8th SOLLAB Doctoral Colloquium

On Solar Concentrating Technologies

25th-26th June, 2012. PSA-CIEMAT

Almería

BOOK OF ABSTRACTS

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Monday 25 of June		
Time	**Activity**	
8:00º	**Registration**	
	Welcome Address	
8:50	'European R&D on CSP: Joint Programming Activities'	Diego Martínez
	TOPIC: 1st SOLAR FUELS **Chair: Robert Pitz-Paal**	
Time	**Presentation Title**	**Presenting Author**
9:00	Fuel production by reduction of CO2 using concentrated sunlight – A material study	Friedemann Call
9:25	Development of a solar reactor for thermochemical water-splitting	Jan Felinks
9:50	Numerical Analysis of Process Dynamics of Thermochemical Water Splitting Process	Matthias Lange
10:05	Two-step solar thermochemical cycle for splitting CO2 via ceria redox reactions – Experimental investigation with a 3.8 kW solar reactor	Philipp Furler
10:30	**Coffee break**	
	TOPIC: 1st POINT FOCUS SYSTEMS **Chair: Jesús Ballestrín**	
Time	**Presentation Title**	**Presenting Author**
11:00	Modeling a falling particle receiver with face-down geometry for large scale electricity generation	Birgit Gobereit
11:25	Optimization of a high temperature solar receiver by poly-dispersion of particles	Freddy Ordonez
11:40	Homogeneous fluidization predicted by CFD-DEM simulations: hydrodynamic stability of gas-fluidized beds	Jan Marti
12:05	A solar particle receiver for small gas turbine systems	Wei Wu
12:30	**Lunch**	

TOPIC: DETOXIFICATION AND DESALINATION Chair: Isabel Oller		
Time	**Presentation Title**	**Presenting Author**
14:00	Optimization of mild solar TiO2 photocatalysis as a tertiary treatment for municipal wastewater treatment plant effluents	Lucia Prieto
14:25	Wastewater disinfection by solar photo catalysis	Majdi KACEM
14:50	Degradation of acetaminophen using TiO_2 supported on glass spheres irradiated in a CPC Solar Pilot Plant.	Margarita Jimenez
15:15	Combined Electricity and Water Production basing on Solar and Wind Energy	Massimo Moser
15:40	**Coffee break**	
TOPIC: 1st LINEAR FOCUS SYSTEMS Chair: Robert Pitz-Paal		
Time	**Presentation Title**	**Presenting Author**
16:10	Test bench for parabolic trough receivers characterization	Carmen Fernández
16:35	The once-through concept in DSG power plants– Design aspects of the demonstration plant	Jan Fabian Feldhoff
17:00	Design of a novel cavity receiver based on air for trough concentrating solar power	Philipp Good
17:25	Investigations on soiling in Morocco and Spain	Fabian Wolfertstetter
TOPIC: PV SYSTEMS Chair: Diego Martínez		
Time	**Presentation Title**	**Presenting Author**
17:50	Experimentation and optimization of a PV/Diesel hybrid system for the electricity generation in rural and peri-urban areas of sub-Saharan Africa countries: The “flexy-energy” concept	Daniel Yamegueu
18:15	On-sun tests and design optimization of a 600x CPV collector based on an inflated trough primary with tracking secondary optics	Thomas Cooper
TOPIC: 2nd POINT FOCUS SYSTEMS Chair: Diego Martinez		
Time	**Presentation Title**	**Presenting Author**
18:40	Conception by inverse methods of innovative optics for concentrated solar power : the application to beam down concentrators	Olivier Farges
19:05	Two interesting wavelength bands for IR thermometry	Aitor Marzo

Tuesday, 26 of June		
TOPIC: 3rd POINT FOCUS SYSTEMS **Chair: Jesús Ballestrín**		
Time	**Presentation Title**	**Presenting Author**
9:00	Accelerated aging of a material used in high-concentration solar receivers	Antoine Boubault
9:25	Degradation mechanisms of tube type receivers exposed at high solar flux	Eneko Setien
9:50	Modelling approaches for dynamic wind loads on heliostats	Felipe Vásquez
10:05	Control of the flux distribution on a solar tower receiver using an optimized aim point strategy: Application to THEMIS power tower	Adrien Salome
10:30	**Coffe break**	
TOPIC: 4th POINT FOCUS SYSTEMS **Chair: Bernhard Hoffschmidt**		
Time	**Presentation Title**	**Presenting Author**
11:00	Design and thermal analysis of a volumetric receiver for the PSA Solar Furnace	Maria Isabel Roldán
11:25	Analysis of convective losses of cavity receivers and adequate reduction strategies	Robert Flesch
11:40	A modular ceramic cavity-receiver for high-temperature high-concentration solar applications	Peter Pozivil
12:05	Analysis of the air return ratio and influence of wind for the open volumetric air receiver	Daniel Maldonado
12:30	**Lunch**	

TOPIC: STORAGE Chair: Eduardo Zarza		
Time	**Presentation Title**	**Presenting Author**
14:00	Steelmaking slag, a valuable material for high temperature thermal energy storage	Guilhem Dejean
14:25	Generic heat and mass transfer model of a thermochemical packed bed reactor for thermal storage of solar energy	Stefan Ströhle
14:50	High temperature latent heat storage for thermal protection of concentrated solar absorbers : application to the PEGASE project	David Bellard
15:15	High temperature thermal storage for concentrating solar power: Model and experimental results	Giw Zanganeh
15:40	**Coffee break**	
TOPIC: 2nd LINEAR FOCUS SYSTEMS Chair: Eduardo Zarza		
Time	**Presentation Title**	**Presenting Author**
16:10	Non-destructive optical efficiency measurement of parabolic trough receivers using a solar simulator with linear focus	Johannes Pernpeintner
16:35	Three-dimensional optical and thermal numerical model of solar tubular receivers in parabolic trough concentrators	Men Wirz
17:00	Measurement and modelling of parabolic trough mirror shape in different mirror angles	Siw Meiser
17:25	Low power cogeneration from concentrated solar energy	Arnaud Jourdan
TOPIC: 2nd SOLAR FUELS Chair: Bernhard Hoffschmidt		
Time	**Presentation Title**	**Presenting Author**
17:50	Two-step redox hydrogen production plant simulator tool	Alberto de la Calle
18:15	Solar-driven steam gasification of sugarcane bagasse	Michael Kruesi
18:40	Solar fuels production from thermochemical cycles: kinetic study of the solar reduction of metal oxides	Gaël Levêque
19:05	Adjournment	Diego Martínez

TOPIC: 1st SOLAR FUELS

Fuel production by reduction of CO2 using concentrated sunlight A material study

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Synthesis gas (syngas, $CO:H_2$ 1:2) as an intermediate product is an universal precursor for the production of a very broad variety of chemical substances like gaseous and liquid synthetic fuels, polymers, ammonia, methanol, etc. In order to cover the required heat demand for the generation of carbon monoxide (CO) solely from carbon dioxide (CO2), employing concentrated solar energy may be a viable alternative to the state-of-the-art methods like steam reforming or partial oxidation of fossil resources. This emission-free CO production may be carried out in a two-step thermochemical cycle using an oxide material as the catalyst. The two steps are:

Regeneration of the metal oxide (MO) (1200-1400 °C): $MO_{ox} \rightarrow MO_{red} + O_2$

Splitting of CO_2 into CO (700 to 1000 °C): $MO_{red} + CO_2 \rightarrow MO_{ox} + CO$

Redox-material groups for this thermochemical cycle were identified with the aid of thermochemical calculations and comprehensively presented in an Ellingham diagram in previous project stages. Ceria-based materials were found to be the most promising candidate to undergo experimental investigations.

