SOLLAB
ALLIANCE of EUROPEAN LABORATORIES
on solar thermal concentrating systems

SFERA

12th SOLLAB Doctoral Colloquium

Rodalquilar, AlmerÍa, Spain, June 6-8,2016

BOOK OF ABSTRACTS

12th SOLLAB Doctoral Colloquium

6-8th June, 2016, Rodalquilar, Almería, Spain

Organizing committee:

María Castro Alférez (Plataforma Solar de Almería CIEMAT)

Alejandro García Segura (Plataforma Solar de Almería CIEMAT)

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Sixto Malato Rodríguez (Plataforma Solar de Almería CIEMAT)

Foreword

Dear colleagues,

Welcome to 12th SOLLAB Doctoral Colloquium.

The Colloquium is the key annual event of the European Alliance SolLab, alliance of Laboratories for Research and Technology on Solar Concentrating Systems. Members are: PROMES (Processes, Materials and Solar Energy Laboratory) of Centre National de la Recherche Scientifique, France; Solar Research Division of Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Germany; Plataforma Solar de Almería of Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Spain; Solar Technology Laboratory of Paul Scherrer Institut (PSI) and Professorship in Renewable Energy Carriers of ETH Zurich, Switzerland. On behalf of PSA team we would like to welcome you to 12th SOLLAB Doctoral Colloquium in Rodalquilar, Almería.

The event is being held June 6 – 8 at the "Hotel de la Naturaleza Rodalquilar". This year we are being hosted by PSA team. They are excited to host the SolLab after 4 years and are prepared to make this a rewarding and memorable experience for each of you. Throughout the three days there will be rich programming, targeted matchmaking and an abundance of networking opportunities. We will learn about 31 doctoral theses focused on: Measurements, Characterization & Materials; Desalination and Solar Photochemistry; Solar Thermochemistry; Linear Focusing Systems; Thermal Energy Storage; Central Receiver Systems. Even so, the success depends on how well you take responsibility not only for your own presentations, but taking initiative to ask to the other speakers. We want you to be successful and we will do all that we can to ensure that you are successful – but you must do your part as well.

We acknowledge the financial support of EU 7thFP through the project SFERA2 (http://sfera2.sollab.eu/). If you have any questions or concerns you can contact Dr. Isabel Oller or me. I am personally thankful to Alejandro García and María Castro for the competent organization of this event. And the team of PSA for supporting them.

I'd like to personally welcome each of you to the 12th SOLLAB Doctoral Colloquium. Let's work together to make this the best year ever!

Sixto Malato Rodríguez
Director
CIEMAT-Plataforma Solar de Almería (www.psa.es)

Program 12th SOLLAB Doctoral Colloquium

MONDAY, 6th June 2016

9:00-9:10	Welcome		
	SOLAR THERMOCHEMISTRY		
9:10-9:30	Particles reactor based on the fluidized bed configuration	Lucia Arribas	IMDEA
9:30-9:50	Mechanism of carbothermic reduction of magnesium oxide	Adrian Coray	ETH
9:50-10:05	High-efficiency CSP plants based on thermo-electro-chemical conversion devices	Elena Díaz	IMDEA
10:05-10:20	Analyzing nonstoichiometric redox materials for solar thermochemical gas splitting	Marie Hoes	ETH
10:20-10:40	In situ thermo-mechanical diagnostics of materials subjected to high solar flux: Test device development	Yasmine Lalau	PROMES
10:40-11:10	**COFFEE BREAK**		
11:10-11:25	Product distribution from solar pyrolysis of agricultural and forestry biomass residues	Rui Li	PROMES
11:25-11:40	Experimental and theoretical assessment of a solar thermal calcination reactor	Gkiokchan Moumin	DLR
11:40-12:00	A pressurized high-flux solar reactor for the thermochemical gasification of carbonaceous feedstock	Fabian Müller	ETH
12:00-12:15	Calcination of CaCO3 using Continuous Fluidized Bed Solar Reactors	Inma Perez	PROMES
12:15-12:30	Particle mix reactor for reduction of redox materials in solar thermochemical water splitting	Sebastian Richter	DLR
12:30-12:45	Solar thermochemical splitting of CO2 via isothermal redox cycling	Maria Tou	ETH
13:00	**LUNCH**		
	DESALINATION AND SOLAR PHOTOCHEMISTRY		
14:30-14:45	Modeling, optimization and control for efficient management of resources in solar desalination processes	Jose Carballo	PSA
14:45-15:05	Mechanistic modelling solar water disinfection based on intracellular ROS generation and influence of solar mild heat	María Castro	PSA
15:05-15:20	Solar photochemical and photocatalytic processes for fresh-cut industry wastewater treatment and reuse	L. Samira Nahim	PSA
15:20-15:35	Integration of photochemical solar processes with others advanced techniques and elimination of the contaminants emerging concern in the landfill leachate treatment	Ana Ruiz	PSA
18:00	**KAYAK**		

TUESDAY, 7th June 2016

MEASUREMENTS, CHARACTERIZATION & MATERIALS			
09:30-09:50	Backward-gazing method for measuring heliostats optical errors	Mathieu Coquand	PROMES
09:50-10:10	Analysis of solar reflectors behavior under special environments affected by highly corrosive pollutants	Alejandro García	PSA
10:10-10:30	Coatings optimization for solar receiver tubes using modified solar spectrums	Antoine Grosjean	PROMES
10:30-10:50	Flux density measurement for industrial-scale solar power towers	Matthias Offergeld	DLR
10:50-11:30	COFFEE BREAK		
11:30-11:50	Airborne optical characterization of parabolic trough collector fields	Christoph Prahl	DLR
11:50-12:10	Erosion of mirrors in desert environments	Florian Wiesinger	DLR
12:10-12:30	Atmospheric Extinction of Solar Radiation in PSA. Application to Solar Thermal Electric Plants	Maria Elena Carra	PSA
12:30-12:45	Development and benchmarking of All Sky Imager derived DNI nowcasts	Pascal Kuhn	DLR
13:00	LUNCH		

LINEAR FOCUSING SYSTEMS			
14:30-14:45	Modelling of innovative heat transfer fluids used in solar receiver tubes	Rafael Aguilar	PSA
14:45-15:05	Experimental and Numerical Investigation of a Pilot Parabolic Trough Power Plant Including a Thermocline Thermal Energy Storage	Thomas Fasquelle	PROMES
15:05-15:20	Optimizing design of a Linear Fresnel Reflector for process heat supply	Diego Pulido	PSA
21:00	GALA DINNER		

WEDNESDAY, 8th June 2016

THERMAL ENERGY STORAGE			
11:00-11:20	Solar thermochemical energy storage via solid-gas redox reactions	Laurie André	PROMES
11:20-11:40	Thermal Energy Storage Materials Made Of Natural And Recycled Resources For CSP In West Africa	Eric S. Kenda Nitedem	PROMES

CENTRAL RECEIVER SYSTEMS			
11:40-11:55	Simulation and optimization of Solar Tower plant receivers	Peter Schöttl	ETH
11:55-12:15	Experimental analysis of the forced convective heat loss from cavities of multi-MW scale solar central receiver systems	Silvan Siegrist	DLR
12:15-12:35	Experimental investigation of heat transfer in a directly irradiated ceria particle bed under vacuum conditions	Johannes Grobbel	DLR
13:00	LUNCH		

Particles reactor based on the fluidized bed configuration

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The fluidized bed is developed by passing a fluid through a bed of solid particles to promote their motion, until the heterogeneous medium acquires the macroscopic properties of a fluid. When the carrier is a gas, the behavior of the bed is similar to the boiling of a liquid. The quality of fluidization is determined by: particle sizes, density and distribution, type of particles (Geldart classification), gas density and bed geometry. The movement causes a great contact between solid particles and fluid related with higher heat and mass transfers [1]. Thus, a fluidized bed configuration represents a good alternative for high temperature solar applications, such as, chemical reactions or thermochemical processes. In the case of a directly irradiated fluidized bed, by transparent walls or windows, the direct absorption of solar energy permits higher operating temperatures, hence availability of high-grade thermal energy [2].

The aim of this work was to study the fluidization conditions as a function of temperature, room and high temperatures, in a fluidized bed reactor directly irradiated by a high flux solar simulator (7 kWe).

