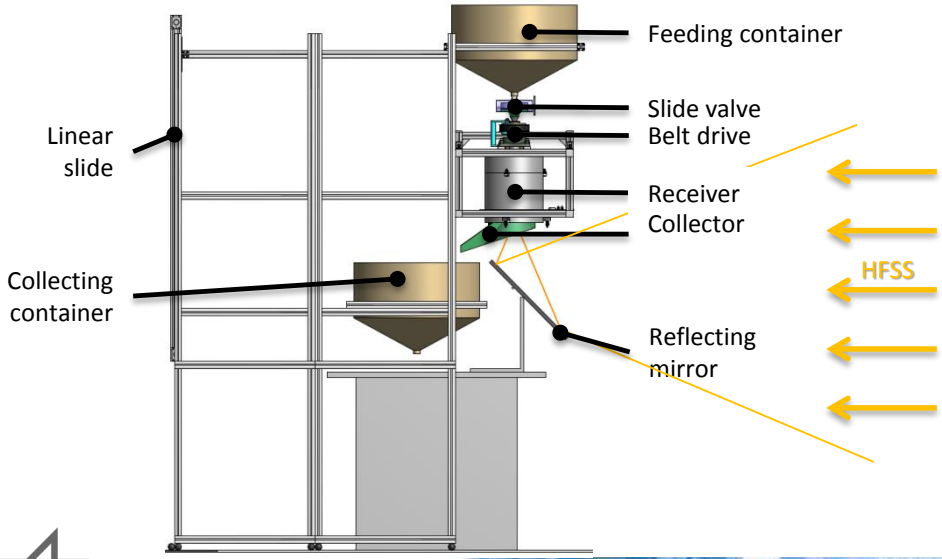


- Particle film tests
  - optical dense film
  - good controllability regarding particle retention time

PROTOTYPE AND EXPERIMENTS – “CentRec15” Experimental Results High Flux Solar Simulator

- Measured wall temperatures indicate homogeneously distributed particle film
- 900 °C particle outlet temperature achieved
- Receiver efficiency about 75% at 900 °C ($q_{in} \approx 0{,}66$ MW/m²)





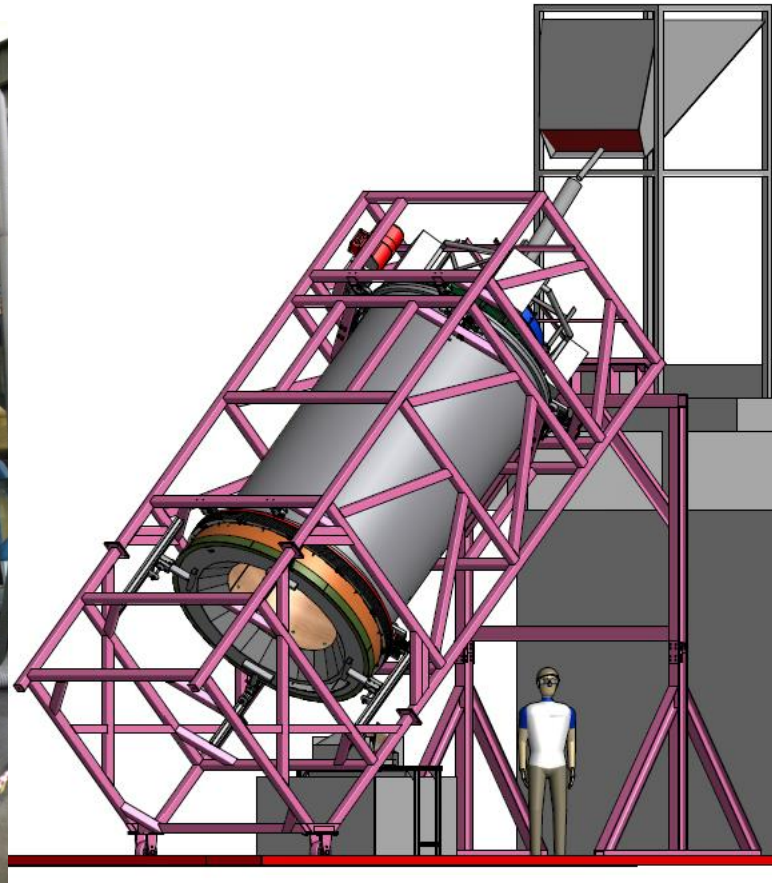
PROTOTYPE AND EXPERIMENTS – Upscaling

- Lab scale prototype ⇒ Future pilot plant prototype
- Aperture Ø 137 mm ⇒ **Aperture Ø 1130 mm**
- 7.5 kW_{th} ⇒ **Commercial setup 2.5 MW_{th}**
- Particle T_{out} 900°C reached ⇒ Design particle T_{out} 1000°C