In the recent project phase, zirconia-doped ceria materials were synthesized and characterized by means of XRD and SEM. The performance dependency on the zirconia-content was investigated in lab-scale experiments, mainly thermo-gravimetric experiments. The maximum yields of O_2 and CO will be discussed as well as the achieved improvements of conducting and analyzing thermo-gravimetric experiments.

Development of a solar reactor for thermochemical water-splitting

Jan Felinks[1], Martina Neises[1], Martin Roeb[1], Christian Sattler[1], Robert Pitz-Paal[1]

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Hydrogen is an energy carrier with a great future potential. The field of application is huge because it has a high energy density and it is easy to handle. Furthermore the big advantage of emission-free combustion makes it unrivalled. A big challenge is the hydrogen production from renewable energy sources on an economic and industrial scale.

The present work deals with the production of hydrogen by thermochemical water-splitting. The reacting material is a metal oxide that is oxidised by the water-splitting reaction with water and then thermally reduced at temperatures up to 1400°C. The redox-material remains solid during the whole cycle. The purpose of this work is to develop a novel solar reactor for the described process that supports temperatures of about 1400°C needed for the thermal reduction step. The major points of the novel design are to achieve high reacting surface areas for the chemical reaction and a high thermal efficiency of the reactor.

Up to now a literature research of existing reactor concepts and the collection of requirements have been done. High reacting surface areas can be realised with a particle reactor, for example a fluidised bed. The high temperature needed for the thermal reduction can be achieved with a directly irradiated reactor concept without the use of a heat transfer fluid. An overview of possible reactor concepts has been outlined. In order to evaluate these concepts a system of criteria was created which helps to choose the most promising one.

The next steps are to choose a suitable reactor concept and to develop a new experimental reactor based on this concept.

Numerical Analysis of Process Dynamics of Thermochemical Water Splitting Process

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The project HYDROSOL-3D aims to design a 1MWth plant based on a thermo-chemical water splitting cycle. The cycle works as follows:

In a first step (about 900 °C), water and metal oxide (MO) react in such a way that the metal oxidizes and thus takes up oxygen from the water, leaving hydrogen as a product gas:

$H_2O + MO_{RED} \rightarrow H_2 + MO_{OX}$

In a second step, the oxidized metal oxide is reduced at higher temperatures (about 1300 °C); oxygen leaves the material and can be carried out by an inert gas flushing stream. This step regenerates the metal oxide so it can be used for water splitting again:

$MO_{OX} \rightarrow MO_{RED} + O_2$

To get a realistic overview of an achievable efficiency of the complete hydrogen generation process it is important to critically examine all loss mechanisms. Some of these can only be studied thoroughly using dynamic modeling approaches. Therefore, a dynamic process model is being established in the commercial software Aspen Dynamics. The core part of the process model is the reactor which had to be created from the ground up (using Aspen Custom Modeler software), since it is not a standard unit operation available in Aspen. Model validation could be carried out based on test campaign results from predecessor project phases.

Other loss mechanisms do not need numerical techniques, but can be analyzed based on thermodynamic considerations. One of these is the loss due to preparation of nitrogen which is used as flushing gas in the process. This flushing nitrogen is required to be of high purity for chemical regeneration of the metal oxide to take place. The minimum work needed to supply the nitrogen is calculated by thermodynamic analysis and different scenarios of purity requirements are compared.

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

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Solar thermochemical approaches for 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. In contrast to direct thermolysis of CO_2, two-step thermochemical cycles further bypass the CO/O_2 separation problem. 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 CO_2, thereby releasing CO and re-incorporating oxygen into the lattice. The two-step 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 CO_2: $CeO_{2-\delta} + \delta\ CO_2 \rightarrow CeO_2 + \delta\ CO$ (2)

We report on recent experimental studies for splitting CO_2 using concentrated solar energy. A novel, macro-porous CeO_2 structure was developed and tested in a 3.8 kW solar reactor prototype which was previously described in detail.[1, 2] 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.

1. W. C. Chueh, C. Falter, M. Abbott, D. Scipio, P. Furler, S. M. Haile and A. Steinfeld, *Science*, 2010, **330**, 1797-1801.

2. P. Furler, J. R. Scheffe and A. Steinfeld, *Energy & Environmental Science*, 2012, **5**, 6098-6103.

TOPIC: 1^{st} POINT FOCUS SYSTEMS

Modeling a falling particle receiver with face-down geometry for large scale electricity generation

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Efficiency increase of a solar tower power plant and therefore cost reduction for electricity generation is very important. This is the motivation for the development of new receiver concepts. A falling particle receiver is one of the emerging concepts. Sandlike ceramic particles can be used as absorber, heat carrier and storage medium. Due to the high melting point of the particles, a high receiver outlet temperature can be achieved. The benefit of the higher working temperature is higher power block efficiency and increased storage density. To minimize heat losses the receiver is designed as a cavity with a downwards facing aperture. The scheme of a power tower with face down particle receiver is shown in figure 1.

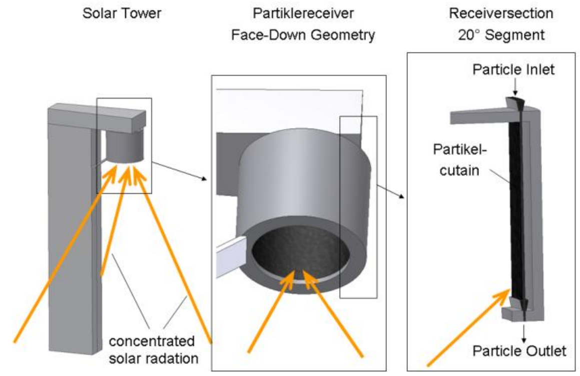

Fig. 1: Solar power tower with falling particle curtain in face down cavity; different views: tower (left); cavity, view from below (middle); receiver section, curtain, hopper,

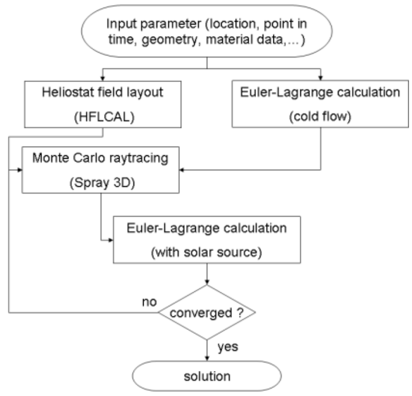

Fig. 2: Schematic view of modeling workflow

A new model was developed to assess the receiver performance. The objective of the modeling is to get a deeper understanding of the physical effects in the receiver. These are mainly particle movement, solar radiation, thermal radiation, heat transfer by convection and streaming (especially due to wind). On the other hand, the computational effort should be small enough to be able to do several calculations for design and optimization in a suitable calculation time with a common personal computer. Therefore the Euler-Lagrange (EL) method was chosen for the modeling. The air is treated as continues phase and the particles as discrete phase. The accordant equations are solved iteratively and are coupled with source terms. The concentrated solar radiation from the heliostat field is determined by a raytracing program. The raytracer provides volumetric heat sources for the particles and a flux distribution for the cavity walls. These are used as boundary condition for the EL calculation. The raytracing and the EL computation are solved iteratively, too. The usual workflow is shown in figure 2. The results of the modeling are global quantities as efficiency and the classification of the heat losses. In addition, the determination of local quantities enables to analyze the relevant physical effects and optimize the receiver. Some results are presented and discussed to illustrate the utility of the new model.

Optimization of a high temperature solar receiver by poly-dispersion of particles

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Volumetric solar receivers may be used to heat or preheat a working fluid (air) to a prescribed temperature required for the operation of thermodynamic cycles. Obviously, the conversion efficiency of solar energy into work is better when high working fluid temperature is involved. Volumetric receivers have demonstrate good performances working at high temperatures. This study focus on particle receivers that are candidates to accomplish this task.

