

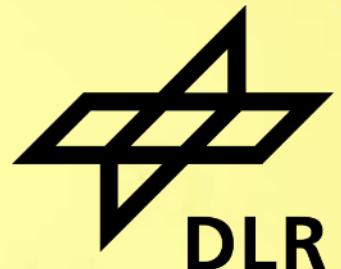
# **THE THEORY OF HEAT AND MASS TRANSFER PROCESSES IN POROUS OF SOLAR RECEIVER**

Public lecture for DAAD scholarship holders



# SOLAR RESEARCH AT THE GERMAN AEROSPACE CENTER

Part 1 of Public lection „The theory of heat and mass transfer processes in porous of solar receiver”



# German Aerospace Center

## Research Centre + Space Agency + Project Management Agency



### AERONOTICS



### SPACE



### ENERGY



### TRAFFIC



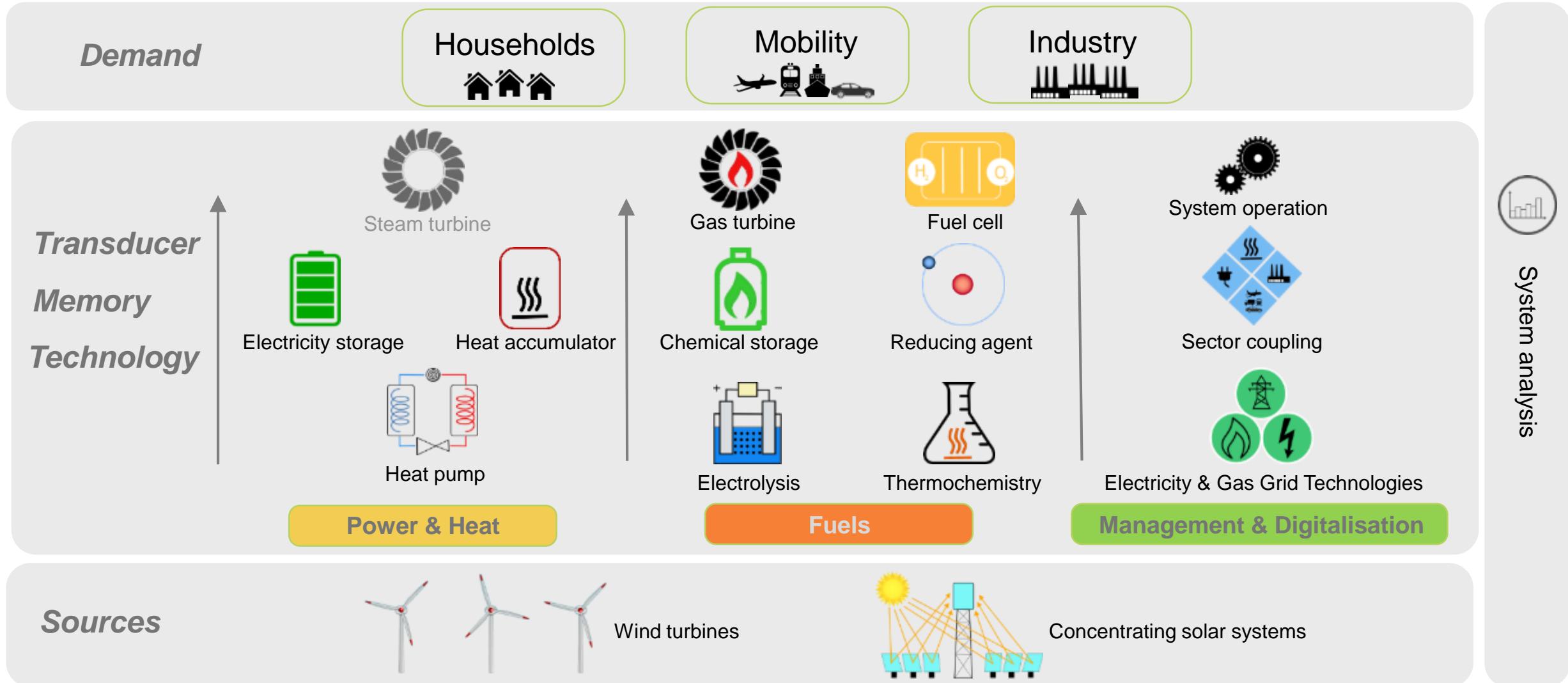
**SECURITY**  
Civil & Defence Security Research



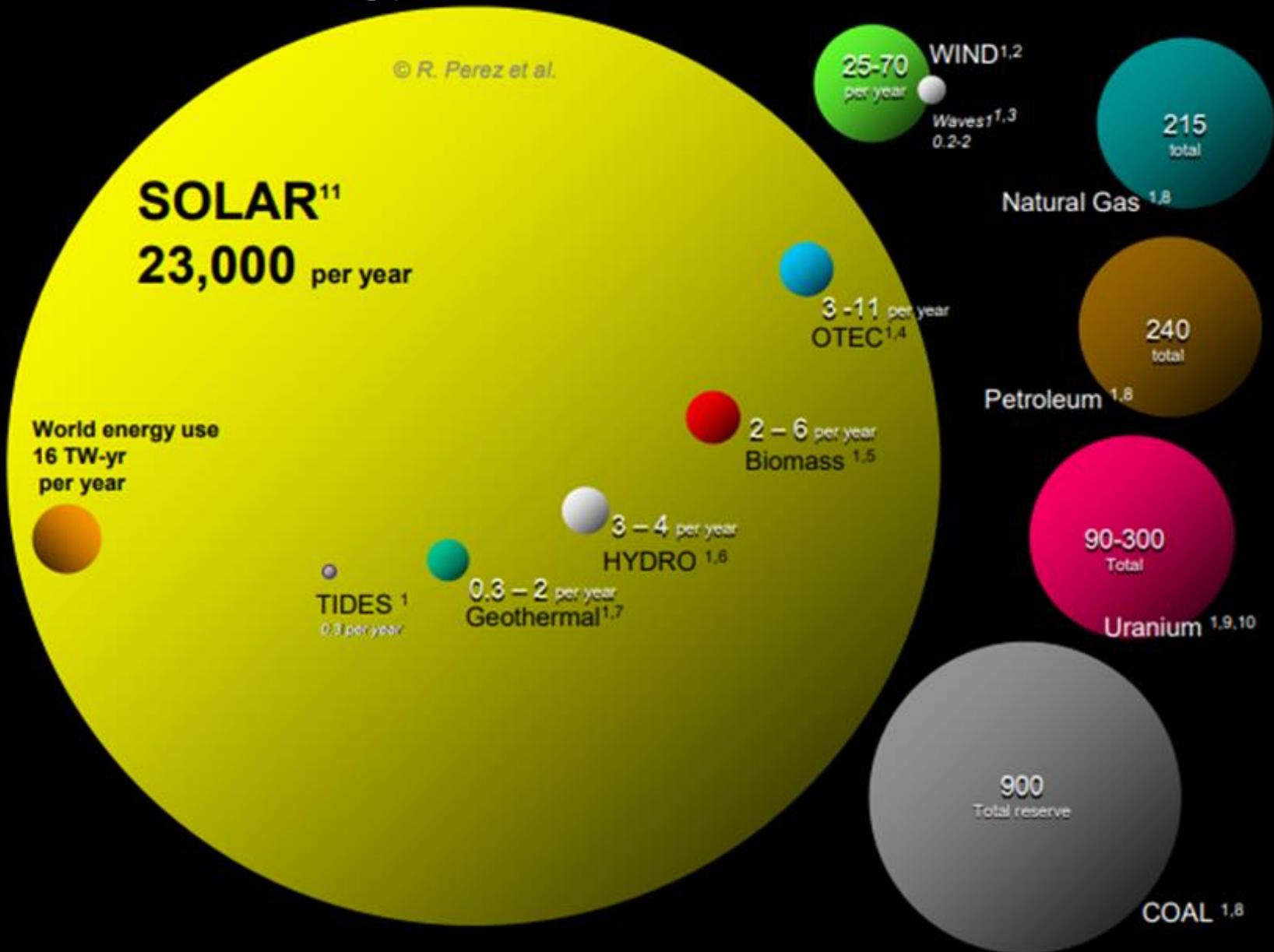
**DIGITISATION**  
Quantum Technologies & Systems Modelling



# DLR Energy Research: Controllable Sustainable Energy



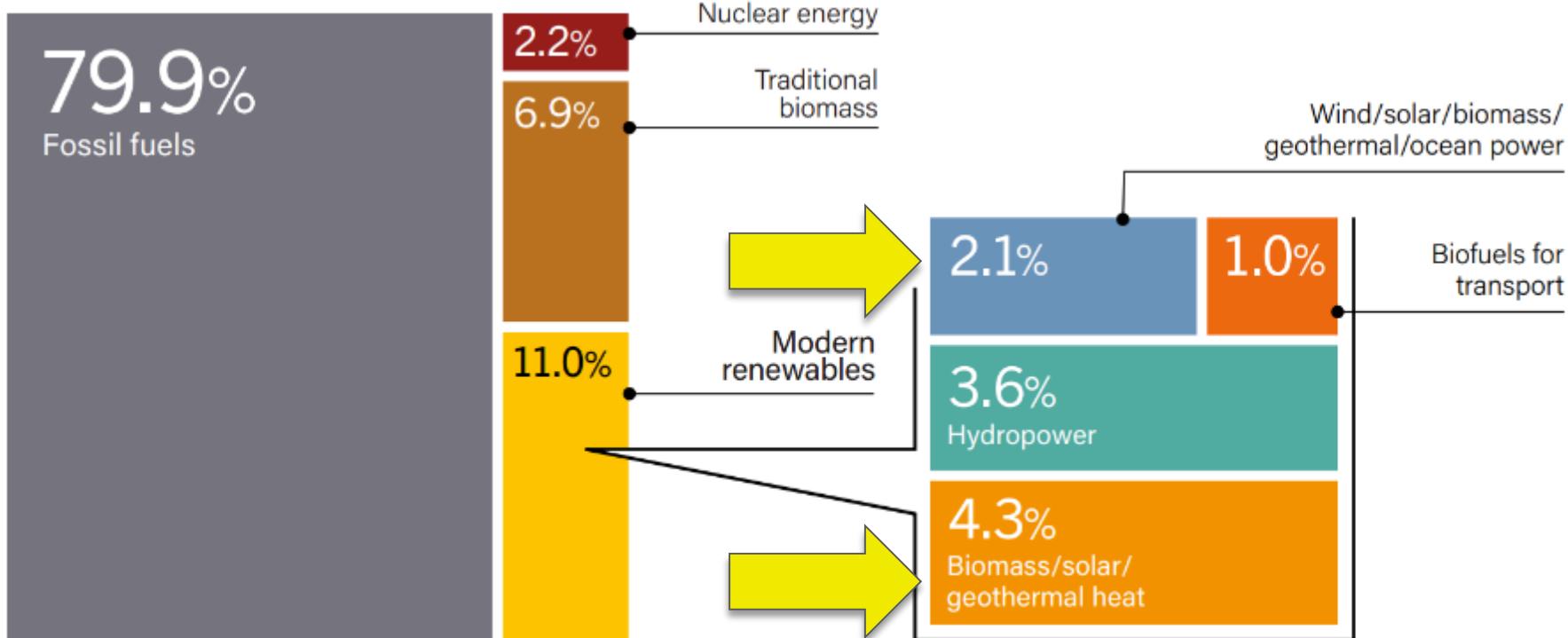
# The sun: energy for the future



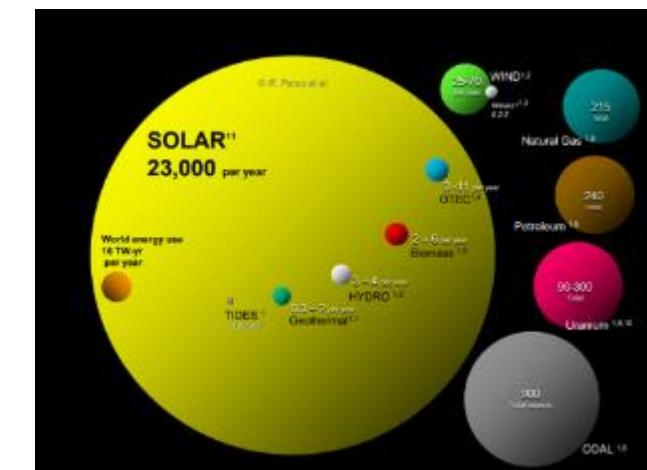
## Available solar energy:

- More than 90% of renewable energy resources
- Energy for 10,000 Earths

# Energy resources used worldwide



Source: REN21 (2020): Global Stature Report 2020 (figures from 2018).