- **Specific hardware costs of presented prototype 100 €/kW_{th}**

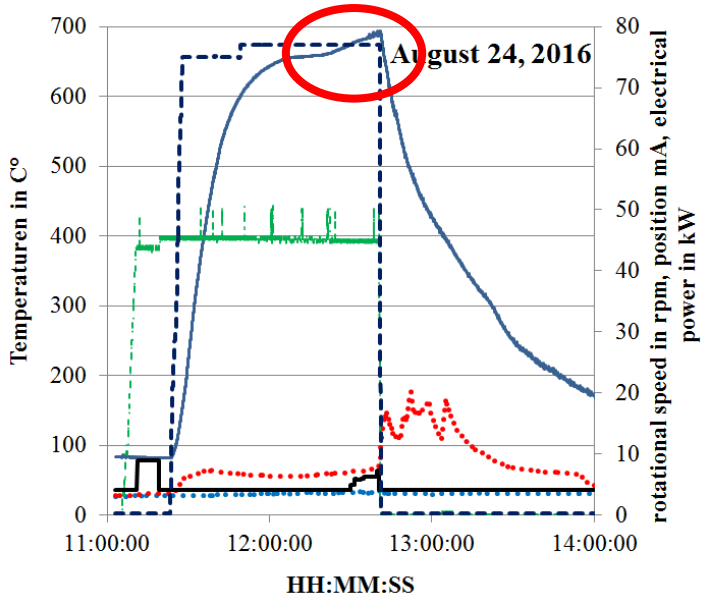
PROTOTYPE AND EXPERIMENTS – “CentRec500“

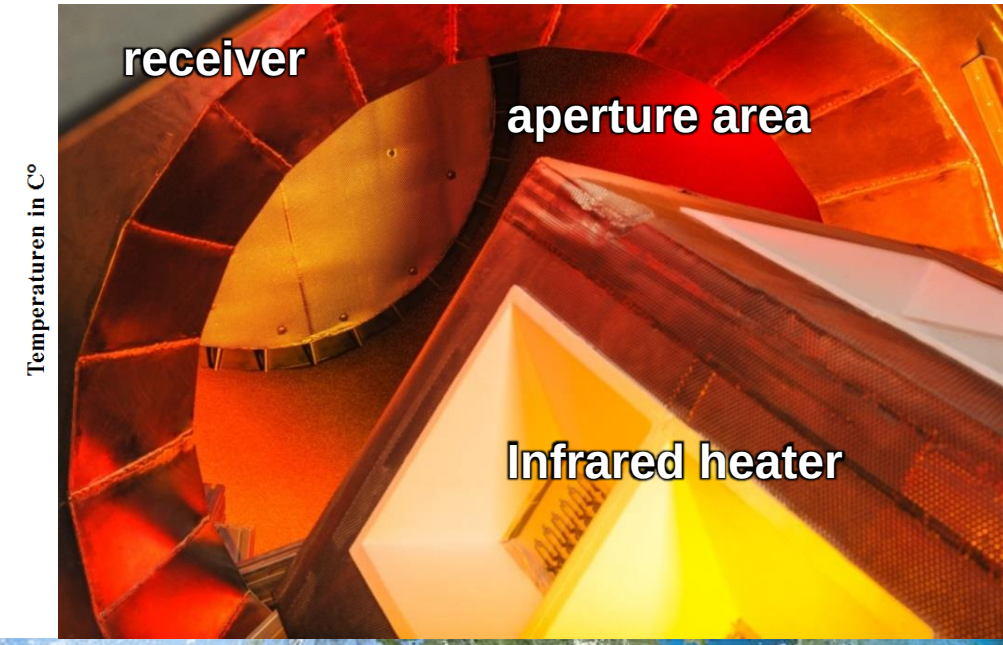
How CentRec Looks Like



PROTOTYPE AND EXPERIMENTS –"CentRec500" cold particle and non-solar tests with IR-heater (100 kW_{el})

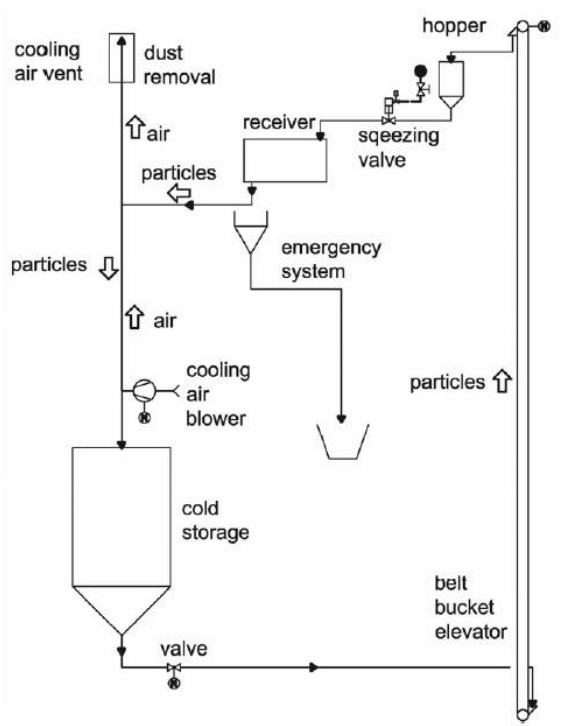
- Optical dense film
- Particle outlet temperature 420°C
- Temperature on inner wall 700°C