Different particle receivers were previously investigated, but there is not sufficient information about the optimum values of parameters that drive the receiver efficiency. The objective of this work is to optimize a solar receiver having a particle polydispersion.

For this, a simple mono-dimensional geometry (1D) has been considered. The 1D solar receiver is constituted of a cloud of particles embedded in a non-participative gas (air). A simplified model has been developed (cold media, spherical particles, two-stream approximation to solve radiative transfer equation) in order to simulate the receiver with sufficient accuracy and lower computation time. The model has been validated with a Monte Carlo code developed in PROMES.

This model has been used to optimize all variables that drive the single layer 1D particle receiver efficiency (refractive index $m=n+ik$, particle radius r and volumetric fraction f_v), with help of a particle swarm optimization (PSO) algorithm.

In future works, 1D particle receiver with multiple layers will be studied and a 3D particle receiver will be designed to study the coupling effects between radiation heat transfer and fluid flow in such a particle receiver

Title: Homogeneous fluidization predicted by CFD-DEM simulations: hydrodynamic stability of gas-fluidized beds

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A coupled CFD-DEM model is used to simulate a dense fluidized particle system of fine particles (< 100 μm). The CFD-DEM approach allows simulation of the continuous fluid phase by a CFD algorithm while the motion of the particulate phase is captured by the discrete element method (DEM). The DEM allows the dynamic tracking of individual particles along the system. This approach is applied to characterize hydrodynamically the stability of fluidized beds and to obtain a detailed insight in the discrete particle motion.
Such a fluidized bed is used as a high-temperature heat transfer medium for a central receiver concentrating solar power system. The solid phase consists of any particulate mineral, (e.g. quartz sand) that withstands the required temperatures. Additionally, the solid particles can be used as a thermal energy storage medium due to their high heat capacity. The homogeneous fluidized bed rises slowly in hot tube bundles in a directly-irradiated solar receiver. The hydrodynamics of the fluidized bed and the particle locations are investigated for determining the conductive, convective and radiative heat transfer from the hot tube wall to the dense particle suspension.
The particles belong to Group A according to Geldart's classification, which enable homogeneously fluidization without forming large bubbles. For the stability analysis, the minimum fluidization velocity, minimum bubbling velocity, and the homogeneous bed expansion is considered. The minimum fluidization velocity indicates the beginning of the homogeneous fluidization whereas the minimum bubbling velocity indicates the end of the homogeneous fluidization state. Validation is accomplished by comparing numerical results with those derived from models and experimentally from literature.

A solar particle receiver for small gas turbine systems

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For the application to small-scale CSP systems (100kW$_{el}$ – 1MW$_{el}$) a novel solar particle receiver in combination with a small gas turbine system is developed and optimized with regard to high efficiency, high durability and low costs. A key characteristic of the Centrifugal Particle Receiver (CentRec) concept is to utilize a receiver rotation in order to adjust the particle outlet temperature to different load conditions.

Within the scope of identifying the thermal receiver efficiency, an electrical heated test receiver is built in order to study the convection losses in a rotating cylindrical cavity under laboratory conditions. Since special attention is paid on the effect of rotation on convective losses, particles are neglected in this test rig. Three heating wires with a maximum power of 2300 W each are used to provide the desired heat input. The mean receiver wall temperature is determined by 21 thermocouples, distributed all over the receiver walls, while three measuring transducers for active power detect the heating power. The convective losses at a certain wall temperature can be then calculated by $Q_{conv} = Q_{el} - Q_{cond} - Q_{rad}$ with the conduction and radiation losses being determined experimentally and analytically. Extensive tests for three different temperatures at various rotation rates and receiver inclination angles have shown that the convective losses are indeed affected by receiver rotation. However, compared to the influence of the inclination angle where the losses can be decreased up to 80% rotational effects are rather small, with about ± 10%. Looking at the overall thermal losses, the influence by receiver rotation would be less than 1% which can be therefore neglected. For a first receiver efficiency analysis well-known correlations from literature can be used with sufficient confident without their adjustment to rotation.

At the moment, a CentRec prototype in laboratory scale (15 kW$_{th}$) is built for experiments in the high-flux solar simulator at the DLR in cologne. A comprehensive test campaign is planned in order to determine essential features of the receiver as well as its overall thermal efficiency. Moreover, the results are used to validate the analytical model which is developed. It considers particle movement dependent on rotation rate and mass flow as well as the corresponding temperature distribution. Radiation, conduction and convection losses are calculated by the model leading to the overall thermal receiver efficiency.

TOPIC: DETOXIFICATION AND DESALINATION

Optimization of mild solar TiO2 photocatalysis as a tertiary treatment for municipal wastewater treatment plant effluents

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The appropriate catalyst concentration for industrial wastewater treatment is several hundred milligrams per liter in solar photoreactors. Nonetheless, when the purpose of eliminating emerging contaminants in municipal wastewater treatment plant (MWTP) effluents is for reuse of the water, and they are present at extremely low concentrations, a tertiary treatment with a much lower photocatalyst concentration might be possible. TiO2 concentrations of only tens of mg L^{-1} were selected to evaluate the influence of catalyst load, initial hydrogen peroxide dose and radiation intensity on the degradation rate of five emerging contaminants (100 μgL^{-1} of ofloxacin, sulfamethoxazole, flumequine, carbamazepine, and 2-Hydroxy-biphenyl) spiked in a real municipal wastewater treatment plant effluent. Response surface methodology based on a spherical central composite design was used to optimize the parameters to find the maximal degradation rate. The experiments were carried out using an Evonik P-25 titanium dioxide suspension in a Suntest solar simulator. It has been demonstrated that the use of hydrogen peroxide is highly recommendable for working with TiO_2 at low concentrations and high photon flux must be avoided. It has also been demonstrated that too low (less than 40 mg L^{-1}) TiO_2 concentration is not recommendable. One of the main drawbacks of reducing catalyst loads is the waste of useful solar photons passing through the reactor without reacting with TiO_2. Accordingly, during this work, lab and pilot-scale experiments were performed with real MWTP effluents to evaluate the kinetics under realistic (low) concentrations, and analyzed by liquid chromatography-mass spectrometry (LC-MS).The low concentration of TiO_2 selected could be a good, cheap and simple alternative MWTP tertiary treatment for removal of contaminants, but the photoreactor design must be optimized for shorter treatment times

Wastewater disinfection by solar photo catalysis

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This work is part of wastewater reuse and focuses on the disinfection of wastewater by advanced oxidation process (AOP): heterogeneous solar photo catalysis. The study aims to demonstrate the feasibility of the photo catalytic disinfection and to scale up an industrial wastewater disinfection pilot by solar photo catalysis. In this study, work will focus on the disinfection of *Escherichia coli* (indicator) through a photosensitive material (TiO_2) placed on different media (powder, cellulose matrix impregnated with TiO_2 ...). The first part is to study the role of the media during the photo degradation process essentially by evaluating the adhesion capacity of the microorganism "*Escherichia coli*". Then, experiments will be performed into photo reactors with controlled conditions. These will identify key parameters that govern the disinfection namely the irradiation intensity, catalyst concentration and the initial microbial load. The aim is to establish a kinetic model representing the photo degradation of "*Escherichia coli*" and to valid it under dynamic conditions (flow rate, intermittent irradiation and variable microbial load).

Degradation of acetaminophen using TiO2 supported on glass spheres irradiated in a CPC Solar Pilot Plant.

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Water is the most important resource for life sustaining, it is essential to fulfill our daily needs. Actually, pharmaceuticals contaminants are considered as one of the most important kind of pollution, and they are classified as emerging contaminants. The drugs most frequently detected in high concentration levels are salicylic acid, carbamazepine and acetaminophen **[1-6]**.The heterogeneous photocatalysis with TiO_2 has been proposed for eliminating different pollutants from water (for instance: drugs), even though, the recovering of the catalyst is still a complex process. As a result from this limitation, different techniques for immobilizing TiO_2 catalysts have been developed.

