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Session 1

Energy storage & Solar fuels

Chair: Martin Roeb, DLR

Autothermal Hybridization of a High-Temperature Solar Biomass Gasifier

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1. Introduction

Solar gasification of biomass is attractive to produce a green, value-added syngas – containing mainly hydrogen and carbon monoxide – while storing solar power into chemical fuel. Multiple reactor designs have been studied since 1980 [1], and hybridization has recently become a central topic to cope with the fluctuations of the solar resource [2]. Indeed, experiments [3,4] have shown that in-situ oxygen injection could increase the reactor temperature to ensure continuous operation. In this work, new results are provided about the impact of oxygen addition, and dynamic hybrid gasification runs are detailed.

2. Material and methods

Gasification of beech wood millimetric particles was performed in a 1.5 kW_{th} spouted-bed reactor (Figure 1), placed at the focal point of a 2 m diameter parabolic mirror. It featured a conical cavity where solid particles were stirred by a stream of argon and oxidizing agents (H_2O and O_2). An alumina cap covered by zirconia felts restricted the aperture area to limit re-radiation losses. The reactor was sealed with an argon blown glass window.

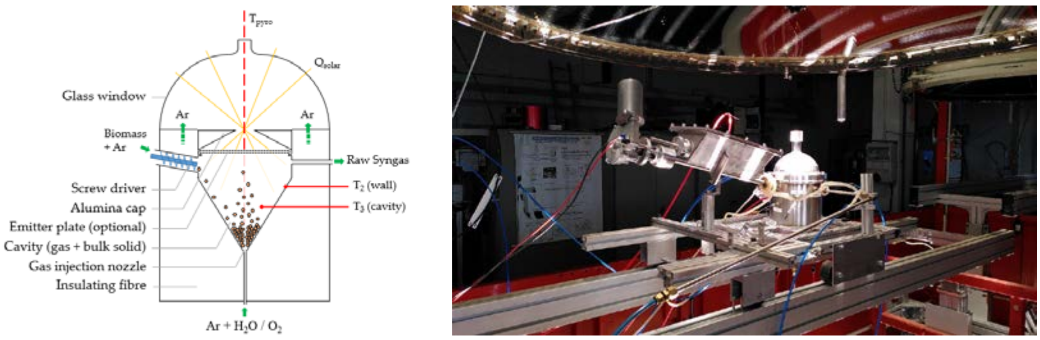

Figure 1. Scheme of the reactor cavity (left) and photograph of the reactor (right)

3. Experimental results

On the one hand, series were performed under constant solar power with a growing oxygen input flow rate (Figure 2-a). A nominal temperature of 1200 °C was set inside the cavity. No water was injected, and the output syngas was dried before analysis. The results showed a proportional increase of the CO_2 yield with the inlet O_2:C fraction. Meanwhile, a decrease of the H_2, CO, CH_4 and C_2H_m yields was observed, in coherence with the trends observed at thermodynamic equilibrium (CANTERA [5]). As a result, the energy upgrade factor U (ratio between lower heating values, Equation 1) decreased as well, ranging from 74% to 43%.

$$U = \frac{LHV_{syngas} \cdot m_{syngas}}{LHV_{feedstock} \cdot m_{feedstock}} \quad (1)$$

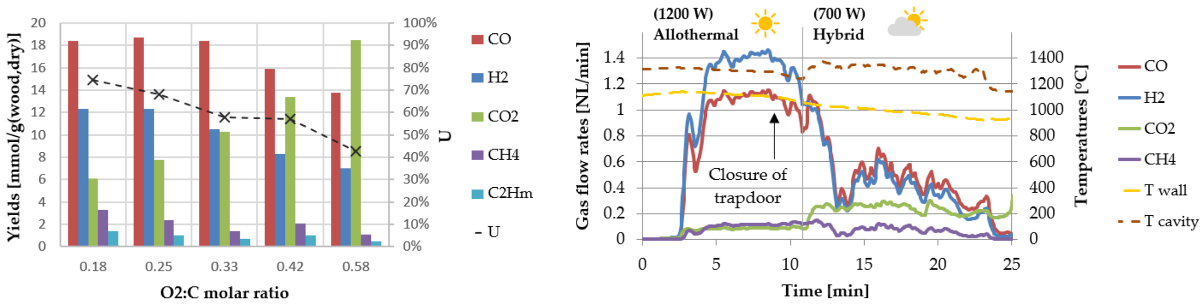

Figure 2. Yields of syngas components and U measured at several O2:C ratios (left) and time evolution of gas species and temperatures during hybridization (right)

On the other hand, dynamic series were carried out to assess dynamic performances during a cut of solar power input (Figure 2-b). Allothermal gasification of 1.2 g/min of wood was first performed with a 0.2 g/min H_2O stream. After the partial closure of a trapdoor, oxygen (0.25 NL/min) and additional biomass (+ 0.2 g/min) were injected to counterbalance the solar power drop (from 1200 to 700 W). The temperature inside the cavity could be efficiently maintained to its initial value, while the walls temperature decreased by 200 °C. This however resulted in an alteration of the syngas production, with the H_2 yield dropping from 31.6 to 19.5 mmol/$g_{wood,dry}$ and the CO yield dropping from 27.1 to 22.1 mmol/$g_{wood,dry}$. The CO_2 production rate was multiplied by 3 in the same time.

4. Conclusion and perspectives

Hybridization of the reactor was possible despite a 40% loss of solar power, maintaining the cavity temperature at 1300 °C. Oxygen injection however altered the syngas quality and the reactor performances. Maintaining the syngas composition (and especially the H_2:CO ratio) would require a controlled addition of both oxidizing agents. This will be investigated in future research works, along with the detailed modelling of the gasifier dynamics.

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A New Hybrid Solar/Electric Reactor for Methane Pyrolysis in Gaseous or Liquid Phase

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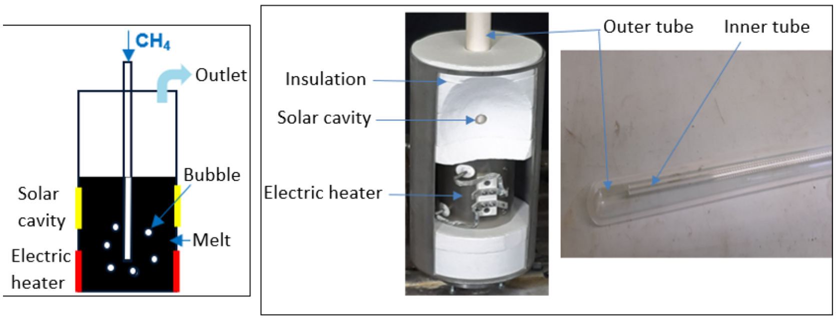
1. Introduction

Methane cracking in molten metals/salts appears as a new approach for hydrogen production with less coking and catalyst deactivation issues often encountered in gas-phase pyrolysis. In melts, the gas-liquid interface is continuously renewed and the carbon floats atop driven by buoyancy. Moreover, melts are better media than gases to boost heat transfer, which could result in higher conversions [1]. Coming to the means of heating, solar cracking ensures pure hydrogen production without greenhouse gas emissions. However, due to the solar resource variability hybridization is required for continuous processing. Thus, a hybrid solar/electric reactor, never investigated in molten pyrolysis to date to the best of our knowledge, could be a novel promising strategy to build a flexible methane cracker (Fig.1) [2].



a) b)

Fig.1. a) Scheme representing the concept of methane pyrolysis in molten media. b) Hybrid solar/electric reactor for methane pyrolysis installed at PROMES-CNRS laboratory in Odeillo (France).

2. Modeling and simulation

Before experimentation, a simulation of this reactor through ANSYS Fluent was useful to evaluate the performance of such a system. Briefly, the geometry (Fig.2.) consists of an inner tube (3 mm inner diameter, 310 mm length) used to feed methane in an outer tube (25 mm inner diameter, 320 mm length) closed at one end. The electric heater is represented by an 85 mm heated segment (long red line) near the reactor bottom, while the solar cavity is approached by another 50 mm heated segment (short red line). Green lines correspond to insulation while the top of the tubes (orange lines) are water cooled (Fig.2).

3. Results and discussion for gas-phase pyrolysis

During the gas-phase pyrolysis, the flow is set to 0.42 NL/min CH_4 diluted with argon (50% mole fraction) initially at 25 °C, to limit decomposition on the hot reactor walls and consequently to avoid formation of stuck coke. Temperatures of the electric heater and the solar cavity were both fixed at 1473.15 K. The temperature profile throughout the reactor demonstrates the benefit of such an approach (Fig.2). A hybrid system allows to reach desired temperatures along a great height of the reactor which definitely increases the effective residence time for conversion. This feature should be more important when conducting pyrolysis in melts since some metals require stable heating to avoid solidification. Consequently, hydrogen mole fraction was very high, resulting from a nearly complete decomposition of methane (≈ 100%). This result will be compared with solar pyrolysis in molten media.

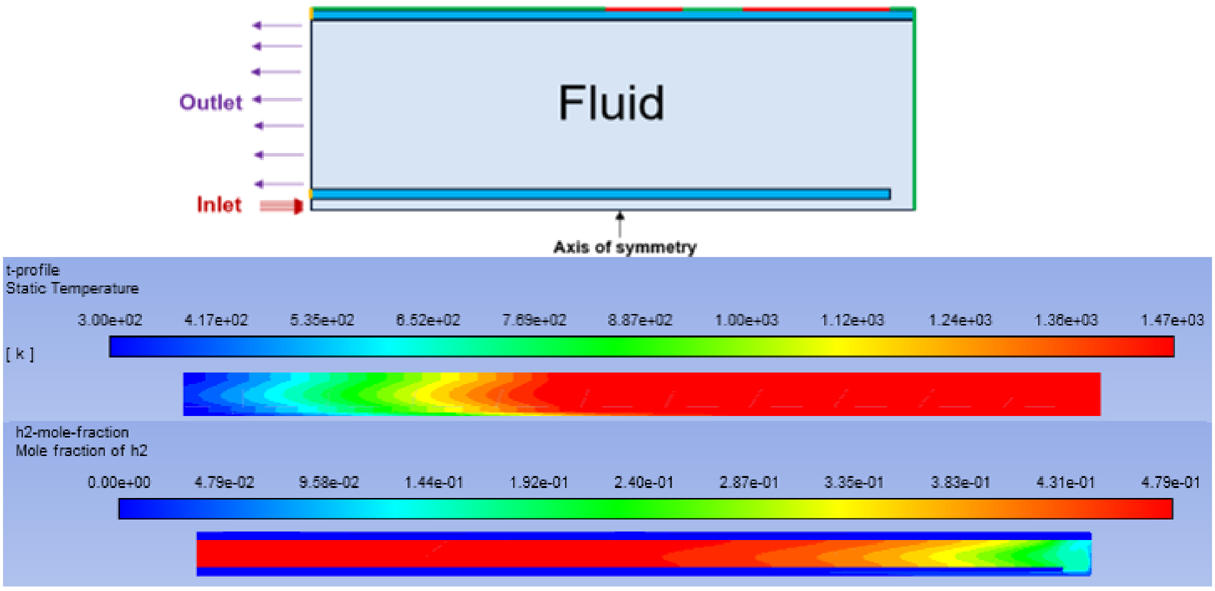


Fig.2. Reactor configuration with simulation results (Temperature and H_2 production profiles)

4. Conclusion

A hybrid electric/solar reactor could be beneficial to overcome solar energy variability, but also to boost conversion if coupled with solar energy at the same time. It helps to keep advantage of the green asset of solar energy against the environmental impacts that derive from electric heaters or any other conventional energy source. The objective of the work is to compare gas-phase pyrolysis against molten media pyrolysis in the same hybrid solar reactor. Electric heaters also open the way for continuous operation thanks to temperature control.

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Synergies between direct air capture technologies and solar thermochemical cycles in the production of chemicals

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The sustainable production of chemicals that can be used as fuels but also as a feedstock for the chemical industry is of capital importance for decarbonizing our economy and tackling the current climatic challenge. A promising approach is obtaining carbon dioxide from direct air capture (DAC) and transform it into useful products that would close the carbon cycle when consumed. This concept is commonly known as carbon capture and utilization (CCU). However, CCU is usually an energy intensive process that must be strictly driven by renewable power to avoid jeopardizing the carbon-neutrality of the final product. Our recent work focuses on the production of methanol and demonstrates that solar thermochemical cycles (TCC) can be an effective solution thanks to the possible synergies between the different parts of the process. These synergies have been collected in five possible scenarios aimed to reduce the specific energy consumption. To assess the scenarios, we combined data from low and high temperature DAC with an Aspen Plus® model of a plant that includes water and carbon dioxide splitting units via TCC, CO/CO_2 separation, syngas storage and methanol synthesis. We paid special attention to the energy required for the generation of low oxygen partial pressures in the reduction step of the TCC by comparing the usage of vacuum, sweep gas and a combination of both. In addition, the overall water consumption was also assessed. Results show that suggested synergies, in particular, co-generation, are effective and can lead to solar-to-fuel efficiencies up to 10.2% (compared to the 8.8% baseline), thus providing a basis for future works combining DAC and TCC.

Investigation of oxygen transport in solid-solid heat exchangers for solar thermochemical redox cycles

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Solar thermochemical redox cycles for H_2O/CO_2-splitting are a promising technology for the renewable production of syngas. Syngas is a versatile chemical building block and can be processed to many valuable carbon-based products. In combination with a Fischer-Tropsch synthesis for example, solar thermochemical H_2O/CO_2-splitting can be used to produce carbon-neutral liquid fuels, since utilization of CO_2 as a feedstock has the potential to create a closed carbon cycle.

For the splitting of H_2O or CO_2 a redox material is oxidized at moderate temperatures, while H_2 or CO is produced. To regenerate the redox material's capacity to incorporate oxygen in its lattice, it is reduced at high temperatures in a solar reduction step. It was shown that a large portion of the overall energy demand of this process is associated with sensible heating of the redox material from the oxidation to the reduction temperature [1, 2]. Therefore solid-solid heat exchangers are frequently discussed as a measure to improve the efficiency of solar redox cycles [3-7]. In such heat exchangers heat is recovered from the hot reduced redox material and used to preheat the cold oxidized material prior to the next reduction step.

Another aspect studied to improve the process efficiency is continuous operation of the receiver-reactors. For that purpose, the solid redox material has to be cycled between a reduction and an oxidation chamber. Different technical solutions for this approach have been proposed [2, 7-9]. In systems that comprise continuous operation and direct solid-solid heat recovery between hot and cold redox material, an unwanted oxygen-crossover between the two material streams might occur. As the temperature of the cold oxidized stream rises it might release oxygen, which can then be taken up by the hot reduced stream that is being cooled down, which is illustrated in Figure 1. The reduced material is thereby oxidized in the heat exchanger, which lowers the material's capacity to split H_2O or CO_2. Prevention of this oxygen transport by physical separation of the two material streams with a wall might however also reduce the heat exchanger efficiency.

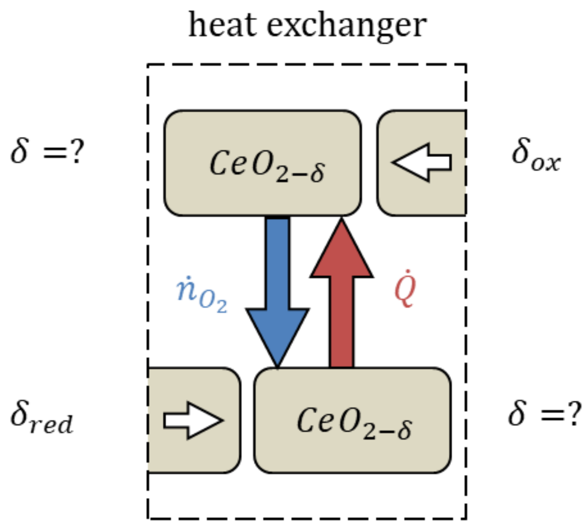

Fig. 1: Oxygen-crossover in a solid-solid heat exchanger for ceria-based solar redox cycles.

The effect of oxygen-crossover was briefly discussed by Siegrist et al. [7]. To gain better understanding of the oxygen transport in solid-solid heat exchangers, we derived a thermodynamic model for ceria-based cycles, which calculates the extent of unwanted oxidation [10]. In the present work, an experimental setup is designed to study the impact of kinetic limitations on the effect. The test rig is capable to reduce and oxidize redox materials under vacuum conditions with adjustable levels of inert gas. The development and operating principle of the test rig will be presented alongside the current status of the work.

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Application scenario of thermochemical thermal energy storage in solar powered high temperature electrolysis process

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The direct coupling of a high temperature electrolysis (HTE) with a direct steam generating solar receiver is challenging. Indeed, it is important to minimize fluctuations and to provide high temperature energy for short and long term off-sun operation and during stand-by conditions. Hence, thermal energy storages (TES) are investigated. Conventional CSP plants are using sensible molten salt storage systems. Those are typically operated in a temperature range below 565°C. Thermoneutral operation of solid oxide electrolysis cells is reached at temperatures above 700-800°C which is targeted to minimize the electrical energy demand. Therefore, other storage materials than molten salt should be used. Another storage possibility is the concrete storage developed especially for the air solar tower in Jülich, which stores also at higher temperature. The used TES system in the investigated process must be able to store energy at higher temperatures than conventional CSP TES. All TES technologies are considered and sensible storage systems with additional redox reaction are promising candidates. They can be used in a temperature range of 400-1200°C and are able to reduce ambient air by its oxygen content which is beneficial for the HTE.

Using a sensible TES with a redox reaction and the direct coupled system demands a different approach. A new process for HTE with an electrical power of 100 MW was developed and evaluated in a steady state simulation using Aspen Plus®. To evaluate the storage integration, a 1D FDM packed bed model was created which takes thermochemical reaction into account. Those materials promise a cost reduction as their energy density is higher. A solar to pressurized hydrogen efficiency of over 26% was achieved based on the higher heating value of hydrogen. The TES system is used to keep the temperature of the HTE close to thermoneutral operation during off-sun periods. This decreases the startup time of the entire process and increases the yield of produced hydrogen.

Solar photocatalysis applied to hydrogen production: experimental details and first approach based on commercial semiconductors

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Global energy consumption due to carbon- based fossil fuels is increasing causing environmental contamination and the depletion of fossil fuel reserves. In consequence, to develop renewable energy resources is needed. Among the different options, a sustainable and clean energy source is hydrogen produced from solar energy, in particular, by heterogeneous photocatalysis. Photocatalysis permits to produce hydrogen at ambient temperature and using simple solar photoreactors, working without concentrating solar light. The advantages of hydrogen as a renewable alternative to fossil fuels, permit to continue producing hydrogen efficiently and as large scale processes. The efficiency of water splitting by heterogeneous photocatalysis is enhanced thanks to the presence of sacrificial agents (organic electron donors). Organic contaminants from urban and industrial wastewater effluents can be used as sacrificial agents at the same time that the degradation of the contaminants is achieved.

