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1 Introduction

The HYDROSOL research group has introduced the concept of monolithic honeycomb solar reactors for performing redox pair-based cycles for the production of hydrogen from water using solar energy [1] inspired from the well-known automobile catalytic converters. The basic idea proposed, developed and demonstrated within the HYDROSOL and HYDROSOL-II projects was to combine a monolithic honeycomb support structure capable of achieving high temperatures when heated by concentrated solar radiation [2], with a redox pair system [3,4] suitable for the performance of water dissociation and for regeneration at these temperatures. With this configuration, the complete operation of the whole process (water splitting and regeneration of the metal oxide) can be achieved by a single solar energy converter. In addition, by using a two-chamber reactor the two steps of the cycle can be performed in parallel and therefore a hydrogen production process in a quasi-continuous mode can be achieved [5] on a reactor configuration not involving either moving parts or moving solid particles. The present work describes the realisation and successful test operation and pilot plant demonstration of this technology in a 100 kW scale on a solar tower platform.

2 Reactor

The successful testing and the suitable behaviour of the laboratory-scale reactor in the earlier stages of the project [6] have provided a basis for the design of the pilot reactor. Whereas the general reactor concept was kept - i.e. a dual module solar hydrogen production reactor consisting of two adjacent reaction chambers that provides for quasi-continuous solar hydrogen production since one module splits water while the other is regenerating the redox material - the scale-up of the reactor from 10 kW_{th} to 100 kW_{th} was basically realised by increasing the absorber surface. Three times three (a total of 9) individual pieces of square-shaped monolithic honeycomb absorbers made of siliconized silicon carbide (siSiC) each with dimensions of 146x146 mm were assembled as one absorber module and mounted to form a square with slightly shaped concave surface (Fig. 1a).


(a) (b)

Figure 1: Pilot, 100 kW-scale HYDROSOL solar reactor: (a) front face of reactor's individual chamber consisting of nine SiC square-shaped blocks; (b) dual chamber reactor completely assembled and installed at the SSPS tower, ready for operation.

3 Operation and Control Concept

In a solar platform facility, the different heat demands of the two steps of the cycle are realized in the HYDROSOL process not by moving the reactors but by adjusting the flux density on each reactor module when the status of the cycle is switched from regeneration to splitting and vice versa by re-alignment of a part of the solar concentrators. Thus, for powering the two modules of the reactor with different solar flux, the heliostat field (Fig. 2a) is "partitioned" into different parts that are actuated separately [7]: a "fixed" part tracked as usually in solar fields covering the basic load for both receiver modules and a "flexible" part which is also tracked but additionally re-focused at regular intervals simultaneously to the switch over of modules from one process step to the other (Fig. 2b). During the splitting process, steam is fed in from a steam generator into the so-called "east" reactor chamber operating at e.g. 800°C. At the same time, nitrogen as flushing gas is fed into the "west" reactor chamber operating at e.g. 1200°C, in order to release the oxygen from the metal oxide redox system. After a half-cycle of 20-30 minutes, a part of the heliostats' focus is moved from the west to the east chamber to realise the necessary temperature increase up to 1200°C to perform the regeneration of the redox system in the east chamber, whereas the west chamber is cooled down to 800 °C to proceed with the splitting of water at that temperature.

