SOLLAB
ALLIANCE of EUROPEAN LABORATORIES
on solar thermal concentrating systems

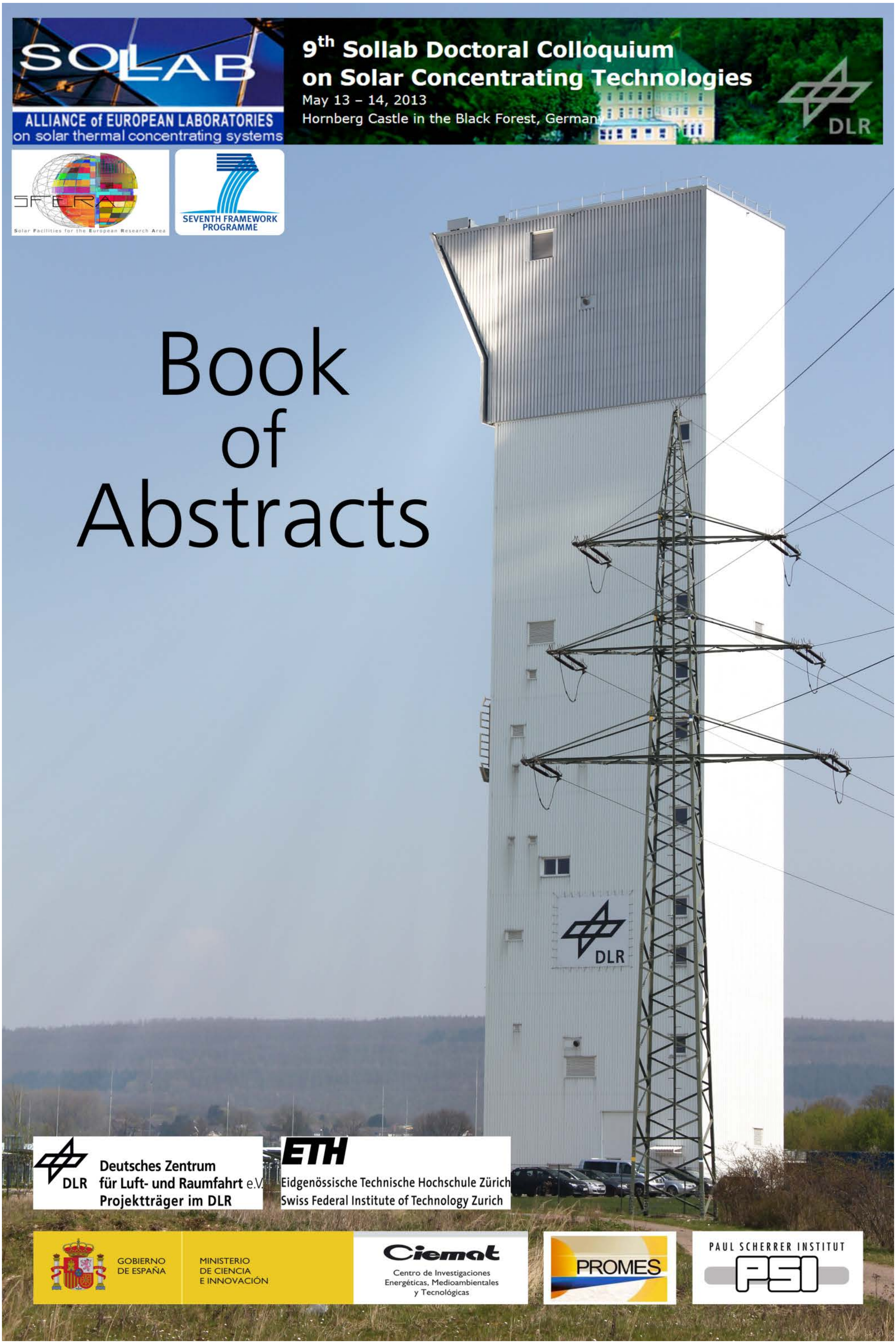
9th Sollab Doctoral Colloquium on Solar Concentrating Technologies

May 13 – 14, 2013

Hornberg Castle in the Black Forest, Germany

SFERA Solar Facilities for the European Research Area

SEVENTH FRAMEWORK PROGRAMME



Book of Abstracts

Deutsches Zentrum für Luft- und Raumfahrt e.V. Projektträger im DLR

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PROMES

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DLR

Programm of the 9th Sollab Doctorial Colloquium on Solar Concentrating Technologies

May 13 – 14, 013
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Monday, May 13th

08:30	Registration	
09:00	Welcome	
	Solar Thermochemistry	
09:15	Hydrogen production by reduction of H_2O using concentrated sunlight and metal-redox-reactions	Nicole Knoblauch
09:30	Evaluation of process variants for solar reforming of methane and investigation of reference process	Henrik von Storch
09:45	Reduction of cerium dioxide in an aerosol tubular reactor for the thermal dissociation of CO_2 and H_2O	Michael Welte
10:00	Metal oxide reduction using a solar-driven vacuum thermogravimeter	Michael Takacs
10:15	Mechanism of syngas production via solar zinc particle oxidation with carbon dioxide and steam	David Weibel
10:30	Determination of effective transport properties of reticulated porous ceramics for solar fuel production	Simon Ackermann
10:45	**Coffee Break**	
	Point Focusing Systems	
11:15	Optimization of high temperature volumetric solar absorber made of silicon carbide ceramic foam	Sébastien Mey
11:30	Proof-of-concept test of a Centrifugal Particle Receiver	Wei Wu
11:45	Dense suspension of particles as a new heat transfer fluid for concentrated solar thermal power	Hadrien Benoit
12:00	A radiative optimized solar particle receiver	Freddy Ordóñez
12:15	Modal analysis of a heliostat	Felipe Vásquez
12:30	Development of qualification methods for open volumetric air receivers with recirculation	Arne Tiddens
12:45	Atmospheric beam attenuation in solar tower plants	Natalie Hanrieder
13:00	**Lunch**	
	Linear Focusing Systems	
14:30	Off-sun testing and thermal modeling of a novel receiver prototype for parabolic trough concentrators	Men Wirz
14:45	Modeling Direct Steam Generation in Solar collectors with multiphase CFD	David H. Lobón

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15:00	Optimization of single-stage pneumatic trough concentrators for maximum geometric concentration	Max Schmitz
15:15	Nondestructive optical efficiency measurement of parabolic trough receivers using a solar simulator with linear focus	Johannes Pernpeintner
15:30	Beyond 600 °C with a solar parabolic trough	Philipp Good
15:45	Modeling and control of the once-through concept in Direct Steam Generation parabolic trough plants	Fabian Feldhoff
16:00	**Coffee Break**	
	Detoxification and Desalination	
16:30	Micropollutants removal from natural water applying AOPs processes in combination with nanofiltration	Sara Miralles-Cuevas
16:45	Cork boiling wastewater treatment by solar photo-Fenton at pilot plant scale: Toxicity and biodegradability assessment	Estefania De Torres-Socías
17:00	Experimental analysis of two prototypes of membrane distillation using solar energy	Alba Ruiz-Aguirre
17:15	Modelling and optimization of integrated parabolic trough solar power and multi-effect desalination plants	Bartolomé Ortega-Delgado
17:30	Solar photooxidation mechanism of pesticides found in citrus processing industry wastewater using TiO_2 catalyst supported on glass beads	Margarita Jiménez
17:45	Modeling and simulation of photo-Fenton reactions in CPC solar reactor: formic acid case	Maria Castro-Alférez
	Solar Thermochemistry	
18:00	Solar-driven direct air capture of CO_2 (DAC): sorbent material and sorption reactor concept development	Yi Cheng Ng
18:15	Exploratory tests for the use of concentrated solar energy in zinc recycling processes	Nikolaos Tzouganatos
18:30	In-situ measurement of C, H, O, and metals (K, Na, Ca, Cu and Ni) concentration in biomass during solar gasification	Kuo Zeng
18:45	**Break**	
19:00	**Barbecue**	

Programm of the 9th Sollab Doctorial Colloquium on Solar Concentrating Technologies

May 13 – 14, 013
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Tuesday, May 14th

	Storage	
09:00	High temperature thermal storage for concentrating solar power: Numerical modeling, experimental validation and scale-up design	Giw Zanganeh
09:15	High temperature thermochemical storage of solar energy: model development, verification and validation	Stefan Stroehle
09:30	Experimentation of a high temperature thermal energy storage prototype using phase change material for the thermal protection of a CSP tower solar receiver	David Verdier
09:45	High-temperature thermochemical heat storage based on the reversible reaction of metal oxides	Michael Wokon
	Fundamental CSP Research	
10:00	Cloud detection using ground-based camera images	Rémi Chauvin
10:15	Combined experimental-numerical approach to determine radiation properties of particle suspensions	Jan Marti
10:30	Investigations on Soiling of Solar Mirrors at the Plataforma Solar de Almeria	Fabian Wolfertstetter
10:45	**Coffee Break**	
	Solar Thermochemistry	
11:15	Development of a solar receiver-reactor for the reduction of metal oxides	Jan Felinks
11:30	Solar-assisted hydrothermal gasification of biomass: Process concept and thermodynamic analysis	Sebastian Viereck
11:45	Chemical storage of concentrated solar radiation through thermochemical cycles by doped ceria: beyond the splitting of water and carbon dioxide	Fangjian Lin
12:00	Potential for combined methane solar cracking and carbothermal SnO_2/Sn cycle process	Gaël Levêque
12:15	Two-step solar thermochemical cycle for splitting H_2O and CO_2 via ceria redox reactions – Experimental investigation with a 3.8 kW solar reactor	Philipp Furler
12:30	Solar-driven steam gasification of biomass char – A comparison of heat transfer and reaction rates for a packed bed and a loose bed supported by ceramic foam	Michael Kruesi
12:45	**Lunch**	

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Tuesday, May 14th

	Point Focusing Systems	
14:00	A pressurized air receiver for solar-driven gas turbines	Peter Poživil
14:15	Optimized design of advanced material concept for solar air receiver	Raffaele Capuano
14:30	Study of the influence of the BRDF and the incident flux directionality on the absorption efficiency of a cavity receiver	Florent Larrouturou
14:45	Analyses of the air return ratio and the influence of wind for the open volumetric air receiver technology	Daniel Maldonado
15:00	Analysis of convective losses of cavity receivers and adequate reduction strategies	Robert Flesch
15:15	**Coffee Break**	
15:30	**Social Program**	
19:00	**Dinner**	

List of Participants

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Hydrogen production by reduction of H_2O using concentrated sunlight and metal-redox-reactions

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Hydrogen production via a two-step water splitting cycle with concentrated solar energy is a promising alternative to finite fossil fuels. The clean and CO_2 free process enables storing solar energy as synthetic fuel, in form of hydrogen. The two step process can be described by a solar driven reduction of a metal oxide and re-oxidation of the suboxide during the splitting of water.