The aim of this work was evaluate the durability and photocatalytic activity of supported TiO_2 on glass spheres using firstly as a test reaction, the decomposition of dichloroacetic acid, and afterward, to carry out the degradation of Acetaminophen drug.

TiO_2 photocatalyst was prepared by sol-gel technique **[7]** and then, all the glass spheres were covered with sol by dip-coating and dried at 110 ˚C for 90 min and later heat-treated at 400 ˚C for 300 min at a rate of 3 ˚C min^{-1} [12]. In the next step, the glass spheres were tested on dichloroacetic acid degradation in order to demonstrate their photocatalytic activity. For this procedure, the solution used was 10 mgL^{-1} Dichloroacetic acid under a simulated solar radiation in a chamber Suntest, XLS+ Heraeus, Gemany which simulates the outdoors solar radiation and two different reactors. Base on these results, TiO_2 supported on glass spheres was used for degradation of 100 μgL^{-1} of acetaminophen at different conditions of reaction under sun irradiation through the Compound Parabolic Collector (CPC) solar plant at the Plataforma Solar de Almería.

The dichloroacetic acid was degraded 30% after 360 min and 1.7 mgL^{-1} of chlorides were released. The degradation using a tubular CPC reactor decreases slower than the other reactor, because the reactor tube CPC absorbs part of the incident photons. The degradation of acetaminophen in CPC pilot plant can be adjustment at pseudo-first-order kinetics **[8].** The first experiment was performed with distilled water, in this case, the total of concentration of acetaminophen was eliminated after 23 min of irradiation. On the other hand the stability and photocataly activity of the TiO_2 spheres was evaluated. The catalyst coating on spheres showed very good mechanical stability and photocatalytic activity after five cycles with real effluent Municipal Wastewater Treatment Plants (MWTP).

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Combined Electricity and Water Production basing on Solar and Wind Energy

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Solar and wind technologies both present huge potential in the MENA region. Each technology has different performance characteristics, so that the question arises over which technology will provide most economic and sustainable electricity supply.

Generally speaking, most of the MENA countries are characterized by rapidly increasing power demand, so that the installation of additional load will require the installation of equivalent firm supply capacity. As this quality of power supply cannot be provided by wind or PV plants alone, backup capacity will be required. Such backup plants will be forced to operate at part load conditions whenever the renewable electricity generation will satisfy or exceed the given load. This will cause additional cost due to the fact that those plants will run with lower plant efficiencies.

Therefore, in order to get comparable and resilient results when comparing different solutions to cover an additional load (which in the analyzed case is an additional desalination plant), options with equal power supply quality should be compared, taking into account overall system cost. This means that backup, storage and grid management cost are also considered. In this case, the optimal power generation mix is a function of site-specific available renewable resources, specific investment cost, fuel cost and share of renewable power generation on the total power requirements. Also the impact of different financial boundary conditions on the optimal plant design is shown.

TOPIC: 1^{st} LINEAR FOCUS SYSTEMS

Test bench for parabolic trough receivers characterization

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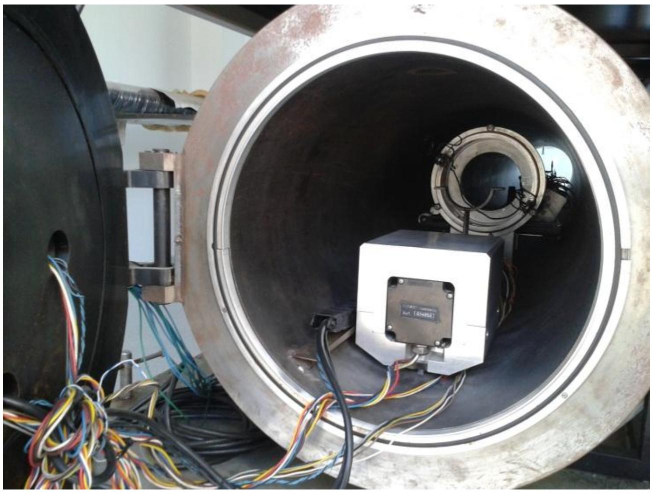
Nowadays, solar parabolic trough collectors are one of the renewable technologies for electricity production with better prospects for the future. However, it is necessary to continue improving their efficiency in order to increase their competitiveness. The receiver tube is one of the essential components of this type of collector, in which heat losses are closely related to the optical characteristics of coatings.

It arises the need to create test benches to characterize the new receiver tubes and checking the improvements of the new selective coatings. In this way, we avoid to mount the tubes on the collector fields and test them under normal operating conditions for a long time. Test benches allow us to reproduce the influence of different variables in the performance of the receivers and control them.

The test bench, in which we are working on, is a vacuum chamber where the studied receiver tube is placed inside. The inner surface of the receiver is heated up to operating temperatures by thermal resistances, in addition wall temperatures of the camera and receiver are recorded. These data, combined with the applied heating power, will allow us to calculate the thermal losses, using energy balances. Furthermore, the test bench provides thermal maps of the receiver surface. This method could standardize the characterization of receivers and therefore offers quality control and performance guarantees.



Acknowledgment. First author wishes to thank to the Plataforma Solar de Almería and CIEMAT for the financial assistance awarded for her PhD research period, during which this work is being conducted.

The once-through concept in DSG power plants – Design aspects of the demonstration plant

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Parabolic troughs are currently the most mature solar concentrating systems. While most of the commercial plants currently use synthetic oil as heat transfer fluid, the direct steam generation (DSG) gains further industrial interest and first commercial plants are already in operation in Spain and Thailand. These plants use the robust recirculation mode, in which the solar fields for evaporation and superheating are separated by steam drum in the field. Operational data show that this concept works reliably even under transient weather conditions.

To further reduce the complexity of DSG solar fields, the so-called once-through concept is considered as alternative for DSG. Its solar field consists of identical parallel loops in which pre-heating, evaporation and superheating take place without additional separator. This allows an easy solar field scale-up analog to an oil field, while offering further efficiency and cost advantages.

The thesis analyzes different aspects of the once-through concept and compares the results with the recirculation mode. These aspects are investment, reliability, controllability, system complexity, operation & maintenance procedures as well as the overall system performance.

The DISS test facility (DIrect Solar Steam) is currently modified to allow the proof of concept and further analyze the mentioned aspects. The design of the test facility and the thesis-specific changes will be presented. In addition, further details on reliability (e.g. the methodology of life time assessments) and controllability (e.g. the methodology of temperature stability analyses) will be mentioned.

Design of a novel cavity receiver based on air for trough concentrating solar power

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A linear solar receiver using air at atmospheric pressure as heat transfer fluid is developed for use with one-axis tracking trough concentrators. The technical feasibility of this concept has been successfully demonstrated with a 42 meter long tubular absorber contained in a cylindrical cavity erected in Biasca, Switzerland [1, 2]. In order to increase the active surface area for convection heat transfer from the tube wall to the heat transfer fluid, a novel cavity design is proposed. The new receiver is designed for a maximum operating temperature of 650 °C at a geometric concentration of 100 suns, which is achieved by a linear trumpet secondary concentrator attached to the receiver aperture. A numerical heat transfer model has been developed to analyse the thermal performance and pumping power requirements for different geometric dimensions and under various operating conditions.

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Investigations on soiling in Morocco and Spain

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A measurement concept for investigation on soiling of solar reflectors in different climatic zones in Spain and Morocco is presented. In the course of a project called Morocco Meteonet Solar (MMS) the DLR is working closely together with the university Mohamad Premier in Oujda, Morocco and the Moroccan energy supplier ONE. Together we have agreed on installing four fully equipped meteostations in the east of Morocco. The stations will be in different climatic zones ranging from maritime to semi-desertic and desertic as well as urban. These stations build the basis for the installation of further instrumentation for investigations on the environmental influences on solar mirrors such as soiling rates and degradation.