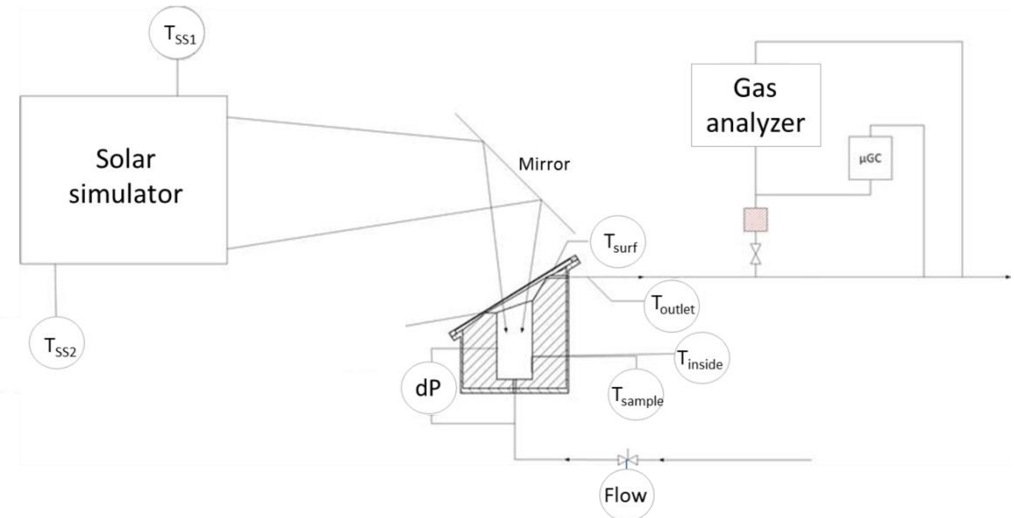

Figure 1. Schematic representation of solar simulator setup

Thermal characterization of the reactor was carried out using silicon carbide as inert material. Cold measurements were made using alumina and silicon carbide fluidized in two different tubes (33 mm and 80 mm of inside diameters), obtaining the minimum fluidization flow of each material. These results were compared with high temperature studies (800 – 1000 ºC) that were developed with silicon carbide particles.

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[1] P. Lettieri, D. Macri, *Effect of Process Conditions on Fluidization*, KONA Powder and Particle Journal, 2016, 33, 86-108

[2] C. Tregambi, R. Chirone, F. Montagnaro, *Heat transfer in directly irradiated fluidized beds*, Solar Energy, 2016, 129, 85-100

Mechanism of carbothermic reduction of magnesium oxide

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Magnesium (Mg) has been considered as an attractive substitute for the 50% denser aluminum (Al) to lightweight vehicles and reduce their fuel consumption [1]. It is commercially produced mainly by the so-called Pidgeon process, which is based on the reduction of magnesium oxide (MgO) with ferrosilicon (FeSi) [1]. Compared to the process for making Al, this process, however, consumes as much as two times more energy (354 versus 177 MJ/kg) and releases three times more CO_2 (42 versus 14.6 kg CO_{2eq}/kg) [2, 3]. Therefore, in order to gain an efficiency benefit by lightweighting, the embedded energy content in Mg must be reduced. One way to accomplish this is to replace the reductant FeSi with carbon (C) because the production of FeSi alone is responsible for 32% of the total energy consumption and 24% of the total carbon footprint by the Pidgeon process [3]. However, the reduction of MgO with C requires almost twice the energy needed for the reduction with FeSi (24.7 versus 13.6 MJ/kg Mg) [4]. Whether the production of Mg with C as reductant is less energy-intensive than with FeSi is therefore mainly dependent on the energy conversion efficiency of the MgO reduction process step. First estimations show that efficiencies of 7% and 30% would be sufficient to outperform the Pidgeon and the commercial Al production processes, respectively. In terms of CO_2 emissions, the production of Mg using C would outperform the aluminum production only if a renewable energy source like solar energy is used to provide the heat for the reduction.

As the first step towards a successful development of the carbothermic MgO reduction process, the reaction mechanism was elucidated. It was assumed that the overall reduction reaction proceeds through the formation of a gaseous intermediate on the MgO surface (either O_2 or CO_2) that diffuses to the carbon surface where it is consumed. By increasing the partial pressure of a tested gaseous intermediate above its equilibrium pressure and evaluating its effect on the kinetics of the reduction of MgO, it can be determined whether the tested intermediate is participating in the reaction mechanism or not. As an increase in O_2(g) partial pressure suppresses the reduction rate, it has been concluded that the mechanism of carbothermic MgO reduction is dominated by a dissociation of MgO into Mg(g) and O_2(g), followed by the consumption of O_2(g) in the reaction with C that produces CO(g).

References:

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High-efficiency CSP plants based on thermo-electro-chemical conversion devices

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Concentrating solar power is one of the best options for renewable electricity generation because of its dispatching capability due to thermal storage. Nevertheless, current conversion efficiency of CSP plants is lower than 20% and production cost must be reduced in order to be competitive with other renewable power sources. Significant research have been performed on collectors and receptor design, new heat transfer fluids, thermal storage or even advanced thermodynamic cycles with efficiency increment and cost reduction as main drivers [1].

This work aims at evaluating various CSP flow diagrams in which the power block is replaced by an electrochemical system (battery) (Figure 2). The receiver acts as a reactor where the discharging product from the battery decomposes thermally. Therefore, energy losses and investment cost of the power block would be avoided; the integration in the grid would be improved due to higher operational flexibility; efficiency would be independent of power load and the large amount of refrigeration water would be mostly eliminated.

Various batteries and reactants are proposed. Metal air batteries have garnered much attention recently as a possible alternative due to their extremely high electric energy density compared to that of other rechargeable batteries [2]. Thus the performance of Zn/O and Mg/O batteries have been analyzed with different reduction approaches. Also Na/S batteries, which use liquid sodium and sulfur as the anolyte and catholyte, are described [3] along with one and two steps solar reduction reactor.

Thermodynamic calculations together with mass/energy balances have been conducted to estimate the systems's solar-to-electricity efficiency and carry out a comparative assessment. Results show that the proposed concept has great potential to improve CSP functionality.

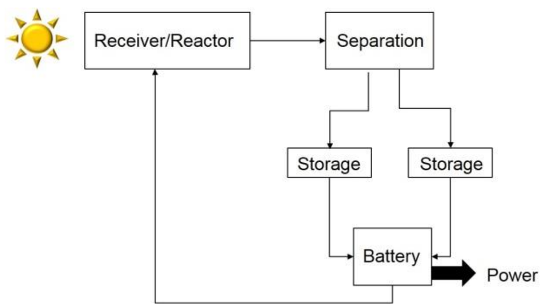

Figure 2: System layout

References:

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Analyzing nonstoichiometric redox materials for solar thermochemical gas splitting

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Solar-driven thermochemical redox cycles utilizing nonstoichiometric metal oxides are a promising way to split H_2O and CO_2 to produce H_2 and CO (syngas), a precursor for the synthesis of liquid fuels. The choice of the redox material is crucial for the effective operation of the process. Reduction temperature, the temperature difference between reduction and oxidation as well as the reduction extent greatly influence the efficiency and the design of the reactor. By identifying the thermodynamic characteristics of the redox material, these properties can be predicted. Another important aspect is the material's long term stability to ensure a steady operation. The aim of this future study is to find suitable metal oxides for solar thermochemical gas splitting, by conducting a rigorous material analysis.

In a first step, a density functional theory analysis will be realized and promising materials will be determined. These will then be synthesized and their structure will be analyzed by X-ray diffraction and scanning electron microscopy to ensure the desired composition. Oxygen nonstoichiometry will be measured by thermogravimetric analysis [1]. The reduction under several oxygen partial pressures and oxidation under CO_2 and H_2O atmosphere will be investigated. A defect model, evaluated with the experimental results, will be used to describe oxygen nonstoichiometry as a function of temperature and oxygen partial pressure. The thermodynamic properties, namely the partial molar enthalpy, entropy and Gibbs free energy will be extracted. Finally, long term stability of the metal oxides will be investigated by conducting cycling experiments under H_2O and CO_2 oxidation atmosphere. Possible segregation of the material will be examined by scanning electron microscopy and energy dispersive spectroscopy. Based on the results of this analysis, the studied redox materials will be compared with regard to their use in solar thermochemical reactors.