Reduction $MO_x \rightarrow MO_{x-y} + y\ ½\ O_2$

H_2 producing step $MO_{x-y} + y\ H_2O \rightarrow MO_x + y\ H_2$

Redox equilibria of the employed metal oxides play an important role in the hydrogen producing step. Suitable metal oxides can be selected on the basis of thermodynamic calculations. Ceroxides with a various dopants are considered as promising materials for solar thermal water splitting. The challenge is to combine different doping materials to improve redox kinetics by accelerated solid-state oxygen diffusion.

In the recent project phase self-supporting porous doped ceria ceramics were synthesized by replica methods and characterized by XRD and SEM. The reduction and oxidation behavior was investigated by thermo-gravimetric experiments. For a deeper insight into redox-kinetics corresponding dense CeO_2-based ceramics were investigated by SIMS techniques and conductivity measurements.

Evaluation of process variants for solar reforming of methane and investigation of reference process

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Reforming of methane is a well understood process that has been practiced commercially for several decades now. It is highly endothermic and therefore an attractive possibility for efficient storage of solar energy. The feasibility of solar reforming of methane has been proven in a number of projects since the late 1980's. The product of solar reforming is syngas, a mixture of mainly hydrogen and carbon monoxide, with solar energy stored as an increase in heating value of approximately 25 %. Though, syngas is merely an intermediate product, its consequent utilization has to be taken into account when evaluating the performance and potential of solar reforming processes.

In the present study an evaluation of existing technologies for solar reforming and possible consequent utilizations has been carried out in order to define a reference process. The evaluated solar reforming technologies included directly irradiated receiver-reactors and indirectly heated reactors with utilization of heat carrier fluid. For syngas utilization a number of different concepts have been evaluated, including conventional syngas applications such as methanol synthesis or hydrogen purification as well as new solar syngas specific applications such as a solar chemical heat pipe.

As reference process the indirectly heated reforming with consequent methanol synthesis has been selected. Therefore, it is considered the most promising process for utilization for solar reforming. This process is being further investigated regarding the dynamic behavior of its core units and the overall process. The aim of the Investigations is the determination of expected annual production and solar share in product, as well as the efficiency of solar energy storage and expected cost of product.

Reduction of cerium dioxide in an aerosol tubular reactor for the thermal dissociation of CO_2 and H_2O

Michael Welte[1], Jonathan Scheffe[1], Aldo Steinfeld[1,2]

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Cerium dioxide has shown great potential for use in two-step solar thermochemical cycles for solar fuel production. The first step consists of a high temperature reduction (> 1673 K) and is followed by a subsequent oxidation step (< 1273 K) with water, carbon dioxide or a mixture of the two to produce hydrogen and/or carbon monoxide. In this talk we present experimental results using a particle reactor concept for the high temperature endothermic reduction step of this cycle. It is based on aerosol flow of ceria particles in an externally heated tubular reactor having resident times of < 2s during thermal reduction. Experiments were performed for varying particle sizes (12 µm, 21 µm) and reduction temperatures (1723 K- 1873 K). Conversions with smaller particles were roughly 50% greater than larger particles, resulting in average deviations in stoichiometry (δ) ranging from 0.025 and 0.045 between 1723 K and 1873 K. These results indicate that short residence times on the order of 1-2 s are sufficient to obtain high conversions for all experimental conditions, proving the concept of an aerosol tubular reactor feasible for the thermochemical reduction of cerium dioxide. This concept affords the ability to isothermally operate the reduction reactor, efficiently heat ceria particles, provides rapid kinetics and offers the potential to decouple reduction and oxidation reactors for 24/7 fuel production.

Metal oxide reduction using a solar-driven vacuum thermogravimeter

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We present a kinetic study performed in a solar-driven vacuum thermogravimeter (solar-TG), in which solid reactants are directly exposed to high-flux solar irradiation while their weight change is continuously monitored. The system allows testing under a total vacuum pressure as low as 10 mbar. With this arrangement, the rate of thermochemical reactions can be examined under the same radiative heat transfer characteristics and heating rates typical of solar reactors. The solar-TG system is used to investigate metal oxides redox cycles for splitting H_2O and CO_2 and for high-temperature heat storage. Operation of the metal oxide reduction under vacuum pressures is of special interest because it eliminates the need for purge gas, thus simplifying the process and avoiding energy penalties associated with inert gas recycling.

Mechanism of Syngas Production via Solar Zinc Particle Oxidation with Carbon Dioxide and Steam

David Weibel[1], Anastasia Stamatiou[1], Aldo Steinfeld[1,2], Zoran Jovanovic[1]
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The two-step thermochemical Zn redox cycle has been considered for producing renewable H_2 and CO (syngas) from concentrated solar power [1]. In the first, high-temperature endothermic reduction step ZnO is thermally dissociated by solar heat into a gaseous mixture of Zn and O_2. After quenching the reduction product, the solid Zn is precipitated, separated from O_2, and fed into the second, non-solar oxidation step where it is re-oxidized with CO_2 and H_2O (steam) to produce syngas. The produced solid ZnO is then recycled into the reduction step to complete the cycle.

The slow, diffusion limited reaction of H_2O and CO_2 with pure solid Zn has favored development of Zn oxidation reactor concepts that utilize Zn as vapor or liquid as preferred ways of achieving high conversions of Zn necessary for high energetic cycle efficiency. These unconventional concepts, however, often lack feasibility on a large scale, mainly because of challenges brought in by reactant handling and product recovery and also suffer from energetic inefficiency. At the same time, experiments with the Zn particles produced by solar reduction have shown that they could be fully converted within a reasonable reaction time, which disagreed with the observations made with commercial Zn particles [2]. Further investigations have identified the presence of residual ZnO in solar reduction product, originating from either incomplete reduction of ZnO or partial recombination of Zn and O_2 during quenching, as the key factor promoting the conversion of solid Zn. This important finding offers the opportunity to apply a conventional, scalable gas-solid reactor to carry out the oxidation of solar Zn and produce syngas.

In order to select and design an appropriate gas-solid reactor, a kinetic model based on deeper insight into the reaction mechanism is required. Therefore, the oxidation of commercial Zn/ZnO mixtures (as substitutes for solar Zn) has been studied by means of thermogravimetry. It has been found that both the chemical properties and specific area of the ZnO surface have a strong influence on conversion rate and the final conversion of Zn. The reaction with H_2O has been found to be considerably faster than with CO_2 yet yielding lower final conversions. Based on these experimental findings several possible reaction paths have been proposed.

References

1. Steinfeld, A., *Solar hydrogen production via a two-step water-splitting thermochemical cycle based on Zn/ZnO redox reactions.* International Journal of Hydrogen Energy, 2002. 27(6): p. 611-619.
2. Stamatiou, A., A. Steinfeld, and Z.R. Jovanovic, *On the Effect of the Presence of Solid Diluents during Zn Oxidation by CO_2.* Industrial & Engineering Chemistry Research, 2013. 52(5): p. 1859-1869.

Determination of effective transport properties of reticulated porous ceramics for solar fuel production

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Solar thermochemical cycles for dissociation of CO_2 and H_2O inherently operate at high temperatures and utilize the entire solar spectrum. As such, they provide a thermodynamically favorable path to solar fuel production with high energy conversion efficiencies without the need for precious metal catalysts. Recently, record solar-to-fuel energy conversion efficiencies of 3.5% peak and 1.7% average were obtained for CO_2 conversion to CO, roughly 4 times greater than the next highest reported values to date for a solar-driven device [1]. In the framework of the CCEM-project "Solar thermochemical production of fuels from CO_2 and H_2O using ceria redox reactions" (jointly performed by PSI, ETH, and EMPA), reticulated porous ceramics (RPC) made of cerium dioxide (ceria) and doped ceria are developed for further improving the efficiency of this process. The novel RPC foam structure features mm-sized pores for efficient radiative heat transfer. High-resolution tomography of these complex RPC's is required for obtaining their detailed 3D porous structure, which in turn is needed for the accurate determination of their morphology and effective heat/mass transport properties. These effective properties can be computed by direct pore level simulations (DPLS) of the mass, momentum, and energy conservation equations using the exact 3D digital geometry. The proposed tomography-based pore-scale computational analysis enables the design and optimization of these porous materials within a thermochemical reactor for efficient solar fuel production.

References

1. Furler, P., et al., *Solar Thermochemical CO2 Splitting Utilizing a Reticulated Porous Ceria Redox System.* Energy & Fuels, 2012. **26**(11): p. 7051-7059.

Optimization of high temperature volumetric solar absorber made of silicon carbide ceramic foam

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Nowadays, development of electro-solar power plant is progressing rapidly. Increasing "solar-to-thermal" efficiency is the key step to become more competitive in front of current dominant power plant. In this context, the OPTISOL project (from the ANR-SEED* program), aims to design new kinds of solar receivers: high temperature volumetric solar absorbers with controlled radiative properties made of silicon carbide (SiC) reticulate porous ceramic (RPC).

Focusing on radiative properties (absorption coefficient, scattering coefficient, scattering phase-function) of these materials (SiC RPC), several predictive models are compared to spectral transmittance and reflectance measurements (bi-directional and directional-hemispherical) in the aim of determining new correlations based on ceramic foam characteristics (struts/pores size and porosity).

A mono-dimensional modelling is developed to solve Navier-stokes equations (conservation of mass and momentum) and energy equations (coupled heat transfers) inside the absorber. Several radiative models are tested to approximate the radiative transfer equation and compute the radiative source term (Rosseland, P-1 model, and two-flux approximation). Numerical simulations are compared to reference results obtained with Monte-Carlo algorithm using net-exchange formulation.

Experiment will be conducted at the 6kW solar furnace in PROMES-CNRS Laboratory, involving a flux density homogenizer designed to uniformize the Gaussian spatial distribution of concentrated solar power at the focal point. Thus, the experimental and numerical results will be compared, aiming the choice of the radiative approximation and properties models of the 1D modelling.

* ANR-SEED: this is a program focused on Decarbonised and Efficient Energetic Systems (SEED) from the National Agency for Research (ANR) in France.

Proof-of-concept test of a Centrifugal Particle Receiver

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As a Proof-of-Concept a Centrifugal Particle Receiver (CentRec) has been tested at laboratory scale (~10kW$_{th}$) in the High Flux Solar Simulator in Cologne, Germany. Small bauxite particles produced for the oil and gas industry are used as the absorber, the heat transfer and storage media at the same time. A defined receiver rotation is used in order to control the particle retention time in the receiver and to adjust the particle outlet temperature to different load conditions. The functional principal of the receiver is described in more detail in [1].

First experiments were conducted with various power levels and mass flows at two different receiver inclinations. Particle outlet temperatures of up to 900°C were demonstrated and the expected simple control capability of the receiver concept could be verified. As the first receiver prototype was not optimized for accurate performance measurements, a second test campaign is currently under preparation to obtain detailed receiver characteristics. A special rotating measurement system has been developed in order to determine the particle outlet temperature directly at the receiver outlet. For model validation purposes, additional experiments will be conducted quantifying and evaluating each single loss mechanism.