TOPIC: PV SYSTEMS

Experimentation and optimization of a PV/Diesel hybrid system for the electricity generation in rural and peri-urban areas of sub-Saharan Africa countries: The “flexy-energy” concept

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For most countries, increase in energy security, improvement in trade balance and decrease in dependence on imported fossil fuels are the main drivers for use of the renewable energies. Another major interest in using renewable energies is the remote rural areas electrification. In many cases and particularly in sub-Saharan Africa region, these areas being located so far from power stations, the distribution networks or utility lines are not cost-effective to install. Therefore, the photovoltaic power production promises to be a clean, widely applicable renewable energy source available for the electrification of rural and peri-urban areas of sub Saharan Africa region. But the vulnerability to unpredictable climatic changes and the dependency on weather conditions remain some of the drawbacks of the photovoltaic systems. For these reasons, many studies propose the combination of the photovoltaic power generation systems with diesel generators to meet efficiently the load demand. A new concept on hybrid systems called “flexy-energy” was proposed by the research team of LESEE[1] of 2iE foundation and is based on a PV/Diesel hybrid system without batteries storage with the flexibility to fuel the diesel generator either with diesel or with biofuel (mainly local vegetable oils). The general goal of this concept is to contribute to supply sustainable and affordable energy services to rural and peri-urban populations in sub-Saharan African. To assess the technical and economical feasibility of this concept, a PV/Diesel hybrid system without storage has been set up on the site of the International Institute for Water and Environmental Engineering (2iE) at Kamboinsé (12°22’ N and 1°31’W), located at fifteen kilometers in North of Ouagadougou, capital of Burkina Faso. The prototype consists in a 9.2 kW diesel generator coupled with a PV array of 2.85 kW*p* through an inverter rated at 3.3 kW. This paper deals with the experimentation and the optimization of this prototype. First, the “flexy energy“concept is presented. Second the experimental results of high interest obtained with this prototype are presented as well as the optimization approaches of the system.

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On-sun tests and design optimization of a 600x CPV collector based on an inflated trough primary with tracking secondary optics

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We report the on-sun prototype test results and design optimization of a novel 600x CPV system. The design is unique in that it diverges from the classic 2-axis tracking module array concept utilized by most CPV systems. Rather, the design borrows from the mature CSP industry, which has shown single-axis tracking trough geometries to be a robust and economically sound method for concentrating sunlight.

The primary mirror is constructed from a multi-layer stack of aluminized polymer membranes, whose precise shape is achieved through regulation of the differential pressure between individual sheets [1]. The primary tracks on a North-South axis, achieving a primary geometric concentration of 60x. To augment the concentration to levels suitable for HCPV, a novel two-stage concept was developed, utilizing an array of tracking-integrated non-imaging reflective concentrators placed along the line-focus of the trough [2]. By tracking the reflected incidence angle of the sunrays, the secondary stage achieves a concentration of 10x, yielding an overall geometric concentration of 600x. A 5 by 1 string of series-connected 1 cm^2 square III-V triple-junction (3J) cells is coupled to the exit of each secondary concentrator. In August 2011, the first set of on-sun tests were conducted on a 45 m long full-scale prototype of the system in Biasca, Switzerland, serving as an experimental proof-of-concept of the design.

An optical model of the system was developed using the in house VeGaS ray-tracing code [3] and validated vis-à-vis the experimental results. The validated model was used to optimize the secondary reflector geometries with respect to optical efficiency, minimization of localized hot-spots on the secondary concentrator, and the spatio-angular distribution of flux on the cell array. A 200 kW demonstration plant based on the optimized design is currently being constructed in Biasca, Switzerland, with commissioning planned for late 2012.

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TOPIC: 2nd POINT FOCUS SYSTEMS

Conception by inverse methods of innovative optics for concentrated solar power : the application to beam down concentrators

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Reflective solar tower, also known as “beam down” optics, where firstly cited by Rabl in the middle 70's. By inverting the path of the solar rays from the heliostats field to a final receiver placed on the ground, there is no need to build a tower carrying lots of heavy components. The principle is based on quadratic surface properties such as ellipsoid and hyperboloid : each rays orientd to one of its foci is reflected to its second. Numerous research studies concluded that hyperboloid shape give better results than ellipsoid one. Those plants can have advantage to reach high temperatures (more than 1100K) and could then be applied to solar chemistry or efficient conversion of solar energy, via Brayton cycle for exemple. In this context, the « High Temperature Solar Energy » team of RAPSODEE Center develop a numerical tool based on Monte Carlo method : the public domain development environment EDStar. This thesis investigate simulation of solar central receiver and multicriteria optimization, applied to reflective solar tower.

EDStaR (numerical Environnement of Development for Statistical Radiative simulation) is a coding environnement used for simulations. Using Monte-Carlo methods, it takes advantages of advanced rendering techniques in computer graphics community : it can manage complex geometries with the use of the numerical library PBRT (Physically Based Rendering Techniques). It takes the benefit of all the modern possibilities of computing such as massive parallelization, acceleration of the ray tracing in a complex geometry and estimation of sensitivities. Sensitivities are of great interest in design optimization process and a part of this subject is to developp a mathematical method to obtain sensitivities to geometrical parameters associated with a Monte Carlo algorithm. As a solar plants have many parameters to be set, such as heliostats field layout, number, weight, height of héliostats,… The multicriteria optimization will be an hybrid method, using both sensitivities to some geometrical parameters and evolutionnary algorithm for others parameters. Among all evolutionnary algorithm, we choose to work with Particle Swarm Optimization which was first intended for simulating social behaviour, as a stylized representation of the movement of organisms in a bird flock or fish school.

Two interesting wavelength bands for IR thermometry

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Infrared measurement of the thermal radiation emitted by solar irradiated material surfaces is the most reliable alternative to contact thermometry which is inadequate for measuring surface temperatures. However, reflected solar radiation and the use of windows in some test can be important sources of error in this non-contact methodology.
A promising method for eliminating this solar perturbation is by using centered pass-band filters on the spectral bands where the solar radiation has been attenuated, creating solar-blind sensor.
Six wavelength bands are analyzed in this paper, four that can be used to measure through quartz windows and another two that can be used to measure the temperature of the quartz window itself.
Finally, it has been developed a method to measure surface temperatures with an IR camera prototype with band-pass filters centered on two of the six wavelength bands analyzed. Now a day, this camera is being used in the solar furnace of the Plataforma Solar de Almería.

TOPIC: 3rd SOLAR FUELS

Accelerated aging of a material used in high-concentration solar receivers

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One of the most crucial issues for designing reliable technologies with higher efficiencies and lower maintenance costs is the durability of the materials used in solar receivers. Our study focuses on the aging process of a superalloy coated with a high-temperature black paint which is commonly used in solar receivers.
Considering the fact that the principal chemical and physical aging factors are catalyzed by the amount of solar energy that a material absorbs and dissipates, a numerical model was implemented to study the thermal behavior of the material for different configurations of boundary conditions.
Two sensitivity studies highlighted the most influencing boundary conditions to increase the thermal aging factors, as well as the material properties that are representative of the material aging and which need to be monitored during experimental aging tests. Different solar irradiation cycles are simulated to ascertain the optimal conditions to accelerate the degradation mechanisms. Two aging strategies are being tested with a novel device named SAAF (Solar Accelerated Aging Facility) which is introduced. We used a 2-m diameter parabolic solar furnace to perform cyclic solar irradiations on material samples that are cooled by air at the rear face.
After accelerated aging tests, some important thermo-optical and thermophysical properties were monitored to analyze the decrease of the material's thermal performances. For this purpose, two devices were used: an impulse photothermal method to estimate the bulk thermophysical properties; and an optical fiber solar reflectometer to measure the directional solar reflectivity of the material's coated surface.