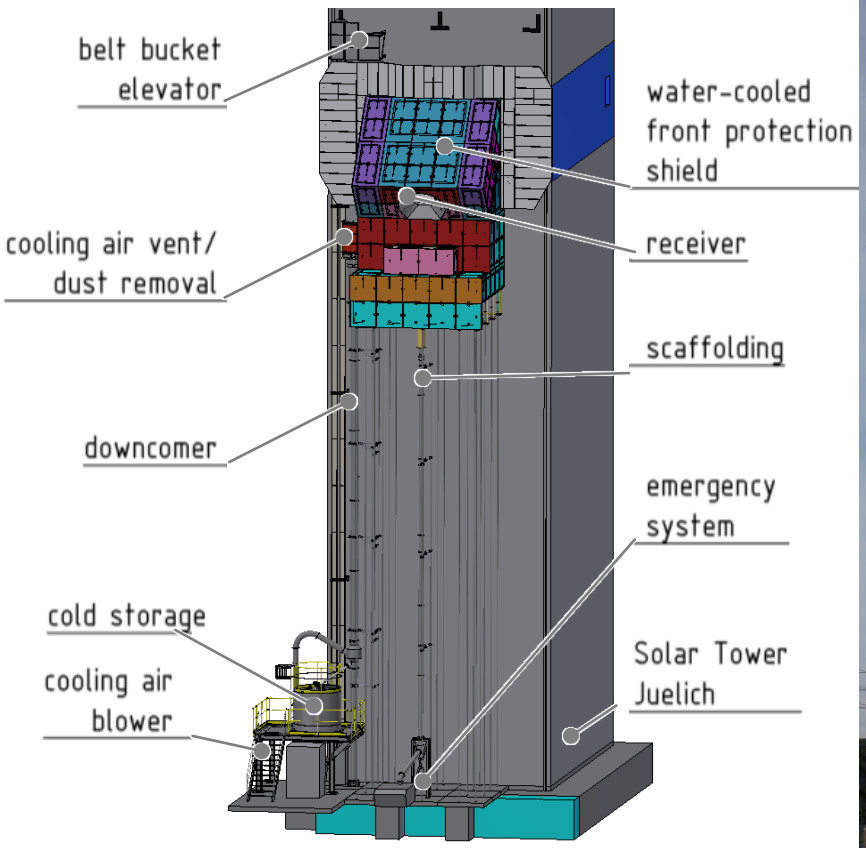




PROTOTYPE AND EXPERIMENTS –"CentRec500" On-sun test in Solar Tower Juelich

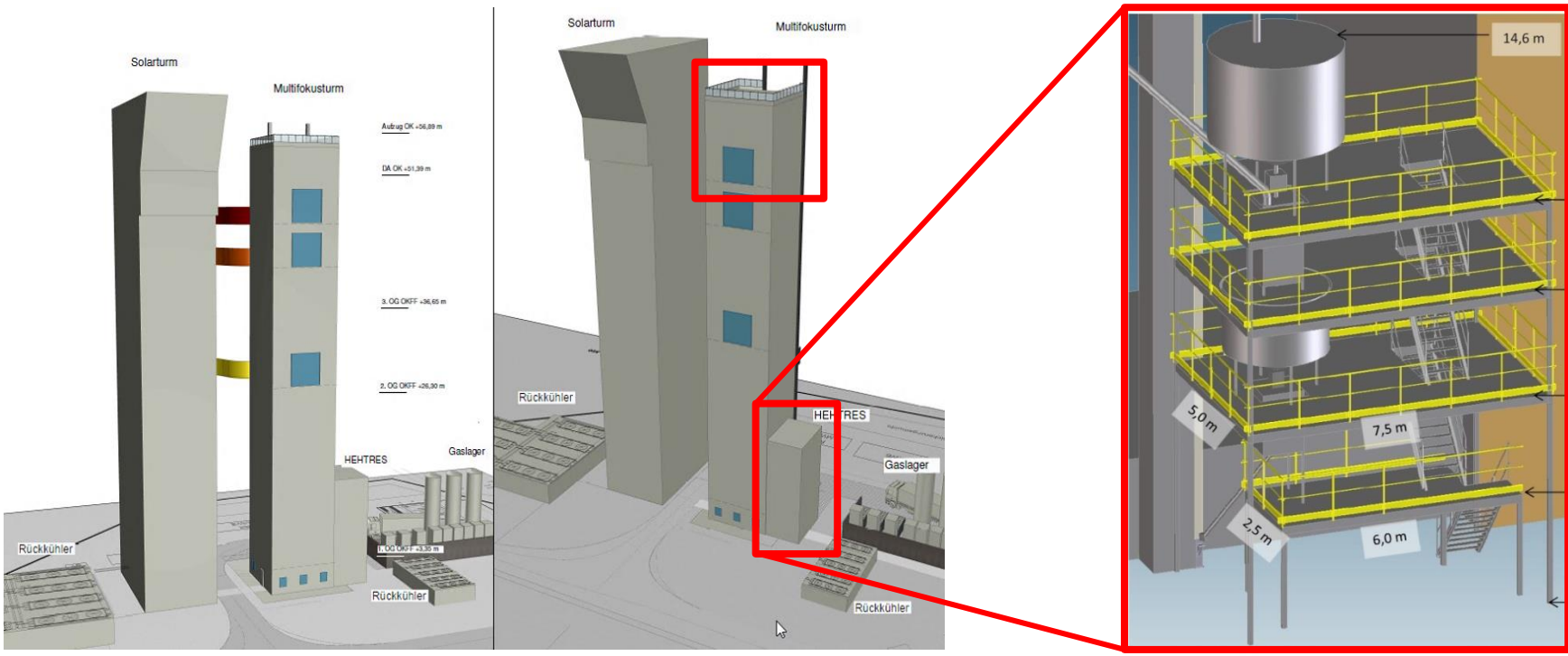
- Receiver tests in Jülich Solar Power Tower in 2017 (500 kW_{th})





HEHTRES
„High Efficiency High Temperature REceiver System“

- Test facility for particle systems in „Multi Focus Tower“ Jülich, Germany
- Receiver 1 MWth @ 900°C, storage, transport system, heat exchanger
- Commissioning 2020



Thank You For Your Attention!