The developed FE-model calculates the thermal performance of the receiver using the commercial software ANSYS. The incoming power from the High Flux Solar Simulator is modeled with a ray-tracing code, whereas optical losses are simultaneously calculated as well. Instead of simulating single particles, their helical trajectories are modeled as “fluid lines” with a defined mass flow, consisting of the particle material properties. Convective losses are calculated using the correlation developed by Clausing [2], conduction losses have been quantified experimentally and radiation losses are determined by radiosity calculation, considering grey diffuse radiation exchange.

References:

[1] W. Wu, B. Gobereit, Cs. Singer, L. Amsbeck and R. Pitz-Paal, Direct Absorption Receivers for High Temperatures, SolarPACES 2011, Granada

[2] A. M. Clausing, J. Waldvogel, L. Lister, Natural convection from isothermal cubical cavities with a variety of side-facing apertures, J. Heat Transfer. 109 (1987), pp. 407 – 412.

Dense suspension of particles as a new heat transfer fluid for concentrated solar thermal power

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Here is presented a new concept of heat transfer fluid (HTF) for CSP applications; it uses dense suspension of small size solid particles. This innovation is currently developed in the frame of both a National and a European project (CSP2 FP7 project). The dense suspension of particles receiver (DSPR) consists in creating the upward circulation of a dense suspension of particles (solid fraction in the range 30%-40%) in vertical absorbing tubes submitted to concentrated solar energy. The suspension acts as a heat transfer fluid with a heat capacity similar to a liquid HTF but with no temperature limitation but the working temperature limit of the receiver tube. Suspension temperatures up to 750°C are expected for metallic tubes, thus opening new opportunities for high efficiency thermodynamic cycles such as supercritical steam and carbon dioxide.

This paper presents the first experimental results that were obtained during on-sun testing with CNRS solar facility of a single tube DSPR at low temperature (outlet temperature less than 300°C).

In this lab-scale experimental setup, the solar absorber is a single opaque metallic tube that is located inside a cylindrical cavity dug in a receiver made of alkaline-earth silicate (Insulfrax®), and submitted to the concentrated solar radiation through a 0.10m x 0.50m slot. The absorber is a 42.4 mm o.d. AISI 310S stainless steel tube (wall thickness 3.2 mm). The upward solid circulation is created inside the tube. Suspensions of silicon carbide have been studied, mainly because of its thermal properties, availability and rather low cost. The chosen particles mean diameter (63.9 mm) permits a good fluidization quality with almost no bubbles, for very low air fluidization velocities (U_{mf} = 5 mm/s at 20°C).

Solar flux densities in the range 200-250 kW/m² have been tested resulting in solid particle temperature increase ranging between 50°C and 150°C. The mean wall-to-suspension heat transfer coefficient ($h_{w,p}$) was calculated from experimental data. It is very sensitive to the average particle residence time inside the absorber, which ranged between 20 and 60 seconds, and also to the solid volume fraction of the suspension, which was varied from 27% to 36%. These latter values are one order of magnitude larger than the solid fraction in circulating fluidized beds operating at high air velocity (several m/s) contrarily to our operating conditions (air superficial velocity in the tube about 10 cm/s). Heat transfer coefficients ranging from 200 W/m².K to 800 W/m².K have been obtained, thus corresponding to a 600 W/m².K mean value for standard operating conditions (high solid fraction) at low temperature. This means that a circa 900-1000 W/m².K heat transfer coefficient may be expected at high temperature, because $h_{w,p}$ increases drastically with temperature.

A radiative optimized solar particle receiver

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To become competitive into the energy market, Solar Thermal Power Plants (STPP) need to increase their efficiency. This can be achieved by increasing the working temperature of the solar thermodynamic cycle. That means increasing the temperatures at the receiver outlet. Volumetric receivers, and more specifically particle receivers, are relevant candidates to achieve high efficiencies at high temperatures. However, only few studies exist about the optimal properties of particle materials or optimal working parameters for solar particle receivers.

We investigate a solar particle receiver modeled as a mono-dimensional and homogeneous slab of particle dispersion built from a single or multiple materials, submitted to a concentrated and collimated solar radiation (C=600), with a high constant temperature (T=1100 K) and with a reflective wall at the end of the receiver (a geometrical thickness of 1 m is considered). The Radiative Transfer Equation (RTE) is explored with a two-stream method and an appropriate hybrid modified Eddington-delta function approximation. The single particle optical properties are modeled using the Lorenz-Mie theory, the single particle phase function is approximated as the Henyey-Greenstein phase function and the volume optical properties is taken as the sum of the properties of all particles (independent scattering hypothesis).

A Particle Swarm Optimization (PSO) algorithm is used to optimize the particle radius, the volume fraction and the refractive index (the real and the imaginary part) of an ideal theoretical material constituting the particles of the investigated volumetric solar receiver. The research range for the particle radius includes large radii to avoid coagulation phenomena in the receiver (10μm < r < 100μm). The chosen range for the volume fraction span over representative orders of magnitude bounded by a maximum value that insures the validity of independent scattering ($1x10^{-7} \leq f_v \leq 1x10^{-4}$). For the refractive index representative ranges were chosen that correspond to dielectric and metals (2.0≤ n ≤4.5 and 0.0001≤ k ≤25).

The results show three spectral bands where the imaginary part of the refractive index adopts a selective behaviour, moderate values are observed in the visible region which guarantee a strong absorption of the solar flux. In the infrared region, high values are found that insure a high reflectivity of the particles. Results show that the optimal imaginary part of the refractive index increases from 0.006 to 0.03 in the spectral band between 0.3 and 1.35 μm, from 0.03 to 25 in the spectral band between 1.35 and 2.5 μm. It remains constant with a value of 25 in the spectral band between 2.5 and 12.4 μm.

Finally, in the research range the optimal values found are r=10 μm for the particles radius, $f_v=4x10^{-5}$ for the volume fraction (corresponding to an average optical thickness τ=6) and n=2 for the real part of refractive index. These values correspond to a particle receiver efficiency of η=92.5%.

Modal analysis of a heliostat

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When designing heliostats it is essential to provide reliable loading data for dimensioning the structure and its components, specially the drives. This data includes information about static loads for designing against overstressing, as well as dynamic loads to account for structural failure caused by fatigue. Furthermore, this data is required to estimate the pointing accuracy of the mirrors under extreme loads. The present work focusses on the prediction of the dynamic loads acting on the heliostats. These time dependent forces are generated by the interaction between the dynamic behaviour of the structure and the fluctuating wind forces. In order to model the dynamic behaviour of a heliostat and obtain information about its natural frequencies and mode shapes, a numerical modal analysis is performed using commercial finite element (FE) software. A detailed FE model has been generated based on a real scale heliostat with a mirror surface area of 8 m^2. Modal tests are performed on the same heliostat structure using an impact hammer and accelerometers. The experimental results are used to validate the FE model and provide further information, e.g. damping ratios. The results of the first seven modes are presented here. The comparison of the simulation and experiments shows a very good agreement in the natural frequencies and mode shapes.

Development of qualification methods for open volumetric air receivers with recirculation

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In solar power tower plants with open volumetric air receivers, the heat transfer medium air is sucked through the receiver and after passing the heat exchanger or heat storage is returned to the receiver front. To improve the efficiency of the power plant the fraction of recirculated air has to be maximized. This Air Return Ratio (ARR) is dependent on geometry and design, environmental conditions and operational modes. The ARR can be increased by a geometrically optimized receiver, wind protection measures and through improved operational modes. These optimizations are only possible if the ARR is measureable.

The air cycle is an open system and hence the ARR cannot be measured with mass flow meters. A tracer gas method, whereby an easily detectable gas is added to the air flow and measured later on, has been chosen. The state of the art tracergas methods however cannot operate under the extreme conditions of a solar receiver. The most commonly used tracer gases (SF_6, CO_2, forming gas) are either not stable under the occurring surface temperatures of the receiver of up to 1000°C or have to be added in too large quantities to be measureable against their high natural background concentrations. SF_6 should furthermore be avoided due to climate protection reasons. Helium has been chosen as tracergas on the basis of its inert nature and low natural concentration. To further improve the precision of the ARR measurement a new method is being developed, combining the energy balance of the receiver with the helium based tracergas method.

Atmospheric Beam Attenuation in Solar Tower Plants

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Atmospheric extinction between the heliostats and the receiver of solar tower plants is known to cause significant losses of reflected Direct Normal Irradiance. This phenomenon limits the size of the heliostat field. Usually, no detailed information about the local meteorological conditions is available for many sites that are now of interest for tower plant projects. Therefore, only standard atmospheric conditions are commonly used to describe the attenuation based on height profiles of relative humidity and aerosol concentration. These used standards can differ strongly from the actual meteorological circumstances which are present at for CSP interesting sites. Therefore, measurement methods are developed to estimate specific local atmospheric losses of DNI in a solar tower plant.

First of all, the existing models to determine the extinction in tower plants which are commonly implemented in Raytracing tools, like the Pitman and Vant-Hull model, are presented. Different commercially available instruments that can provide the input for the state of the art models are described, tested and intercompared. The choice of the tested instrumentation and the evaluation of the different instruments have been performed. Several months of atmospheric transmittance measurements from the Plataforma Solar de Almería (PSA) are presented. These data provide a base for further evaluation of the investigated instruments.

The FS11 scatter meters display satisfying accuracies on transmittance measurements and their robust composition and low sensitivity to soiling facilitate application at remote sites. The Optec LPV-4 transmissometer obtains high accuracies for clear conditions if large working path distances are used to exploit the preciseness of the instrument.

In a further step, radiative transfer models are exploited for model approaches of transmittance profiles for standard atmospheric conditions. Additionally, one FS11 scatter meter, the receiver sensor of the Optec LPV-4 transmissometer and additional sensors e.g. particle counters will be mounted at the top of the CESA1 tower of the solar tower plant at PSA to obtain information about the present vertical transmittance profiles. The modelled approaches will be exploited for the evaluation of the measured results, their accuracy and systematic errors. In addition, simultaneous measurements with a tiltable LIDAR system will be performed to investigate vertical backscatter profiles and aerosol layers. The radiative transfer model results facilitate a conclusion to the purpose of which spectral corrections of the sensor signals are necessary. Temperature and water vapor density profiles will complete the generation of transmittance height profiles to determine atmospheric attenuation in solar tower plants.

Off-sun testing and thermal modeling of a novel receiver prototype for parabolic trough concentrators

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In the HITECO project, a novel parabolic trough receiver is being developed that allows maximum heat transfer fluid temperatures of 600°C and active control of the pressure level in the vacuum annulus. Higher temperatures, less severe working conditions, and simpler manufacturing and assembly lead to higher efficiency and lower cost of electricity production. To determine the thermal performance of the new design, off-sun tests are conducted with a receiver prototype. A detailed heat transfer model is used to evaluate the expected performance of the system, using spectral reflectance data of the developed selective coating. The heat loss is determined as a function of the absorber tube temperature, as well as the pressure and composition of the gas present in the vacuum annulus of the receiver. In the test setup, the gas composition and pressure level are controlled with an active vacuum system, and an impedance heating system is used to control the absorber tube temperature. The computed heat loss and temperature values in the receiver prototype facilitate specifying the requirements of the heating system and all other test and measurement equipment. Detailed heat transfer analyses are performed on various structural components of the receiver prototype to determine the end effects on the heat loss of the main part of the receiver. The results confirm that no parts reach critical temperatures during the tests. The prototype is also compared to historical and current parabolic trough receivers. The results reveal that the thermal performance of the prototype is comparable to state-of-the art receivers.