# Institute of Solar Research



Concentrating  
solar technologies



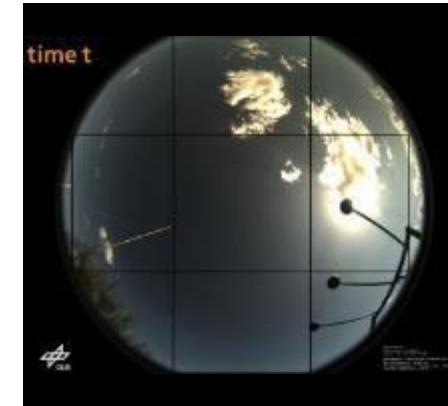
Quality assurance and  
operational optimisation  
for solar power plants and  
photovoltaic systems



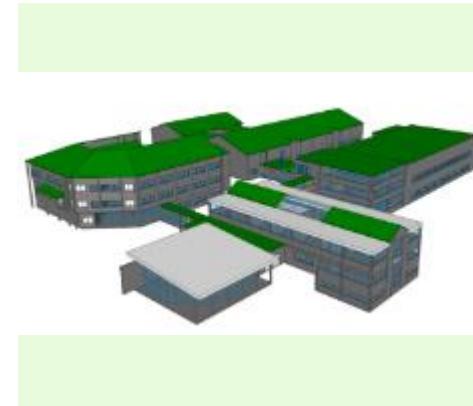
Agri Photovoltaics



Solar energy  
meteorology



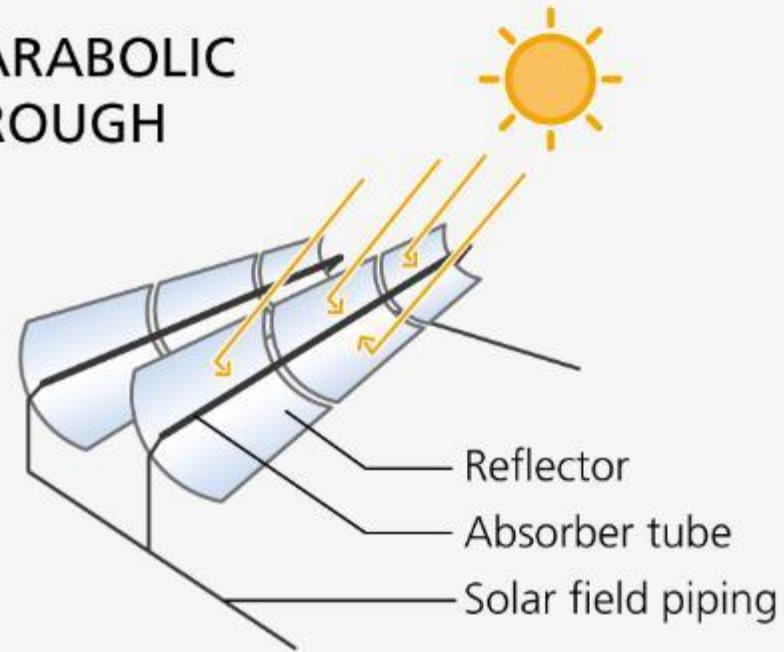
Heat transition:  
Energetic building  
assessment



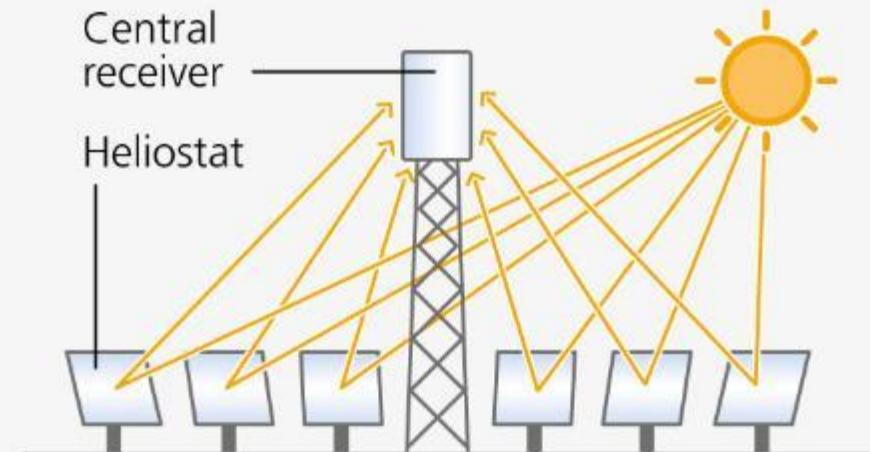
# In a nutshell: How does a solar thermal power plant work?



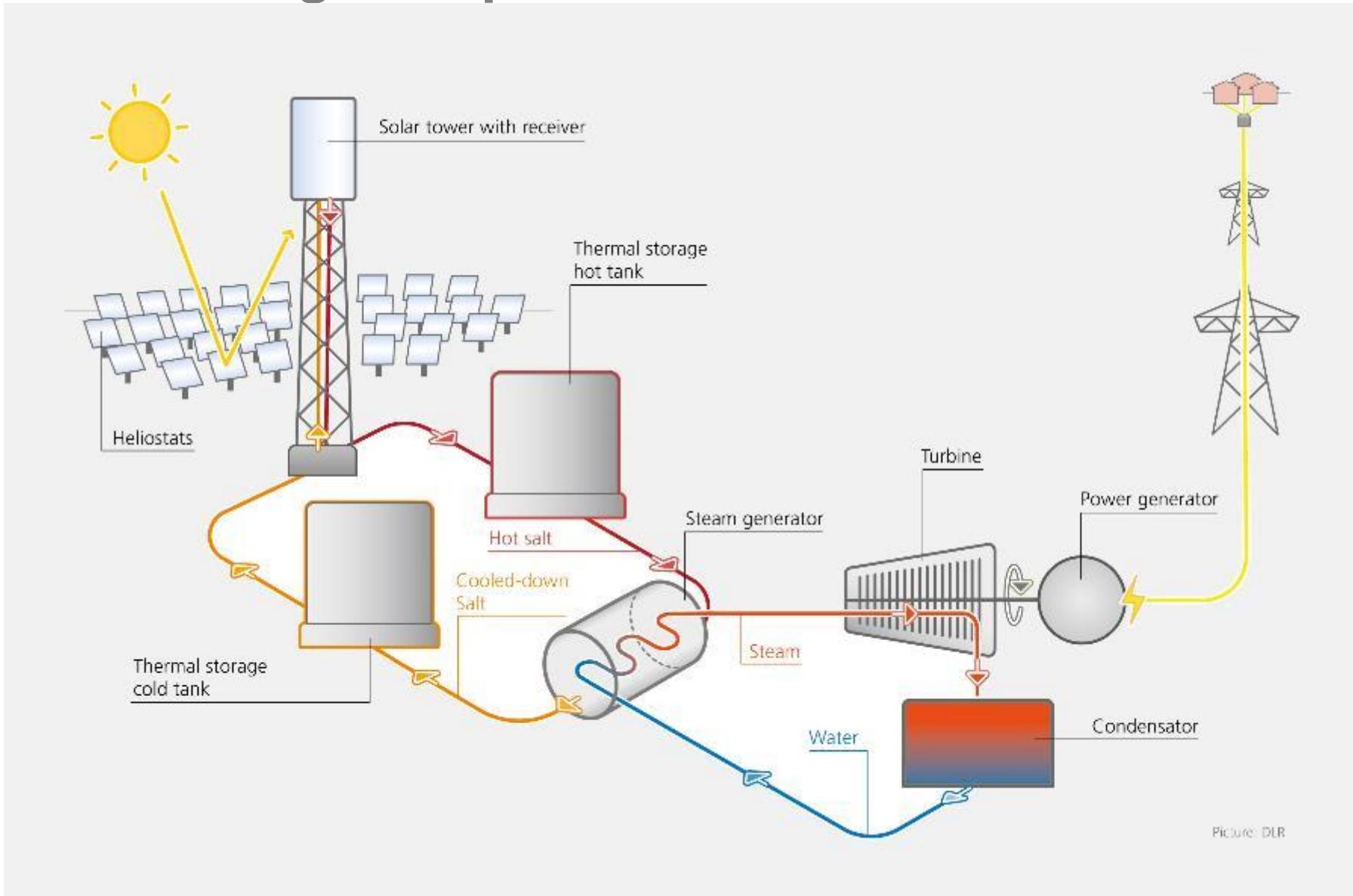
**PARABOLIC  
TROUGH**



**SOLAR TOWER**



# In brief: from high temperatures to electric current



Picture: DLR

# The advantages of CSP technologies in a renewable energy system



- CO<sub>2</sub>-free
- Sustainable energy storage
- 24/7 Energy
- Adjustable
- Hybrid power plants with PV possible
- Can be used in district heating networks
- Can provide process heat for industrial plants
- Without rare resources

# Milestones of the Institute of Solar Research



**02/2011**

DLR founds  
**Institute of  
Solar  
Research**



**06/2011**

Takeover of the  
**Jülich Solar  
Tower**



**03/2017**

Inauguration  
of **Synlight** in  
Jülich



**06/2020**

Spin-off of the  
**Institute of  
Future Fuels**

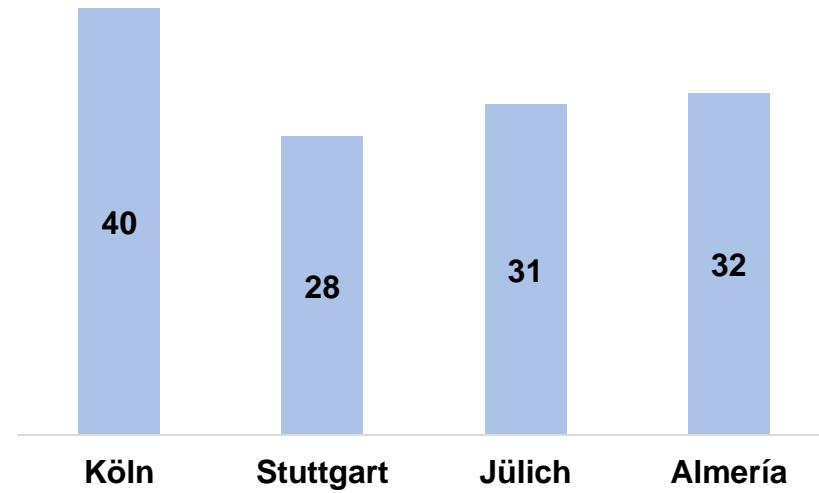


**07/2020**

Inauguration of  
the Jülich  
**Multifocus  
Solar Tower**



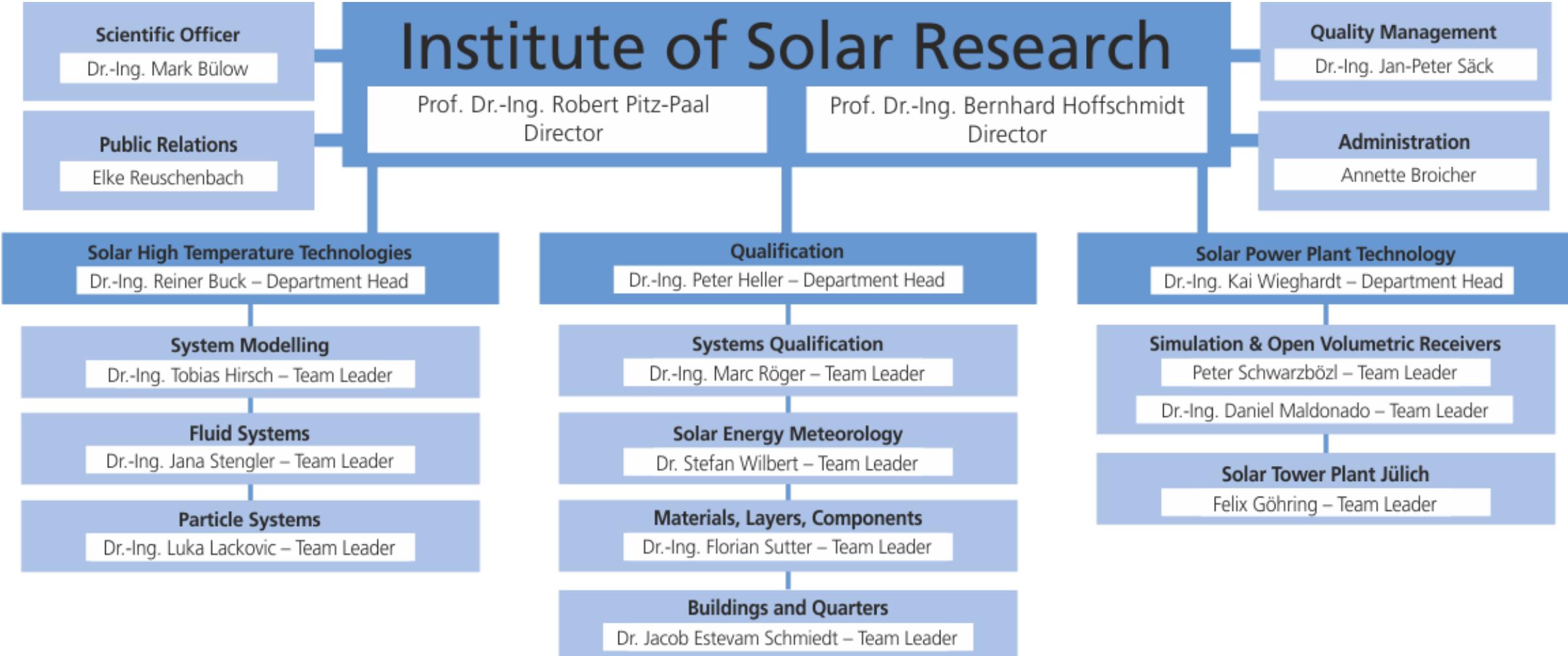
# Solar research at our four locations



# Organisational chart



## Institute of Solar Research



# Institute of Solar Research



Departments for the development and optimisation of solar thermal power plants

Technology development: efficient and economic use of solar energy for the production of electricity, heat and fuels