Degradation Mechanisms of tube type receivers exposed at high solar flux.

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One of the main challenges of solar central tower technology is to increase the reliability (i.e. thermal efficiency, exergetic efficiency and durability) of the highly irradiated receivers. The solar central tower plants receivers must work at high temperatures in order to increase the global efficiency of the process. Moreover, solar plants operate in cyclic conditions, which jeopardize the thermal efficiency and durability of the receiver.

The tube type receivers work not only at high temperatures but also endure heterogeneous high solar flux and usually high pressure under cyclic conditions. These severe conditions activate degradation mechanisms such as low cycle fatigue, oxidation at high temperatures and creep. In order to be able to predict the material behavior after long exposure time an accelerated aging test are required.

An in-house mechanical and thermal model of the receiver has been used for previous understanding of test condition effects. The model is based in the knowledge of other industries as nuclear or aeronautic industry, not including the effect of solar radiation.

In order to understand the effect of solar radiation the accelerated aging tests are running. Two aging methodologies are being compared: i) cyclic thermal aging in an oven and ii) cyclic thermal and solar radiation aging in a solar dish.

Modelling approaches for dynamic wind loads on heliostats

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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. The flow conditions in the heliostat field are characterized by the atmospheric boundary layer, wind gusts and vortex shedding generated by the heliostat structures. Modelling these flow conditions requires a transient approach capable of resolving a wide range of turbulence scales present in the flow. For this purpose, CFD methods such as Large Eddy Simulation (LES) are considered. To study the capabilities and computational effort of LES for this application, a highly resolved LES [1] of an inclined flat plate has been chosen to compare the performance of a commercial CFD code. The results obtained in this benchmark are presented and further methods to be considered are proposed. To model the dynamic behaviour of a heliostat and obtain information about its natural frequencies and modes of vibration, a numerical modal analysis has been performed using commercial finite element (FE) software. A detailed FE model has been developed based on a real size heliostat prototype. The results of the simulations are presented and the methodology to validate the numerical model is explained.

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Control of the flux distribution on a solar tower receiver using an optimized aim point strategy: Application to THEMIS power tower

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Life time of components is one of the technological bottle-neck in the development solar tower power plant technology. The receiver, which is submitted to high and variable concentrated solar flux density is particularly concerned: High, variable and non homogeneous solar flux on the solar receiver walls results in strong stresses because of high temperatures, thermal shocks and spatial temperature distribution that contribute to the decrease of the life time of this key component. This work aims at presenting an open loop approach to control the flux density distribution on a plane receiver for a solar power tower by using a computer code to generate simulated flux density distribution on a grid of aim points on the receiver surface using HLFCAL method, and an optimization algorithm using TABU meta heuristic to choose the best distribution for the heliostats on the defined aim points with respect to certain constraints. This approach has been developed and validates using the example of THEMIS Solar Power Tower in Targasonne, France.

TOPIC: 4^{th} POINT FOCUS SYSTEMS

Design and thermal analysis of a volumetric receiver for the PSA Solar Furnace

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The need to reduce pollution in intensive power-consuming industrial processes has led to studies of supplying thermal energy with solar-power systems. Previous research has demonstrated the possibility of using solar thermal power in high-temperature industrial processes by means of high-temperature solar receivers.

Experimental research requires funding and time to build a facility that can reproduce the industrial-process conditions. In order to optimize resources and to avoid the assembly of several different facilities, Computational Fluid Dynamics is used as a method to analyse the parameters which determine the evaluation of a process.

For this purpose, the computational fluid dynamics-code FLUENT has been used in the current study. This software has allowed carrying out the simulation and thermal analysis for the main components of a volumetric receiver installed in the Plataforma Solar de Almería's Solar Furnace (PSA Solar Furnace). On the one hand, different configurations have been proposed for the design of a solar prototype, in order to select the best configuration to reach the temperature range, required in high-temperature industrial processes, inside the prototype cavity. Therefore, different configurations have been considered using several geometries, refractory materials and different thicknesses for these materials. On the other hand, the experimental configuration of the absorber material has been evaluated and other designs, according to the porosity, have been proposed in order to improve its efficiency.

As a result of using the Computational Fluid Dynamics, a group of simulations has been obtained from the previous configuration proposed. These simulations show the thermal profiles required for the evaluation and selection of the optimal configuration. In the case of the solar-prototype analysis, the selected configuration is used in the experimental facility but, in the case of the absorber analysis, this configuration is proposed as a future improvement for subsequent developments.

The experimental setup evaluation has allowed validating the simulation models used and the study of several different aspects, such us the influence of the focal distance, the effect of the baffle plate and the one of the insulating material, the absorber efficiency and its homogeneity, the effect of the flux-distribution variation, and the process temperature reached according to the volume treated.

The methodology used in the development of this study has led to demonstrate the possibility of reaching the temperature required by several high-temperature industrial processes, using concentrated solar energy, and to analyse the effect of the parameters which influence the achievement of that objective.

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.

In this thesis the influence of wind on the losses will be examined in detail by CFD calculations and experiments, in order to develop a better understanding of the relevant heat transfer mechanisms. The focus of the examination lies on large cavities for megawatt scale plants. The gained knowledge will be used in a next step to develop strategies to reduce the convective losses, e.g. geometric modifications (wind guards) or the usage of sealing air. The CFD models and experiments are going to be modified to analyze and compare the different strategies, in order to find a suitable concept to reduce the influence of wind on the efficiency of cavity receivers.

A modular ceramic cavity-receiver for high-temperature high-concentration solar applications

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In previous publications [1, 2] we reported the novel design of an air-based pressurized solar receiver for power generation via solar-driven gas turbines. The main component of the indirectly irradiated 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 set of silicon carbide cavity-receivers attached to a compound parabolic concentrator (CPC) were tested at the solar tower of the Weizmann Institute of Science (WIS) at stagnation conditions for 35 kW of solar radiative power input at a mean solar concentration ratio of 2000 suns and temperatures up to 1600 K. In the scope of the field campaign only the inner cylinder was tested, no air-circuit was yet incorporated and no RPC was installed. A heat transfer model coupling radiation, conduction, and convection was formulated by combined Monte Carlo ray-tracing and CFD techniques, and validated against experimentally determined temperatures, measured by means of infrared thermography. The model was applied to elucidate the effect of material properties, geometry, and reflective coatings on the thermal performance of the cavity. Using the validated mode it was determined that 85 – 89% of the incident solar radiation was conducted across the cavity walls and available as useful power, while re-radiation was the dominant source of heat loss [3].

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

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Open Volumetric Air Receivers are a promising option for solar central receiver power plants. While the receiver-concept is modular the heat transfer fluid, air, is not limited in temperature. The technology is based on irradiating ceramic absorber combs that, in turn, heat up ambient air, which is sucked through the combs from the ambient. 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. 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 presumably 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. In previous works (e.g. Ahlbrink et al.) the air return ratio is assumed to be constant and set as the average value of measured data from test facilities at the PSA and Jülich.
The aim of the thesis is to study the flow phenomena in front of the receiver in order to calculate and forecast air return ratios in different operating and wind conditions. If applicable, improvements of the air return system should be elaborated. CFD results of a receiver segment and measurements of the research and development power plant Jülich will be used to analyse the described effects. In a further step a measurement method to detect relevant wind data will be prospected.