Among the main objectives of the PhD Thesis, are: i) the study of novel photocatalysts for solar driven hydrogen production ii) optimization of the conditions that maximize hydrogen production for each catalyst, iii) optimization of the photoreactor design and iv) Simultaneous hydrogen production, decontamination and disinfection of wastewater.

Experiments are carried out in photocatalytic reactor based on a stainless steel tank (27 L) coupled to a compound parabolic collectors (CPC) (14.25 L, 2.1 m^2 of illumined surface). The pilot plant was designed to flow water or wastewater through CPCs where photocatalyst was illuminated and hydrogen is produced in liquid phase but transferred to gas phase in the head-space of recirculation tank. Anoxic conditions are needed and therefore N_2 gas with a maximum flow rate of 500 mL/min was bubbled in the system flowing. N_2 is also used to entrain continuously hydrogen produced.

During the experiment, temperature and pH are monitored. Moreover, degradation of sacrificial agents is studied by measures of dissolved organic carbon, CO_2 and carboxylic acid concentration. Evolution of hydrogen produced is measured by using a gas microchromatograph (Agilent technologies MicroGC 490). Solar UV radiation intensity is measured using a radiometer (Kipp & Zonen CUV3 (300-400 nm).

Previous experiences in the PSA about hydrogen production, consisted of the use of this pilot plant testing different sacrificial agents as formic acid, glycerol and others and catalysts, as Pt/(TiO_2-N) and Pt/(CdS-ZnS) [1], [2], Cu/TiO_2 [3] and (CuO + TiO_2 mixtures [4].

During the first months of investigations, preliminary results have been obtained using the photocatalyst formed by the mixture CuO/TiO_2 applied to glycerol photoreforming as sacrificial agent. Glycerol was used as sacrificial agent, as it is the main by-product in wastewaters from in biodiesel production, with the final objective to valorise wastewaters for hydrogen production. The hydrogen production was maximized with a proportion of 1:10 of the mixed CuO:TiO_2, with a concentration of the catalyst of 100 mg/L and 0.075 of glycerol as sacrificial agent (Fig. 1). Hydrogen production was also evaluated in water containing a recalcitrant organic contaminant, imidacloprid, and a standard water pathogen *Escherichia coli.*

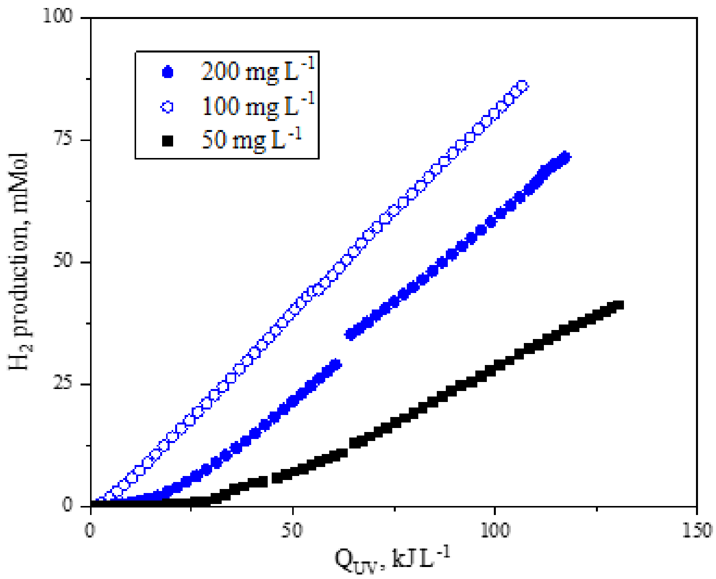

Fig. 1. Photocatalytic H_2 generation at different concentrations of photocatalyst. Reaction conditions: TiO_2-CuO (10:1), glycerol. = 0.075 M, V = 25 L.

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Computational screening and experimental validation of binary and ternary metal nitrides for the solar-driven thermochemical production of green ammonia

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The current conventional production of ammonia relies on the Haber-Bosch process, which involves the catalytic high-pressure reaction between H_2 and N_2. Because the formation of both H_2 and N_2 require energy-intensive processes, the worldwide ammonia production is responsible for 1.2% of the anthropogenic global greenhouse gas emissions. Furthermore, the high pressures necessary to increase the yield and the large recycle flows of the unreacted H_2 and N_2 impose demanding requirements on the equipment and process, therefore increasing the cost and complexity thus favouring large, centralized plants. An alternative to this process is the multi-step thermochemical cycle based on metal nitrides, which promises to mitigate or even eliminate concomitant CO_2 emissions. This is because the high-temperature heat for the endothermic reaction steps can be supplied by concentrated solar energy. Previous studies on this cyclic process have proven the synthesis of ammonia at much lower pressures – even around ambient conditions. Nevertheless, the availability of literature and experimental data of metal nitrides is scarce. In an effort to investigate a broader range of candidates, the screening in this study utilizes DFT (Density Function Theory) calculations from open-access databases to approximate the Gibbs free energy of metal nitrides. The probable reaction pathways involving hydrogenation (H_2) or hydrolysis (H_2O) of metal nitrides as well as the re-nitridation to recycle the metal nitride are identified with Gibbs free energy minimization. Selected candidate materials will be experimentally validated via thermogravimetric analysis and using a high-pressure microreactor system. The motivation and initial objectives of this project are outlined.

On-Sun Experimental Investigation of a Solar Reactor for Thermochemical Syngas Production via Methane Reforming Utilizing a Ceria Redox Cycle

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Solar thermochemical processes offer a sustainable pathway to produce liquid hydrocarbon fuels for transportation. A precursor to this is syngas, a mixture of H_2 and CO. Within this context a dry two-step thermochemical hybrid redox cyclic process for syngas production is introduced using CeO_2 as the redox material, and CH_4 as a reducing agent. The process can operate isothermally in the range 800-1200°C and achieve high non-stoichiometries (δ) of $CeO_{2-\delta}$, indicating a commensurate proportion of O_2 exchange. The hybrid redox cycle is represented by two steps:

endothermic reduction: $\mathrm{CeO_2} + \delta\mathrm{CH_4} \longrightarrow \mathrm{CeO_{2-\delta}} + \delta\mathrm{CO} + 2\delta\mathrm{H_2}$

exothermic oxidation: $\mathrm{CeO_{2-\delta}} + \delta\mathrm{CO_2} \longrightarrow \mathrm{CeO_2} + \delta\mathrm{CO}$

The process can also be performed by co-feeding CH_4 and CO_2 over the redox material to the effect of dry reforming:

endothermic dry reforming: $\mathrm{CO_2} + \mathrm{CH_4} \xrightarrow{\mathrm{CeO_2}} 2\mathrm{CO} + 2\mathrm{H_2}$

We report on a joint collaboration of Synhelion, IMDEA Energía, and ETH Zurich, to experimentally investigate the hybrid redox cycle and reforming reaction at the concentrating solar tower facility of IMDEA Energía in Spain. The solar reactor consists of a cavity-receiver with a windowed aperture and lined with reticulated porous ceramic (RPC) made of CeO_2, totaling 21 kg. The main operating conditions were: solar radiative power input of approximately 10 kW, nominal cavity temperatures between 800-1200°C, gas mass flowrates of 100 L_n/min (L_n denotes normal liter), and up to 40% reactive gas concentrations diluted in Ar. Various operating modes are tested including CH_4 cracking, cycling at high δ regimes, CH_4-CO_2 co-feeding, and implementation of a tubular (non-solar) reactor downstream of the solar cavity. Overall, the project demonstrated the feasibility of operating the hybrid redox cycle with a directly-irradiated solar reactor in a solar tower configuration.

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Session 2

Modelling and control strategies

Chair: Jose Antonio Sánchez, UAL

MILP Algorithm for Optimal Control Strategy of a Hybrid Concentrated Solar System for SHIP

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1. Introduction

Solar Heat for Industrial Processes (SHIP) is an increasing trend in research as a way to decarbonize the industry. Indeed, 74% of industrial final energy consumption is in the form of heat [1].

Whenever the solar field is hybridized, heat losses in the solar field can be compensated by lowering the solar field's outlet temperature – this concept is called Flexible Heat Integration by Rashid et al.[2]. Optimization on a mathematical basis becomes necessary when storage and variable heat demand are considered. Mixed Integer Linear Programming (MILP) algorithms provide exact optimum and low computation time, in comparison with non-linear algorithms. Nonetheless, they require a simplified model. Therefore, co-simulation is performed, i.e. a control trajectory is obtained from the MILP algorithm, and injected in a more complex and realistic model to ensure that the control is feasible and of good quality.

In this paper, the model is described, followed by the results of a case study with a 280°C hot oil's demand, necessary for the production of wood-based panels. The optimized system is constituted of a low-cost parabolic trough in series with a linear Fresnel, a dual phase thermocline storage and a biomass boiler. In a previous work [3], a set of simulations realized on specific heat demand profiles with a 0D solar field and a two-tank storage have shown a relative increase of the solar fraction up to 4% on a 300°C temperature range, as compared with a control trajectory aiming for a constant outlet temperature. The objective of the reported work will be the upgrade of this model to 1D with a thermocline thermal storage.

2. Methodology

The overall system is coded in C++. The MILP solvers implemented are CBC (open source) and CPLEX (commercial). Time discretization is hourly. The plant model is not described for the sake of brevity, whereas a first glance to the MILP algorithm is given.

MILP algorithm necessitates linearized equations. Due to the high number of non-linearities involved in the solar field heat losses, it is impossible to write as such this equation. The methodology implemented is a discretization of the temperature level: the corresponding mass flow rate considering inertia is calculated for every temperature at hour h and at hour h-1, and binary variables corresponding to this choice allow the MILP algorithm to know the results, reducing consequently the boiler use – which is the cost function.

3. Results

Results of a sensitivity analysis from the first set of simulation [3] are presented in Figure 1. In this sensitivity analysis, four demand curves, i.e., DC were investigated, as presented on the left in Figure 1. The heat losses coefficient a_1(in W/m².K) is varied, and compared with two other control approaches: CA1 always works at the process temperature (in the previous set, taken as 350°C) and CA2 works at the demand mass flow rate (and therefore, most of the time, at lower temperature). The annual solar fraction as a function of the heat loss coefficient is presented on the right in Figure 1. The comparison shows an increase in solar fraction from the MILP control greater with higher heat losses, which would allow for less efficient (and less costly) receivers and/or solar field. These results will be compared and discussed with the new proposed configuration including a thermocline thermal storage model.

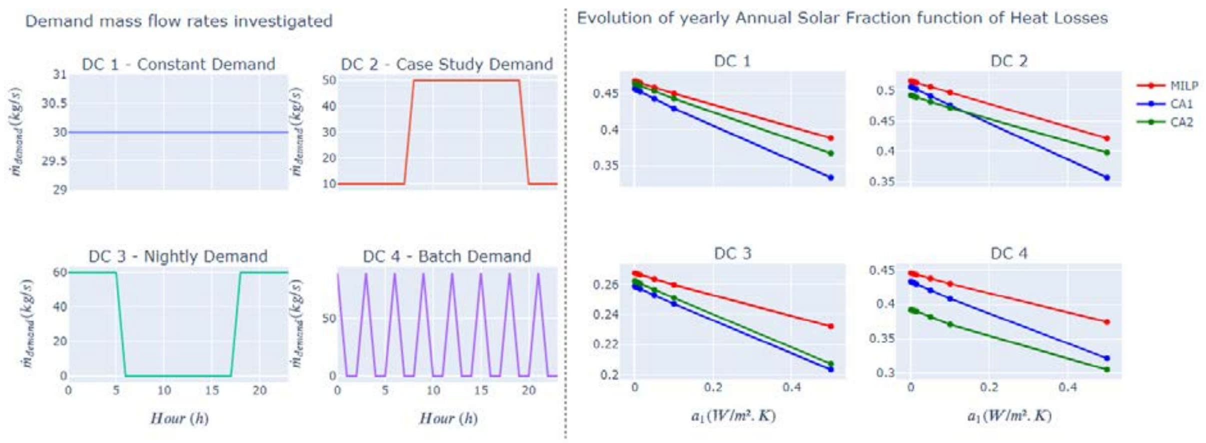

Figure 1. On the left: investigated curves of demand mass flow rates. On the right: evolution of the annual solar fraction with the heat loss coefficients a_1, with the corresponding demand curve

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Performance study of the solar thermodynamic plant of LLO

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1. Presentation of the solar power plant of Llo

Inaugurated and commissioned in 2019, the Llo solar power plant is a solar thermodynamic plant built and operated by SUNCNIM, a subsidiary of the CNIM Group. The solar plant is based on Fresnel linear concentrator technology with direct steam generation and is equipped with a steam storage system. The solar array consists of 170 modules, each with 140 primary reflectors, for a total collection area of 152,796 m². The electrical production is ensured by a Rankine cycle combined with a turbo-alternator group developing a nominal power of 9 MW_{elec}. The thermal storage is composed of 9 steam accumulators of 120 m^3 each. The energy is stored as sensible heat by storing pressurized water at high temperature (70 bars, 286°C).

2. Performance ratio and performance guarantees

The performance of the power plant is evaluated thanks to a performance ratio (PR) between the electrical energy produced and the incident solar energy on the primary reflectors:

$$PR = \frac{\int P_e(t).dt}{\int DNI(t).dt * A_p}$$

with, $\int P_e(t).dt$ the electrical energy produced, $\int DNI(t).dt$ the incident solar energy and A_p the total collection area.

Using a simple model to predict the electrical output of the plant, SUNCNIM defines performance guarantees from which monthly performance ratios are derived (Fig. 1).

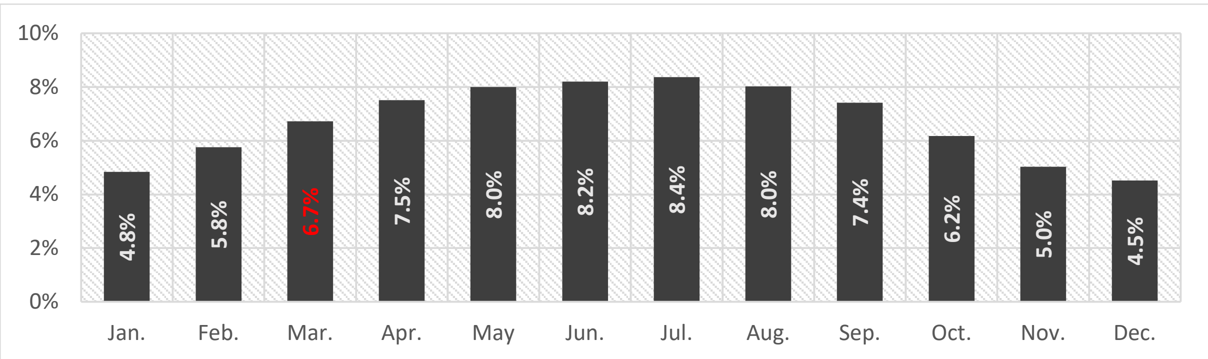

Fig. 1 : Expected monthly performance ratios

3. Current performance

On 29/03/2021, the performance ratio calculated via the experimental data measured on site is equal to 6.65% as compared to an average value of 6.7% for the plant model in March. Firstly, for a good day, the plant seems to reach the expected performance despite the repair works of the solar fields, from spring 2020, following two exceptional weather episodes at the beginning of the year (storm Gloria and hail fall). However, the unavailable part of the field prevents from reaching the expected performance for less favorable days and thus the monthly guarantees too. Fig. 2 presents the evolution of electrical production, operating pressures and incident solar power from experimental data measured on 29/03/2021. Electricity production for the study day was slightly out of sync with the sun's path, as night temperatures are still low at this period of the year and a layer of frost was deposited on the primary reflectors slowing down the temperature rise of the installation in the morning. Thus, the turbine reached a power of 9 MW_{elec} at around 12:30 pm for a duration of about 6 hours of nominal production. Then, the energy stored during the day was recovered via a sliding pressure regulation. Finally, the turbine was stopped at around 2h am the next day when the storage pressure had reached the turbine stop pressure.

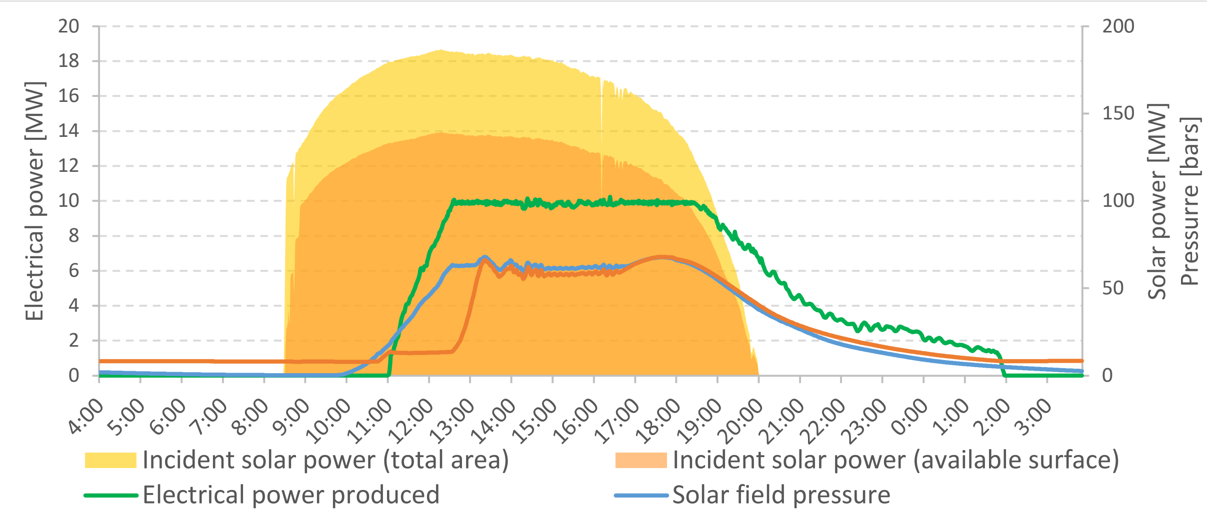

Fig. 2: Evolution of electrical production, operating pressures and incident solar power on 29/03/2021

4. Objective of the research project

A numerical model to calculate the performance of the power plant's sub-assemblies is being designed and will be validated by comparing its results with experimental data. The goal is to optimize the operating strategies and particularly the management of the storage system. This work will also answer the need concerning the lack of precise information on these plants and in particular for the regulation systems [1].