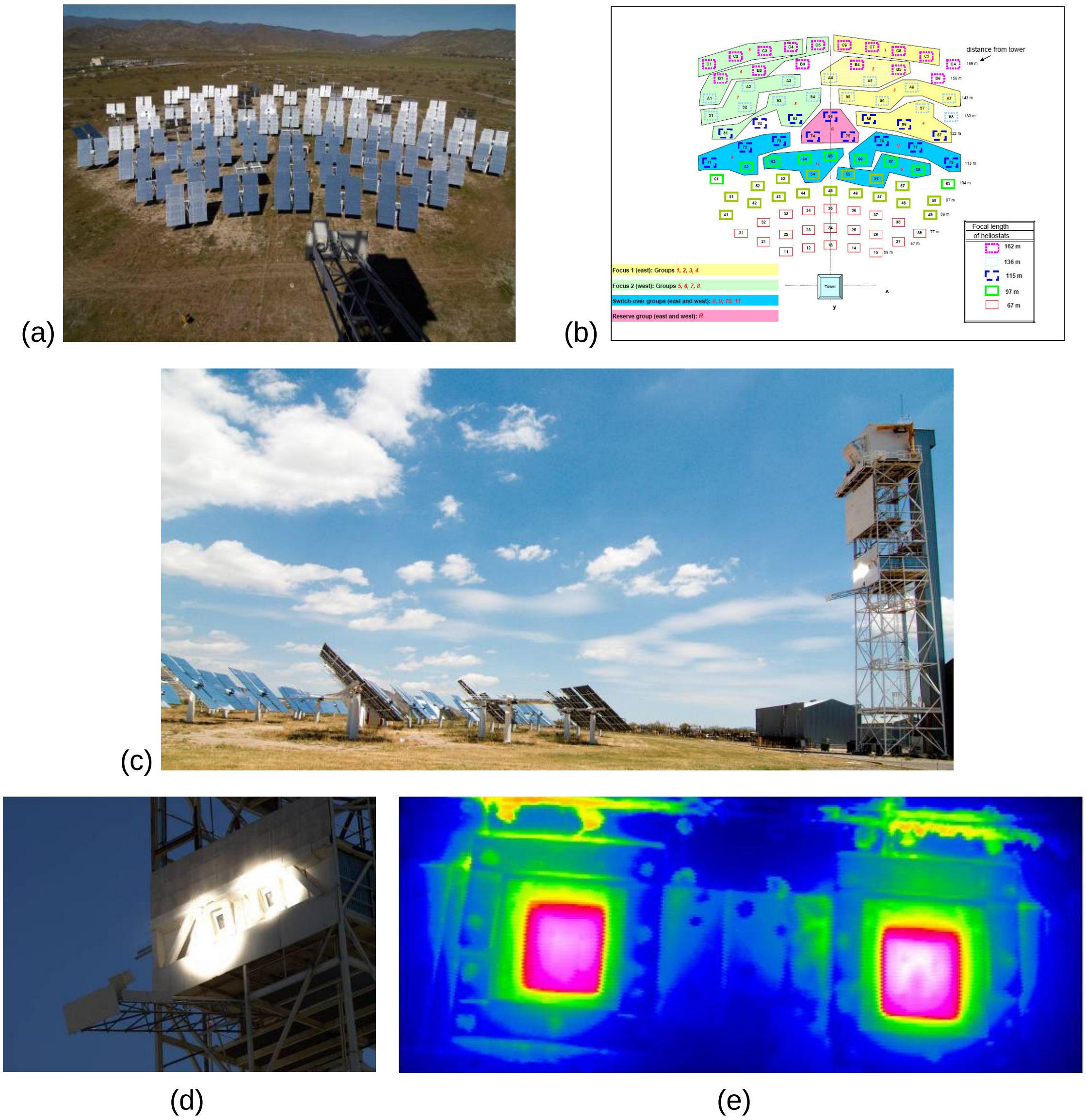

Figure 2: **(a) SSPS-CRS heliostat field view from the reactor's level; (b) implemented partitioning of heliostat field and selected partitioned groups for the operation of the reactor; (c) operation of the HYDROSOL reactor under irradiation; (d) dual focus produced by the solar field at the front face of the two reactor chambers; (e) temperature profiles at the front face of the two reactor chambers by thermal camera.**

4 Thermal Qualification

First, an exhaustive thermal qualification of the pilot plant has been carried out using uncoated ceramic honeycombs as absorbers i.e. without a redox system. All tests were carried out with air instead of nitrogen and without water vapour. Those tests helped to develop and validate the operational and measurement strategy. To control the temperature, the volume flow and pre-heater temperature for the working medium – air - as well as the number of heliostats focused on the two modules of the receiver were systematically varied or used to compensate for the fluctuations of the receiver temperature caused by other (outer) parameters like Direct Normal Irradiance (DNI), ambient temperature, wind speed and direction. It was concluded that there is only little usefulness of employing feed gas preheating and mass flow of the feed gas as control parameters, whereas the preferred way of controlling the process temperature is by the heliostats themselves. Solar flux fluctuations are compensated by adding or removing individual heliostats to the two foci. A control strategy was set up by using high-flux mirrors for the “coarse” adjustment and low-flux heliostats for the “fine-tuning” of the temperature control. For both tested cycle temperatures, 800 °C and 1200 °C, the control by heliostats ensured sufficiently steady states.

5 Hydrogen Production Experiments

For the hydrogen production experiments, the “blank” siSiC monolithic absorber structures were replaced by a set of 18 monoliths coated with iron-zinc mixed oxide. The results of an experimental campaign on 23/04/2009 are shown in Fig. 3. Test conditions were as follows: 5 Nm/h of nitrogen, 2.5 kg/h of water steam, the temperature of the different gas preheaters was 200°C, a production temperature of 900°C and a regeneration temperature of 1200°C was applied (Fig. 3a). Though the pilot plant faced an operation break of several weeks before this campaign, the hydrogen production could be recovered with similar production rates as observed in the previous campaign. Obviously the system and in particular the metal oxide does not suffer significantly from longer operational breaks and from longer exposure to “outdoor” conditions. Beyond this only a slight decrease of hydrogen production rate and yield was observed (Fig. 3b).