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R&D on (Solar) Particle Technologies at DLR

Particle Technology Working Group Meeting

19./20.04.2017, Riyadh, Saudi Arabia

R. Buck

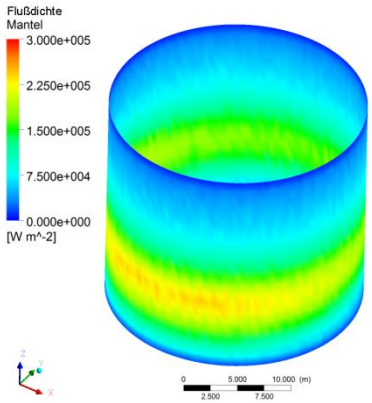
DLR

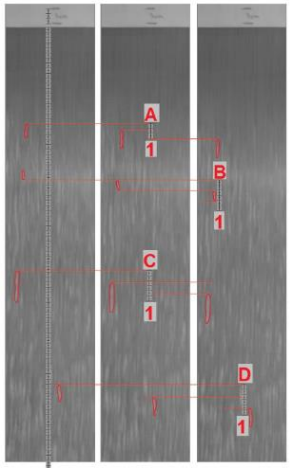
Falling Particle Receiver

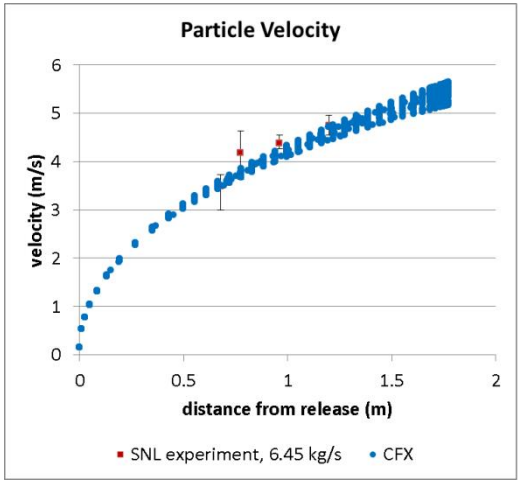
PhD thesis about experiments and modeling (DLR institutional funding)

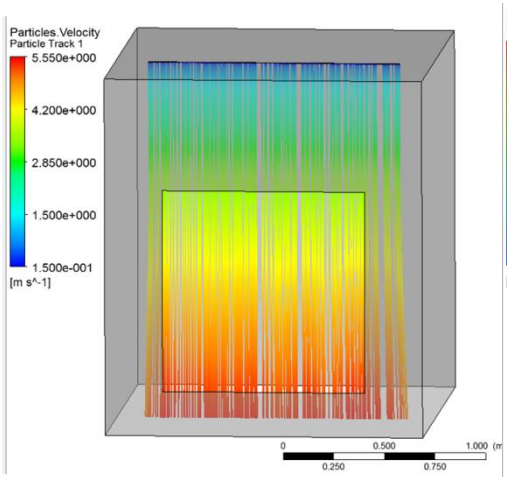
Model validation (Sunshot Particle Receiver Project)

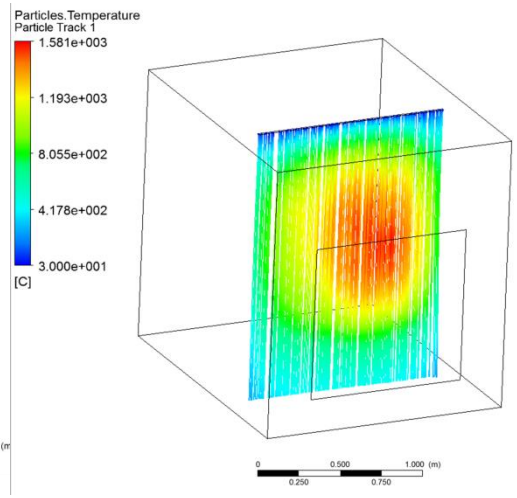
- Sintered Bauxite particles (proppants)
- State of Work:
  - Model developed for cylindrical cavity receiver, 400 MW_{th}, 200 → 800°C
    - Cold flow validated with falling particle experiments
    - Receiver efficiencies: 59%@20% load, 92%@full load, 3 recirculations
  - Model for 1 MW_{th} SNL prototype
    - Cold flow: good agreement between model an SNL experiments
    - Hot flow: not yet completed











Contact: Birgit.Gobereit@dlr.de

Solar rotary kiln to treat reactive particles

SolPart project (EU-H2020 funding)

Solar treatment of reactive particles at industrial scale (application: calcination of cement raw meal and phosphate)

Solar reactor:

- Continuously operated solar rotary kiln to heat and calcine particles of cement raw meal at ≈ 1000°C (solar) under air and CO_2 atmosphere. Numerical and experimental analysis.