References:

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In situ thermo-mechanical diagnostics of materials subjected to high solar flux: Test device development

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A better evaluation of materials behaviour in Concentrated Solar Power (CSP) plants, such as high temperature steels or ceramics, will help to develop higher performance materials for more efficient processes [1] [2]. This knowledge will also lead to better operating cost estimations for innovative CSP plants such as towers with pressurized air turbines. In order to assess the mechanical suitability and the lifetime of the CSP key components such as solar receivers, it is essential to know their ability to sustain mechanical stresses induced by a high spatio-temporal temperature variation.

Moreover, the investigation of the thermo-mechanical behaviour under concentrated solar irradiation, especially when it is in-situ and non-destructive, is a difficult task that has been rarely done [3]. Therefore, the final aim of this work is to define and experimentally validate new methodologies for a comparative evaluation of high temperature CSP receiver materials ability to sustain cyclic thermal gradients. A solar facility test device will be developed to allow crack monitoring and localisation by acoustic emission techniques and kinematic field measurement by digital image correlation method.

In this communication, the preliminary work based on numerical modelling for measurement feasibility, fixture design, and material behaviour prediction will be presented. The modelling for strain and temperature field prediction use code ASTER and measured temperature dependent properties of SiC and Inconel 625. First validation tests will also be presented.

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Product distribution from solar pyrolysis of agricultural and forestry biomass residues

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Pyrolysis is one of the most attractive process to convert biomass to bio-gas, bio-oil and bio-char. Utilization of concentrated solar energy as a heat source for the pyrolysis reactions increases the energy conversion efficiency and reduces the pollution discharge [1].

In this study, solar pyrolysis of different types of agricultural biomass (grape stalk, grape marc, pine sawdust and peach pit) has been conducted in a lab-scale solar reactor. The effects of final temperature, heating rate and feedstock variety on product distribution are investigated. Powders of biomass were compressed to cylinders with 10mm diameter and 5mm height for the experiments. The studied experimental parameters are: reaction temperature from 800°C to 2000°C, heating rate from 10°C/s to 150°C/s with a constant sweep gas flow rate of 6NL/min.

The experimental results show the same tendency of product distribution versus final temperature and heating rate with varieties of biomass. The gas yield generally increases with the temperature and heating rate. The maximal gas yield was 63.5wt% obtained with pine sawdust at 2000°C and 50°C/s.

Besides, the gas product compositions for different types of biomass are different. For example, the $\mathbf{H_2/CO}$ ratios versus final temperatures are totally different as shown in Fig1. The pyrolysis characteristics of different kinds of biomass can be explained with their chemical properties (composition and constituents). The energy upgrade efficiencies from different types of biomass are also reported in this study.

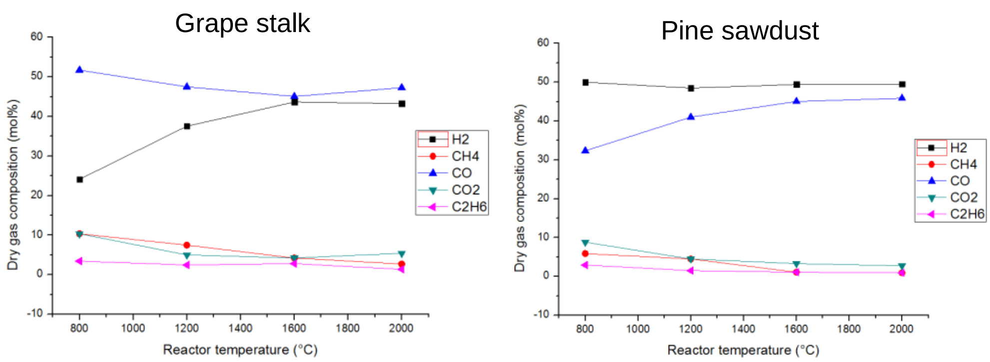

Figure 1. Dry gas compositions of pyrolysis gas product from different biomass with heating rate of 50°C/s.

References

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Experimental and theoretical assessment of a solar thermal calcination reactor

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Cement is the main ingredient of concrete, which itself is the second-most used commodity after water. The main energy consuming step for cement production is the calcination, through which $CaCO_3$ is thermally decomposed to CaO and CO_2. Due to this, cement plants are responsible for 5 % of current anthropogenic CO_2-emissions. Substituting the fossil fuels with solar energy would lower this emission by two percentage points. Additionally, the demand for cement is expected to grow further, thus realizing a solar process is getting more and more important [1].

The European project SOLPART aims to develop a solar process for particle treatment in non-metallic minerals' industries. Several reactor designs for solar calcination of CaCO3 – including a fluidized bed, cyclone reactor and rotary kiln [2-4] – have been suggested in the literature. The present work is focused on designing and manufacturing a new reactor for such processes and especially the cement industry. The reactor will be designed for process temperatures up to 1000 °C and it will be combined with a storage for an all-day operation. Since the processed powder is in the size of few µm, dusting and particle deposition are major challenges. The new approach will specifically address these challenges and at the same time aim at high solar-to-chemical efficiency.

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A pressurized high-flux solar reactor for the thermochemical gasification of carbonaceous feedstock

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We report on the design and experimental demonstration of a 3 kW solar gasification reactor for thermochemically converting carbonaceous materials to high-quality syngas [1,2]. It uses a windowless SiC cavity to efficiently absorb and transfer concentrated solar radiation to an annular gas-particle vortex flow created by injecting tangentially a charcoal-water slurry at high pressures. Experiments were carried out in a high-flux solar simulator under an average solar concentration ratio equivalent to 3720 suns. For slurry feeding rates in the range 0.42 – 1.26 g/min, H_2O:C molar ratios in the range 1.47 – 1.98, and absolute reactor pressures in the range 1 – 6 bar, the nominal reactor temperature ranged between 1009 and 1273 °C yielding carbon conversion up to 94 % within residence times of less than 4 seconds. The solar-to-fuel energy conversion efficiency, defined as the ratio of the heating value of the syngas produced to the solar radiative energy input and the heating value of the slurry converted, reached 19 %, while the energy content of the feedstock was solar upgraded by 34 %.

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Calcination of $CaCO_3$ using Continuous Fluidized Bed Solar Reactors

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Lime and cement production are energy intensive process. Cement industry is responsible of the 5% of the CO_2 global emissions [1]. CO_2 is released in the classical production process both from the raw material decomposition and from the energy generation by combustion that is necessary for the process. Thus replacing combustion by solar heat results in both fossil energy and CO_2 emission reduction. The first studies aiming to process reactive particles in solar reactors started in the early 1980s, the direct absorption fluidized bed proposed by Flamant et al. [2], achieved conversion up to 80% in batch operation. Then Meier et al. [3] proposed an indirect heating 10 kWth solar multi-tube rotary kiln for continuous operation.

SOLPART [4] project integrate 11 partners from different countries. The project aims at supplying totally or partially the thermal energy requirement for $CaCO_3$ calcination by high temperature solar heat thus reducing the life cycle environmental impacts of the process and increasing the attractiveness of renewable heating technologies in process industries. As a first stage, various innovative solar lab-scale reactor concepts based on fluidized bed or moving bed and rotary kiln are going to be tested at *PROMES-CNRS Laboratory* and *DLR, Institute for Solar Research* respectively. Secondly, one of the lab-scale reactors concepts is going to be chosen to be developed at pilot scale.

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[4] http://www.solpart-project.eu/.

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Particle mix reactor for reduction of redox materials in solar thermochemical water splitting

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Due to high theoretical efficiencies thermochemical redox cycles are attractive potential processes for the production of hydrogen by means of solar radiation. Special research interest concerns two-step cycles using metal oxides, especially ceria, being alternately oxidized and reduced.

In the present work the redox material is considered in a particulate form. On the one hand, this approach appears to be advantageous with respect to heat recovery [1], scalability and mechanical stability. On the other hand the use of particles enables the decoupling of the process steps – absorption of solar radiation, thermal reduction, heat recovery and oxidation – which proceed on different time scales. This is an important measure to tackle the challenging process requirements due to temperatures well above 1000 °C as well as low oxygen partial pressures [2].

Herein the focus is on the spatial and temporal decoupling of solar absorption and thermal reduction. It is conceptually realized by the introduction of an additional cycle of inert absorption particles. These particles absorb concentrated solar radiation in a particle receiver and are mixed with redox particles in the reduction reactor, to which they transfer heat and thus sustain the reaction.

An analysis of this indirect, particle-based concept has shown that despite the additional heat exchange step its solar-to-fuel efficiencies differ insignificantly from the efficiencies expected for direct irradiation concepts [2,3].