TOPIC: STORAGE

Steelmaking slag, a valuable material for high temperature thermal energy storage

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Introduction

Thermal energy storage is a key point for the development of thermodynamic solar power plants. Concerning the storage of large amount of heat, thousands of tonnes of material are needed for each plant, inducing huge quantities of material consumed each year to follow development scenario of CSP from IEA [IEA 2010]. Beyond its good physical and thermomechanical properties, price and availability of a candidate material are therefore critical. Ceramic materials obtained from vitrification of industrial wastes have proven to be of interest [Py 2011]. In the present study, other industrial wastes, steelmaking slags, are considered. These materials present interesting thermophysical properties and no environmental hazard. In the present paper, preliminary characterizations of these different slags are presented and compared to more conventional storage materials.

Materials and method

Eight slags from French production of iron and steel are compared in order to choose the best candidate(s) for thermal storage. Best candidates are compared to more conventional materials. Chemical composition, density, XRD, SEM, DSC-ATG, heat capacity, thermal conductivity, thermal expansion and Young’s modulus are used to differentiate these candidates. Heat capacity, DSC-ATG, thermal conductivity, thermal expansion and Young’s modulus are measured from ambient to 1000 °C. A comparison is also made between raw (with porosity) and shaped (without porosity) materials.

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Acknowledgements

The authors want to acknowledge the Arcelor-Mittal Company (FRANCE) for providing us samples of slags.

Generic heat and mass transfer model of a thermochemical packed bed reactor for thermal storage of solar energy

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Efficient and reliable thermal energy storage allows CSP plants to provide dispatchable energy and is considered to be one of the key factors to reduce the corresponding Levelized Cost of Electricity (LCOE). Suitable thermochemical reactor concepts for thermal storage in high temperature CSP plants are being investigated within the framework of the EU-project "TCS Power".

This presentation covers the description of a generic, one-dimensional heat and mass transfer model, applied to a thermochemical packed bed tubular reactor (PBTR). The investigated reaction is performed with manganese oxide and air ($6Mn_2O_3 \leftrightarrow 4Mn_3O_4 + O_2$), with reaction temperatures of oxidation and reduction around 750°C and 920°C, respectively. The numerical model solves the energy balance for each phase along with the material balances. Results of the one-dimensional model, as well as experimental results of kinetic measurements will be shown and discussed. A brief outlook on an upcoming, improved numerical simulation tool for a PBTR will conclude the presentation.

High temperature latent heat storage for thermal protection of concentrated solar absorbers : application to the PEGASE project

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The French PEGASE project (Production of Electricity with Gas turbine and Solar Energy) aims at operating a demonstration plant using the Hybrid Solar Gas Turbine technology at the THEMIS site in Targasonne (France). One of the main objectives is to develop a 4 MWth pressurized air receiver with a surface absorber based on a compact heat exchange technology. Such an absorber is suitable for large-scale pressurized air solar receivers. Based on the advantages offered by these technologies, the Mini-PEGASE task focuses on the development of a 1/10 pilot receiver relying on the assembling of 16 modules, divided in two stages, and surrounded by a cavity. The goal is to be capable of preheating pressurized air from 350°C at the inlet up to the target outlet temperature of 750°C.

An absorber mock-up of 20 kWth has been tested at the 1 MW solar furnace of the PROMES-CNRS laboratory in Odeillo. More than one hundred measuring points have been done in order to test the mock-up with a various panel of operating parameters: incident flux (0 – 600 kW/m²), air flow rate (60-140 g/s), air input temperature (20 – 500 °C) and air pressure (4 – 7.5 bar). The thermal objectives have been reached: the operating points have been tested, an air outlet temperature of 800°C and a maximal temperature increase of 340°C have been measured. Thanks to the characterization of this mock-up, a 400 kWth demonstration plant is up to be developed at the THEMIS site.

Moreover, a high temperature energy storage module is developed, in order to protect the facilities while sudden variations of solar flux. As the solar flux is transient, a storage module is necessary to increase the thermal inertia of the absorber and to reduce the effect of the thermal shocks. A system using latent heat storage is designed, in order to limit the air outlet temperature decrease from 750°C to 600°C after 10 minutes without solar flux. Each absorber of each stage has to be protected by thermal storage modules. As we suppose that all absorbers of each stage have the same operating point, two kinds of storage modules have to be designed. Each of these two modules must be shaped as an extrusion of the absorber, and the storage volume must be the same for the two stages.

Two phase-change materials (PCM) have been selected, depending notably on the working temperature of the two stages of the absorber: a metallic alloy is used for the first stage and a molten salt is used for the second stage. A composite architecture, coupling a PCM and a highly-conductive copper matrix, is needed to increase the global thermal conductivity of the module, especially for the second stage. Though, several parameters, like PCM mass rate and matrix geometry have been optimized. A numerical parametric analysis was performed, in order to design two storage modules satisfying the requirements of the two stages.

High temperature thermal storage for concentrating solar power: Model and experimental results

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A thermal energy storage system, consisting of a packed bed of rocks as storing material and air as high-temperature heat transfer fluid, is analyzed for concentrated solar power (CSP) applications. A 6.5 MWh_{th} pilot-scale thermal storage unit immersed in the ground and of truncated conical shape is fabricated and experimentally demonstrated to generate thermoclines. A dynamic numerical heat transfer model is formulated for separate fluid and solid phases and variable thermo-physical properties, and validated with experimental results. The validated model is further applied to design and simulate a thermal storage unit of 6.6 GWh_{th} capacity during multiple 8hr-charging/16hr-discharging cycles, yielding 95% overall thermal efficiency.

TOPIC: 2^{nd} LINEAR FOCUS SYSTEMS

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 requirement of an uncertainty < 1 %. Optical efficiency is the combination of reflection and absorption losses at the glass envelope, reflection losses at the absorber coating, and geometrical loss at the bellows due to shading.
In the test bench the receiver is situated in the linear focus of the solar simulator, which is operated with 4 metal-halide-lamps of 4 kW_e each. Water runs through the receiver, cools the absorber to ambient temperature and thermal losses are negligible. The enthalpy increase of the water of ~ 6 kW in the receiver is determined through the measurement of volume flow (~ 0.85 m^3/h) and inlet and outlet temperatures (ΔT ~ 4 K). A spiral displacement body inside the receiver increases the heat transfer from absorber to water. The measured enthalpy increase 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 0.3 % (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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Three-dimensional optical and thermal numerical model of solar tubular receivers in parabolic trough concentrators

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Monte Carlo ray tracing, coupled to a finite volume solver, is used to model three-dimensional heat transfer in a parabolic trough solar concentrator system. An in-house ray tracing code is used to determine the non-uniform distribution of incident solar radiation and the radiative exchange between the various receiver surfaces and the atmosphere. Diffuse, specular and Fresnel surfaces together with absorbing media are used to model different radiative effects at the concentrator and the receiver. As opposed to the vast majority of conventional parabolic trough concentrator models that assume gray surfaces and opaque glass behavior in the infrared spectrum, this new model allows for the use of very detailed spectral emissivity and transmissivity data for the receiver and concentrator surfaces.

The results of the ray tracing are combined with a finite volume representation of the receiver to determine the heat gain/loss around the receiver's circumference and along the system's axis. The thermal performance is predicted using spectral data as well as gray surface assumptions and temperature correlations for the absorber tube emissivity found in literature. Both approaches are compared to experimental data of on-sun field tests and off-sun lab tests. The computed heat losses and thermal efficiencies agree well with experimental data. The use of spectral properties is expected to provide greater predictive power than the gray approach if accurate data is available. Besides the beneficial information on peak temperatures and heat flux, which can reach critical values at elevated temperatures, the new three-dimensional heat transfer model also has the potential to predict glass temperatures and the radiative behavior more accurately, as transmitted radiation is taken into account.