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Digital Operator for Solar Thermal Power Plants

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Solar thermal power plants do typically not operate under steady-state conditions. The moving sun, changes in direct normal irradiance or the occurrence of clouds face operators of those plants with dynamic situations. Stabilization of minor disturbances and safety functions are realized within the distributed control system, but the overall optimization of the plants performance is normally done by the operator. Especially under continuously changing conditions this is a quite complex task. Moreover, optimal operation often involves approaching operating limits. Consequently, fast interpretation of changing process variables and taking correct action is crucial for the optimal operation of solar thermal power plants. With increasing experience operators learn heuristics to solve this task. These heuristics significantly reduce problem complexity and neglect some information because of the limited ability of humans to handle numerical data. In contrast computers are orders of magnitude faster, and more accurate in processing numerical data. Therefore, a digital operator should outperform a human operator. However, it is typically difficult to translate the learned heuristics into a set of machine-readable instructions. In the following, two approaches to realize the concept of a digital operator are discussed.

The idea of the first approach is to extract the operator's experience and learned heuristics from data. Therefore, an artificial neural network might be trained to predict the operator's actions from a suitable amount of process variables and environmental conditions as input. Once the artificial neural network performs well, it might suggest control actions to the human operator. With increasing level of confidence, it might even replace the human operator in the loop with a suitable amount of human supervision and option for intervention. Such a concept has been commercially proven for the operation of a boiler of an incineration plant [1].

The second approach is comparable to model predictive control. The process is represented by virtual models, which are either physical simulations or derived from process data and predict the plant's output. A suitable cost function is formulated and an optimization algorithm determines control actions. Once again, those control actions might either be handled as suggestions for the operator or directly feed into the distributed control system. [2]

Advantages of the first approach are potentially lower computational costs once the neural network is trained, as the control actions are determined directly in contrast to the iterative procedure of an optimizer. However, this approach potentially results in a monolithic design, which is typically hard to adopt and maintain. Potential changes in the power plant, either intentionally due to major overhauls or unintentionally due to wear might require a complete revision of the digital operator.

The second approach can be designed in a modular way. Process models, the cost function and the optimization algorithm can be evaluated, adopted and improved individually. However, in contrast to the first approach it does not profit from heuristics learned by the human operator and might be more sensitive to model and measurement uncertainties. Especially in the domain of solar power towers measures have already been developed to reduce uncertainties. For example, heliostat calibration aims at reducing errors of geometric models, deflectometric measurements provide knowledge of mirror shape and cloud nowcasting provides spatial information of the irradiation to reduce uncertainties in the prediction of flux on the receiver [3,4,5]. Nevertheless, there are still significant time dependent inaccuracies.

Therefore, for the development of a digital operator, the author proposes to start with the evaluation of methods that quantify uncertainties in the flux prediction. Then, it should be evaluated, whether the feedback of reflected sunlight on the receiver [6], infrared and temperature measurements can reduce inaccuracies of the process model. Finally, a cost function and optimization should be developed, which take the remaining uncertainties into account.

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Dynamic optimization associated with advanced predictive control for solar thermal generation systems

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One of the paramount manners for achieving climate neutrality, stimulating a fair and prosperous society in favor of a better quality of life of current and future generations, and promoting a resource-efficient economy, is developing diversified and sustainable energy sources. Given the current global scenario, the economic-environmental balance's main challenge is maintaining sustainable development through the use of renewable energies. In the following years, the global energy demand is expected to achieve about 32 TW approximately [1], and one of the most known, abundant, and sustainable sources to provide such an amount of energy is the sun. This star provides about 75000 TW of power to the Earth's surface, and this only concerns the direct use of solar irradiance, not to mention that other renewable energy sources derived from the sun [1]. Therefore, in the last decades, solar system generation has received particular attention from research groups of different areas to contribute to this technology's enhancement and development.

Although the application of solar thermal energy has grown in recent years, there are still concerns about how to become economically attractive. This issue can be addressed by reducing general operating costs or improving energy production efficiency [1,2]. Such aspects make room for the automatic control engineering field to develop innovative strategies that diminish operating costs and optimize solar plants' energy production.

Therefore, this doctoral investigation plan intends to study, design, and implement dynamic optimization strategies for advanced control systems for solar power generation plants. This power generation system is a complex dynamic process characterized by nonlinearities, multiple disturbance sources, significant transportation delays, highly varying energy sources, and the power source is not available all the time. Hence, it requires the use of advanced control strategies to improve production and efficiency. This research project also proposes implementing a multilayer control structure based on real-time optimization (RTO), capable of continuously evaluating the process operating conditions to maximize the plant's economic productivity.

The particular objectives of this research project are i) study in detail solar thermal facilities (for instance, the Centro de Investigación en Energía Solar - CIESOL, located at the University of Almería), based on the analysis, modeling, and simulation of solar plants and other associated systems, ii) design multivariable control algorithms based on advanced predictive control and optimization frameworks to reduce power generation costs, making the most use solar resources, considering the plant's operating modes, considering the connections between the various systems that constitute a solar thermal installation, and iii) analyze the economic impact achieved by using the proposed control techniques. The goal is to study the economic and energy benefits of the entire control structure based on the results of real experiments compared to the strategies currently used in different facilities.

Recent results in the framework of this project are focused on improving control and operating performance on a thermal solar facility composed of different auxiliary systems. The first results are presented as a new hybrid practical nonlinear predictive control for a thermal solar plant facility, wherein hybrid models and process operation conditions are formulated in a single-layer control optimization problem. In addition, the proposed strategy can account for the forecasting of operating modes, which gives intriguing prospects since the controller can provide optimal solutions considering the future solar plant configuration. Later, a novel control formulation is developed to address closed-loop stability incorporating disturbance rejection for controlling solar collector field systems. This new approach has an outstanding potential to be implemented in a real system, proving to be very attractive for application on solar plant facilities since this process is constantly disturbed, and this new control approach can assure the plant control scheme being always stable independently from its tuning.

Therefore, the contributions of this work are motivated based on the essential need for the development of renewable technologies, especially concerning solar energy generation systems. In this case, applying principles from the control engineering field in solar energy generation systems is essential to increase operating income, reduce costs and even optimize the operation of this renewable energy source under economic criteria. Thus, the fruitful results of this study permeate the purposes of promoting sustainably efficient economic development, improving the quality of life of future generations, and, concomitantly changing, albeit slowly, the perspectives of a more equitable and harmonious society.

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Session 3

Solar receivers

Chair: Francoise Bataille, CNRS – PROMES

Control of Particle Mass Flowrate in a Fluidized Bed Solar Receiver

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To meet electricity demand amidst global climate change issues, societies need to produce electricity through clean and reliable source of energy [1]. Concentrated solar technologies present promising results to reach carbon neutrality. Molten salts are commonly used as Heat Transfer Fluid (HTF) and Thermal Energy Storage (TES) medium in solar towers [2], but they present several drawbacks as limited operating temperatures (220 – 565°C) and a high cost (around 1000 $/ton). To overcome these issues, several laboratories are developing new receivers technologies using particles as HTF and TES medium [3]. In particular, the PROMES laboratory of the French National Center for Scientific Research has developed a solar tubular receiver with a fluidized-bed of particles as HTF [4]. This receiver technology allows to store heat cheaply (around 150 $/ton) and to reach higher temperature (900°C) than current technologies, thus increasing the Carnot efficiency and enabling the use of new generation of thermodynamic cycles as proposed by the Next-CSP project [5].

The use of fluidized particles as HTF in solar receivers is new and need to be fully understood to deploy this technology at large scale. Wherefore, a mock-up at ambient temperature was built at PROMES to study hydrodynamic regimes of fluidized beds, key elements for tube-particles heat exchange, and how to control the flow of particles at the exit of the tube. This mock-up is composed of a fluidized bed inside a vessel called "dispenser" and a 45mm internal diameter transparent tube of 3m high which is immersed in the dispenser. An air flowrate, q_{ae}, is injected at the bottom of the tube in order to get a stable particle flow and to control the hydrodynamic regime in the tube. By applying a pressure, P_d, in the dispenser thanks to a pressure valve, the fluidized bed rises up in the tube until it reaches its upper end, thus creating a flow of particles, F_p. This height or flow of particles is a direct combination of the pressure applied (closing of the valve) and the air flowrate injected.

To regulate the particle flowrate/height of the fluidized bed in the tube, the control parameters are the pressure of the dispenser, P_d (Fig.1.a) and the air flowrate, q_{ae} (Fig. 1.b).

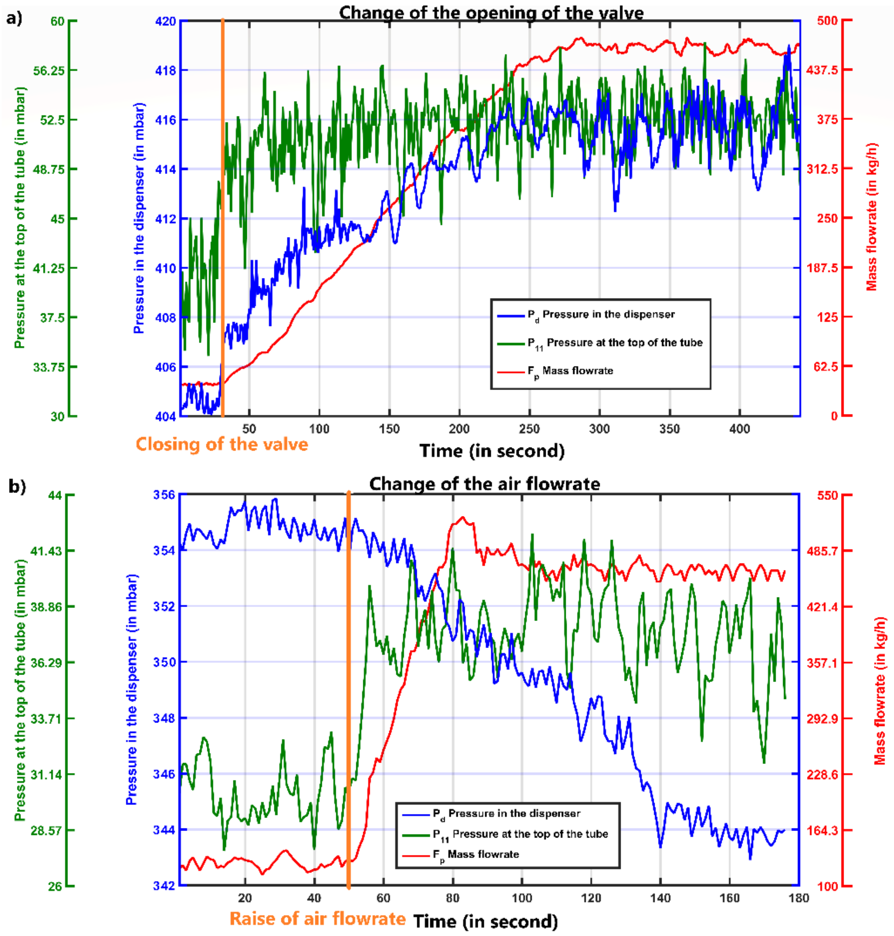

Fig.1: Particle mass flowrate (in kg/h, in red), pressure (in mbar) in the dispenser (in blue) and at the top of the tube (in green) versus time (in second) for a) a closing of the valve and b) an increase of the air flowrate.

First, both the change of the opening of the valve and the change of air flowrate seem to trigger a response of a 1^{st}-order system. Second, the change of pressure has a long-term impact on the particle flow (95% response time ~ 300s) whereas a change of the air flowrate has a much smaller response time (less than 30s). Regulating the particle flowrate with the air flowrate seems to be the best way to quickly adjust the receiver's operating conditions to a change of the available solar ressource. Third, the raise of particle mass flowrate induced by a change of air flowrate causes a diminution of the pressure in the dispenser. A numerical model was developed in order to understand the response time of the regulation of F_P by the change of the opening of the valve and will be presented. A predictive method for regulating quickly and precisely the mass flowrate by q_{ae} will also be discussed.

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Identification and Characterisation of the Fluidization Regimes in a Fluidized Bed Solar Receiver

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A tubular solar central receiver technology based on the use of fluidized particles as heat transfer fluid and storage medium has been developed by the PROMES laboratory (CNRS, France) [1]. The particles are circulating through vertical irradiated tubes of high aspect ratio (height/internal diameter). The use of particles enables the receiver to reach higher temperatures compared to molten salt, commonly used in commercial solar power plants. Thus high efficiency heat-to-electricity cycles can be powered, increasing the sun-to-electricity efficiency [2]. In the "particle-in-tube" concept, the tubes are immersed in a fluidized bed vessel named the dispenser. The particles are circulating by both applying a differential pressure between the dispenser and the upper part of the tubes and by controlling the flow rate of a secondary air flow rate injected at the bottom of the tubes, namely the aeration.

Several fluidization regimes can occur in such a system, depending on the experimental parameters: bubbling, slugging or even turbulent and fast fluidization regimes, which strongly affect the thermal performances of the receiver [3]. Because of a strong particles mixing, the bubbling and turbulent regimes must be preferred in on-sun conditions. The identification and the characterization of the fluidization regimes are thus critical.

A 1-tube cold mock-up (i.e. at ambient temperature) has been set-up and instrumented with pressure sensors along the tube height (3 m). The tube is made of glass, with an internal diameter of 45 mm, which allow optical access. Group A Olivine particles with mean diameter of 61 µm are selected for their good thermal, mechanical and fluidization properties [4]. When a structure (such as bubbles, slugs and clusters of particles) moves upward in the tube, it causes respectively a positive and a negative pressure at its top and its wake. The recorded pressure signals result hence in a succession of upper and lower peaks. Several analysis methods of the temporal pressure signals have been compared in order to study the evolution of the air/olivine flow structure with the experimental parameters.

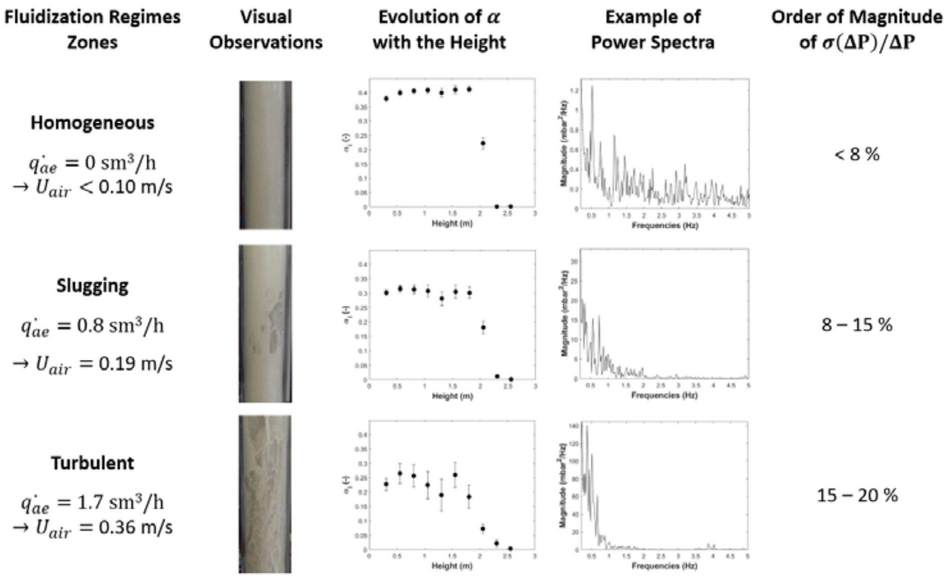

Fig.1. Identification and characterization of fluidization regimes encountered in the tube.

The methods are: the visual observation, the calculation of the local particles volume fraction α, the incoherent analysis (calculation of the power spectra by Fourier Transform, in the frequency domain), the cross-correlation (in the temporal domain), and the calculation of the differential pressure fluctuations $\sigma(\Delta P)/\Delta P$. The results are compared and combined to identify the fluidization regimes encountered in the tube. Several regimes are identified depending on the experimental conditions. They can however be classified in “regimes domains”. The three main domains are presented in Fig.1. First, the homogeneous domain, with a single bubbling regime without evolution with the height. Second, the slugging domain, characterized by a single bubbling regime at the bottom of the tube followed by wall slugs and then axisymmetric slugs, formed by bubbles coalescence. Third, the turbulent domain. Here, the turbulent and fast fluidization regimes are very similar from a visual point of view but can be distinguished using a pressure signal analysis. Both regimes are characterized by a strong mixing.

Future works will focus on the integration of all the tests performed with the mock-up, with large ranges of air and particles flow rates, in order to establish a map of the fluidization regimes and their transitions in such a system. Furthermore, on-sun tests are currently being performed at the Odeillo’s solar furnace (France) to identify the influence of the temperature in the apparition of the different regimes and to study the associated heat transfers.

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Numerical and Experimental Modelling of Centrifugal Particle Solar Receiver

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Particle solar receivers promise economical and operational advantages compared to the molten salt based solar receivers. In Centrifugal type particle solar receivers, the ceramic particles which are accelerated centrifugally and gravitationally, descend through the inclined rotating receiver, and form a thin particle film layer while being directly exposed to the solar radiation through the receiver aperture. Depending on the receiver rotation speed and the particle mass flow rate during operation, an opaque particle film with a certain thickness and velocity profile can be achieved in order to adjust the particle outlet temperature. In this study, firstly, a Discrete Element Method (DEM) based numerical model is created by means of open source tool, LIGGGHTS. Secondly, a set of experiments for various receiver rotation speeds and particle mass flow rates is conducted, and experimentally obtained raw results are post-processed by means of an Image Processing Routine based on 4BestEstimate algorithm [1]. Experimentally obtained particle velocity and film thickness is compared with the DEM model results. In order to reduce the number of particles in the simulation, the receiver size is scaled down by adjusting the rotation speed and the particle mass flow rate thanks to scaling laws. Finally, a separate thermal model is developed in MATLAB, which uses particle positions produced by DEM model every time step. As a major heat transfer mechanism, the radiation is modelled as short-range radiation occurring between particle-particle and particle-wall pairs in close proximity, and long-range radiation occurring between large surfaces of the receiver, hot and cold regions of the particle film and aperture plane. In order to model the short-range radiation heat exchange, particle-particle and particle – wall radiation distribution factors are derived based on local solid fraction, the distance between pairs and particle optical properties. Incoming solar rays reflected by the heliostat field and striking the particle film by passing through the aperture plane are distributed the moving particles as a function of local solid fraction and effective incidence angle. A radiation enclosure model is employed to model diffuse reflections and re-emissions from surfaces. A particle scale conduction model for the conduction heat transfer between particle and particle-wall pairs through the contact area and interstitial fluid is also developed. The complete thermal model is employed to calculate temperature distribution in the receiver under various flux distributions so that the film thickness can be optimized to reduce the excessive temperature gradients.