Focus of the presented work is the development, demonstration and experimental analysis of the indirect particle mix reduction reactor. This reactor is based on a binary particle mixture including the associated components – mixing unit, separation unit, conveying and measuring facilities. Design aspects and process requirements of the reactor under the prevailing conditions will be discussed and a first draft of the reactor design is introduced.

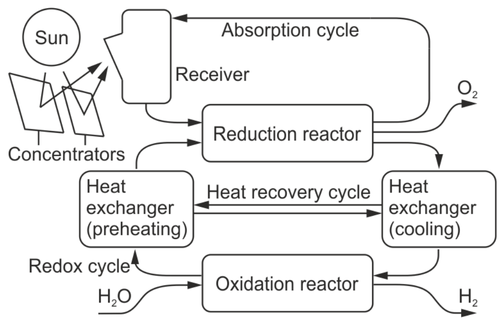

Figure 3: Scheme of the indirect process

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Solar thermochemical splitting of CO_2 via isothermal redox cycling

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Solar-driven splitting of CO_2 and H_2O to produce CO, H_2 (syngas) and O_2 is performed via thermochemical redox cycling. Ceria is selected as the redox material because of its fast reaction kinetics and crystallographic stability. This work investigates the thermodynamic limits of isothermal redox cycling as a function of temperature and pressure. A novel solar reactor concept is presented and used to experimentally demonstrate the isothermal production of CO and O_2 from CO_2 under simulated concentrated solar radiation.

Modeling, optimization and control for efficient management of resources in solar desalination processes

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Shortage of fresh water resources, salinization and contamination of the sources are some of the major problems to be tackled by humanity. Currently one of the main technologies used for desalination is thermal distillation. However, these techniques are considered energy inefficient, therefore the main goal of this work is to optimize such processes. The first work carried out is related to the optimization of the operating conditions of a Multi-Effect Distillation unit (MED) at Plataforma Solar de Almería (PSA), for this work a dynamic model of this facility has been used [1][2]. A paper related to this work is going to be presented at the Desalination for de Environment: Clean Water and Energy (EDS) conference, in where operating conditions of the MED unit have been optimized considering energetic and distillate production criteria [3].

Ongoing work includes the validation of the previous results through an experimental test campaign in the facility, analysis and optimization of the MED operating conditions plant attending to exergetic and economic criteria, coupling of the MED model with a double-effect heat pump (DEAHP) model [4], modeling of the gas boiler and the solar parabolic trough collectors field (NEP field), modeling and simulation of an adsorption system to vary the sea water temperature and finally a complete system optimization and validation attending to energy, exergy and economic criteria, see fig 1 for an overview of the whole system fig1.

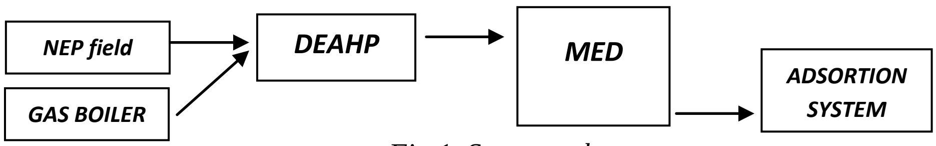

Fig 1. System *scheme*

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Mechanistic modelling solar water disinfection based on intracellular ROS generation and influence of solar mild heat

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Solar water disinfection (SODIS) is a household technique recommended for use in areas with difficulties to access to safe drinking water. Applying SODIS method to contaminated water containing pathogens, a reduction of the microbial load is reached. This simple process consists on the exposure of transparent containers full with contaminated water to direct sunlight during at least 6 hours. Temperature is a very important factor in this process, at certain values above 45 ºC microbial inactivation runs faster, which is attributed to a synergetic effect between temperature and solar UVA radiation. The beneficial effect of high temperatures to SODIS is well known and reported in literature [1].

This work is the first attempt to model the effect of temperature on pathogen inactivation by SODIS, it is specifically proposed for *E. coli* bacterium inactivation. The presented model considers that bacterial inactivation under solar irradiation is the result of an accumulation of lethal and sub-lethal damages to different targets inside the cells generated by intracellular Reactive Oxygen Species (ROS). ROS formation is promoted by UVA photons action and by thermal effect. Also, the bacterial natural defense mechanisms to regulate internal ROS excess are affected during solar disinfection process. These are mainly catalase (CAT) and superoxide dismutase (SOD), two enzymes that act against oxidative stress, decomposing some of the intracellular ROS formed. Nevertheless, these enzymes are inactivated under solar radiation and mild-high temperatures during SODIS process. This model will predict bacterial inactivation profile under solar radiation at different irradiance intensity and temperature values.

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Solar photochemical and photocatalytic processes for fresh-cut industry wastewater treatment and reuse

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Over the past 20 years, the consumer demand for healthy and fresh foods has increased, stimulating rapid development of the so-called fresh-cut produce industry. This industry is one of the major water consumers, due to the huge use of potable water to perform washing operations required to guarantee the safety and quality of the product. Fresh-cut products are marketed as ‘‘ready-to-eat’’ with the absence of a sterilization or pasteurization step, thus the washing process has become a critical process in the preparation [1, 2].

Washing water in this industry is characterized by high values of chemical oxygen demand, traces of chemical pollutants (e.g. pesticides) and the presence of pathogens like *Escherichia coli* O157:H7 and *Salmonella* spp, which becomes a problem for water reuse purposes. Commercial operations usually use disinfectants as chlorine during wash processes to increase the rate of microbial reduction and to prevent the potential cross-contamination in the fresh end-product. However, this disinfectant has been identified as a concern mainly due to public health issues because can produce unhealthy by-products including carcinogenic and mutagenic chlorinated compounds [3]. Therefore, search for alternative methods of disinfection and decontamination of wash waters from the fresh-cut industry is a current challenge to avoid the use of chlorination as well as to improve the efficiency of the use of water resource by the integration of washing-reuse processes.

This contribution presents different photochemical (solar only and H_2O_2/solar) and photocatalytic (photo-Fenton) processes for the treatment of wash waters from the fresh-cut industry to ensure removal of pathogenic *E. coli* O157:H7 and *Salmonella enteritidis* and traces of a cocktail of pesticides. Furthermore, reuse of treated wash water will be experimentally assessed by in vivo irrigation test in a 30m^2 experimental crop-camera, investigating the uptake of pesticides and transfer bacteria to several crops commonly raw-eat.

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Integration of photochemical solar processes with others advanced techniques and elimination of the contaminants emerging concern in the landfill leachate treatment

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Treatment of urban and industrial wastewaters must meet the requirements of increasingly stronger regulations. The regular presence of micropollutants (MC) has been demonstrated in thousands of publications in recent years and therefore there is an emerging concern on this issue. These MC are pesticides, industrial compounds, steroids, antibiotics, drugs, etc. which origin is usually urban water, hospital, industrial wastewater, landfill leachate, aquaculture, livestock and agricultural runoff.

The objective of this work is the application of efficient technologies for removal of contaminants of emerging concern, listed in 2013/39/EC Directive or significant risk substances according to 2008/105/EC Directive. For this objective, it is carried out a physicochemical pre-treatment stage for reducing not only suspended solids but also color and turbidity, and after, an advanced chemical oxidation step based on solar photo-Fenton process or ozonation (O_3/OH^-, O_3/H_2O_2 with and without solar radiation) will be studied. The effect of using a nanofiltration system in the treatment line for improving the effluent quality will be assessed, evaluating different commercial membranes, treatment of the proceeds from the membrane system, etc.

With this aim, this work will be complemented with the study of mild photo-Fenton process using natural organics present in some industrial wastewater, taking advantage of the humic like substances (HLS) ability may have them to increase the solubility of contaminants and stabilize iron in solution favoring the process. Results obtained applying photo-Fenton process for the removal of MC with HLS addition as additives will be compared with results acquired adding real complex wastewater, such as landfill leachate like a tertiary treatment catalyst; focusing in its recovery considering waste valorization is a key topic.