Solar high temperature technologies



Solar power plant technology



Qualification



Chairs in Aachen

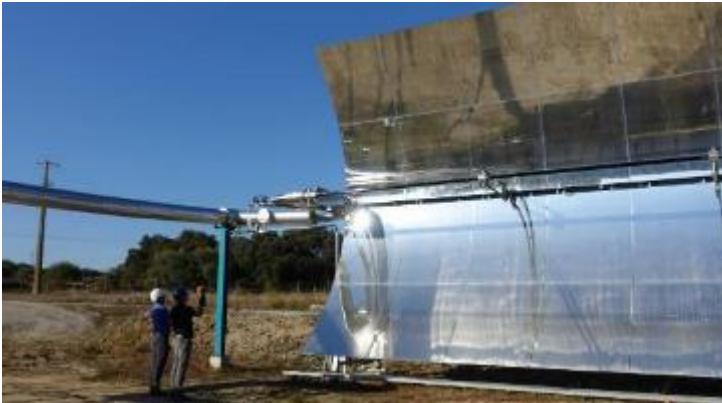


# Department Solar High Temperature Technologies



Head of Department: Dr.-Ing. Reiner Buck

## "Fluid Systems" Dr.-Ing. Jana Stengler



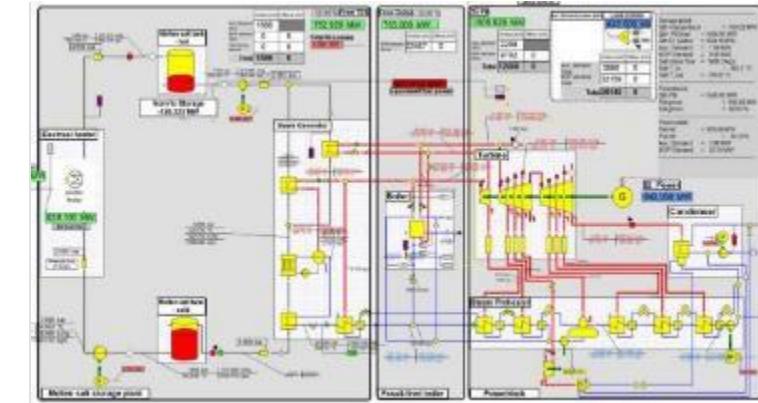
- Heat transfer in liquids and gases
- Operation of liquid salt plants
- Solar process heat

## "Particle systems" Dr.-Ing. Luka Lackovic



- Heat transfer in particles
- Development of particle receivers and heat exchangers
- CFD/FEM/DEM modelling

## "System Modelling" Dr.-Ing. Tobias Hirsch



- System modelling and design
- Techno-economic evaluation
- Operating behaviour and control of parabolic trough systems

▪ 30 employees at the locations and plants in Stuttgart, Cologne and Évora (Portugal)

# Department Solar Power Plant Technology



Head of Department: Dr.-Ing. Kai Wieghardt

## "Simulation and Open Volumetric Recievers" Peter Schwarzbözl



- Controls for CSP and heliostat arrays
- Automation, dyn. simulation
- Flux density measurements

## ■ Employees at the Jülich site

## "Jülich Solar Tower Power Plant" Felix Göhring



- Trial operation of the plants:
- Jülich experimental solar thermal power plant
- Multifocus Tower Jülich

# Department Qualification



Head of Department: Dr.-Ing. Peter Heller

## "System qualification"

Dr.-Ing. Marc Röger



- Opt. qualification of solar fields
- Thermal characterisation of receiver systems

## "Solar Energy Meteorology"

Dr. Stefan Wilbert



- Determination of meteorological parameters
- Analysis of the impact on CSP

## "Materials, Layers, Components"

Dr.-Ing. Florian Sutter



- Test methods and tests of components
- Durability of materials and components

## "Buildings and Quarters"

Dr. Jacob Estevam Schmiedt



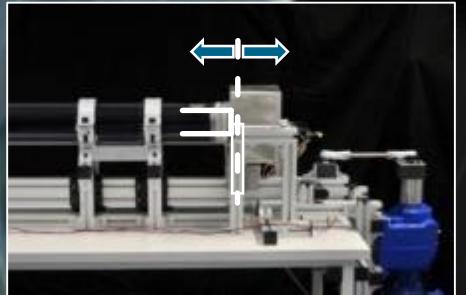
- Energy analysis of buildings
- Basis for rehabilitation planning

■ 40 employees at the sites in Cologne, Jülich, Oldenburg and Almería (Spain)



# PLATAFORMA SOLAR DE ALMERÍA

OWNER AND OPERATOR: CIEMAT



# QUARZ® LABORATORY



# PROCESS HEAT TEST FACILITY



# EVORA MOLTEN SALT PLATFORM

# JÜLICH EXPERIMENTAL SOLAR THERMAL POWER PLANT

# Spin-offs of the Institute of Solar Research



2007



Optimising solar field performance and maximising system lifetime



2016



Heliostat design and control. Today Synhelion Germany



2017



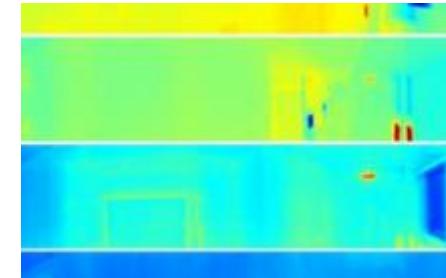
Particle receiver technology. Today part of Heliogen



2019



3D capture and energy-efficient analysis of buildings



2020



Fully automatic condition monitoring of CSP and PV plants



- Development of alternative fuels

Technology development for the efficient and economic production  
of energy sources for a global, renewable energy economy

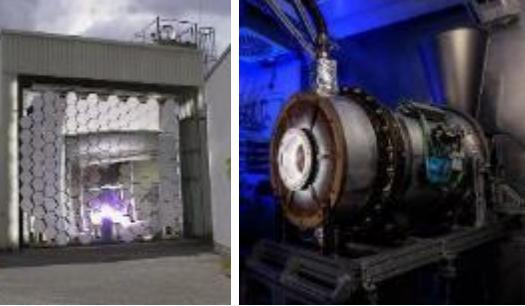
Solar chemical processes



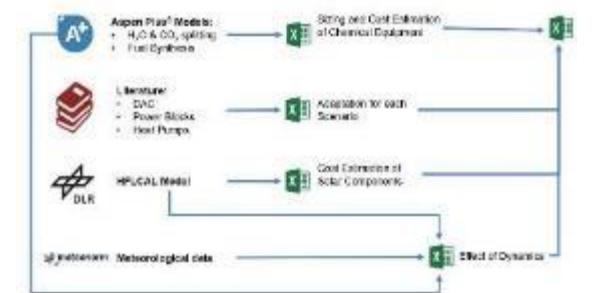
Material and  
component design



Demonstration

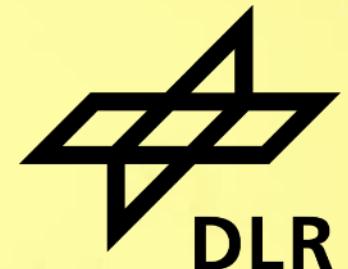


Evaluation



# **THE THEORY OF HEAT AND MASS TRANSFER PROCESSES IN POROUS MEDIA**

Part 2 of Public lection „The theory of heat and mass transfer processes in porous of solar receiver”



# The theory of heat and mass transfer processes in porous media



## Purpose

- Improve the quality and accuracy of existing calculations of heat and mass transfer processes in receivers.

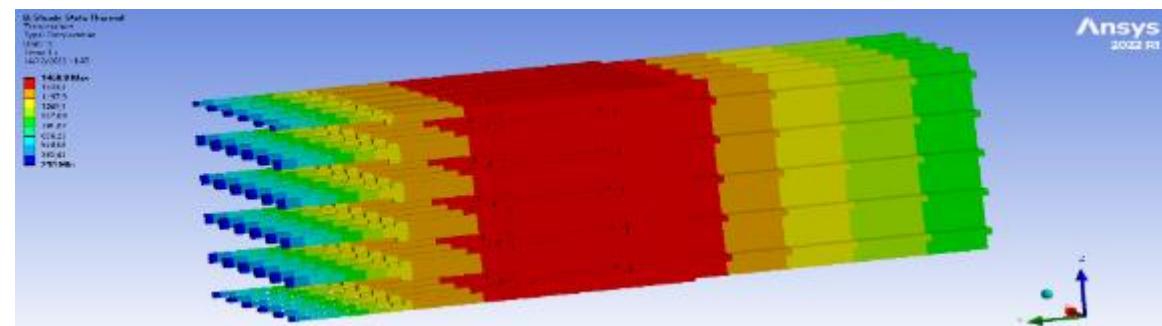
## Tasks

- AP 1 Basics
- AP 2 Modeling
- AP 3 Related technical tasks
- AP 4 Support to projects
- AP 5 Analysis of potential

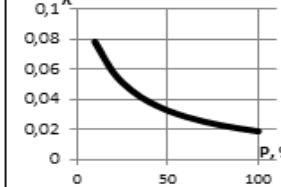
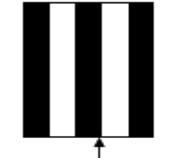
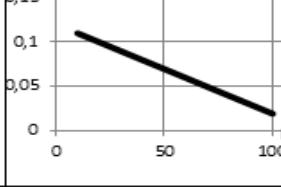
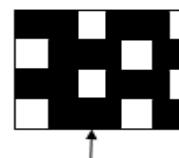
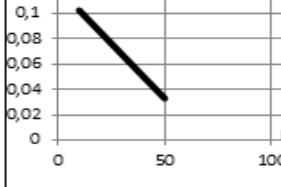
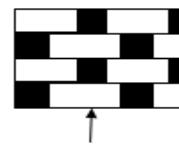
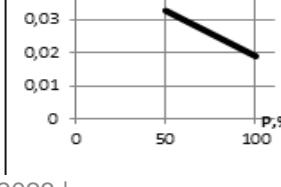
## Partner

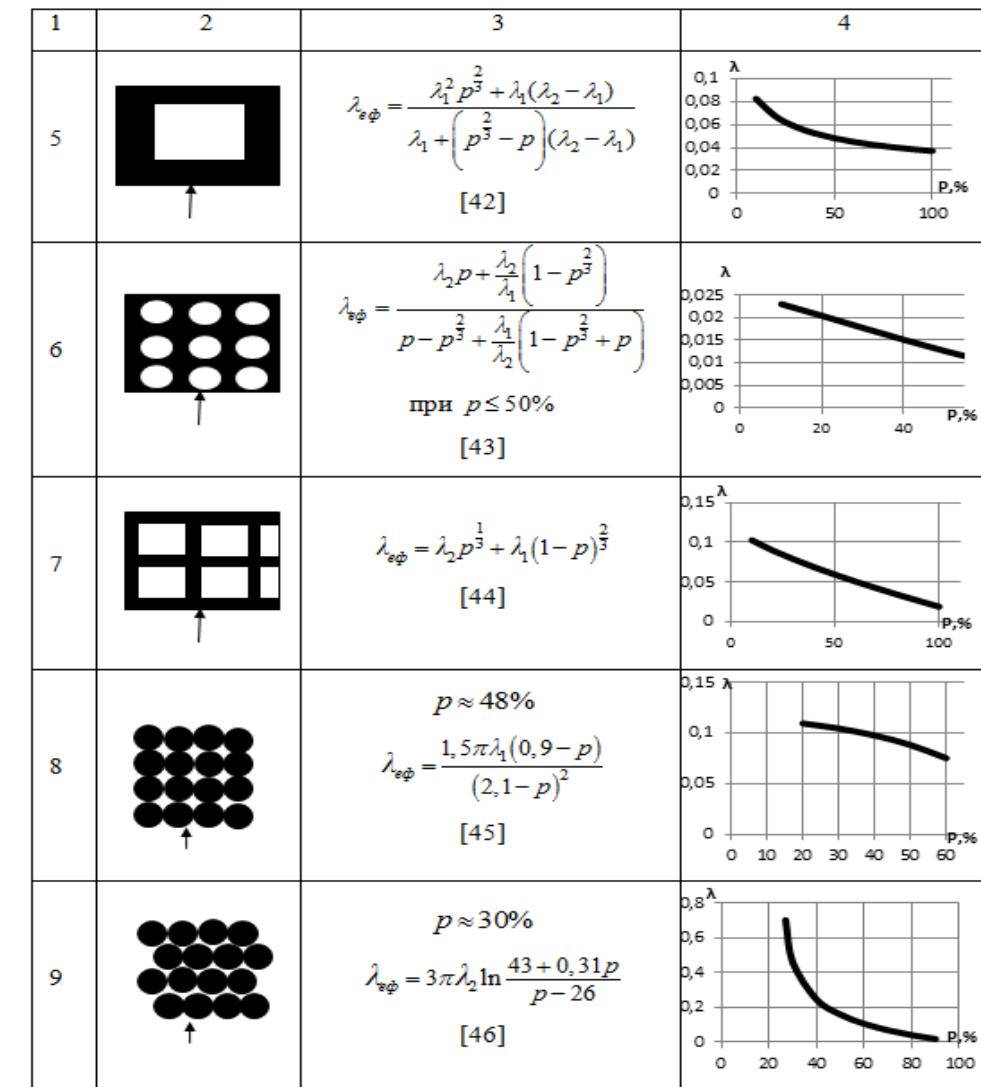
- DAAD
- Synlight
- FH Aachen
- RWTH Aachen

$$\rho_s(c_p)_s \frac{\partial T_s}{\partial \tau} = \frac{\partial}{\partial x} \left( \lambda_s \frac{\partial T}{\partial x} \right) - \alpha A_v (T_s - T_f) + q_{source}$$
$$\rho_f(c_p)_f \left( \frac{\partial T_f}{\partial \tau} + u T_f \right) = \frac{\partial}{\partial x} \left( \lambda_f \frac{\partial T}{\partial x} \right) + \alpha A_v (T_s - T_f) + q_{source}$$