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Numerical simulation of Convective Heat Transfer Coefficient in 3D Wire Mesh Absorbers

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1. Introduction

In the last years, the levelized cost of energy has been reduced due to different technological advances. One of the technologies with the biggest possibilities of improvement is the concentrating solar power technology. This technology is striving for obtaining better solar to electric efficiencies in solar power plants [1]. Nowadays, molten salts are the applied commercial technology in these solar power plants which is able to reach around 560°C as fluid operational temperature. This operational temperature allows to work with subcritical Rankine Cycles but according to literature the most efficient cycles are the Combined Cycles which need operational temperatures over 800°C. Research is needed to attain that operational temperature, having with volumetric air receivers a potential candidate. Volumetric air receivers' technology has usually been tested with ceramic volumetric receivers, however, some benchmarked papers point out the prominence of geometrical parameters in metallic volumetric absorbers [2]. In the present research, numerical simulations of convective heat transfer coefficient (HTC) between the fluid (air) and a wire stagger stack are performed under the same steady operation conditions. The results show a comparison of the HTC between distinct porosities (95% - 80%) and diameters (1 mm – 0.1 mm).

2. Methodology

To define wire mesh screens is mandatory to highlight two geometrical properties[3], wire diameter, d (mm) and, mesh count, M (mm^{-1}). There are other geometrical parameters derived from the wire diameter and the mesh count such as volumetric porosity (ϕ), specific surface area (a_v) and pore hydraulic diameter (d_h).

This paper analyses the influence over the HTC through four samples presented in Table 1. In this Table 1 is summarized the main properties of the samples, as well as the porosity of the stagger stack pattern.

Sample	Wire diameter, d (mm)	Mesh count, M (mm^{-1})	Porosity inline, ϕ (%)	Porosity stagger, ϕ (%)	Specific surface area, a_v (m^{-1})
#1	0.1	0.63	95	90.1	3,933
#2	1.0	0.06	95	90.2	396
#3	0.1	2.44	80	63.7	14,001
#4	1.0	0.24	80	64.5	1,417

Table 1. Properties of the wire stagger stack performed in the present work.

3. Numerical Simulation and Results

Numerical simulations have been performed with the commercial program STAR-CCM+ 16.02.009. These numerical simulations encompass the HTC study of the samples in Table 1 under steady conditions and with a laminar flow according to Avila-Marin [4]. So, in order to fulfil a complete HTC study, it has been varied the flow velocity (0.5 - 5 m/s) and the wire temperature (700 – 1500K). Some of the gathered results are depicted in Fig. 1. In which is summarized the convective heat transfer coefficient (HTC) for sample 1 and 3. In both of them have been studied a flow velocity of 0.5 m/s and the complete range of wire temperature. Regarding the results, it is noteworthy the speed for the sample 3 to reach the maximum air temperature in each case and, also, the higher convective heat transfer coefficient value.

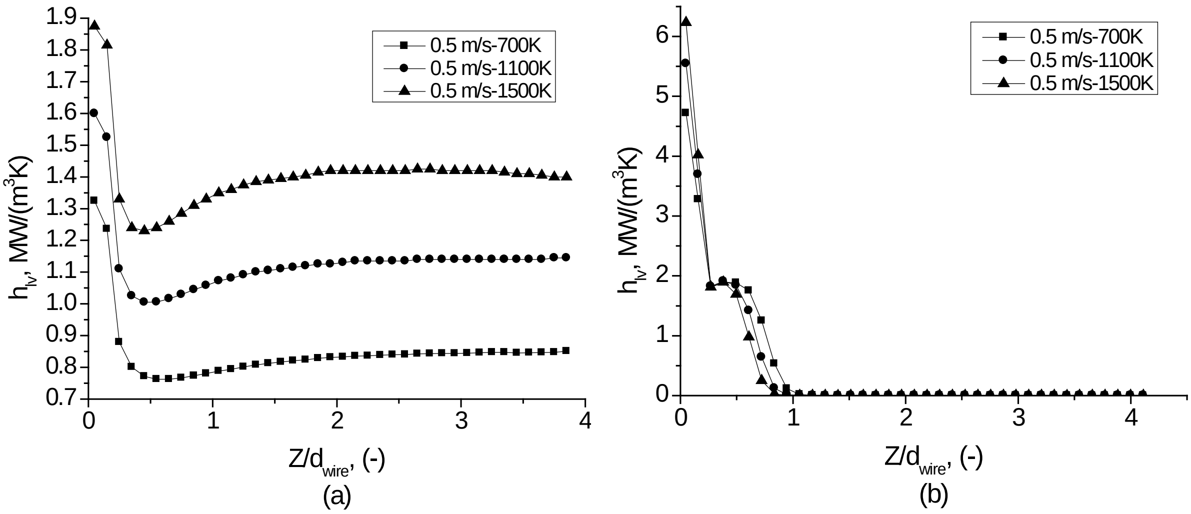

Fig. 1. Convective heat transfer coefficient (HTC) along the stagger stack pattern: (a) Sample 1 and (b) Sample 3.

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Small-Scale CSP Plants Using Reciprocating Engines

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1. The need for Small-Scale CSP plants

Currently operated and designed concentrated solar power (CSP) plants operate at a large scale akin to conventional power plants. Of the tracked 6.41 GW of currently operational CSP capacity worldwide, only 125 MW are smaller than 20 MW nameplate capacity and all of which were constructed before 2016 [1]. The economies-of-scale benefit the construction of large, centralized power plants and allow the integration of large-scale thermal energy storage systems. On the other hand, power grids worldwide are being adjusted towards greater decentralization to ease integration of various renewable energy assets and to ensure access to clean energy for remote communities.

Subsahara Africa, Latin America and India have an addressable market of about 63 GW capacity for small-scale CSP plants in a range of 100 kW to 2 MW, with demand expected to increase further as more communities require electrification [2]. To capture this market, centralized manufacturing facilities for heliostats, power block systems, and receiver units need to be combined with easy and quick on-site assembly and simple-to-operate power electronics. Whereas heliostat prices have declined significantly in recent years due to the economies-of-scale [3], the power block still presents cost and efficiency challenges. Legacy systems use large-scale steam turbines with a power rating in excess of 50 MW_e and investment costs between 800-1000 $/$kW_e$. Smaller stream turbines have higher specific investment costs and entail larger gap and turbulence losses and therefore suffer from an overall reduced efficiency while increasing the plant's Levelized Cost of Electricity (LCOE).

2. Reciprocating Steam Engines

We propose using turnkey, small-scale solar thermal power plants using reciprocating piston steam expanders in the power block. These can be centrally produced using techniques from the automotive manufacturing industry. All other components, such as heliostats, receivers, storage systems and heat exchangers, can also be produced in offsite manufacturing facilities and delivered to the project sites as needed. We have developed a detailed model for highly-efficient gas piston expanders that use state-of-the-art technologies. These include low-friction graphite piston rings, low-turbulence laminar flow valves, and adiabatic, uncooled working chambers. The model was validated using data from CFD simulations, gas springs, and piston compressors available in the literature. These types of expanders are currently being investigated for use in pumped thermal energy storage systems [4,5].

3. Small-Scale CSP Plant Design and Economic Analysis

The small-scale CSP plant design considered in this work uses an open volumetric receiver (OVR) in a central tower to heat ambient air in an open primary loop to 700°C with a ceramic thermal storage system. The secondary water-steam based power loop can be operated either by the receiver loop directly or by discharging the storage system. Due to material constraints in the heat exchanger and expander, an upper temperature limit of 550°C was chosen. The maximum pressure was limited to 60 bar, with a condensation pressure of 0.2 bar. We designed a 1.2 MW_e three-stage expansion cycle with feed water preheating and a single reheating cycle. The final stage expands to superheated steam, to mitigate condensation in the expander, as condensate is difficult to remove from the working chamber. Our model simulates full-load and part-load operating conditions for the reciprocating expander and the heat exchangers. Furthermore, a 1-dimensional model was developed to investigate how quickly the heat exchangers react to temperature changes, to obtain an indication of viable plant startup times and procedures. To estimate the economic viability of this approach we use current cost estimates for small-scale heliostats (3-8 m^2), receiver and storage system cost, and an economics-of-scale approximation for the heat exchangers and reciprocating expanders. Using a year-round generation model for a representative solar power site, we estimate yearly production and obtain an estimate of the LCOE.

Future work will investigate whether small-scale CSP systems can be combined with low-cost photovoltaics and short-term battery systems for daytime production and thermal CSP production for periods of low solar irradiation and during the night.

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Gas-particle trickle flow direct contact heat exchanger for CSP application

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Research activities in the field of concentrated solar power (CSP) are often motivated in enhancing competitiveness against other technologies. One approach is to increase the maximum temperature of the used heat transfer fluid (HTF) in the CSP plant to provide thermal or/ and generate electrical power. HTFs based on sintered bauxite particles provide process temperatures up to 1000 °C, since the material starts to sinter at 1100 °C. A new direct absorbing receiver system has been successfully developed and tested by DLR. The rotating CentRec® receiver system demonstrated at Juelich Solar Power Tower demonstrated under solar conditions particle outlet temperatures up to 950 °C. To push further particle based CSP technology towards commercial application the high particle temperatures have to be transferred to a working fluid, like air, to provide high temperature energy for e.g. in industrial processes or electricity generation in gas or steam turbines. A gas-particle trickle flow direct contact heat exchanger (TFHX) has been identified with great potential for high efficiency heat transfer. State of the art technologies for gas-particle heat transfer with direct contact like mono or multi-staged fluidized beds (FB) and cyclones (CY) are considered as inferior to the TFHX for the desired task. Due to high parasitic losses, regarding the FB, and poor volumetric power density, regarding the CY. Inspired by chemical trickle flow reactors and previous work in literature focusing on the TFHX concept for temperatures up to 500 °C the approach and its applicability for high temperature heat exchanger shall be developed further. In advance a suitable packing structure for the trickle flow heat exchanger has to be identified. For optimized gas-particle heat transfer the assessment criteria are chosen to: (a) even particle distribution within the packing void fraction and (b) high particle retainment due to the obstruction exerted by the packing structure, resulting in reduced mean particle falling velocity and increased particle volume fraction and particle volumetric surface area. A pre-selection process was conducted to identify suitable packing structures, matching the aforementioned assessment criteria. The assessment was performed by using opensource DEM software LIGGHTS-PUBLIC®. The numerically identified packing structure provides a starting point for the experimental test setup, where cold particle flow with gas interaction will be studied to verify the DEM experiments. Consecutively, hot testing is foreseen to investigate heat transfer behavior between the particle and the gas phase within the TFHX.

Development of a multispectral infrared imaging system for the in-situ opto-thermal analysis of solar thermal absorber coatings

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The external tubular receiver design is today dominant among commercial Central Receiver Systems (CRS). A liquid heat transfer fluid flows through the receiver, i.e. a tube bundle heat exchanger, which is externally heated by Concentrated Solar Power (CSP) [1]. The receiver is made of a refractory metallic alloy, such as Haynes 230, and is coated with a high temperature resistant black paint, such as Pyromark 2500 [2].

The receiver surface temperature is monitored in real time by infrared thermography [3] to control the heliostat field, while the coating spectral properties are periodically measured on tower with portable devices, i.e. reflectometers/emissometers. The accurate monitoring of temperature is critical for a safe, efficient and durable receiver operation and maintenance.

In this project, a new infrared measurement technique is being developed and tested in order to bridge both measurement techniques mentioned above, allowing to map the receiver surface temperature and emissivity in central receiver systems. Previous research has investigated the importance of solar blindness on temperature measurements in solar furnaces [4,5], while active pyrometric measurement techniques relying on multiple wavelengths [6,7] have been proposed to measure spectral emittance and temperature. Double Modulation Pyrometry [8,9] has been introduced for indoor artificial solar furnaces, where solarblind pyrometry cannot be applied due to the continuous spectrum of the artificial light source.

The new measurement technique relies on a passive measurement principle, i.e. ratio or two-color thermography [10,11], which is adapted to comply with solar blindness constraints. The measurement principle is primarily applicable if the target exhibits a grey spectral behavior, a slope factor is introduced to account for atmospheric compensation.

This presentation outlines key findings, from the concept search until the system assembly, including material opto-thermal characterization at room temperature and operating temperature (200-800°C).

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Discrete Ray-Tracing Algorithm to Solve Radiative Heat Transfer in Porous Media

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Porous structures can enhance radiation heat transfer and thus the thermal efficiency of solar receivers for concentrated solar applications. To guide their design, we report on a model development based on pore-level ray tracing of the radiative exchange within the porous structure. First, the modeled domain is discretized, allowing to describe any complex geometry by simply prescribing solid and void voxels (single 3D elements with uniform properties). Rays are then launched and traced in the discretized space using voxel traversing algorithms. The ray-solid intersections are found by querying voxel information (solid or void) along each ray's path. In this way, the discrete algorithm takes advantage of the relatively small mean-free paths in porous structures and is computationally fast. This modeling approach is tested by considering a reticulated porous ceramic (RPC) structure (17.8×17.8×17.8 mm) exposed to a uniform radiative heat flux. The new discrete algorithm solves the radiation absorption distribution within the RPC (204'830 voxels, voxel size 169.5×169.5×169.5µm) in 9 seconds using 10^5 rays. In comparison, an in-house surface-to-surface ray tracer solves the same transfer problem in 1’502 seconds (10^5 rays, meshed RPC, 200'000 faces, average edge length: 237 µm). The model is being expanded to solve, at the pore level, the general radiative heat transfer in absorbing, reflecting, and emitting porous structures for its application in the design of high-temperature solar receivers.

State of the Art: Pressurised Gas Receivers & Performance Indicators

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Pressurized gas receivers (PGRs) have the advantage of being able to achieve high temperatures (>1,000 °C) while using an inert and relatively cheaper heat transfer fluid (HTF). However, poor heat transfer characteristics and difficulties in thermal storage have limited their wider adoption [1], [2]. A review of PGRs, including comparisons using relevant performance indicators and applications, is presented.

PGRs can be broadly classified as directly and indirectly irradiated. Directly irradiated receivers require a transparent surface, typically a quartz window, to allow the HTF to be directly irradiated. However, these windows are brittle and limit the receiver's operational pressures (< 10 bar) and temperatures. Indirectly irradiated receivers can be grouped as tubular, modified cavities and microchannel receivers [3]. Tubular receivers are the most developed and their geometries can be configured to take advantage of solar trapping effects and reduce heat losses. They have moderate thermal efficiencies (70-80%) and overall pressure drops (2-3%).

Receivers that use cavities to enhance the optical efficiency and have the HTF flow in the annulus are referred to as cavity receivers. Reticulated Porous Ceramics (RPCs) lining the annular wall, impinging jets or embedded channels are modifications used to increase the heat transfer. They typically have lower pressure drops (>1%) than tubular receivers, but also lower thermal efficiencies (60-70%). Microchannel receivers use larger wetted areas to increase the heat transfer from the irradiated wall to the HTF. Therefore, these receivers have the highest thermal efficiency (>90%), however also suffer the largest pressure drops. Comparing these receiver types, microchannel receivers have the smallest hydraulic diameter and tubular the largest. HTF temperature rise per unit of flow path length and hydraulic diameter is much higher in microchannel receivers than others, although this is offset by higher per unit length (and diameter) pressure drops. Modified cavity receivers show intermediate behavior depending on the heat transfer enhancement technique(s) employed.

Final receiver application determines the acceptable range of these parameters. For instance, if the receiver is directly used as the heat source in a power cycle, its pressure drop is more critical than if an intermediary heat exchanger is used to connect it to the power block.

While it is clear optimization analyses need to be carried out to determine a receiver's optimal geometry, within each PGR subtype for the intended application, there is no clear consensus on which objective functions to use for receiver optimization [1]. Continued lack of a standardized figure of merit hampers comparative analyses on PGRs. Multi-objective optimization techniques have been used in the past [4], but there is also the scope of applying heat exchanger optimization techniques, such as goodness factors [5] or exergy minimization functions [6] to PGRs to facilitate comparison between them.

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Session 4

Solar field

Chairs: Robert Pitz-Paal, DLR

Manuel Romero, IMDEA

Development of a methodology to study the degradation of solar field reflectors of concentrating solar-thermal systems

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The reflectors of the solar field of Concentrated Solar Thermal (CST) systems are one of the key components of the technology. Their quality directly influences the optical performance of solar collectors and thus the energy conversion efficiency. During the service lifetime of CST installations, the reflectors are exposed to the harsh outdoor conditions on site and are prone to suffer degradation, which may decrease their reflectance and with that the optical quality. Plant operators nowadays regularly check the state of their solar field reflectors in two ways: reflectance measurements on a number of selected facets and routine checks for obvious signs of degradation (e.g. corrosion spots, cracks in the glass) [1]. This procedure, which is not standardized, has some shortcomings: firstly, different commercially available reflectometers are designed to measure considerably different reflectance parameters which may not be the most appropriate ones for the specific case. Secondly, by reflectance measurements and naked eye inspections certain degradation mechanisms, especially in early stages, may not be detected. The detailed analysis of the degradation mechanisms is usually performed in the laboratory of specialized research institutes on small samples cut out of formerly exposed facets.

This thesis project focuses on the development of a procedure to measure the degradation of the reflectors while they are installed in the field, with the aim to improve the significance of reflectance measurements and to close the gap between routine checks during regular operation and maintenance (O&M) and the more complex and elaborate laboratory analysis.

The first task in the project was to identify the main degradation mechanisms detected for silvered-glass mirrors, the by far most widely used type of reflector. The main mechanisms which can deteriorate the reflectors and decrease their reflectance are [2]:

- Corrosive attack of the reflective silver layer, developing from the facet/sample edges or penetrating the protective back side layers

- Silver tarnishing
- Mechanical degradation of the front glass surface, through erosive attack by airborne particles or abrasion (e.g. by contact cleaning in the presence of dust and sand particles).

One task is dedicated to the equipment for reflectance measurements in the field. There is a variety of commercially available and widely used reflectometers, which all measure considerably different reflectance parameters [3]. All commonly employed reflectometers are being purchased for this task and will be tested in an extensive outdoor measurement campaign. The main purpose of this task is to characterize these devices, compare the measurements among each other and to evaluate their suitability for the measurements in CST systems.