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Backward-gazing method for measuring heliostats optical errors

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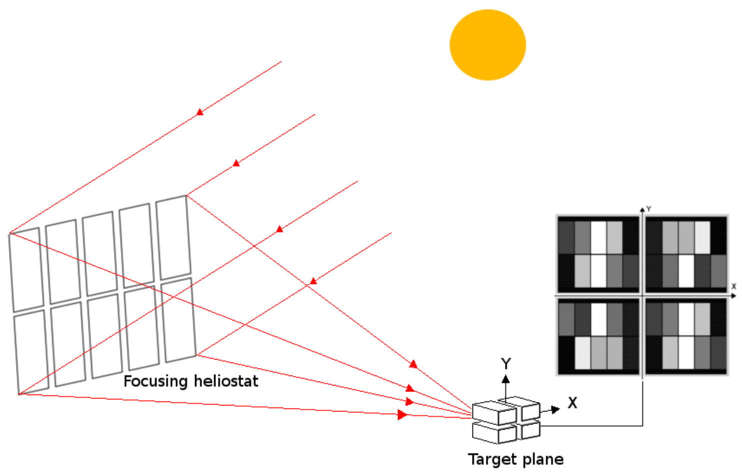
The conversion of sunlight into electricity is one of the most promising way for the production of green energy in the future. A typical solar tower power plants includes a thermal receiver located at the top of a hundred meters tower and a field of several thousand of heliostats. The pointing and canting accuracies and the surface shape of the solar concentrators have a great influence on the solar power plant efficiency. One of the challenge that has to be solved in such a plant to reduce the time and the efforts devoted to adjust the different mirrors of the faceted heliostats, which could take several months on an industrial size plant if the current state-of-the-art method is used. Thus, a method which would permit to adjust quickly all the heliostats of a plant is essential for the deployment of concentrated solar power.

We propose a new method to determine heliostats optical errors in solar tower power plants. The purpose of this method is to characterize the errors of the concentrating surface by calculating the slopes and wavefront errors of the heliostats using cameras located near the receiver plane.

The principle will be briefly exposed, followed by modeling and simulation results.



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Analysis of solar reflectors behavior under special environments affected by highly corrosive pollutants

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Solar Thermal Electricity (STE) plants are frequently located near industrial facilities to provide electricity or process heat [1]. These sites may be affected by corrosive gases and other air pollutants that can seriously degrade the surface of solar reflectors. This work is focused on the durability analysis of solar reflectors in corrosive atmospheres, which is a key issue to be considered in the selection of mirror and site candidates in order to meet the economic feasibility.

Three reflector materials have been selected; silvered glass-based reflector type 1, silvered glass-based reflector type 2, and aluminum-based reflector. Each one is a representative candidate of present-day existing technologies. These types of reflectors are to be exposed both at targeted outdoor sites and in accelerated aging tests. On one hand, several standardized norms have been chosen to simulate the behavior of reflectors in a wide variety of aggressive industrial areas in a realistic way [2, 3]. They combine a number of environmental parameters, such as temperature, relative humidity, time, and controlled concentrations of the most prevalent air pollutants. Given that these standards were not originally designed for solar reflectors, the suitability of their testing conditions is to be proved, being time one of the most limiting variables in the process. On the other hand, outdoor experiments are as important as indoor ones. They will inform about the real corrosion mechanisms happening in different environments and will be a reference to validate the selected accelerated testing conditions. Therefore, representative outdoor sites have been targeted and collaborative agreements with private companies and institutions are being established to promote outdoor exposures.

Microscopic and chemical characterizations of the weathered materials are being performed after the testing campaigns. For instance, changes in microscopic inspections and in reflectance measurements reveal the degree of deterioration of the samples after the tests and the role that the corrosive gases may have had in the process. This way, conclusions about the selection of the best reflector candidates under certain environmental conditions, their lifetime estimations and the most suitable, reproducible accelerated test program will be drawn.

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Coatings optimization for solar receiver tubes using modified solar spectrums

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Solar receiver tubes, a key element for CSP, are made of one glass tube which requires an antireflective coating and one receiver metallic tube which requires a selective coating. We propose to study the optimization of these two different coatings using solar spectrums modified by reflection, transmission or atmospheric conditions. Conventionally the ASTM G173-03 solar spectrum is used to calculate the solar transmissivity or absorptivity of each surface, independently of their position in the solar captor [1]. In reality the solar spectrum is modified by every interface met before the absorber. In the case of CSP we can note at least one mirror reflectivity and one glass transmission. In order to express the optical efficiency of the concentrating device as a single value, we focus our attention on the actual solar spectrum received by each surface requiring a coating. This approach allows another calculation of the captor efficiency, the solar transmittance or the solar absorptance. Using numerical calculation on Scilab it is possible to optimize the coating parameters (thickness and inclusion rate for example) in order to found the higher solar efficiency. SMARTS software proposed by Gueymard [2] is used for solar spectrum generation for the study of the impact of atmospheric conditions on coatings optimization.

As an example, porous SiO_2 has been identified as a good material for solar antireflection coating in many studies [3]. We propose an antireflective coating for BK7 glass for solar spectrums modified by silver or aluminum reflection. The results show that antireflective coatings dedicated for solar spectrums reflected by a silver mirror must have a more important thickness. In the same way we compare the design of a typical selective coating ($W\text{-}Al_2O_3$ cermet on a tungsten infrared reflector [4]) for different solar spectrums. For the same absorber temperature, the cermet's inclusion rate and the thicknesses which insure the optimal solar thermal conversion can be different.

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Flux density measurement for industrial-scale solar power towers

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For separate acceptance tests of a solar power tower's heliostat field and receiver, it is necessary to determine the solar flux density distribution over the whole absorber surface. Integrating the flux density delivers the receiver input power, which is required for calculating the energy conversion efficiencies of both heliostat field and receiver. Furthermore, flux density measurement is valuable for supervision and control during operation of a power tower.

Flux density at small-scale prototype receivers has mostly been measured by using a camera and a moving bar so far. The moving bar is a white diffusely reflecting target which is moved quickly through the radiation's focus in front of the absorber surface. At the same time, a digital camera captures the radiation reflected off the moving bar, which allows determining the incident flux density. At industrial-scale receivers though, the installation of a moving bar is expensive due to difficult construction [1]. That's why a measurement method without any moving parts is under development. For this purpose, the radiation reflected off the absorber itself can be measured in order to calculate the incident flux density [2]. Achieving a satisfying measuring accuracy under all relevant conditions is a main aim of the presented thesis.

The central challenge with this measuring method is the correct consideration of the absorber's reflectivity and its various dependencies. In particular, the reflectivity varies because of material inhomogeneities and depends on the directions of incidence and observation. The improvements will be implemented and tested at the Solar Tower Jülich. Subsequently, the improved flux density measurement system will be validated and used in a demonstrational acceptance testing at the Solar Tower Jülich, including a comparison of measurements and simulation results. The method's transferability from open volumetric to tube receivers will finally be examined using a tube receiver model and a solar simulator.

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Airborne optical characterization of parabolic trough collector fields

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Meeting tight tolerances of the geometry is of prime importance for the optical performance of parabolic tough collector (PTC) fields. Thus, the optical, mechanical, and thermal properties of all components of the solar field are crucial for the efficiency of the power plant. So far, ground based determination of geometry parameters was time consuming and applicable to only small fractions of the solar field. Despite advanced optimization of all processes, the measurement volume is limited and the effort during evaluation is comparatively high. For this reason, the application of unmanned aerial vehicles (UAVs) offers virtually unlimited accessibility, flexibility, measurement volume and -speed, excellent data quality and full automation of both data acquisition and -processing. The topic of this thesis is the comprehensive, large scale, and thus airborne assessment of PTC geometrical properties and the subsequent deduction of the optical performance via Ray Tracing (RT) analysis. This measurement system has been labelled “QFly” and consists of an UAV from microdrones (MD4-1000), payload (VIS and IR cameras) and related software for flight path planning, data acquisition and evaluation. QFly geometry measurements regarding mirror shape and absorber tube position have been validated with independent methods.

A rapid field scanning (QFly Survey) provides qualitative and quantitative overview on prominent areas, e.g. misalignment of collector modules and tracking deviations. Survey data acquisition for a 50 MW PTC field can be completed in less than 3 hours without interference with plant operation. Images are taken from about 200 meters altitude from several east-west overflights. Several measures are developed to quantitatively examine each collector on possible deficiencies by mirror shape, module orientation, torsion or tracking deviations by exploiting the deflectometric TARMES [1] principle using both the absorber tube and illuminated bellow protections as pattern when the field is operational near zenith.