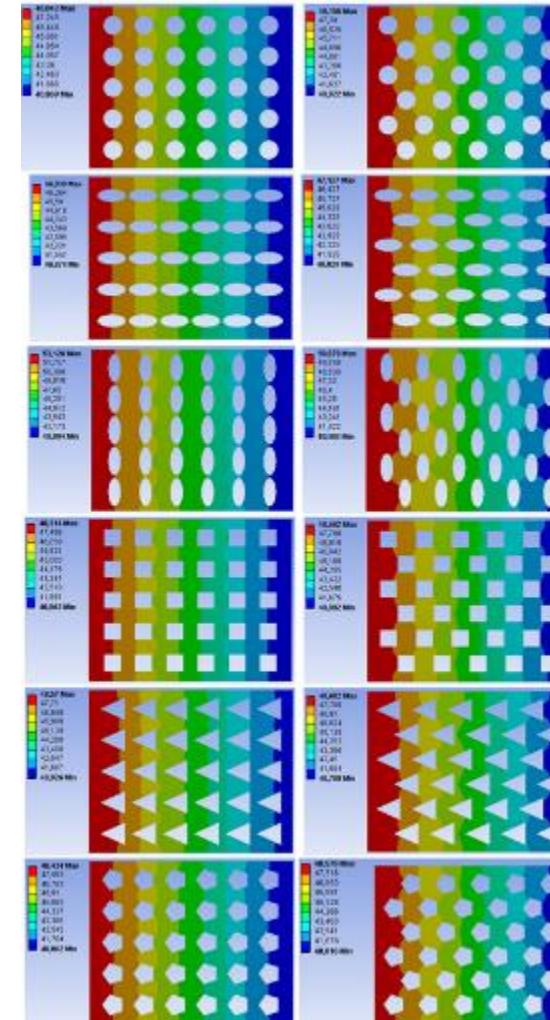
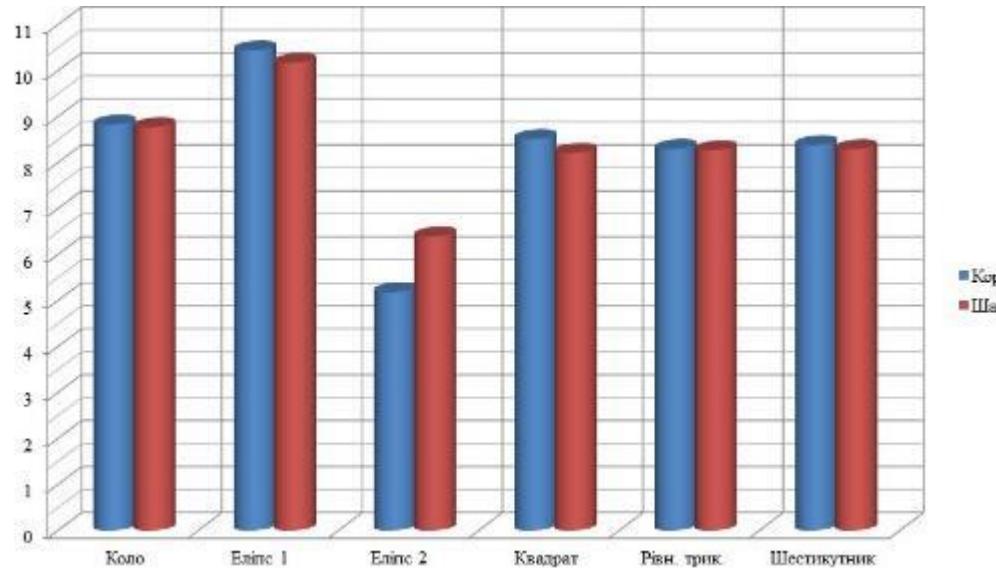
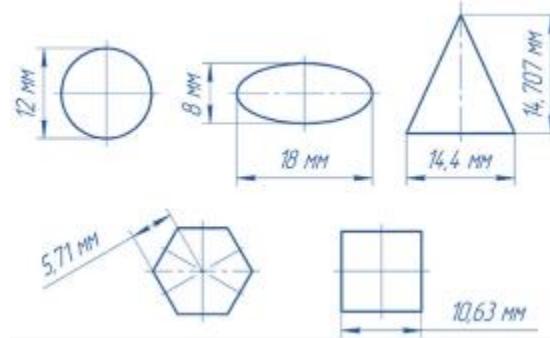


# Influence of structural characteristics of porous materials on the intensity of heat and mass transfer processes

двофазних систем			
№ п/п	Схема розташування пор	Формула для розрахунку ефективного коефіцієнта тепlopровідності	Приклад $\lambda_{\text{eff}} = f(p)$
1	2	3	4
1		$\lambda_{\text{eff}} = \lambda_2 \frac{100}{\lambda_2(100-p) + p}$ [3]	
2		$\lambda_{\text{eff}} = \lambda_1 \frac{100-p}{100} + \lambda_2 \frac{p}{100}$ [3]	
3		$\lambda_{\text{eff}} = \lambda_1 \frac{100-p}{100} + \lambda_2 \frac{p}{100}$ при $p \leq 50\%$ [41]	
4		$\lambda_{\text{eff}} = \lambda_2 \left[ \frac{4(1-p)}{1 + \frac{\lambda_2}{\lambda_1}} + (2p-1) \right]$ при $p \geq 50\%$ [41]	



# Study of the influence of pore shape on the thermal conductivity coefficient of porous structures and thermal protection structures without taking into account convection inside the pores



Thermal conductivity coefficients of porous materials and products with different pore shapes

# Time plan

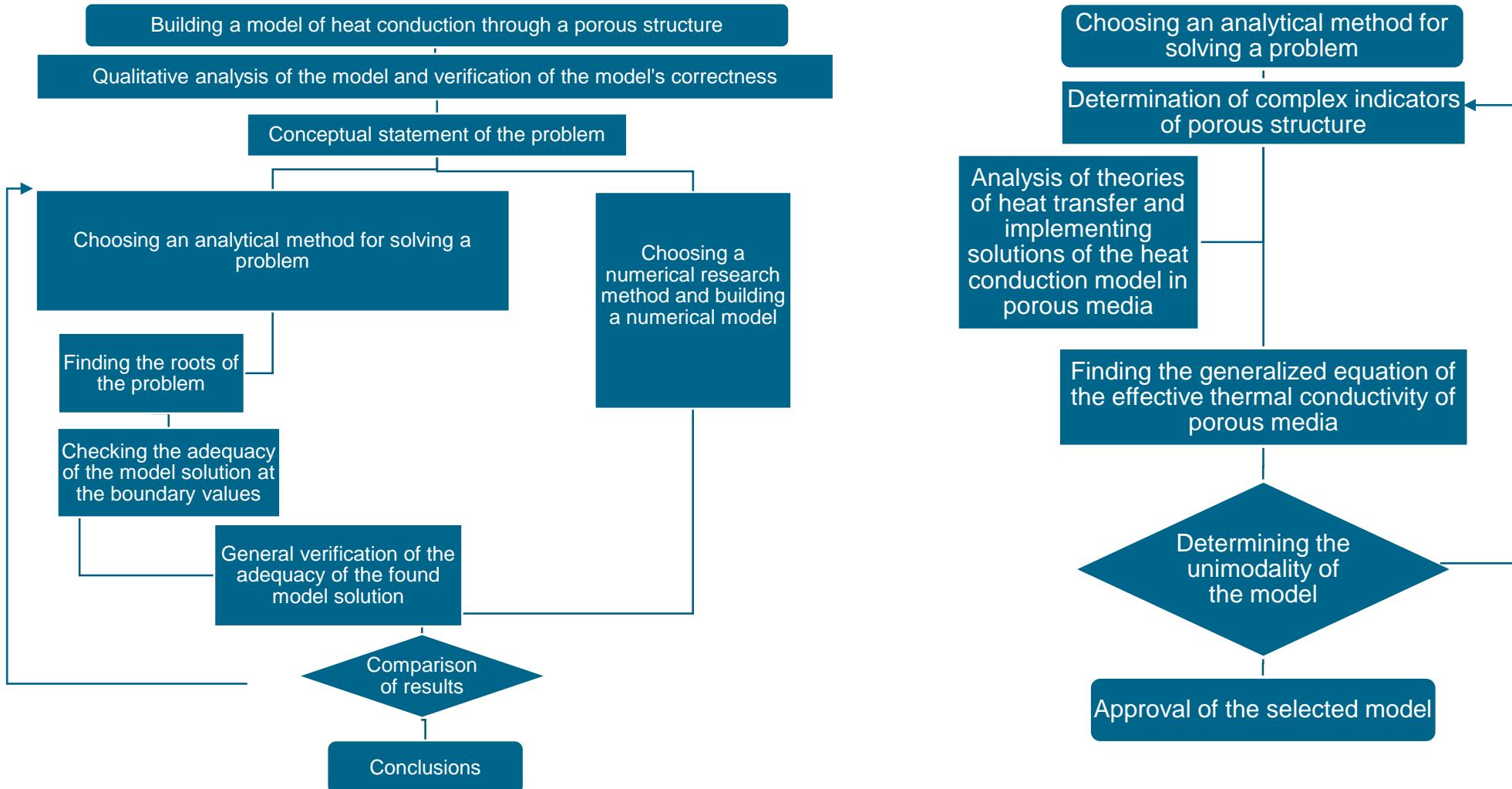
## The theory of heat and mass transfer processes in porous media



Prof., Dr Ing Cheilystko Andrii

		Month	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
	Tasks	No Month	1	2	3	4	5	6	7	8	9	10	11	12
1	WP 1 Basics	Cooperation												
1.1	Complex input factors of the model	DLR												
1.2	Output factors of the model	DLR												
1.3	Functional dependence of efficiency in optimisation													
2	WP 2 Modelling													
2.1	Analyse the error caused by simplifications													
2.2	Mathematical model of the heat and mass transfer in a porous absorbers													
2.2.1	Thermal conductivity model	DLR												
2.2.2	Convective heat transfer model	DLR												
2.2.3	Pressure drop model	DLR												
2.3	Verify the mathematical model	DLR												
2.4	Incorporating the theories into university curricula	RWTH Aachen												
3	WP 3 Technical tasks													
3.1	Aerodynamics of the front surface of the receiver	DLR												
3.2	Optimising the design of CSP introducing a power factor	DLR												
3.3	Heat and mass transfer in a porous catalyst	DLR												
3.4	Development of measures for the introduction of small CSP in the Ukraine	DLR, Kielce University (Poland), Ukrainian university												
4	WP 4 Support to projects													
4.1	Design optimisation VoCoRec	DLR												
4.2	Design optimisation O4S	DLR												
4.3	Development of a new receiver design													
4.4	Supervisor of the Master's thesis													
4.5	Project on a new chemical receiver													
5	WP 5 Potential analysis													
5.1	SWOT analysis													
5.2	Scientific potential													
5.3	Assessment and technical potential	DLR												

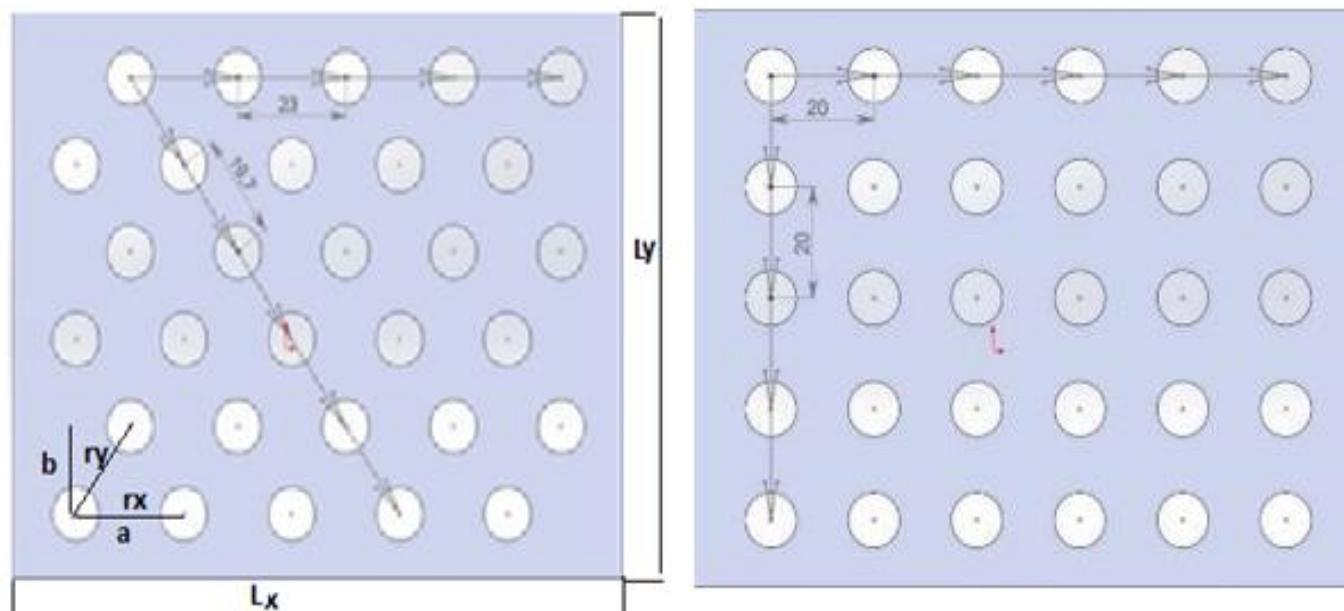
# Methodology for finding the equation of effective thermal conductivity



# The dislocation vector

The volume of a unit cell can be calculated from the constant lengths and angles of the lattice. If the sides of the cell are represented as vectors, the volume is equal to the scalar triple product of these vectors

$$V_{cell} = a s b \sqrt{1 + 2\cos\alpha\cos\beta\cos\gamma - \cos^2\alpha - \cos^2\beta - \cos^2\gamma}$$



$$(\bar{k}_y)_y = n_y \langle r_y \rangle / L_y$$

$$(\bar{k}_y)_x = n_x \langle r_x \rangle / L_x$$

Locations with vectors on them  $k_y=1.182$  (left),  $k_y=1$  (right)

# New equation

Equation DLR of the effective coefficient of thermal conductivity

$$\lambda_{eff,s} = \frac{\frac{\lambda_f \lambda_s}{\lambda_s \emptyset + \lambda_f(1 - \emptyset)}}{\frac{\lambda_s}{\lambda_f} \emptyset + 2\Psi + \frac{\lambda_f}{\lambda_s}(1 - \emptyset) + 1} \left[ \frac{\lambda_s}{\lambda_f} \emptyset + (1 - \emptyset) + \Psi \right] \left[ \emptyset + \frac{\lambda_f}{\lambda_s}(1 - \emptyset) + \Psi \right]$$

$\Psi$  - indicator of porous structure;

For different models of heat transfer, the solution of this model has different roots  $\Psi$ .