Another task is the investigation of microscopic defects in the field and ways to analyze them. All of the above mentioned mechanisms can start developing gradually, making it difficult to detect them at an early stage, without performing a detailed analysis in the laboratory. In this task the use of a portable microscope is investigated, which can be taken to the field and perform measurements without removing samples from the sites. The capability of the microscope to detect different kinds of defects is investigated.

When reflectors show stronger degradation (e.g. larger parts of the surface corroded, bigger erosion defects), this degradation is often extremely inhomogeneous and cannot be quantified adequately by punctual reflectance measurements. During laboratory analysis, camera based systems are usually used to determine the expansion of degraded areas on reflector samples. To address this issue, the employment of a camera based system for field measurements is studied, to automatically analyze the degradation on in-field facets.

Also, the necessity for further measurement parameters and additional equipment is evaluated. All this information then serves as the input to define a complete measurement procedure to perform the analysis of the reflector degradation in the solar field.

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Design and characterization of selective coatings for high/medium temperature solar thermal applications

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1. Introduction

Nowadays, solar energy is considered as one of the sustainable clean energies that will play an essential role in impending the climatic crisis. Solar thermal conversion method is the easiest and immediate method of harnessing solar energy; attracting increasingly interest the Concentrated Solar Thermal (CST) systems. High thermal efficiency in these systems is reached with the aid of spectrally selective absorber coatings (SSACs) that ensure a high absorptance of the solar irradiation in the solar wavelength range and a low thermal emittance in the mid/far-infrared wavelength ranges. Therefore, the SSAC is an essential component in CSP technologies to govern the overall performance. These selective absorber coatings must be stable in air, easily applied on large scales, and able to withstand thousands of heating and cooling cycles; being in this way mandatory for this receiver material to accomplish long-term stability in terms of microstructural, thermo-optical and mechanical characteristics. So far, the latest generation solar absorber material used for central solar receivers of CSP plants is the paint commercially known as Pyromark 2500 but its solar absorptivity was considerably decreased after aging above 750ºC [1]. The researches carried out on the development of highly thermally stable SSACs by dip-coating method reached a maximum of 500ºC operating temperature without degradation [2]. Within my PhD thesis, in accordance with next-generation power towers (operating temperatures exceeding 650ºC), the main purposes focus on increasing the collection efficiency of the current power tower by: 1) designing a multilayered absorber based on metallic spinels stable at these high temperature conditions. 2) developing an absorber for being applied in solar particle receptors. Both materials, separately, could be the solution for the desired balance between the conversion efficiency and thermal stability. In parallel, as there is no commercial selective absorber for non-evacuated tubes for medium temperature receivers, the use of a commercial Thickness Sensitive Spectrally Selective (TSSS) absorber paint would be an interesting solution. In this way, two commercial paints are analyzed by using dip-coating methodology. In this work the results obtained up to now are presented.

2. Experimental and Results

The application process of both current commercial Solkote and Pyromark paints by dip-coating has been studied. With respect to Pyromark, the painting thickness could not be adjusted by dip-coating since, regardless of the applied extraction speed, all the samples present the same specular hemispherical reflectance curve and consequently the same solar absorptance value (0.974). By thinning the paint (trying different solvents), both the optical and adhesion properties are adversely affected. Thus, optimizing the process of applying Pyromark paint by dip-coating is ruled out. In counterpart, it has been possible to optimize both the extraction speed and the number of layers to which the Solkote paint could be applied to register promising optical selectivity properties. These favorable results allowed thinking in the use of the commercial Solkote paint as TSSS absorber paint for medium temperature solar thermal applications. The application of this commercial paint as selective solar absorber ensures the maintenance of the high solar absorptance value and the reduction of the thermal emittance value that is so limiting in commercial paintings. All the samples prepared using Solkote are being analyzed through tests of thermal resistance (at 400ºC) and environmental durability (constant condensation at 40ºC).

A spectrally selective solar absorbing coating based on a six layered system deposited by dip-coating has been designed. The layers that will constitute the complete absorber have been studied by adjusting the composition/ratio of each component and are being deposited individually in order to analyze the variables of preparation in the optical properties. Two types of anti-diffusion barriers have been studied and developed to improve the thermal stability at high temperatures of the absorber by retarding upwards thermal diffusion from the IR reflector material. The effect of the temperature (500, 600, 700 and 800ºC) on the anti-diffusion layers thicknesses has been analyzed.

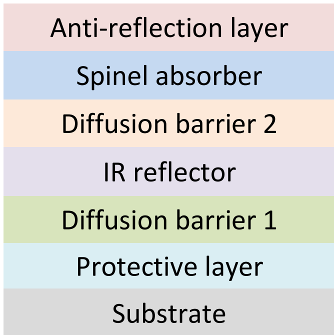

Figure 1. Scheme of the absorber configuration.

Regarding absorbers optical characterization, no protocol for measuring the optical properties of particles of solar receptors exists. Different materials of windows (quartz of different thicknesses, germanium, KCl) are being studied through the spectrophotometers measurements for optimizing the procedure and establish a standardized methodology.

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Characterization of the optical and thermal properties of materials exposed to high concentrated solar radiation

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Greenhouse gas emissions from industrial processes (chemical, metallurgical, …) and those that require fossil fuels to generate electricity can be mitigated with renewable energies such as Concentrated Solar Thermal (CST) energy and in particular with point focus technologies: i.e. solar towers, parabolic dishes and solar furnaces. To achieve better efficiencies or to cover very high temperature industrial processes energy demand, these technologies need to increase the operating temperature, mainly in the central receiver of solar towers. This temperature increase is associated with an increase in solar concentration and, therefore, higher requirements for the materials used as receivers in these systems.

For this reason, there is a wide field of research focused on the behaviour of materials subjected to high fluxes of concentrated solar radiation [1]. This doctoral work aims to make contributions in the experimental characterization of materials for high concentration systems, from the optical and thermal performance, and durability estimation, as well as the development of simulation models of the system developed and analysed with CFD tools. To continue the research on materials for high concentrating solar technologies, a new testing platform, under development, with new features that will allow to further study the behaviour of materials subjected to high fluxes (>1MW/m^2) of concentrated solar radiation and high temperatures (>800ºC).

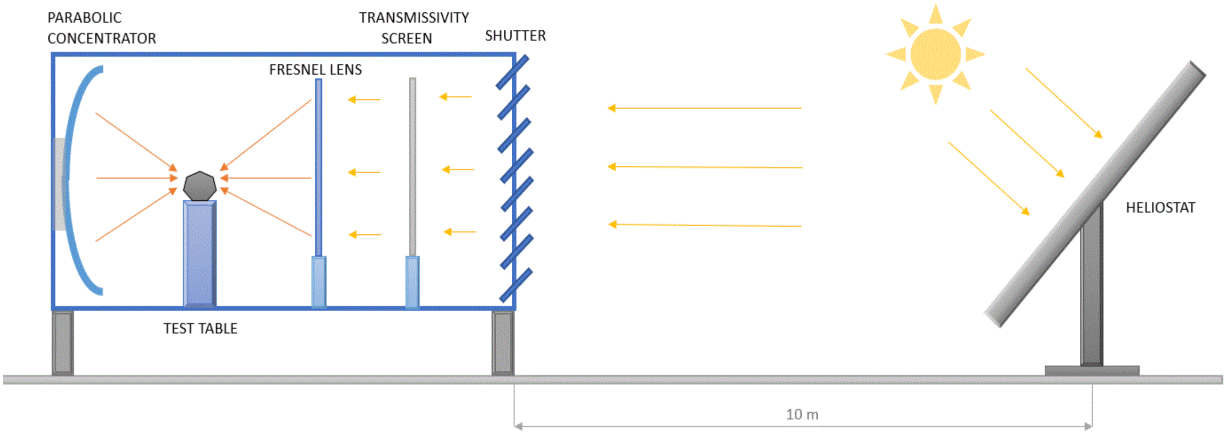
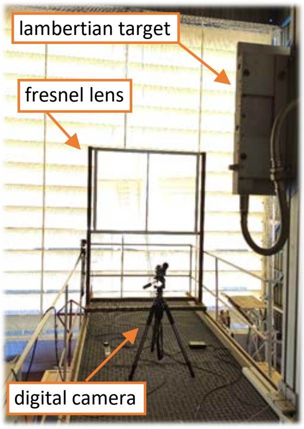


Fig. 1. Sketch of the new facility for materials testing under high solar fluxes.

The new solar furnace under development at Plataforma Solar de Almería (PSA) includes the following components (See Fig. 1): a 12 m^2 flat heliostat will follow the sun during the day for redirecting the solar radiation to either a Fresnel lens or a parabolic shape mirror concentrator. A shutter together with a variable transmissivity screen will accommodate the solar radiation to the different requirements of the material tests. While the new facility is being built, an energetic characterization of the Fresnel lens has been performed on the SF60 solar furnace at the PSA [2]. Fig. 2 shows the experimental setup as well as first results of the Fresnel lens characterization.



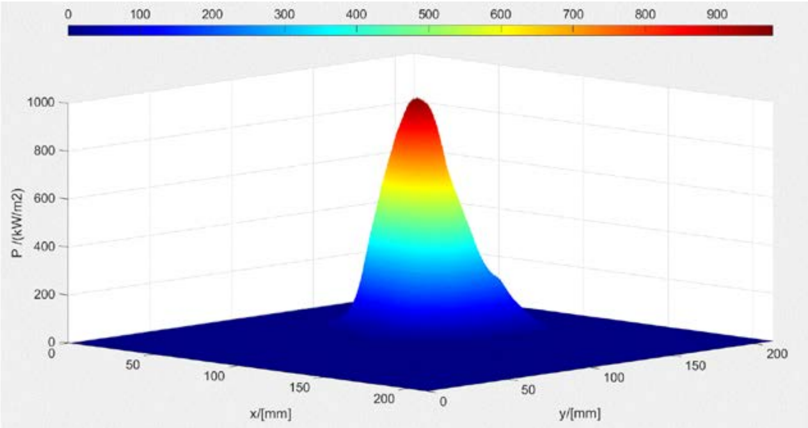


Fig. 2. Fresnel lens experimental setup (left) and measured flux (right)

Using a lambertian target with a Gardon radiometer and a CCD camera for capturing images of the lambertian surface [3], has been possible to measure the main concentration parameters of the Fresnel lens (see Table I).

Table I. Fresnel lens optical and energy parameters measured during its optical characterization.

Focal length (m)	3.5 ± 0.02
Lens transmissivity	0.91
Energy (kW)	1.24 ± 0.03
Flux peak (kW/m^2) (@ 900W/m^2)	976.65 ± 0.03
90% energy radius (m)	(32 ± 0.5)10^{-3}

Acknowledgment

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Numerical Investigation of a Trapezoidal Cavity Multi-tube Receiver for a Linear Fresnel Collector

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1. Introduction

The aim of this work is to contribute to the thermal analysis of multi-tube receivers designed for linear Fresnel solar collectors (LFC). The numerical investigation that is being carried out is applied to a specific trapezoidal cavity receiver designed for an innovative LFC, which is under construction at Plataforma Solar de Almería (PSA).

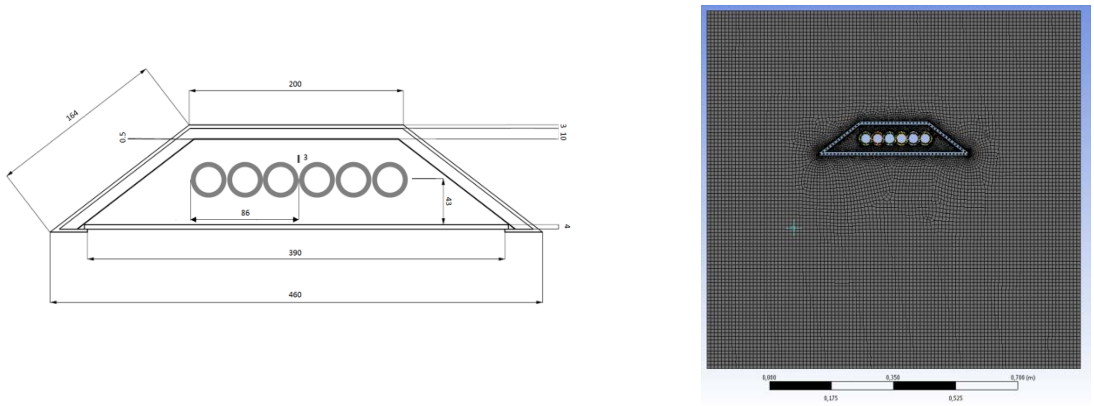
In the work by Reddy et al. [1] radiation and convection heat losses in cavity receivers are studied assuming that the receiver temperature is constant, for different geometric parameters, insulation thicknesses, etc. Facão et al. [2] applied the Boussinesq model and obtained a correlation for the global heat transmission coefficient that depends on the temperature difference between tubes, which are at the same temperature, and the environment. The objective of the first investigation done for this PhD thesis is to obtain multivariable correlations to predict heat loss of the linear receiver of the new design of LFC. These numerical correlations will be used to simulate the thermal behavior of the whole system through a 1D model.

2. Methodology

A thermal study is carried out on a trapezoidal cavity receiver like the one shown in Fig. 1.a, by mean of a two-dimensional model shown in Fig. 1.b. The absorber is composed of a double grid with 3 tubes each, so that in a cross section of the receiver there are 6 parallel tubes. In this study, numerical correlations are obtained that relate the heat loss q (W/m) in each of the tubes and through the glass to the environment, as a function of the temperature difference ΔT between the absorber tubes and the environment according to equation (1):

$$q_{t_1}, q_{t_2}, q_{t_3}, q_{glass} = f(\Delta T_1, \Delta T_2, \Delta T_3) \quad (1)$$

where T_1, T_2 and T_3 are the pair of tubes of each grid, numbered from the center to the left/right.



(a) (b)

Fig. 1. Trapezoidal cavity multi-tube receiver considered in the study: a) cross-sectional scheme; and b) fluid domain and meshing.

The ANSYS-Fluent software is used to perform numerical simulations using finite volumes for different tube temperatures, so that correlations such as those shown above can be obtained. Fig. 1.b shows the fluid domain in which the simulation is performed and the optimal meshing defined for the simulations. The mesh size is the smaller the closer the element is to the critical parts of the receiver (tubes, cavity walls and glass window).

These results will serve to obtain multivariable correlations to calculate the heat loss of the system, as a function of the temperature of each tube of the receiver panel. These correlations will be included in a one-dimensional model of the cavity receiver of the LFC, in which the radiation reflected by the mirrors will be taken into account and it will be possible to simulate, depending on the fluid inlet conditions, the outlet conditions, and therefore, the amount of energy that can be obtained from the LFC system investigated.

In parallel, a LFC prototype is being built at the PSA, in order to obtain experimental data for checking the performance of the system and that will helps to validate the numerical model that is being carried out. The receiver panel of the prototype is being manufactured and includes a high number of temperature sensors in both the receiver panel and attached to the cavity walls and glass window, so once installed and tested, the experimental set-up will provide very useful data to complete the numerical study. Once the model is validated, alternative configurations of the receiver will be simulated to obtain those options that optimize the system performance depending on the operating conditions.

Acknowledgment

This research work is receiving ERDF funds from the Spanish government within the framework of the SOLTERMIN project (Ref. ENE2017-83973-R).

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Condition Monitoring for Parabolic Trough Fields – Soiling determination

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An established source of renewable energy with the capability to deliver dispatchable electricity is concentrated solar power (CSP). Over 60 % of the todays CSP plants are of the parabolic trough type [1]. Within the solar field a large amount of measurement instrumentation is present from solar field level up to collector level. The data handling in today's CSP plants is very heterogeneous. In some plants most of the collected measurement data is recorded, whereas in other plants measurements are just used for direct control tasks and not recorded. In general, the stored data is not used for a comprehensive data analysis. The question arises how different data sources can maximize the knowledge about the field condition. The main challenges to answer this question are the varying field conditions due to solar irradiation and plant component condition, as well as limited measurement instrumentation.

In this context the use of data analysis algorithms based on machine learning approaches is a promising step towards an autonomous operation of a CSP plant [2], [3]. The first step of the PhD project focuses on the available measurement instrumentation in the solar field. This knowledge is the foundation for further data driven approaches. The measurement equipment in the solar field is mainly industry standard with low standards regarding measurement uncertainty. New approaches in solar field monitoring, e.g. air-borne systems, or systems who deliver spatially resolved DNI maps can improve the measurement accuracy and help to progress solar field models and controller strategies.

One major influence on collector performance is soiling. This effect reduces reflectivity, is always present and therefore overlays other performance reducing effects. The influence of soiling can be estimated by measuring the mirror reflectance and calculating the cleanliness. These field measurements are accurate but only deliver point measurements. In order to estimate the influence of soiling on each collector in a parabolic trough field we created a data-based soiling model. The model predicts gloss values based on parameters like collector position in the field and days since last cleaning. It considers seasonal aspects like week of the year, irradiance, collector focus states and dumping in order to distinguish operation conditions. In a later stage additional meteorological data shall be used to include impacts of ambient conditions. As ground-truth values for the model we used gloss measurements, since there were not enough reflectance measurements available. The model output is a prediction of the gloss value at a single collector.

In order to model the complex behavior of soiling and collector performance we use a decision tree approach. Decision trees are interpretable models, which can be used for classification and regression problems. We used adaptive boosting to further improve the prediction of the decision tree. Fig. 1 shows a comparison of predicted vs. measured gloss together with the data availability shown by different colors. The black line indicates a perfect alignment of predicted data from the model and measured data. With this first model we achieved a good match at high gloss values, but insufficient values at low gloss values. Possible reasons for this could be the unevenly distributed data availability, or meteorological effects, which are not considered in the present model. However, the overall coefficient of determination R^2 reaches 0.745 for this model. This model serves as a baseline for evaluating future models with neural networks and additional operational and meteorological data input.