Storage:

- Particles produced in 8h are stored at a temperature higher than 900°C and delivered during 24h
- Numerical and experimental study

Handling:

- Particles flow is controlled through a short vibrating pipe, placed below the storage

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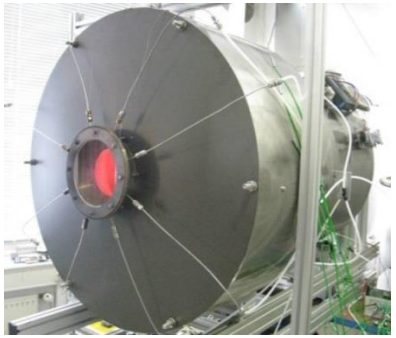
DLR

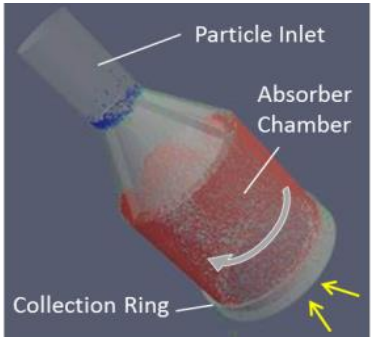
Particle Receivers for Thermochemical Systems

RedoxStorE project (DLR institutional funding)

- Storage by thermochemical reaction and sensible heat
- Particles based on Mn-Fe-mixtures:
  - Oxidation at ≈ 800°C (discharge)
  - Reduction at ≈ 1000°C (charge, solar)
- Properties of various mixtures measured
- System components under development

Contact: stefania.tescari@dlr.de





PEGASUS project (EC co-funded)

- Sulfur-based thermochemical cycle for power generation with long-term storage
- Receiver for heating of catalytic particles
- Hot particles used for H_2SO_4 evaporation and decomposition
- Gas turbine with Sulfur combustor

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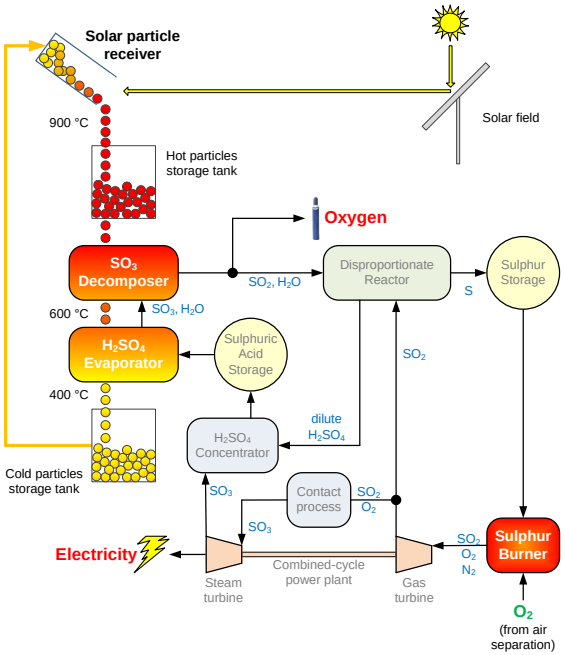
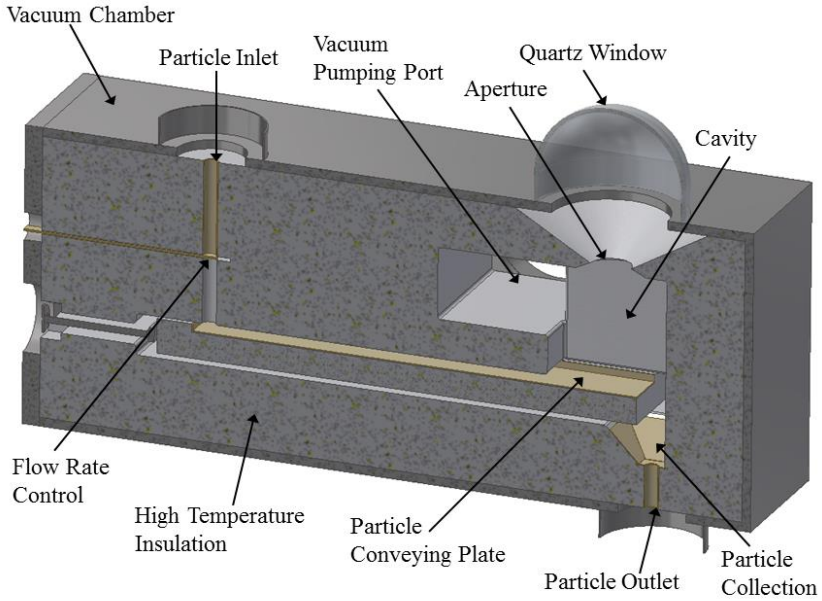
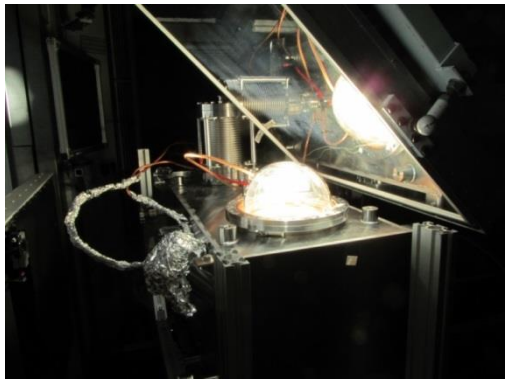


HEST-HY Project

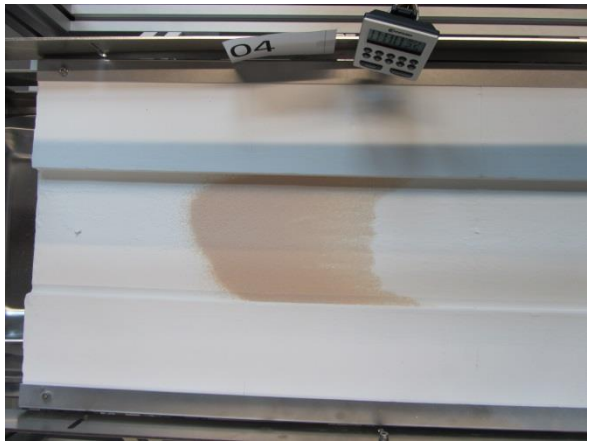
Subcontract SNL, STCH project, DoE funding