Modeling Direct Steam Generation in Solar collectors with multiphase CFD

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The direct steam generation in parabolic-trough solar collectors, using water as heat-transfer fluid, is an attractive option for the economic improvement of parabolic trough technology for solar thermal electricity generation in the multi megawatt range or industrial process heat supply. The advances in direct steam generation are expected to reduce the construction, operation, and maintenance costs making it a competitive alternative to conventional SEGS-like parabolic trough power plant which use thermal oil as heat transfer fluid [1].

The computational fluid dynamic is used to implement an efficient multiphase model capable of simulating the behavior of direct steam generation in parabolic-trough solar collectors. This work describes the modeling methodology and summarizes the comparison of simulation results with the measurements taken at a DSG solar test facility located at the Plataforma Solar de Almería, Spain.

The large size of a DSG facility represents a particular challenge for CFD modeling. The facility is composed by hundreds of meters of collectors, connected by complex junctions of discontinues diameters. Furthermore both solid and fluid domains should be represented in the CFD model in order to correctly analyze temperature and consequently stress distribution on the components [2].

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Optimization of single-stage pneumatic trough concentrators for maximum geometric concentration

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With the goal of overcoming the shortcomings of regular parabolic troughs for CPV and CSP applications, an alternative trough design has been proposed, using pressurized metallized membranes as reflectors and modular concrete support structures [1]. In static equilibrium, long lightweight membranes clamped along the length of their edges and inflated with a uniform pressure assume the shape of a cylindrical trough. In the first design concept [1], a secondary corrector mirror was used to compensate for the spherical aberration inherent with the cylindrical trough primary. In an improved design concept [2], the need for the corrector mirror was eliminated by the introduction of multiple overlapping mirror membranes, which form a multicircular primary mirror profile - referred to as Arc Spline - designed to closely approximate the shape of a parabola.

In this work we report on a novel approach for the optimization of multicircular arc profiles to maximize directly the geometric concentration of the system considering full-intercept of all rays within a given design acceptance angle. The approach is used to develop improved designs, whose performance is further investigated by Monte Carlo ray-tracing. Additionally, alternatives to the Arc Spline multicircular mirror are presented in order to study the influence of increasing or decreasing the degrees of freedom on the performance of inflated membrane troughs.

The new optimization approach illustrates the potential to increase the achievable average concentration compared to ad-hoc parabola shape approximation method [2] by 9% (for N = 4 arcs). It is further shown that increasing the degrees of freedom of multicircular profiles from the base Arc Spline, only negligible performance improvements (0.02% higher average concentration for N = 4 arcs) can be achieved, while reducing the degrees of freedom only by 1 causes a dramatical performance drop. This suggests that the condition of arc tangency inherent to the design of the Arc Spline yields a nearly ideal exploitation of the possibilities of multicircular profiles.

Overall, a higher full-intercept geometric concentration with lower peak concentrations compared to the shape approximation method is achieved with the new approach, which has a positive effect on the overall efficiency of a CPV or CSP system, a more uniform power distribution benefiting the performance of the PV cells as well as the importance of reradiation from hot spots on tubular receivers.

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Nondestructive optical efficiency measurement of parabolic trough receivers using a solar simulator with linear focus

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While heat loss testing at parabolic trough receivers is a well-established technique [1], the measurement of the optical efficiency is not trivial due to the high accuracy goal of an uncertainty < 1 %. Optical efficiency is the combination of reflection and absorption losses at the glass envelope, reflection loss at the absorber coating, and geometrical loss at the bellows due to shading.

The test benches for the optical efficiency measurement of parabolic trough receivers developed at DLR work on the principle of calorimetric measurements of receivers irradiated with solar simulator solar simulator light.

4 (6) Metal-halide-lamps of 4 kWe (2.5 kWe) are used as solar simulator lamps. The optics is an elliptical mirror cylinder with flat end mirrors. No filters are part of the optical pathway. Water runs through the receiver, cools the absorber to ambient temperature and thermal losses are neglected. A spiral displacement body inside the receiver increases the heat transfer from absorber to water. The measured enthalpy increase per time of ~ 5 kW is compared to the enthalpy increase in a reference receiver. The ratio yields the relative optical efficiency of the two receivers under solar simulator light. It has been demonstrated that this measurement is possible with a reproducibility of 0.25 % (1 σ). The Homogeneity of the linear focus in longitudinal direction has been determined using the camera-target-method to be ± 5 % of the average.

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Beyond 600 °C with a solar parabolic trough

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Current designs of solar parabolic trough receivers are usually restricted to operating temperatures below 450 °C, which constrains the attainable heat-to-electricity efficiency of the power block. This limit is primarily imposed by the solar concentrating optics, thermal stability of the selective absorber coating, and the commonly used thermal oils as heat transfer fluid (HTF). To overcome this limitation, several fundamental modifications have been implemented [1, 2]: 1) The thermal oil has been replaced by air as HTF, which is free of cost, practically has no operating temperature limit, is nonpolluting, and enables the utilization of a low-cost thermal storage [3]. 2) The selective coating has been eliminated by the use of a cavity-receiver. 3) A novel receiver based on an array of cross-flow cavities has been designed for a maximum operating temperature of 650 °C, as shown in Figure 1. A prototype receiver composed of five cavities has been fabricated and tested on a solar trough segment. In parallel, a numerical heat transfer model has been developed and experimentally validated. The engineering details of the receiver design and results of the experimental campaign will be presented.

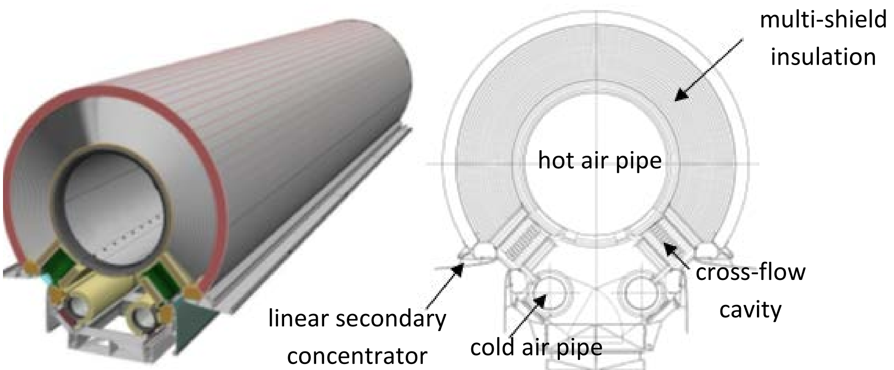

Figure 1: Novel cross-flow receiver design for parabolic trough CSP and operating temperatures up to 650°C.

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Modeling and control of the once-through concept in DSG parabolic trough plants

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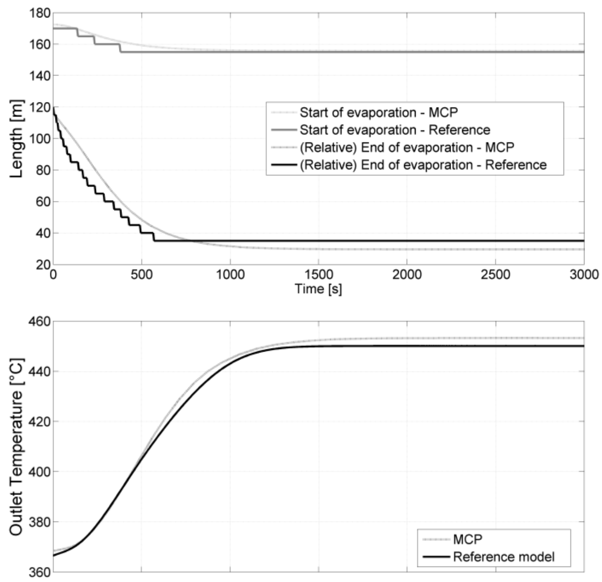
While most of the commercial parabolic trough power plants currently use synthetic oil as heat transfer fluid, the direct steam generation (DSG) is now in operation in first commercial plants in Spain and Thailand. These plants use the robust recirculation mode, in which the solar fields for evaporation and superheating are separated by a steam drum in the field. To further reduce the cost and complexity of DSG solar fields, the so-called once-through concept is considered as alternative. Its solar field consists of identical parallel loops in which pre-heating, evaporation and superheating take place without additional separators. This allows an easy solar field scale-up, while offering further cost advantages.

One of the main challenges is the control of the outlet temperature during transients, e.g. passing clouds. Simple control concepts with PI-controllers alone do not lead to satisfactory results due to the dynamic characteristics of the system. Advanced concepts for direct commercial application are based on adaptive controllers with a feed forward term. These concepts have been developed and shall be tested at the extended Direct Solar Steam (DISS) test facility at the Plataforma Solar de Almería (PSA). For mid-term research, model predictive controllers might be an option to further improve the control quality. A fast model with concentrated parameters has been developed for these predictive approaches and will be validated by experiments, too. The presentation will give an overview on modeling of the dynamic system, concepts to be tested as well as the current status of options for predictive controllers.



Comparison of models with local discretization (reference) and with concentrated parameters (MCP) for a DNI step from 850W/m² by 100 W/m²; top: loop outlet temperature; bottom: start point of evaporation; and end of evaporation relative to the 700 m loop position.

Micropollutants removal from natural water applying AOPs processes in combination with nanofiltration

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The growing demand of water and the continuous discovery of new potentially harmful contaminants make clear the need for further research in all areas that can contribute to protecting human health and the environment, achieve sustainable water use and mitigate the effects of the drought and climate change. However, this problem is further compounded because these new contaminants (detergents, pharmaceuticals, personal care products, flame retardants, antiseptics, industrial additives, steroids, hormones, etc) are not eliminated with conventional treatments because they are designed for resisting against organisms. Physical treatments, such as membrane nanofiltration (NF) and reverse osmosis (RO) are shown to be the most promising technologies to remove these micropollutants. However, these techniques are not destructive so that all micropollutants are encountered in the concentrate that must be treated, although they are normally discharged into the aquatic environment untreated. The combination of membrane physical treatment with AOPs at the outlet of a Municipal Wastewater Treatment Plant (MWWTP) secondary stage has been studied in the last years. Pérez-González et al. 2012 reported the state of the art and review of the concentrate treatment by AOPs. The main technologies applied on NF/RO concentrates are: ozonation (O_3), Fenton process, photocatalysis and photooxidation, sonolysis and electrochemical oxidation, but as they are mainly based on removing DOC, the study of the micropollutants elimination is very limited.

Treating membrane concentrates by AOPs has the advantage that degradation follows a first-order kinetic (r=kC). The concentrates usually has higher concentration of the micropollutants and higher reaction rates could be obtained. Besides, when reagents such as O_3 and H_2O_2 should be used for running the AOP, they could be used more efficiently at higher initial concentration of contaminants.