Exemplarily the hydrogen production cycles of one test week in July 2009 are shown in Fig. 3c. The cycles involved faced different conditions, since the influence of process parameters was analysed. Parametric tests included the variation of the cycle length, the variation of mass flow of steam and the variation of the water splitting temperature. In this week more then thirty cycles were carried out with the same (fresh) coating. As a trend it can be stated that increased water splitting temperatures lead to higher hydrogen production rates. Higher water concentrations in the feed stream have only little influence since the there already is a surplus of steam in the reactor. The time needed to switch a module between water splitting and regeneration mode could be significantly reduced by defocusing all heliostats of the modules which has to be cooled down from regeneration temperature. The modified heliostat grouping turned out very helpful in term of process control, of a fast switch between operation modes, and of keeping conditions as constant and as reproducible as possible over a day.

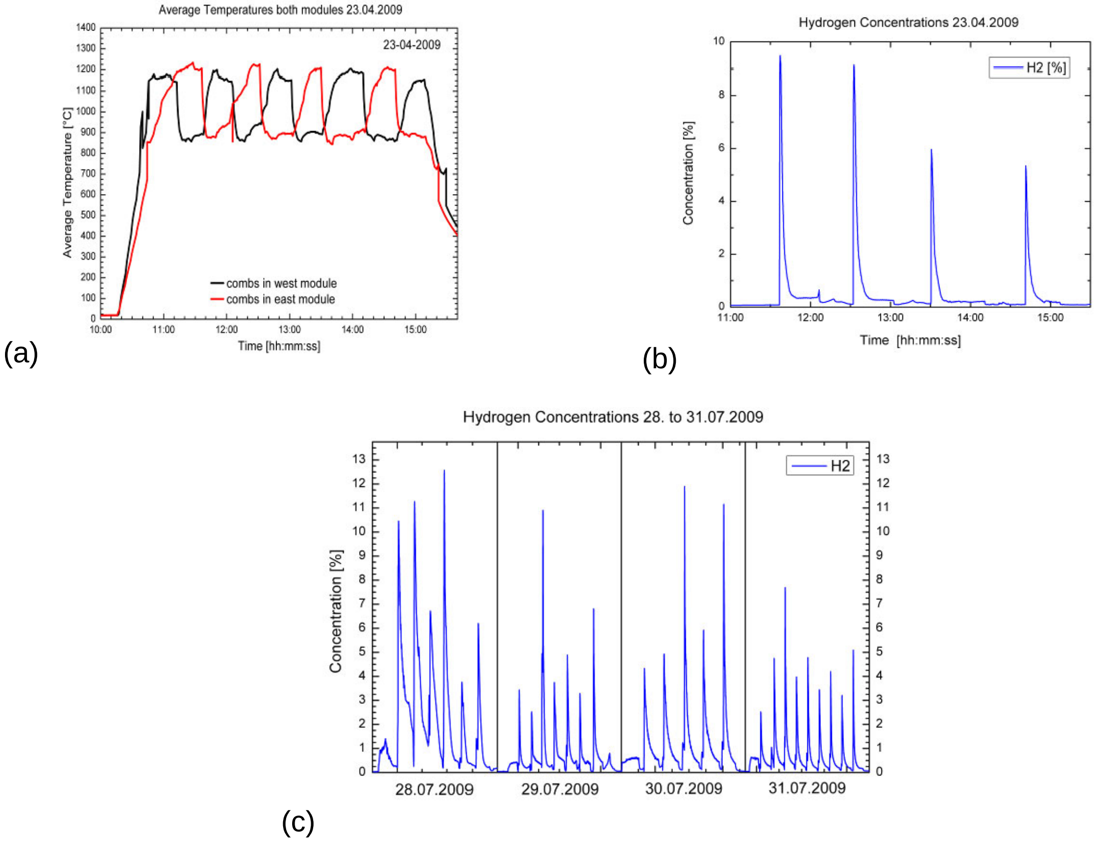

Figure 3: **(a) Average temperatures of both modules and (b) Hydrogen concentrations, of experimental campaign of 23.04.2009; (c) Hydrogen concentrations (western module) of experimental campaign between 28-31.07.2009.**

6 Summary

A 100 kW pilot plant for two-step solar thermo-chemical water splitting via monolithic honeycomb solar reactors based on the HYDROSOL two-chamber solar receiver-reactor technology has been developed, installed and test operated at the SSPS solar tower plant at PSA in Spain. At first, thermal qualification of the pilot plant has been carried out using uncoated ceramic honeycombs as absorbers, in order to develop and validate operational and measurement strategy as well as to create essential knowledge on the dynamics of the system during thermal cycling. Potential control parameters capable of ensuring sufficient constant temperature levels have been analyzed. It was concluded that the preferred way of controlling the process temperature is by the heliostats themselves which can be applied to ensure sufficiently steady states and compensation against solar flux fluctuations.

A number of hydrogen production cycles applying honeycombs coated with redox material in several experimental series have been successfully carried out demonstrating the feasibility of solar water splitting via the HYDROSOL technology in the 100 kW-scale pilot scale under real conditions. Significant concentrations of hydrogen were produced with a conversion of steam of up to 30 %. Pilot plant tests on optimizing the process conditions are being continued by using absorber monoliths with different coatings from on-going material development studies, to demonstrate the high potential of the particular technology for further scale-up.

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