- Hydrogen production by Redox Cycles
- Particles ~250µm Cerium Oxide
- Separate chambers for Reduction (DLR) and Water Splitting (Sandia)
- Particle flow rate controlled by variable orifice
- Particle heated in continuous moving thin bed
- Target temperature: 1450°C
- Partial vacuum system: 10pa min., 1atm max.
- Narrow tubes packed with particles between components for pressure separation




Reduction Reactor Testing at DLR

Full Reactor at Sandia


Particle Transport Tests

Contact: justin.lapp@dlr.de

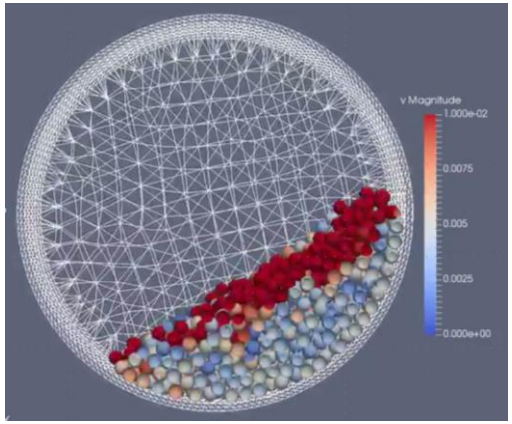
Modeling of vacuum particle receiver reactors for thermochemical fuel production

Dissertation Johannes Grobbel

(DLR institutional funding)

- Experimental investigation of heat transfer in ceria particle beds under vacuum conditions

- Development of versatile discrete element method (DEM) model for solar particle receivers:
  - heat transfer model for dense particle beds, including radiation
  - chemical reaction model
  - implementation in CFDEM/LIGGGHTS code
  - validation with lab experiments

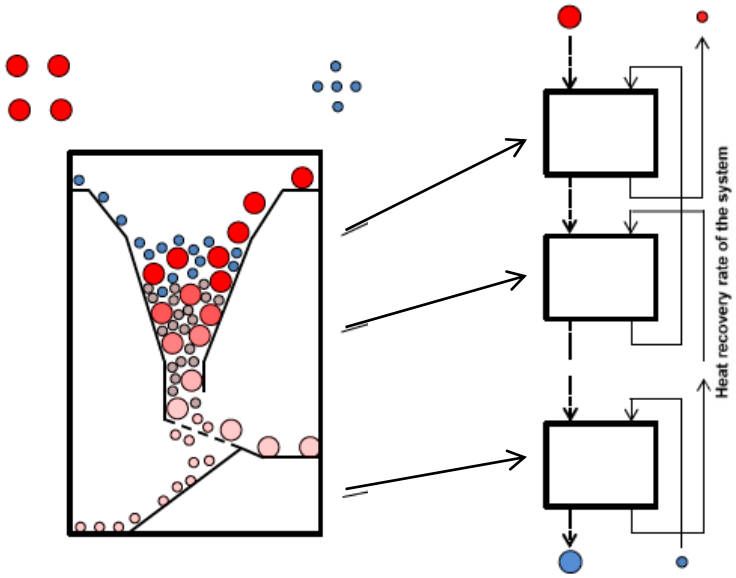


Contact: johannes.grobbel@dlr.de

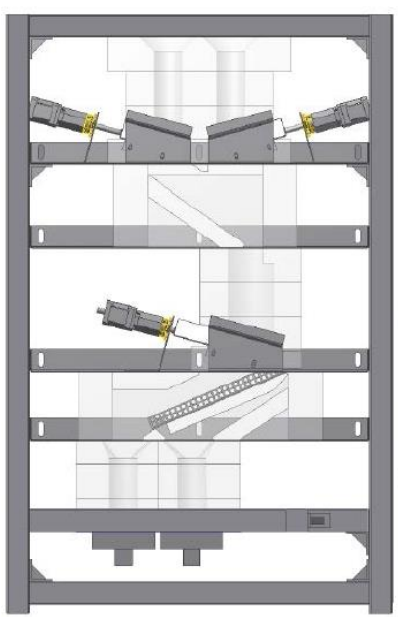
DLR

Solid State Heat Recovery: Particle-Particle Heat Exchanger

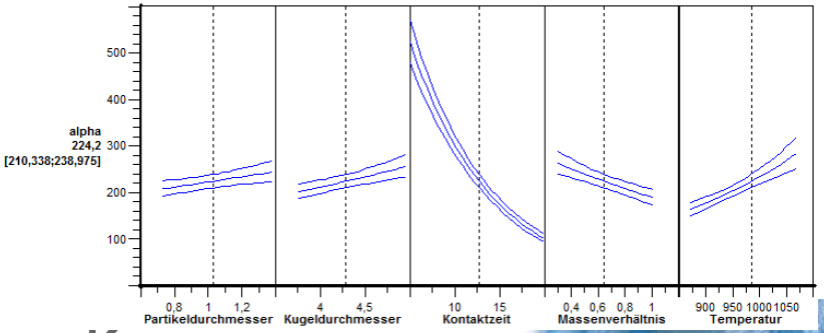
Concept: Combine co-current HXs to obtain quasi counter-current HX