For open channel structure

$$\Psi = \frac{1}{k_y} (\emptyset - 1) \frac{(\lambda_s - \lambda_f)}{\lambda_s \lambda_f} [\lambda_f(\emptyset - 1) - \lambda_s(\emptyset)]$$

For porous mesh or catalyst, the following solution is recommended (this equation considers the uncertainty of  $k_y$ )

$$\Psi = (\emptyset - 1) \frac{1 - \frac{\lambda_f}{\lambda_s} + \sqrt{\left(1 - \frac{\lambda_f}{\lambda_s}\right)^2 + 4}}{2} + \emptyset \frac{1 - \frac{\lambda_s}{\lambda_f} + \sqrt{\left(1 - \frac{\lambda_s}{\lambda_f}\right)^2 + 4}}{2}$$

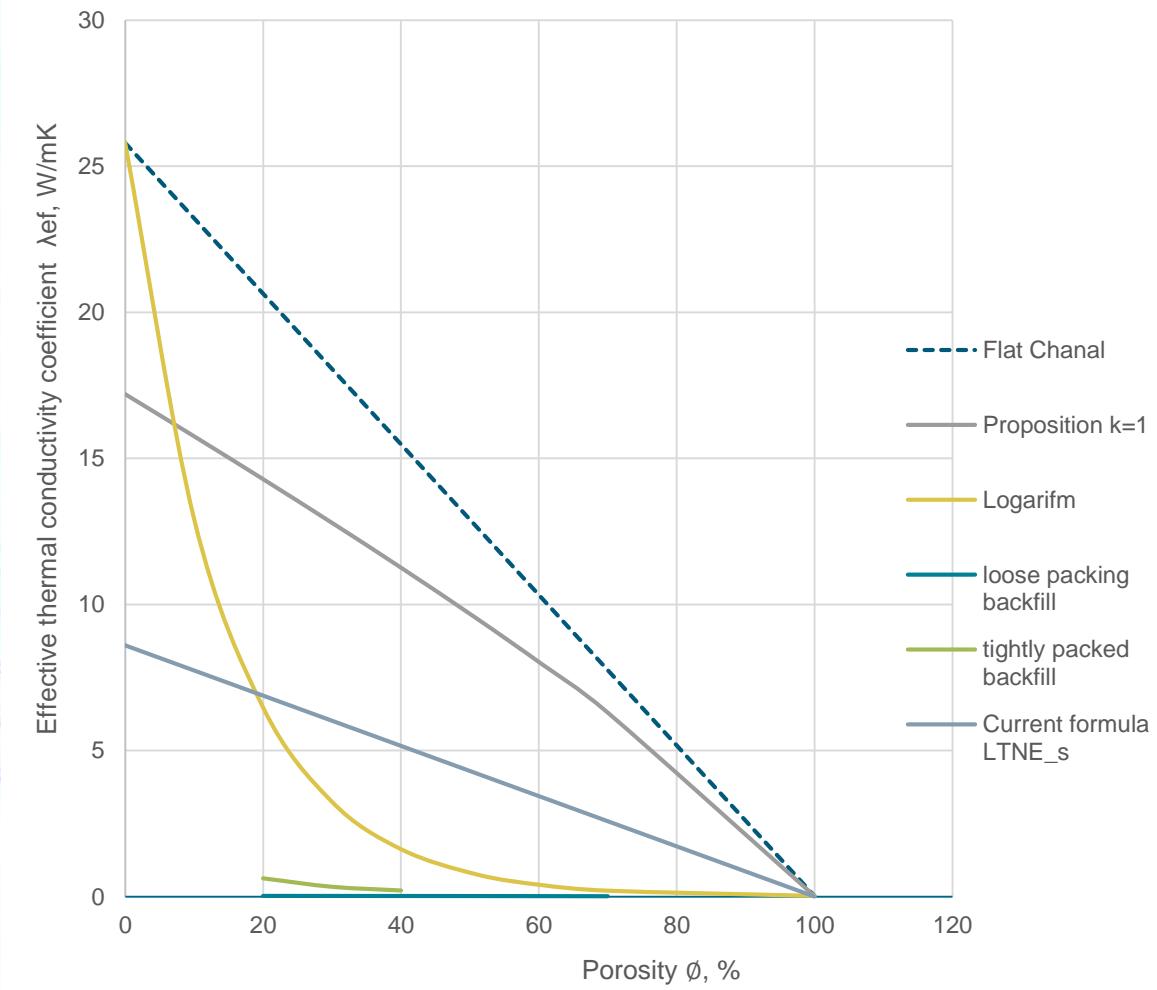
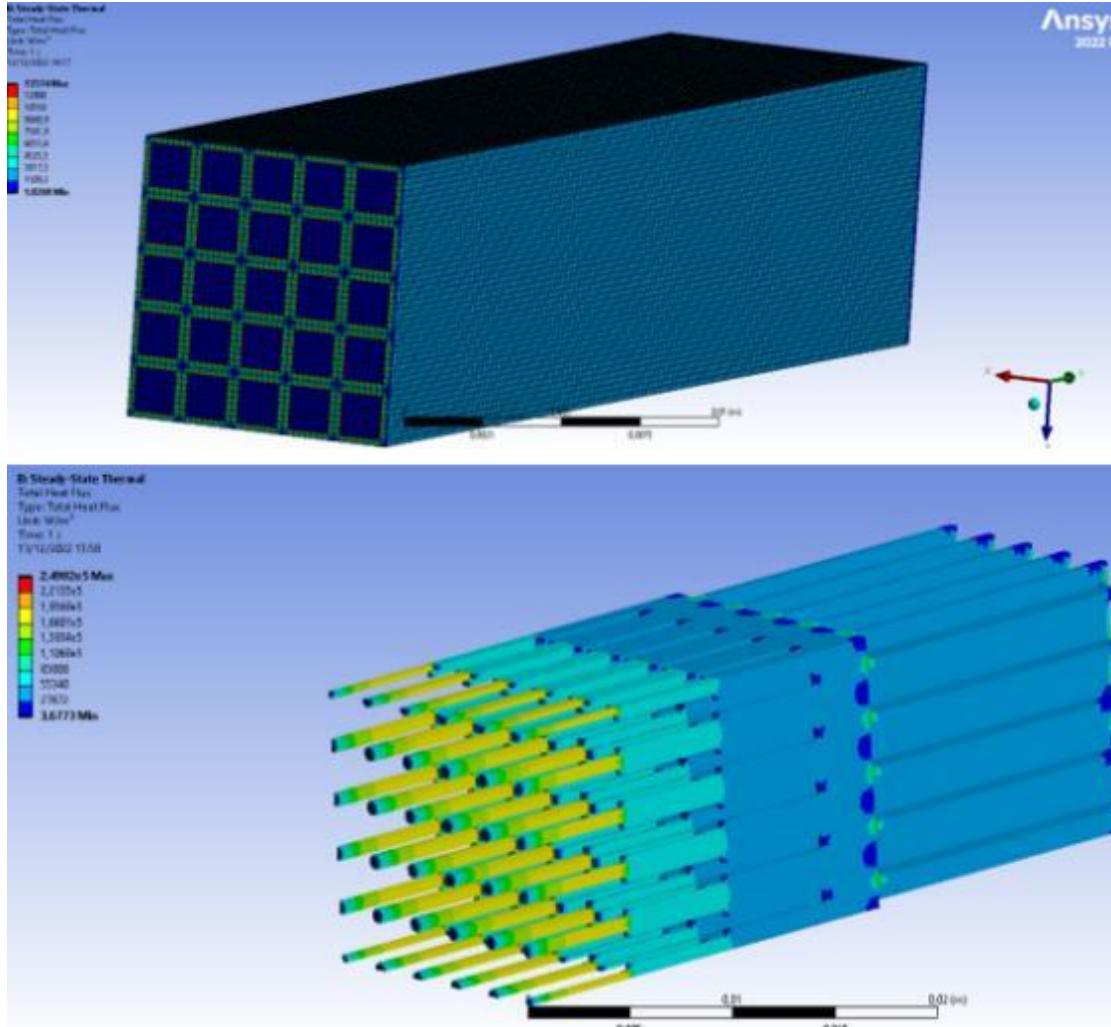
For fluid in the LTNE model

$$\Psi_f = \left( k_y \frac{1 - \frac{\lambda_f}{\lambda_s} + \sqrt{\left(1 - \frac{\lambda_f}{\lambda_s}\right)^2 + 4}}{2} \right)^{1-\emptyset} \times \left( k_y \frac{1 - \frac{\lambda_s}{\lambda_f} + \sqrt{\left(1 - \frac{\lambda_s}{\lambda_f}\right)^2 + 4}}{2} \right)^\emptyset$$

For porous open absorbers in the LTNE model

$$\Psi_s = \frac{1}{k_z} (\emptyset - 1) \frac{(\lambda_s - \lambda_f)}{\lambda_s \lambda_f} [\lambda_f(\emptyset - 1) - \lambda_s(\emptyset)]$$

# Comparison of different models of calculation of the effective coefficient of thermal conductivity



# Volumetric solid-fluid convective heat transfer coefficient

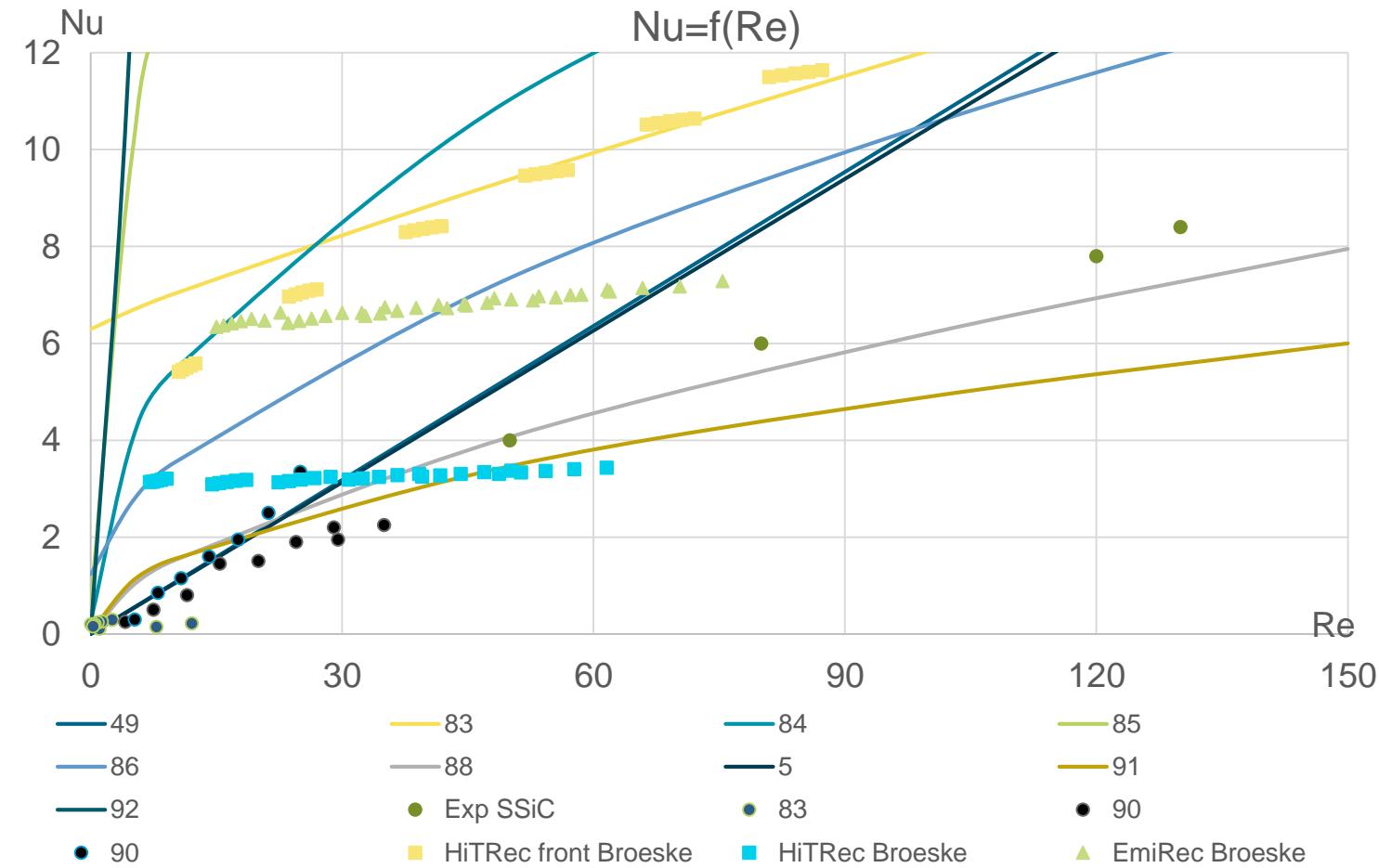


$$\frac{\partial}{\partial x} \left( \lambda_{s\_ef} \frac{\partial T}{\partial x} \right) - \alpha A_v (T_s - T_f) = 0$$

$$\frac{\partial}{\partial x} \left( \lambda_{f\_ef} \frac{\partial T}{\partial x} \right) + \alpha A_v (T_s - T_f) = 0$$

$$\alpha_v = \frac{Nu \cdot \lambda_f}{\langle d_{pore} \rangle}$$

$$Nu = \frac{Nu_0}{\tanh(2.43Pr^{\frac{1}{6}}X^{\frac{1}{6}})}$$



# How to determine the heat transfer coefficient?



The heat flux can be determined by the temperature gradient in the body or by the power of the electric heater. The wall temperature can be measured. The temperature of the liquid at a distance from the wall is a conditional value