In this work, the main objective was to study the combination of nanofiltration with solar photo-Fenton and ozonation in natural water, for the removal of micropollutants contained in the effluent of a MWWTP. In addition, the behaviour of the individual processes was evaluated (degradation kinetics, reactants consumed, etc). Besides, toxicity was analysed in order to determine if the concentration step followed by AOP was successful degrading the contaminants without producing more toxic intermediates.

Cork boiling wastewater treatment by solar photo-Fenton at pilot plant scale: Toxicity and biodegradability assessment

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Cork processing includes a stage in which slabs are immersed in boiling water during one hour in order to improve their physic-chemical characteristics. This step requires great volumes of water (around 400L per ton of cork). As a consequence, the resulting wastewater contains undesirable corkwood extracts (phenolic acids, tannic fraction, 2,4,6-trichloroanisol, pentachlorophenol, etc.) which are not easily removed by conventional treatments. Despite of their characteristics, these effluents are usually discharged into the environment without any previous treatment or directly to municipal wastewater treatment plants (MWWTPs) involving active sludge low efficiencies, along with real environmental impacts to superficial and underground aquatic/soil systems. Provided that conventional biological processes cannot satisfactorily deal with cork boiling wastewater, one feasible option is the use of Advanced Oxidation Processes (AOPs).

Remediation of cork boiling wastewater was carried out at pilot plant scale by means of solar photo-Fenton process. Moreover, the convenience of a physic-chemical pre-treatment was studied along with the efficiency of two flocculants ($FeSO_4$ and $FeCl_3$). After pre-treatment, good removals of COD, DOC and TSS took place when Fe^{3+} was used as a flocculant. However, raw wastewater exhibited the best results after the solar photo-Fenton process, given that it required lower energy and hydrogen peroxide consumption (main parameters considered in an industrial plant design) than the pre-treated fractions..

Finally, high toxicity values after the physic-chemical pre-treatment were measured for the real wastewater, while biodegradability remained constant. On one hand, solar photo-Fenton process was not able to decrease the inhibition percentage for the pre-treated fractions below the 50% threshold, except for raw wastewater, and biodegradability was slightly improved. Long term biodegradability assay known as Zahn-Wellens test, revealed that only at the end of the solar photo-Fenton process, high biodegradability percentages were attained after an adaptation period of the biological system. This means that, in this case, a subsequent bio-treatment after solar photo-Fenton process is not worthy as no significant reduction of the operating costs would be achieved. In this particular case, the advanced oxidation process tested has been clearly demonstrated to be able to successfully treat real cork boiling wastewater without including a physic-chemical pre-treatment. Additionally, the photo-Fenton treatment has been compared with other advanced oxidation processes based on ozonation. The final selection of the best treatment strategy must be based on technical and economic assessments.

Experimental analysis of two prototypes of membrane distillation using solar energy

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Desalination technologies are a solution to provide water in dry areas where there are brackish resources and/or seawater. However, conventional desalination processes consume plenty of energy and this is the reason why many researchers have focused on developing a desalination process that use regenerative energy sources. Therefore, solar desalination is an ever-growing alternative to produce freshwater in areas with deficit of water.

Membrane distillation (MD) is a thermally driven separation process, which involves the generation of vapour, its transfer through hydrophobic porous membrane and condensation on the other side. The driving force is the vapour partial pressure difference, which is due to the transmembrane temperature difference. Due to the hidrophobicity of the membrane, the liquid phase does not penetrate the pore as long as the minimum entry pressure of the porous membrane is not exceeded. Its main advantages are operating at low temperature (range from 60 °C to 90 °C) and pressure and producing a high quality product. Nowadays, there is little experimentation so as to be able to commercialize MD modules. For that reason, this work presentS the evaluation at the facilities of Plataforma Solar de Almería (SE Spain) of two MD modules, one with a liquid- gap configuration and other with vacuum multi effect configuration. In the first one, there is a non-permeable foil separating distillate from coolant, and the gap is constantly filled with the distillate. During the process, feed water is pumped into the condenser channel, where its temperature is increased by the internal latent heat recovery, then flows through a heat exchanger for further solar heating and finally enters inside the evaporator channel.The second one is built with a steam raiser, 6 stages and a condenser. In the first stage, steam from evaporator condenses on a foil on pressure P1 and temperature T1. In the second stage, the solution is heated by condensation energy form stage 1 and evaporates under negative pressure P2.This process is repeated four times more and finally, the steam is condensed in the condenser unit.

The characterization of the modules was done calculating the distillate flow rate per unit surface of membrane and the heat efficiency, evaluated through the gained output ratio. Also, the quality of the product has been evaluated by measuring the conductivity of the distillate. The influence of salinity, temperature and feed flow rate was analyzed by varying them inside the allowed ranges. In both modules, the resulting distillate was of very good quality (conductivity lower than 6 μs/cm), the distillate flux was between 1 and 7 $l/h \cdot m^2$, and the thermal energy efficiency was greater in the vacuum multi effect module.

Modelling and optimization of integrated parabolic trough solar power and multi-effect desalination plants

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Integrated power and desalination plants may provide a key solution for the pressing freshwater deficit and energy problems in many regions of the world. The coupling of a solar power plant based on parabolic trough collectors with a multi-effect distillation (MED) plant is one approach to this concept currently under investigation at the Plataforma Solar de Almería.

At the end of 2011, a new experimental facility has been implemented at the Plataforma Solar de Almería. This facility will allow to study the behaviour of a MED plant, working in low temperature mode or with thermo-compression. A train of different steam ejectors will allow the assessment of the performance of the MED unit as well as the steam ejectors being fed with any of the typical steam extractions available in the turbine of a CSP plant.

The objective of this work is to develop simulation models (stationary and dynamic), to validate them in the experimental facilities of the Plataforma Solar de Almería, and to perform a techno-economic study of the different configurations that can be proposed for the coupling of MED plants with parabolic trough power plants, in order to find the optimal one for a specific scenario that can maximize the production of power and water, with the minimum of solar collection area.

Solar photooxidation mechanism of pesticides found in citrus processing industry wastewater using Tio_2 catalyst supported on glass beads

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In the last years, the improvement of analytical techniques has made possible to identify the presence of so called *emerging contaminants* in water bodies. These are xenobiotic compounds (pharmaceuticals and personal care products, pesticides, drugs, hormones, flame retardants etc.), most of them refractory to processes applied in conventional wastewater treatment plants (WWTP) and continuously discharged into the hidrological environment. Although present at trace levels (μgL^{-1}-ngL^{-1}), numerous studies have shown the negative effects of cronic exposition to these compounds on the environment [1].

In order to efficiently eliminate these compounds it is therefore necessary to implement tertiary treatments in WWTP, among which the Advanced Oxidation Procesess (AOPs) stand out. AOPs base their efficiency on the generation of hydroxyl radical (HO·), species capable of oxidizing most organic compounds to CO2 and H2O. Among AOPs, TiO2 photocatalysis generates HO· radicals (among other species) from the photoexcitation of the semiconductor. Taking into acount its band-gap (~3.2 eV) it can be excited by UVB/UVA solar light [2].

In the present work TiO2 catalyst supported on glass beads was prepared (sol-gel method) and used in a CPC solar pilot plant for the photocatalytic degradation of a mixture of 100 ppb each of imazalil (fungicide for post harvest use on bananas, citrus, etc), thiabendazole (benzimidazole fungicide used to control a variety of fruit and vegetable diseases) and acetamiprid (neonicotinoid insecticide), pesticides commonly found in citrus processing industry wastewater [3-5]

The relative contribution of photolysis, adsorption onto TiO_2 and participation of the different species generated during photoexcitation of the semiconductor ($HO^{\cdot}$, $O_2^{\cdot-}$, h^+, etc.) on the degradation of the selected compounds was studied.

According to the results, thiabendazole is mainly degraded by direct solar photolysis, with HO· radicals also contributing in a lesser extent. On the other hand, $HO^{\cdot}$ radical seems not to be involved in imazalil degradation, being photolysis, adsorption and reaction with $O_2^{\cdot-}$ the main degradation pathways. Finally, acetamiprid solar TiO_2 photocatalytic degradation takes place almost exclusively through $HO^{\cdot}$ oxidation.

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Modeling and simulation of photo-Fenton reactions in CPC solar reactor: formic acid case

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In recent years an increasing interest in solving the problems of environmental water pollution has occurred. Advanced oxidation processes (AOPs) have been presented as an efficient treatment for dealing with the degradation of hazardous chemical compounds and pathogens removal of polluted water sources [1]. The successful applications of AOPs lay in the generation of hydroxyl radicals (OH•), a high oxidant reactive specie which can oxidize almost all organic chemical compounds till H2O and CO2. Between all AOPs available, the interest of the researchers has been focused in the photo-Fenton reactions by their high efficiency in the treatment of water (detoxification and disinfection) [1]. The photo-Fenton process is a catalytic cycle involving iron salts, hydrogen peroxide and photons (wavelength lower than 580nm) and as results, hydroxyl radicals are generated.

Traditionally, modelling of photocatalytic reactors has been based on heterogeneous photocatalysis with TiO_2. Nevertheless, modelling of homogeneous photocatalysis by the photo-Fenton process has not been deeply investigated to date. In addition, modelling becomes complex if the process is carried out under natural solar radiation due to the latitude variability of photon distribution and the solar radiation propagation through the atmosphere (direct and diffuse).

This study focuses on the modelling of formic acid degradation in water by photo-Fenton reactions under concentrated natural solar radiation. For this purpose a solar radiation model is developed and a kinetic model for the formic acid degradation will be considered [2]. Fluent software, i.e., a Computational Fluid Dynamics software (CFD), is used for developing the solar radiation model. Furthermore, the experimental validation is performed in a Compound Parabolic Collector (CPC) photoreactor located at the Plataforma Solar de Almería (Spain). This system is composed by a photoreactor which is a single borosilicate glass tube (external diameter of 70 mm) with an anodised aluminium CPC mirror [1].

One of the principal parameters required for defining the model is the local volumetric rate of photon absorption (LVRPA). In the literature, different methodologies are applied to obtain this parameter. The most rigorous studies propose a method to solve the so-called "radiative transfer equation (RTE)" by using a mathematical tool in which the numerical solution depends on the photon source and the reactor geometry [3]. Other studies propose an empirical alternative to the RTE method [4]. In this work, the LVRPA is obtained by direct measurements of the solar irradiance using a submersible pyranometer located inside the tubular photoreactor. Nevertheless, this method will be also validated with actinometry using ferrioxalate as the actinometer.

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Solar-Driven Direct Air Capture of CO_2 (DAC): Sorbent Material and Sorption Reactor Concept Development

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Direct air capture of CO_2 (DAC) refers to the concept of capturing CO_2 from ambient air. It has been recognized as the only way to mitigate the CO_2 emissions from the transportation sector that account for 60% of the total CO_2 emissions today. Its feasibility, however, is constrained by (a) low CO_2 concentration in our surroundings (390 ppm) which necessitates contacting enormous amounts of air with some kind of a sorbent and (b) energy requirements for sorbent regeneration that can be substantial.