High-resolution and accurate results for mirror shape and absorber tube position are obtained from data acquired with individual overflights over each collector module at lower altitudes (approx. 25 m). Mirror slope deviations in curvature direction can be obtained by means of the TARMES [1] principle with accuracy better than 1 mrad for local deviations and 0.1 mrad for the statistical RMS value. These values have been cross checked with high resolution close range photogrammetry and deflectometric methods with a stationary camera [2]. A full automatic photogrammetric approach for airborne receiver tube alignment has been developed. The absolute measurement accuracy has been also validated with photogrammetric metrology and subsequent evaluation of the eccentricity of the absorber tube within the glass for three absorber tubes. RMS values are in the range from 1.3 – 2.0 mm with mean deviations of < 1 mm.

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Erosion of mirrors in desert environments

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Solar reflectors for concentrating solar power applications can be subject to performance losses due to their permanent exposure to the harsh environmental conditions of desert sites. Usually the assessment of optical materials for particular plant sites is carried out by standardized aging tests like the salt spray test according to ISO 9227 standard for maritime environment or the ISO 16474-3 standard for long-term UV-radiation and cyclic condensation. However there is still a lack of experience regarding the destructive effects of sand- and duststorms on reflector materials and no accelerated aging guideline is formulated yet to predict the performance loss of solar mirrors due to particle erosion to a realistic extent. The majority of CSP plants is situated or planned in desertic regions and an increasing number of plant operators become aware of the threat of erosion due to windborne particles and ask for testing procedures to perform optimized risk analysis for their energy output and cost calculations.

In the framework of this PhD project, various meteorological data from several outdoor sites in Morocco was acquired and evaluated. Besides temperature, wind velocity and relative humidity, information about the dust was collected. Passive dust sampling was accompanied by three different active particle samplers which allowed determining the particle concentration and size distribution in the air. Furthermore soil samples were investigated to determine the shape and the chemical composition of the particles. Moreover reflector samples were exposed in the field and the observations on the ongoing erosion effects on them were taken as a reference for the accelerated erosion simulation in the laboratory on the PSA. Three different erosion simulation setups were tested and evaluated towards their erosion simulation performance: A gravimetrical sand trickling device [1], an open and a closed loop wind tunnel with particle injection. The results of this analysis will permit to select the most appropriate testing method and to correlate it to North African exposure sites. This enables to derive predictions on the erosion behavior over the lifetime of different materials.

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Atmospheric Extinction of Solar Radiation in PSA. Application to Solar Thermal Electric Plants

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Solar Thermal Electric (STE) Plants are usually located in arid or semiarid places with a high percentage of clear skies and frequent high turbidity episodes. Aerosols and water vapor are the atmospheric constituents that more extinction phenomena produce in the lower layers of the atmosphere. Aerosols can reduce up to 40% the solar power reaching the receiver after being reflected by the heliostats [1].

Solar Irradiance level on receiver aperture is a critical input for the electricity production in STE Plants. This magnitude depends on extinction produced along the heliostat-receiver path. An exhaustive analysis and knowledge of extinction contribute to the progress of STE technology and to integrate this kind of systems in the power grids, decreasing the uncertainty in the production.

An overview about the extinction level due to aerosols and the impact of it in the STA Plant production for the emplacement of Plataforma Solar de Almería (PSA) are presented. Transmittances at different slant ranges are determined using the Radiative Transfer Code Libradtran [2]. Four years of aerosol measurements in PSA have been obtained from AERONET (Aerosol Robotic Network) [3] and used in the radiative equations.

The extinction model obtained for PSA is introduced in Solar Advisor Model (SAM) [4] with the purpose of simulate the impact of extinction in power production of a hypothetical STE Commercial Plant locate in PSA. Results show the extinction and their limits at PSA and how the production can be affected for these values in energetic and economic terms.

This study is a scientific basis for future experimental studies of extinction measurement at PSA. These results provide an approach to the phenomenon of extinction and its consequences on the production of a STE Plant.

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Development and benchmarking of All Sky Imager derived DNI nowcasts

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Ground-based All Sky Imagers (ASI) can be used to predict 3D positions of clouds and the corresponding DNI maps above solar plants. The accuracy of these ASI-derived DNI nowcasts must be known for industrial applications. Although many nowcasting systems are proposed and validated (e.g. [1]), comparability amongst different systems is not trivial. Besides developing nowcasting systems, this PhD project aims at establishing a general benchmarking framework for nowcasting systems and at improving DLR's nowcasting system.

Benchmarking of nowcasting systems

To benchmark ASI-derived DNI maps, twenty pyranometers, six pyrheliometers and a shadow camera system are utilized at the Plataforma Solar de Almería (PSA). This benchmarking system generates irradiance maps, which are compared to nowcasted data (s. fig. 1). Benchmarking is achieved using a four steps approach: (1) The 1 min averages of DNI in each pixel of the nowcasted DNI map which contain radiometers are compared with their ground measurements. (2) The average DNI over an area corresponding to the solar field of a parabolic trough plant from the nowcasted DNI maps is compared to that from the reference derived from shadow cameras and ground measurements. (3) Nowcasted and reference temporal and spatial DNI variability classes defined in [2] are compared to each other. (4) Furthermore, ASI-derived nowcasts are compared to persistence forecasts.

Determination of optimal nowcast configuration

Various subsystems with several possible implementations constitute a nowcasting system. The optimal configuration will be determined using the developed methodology. Key decisions concern the number of ASIs, the approach to derive cloud heights and different algorithms for cloud segmentation. The chosen setup will be optimized and validated.

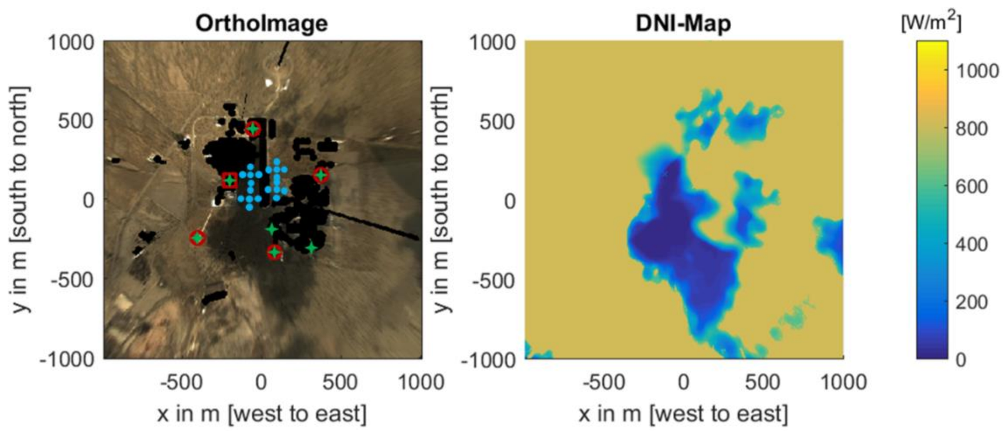

Fig. 1: Left: Instrument setup at PSA. Black pixels are excluded from the evaluation. Red circles indicate the position of the ASIs. The red square is at the position of all six shadow cameras. The green stars represent two-axis trackers with pyrheliometers and pyranometers. The blue circles mark Si-pyranometers.
Right: Reference DNI map generated from the image on the left and ground data (15/09/2015).

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Modelling of innovative heat transfer fluids used in solar receiver tubes

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Concentrated Solar Thermal (CST) technology represents a reliable path in the search for sources of clean and renewable energy. Currently, the electricity cost using this technology is still not competitive with the production by fossil fuels. For this reason, the research continues being focused on improving the performance of different components in solar thermal electricity (STE) plants.

Nowadays, one of the technological constraints of facilities with parabolic trough collectors (PTCs) comes from the heat transfer fluids (HTF) used [1]. At present the fluids widely used in commercial solar power plants are synthetic oils that are rapidly degraded to exceed 400°C, conditioning its performance. That is why it is being investigated the use of alternative fluids that do not limit the operating temperature and allow to increase the plant performance to the theoretical limits.

Therefore, a possible alternative to conventional HTF are supercritical fluids, which are substances at a pressure and temperature over its critical point, where separate liquid and gas phases do not exist. These have excellent heat transfer properties and are thermodynamically stable.

This work is focused on contributing to the development of this research. It is planned to conduct a bibliographic review which aims to collect the characteristics and applications of supercritical CO_2 (s-CO_2) in CST technology as well as looking over the simulation methodologies applied up-to-date to study the behavior of different types of HTF in solar receiver tubes. Furthermore, a first approach considering a simple one-dimensional model is carried out to analyze the heat transfer in a horizontal receiver pipe of a parabolic trough collector [2]. This model is used to study the behavior of supercritical s-CO_2 as working fluid.