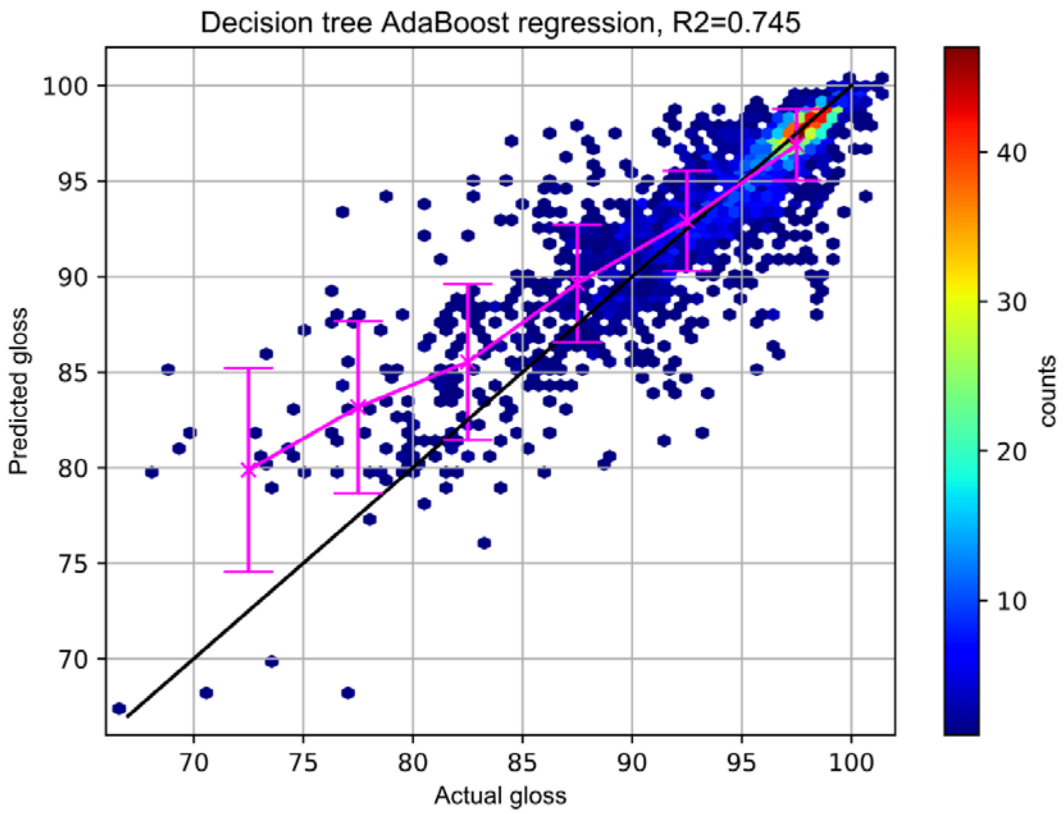

Fig. 1. Validation data of gloss prediction from regression decision tree with adaptive boosting

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Development of a Self-Configuring Controller for the Heliostat Aiming of Solar Tower Plants

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Currently, there exist many open-loop and about a handful of different closed-loop controllers to control the flux density of a solar power tower. Most control algorithms have many hyperparameters that have to be configured. The optimal performance usually depends on the correct setting of these hyperparameters. Furthermore, the optimal hyperparameter configuration might change when deploying the controller on a real plant as the real plant might diverge from the simulated plant. Also, during operation the characteristics of the real plant might alter, so that the controller needs to be reconfigured. The configuration at the plant should be done as fast as possible as a reconfiguration shall not cause a long downtime of the plant. In practice, if a problem occurs during operation a specialized engineer must be on site to reconfigure the control. Otherwise, the plant must be controlled manually or by a simpler but not so effective control. This has to be done carefully as an incorrect setting of the hyperparameters can also cause safety-critical conditions.

The aim of this work is to develop a self-configuring control system, which tackles the problems mentioned in the previous paragraph. Thus, the self-configuring control system shall automatically determine near optimal hyperparameters of the controller in a robust manner within a few trials.

Another area of application is to compare different receiver technologies fairly. For a fair comparison, not only the efficiency, but also the costs, which occur due to downtimes, component failure and maintenance costs, are important. Downtimes and component failure may be improved through a well-designed controller. The hyperparameter optimizer can facilitate a fair comparison. It can find a near optimal controller configuration for different receivers, which is optimized with respect to the same cost function. The cost function could consider not only the efficiency but also other objectives such as the lifetime and other economic objectives. It is also part of the work to identify a set of representative test scenarios, receiver types and heliostat fields and to develop a test environment, in which the efficiency of the controllers can be determined in a general way.

A scheme of the self-configuring system is shown in Fig. 1. It consists of the hyper optimizer, the controller and the controlled plant.

As a controller, the ant colony algorithm is used. It is an open-loop control algorithm based on a numerical model of the solar tower plant. The controller showed good performance with respect to computational time and the efficiency of the heliostat aiming [1]. However, as an open-loop control it cannot compensate for modeling errors or other disturbances. Thus, this control algorithm is transformed into a closed-loop controller by converting the numerical model to an adaptive numerical model compensating for modeling errors and disturbances. Thus, the controller is able to control the flux density on the receiver, restrict the maximum flux density and flux density gradient for different receiver shapes (e.g. flat and cylindrical).

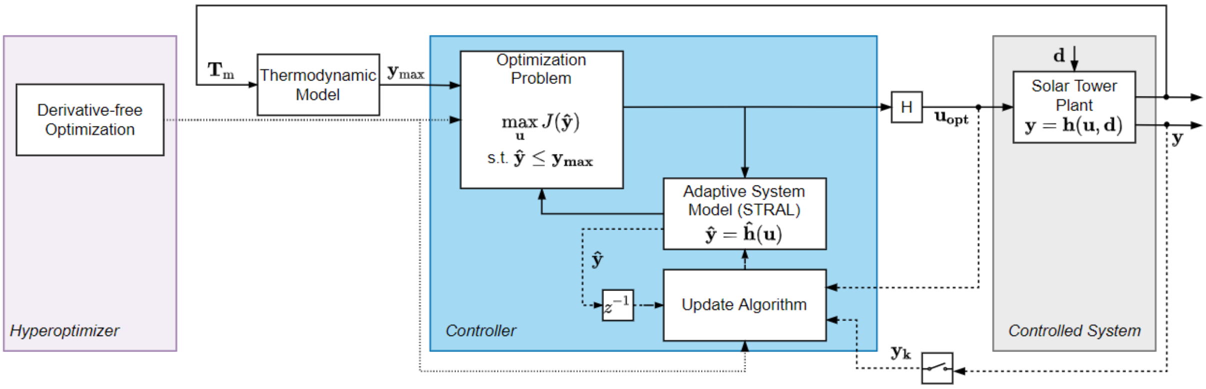

Fig. 1. Scheme of the self-configuring control system.

The objective of finding an optimal configuration in only a few trials is known under the term micro-data reinforcement learning in the robotic field [2]. Here, Bayesian optimization showed to be at least an order of magnitude more data-efficient than competing methods [2]. The data-efficiency can be enhanced especially by using prior knowledge from simulations to accelerate learning on the actual task (e.g. the real plant or time-consuming simulations). It also showed to be successful within the field of combinatorial optimization, which may be suitable for the ant colony optimization [3]. Furthermore, Bayesian optimization inherently can tolerate stochastic noise in function evaluations, which is useful, as measurements of sensors are usually subject to noise. In conclusion, Bayesian optimization is a gradient-free black-box global optimization method. At the same time, it is sample efficient and robust to noise. Due to these reasons, the Bayesian optimization algorithm is chosen as hyperparameter optimizer. However, it must be noted that Bayesian optimization is limited to low-dimensional parameter spaces (less than 20) [4]. This is not considered as a problem as most controllers do not have too many hyperparameters or the hyperparameter space can be reduced.

First studies already show that the Bayesian optimization can find hyperparameter configuration for the ant colony optimization that outperform these selected by proficient colleagues. In future, the Bayesian optimization will be applied to aim point control and to an actual solar tower plant.

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Heliostat Drift Correction by Parametrized Analysis

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Drift, a time-dependent pointing error, is a critical factor in central tower plants, severely affecting performance. This research consists on optical analysis on drift of tilt-roll heliostats considering geometrical parameters associated with their mechanical structure. Experimental drift of several heliostats (Fig. 1) on the very-high concentration solar tower (VHCST) at IMDEA Energy, Móstoles, Spain (40.3393 N, 3.8804 W) [1, 2] was evaluated and analyzed. Misalignments associated with geometrical parameters previously mentioned were obtained. Drift was revaluated considering these parameters, enhancing pointing accuracy.

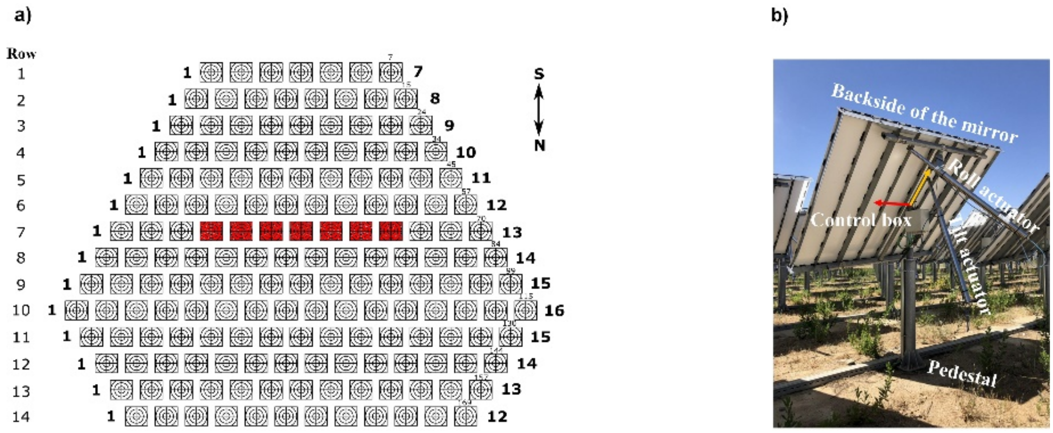

Fig. 1: (a) Solar field layout. Drift has been evaluated for heliostats marked in red; (b) Heliostat dual-axis tracker based in tilt and roll motions.

Drift was experimentally measured by recording flux maps along the day with a CCD camera (Prosilica GT1920) and a Lambertian target. This process is performed automatically by a customized in-house Matlab code able to control both solar field and camera. Corresponding drift curves were obtained by determining the displacement of the center of gravity of every flux map regarding target's center and plotting them as function of its location on the target (Fig. 2(a)) and the local time (Fig. 2(b)). During the drift tests, strokes of tilt and roll motors were recorded, as well as the offset needed to be applied to move the flux map centroid to the target's center. Discrepancy between computed strokes and the ones needed for pointing to center can be due to misalignments in several geometrical parameters of heliostat's structure.

Later, an optimization routine was employed for finding the misalignments values. The objective function to be minimized was:

$$J = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\Delta t_i^2 + \Delta r_i^2}, \qquad \text{Eq. (1)}$$

where N is the number of flux maps acquired along the day, and *Δt* and *Δr* are the differences between strokes of tilt and roll motors experimentally recorded for pointing to the target's center, and strokes numerically computed considering several geometrical parameters. In this study, two misalignments have been considered: pedestal rotation and facet canting error. The latter is given by two parameters: the facet tilt angle and the angle that indicates the facet tilt direction. Fig. 2 shows drift curves of heliostat 7-8 (eighth heliostat of the seventh row) before and after finding optimal values of the three parameters under study. It is seen how drift, which main component is vertical, is improved by this new algorithm, making the heliostat to aim properly during the whole day.

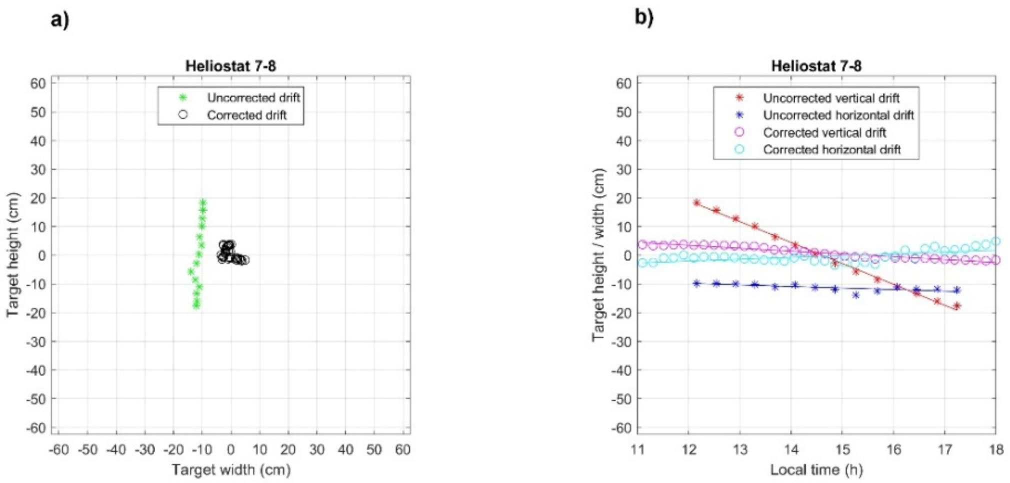

Fig. 2: (a) Drift curve along the day; (b) Drift vertical and horizontal components as function of local time, with their respective linear fits.

A new algorithm was tested with seven heliostats of the VHCST facility, reducing drift and significantly enhancing pointing accuracy. Future research will consider more geometrical parameters, such as pedestal tilt or lack of perpendicularity between both axes, for further pointing accuracy improvement.

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Session 5

Solar Energy, water, food nexus

Chair: Sixto Malato, CIEMAT-PSA

Application of Advanced Integrated Technologies (Membrane and Solar Photo-Oxidation Processes) for the Removal of CECs contained in Urban Wastewater

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The demand for water in the World is increasing every day, due to increased water use by humans for agriculture and industry, and lower availability due to climate change, soil salination and water pollution. Solutions for this problem can be found in the recycling and reuse of existing wastewater streams. To enable this, Contaminants of Emerging Concern (CECs) need to be removed from these urban wastewaters (UWW). These microcontaminants (MCs) originating from e.g. pesticides and pharmaceuticals, with concentrations in the range of ng to µg/L, often pass conventional wastewater treatment methods resulting in further water pollution, bioaccumulation, microbiological resistance, and endocrine disruption.

Advanced oxidation processes (AOPs) produce $^{\bullet}OH$ that are highly reactive and nonselective, ideal to remove MCs. Solar photo-Fenton, one of these AOPs, is based on the catalytic cycle of iron under solar UV-vis irradiation and H_2O_2, can be applied in a wide pH range using Ethylenediamine-N, N'-disuccinic acid (EDDS). Where classic AOPs demand sunny areas, electrooxidation AOPs (EAOPs), offer the possibility to degrade the MCs all day and year round, without the need of high levels of solar intensity and solar hours.

The application of membrane technologies in wastewater treatment is very common nowadays, as they offer cheap and effective ways to provide clean water. Thereby, the application of membranes significantly lowers the further processing costs when used for preconcentration. Especially Nanofiltration (NF) and ultrafiltration (UF) membranes are used, as they provide high flux, low fouling, and operate at low pressures. The application of special properties membranes, such as photoactivity, further guarantee their applicability.

The recovery of valuable nutrients from the same water streams lowers the operation cost by their economic valorization, and has a positive effect on the environment, as conventional methods, such as mining, and energy intensive synthesis and purification processes are not necessary. Another advantage is the prevention ecosystem disruption by their discharge. During this project several objectives in the field of NF, AOPs and material science were completed, with the aim to combine them to create synergetic hybrid systems.

First, the effects of salinity and operational parameters on preconcentration by NF were assessed, using Caffeine, Imidacloprid, Thiacloprid, Carbamazepine and Diclofenac, MCs commonly found in UWW, as target compounds. Concentrate and permeate volumes were then successfully treated by solar photo-Fenton at classical pH 3 and circumneutral pH using an Fe-EDDS complex, H_2O_2 and persulfate as oxidizing agents, at lab and pilot plant scale.

Further research was conducted with NF for the recovery of valuable nutrients. Herefore, NH^{4+} was successfully recovered from saline waters at pH 9, till different concentration factors (CFs), creating enriched ready-to-use permeate volumes for crop irrigation and fertilization. Solar photo-Fenton was again successfully applied at pilot plant scale using the previously found optimum parameters, for the degradation of before mentioned target compounds. This time at circumneutral pH, and up to pH 9, using the Fe-EDDS complex. The results were compared with the treatment of the saline concentrate volumes using different EAOPs and an electro cell containing a Boron Doped Diamond (BDD) anode. It was found that Solar Assisted Anodic Oxidation (SAAO) delivered the best performance, with minimum energy and reactives. Finally, phytotoxicity, and acute and chronic toxicity of the permeate volumes was assessed, showing that the permeate volumes till CF=2 can be used for irrigation after at least 50% dilution.

Thereby, different types of photoactive ceramic UF membranes were developed. Using SiC membrane supports, different Y-doped ZrO_2 and SiC/TiO_2 intermediate layers were successfully developed for the application of photoactive UF membrane layers, consisting out of ZrO_2 and TiO_2. The photoactive membrane layers were assessed using different target compounds such as humic acid (HA), phenol and before mentioned MCs. The photoactive membranes showed to possess self-cleaning capabilities, as fouling was significantly reduced by solar irradiation, resulting in flux restoration. Furthermore, an assessment of the bacteria retention by the TiO_2 UF membrane was performed by using P. aeruginosa as a target species.

The final work in this project involves the assessment of Caffeine, Imidacloprid and Carbamazepine degradation by autochthone algae, grown in secondary effluent of an UWW treatment plant, using a pilot plant raceway pond reactor. Differentiating the MC concentration in the secondary effluent over time, as well as the absorbed concentration by the algae.

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Towards the operation of solar membrane distillation systems in batch for concentration of brines

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Membrane distillation (MD) is a thermal separation process commonly used for desalination, in which steam molecules pass through a microporous hydrophobic membrane, and of which driving force is the difference in vapor pressure gradient, created by a temperature difference between both sides of the membrane. Thermal energy is needed to desalinate water with this technology, which is often supplied using a solar collectors field. The advantages of MD compared to other desalination processes are: rejection of 100% of the non-volatile ionic solutes can be easily reached; low operating temperatures compared to conventional distillation (not higher than 80 ºC); low operation pressures in comparison with nanofiltration or reverse osmosis (equal or lower than atmospheric), resulting in less membrane fouling; capacity to treat solutions with much higher saline concentrations (such as the brine output from reverse osmosis plants) or with certain contaminants that can affect conventional non-hydrophobic membrane; and without the need of physical or chemical pre-treatments as required in other membrane technologies.

Operation in pilot-scale MD plants has been focused on single-pass desalination. However, the recovery ratio, which is the quotient of the permeate flow rate and the feed flow rate, is very low in MD operation with spiral-wound modules. Therefore, to achieve higher concentration of the feed, it has to be recirculated through the module, operating in batch. In batch operation, the brine is concentrated further and its volume reduced, as the permeate is separated. This type of operation is expected to achieve high permeate fluxes without a strong penalty in thermal energy efficiency [1]. In addition, as a result of batch operation, besides the permeate a highly concentrated brine is obtained, which could subsequently be subject to further evaporation processes to achieve zero liquid discharge (ZLD) desalination.