This talk consists of two parts. The first part focuses on the development of a novel amine-based porous sorbent material based on activated pyrolyzed wood having a high specific surface area. The second part describes the application of solar energy for driving the temperature-vacuum swing cyclic adsorption/desorption process.

The preliminary sorbent characterization results indicate that the amine functionalization of the activated pyrolyzed wood is feasible. However, the CO_2 adsorption tests of the current sorbent material imply substantial diffusional limitation. In parallel, a sensitivity analysis of a solar-driven sorption reactor concept based on the monolithic configuration is being conducted to set its benchmark performance and evaluate its overall technical feasibility.

Exploratory tests for the use of concentrated solar energy in zinc recycling processes

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The dominating conventional Zn recycling process is the so-called Waelz process. Waelz oxide (Wox), containing 55-65 % Zn in oxidic form, is produced from electric arc furnace dust (EAFD) generated in large amounts during steel recycling. After its washing treatment to separate off chlorides, Wox is recycled together with ZnO ores to bulk Zn. In the current project alternative process routes for the Wox purification and production of Zn/ZnO using concentrated solar power to supply the high-temperature process heat are investigated. Main goal is the reduction of the electricity consumption and the concomitant CO_2 emissions.

PSI's 10 kW packed bed two-cavity laboratory-scale solar reactor was used for exploratory tests. Promising results were gained for both processes investigated: the solar purification of the Wox (reduction of Cl- and Pb- contents) and the carbothermal reduction of Wox to produce gaseous Zn and CO. In particular, solar purification results have shown that the amount of unwanted elements can be reduced to less than 0.1 % at high temperatures (~1270^{o}C). Zn purities of ~ 90 % wt. were detected in the off-gas products during the carbothermal reduction tests.

In-situ measurement of C, H, O, and metals (K, Na, Ca, Cu and Ni) concentration in biomass during solar gasification

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The efficiency of biomass gasification can be improved by supplying process heat from concentrated solar systems. Gasification with steam and/or oxygen at about 900°C gives syngas ($CO + H_2$), which can then be converted into liquid. It is well known that the composition and distribution of the products of gasification depends on the heating rate of the reactants. Besides, biomass contains many kinds of metals which will influence the gasification process. The most prominent example is that the inherent alkaline metals (K, Na) acted as catalyst during biomass gasification. So this study will focus on the element concentration changes during solar gasification of biomass.

A new measurement way (LIBS) that has not been yet used in biomass gasification will be applied. Laser Induced Breakdown Spectroscopy (LIBS) is a rapid chemical analysis method that uses a short laser pulse to create a micro-plasma on the sample surface. Analysis of the characters of emission lines from this plasma gives information on solid concentration variation during heat treatment.

The investigation of the C, H, O and metals concentration change at different heating rates through biomass solar gasification experiments will be conducted. An improved solar gasification kinetic model will be derived from experimental data which is vital for more accurate design of biomass gasification equipment.

This project is just starting; consequently only the basis of the solar experimental setup and the main principles of LIBS measurements will be presented.

High temperature thermal storage for concentrating solar power: Numerical modeling, experimental validation and scale-up design

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A thermal energy storage (TES) system, consisting of a packed bed of rocks as storage material and air as the high-temperature heat transfer fluid, is analyzed for concentrated solar power applications. A 6.5 MWh_{th} pilot-scale TES unit is fabricated and experimentally demonstrated to generate thermoclines. A time-dependent numerical heat transfer model is formulated for separate fluid and solid phases and validated with experimental data [1]. The thermal properties of the rocks were measured experimentally and implemented in the model. Comparison of the model with experiments showed that 86% of the input energy is stored in the rocks while 14% is lost through the surrounding walls. The high losses are caused by poor insulation and small volume-to-surface ratio of the tank. Sensitivity analyses were carried out to investigate the effect of measurement uncertainties in the rock properties on the results. The time-dependent model was used to design and simulate an array of two industrial-scale thermal storage units, each of 7.2 GWh_{th} capacity, for a 26 MW_{el} round-the-clock concentrated solar power plant during multiple 8 h-charging/16 h-discharging cycles, yielding 95% overall thermal efficiency. Based on the measurements performed on the TES prototype and the results of the numerical model, an optimized TES pilot is currently being constructed. Results of the experimental campaign will be presented.

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High temperature thermochemical storage of solar energy: model development, verification and validation

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Thermochemical storage of high-temperature (450°C-1000°C) thermal energy can be applied to concentrated solar power (CSP) systems for round-the-clock electricity dispatchability. Reversible, non-catalytic gas-solid reactions are used to convert thermal into chemical energy during endothermic charging, and vice-versa for exothermic discharging.

To assist the design process of a tubular packed bed reactor for two reaction systems of interest, $\mathbf{Ca(OH)_2 \leftrightarrow CaO + H_2O}$ and $\mathbf{6Mn_2O_3 \leftrightarrow 4Mn_3O_4 + O_2}$, a numerical heat and mass transfer model is in development. The fluid, streaming through the reactor, serves as both heat transfer medium and gas reactant supplier. It is modeled as a homogeneous phase using unsteady one-dimensional mass and energy balances. Solid reactants are modeled as spherical, porous granules. In order to treat radial gradients in the granules, the unsteady radial energy and mass balances are solved. The temperature profile within a granule is calculated from an energy balance, whereas mass balances track the local concentration of the gases within the pores, affected by diffusion and an eventual mass source/sink due to the gas-solid reaction.

In order to ensure the correct implementation of the applied governing equations, a code verification study has been performed. The Method of Manufactured Solutions and a mass/energy conservation assessment will be presented as useful tools for code verification. The validation of the model with suitable experimental data is challenging because few suitable high-quality data sets exist. The presentation will discuss some published experimental data sets, describe requirements for validation-quality experiments, and present preliminary data of our own effort at collecting validation data from a packed-bed tubular reactor.

The presented work is part of the project *TCSPower* funded by the European Union.

Experimentation of a high temperature thermal energy storage prototype using phase change material for the thermal protection of a CSP tower solar receiver

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The study deals with the problem of thermal inertia and life time of the solar receiver of a Concentrated Solar Power (CSP) tower plant. Indeed the intermittence of solar contribution, in particular the one due to cloudy events, causes important temperature fluctuations of the receiver and contributes to its premature ageing. This is the reason why the PROMES CNRS laboratory develops a Thermal Energy Storage (TES) prototype for the protection of a surface solar receiver using pressurised air as heat transfer fluid (Mini Pegase project*). Once the receiver is no longer irradiated, the temperature of the air flowing in the receiver, at 750°C in normal operation conditions, decreases below 400°C in less than 15 minutes. The aim is to maintain this temperature up to 600°C thanks to the thermal storage. Besides, the storage should enhance the life time of the receiver during its operation, by decreasing the temperature gradient in the materials. The prototype, 1/10 scale, is designed based on a technology using both Phase Change Material (PCM) and a metallic matrix geometry shaped fins in order to stimulate the heat transfer inside the storage module. The chosen metal is the copper, as for the receiver, because it has a great thermal conductivity and resists at high temperatures fewer than 1000°C. The storage has to operate in the range of 600 – 800°C. Thus the lithium carbonate has been selected because of its phase change temperature, 723°C, its high heat capacity and latent heat, and its relative high thermal conductivity regarding the others PCMs. Otherwise, the lithium carbonate is stable with copper at high temperatures. The experimental study aims at characterizing the dynamic behaviour of the TES module thanks to a battery of thermocouples placed on the all height of the prototype. In the same time, a numerical model is developed to simulate the phase change in the prototype and to describe the TES thermal behaviour. The model uses a coupling between the heat equation and an equation of diffusion to describe the transformation of the PCM. In a first time, the prototype operates with paraffin waxes, which phase change occurs around 50°C, in order to observe visually the evolution of the melting front and compare the model to experimental results. Then, in a second time, the prototype will operate with lithium carbonate. In that case, the evolution of the melting front will be given by only the thermocouples because the TES module will be entirely insulated to operate between 600 and 800°C.

Along the thesis, the characterization of the prototype will lead to the development of a model and the conception of a prototype coupling a receiver module and its storage module.

*PEGASE project: Production of Electricity from Gas turbine And Solar Energy

High-temperature thermochemical heat storage based on the reversible reaction of metal oxides

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Thermal energy storage is essential in concentrated solar power systems to increase efficiency and to decouple solar energy supply and energy demand. Use of the enthalpy of reversible gas-solid reactions to store thermal energy constitutes a promising concept, allowing high energy densities, long term storage with minimal losses and a facile separation of the reactants.

Specifically, metal oxides offer a potential to be employed as high-temperature thermochemical storage materials in solar tower power plants with volumetric air receivers.

During the sunshine hours the heat transfer fluid air with excess heat is directed to the storage to reduce the metal oxide and store heat (storage charge). In the evening hours or during cloud cover atmospheric air can be used for re-oxidation of the metal oxide to release heat (storage discharge).

$$MeO_{oxidized} + \Delta H_r \rightleftharpoons MeO_{reduced} + O_2$$

The application of air as heat transfer fluid and carrier of the reactant oxygen allows the implementation of an open loop operation with direct contact heat transfer from the fluid to the metal oxide particles and vice versa. Hence, gas storage is not necessary with this concept.

As the equilibrium temperature of the reversible redox reaction of Mn_2O_3/Mn_3O_4 amounts to approximately 900 °C in air, manganese oxide has been selected as suitable heat storage material for an application in solar tower power plants. Moreover, it is non-toxic and abundant in nature.

$$6\ Mn_2O_3 + \Delta H_r \rightleftharpoons 4\ Mn_3O_4 + O_2,\ \Delta H_r = 32\ kJ/mol$$

In this presentation several aspects comprising the characterization of the storage material and the design of a storage reactor on a laboratory scale are discussed. Thermal analyses were conducted to study the reaction kinetics, reversibility, equilibrium temperature and reaction enthalpy of the redox reaction. So far most work has focused on studying manganese oxide by thermal analyses in the milligram-range. For scaling up the reaction, a storage reactor design with a packed bed of about 300 g storage material has been developed.

Cloud detection using ground-based camera images

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In a context of sustainable development, enthusiasm for Concentrating Solar Power (CSP) systems is developing. At this stage, the main drawback of this technology continues to be cost. Therefore the European research project CSPIMP (Concentrated Solar Power plant efficiency IMProvement) has been recently initiated in order to achieve a better competitiveness of the CSP plants. One challenge of the project is to better forecast the sun's resource in order to better manage the plants, according to the power grid needs.

At sub-hourly forecasting horizon, ground-based cameras are well-adapted to predict the Direct Normal Irradiance (DNI). Indeed, they allow a high spatial and temporal resolution to detect local clouds, which strongly affect the DNI and so the power variations at short-term notice. Moreover, the technological improvements of camera sensors and lenses allow them to directly capture the sky without shadow-band in front of the sun. An experimental unit has been tested at PROMES-CNRS (southern France) and the results are presented in this paper.