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Experimental and Numerical Investigation of a Pilot Parabolic Trough Power Plant Including a Thermocline Thermal Energy Storage

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Thermocline thermal energy storage is a promising technology that may cut cost of parabolic trough power plants [1]. It consists in using one single tank instead of the conventional two-tank technology. The tank can be filled with low cost solid materials in order to replace a part of the costly heat transfer fluid. A deeper understanding of this technology is still needed. A 220 kWh thermocline tank has been built and integrated in a 150 kW_{th} pilot parabolic trough power plant. During a charge, the heat transfer fluid, a synthetic oil, is heated from 220°C to 300°C thanks to the parabolic troughs and an extra 70 kW electrical heating. Then the oil is sent to the top of the thermocline storage, and flows through the alumina spheres that fill the tank. During a discharge, cold oil at 220°C is sent to the bottom of the tank; hot oil is extracted from the top of the tank and sent to the vapor generating system.

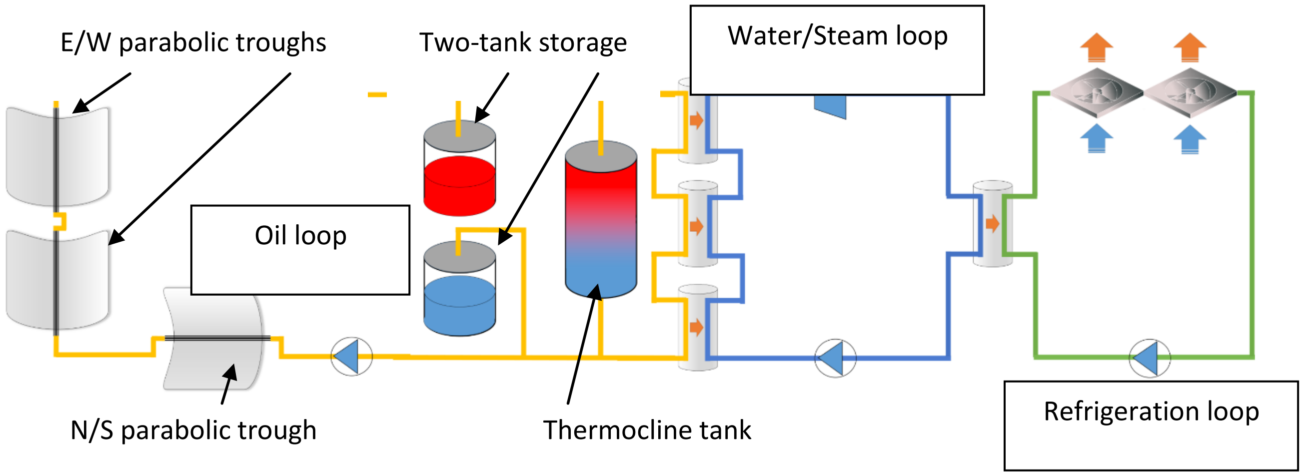

Table 1 : The parabolic trough pilot plant scheme

With this mini-plant, different sets of results were obtained, such as the outlet temperature of the thermocline tank during solar charges and discharges. The thermal behavior of the different components has been simulated and the model was validated by comparison with experimental results. Therefore, parabolic trough energy production and thermocline efficiency can be predicted and optimized.

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Optimizing design of a Linear Fresnel Reflector for process heat supply

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In the field of solar thermal energy generation, a great effort has been done in terms of academic and field research for Parabolic-Trough Collectors (PTC) and Central Receivers systems. Their main characteristics, possible configuration and results expected in several cases of study are well documented [1]. Although it has been put in the spotlight that Fresnel Linear Reflectors (LFR) has similar overall performance compared to PTC, they present lower optical efficiency because of the longitudinal component in the impinging beam radiation for LFR. Beside, economics approaches have shown that its specific cost per energy production makes this technology an interest candidate [2]. As a lack of information about LFR plants and operation conditions was detected as a common denominator, the present work has been focused on this topic.

The design of a LFR prototype for industrial process heat (IPH) applications has been performed. Different characteristics, as width of the mirrors, separation between mirrors rows, number of rows, mirror geometry profile, height, length and configuration of the receiver, were optimized having on goal the maximum energy impinging in the absorber tube surface. For that purpose, an in-house ray tracing computer code (developed in Matlab®) was created in order to study different configurations and geometries of a LFR system prototype. Considering a sunshape distribution [3, 4], within a Monte Carlo probability method, the rays arrive at the mirrors surface, they are reflected taking in count the possible interception, blocking and sun position, and finally they reach the receiver. Those rays reaching the receiver are counted by the simulation code to compute the optical performance of the different designs under study. The output of this in-house code was compared with Tonatiuh software (open source) simulation results, having an acceptable match between both energy distributions in the receiver.

Further work aims to complete the optical design developed with a thermal model of the receiver, and a structural design. The LFR design will also include a studying of the options for the tracking system and an adequate selection of materials for all the components.

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Solar thermochemical energy storage via solid-gas redox reactions

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Thermochemical energy storage consists in storing concentrated solar heat in the form of chemical energy during on-sun hours for later use, during off-sun hours, thus enabling continuous energy production [1].Thermochemical heat storage, shows advantages over latent and sensible heat storage, such as higher energy storage densities, possible heat storage at room temperature in the form of stable solid materials, and long term storage in a large temperature range with a constant restitution temperature. Concentrated solar power (CSP) can provide the heat source required for solid-gas reversible reactions involved in thermochemical energy storage (Eq. 1). The reaction enthalpy stored in the reaction products during the heat charge can be released by reversing the reaction during the discharge.

$$A(s) + \Delta H \rightleftarrows B(s) + C(g) \qquad (1)$$

Improvement of materials properties and tuning of reaction kinetics and reaction temperature can be obtained by the use of additives [2, 3]. The present study aims at investigating the effect of metal addition on the performances and thermodynamic properties of Co and Mn-based mixed metal oxides (Figure 1), which have been identified as interesting candidates for thermochemical energy storage.

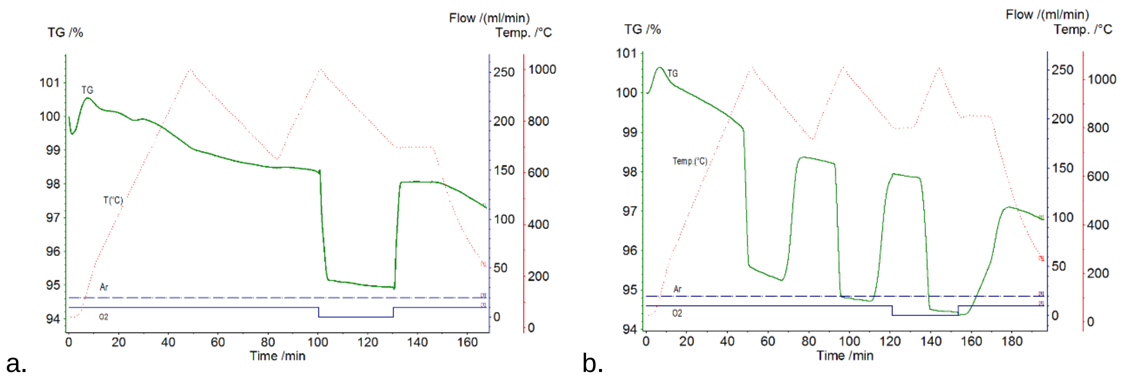

Fig. 1: TGA measurements, a. Fe(10 mol%)-Mn-O, b. Fe(30 mol%)-Mn-O.