Experiments have been carried out at Plataforma Solar de Almería's MD pilot plants for several years. Thermal energy is supplied using a solar field of 10 flat-plate collectors of 2 m^2 effective area each one; this field is capable of supplying a nominal thermal power of 7 kW_{th} at an outlet temperature of 90 ^{o}C. Up to date, modules have been analysed in stationary conditions, thus without recirculating the feed for further concentration. Currently, two modules are under evaluation for this work. Their main difference is the feed velocity for the same feed flow rate. Both are spiral wound modules and their operational mode is V-AGMD (vacuum air gap membrane distillation). Working in this mode increases the performance compared to AGMD (air gap membrane distillation) [2]. To characterize the modules, the permeate productivity, the thermal energy efficiency and the permeate quality are typically analysed.

For conducting this research, steady state experiments will be carried out with feed salinities between 35 and 210 g/L, increasing in intervals of 35 g/L. Other variables of the experiments are: temperature of the inlet stream to the evaporation channel, temperature of the inlet stream to the cooling channel and feed flow rate. From these experiments, stationary empirical models will be obtained for each module. After that, a dynamic model will be developed to be used for simulating batch operation. The inputs of the model will be: initial volume and concentration of the feed, final volume and the aforementioned operation conditions. The outputs will be: final concentration of brine, permeate productivity over time, volume of permeate produced, and thermal efficiency indicators. Finally, the dynamic model will be validated with batch experiments performed with each module.

The results obtained so far correspond to the initial steady state experiments required for the model. They have been obtained for one of the modules (AS24), that has 6 channels of 5 m long and effective membrane area of 24 m^2. Up to date, tests have been performed for feed salinities 35, 70 and 105 g/L. As salinity increases, the permeate flux decreases for the same operation conditions. The temperature of the inlet stream to the evaporation channel is the most influential parameter in the process: as this temperature increases, the permeate flux and the energy efficiency increase. Other important parameter is the feed flow rate, as this increases, the permeate flux does so too, but the thermal energy efficiency decreases. The temperature of the inlet stream to the cooling channel is the least influential, but when it decreases, the permeate flow rate increases.

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Potabilization of water with zero-liquid discharge using low temperature solar thermal energy

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Access to drinking water is a major issue for the 21st century on a global scale. This vital resource is still inaccessible to 2 billion people, due to the absence or inefficiency of sanitation facilities, which affects 2.3 billion people in the inter-tropical zone. Biological micro-organisms (bacteria, viruses, protozoa and helminths) present in poorly sanitised water are the cause of waterborne diseases and mortality [1]. Various water treatment techniques exist to address these problems: chemical treatments such as chlorination or ozonation that require the use of chemical consumables, and physical treatments (membrane filtration) or thermal treatments (pasteurisation) that require energy consumption [2]. The present study aims to evaluate the latter two water treatment techniques exploiting solar thermal energy, which can be easily delivered by conventional solar collectors at low temperature (60-80°C), in order to develop a simple, robust process that is suitable for remote sites with an abundant solar resource that are isolated from sewerage networks.

The first part of the study deals with the evaluation of a thermo-hydraulic process implementing an ultra/nano filtration membrane, powered by solar thermal energy (Fig. 1). In this process the thermal energy is directly converted into hydraulic energy by a Rankine type thermodynamic cycle (ORC) to allow the pressurization of the water to be treated by the membrane filtration process. The hydraulic energy of the produced concentrate is recovered to pre-pressurise the water to be treated and thus improve the energy efficiency of the process [3].

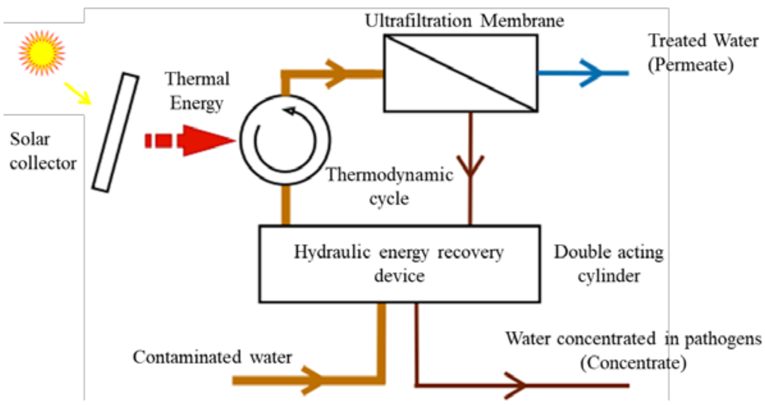

Fig. 1. Block diagram of the membrane filtration process

The second part of the study is dedicated to a pasteurisation process using solar thermal energy. This continuous process, presented by the Fig. 2, consists of heating the water to be treated and maintaining its temperature in a reservoir for a given period of time to kill the pathogens. At the output of the process, a heat exchanger is implemented to recover the thermal energy of the pasteurised water to preheat the water to be treated, thus improving the energy performance of this process.

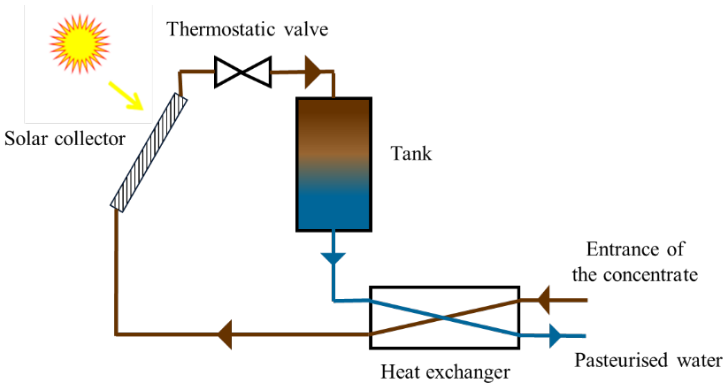

Fig. 2. Diagram of the pasteurisation process

A simplified steady-state modelling of these two solar processes has allowed us to estimate their performances in terms of daily treated water production and specific energy consumed. Thus, it would be possible to obtain during the summer season a daily production of treated water of about 1.2 m^3/m^2 of installed solar collector for the thermo-hydraulic membrane filtration process and of about 0.45 m^3/m^2 for the solar pasteurisation process. The specific energy consumed by each of the processes, related to the solar irradiation, is respectively 4.5 kWh_{solar}/m^3 and 13 kWh_{solar}/m^3. These first interesting results showed the relevancy of these two processes from an energy point of view and also their technological feasibility: the filtration process, which nevertheless discharges an effluent highly concentrated in pathogens has a very interesting energy performance in contrast to the pasteurisation process which however does not discharge any effluent (all the water is treated).

The third part of this study is naturally focusing on the feasibility and the performance evaluation of the coupling of these two processes to obtain a hybrid solar process for the full treatment of contaminated water with zero discharge: the concentrated water leaving the membrane process is then treated downstream by the solar pasteurisation process (Fig. 3). The performance of such an association obtained in a first evaluation is very promising: the daily production and the specific energy consumption have values between those of the membrane filtration process alone and those of the pasteurisation process (0.8 $m^3/day.m^2$ and 6.5 kWh_{solar}/m^3) with the great advantage of eliminating completely all pathogens present in the contaminated water. In addition, this hybrid process has comparable performances as those obtained by solar ultrafiltration processes using photovoltaic solar panels, in which the water is pressurized by electrical pump.

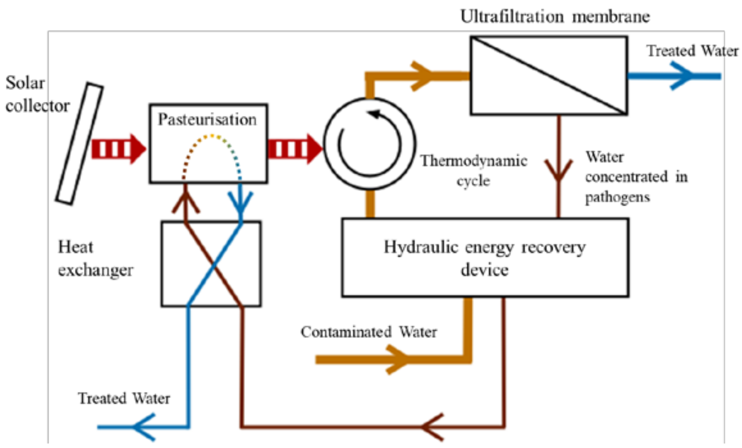

Fig. 3. Block diagram of the hybrid process

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Middle-scale PTC power plant coupled with desalination: A case study of METU Campus

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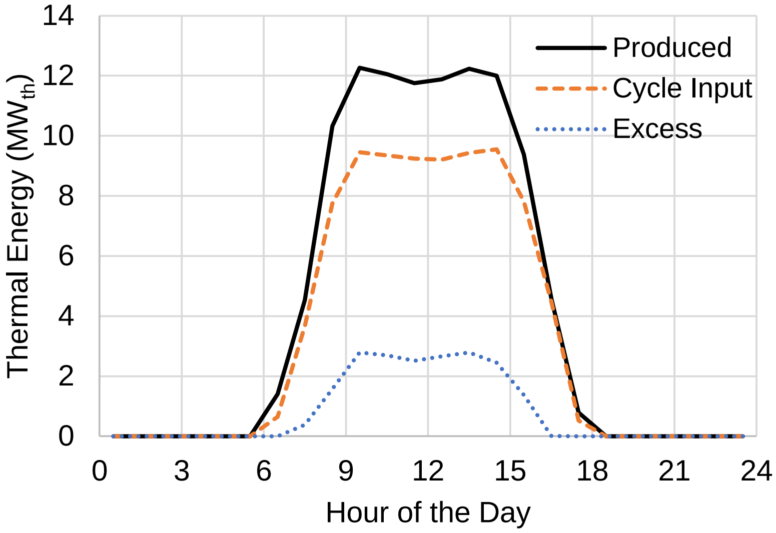
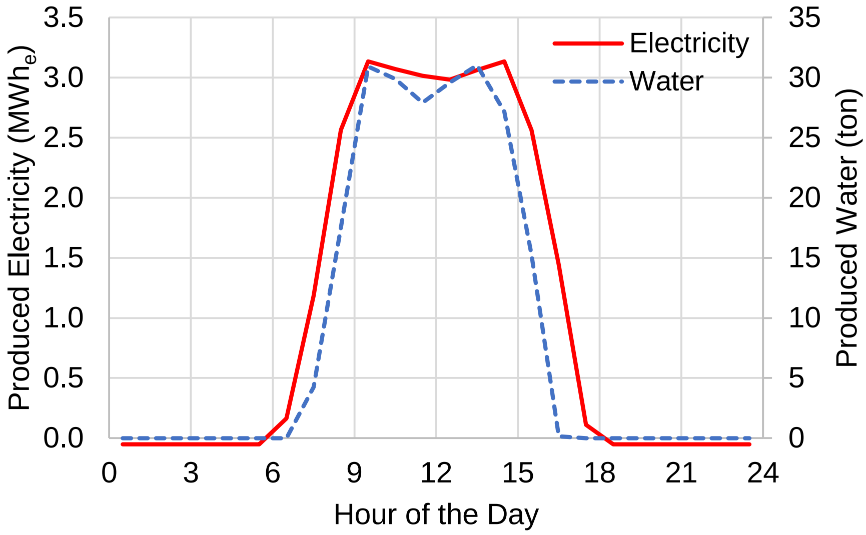
Since carbon-based fuels are depleting rapidly, alternative renewable energy resources have to be used for the world's energy demand. Solar energy is one of the best alternatives for producing electricity, and concentrated solar power systems (CSP) can utilize solar energy for energy generation. Similarly, the world suffers from water scarcity, especially middle east region. Desalination is one of the solutions for the water scarcity problem, and the energy-intensive part of the desalination can be solved using solar energy. About 70% of the water consumption of the region, where the campus resides, comes from abroad via a pipeline, and the electricity is produced by burning fuel oil, and electricity is produced by burning fuel oil. Hence, in this study, Middle East Technical University Campus is analyzed as a case study. As a result, Parabolic Trough Collector (PTC) power plant coupled with desalination would be a sustainable solution for the campus for electricity and water consumption because solar energy is abundant on the island.

This research focuses on the performance analysis of a PTC power plant with desalination to meet the campus electricity and water demand. This suggested hybrid plant consists of a 3.5 MW installed capacity for PTC with a solar multiple of 2. Instead of storing the excess thermal energy, it is used for the thermal energy need of the desalination plant. The hourly thermal and electrical energy production from the PTC plant is simulated using NREL's System Advisor Model (SAM) in addition to the Levelized Cost of Electricity. The utilized and excess thermal energy is input to an MS Excel model where the desalinated water is calculated and compared with the campus water demand. Overall, the ratios of electricity and water demand met by the suggested hybrid system are reported.

The results show that the annual electrical energy production is 9.05 GWh_e, and the excess thermal energy is about 7.05 GWh_{th} which yields about 78,300 tons of desalinated water production compared to 101,560 tons of annual water consumption of the campus. With this system, all the electrical demand and about 77% of the domestic water use of the campus could be provided by the suggested hybrid system. The cost parameters for electricity and water production are obtained. The overall results suggest that hybrid systems could be a solution for future water and electricity demand in regions where sufficient sunpower is present.



(a)



(b)

Figure 1. Daily average of annual (a) produced, power cycle input and excess thermal energy, (b) electricity and water produced from the suggested hybrid plant.

Innovative strategies for urban wastewater reclamation based on solar and conventional treatment integration

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Freshwater resources are under increasing stress, as well as persistent water scarcity problems and/or bad water quality. To mitigate the problem, treated wastewater reuse is an alternative water resource that needs to be properly integrated in the water cycle, since such practices would improve the efficient management of water resources making it sustainable, especially in regions with a high level of water stress.

One of the main problems currently on wastewater reclamation is the presence of contaminants of emerging concern (CECs), as well as pathogen microorganisms, antibiotic resistance genes, or disinfection by-products among others, which are presumed to be harmful to humans and ecosystems. Furthermore, over the last few years, it has been demonstrated that different classes of CECs can be absorbed through the roots of the plants and then transferred to other parts when crops are irrigated with reclaimed water [1].

Therefore, there is still a need to implement new wastewater integrated technologies that allow adapting water quality for reusing purposes to current restrictions, regulations and challenges, as the European Parliament and the Council have published (5th June 2020) the new EU Regulation 2020/741 regarding the minimum requirements for the reuse of water. This Regulation will be mandatory from 26th June 2023 in all the Member States.

The main objective of this work will be the investigation of new advanced tertiary treatment integration at pilot plant scale based on green technologies and renewable energy sources for fulfilling European and National regulations to assure safe wastewater reuse in crop irrigation.

The specific objectives are the evaluation of advanced analytical methods for specific persistent microcontaminants identification and quantification as well as microbial standards measurement protocols in actual UWWTP effluents; experimental design and testing of different tertiary integrated technology strategies at pilot plant scale.

Identification of transformation by products and their fate in the environment, and finally, optimization of operating parameters of best tertiary treatment strategy selected focusing on efficient CEC removal, pathogens and ARG inactivation and analysis of acute and chronic toxicity to ensure preliminary safe potential reuse of treated wastewater.

The project where my PhD is based aims at developing new technologies based on solar advanced oxidation processes for urban wastewater (UWW) reclamation. The project aspires to introduce novel aspects on the development of new photocatalytic systems, the assessment of new microbial pathogens (coliphages and antibiotic resistant bacteria and genes (ARB and ARG)) and organic microcontaminants (OMCs) as treatment quality indicators, the continuous flow operation of pilot plant photoreactors and the development of a making-tool system based on water quality monitoring for UWW reclamation.

Among AOPs, photocatalytic processes based on semiconductors (such as TiO_2 or iron oxides) and on organic photocatalysts have gathered considerable attention, in particular those that can be activated by sunlight [2]. The efforts are focused on developing new photoactive materials based on TiO_2 to improve its solar photocatalytic efficiency [3].

In recent months, different types of new supported photocatalysts have been tested at lab for decontamination and disinfection of wastewater within the framework of the NAVIA project. Obtaining the best results in decontamination with the TiO_2 photocatalyst supported on glass wool, which, in addition, showed a large number of cycles of efficient reuse activity.

On the other hand, the best results for *E. coli* and *E. faecalis* disinfection were obtained with the supported riboflavin catalyst. Both new supported photocatalysts have been tested under different operating conditions in a solar simulator SUNTEST XLS+ (Atlas Material Testing Solutions). Following working plan will be focused on testing new photocatalysts in different photoreactor design and optimize the mechanism of action, with a mixture of several different pollutants (OMCs, pathogens and ARG) and actual UWW treatment plant effluents.

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Technological developments for solar multi-effect distillation processes

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Multi-effect distillation (MED) is an attractive sustainable solution for its simultaneous application in water mining and desalination processes [1]. This technology, combined with solar energy, also contributes to the decarbonization of the desalination industry [2], increasing its potential in this sector even more. The focus of this research work is to support the MED industry in the development of new components and systems and contribute to the development of MED technology to make it more competitive when compared to other desalination processes. Both approaches can be achieved by proposing new standards about the performance indicators of the MED process together with the application of innovative technological improvements and advanced control techniques.

The research activity consists of three major lines of work: (i) standardization of experimental procedures for a reliable evaluation of performance indexes in MED processes, for which automation of low-level operation must be defined and implemented. (ii) Application and evaluation of new technologies aiming to increase the performance of a MED plant. The main strategy is the increase of the current limits of the Top Brine Temperature (TBT) [3], by means of a nanofiltration membrane-based pretreatment of the water, aiming to remove the divalent ions that could provoke scaling on the heat exchanges surfaces and reduce the heat transfer rates [4]. (iii) The last approach concerns a control problem. Usually, MED plants are steadily operated at the conditions for which they were designed [5]. This third work line focuses on developing a hierarchical control architecture for the coupling of a variable energy source (i.e., solar energy) with a MED plant while keeping the operation as efficient as possible by modifying the operating point. This will be accomplished by following the setpoints generated by an optimizer, which will be fed by a model of the plant and the predicted energy generation. A diagram of the proposed methodology can be seen in Figure 1.

All the developments abovementioned will be validated at the pilot facilities located at Plataforma Solar de Almería (PSA) [6].