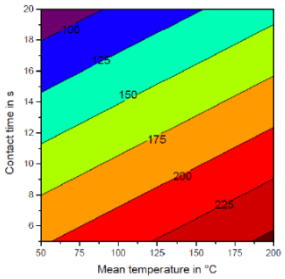


Experimental setup to characterize heat transfer at up to 1100°C



Results show high recovery potential





Felinks et al. ATE, 101 (2016) 101
Felinks et al. ATE, 73 (2014) 1004
Brendelberger et al. ASME (2014) 6421

Contact: stefan.brendelberger@dlr.de

Research Activities Particle Heat Exchanger

Experiment:

- Flow measurements using a transparent HX mockup and PIV analysis
- Thermal measurements with stainless steel HX up to 600 °C

Modelling:

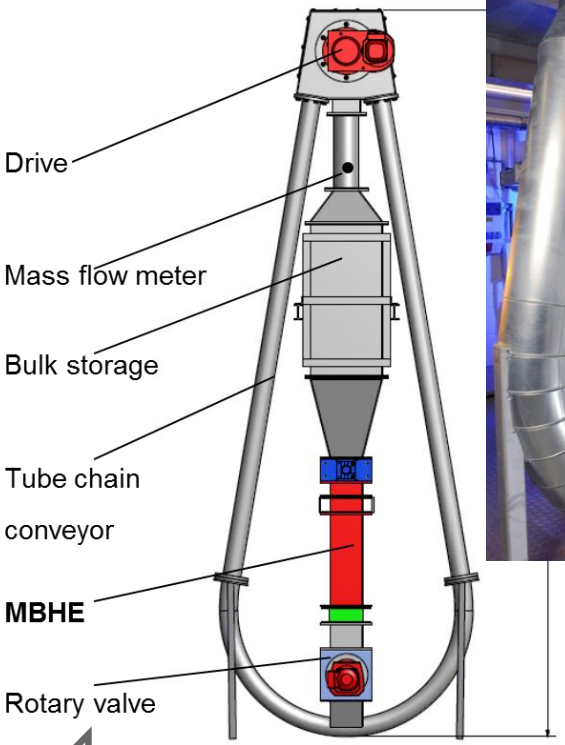
- Continuum-model approach (Eulerian model with two phases)

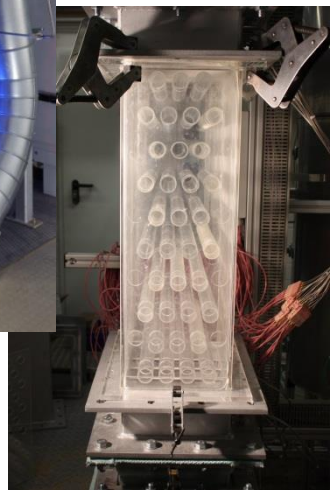
→ Flow field

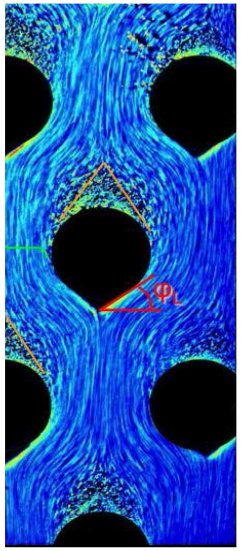
→ Temperature field

- Discrete Element Methode (DEM)

→ Flow field

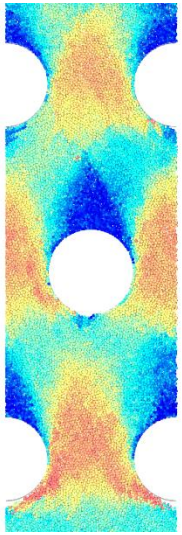






Experiment (Streamlines)

Continuum (Velocity magnitude)



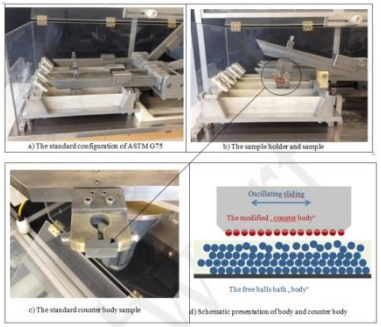
DEM

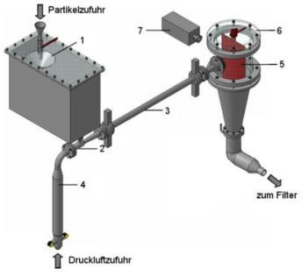
Contact: philipp.bartsch@dlr.de

Investigation of Particle Attrition and Abrasion

Particle attrition:

- Impingement test, modified Miller test, shear cell
- For CentRec conditions:
  particle loss value < 0.32 €Ct/kWh$_{th}$





Abrasion on metallic samples:

- Slow sample movement through heated particle bed
- Increased abrasion at higher temperatures