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Thermal Energy Storage Materials Made Of Natural And Recycled Resources For CSP In West Africa

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According to nowadays constrains, the sustainable development of Concentrated Solar Power (CSP) particularly for West African countries (WAC) plants can be really considered by using locally made components and low cost eco-materials [1]. In this work, first natural stones (laterite and clay) and industrial wastes (bottom ash (BA) and slaked lime (SL)) from WAC are investigated in terms of availability, main properties and their relevance to thermal energy storage applications. Different materials were then prepared and synthesized via thermally treating process by crystallisation after vitrification of samples in a solar furnace. Changes in phase composition and morphology were exanimated using X-ray diffraction (XRD) and scanning electron microscopy (SEM) associated of energy dispersion spectroscopy (EDS) analyses. Thermal behaviours were also study by using coupled thermo-gravimetric (TG) and differential scanning calorimetry (DSC) analyses. After heat treatment, Iron-spinel ($MgAl_{.79}Fe1_{.21}O_4$) with inclusion of repetitive structure of dendrites of magnetite (Fe_3O_4) was observed for heat treated melt-laterite sample. Mullite ($3Al_2O_3$, $2SiO_2$) and hematite (Fe_2O_3) were found in all sintered laterite at 1100 °C. Mullite was also found after heat treatment of melt BA at 1200 °C. Mixtures of BA with 20 % of SL and laterite with 10 % of SL are also highlighting the possibility to elaborate anorthite ($CaAl_2Si_2O_8$) ceramic. Mullite, anorthite and spinel phases have demonstrated elsewhere to lead to refractory ceramics relevant for high temperature thermal energy system (TES) applications [2].The obtained materials can be used as sensible TESM for all kind of CSP processes (from low up to high temperature) with properties in the same range than other available materials and advantageously at lower cost and without conflict of use.

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Simulation and optimization of Solar Tower plant receivers

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The doctoral research project will treat the simulation and optimization methodology for receivers of Solar Tower plants. A specific focus is put on cavity receivers with molten salt as heat transfer fluid.

In a first step, a detailed receiver model will be created. It is expected that modeling of the thermal heat transfer mechanisms in the cavity can be broadly based on the state of the science from literature. The models for the absorbed solar radiation and the coupling of optical and thermal models will extend the current state of the science by introducing new representations for the transient flux on the receiver surfaces. Using the model, the transient temperature distribution on the tube surfaces and in the bulk fluid can be assessed, e.g. to identify hotspots (see Figure 4b).

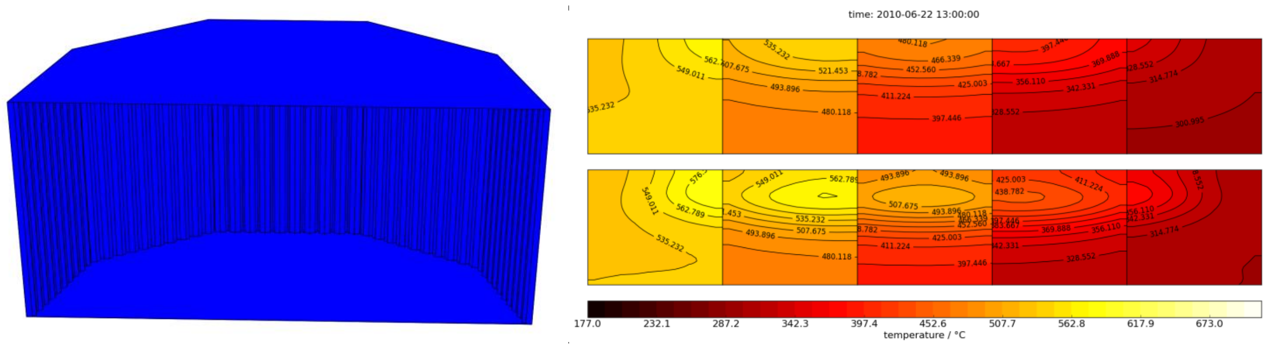

Figure 4: a) Sketch of an exemplary cavity, dimensions are similar to the PS10 receiver [1]. Inlet (300 °C) is at the lower end of the right panel, outlet (550 °C) is at the upper end of the left panel. b) Temperature distribution in the bulk fluid (top) and the tube surfaces (bottom) in the exemplary cavity with five tube panels

In a second step, new methods will be developed to derive simplified models based on the characteristics of the detailed models. Based on these simplifications, the receiver will be investigated in the scope of the integral system with annual simulations. In this part, also costs assessment will be taken into account.

Eventually, the simulation models will be used to develop an optimization methodology for the cavity receiver geometry, which takes into account its complex interactions with the integral system and cost assessment.

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Experimental analysis of the forced convective heat loss from cavities of multi-MW scale solar central receiver systems

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The current state of the research and the need to further investigate the topic of forced convective heat transfer (e.g. due to wind) in cavities of large solar central receiver (SCR) systems has been presented by the authors [1] previously. In this work we present a recent numerical study of the convective heat loss from a simple large cylindrical cavity of the 100 MW size and an experimental setup for a study of the forced convective heat loss from a large SCR cavity. The numerical results show that the convective heat loss is increasing substantially with increasing velocity. Consequently, we are preparing an experimental study in a high pressure wind tunnel in order to investigate the forced convective heat loss from such cavities. The model will include several realistic tower-cavity configurations as well as promising reduction strategies. Measurements will be conducted up to a Reynolds number of around 10^7. The measurement equipment will include constant temperature anemometry (CTA) hot-films mounted on the cavity walls and a Piezo force balance. The results will be used for a comparative study of reduction strategies and for the validation of the numerical model.

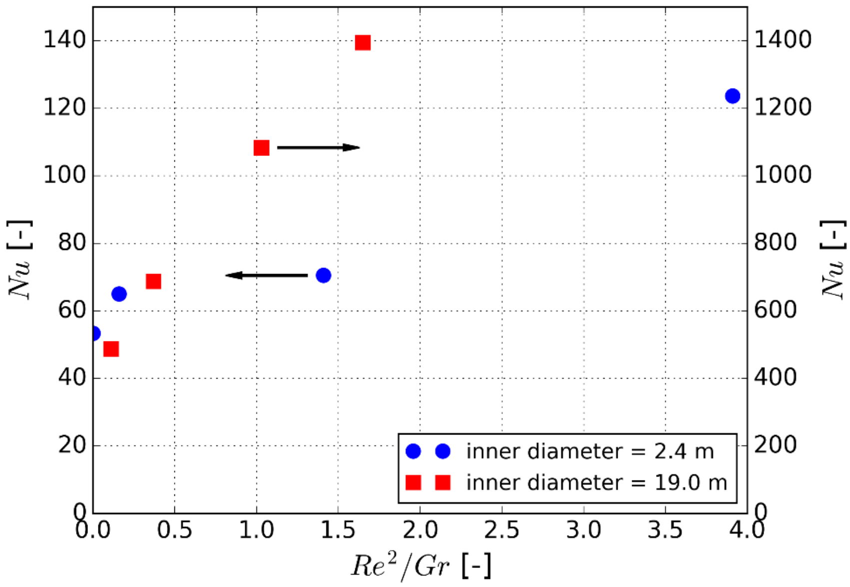

Figure 5: Dimensionless heat loss versus wind speed for two cavities at 60° inclination. Circles represent an inner diameter of 2.4 m (left y-axis, data from [2]) and squares an inner diameter of 19.0 m (right y-axis, own computations).

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Experimental investigation of heat transfer in a directly irradiated ceria particle bed under vacuum conditions

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Several receiver types have been proposed to drive high temperature two-step redox cycles for thermochemical fuel production with concentrated solar power (CSP). A promising approach is to use granular redox particles and move them through the solar receiver reactor. When modeling these solar receiver reactors for reduction of metal oxide particles, a correct representation of heat and mass transfer is essential to obtain accurate results for reaction rates and overall efficiency. However, under vacuum conditions like in recently proposed systems, heat transfer characteristics of irradiated reacting particle beds differ substantially from ambient pressure conditions and available experimental data for thermal properties under vacuum conditions is limited. Especially for the high temperatures during reduction, where radiation is the dominant heat transfer mechanism, there are very few studies with non-reacting particle beds, but no study with beds releasing gas under vacuum conditions. Generally, the bed conductivity for non-reactive particles is lower in vacuum due to missing convective heat transfer in the bed void space. For reacting particles the gas release and the resulting high volumetric flow in vacuum can lead to a self-fluidization of the particle bed, which on the one hand can enhance the heat transfer but on the other hand can lead to an undesired particle liftoff. This experimental study is conducted to understand the behavior under vacuum conditions and to provide thermal bed properties for receiver models at typical conditions in a solar receiver. A fixed bed of ceria particles, as a typical redox material, is heated to temperatures above 1300°C in a vacuum chamber by direct irradiation from a high flux solar simulator. A vacuum is maintained at specified pressures between 25 Pa and 5 kPa by continuous pumping and valve control. Bed temperatures are measured with thermocouples at different positions within the bed. Transient temperature profiles of the bed are recorded for different irradiation flux conditions and operating pressures. The transient data is analyzed and compared to a transient ANSYS simulation with effective thermal conductivities from a literature model.