Measurement and modeling of parabolic trough mirror shape in different mirror angles

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The optical performance of concentrating solar collectors strongly depends on the shape accuracy of the mirrors reflecting the sunlight onto an absorber. Analyzing the gravity-induced change in mirror shape for different measurement positions is critical for performance calculation of concentrating solar power collectors and identifying optimization potential of the concentrator mirrors. This work presents measurement and finite element analyses results of single inner and outer reflector panels of EuroTrough parabolic trough collectors evaluated in different mirror angles.

At the deflectometric test bench in DLR's QUARZ Test and Qualification Center for CSP Technology mirror shape accuracy is determined for two different measurement setups: horizontal mirror position (mirror facing upward and the connecting lines of mounting pads horizontally aligned) and vertical mirror position (load-free mirror position, with mounting pads vertically aligned). In each setup measurements for two different mounting options are performed: mirror fixed via screws to a rigid laboratory support structure and mirror placed onto the support without fixation.
Two finite element model versions (stiff and elastic supports) for single inner and outer reflector panels have been developed. The software ANSYS Workbench is employed to model both mirror geometries and to simulate gravity-induced loading and deformation. In addition to the laboratory measurement positions, the model is used to evaluate 0°, 45° and 90° collector angle.

In order to evaluate the effect of gravity load on mirror shape, the deformed mirror in horizontal measurement position and in each evaluated angle for FEM analysis is compared to the non-deformed mirror shape. The resulting slope deviation from deformation reaches RMS values of 0.5-1.6 mrad which is the magnitude of mirror shape quality itself accomplished by state of the art mirror panels. Stiffer mounting support structure reduces the influence of gravity and consequential deformation significantly.

Low power cogeneration from concentrated solar energy

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The depletion of fossil resources and the continued increase in global energy needs will require a collection of solar energy ever more important. To succeed in transforming this energy, the concentration of solar radiation is particularly interesting. It allows, among other things, the production of electricity from heat at high temperature (> 250 °C) with the possibility of storage.
Several methods exist for solar concentration. Of these, one of the most mature technology is the concentration with parabolic trough mirrors. Since the late 1980s, it is commonly used, with installed capacity now exceeding 2 GW. These large projects (50 MW) currently use a Rankine thermodynamic cycle. To allow uninterrupted use of the turbine, a heat storage in the form of molten salt can be used.
On a smaller scale (a few kW), this method of concentration was also studied. Several manufacturers now offer systems using mirrors with an aperture of about 50 to 100 cm (exclusive production of heat).
In this work, it is necessary to rethink all the problems of current systems and transpose them to the miniature scale: boundary effects have a bigger impact on small systems. The manufacturing cost should also be controlled to satisfy a public demand. It is proposed to work on a solar concentrator for decentralized energy production with a geometric concentration factor of about 10 and an opening angle less than 50 cm. Under these thermal power available conditions and temperature level (about 150 °C), we have coupled an organic Rankine cycle to a Tesla turbine (patent filed in 1913) to generate mechanical energy (electric).
This turbine is original in its ability to circumvent the main drawbacks of conventional turbines. Tesla turbine, rated unconventional, uses smooth discs instead of blades. It is described mainly by the fluid flow on a disk from one speed, pressure or inlet flow.
The numerical results (solar flux density, temperature levels...) can provide guidance on the dimensioning of future prototypes. The experimental results confirm some findings (number of injectors, fluid injection angle ...) and provide food for thought. The goal is to show that it is possible to design a very small parabolic trough concentrator associated with a Tesla turbine, with no significantly reducing the energy efficiency (10 % electrical efficiency and 50% thermal efficiency) or increasing the overall cost of the installation. The solutions consider the optimization of the geometry and materials.

TOPIC: 2nd SOLAR FUELS

Two-step redox hydrogen production plant simulator tool

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The rise of the technologies related with the hydrogen has intensified the research of new ways of hydrogen production. Several thermochemical processes have been developed using concentrated solar energy as the primary energy source. One of the most promising techniques is two-step redox water splitting. In this framework, Hydrosol II Project pilot plant was erected at CIEMAT - Plataforma Solar de Almería with the aim of producing quasi-continuous solar hydrogen from water using a ferrite-based redox technology. In the above mentioned two-step procedure, two different reactions occur, oxidation and reduction and two different amounts of power are required. Two reactors allow the two different reactions be performed in parallel, which, sequentially switched, make hydrogen production quasi-continuous.
A new dynamic model of a solar hydrogen production plant has been developed based on experience with this pilot plant. The model developed under the object-oriented technology of Modelica was designed as a control algorithm test platform. For practical control issues, some simplifications have been assumed to make the model suitable but this accuracy reduction has brought a necessary computational effort reduction. The new model includes both a solar field model and a processing plant model and is able to simulate the concentrated solar power received by the reactors and the thermal and chemical reactor behaviour. The model was calibrated and validated with experimental data and the numerical predictions show good agreement with measurement data.

Solar-driven steam gasification of sugarcane bagasse

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The thermochemical conversion of bagasse, a sugarcane residue, to chemical energy carriers offers an attractive alternative to the limited current usage of this valuable resource. At high temperatures and in the presence of steam, bagasse undergoes steam gasification yielding syngas (mainly H_2 + CO), which can be used to produce liquid fuels e.g. through the Fischer-Tropsch process. The steam gasification is a strongly endothermic process that is traditionally driven by combusting 30-40% of the feedstock [1, 2]. Solar-driven gasification, in contrast, uses concentrated solar radiation as the source of high-temperature process heat to drive the gasification. Thus, solar energy in an amount equal to the enthalpy change of the endothermic reactions is chemically stored, which leads to a syngas with higher calorific content per unit of feedstock. A thermodynamic analysis revealed that bagasse can be upgraded to a product gas with up to 36% higher energy content. Since no internal combustion contaminates the syngas, it is of higher quality with lower CO_2/CO and higher H_2/CO ratios.

In a thermogravimetric analysis reaction rates for the gasification of fast-pyrolyzed bagasse char were measured and a rate law based on the oxygen exchange mechanism was formulated. The residence time required for high conversion of the feedstock lead to the design of a laboratory-scale electrically heated downdraft gasifier that combines drop-tube and fixed-bed concepts. Experimental runs in a temperature range 1073-1573 K yielded high-quality syngas of molar ratios H_2/CO = 1.6 and CO_2/CO = 0.31, and with heating values of 15.3-16.9 MJ/kg, resulting in an upgrade factor (ratio of heating value of syngas produced over that of the feedstock) of 105 %.

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Solar fuels production from thermochemical cycles: kinetic study of the solar reduction of metal oxides

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The production of solar fuels has been rising much interest in the last decade. Through the use of redox thermochemical cycles based on metal oxides, the potential of the solar production of H_2 from water dissociation has been proven. In addition, the possibility of using the same concept to turn water and carbon dioxide into syngas has been demonstrated. These cycles are composed of two steps, the first, endothermic, is the reduction under concentrated solar power of a metal oxide with O_2 release. The second, exothermic, is the reaction between the reduced metal oxide and water/carbon dioxide, leading to H_2/CO production and the regeneration of the metal oxide.
The benefits of such a process are varied. Among them, the combined reduction of CO_2 and H_2O would bring a mix of CO and H_2, the syngas, which is a chemical precursor much used in chemical industry, more particularly to produce liquid fuels by using the Fischer-Tropsch process. This may open a way toward the efficient storage of sun power as chemical fuels, partly solving the two major problems of fossil fuel dependence and the ever rising CO_2 atmospheric concentration.
The solar reduction of metals oxides has been widely investigated, in particular for volatile ZnO and SnO_2 oxides. Of major importance is the kinetics of the reaction, which determines the viability of any large-scale implementation. Based on previous results obtained in a lab-scale solar reactor devoted to the thermal dissociation of volatile oxides, the kinetics of ZnO and SnO_2 solar reduction have been studied with much attention based on different reactor model approaches, in order to establish a reproducible method that can be used to compare the reaction kinetics for various metal oxides.

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