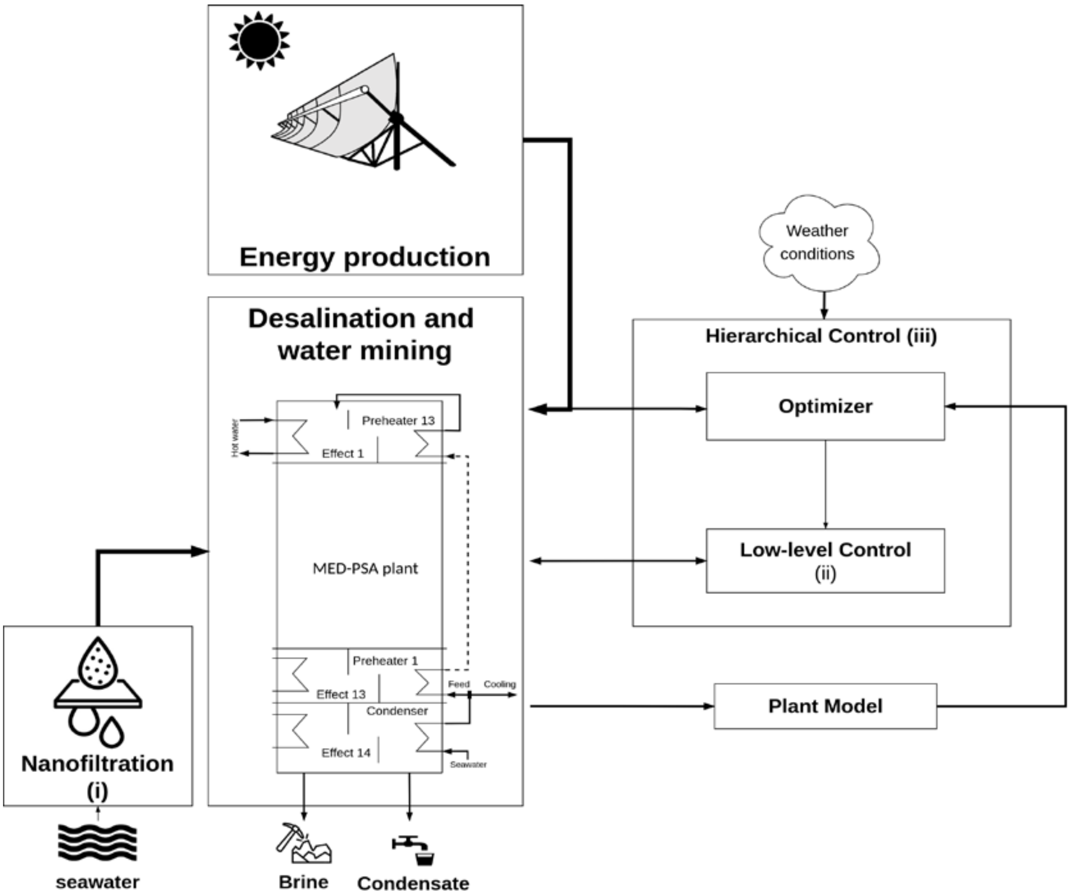

Figure 1. Concept flow diagram of the proposed methodology

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Combination of oxidants for simultaneous bacterial inactivation and micropollutant removal in real WWTP effluents by the solar photo-Fenton process for reuse in agricultural irrigation

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The regeneration and reuse of wastewater in Spain is still limited and is implemented mainly in regions with severe water scarcity. The reuse of treated effluent from wastewater treatment plants (WWTPs) for agricultural irrigation has significant potential to reduce pressure on freshwater sources. The new European Regulation on minimum requirements for the reuse of water (EU) 2020/741 [1], introduces greater restrictions on the maximum permissible values of certain parameters with respect to the Spanish regulation in force (RD 1620/2007) [2]. Consequently, the current regeneration facilities must improve their treatment systems or incorporate new treatments to comply with the new quality requirements. In addition to the regulated parameters, the reuse of water must consider anthropogenic organic micropollutants, such as UV blockers, pharmaceuticals, drugs, as well as bacteria and antibiotic resistance genes, collectively designated as contaminants of emerging concern (CEC). They can result in severe effects on human health and environment. Consequently, there is an urgent need to develop new tertiary treatments, alternatives to conventional treatments such as ozonation and chlorination, since it is necessary to prevent the formation of harmful subproducts and to eliminate micropollutants, which is not possible with chlorination [3]. In this regard, the solar photo-Fenton process is one of the most efficient advanced oxidation processes (AOPs), which are innovative and low-cost treatments based on catalysis and photochemistry. Its effectiveness is based on the large amount of $HO^{\bullet}$ generated by the catalytic oxidation-reduction cycle between iron ions (Fe^{2+} and Fe^{3+}), hydrogen peroxide (H_2O_2) and UV-vis radiation. In addition, this process does not generate toxicity in the treated effluent [4,5]. Regarding the photoreactor, the raceway pond reactors (RPRs) have recently been introduced with promising potential for the disinfection and decontamination of WWTP secondary effluents using solar photo-Fenton. These reactors are made of low cost materials and the liquid depth can be easily varied to change the light path length [6].

Although the operation of the process at acidic pH is the optimal condition for the photocatalytic activity of iron, currently research is focused on optimizing the process at neutral pH with iron complexes, to reduce acidification and neutralization costs associated with the pre- and post-treatments, respectively, as well as avoiding the increase in water salinity [7]. In this regard, the continuous flow operation of the solar photo-Fenton process with Fe (III)-NTA is the most cost-effective option for micropollutant removal. When the treatment is applied for both decontamination and disinfection of WWTP secondary effluents, disinfection is the limiting step. Therefore, the need to investigate alternatives that allow reducing the treatment times associated with the disinfection step arises.

This research addresses the assessment of the combination of oxidants, hydrogen peroxide (H_2O_2) and sodium hypochlorite (NaClO), for the simultaneous bacterial inactivation and micropollutant removal in WWTP secondary effluents using Fe (III)-NTA as iron source under solar radiation. Both oxidants react with iron generating radicals capable of eliminating microorganisms and micropollutants, and regenerated water without chlorination by-products could be obtained.

To this end, experiments were conducted in 5-cm deep RPRs using 19-L batches of simulated WWTP secondary effluent doped with *Escherichia coli* K-12 (10^3 CFU/mL, *E. coli* K-12) and sulfamethoxazole (50 µg/L, SMX), as a reference strain and model micropollutant, respectively. The average solar irradiance was in the range of 25 – 35 W/m^2. Firstly, the H_2O_2/Fe (III)-NTA and NaClO/Fe (III)-NTA processes were assessed and compared. For H_2O_2/Fe (III)-NTA process, oxidant concentrations were 1.47 mM (50 mg/L), 2.94 mM (100 mg/L) and 4.41 mM (150 mg/L) and Fe (III)-NTA concentrations were 0.1 mM (5.5 mg/L) and 0.2 mM (11 mg/L) at 1:1 molar ratio. As for NaClO/Fe (III)-NTA, active chlorine concentrations of 10, 20 and 30 mg/L with 0.1 mM Fe (III)-NTA were studied. The best oxidation conditions obtained were 1.47 mM H_2O_2 /0.1 mM Fe (III)-NTA for micropollutant removal, achieving more than 90% of SMX removal in 20 min, and 10 mg/L active chlorine/0.1 mM Fe (III)-NTA for disinfection, achieving *E. coli* inactivation below de detection limit (1 CFU/mL) in 10 min.

Afterwards, the solar photo-Fenton process using both oxidants was assessed and validated in real WWTP effluents of different composition collected from two municipal wastewater treatment plants called *El Toyo* and *El Bobar* located in Almería, southeast of Spain. The use of both oxidants allowed to combine the high efficiency of bacterial inactivation of NaClO with the capacity of H_2O_2 to remove micropollutants achieving the treatment goal in shorter times than those currently applied.

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Scaling up of raceway pond reactors for advanced treatment of WWTP secondary effluents by solar photo-Fenton process

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Solar photo-Fenton is one of the most studied advanced oxidation processes (AOPs) as an alternative to conventional tertiary treatments for wastewater regeneration. This is due to its high efficiency in terms of simultaneous disinfection and microcontaminant removal. Although at first, this process was carried out in photoreactors such as Compound Parabolic Collectors (CPCs), recent studies at pilot scale have been focused on the use of raceway pond reactors (RPRs) with advantages such as the low construction cost and the greater treatment capacities [1].

The RPR is divided into two channels and mixing is carried out by means of a paddlewheel. At small pilot scale, these reactors are operated as complete mixing. At large scale, all studies on fluid dynamics are related with mass culture of microalgae, and laminar flow along with large mixing times have been reported [2,3]. Another difference is the hydraulic residence times; tens of minutes for the solar photo-Fenton process versus days for microalgae cultures.

This work assesses, for the first time, the effect of fluid dynamics on the solar photo-Fenton process at demonstrative scale RPRs. For this, an RPR of 100 m^2 (25 m length x 2 m width channels) has been built, based on the knowledge of microalgae production. The reactor is placed in the wastewater treatment plant (WWTP) called 'El Bobar', located in the city of Almería (Spain), and managed by the FCC Aqualia company.

To carry out the fluid dynamic study of the photoreactor, stimulus-response tests were performed. To this end, pH pulses were generated with NaOH (50%, w/w) to raise the pH value by one point, as described by Mendoza et al. [4]. The liquid depth (10 and 18 cm) and the paddlewheel speed were modified, to achieve different flow regimes. The motor frequency (15, 25 and 35 Hz) was the operating variable to reach different paddlewheel speeds. The results showed that the higher the liquid depth, the greater the circulation speed and, therefore, the shorter the mixing times. Nevertheless, these mixing times are overly high (> 45 min). Furthermore, the Bodenstein number was calculated to quantify the degree of axial mixing, pointing out that the behaviour of the reactor is plug flow.

In addition, to check the mixing effect on the solar photo-Fenton process, batch tests of 2 h were carried out at acidic pH, at three motor frequency studied and with the higher liquid depth (18 cm). The average radiation was 35 W/m^2 and the reagent concentrations were 1.47 mM H_2O_2 and 0.1 mM $FeSO_4$. The WWTP secondary effluent was doped with 100 µg/L of Acetamiprid as a model microcontaminant due to it is a highly recalcitrant contaminant. Sampling was carried out simultaneously in five different points of the reactor every 15 min. The results showed that, despite the high mixing times in all the conditions tested, 70% of Acetamiprid degradation was achieved after one hour of reaction and up to 87% degradation was reached after 2 hours of treatment.

The obtained results show that, for the continuous flow operation of the solar photo-Fenton process in an 18-cm deep RPR with this geometry, a minimum hydraulic residence time of 60 min would be required. Under these conditions, a treatment capacity of 144 m^3/day would be achieved working 8 hours per day. To improve these operating conditions, a change in the geometry of the reactor is recommended.

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Control and optimization strategies applied to irrigation systems based on desalination technologies for protected agriculture

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In recent years, the problem of water scarcity has been becoming a limiting resource in many agricultural areas. This resource limitation causes 4 billion people in the world are currently facing severe water scarcity. Furthermore, the agricultural sector consumes the most water, followed by the municipal and industrial sectors [1]. Thus, the continued growth of these sectors is contributing to the overexploitation of freshwater reserves, exceeding the renewal limit of this resource. Particularly on agricultural holdings, and considering the successive increase in world population and the continuing limitation of cultivable land, the traditional way of farming will face many difficulties in satisfying the growing demand for food. The greenhouse-based cultivation can become an effective crop-system to solve the mentioned problem. This protected agricultural provides a suitable growing environment for crops, achieving higher yields than outdoor cultivation, and using mainly water and energy.

Spain has a total area of 70,000 hectares covered under plastic, being the province of Almería that most uses this form of intensive agriculture, with approximately 43% of the national total [2]. In this Mediterranean province, the problem is even worse due to a severe structural water deficit. This magnitude of the problem is increased for the energy necessities of these systems. Energy management is necessary to maintain the right conditions for crop yields, generating optimal conditions for sustainable food production. For this, the relationship has been called “water-energy-food (WEF) nexus”, which has been widely studied the last years as one of the crucial problems facing humanity for sustainable development [3]. Therefore, it is necessary to optimize the operation of the greenhouse to improve its use and the efficiency and sustainability in the use of water and energy resources.

In this sense, desalination technologies are progressively becoming a fundamental necessary element, especially in arid or semi-arid areas with water scarcity, such as Almería. These technologies require intensive power generation systems for their operation, so they must be associated with renewable energy sources for their economic sustainability. The use of renewable energy sources in desalination processes not only reduces the economic costs of such processes, but also replaces the use of traditional sources such as fossil fuels, thus contributing to sustainable and efficient environmental development. In this context, the processes of Reverse Osmosis (RO) and Membrane Distillation (MD) with the support of solar energy, are appropriate technologies for the development of small self-sufficient desalination plants, which can be implanted in isolated areas with good solar irradiance conditions.

The main objective that is intended to pursue in this thesis is the modelling, design and implementation of control techniques and optimization algorithms that contribute to the development of commercial MD and RO systems as a source of water resources in greenhouses. This doctoral investigation plan is included within the EQC 2019-006658-P project: Sustainable, Autonomous, Connected and Open Intensive Cultivation System (AgroConnect). This project is distributed in four different subsystems, of which this work focuses on the energy and water generation system, which consists of a photovoltaic generation facility with electrical storage capacity for the complementary supply of irrigation, desalination, climate control, and other electrical consumption systems of the experimental greenhouse, as well as a RO desalination plant, which constitutes the first water generation system from seawater. The resulting osmotic water will mainly supply a fertigation system, which, together with the addition of nutrients and the implementation of advanced control architectures, will make use of fertigation decision support systems and ensure full integration with climate control. MD is the second system of water generation, and it will desalinate the brine generated by the RO system, also with the support of solar energy. Likewise, the resulting distillate will be used to supply humidification equipment, which will make it possible to add humidity to the environment if would be necessary, and even to saturate the greenhouse environment if tests are required.

The particular objectives of this research project are i) to study in detail the reverse osmosis and membrane distillation technology to accurately represent the behaviour of the installations ii) to design advanced control algorithms based on model-based predictive control and optimization techniques to reduce water generation costs, making maximum use of the solar resource, and taking into account the plant operation modes and iii) to analyze the economic impact achieved by using the proposed control techniques. Finally, it is also intended to study the economic and energy benefits of the whole control structure, based on the results of real experiments, and compare them with the strategies currently used in different installations.

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Optimal management of heterogeneous resources of the water-energy-food nexus in greenhouse crop production

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The growth of the world population, together with other environmental factors such as climate change, are putting great pressure on the efficient use of resources to maintain the economy and ensure environmental sustainability. Out of this global concern has emerged the commonly known "water-energy-food nexus (WEF)" [1], which takes into consideration the relationship between these three fundamental resources for human welfare. The WEA nexus has been recognized as a crucial problem that humans must face for the optimal and sustainable development of humankind [2]. One environment where this relationship can be observed is in greenhouse agriculture, where the use of water is fundamental to create the right conditions for food production, while energy is necessary to maintain the right condition for the crop. This thesis project aims to contribute to the analysis, design and application of modeling, control and optimization techniques to achieve an optimal resource management (electricity, cooling/heating, water, CO_2), particularly in a greenhouse-based agro-industrial environment, based on economic aspects and energy efficiency, with special emphasis on the use of renewable energies.

The main objectives of this thesis project are i) Development of physical models of resource generating, consuming and storing systems with a modular philosophy and different levels of abstraction that allow short, medium and long-term dynamic simulation at the system level and their use in optimization. ii) Experimental validation of the developed models under stationary and dynamic conditions. iii) Application of the designed models in the development of production optimization and coordination strategies from the energy, economic and environmental points of view. iv) Development of sensitivity and uncertainty analysis studies using indicators based on energy and economic aspects in the reference production facility. v) Study of the economic and environmental impact produced by introducing the optimization and coordination strategies proposed as a result of the thesis project in the reference facility shown in *Fig.1*.

For the modeling of heterogeneous systems, the use of methodologies based on the paradigm of energy hubs [3] is proposed. A novel contribution of the present thesis project is the inclusion of game theory for the analysis and formulation of management techniques for the optimization of heterogeneous resources [4]. Through its application, the aim is to optimize the synergy between the several elements of a system composed of multiple sources of energy, load or storage. In this way, the maximum benefit will be obtained from the cooperation between each of the systems. The control strategies, according to the literature presented in this paper, will try to be implemented with optimal and centralized control algorithms. For the optimization of setpoints and the set of processes and systems, both heuristic and analytical techniques will be used, as well as evolutionary algorithms and high-performance computing techniques, among others.

The present project aims to make use of these techniques in an agro-industrial environment located at the Institute for Agricultural Research and Training (IFAPA) in La Cañada (Almería) shown in *Fig.1*. The facility is provided with solar thermal and photovoltaic facilities, water desalination and biomass cooling-heating systems with CO_2 reuse.

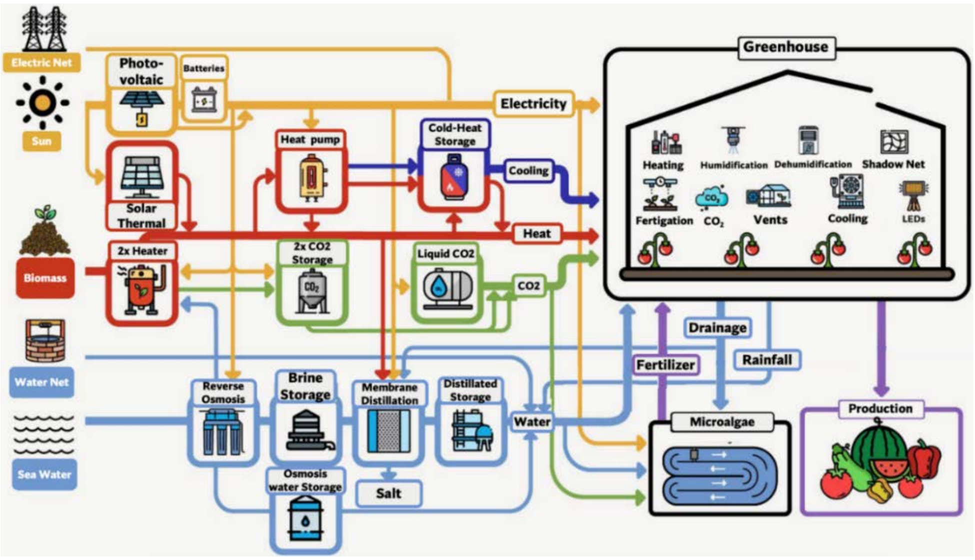

Fig.1. Agro-industrial facility IFAPA UAL.

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