The sub-hourly DNI is assessed from a clear sky irradiance model corrected by a cloudless index ranging between 0 and 1. The clear-sky model [1] is provided by the European Solar Radiation Atlas (ESRA) whereas the cloudless index is determined using the ground-based camera images [2]. Image pixels have been classified into 3 categories named "clear sky", "thick cloud" and "thin cloud". The two first classes were mainly dealt with the normalized red-blue ratio (NRBR), possibly corrected by a NRBR clear sky library [3]. Intermediate pixels were classified using an iterative algorithm minimizing a cost function based on maximum a posteriori - maximum-likelihood (MAP-ML) estimation [4] [5]. In this model, the pixels are represented using three features: the NRBR, the saturation intensity and the RGB Euclidean geometric distance. These features respectively cover the physical, visual and statistical properties of the sky. Although the model leads to a better cloud pixel identification, it requires a larger amount of computation, which limits its range of use. The optimal configuration leads to very good pixel identification results compared to human classification and other algorithms. Coupled with a cloud velocity fields model, it would gives a powerful tool for sub-hourly DNI forecasting.

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Combined experimental-numerical approach to determine radiation properties of particle suspensions

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A combination of experimental measurements with a numerical model is used to find the intensive radiation properties - extinction coefficient, scattering albedo and scattering phase function - of SiC particle suspensions with varying particle loadings. The experimentally determined angular radiation distribution of irradiated SiC samples is applied to fit a collision-based Monte Carlo model with a continuous participating media defining the particle suspension. A validation case with glass microspheres and Mie theory is used to verify the modeling procedure. Two types of SiC particles with dissimilar optical characteristics are examined and the respective radiation properties are determined for porosities between 0.70-0.95. The extinction coefficients of both types of SiC particle are in good agreement with the dependent scattering correlation of Kaviany and Singh.

Investigations on Soiling of Solar Mirrors at the Plataforma Solar de Almeria

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The phenomenon of dust and dirt settling on the concentrators (mirrors) of solarthermal power plants is called soiling. It has significant temporary effects on the efficiency of solarthermal power plants as it blocks and scatters direct sunlight incident on the aperture of the collector before it can reach the receiver. Thus a loss of specular reflectivity corresponds directly to a loss of efficiency of the CSP plant.

In this study a novel measurement principle for the automatic real-time monitoring of mirror soiling rates, called TraCS, is presented and a time series of mirror soiling levels in southern Spain and eastern Morocco are presented. In this setup the mirror is always pointed at the sun at the same angle during a day. The second dataset is manually measured at PSA once a week on mirrors exposed at different tilt angles, orientations and heights to the environment. The two datasets from PSA are intercompared and used as a reference measurement.

The accumulation of dust on the mirror surfaces is influenced by parameters like dust properties (concentration, size, shape, chemistry etc), mirror tilt angles and orientations, ambient temperature, humidity, wind velocity and direction, mirror surface temperature, dew, aerosol optical depth, wind velocity, site characteristics and many more. These parameters are measured at the Plataforma Solar de Almeria together with the reference measurements over a 6 month period.

A comparison of the reference reflectivity datasets to selected weather parameters is presented pointing out the complexity of the climatic influences on soiling and the need for approximations and simplifications in order to come to practical statements on where to expect more or less soiling or when to clean the power plant reflectors to keep losses as low as possible.

Development of a solar receiver-reactor for the reduction of metal oxides

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Hydrogen is an alternative emission-free energy carrier as well as a reactant in many chemical processes, e.g. the ammonia synthesis. The considered approach for the production of hydrogen is based on thermochemical water splitting with metal oxides, e.g. cerium or ferrite oxides. No greenhouse emissions will be released if concentrated solar energy provides the necessary heat of reaction for the process.

The present work deals with the development of a reactor concept for the reduction of the metal oxide. The new concept should be scalable and able to produce hydrogen efficiently in industrial quantities. A calculation tool has been developed using the software EES (Engineering Equation Solver) in order to evaluate the sensitivity of the efficiency with respect to different process parameters.

Those calculations have confirmed the importance of heat recuperation to the chemical efficiency of the process. Furthermore, the effect of flushing gas, vacuum and a combination of both to remove the released oxygen on the efficiency has been investigated. Additionally, the effect of the gas/solid ratio in an indirect concept with a fluidised bed has been analysed.

Based on these findings, a reactor concept for the reduction of metal oxides will be developed. Special attention will be paid to the heat recuperation of the solid metal oxide and the oxygen removal.

Solar-assisted hydrothermal gasification of biomass: Process concept and thermodynamic analysis

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This talk discusses a solar-assisted hydrothermal gasification (HTG) of biomass into methane and other gaseous energy carriers such as hydrogen and/or syngas [1]. This concept consists of two main steps that both could benefit from integration of solar energy: (1) superheating of the biomass-water slurry and (2) supercritical biomass gasification. In contrast to the steam gasification [2], the hydrothermal gasification is suitable for upgrading high-moisture content fedstocks such as sewage sludge and manure without requiring energy-intensive drying pre-processing step. In addition, as it requires considerably lower temperatures (400 - 600°C) that are readily attainable from stored solar heat [3], the solar-assisted HTG can operate continuously.

Due to non-polar properties of supercritical water, salts present in the biomass precipitate during the superheating step which may cause plugging of downstream equipment and fouling of gasification catalysts if used. Therefore, in order to capture the precipitated salts and prevent fouling of the superheater, it is necessary to provide a strict temperature control across the superheater.

Two different concepts for the integration of solar energy are presented for this step: The reverse-flow separator and the fluidised bed separator. In the reverse flow separator, biomass is rapidly superheated in the hot entry section. Salts precipitate and re-solubilise in the cooler outlet section at the bottom. The fluidized bed separator uses hot particles as seeds for the precipitation of the salts.

Thermodynamic analysis is carried out as first means of estimating the product gas distribution at different operating conditions. The results from this analysis are critically compared to in-house experimental data and values from literature. Based on estimated reactor heat duties, different configurations of heat exchanger-reactors have been evaluated in terms of their heat exchanger performance.

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Chemical storage of concentrated solar radiation through thermochemical cycles by doped ceria: beyond the splitting of water and carbon dioxide

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Ceria has many technical applications. In solar thermal energy conversion processes it is used to split water and carbon dioxide into hydrogen and carbon monoxide (syngas) in two-step cycles. In this process ceria's good oxygen storage capacity is important. Ceria can release oxygen and maintain its structure when subjected to high temperatures generated by solar concentrating systems.

The production of syngas has been the focus of the research in solar splitting of water and carbon dioxide. There are no reports in directly generating organic chemicals from water and carbon dioxide using solar thermochemical cycles. Chueh and Haile demonstrated that nickel supported on samarium-doped ceria could act as a reaction medium for selectively generating methane over syngas from water and carbon dioxide in a packed bed reactor [1]. In our project, we aim for direct generation of solar organics by doped ceria using concentrated solar radiation. There are two fundamental processes with this concept: 1) successful reduction of the host ceria at high temperature; 2) direct conversion of solar splitted intermediates or syngas into organic chemicals, catalyzed by the dopants in the low temperature reoxidation step.

Using a modified co-precipitation method, we have successfully incorporated several kinds of metal cations into the ceria lattice, as verified by XRD measurements. Doping offers potential advantages such as high dispersion of active species, improved thermal stability, and increased oxygen storage capacity of ceria itself. So far, we have been testing the phase stability of various cations doped ceria using in-situ high temperature XRD. In some cases, the metal cations doped ceria show superior phase stability and sustain the fluorite structure when heated up to 1400 C for prolonged time. In the next step, we will start testing these materials for the production of organic molecules using a tube furnace.

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Potential for combined methane solar cracking and carbothermal SnO_2/Sn cycle process

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Solar fuels production is of paramount interest to mitigate the long term impact of our energy dependent society over the climate stability. Among the feasible routes, two have raised particular attention in the last years, the solar methane cracking and the two-step thermochemical cycles for water and/or CO_2 splitting.
Solar thermal methane cracking allows decarbonization of a fossil fuel through the production of clean dihydrogen and carbon black[1]. Economical valorization of the carbon black is the *sin equa non* condition to reach competitive price for H_2[2], but its quality highly depends on the conditions and transient production does not reach the industrial quality grade[3].
Hirsch et al.[4] have proposed an interesting alternative to use the carbon black, that consists in its use for enhancing the reduction step of a thermochemical cycle (carbothermal reduction). Second law assessment of this route for the ZnO/C/Zn system shows a good potential with high exergy efficiency.
The present study investigates a similar route, SnO_2 being preferred to ZnO because of its lower reduction temperature and the absence of vaporization (Zn is produced in gaseous and has to be quenched while Sn remains in solid or liquid form).
Thermodynamic calculation shows an interesting potential for the use of carbon black obtained from solar methane cracking in the carbothermal SnO_2/Sn cycle, with an overall exergy efficiency of 86% compared to 71.6% for the most advanced carbothermal cycle, ZnO/C (both results taking into account the methane cracking). The difference is mainly due to a lower reduction temperature, which decreases the reradiation losses, and to reduced requirement for quenching the gaseous product. Experimental investigation of SnO_2 carbothermal reduction was performed for non-referenced carbon sources, a high specific surface area activated charcoal and a nano-sized carbon black obtained via solar methane cracking. The first presents a lower temperature (850-900°C versus 950-1000°C) and a better CO_2 conversion into CO thanks to its porosity that enhances the Boudouard reaction. On the other hand, the activation energy is reduced with carbon black (203.5 kJ/mol versus 266 kJ/mol), and a better chemical conversion is attained thanks to a better contact between reactants that promotes the solid-solid reaction.
SnO_2 carbothermal reduction with an excess of carbon black presents interesting features (controllability, lower activation energy, complete conversion, good CO_2 to CO conversion) compared to previously reported carbon sources. It may become an interesting pathway toward cleaner energy, improving both carbothermal reduction processes and methane cracking profitability.

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Two-step solar thermochemical cycle for splitting H_2O and CO_2 via ceria redox reactions – Experimental investigation with a 3.8 kW solar reactor

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Solar thermochemical approaches for H_2O and CO_2 splitting inherently operate at high temperatures and utilize the entire solar spectrum. As such, they provide an attractive path to solar fuels production with high energy conversion efficiencies without the use of precious metal catalysts. Cerium oxide (ceria) has emerged as a highly attractive redox intermediate because of its favorable thermodynamics and kinetics at moderate temperatures. Reduction proceeds via the formation of oxygen vacancies and the release of gaseous O_2, resulting in the subsequent change in stoichiometry (δ). Oxidation is capable of proceeding with H_2O and/ or CO_2, thereby releasing H_2 and/or CO and re-incorporating oxygen into the lattice. The two-step H_2O/CO_2 splitting solar thermochemical cycle based on oxygen-deficient ceria is represented by:

High-T reduction: $CeO_2 \rightarrow CeO_{2-\delta} + \delta/2\ O_2$ (1)

Low-T oxidation with H_2O: $CeO_{2-\delta} + \delta\ H_2O \rightarrow CeO_2 + \delta\ H_2$ (2)

Low-T oxidation with CO_2: $CeO_{2-\delta} + \delta\ CO_2 \rightarrow CeO_2 + \delta\ CO$ (3)

We report on the development, characterization and experimental testing of an optimized reticulated porous ceramic (RPC) structure made of pure CeO_2 for thermochemical CO_2 and H_2O dissociation. The RPC structure was tested in a 3.8 kW solar reactor prototype which was previously described in detail. [1,2,3] Experiments were conducted at ETH's High-Flux Solar Simulator under conditions that closely approximates the heat transfer characteristics of highly concentrating solar systems such as solar towers and parabolic dishes. The reactor engineering design, experimental setup, and the novel CeO_2 structure are described in detail and measured product compositions and solar-to-fuel energy conversion efficiencies are presented.