Liquid temperature - average mass temperature in the channel

$$\bar{T} = \frac{\int \rho C_p w T dS}{\int \rho C_p w dS}$$

$$Nu = c Re^n Pr_f^m \left( \frac{Pr_f}{Pr_s} \right)^{0.25}$$

$$c = f(\emptyset), \quad n = f(d_e, \overline{u_b}), \quad m = f(d_e)$$

$$\ln Nu = f(\emptyset) + f(d_e, \overline{u_b}) \ln Re + f(d_e) \ln Pr_f + 0,25 \ln \left( \frac{Pr_f}{Pr_s} \right)$$

**The average heat transfer coefficient on any surface F:**

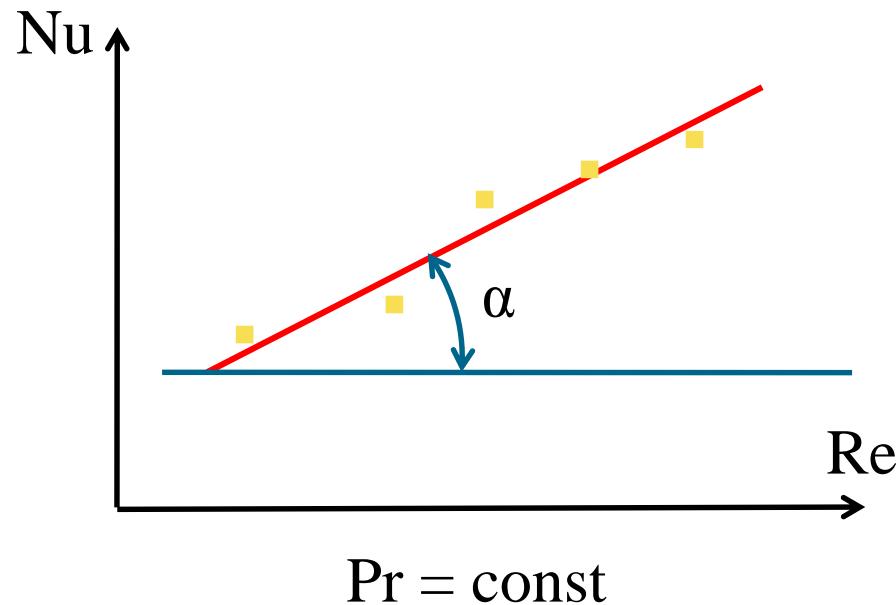
$$\bar{\alpha} = \frac{\bar{q}}{\Delta T} = \frac{\int q dF}{\int (T_{\infty} - T_{cm}) dF}$$

Example of experimental data processing: at forced convection usually



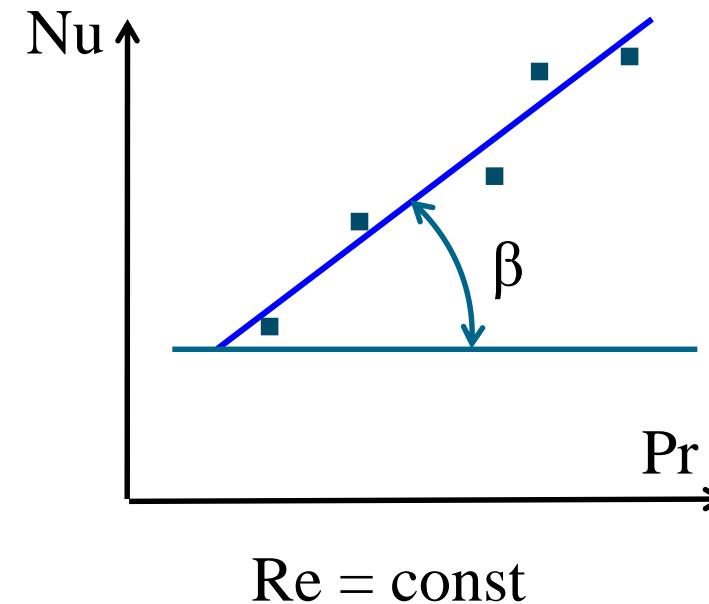
$$\text{Nu} = C \text{Re}^n \text{Pr}^m$$

$$\ln \text{Nu} = n \ln \text{Re} + m \ln \text{Pr} + C_1$$



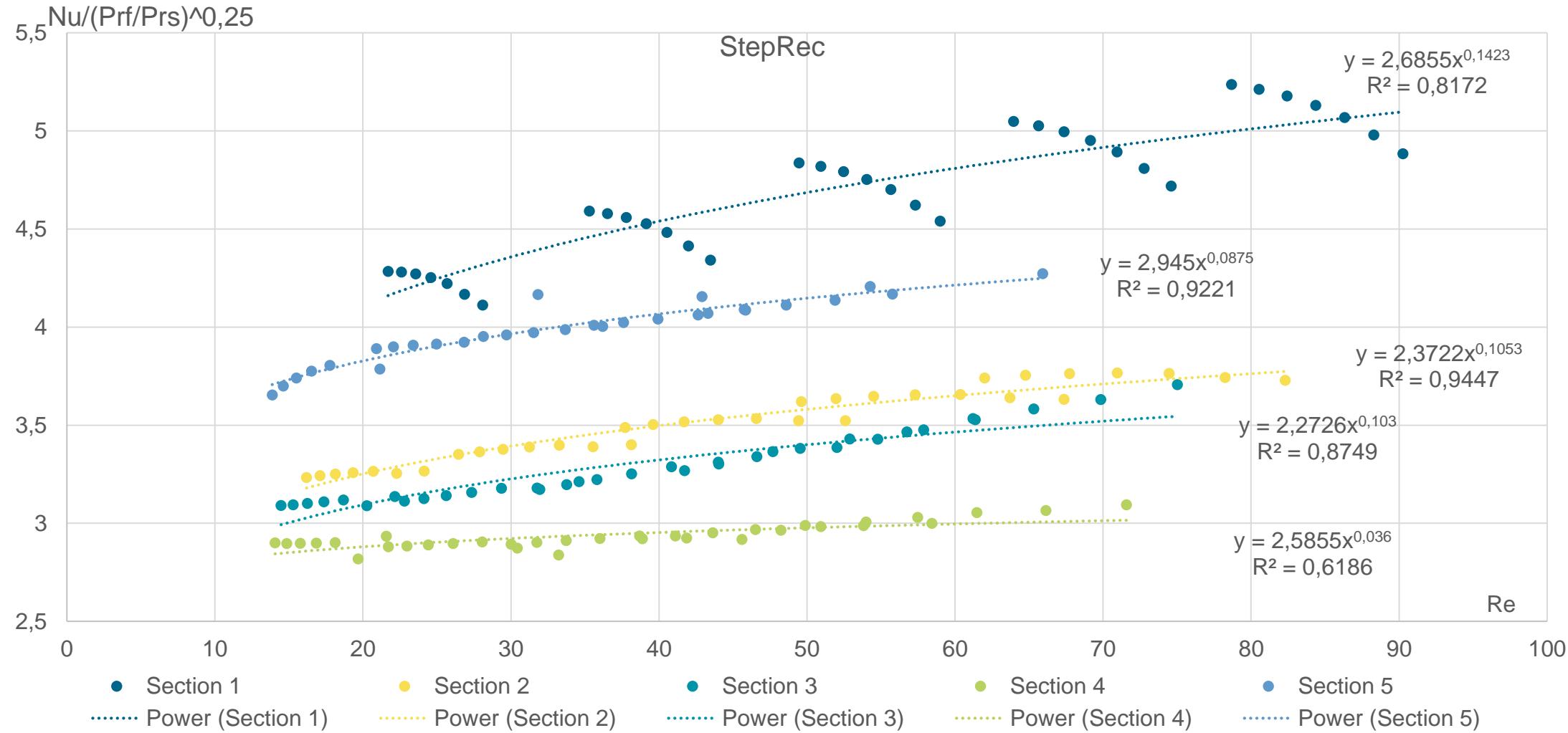
$$n = \tan \alpha$$

$$m = \tan \beta$$



$$C = \frac{\text{Nu}}{\text{Re}^n \text{Pr}^m}$$

# Dependence of the Nusselt criterion on the Reynolds number for the StepRec inside section depending on the Pr criterion



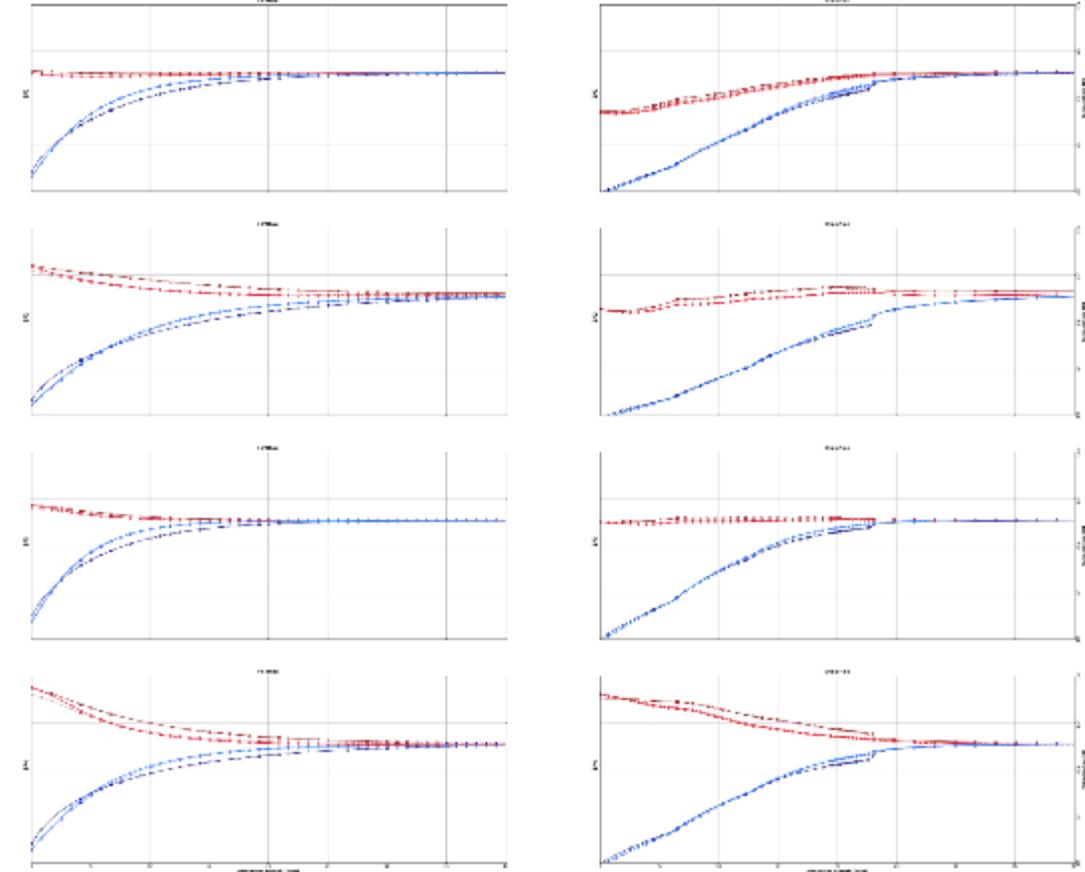
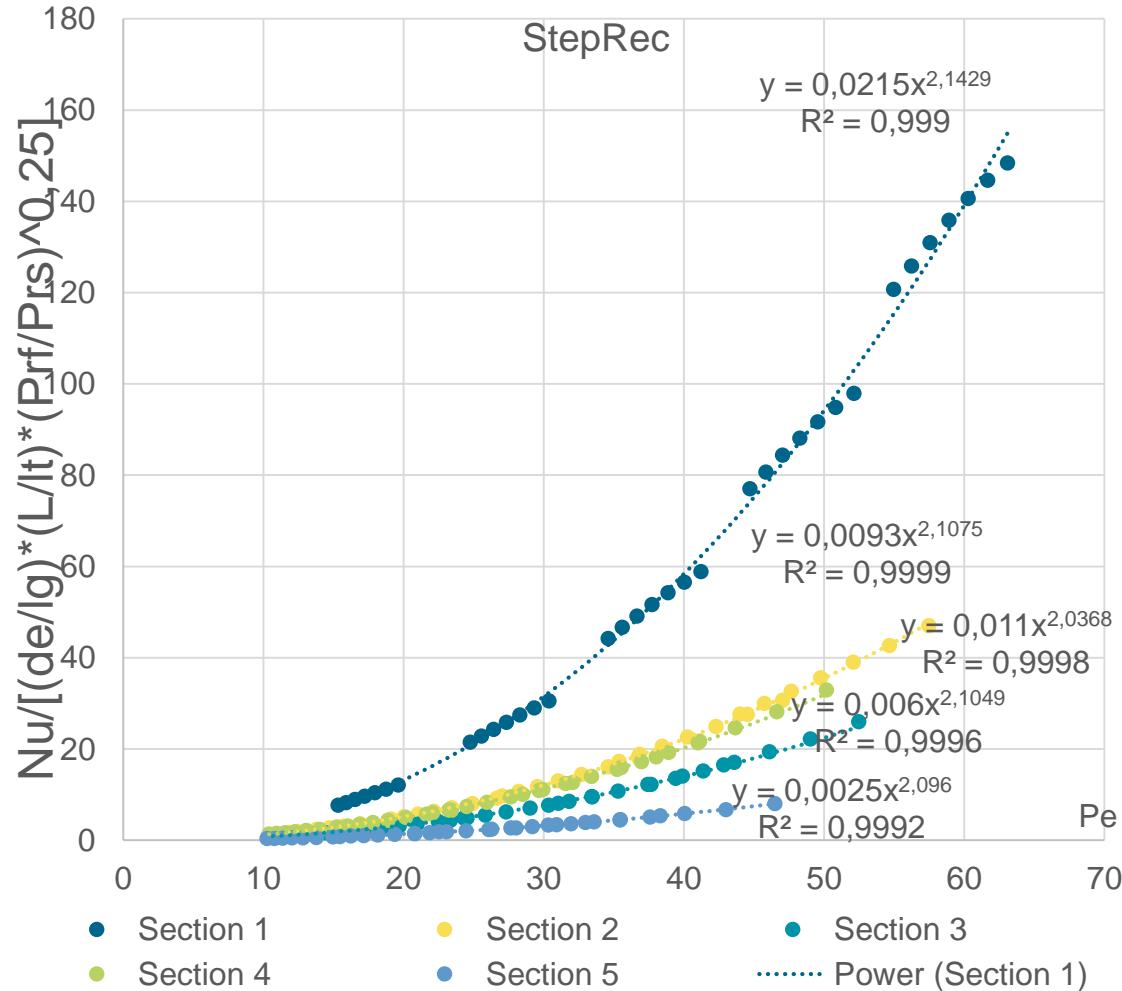
# Probleme