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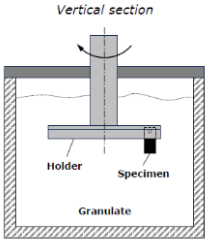
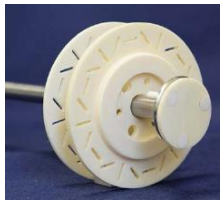
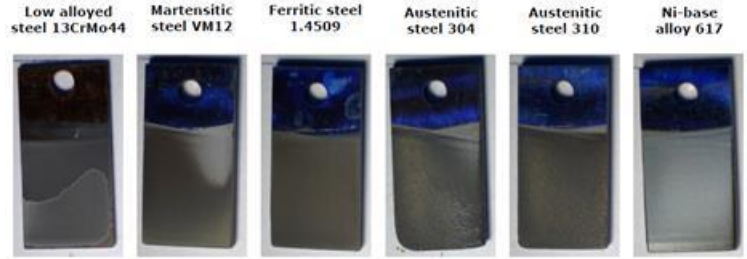
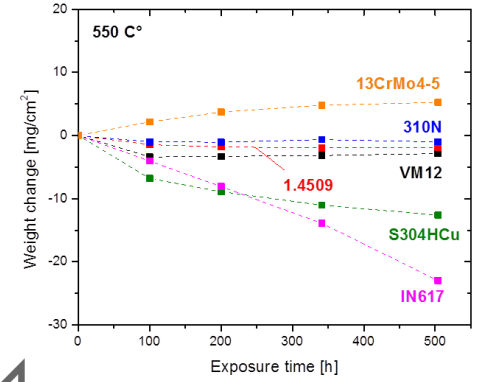
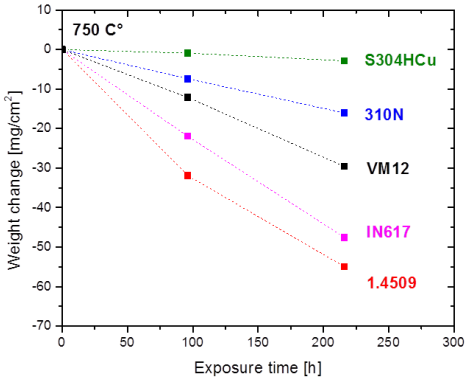








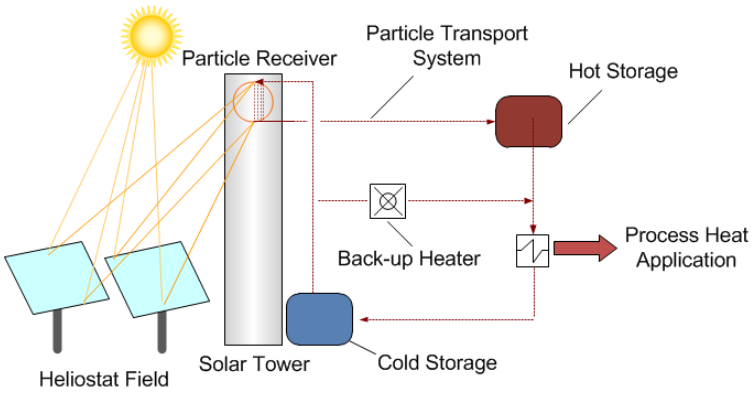


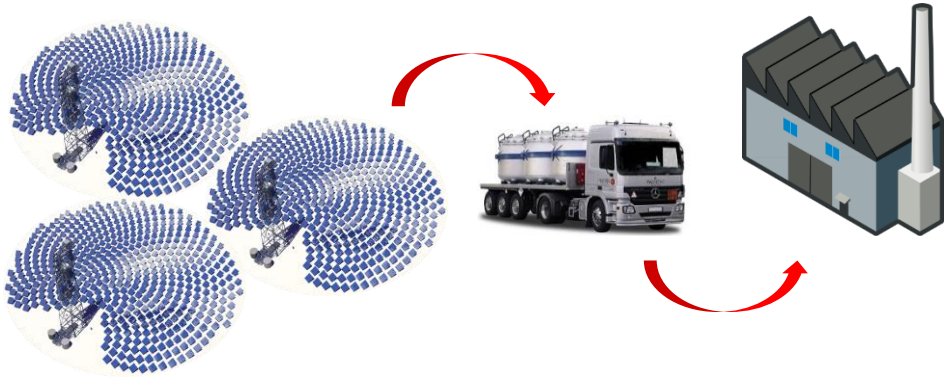
		C	Fe	Cr	Ni	Mn	Si	Mo	Other
Low alloyed steel	**13CrMo4-5**	0.11	bal.	0.82	-	0.53	0.19	0.45	
Martensitic steel	**VM12**	0.11	bal.	11.4	0.2	0.17	0.44	0.27	1.5W, 1.5Co, 0.05Nb, 0.22V
Ferritic steel	**1.4509**	0.02	bal.	17.3	0.17	0.43	0.35	0.02	0.12Ti
Austenitic steel	**S304HCu**	0.09	bal.	18.7	8.7	0.75	0.2	-	0.11N, 2.8Cu, 0.43Nb
Austenitic steel	**310N**	0.07	bal.	24.4	20.9	1.18	0.41	-	0.2N, 0.44Nb
Ni-base alloy	**IN617**	0.06	1.14	21.9	bal.	0.07	0.08	8.7	11.35Co, 1.17Al, 0.5Ti

Particle Receiver System for Process Heat

Modular concept:

- Module specs:
  - 2.5MW_{th} peak / 0.8 MW_{th} baseload
  - 1ha footprint
- Number of modules can be adapted to needed capacity
- Optional: transport of hot particles over some km allows the solar plant to be built off-site
- Use for:
  - Metallurgy
  - Process Steam
  - Process Heat
  - …
- Options for 1st demo plant?





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Questions?