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Solar-driven steam gasification of biomass char – A comparison of heat transfer and reaction rates for a packed bed and a loose bed supported by ceramic foam

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Solar-driven steam gasification of biomass is a promising route to the production of transportation fuels from a renewable resource. At high temperatures and in the presence of steam, biomass is thermochemically decomposed to syngas (mainly H_2 + CO), which can be used to produce liquid fuels e.g. via the Fischer-Tropsch process. As steam gasification is a strongly endothermic process, efficient delivery of heat to the reaction site is crucial. Efficient heat transfer is often achieved by irradiating particles in an entrained flow thus limiting the applicability to a narrow range of particle size. Packed beds allow the use of a larger particle size distribution but suffer from heat transfer limitations due to the low thermal conductivity of the char and the high extinction of the radiation.

This work presents a possible solution to overcome the heat transfer limitation of packed beds by creating a loose bed supported by ceramic foam. In the less optically dense foam, it is expected that radiation penetrates further into the bed creating a more homogeneous temperature profile and increasing the reaction rate. The steam gasification capacity of packed and loose bed was compared by a 1-D radial heat transfer model of a tubular reactor. The influence of varying tube diameter, particle loading in the foam and wall temperature was studied.

The model confirmed that radiation penetrates further towards into the bed due to the higher porosity. However, the model predicts that the more homogeneous temperature distribution is the result of increased solid conductivity and not due to increased radiation penetration as expected. It is predicted that under certain conditions (temperatures, tube diameters and particle loadings) the conversion rates per tube surface area of the loose bed configuration are significantly higher than in the packed bed.

A pressurized air receiver for solar-driven gas turbines

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In previous studies **[1-3]**, we have described a novel design of an air-based pressurized solar receiver for power generation via solar-driven gas turbines. The main component of the indirectly-irradiated receiver concept is a cylindrical silicon carbide (SiC) cavity, surrounded by a concentric annular reticulate porous ceramic (RPC) foam. Absorbed heat is transferred by combined conduction, radiation, and convection to the pressurized gas flowing through the RPC.

A 3 kW prototype was tested with air and helium as working fluids at outlet temperatures up to 1335 K at a pressure of 5 bar **[2]**. In a scaled-up configuration, a set of four SiC cavities attached to a compound parabolic concentrator (CPC) were tested on a solar tower at 32 – 38 kW solar radiative power input. A peak cavity temperature of 1595 K was obtained as measured by means of infrared (IR) pyrometry for an incident solar flux of 2112 kW/m^2 at stagnation conditions. A peak thermal efficiency of 89% is predicted from simulations, with re-radiation being the dominant heat loss **[3]**.

Based on these previous on-sun experiments, a 30 kW receiver prototype comprising a complete air-circuit has been constructed, as depicted in **Fig. 1**. On-sun testing was carried out at the solar tower of the Weizmann Institute, Israel. The engineering details of the design and results of the experimental campaign will be described.

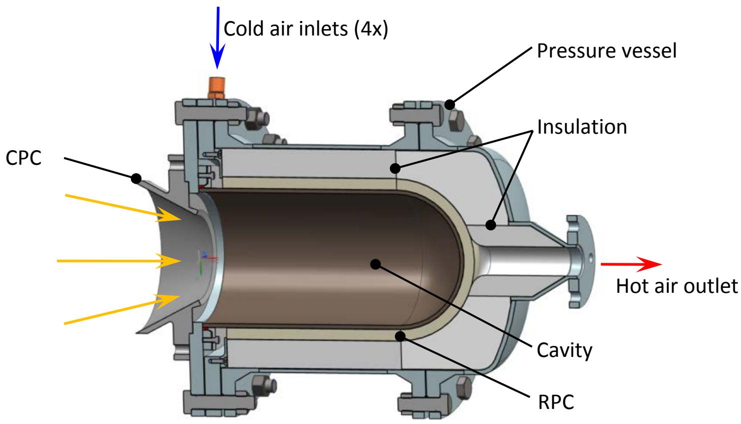

Fig. 1 – Section of the solar receiver prototype consisting of an inner cylindrical cavity and a concentric annular RPC foam, both made from silicon carbide, surrounded by insulation in a sealed pressurized vessel.

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Optimized design of advanced material concept for solar air receiver

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In the past ten years, the HiTRec technology has demonstrated its suitability in large scale tests on different solar thermal plants, such as the PSA in Almeria, Spain and the STJ in Jülich, Germany. As an open volumetric receiver, it offers several advantages compared to tube receivers, such as spreading the radiation absorption process over the depth of the absorber, increasing heat transfer area and reducing re-radiation losses by lowering the outward-facing surfaces´ temperature. Nevertheless, the current design is limited due to the relatively low porosity (50%) and cellularity (about 1000 1 / m) of the HiTRec structure. Innovative material structures with higher values both of porosity and cellularity (respectively up to 95% and about 8000 1 / m) thus represent a high potential for thermal efficiency improvements. The aim of the envisaged work is an innovative air receiver concept that includes the latest developments in the field of high temperature materials.

A review of the state-of-the-art of the numerical models developed so far has been carried out and it has been assessed in order to gather all the necessary numerical features for the description of the absorber behavior. A proper numerical approach has been chosen for the prospective numerical study which will embrace improvements of the radiative model to accurately predict the thermal losses inside the structure. The effective thermal conductivity model for porous structure will be also introduced in the analysis obtaining a complete numerical representation of the material behavior.

The first ceramic material samples made out of SiC, characterized by variable porosity, are currently under investigation and the evaluation of effective thermal properties via experimental analysis useful for the continuum approach is expected using test facilities.

Within this work, a computer model will be developed, with which the performance of the receiver will be described and can allow examining different design variants. The experimental analysis through tests on a laboratory scale under realistic assumptions will be carried out in order to obtain the effective thermal properties needed for the continuum approach and to validate the so developed numerical model.

Study of the influence of the BRDF and the incident flux directionality on the absorption efficiency of a cavity receiver

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The Concentrating Solar Power (CSP) is one of the most promising solutions to produce electricity from a renewable source. The solar power tower technology is a high efficiency concept among the solar thermal power plant but significant cost reductions are necessary to become competitive. One of the main steps to increase the global efficiency of this technology is the minimization of the radiation losses due to solar reflections in the receiver and infrared emission by the surface. The geometry of the receiver (cavity) becomes a compromise between maximum radiation capture and minimum radiation and thermal losses.

Directional selectivity of the surface is a solution to limit these losses: geometry of the cavity, incident solar flux directionality and BRDF (Bidirectional Reflectance Distribution Function) are optimized to increase the number of reflections in the cavity. The aim of this study is to quantify the effect of the BRDF and the incident flux on the effective absorption of the receiver. Because multiple scattering and directional sources are involved, a Monte Carlo Ray Tracing method is used to assess the absorption efficiency for each configuration.

This study takes into account two different parameters: the incident flux (collimated, diffuse or concentrated) and the BRDF (calculated as a sum of a specular part (with a distribution around the perfect specular direction) and a diffused part). For each configuration, ideal BRDF is estimated for all the faces of the cavity.

In order to assess the optimized BRDF in function of the incident flux and the geometry, different models of BRDF are tested. A lot of models are proposed in the literature but only few of them can be used in this study. The main properties considered are energy conservation and reciprocity. Cook-Torrance and Oren-Nayar models are selected.

Analyses of the air return ratio and the influence of wind for the open volumetric air receiver technology

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Open volumetric air receivers are a promising option for solar central receiver power plants. The technology is based on irradiating ceramic absorber combs that, in turn, heat up air, which is sucked through the combs. The hot air is used to drive a conventional steam cycle and is then fed back to the receiver. The return air is blown out in front of the receiver and sucked back in partially in order to reduce heat losses. The efficiency of the system is affected by the air return ratio significantly, as previous numerical works show.

The air return ratio is difficult to forecast due to complex flow conditions in front of the receiver. Strong uplifts as a result of natural convection and the forced shear flow could cause vortexes. Furthermore, the receiver is especially sensitive to wind because of the open concept.

Aim of this study is to develop a simulation model in order to analyze the flow conditions and to predict the air return ratio for different operating conditions. Furthermore, the results of the analysis will be used to develop technical solutions which increase the air return ratio. A CFD model, implemented in OpenFoam, is used to calculate the flow inside and in front of one comb. The challenge is to expand this model to simulate the interaction between various combs without high additional calculation effort. PIV measurements have been performed at the DLR Xenon High-Flux Solar Simulator to proof the feasibility of the measurement method for solar receiver application. Influence parameters like schlieren formation and reflection of the irradiation at the particles have been investigated. A full measurement campaign is planned to gain validation data and to provide suitable boundary conditions for the simulation model. In a further step the model is extended to consider wind conditions at tower height.

Analysis of convective losses of cavity receivers and adequate reduction strategies

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In order to increase temperature in solar thermal central receiver plants for power generation or for chemical processes it is important to develop receiver designs with low thermal losses. Cavity receivers match this requirement, since they have low thermal and optical losses. Losses caused by natural convection can be reduced by using cavity receivers with high tilt angles (downward facing receivers). Several studies have been carried out to analyze the relevant mechanisms and estimate the losses. Most of them deal with small cavities for parabolic dishes. Several correlations and models were developed, in order to estimate the convection losses. The majority of these models and correlations are suitable for no-wind conditions. Only the model developed by Clausing (1983) includes wind velocity as parameter. This model estimates the convective losses for most receiver geometries under no-wind conditions very accurately. However, it predicts the influence of wind to be almost negligible, although many other experimental and numerical analysis indicate that wind has a substantial impact on the convection losses of those receivers and thus on the efficiency. Anyway, the influence of wind on large cavity receivers has not been analyzed in detail.

In this thesis, the influence of wind on large Cavity receivers for solar thermal central receiver plants is analyzed in detail using a numerical as well as an experimental approach. In order to validate the simulation model with the experiment, it is necessary to perform the experiment with known boundary conditions. Therefore, the experiment will be performed in a wind tunnel. As it is not feasible to use a full scale cavity in a wind tunnel, a small cavity is planned to be used in the Cryo-Tunnel Cologne. The similitude approach is applied to keep the flow in and around the cavity comparable to the one of a full scale receiver.

In a first step, a simulation model for the model receiver in the Cryo-Tunnel is developed. After a successful validation, simulation will be performed for a full scale receiver. The gained knowledge from experiment and simulation will be used to develop reduction strategies for the convective losses.