Based on the research, additional avenues have been opened for scientific and technical experimentation, the solution of which requires additional time or human resources:

- Geometric optimization of the shape of various absorber structures;
- Modeling of the vortex in front of different receiver structures;
- Optimization of the geometric dimensions of OVR.

# Nu vs. Pe dependences for the StepRec type absorber with the capillary effect and effect from the thickness of the thermal layer and with considering the heat exchange of internal layers



Depth dependence of air (blue) and solid (red) temperatures of HiTRec (left) and StepRec (right) absorbers for four different operating points (different angle and power of the irradiation energy)

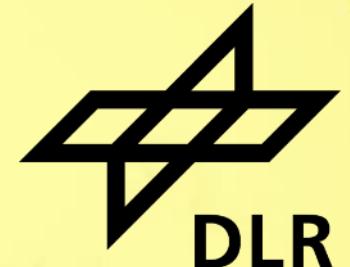
# Conclusion of research



- 1. New analytical calculation formula for the effective thermal conductivity coefficient for porous media with open pores has been proposed, which can be applied to the absorbers of open receivers of the solar tower. The proposed formula includes dislocation vector that allows to calculate different porous structures with the same porosity value.
- 2. The proposed criterion dependence for the calculation of the Nusselt number includes the calculation of the lengths of the hydrodynamic and aerodynamic layers. The constants for the proposed dependencies for modern types of solar receiver absorbers are obtained. Validation of the results on a numerical model showed high reliability of the obtained results.

# PRACTICAL SOLUTIONS

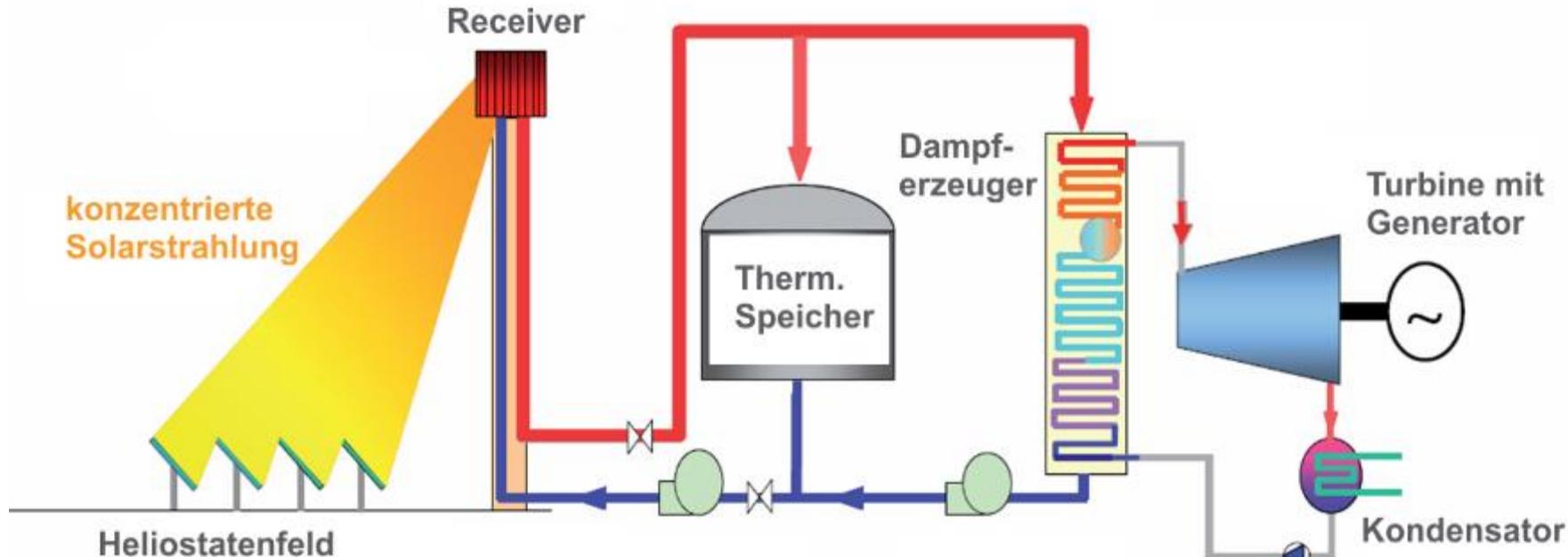
Part 3 of Public lection „The theory of heat and mass transfer processes in porous of solar receiver”



# Principle Tower Power Plant Basics



Tower power plant = sun + heliostat field + Receiver



Quelle: DLR (2008)

# Einteilung von Receivern

## Reale Beispiele



Quelle: Solar Two



Quelle: energy.gov



Quelle: Beyond Zero Emissions



Quelle: Sandia Nationals Lab



Quelle: DLR



Quelle: Afloresm

# Energieverluste an Receivern

## Verlustmechanismen



- Absorbed energy

$$\dot{Q}_{\text{abs}} = \alpha A_{\text{rec}} E$$

- Radiation losses

$$\dot{Q}_{\varepsilon} = \varepsilon A_{\text{rec}} \sigma T_{\text{rec}}^4$$

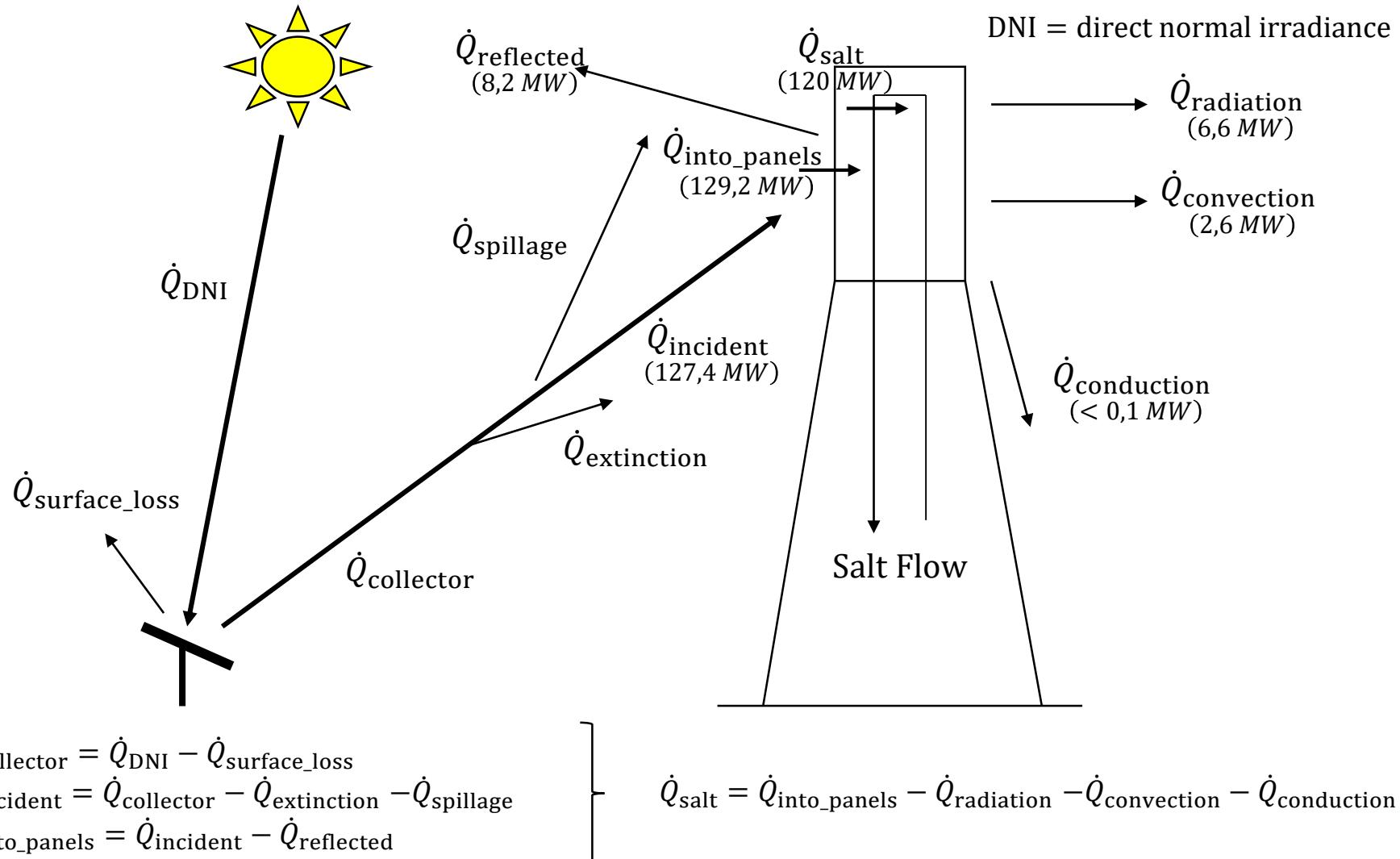
- Convection losses

- Natural convection: correlation for plane plate
- Forced convection: correlations for (rough) cylinders with crossflow

- Calculation of available power

$$\dot{Q} = \alpha A_{\text{rec}} E - \varepsilon A_{\text{rec}} \sigma T_{\text{rec}}^4 - \dot{Q}_{\text{conv}}$$

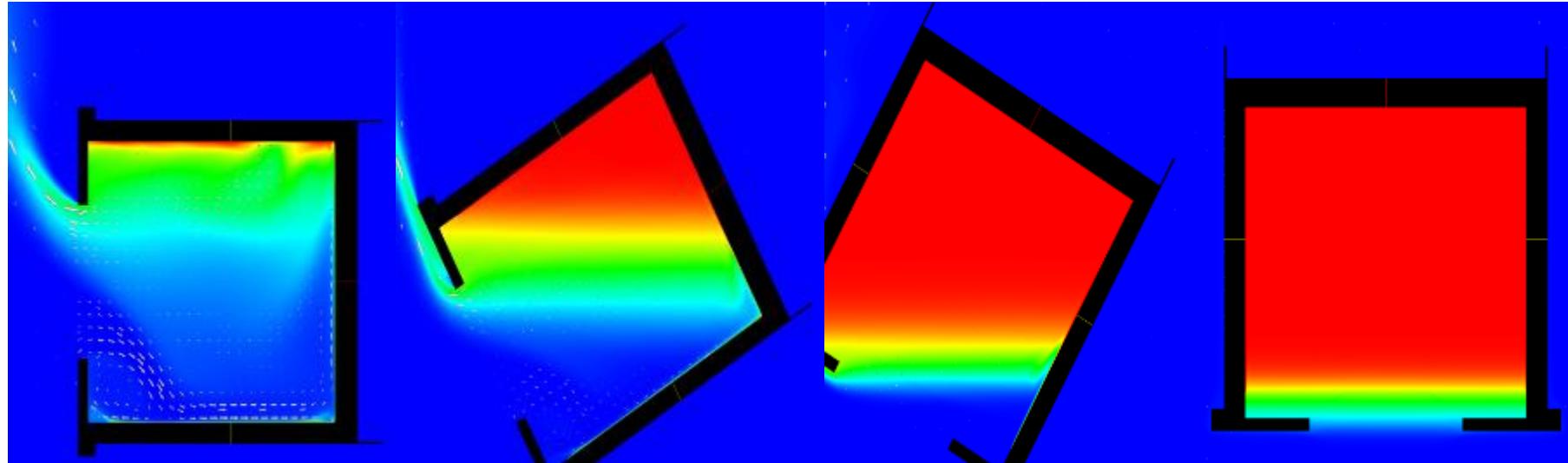
# Energieverluste an Receivern



A photograph of a solar power facility under a clear blue sky. In the foreground, several solar panels are angled towards the sun. In the background, a tall, light-colored concrete tower with a dark rectangular opening at the top stands prominently. The sun is visible in the upper right corner, casting bright rays.

# OPEN VOLUMETRIC RECEIVER

# Energy losses at receiversLoss mechanisms Cavity - convection

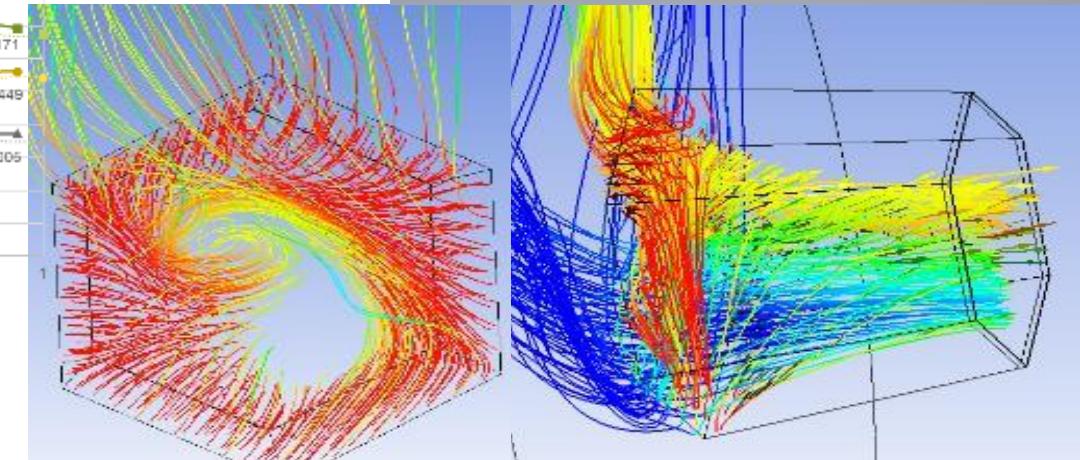
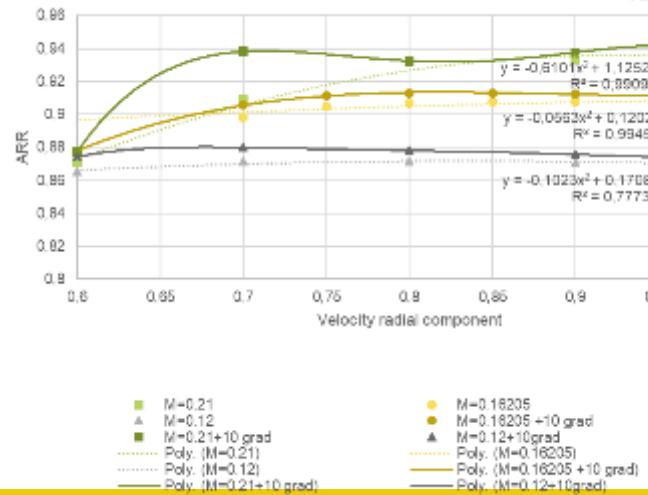
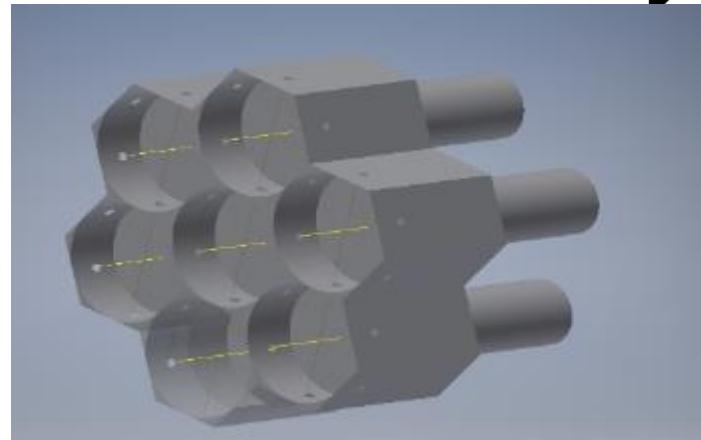
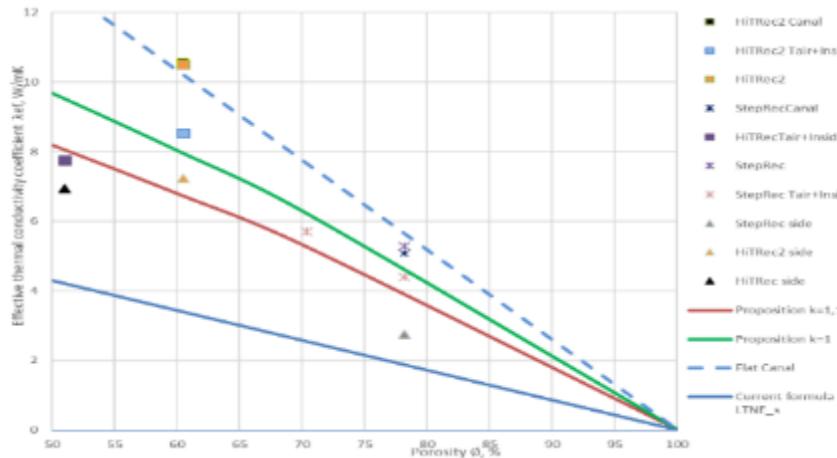


$\dot{Q}_{conv}$  can be calculated with the help of models/correlations

Quelle: DLR (2015)

# Results

- Simulationen HMT
- Simulationen Vortex
- Neues Design

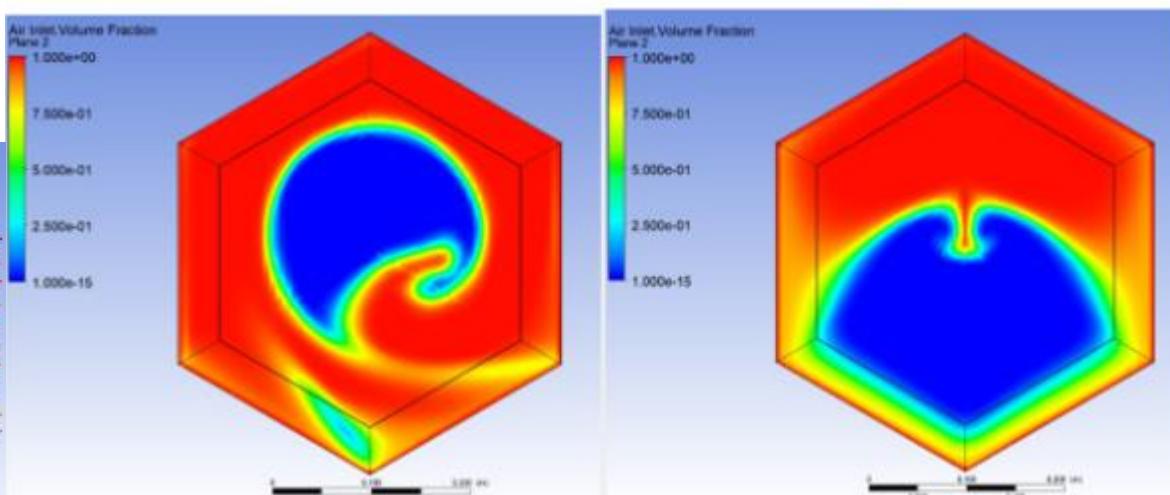
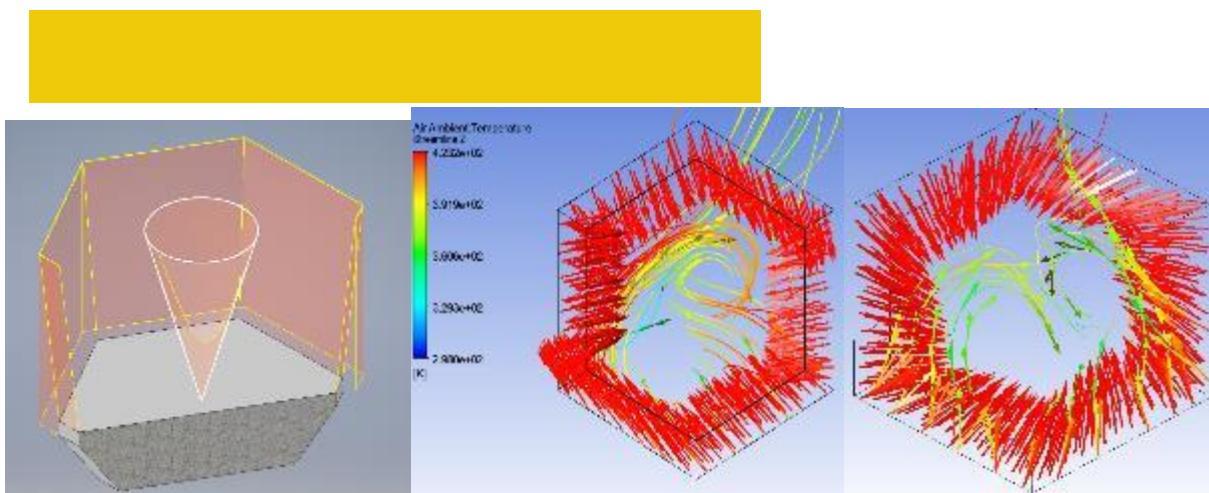
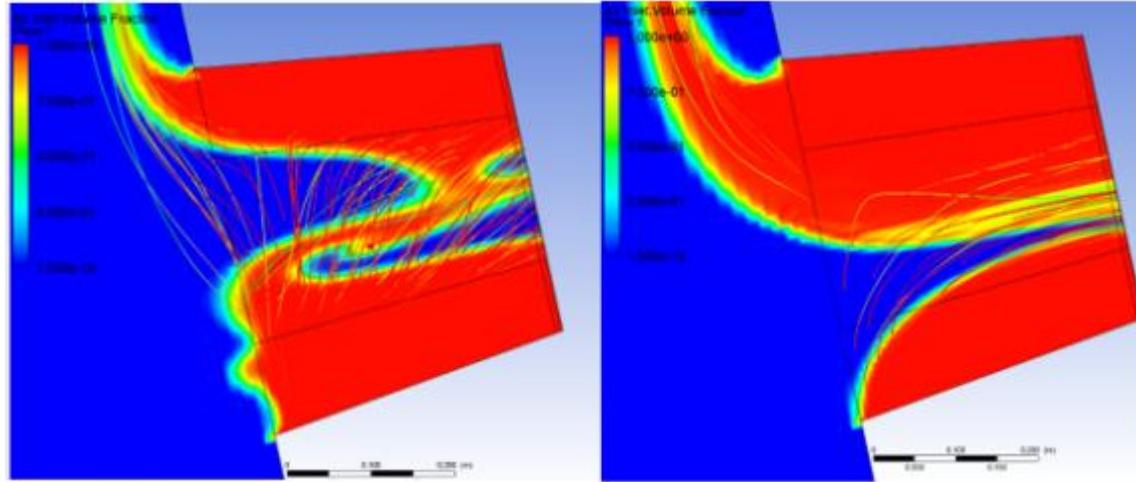
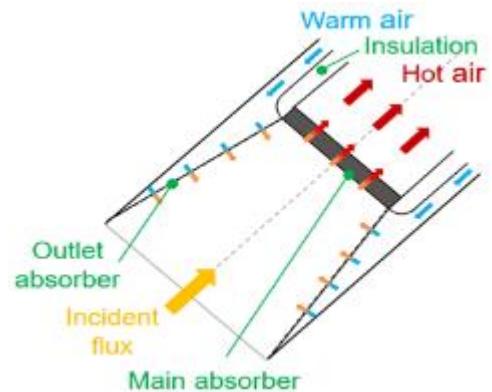
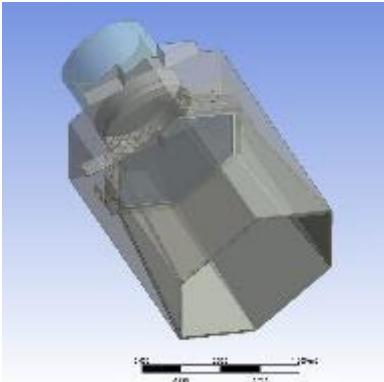


- Outstanding : Mathematical model of heat and mass transfer in a porous absorber.

# Improving a VoCoRec solar receiver



Geometric model and appearance  
VoCoRec



# Outlook



- AP 5 Potential analysis
- the actual DLR equation for the calculation of the effective thermal conductivity coefficient
- the actual DLR equation for the calculation of the Nusselt criterion
  
- Publication of the results (2 articles were published and 2 international conferences were attended, 11 discussion panels and an open lecture for students of FH Aachen. Another 5 articles have been submitted for publication and are under review)
- Application of open scientific ideas and approaches to existing projects

Thank you for the tremendous support of the entire DAAD and DLR team!

# Impressum



Thema: The theory of heat and mass transfer processes in porous of solar receiver

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Cheilytko A. Influence of structural characteristics of porous materials on the coefficient of thermal conductivity (2022). *Journal of New Technologies in Environmental Science.* N 3 (V 6).P.104-112 Doi: 10.53412/jntes-2022-3-

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