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Exploitation of thermochemical cycles based on solid oxide redox systems for thermochemical storage of solar heat. Part 5: Testing of porous ceramic honeycomb and foam cascades based on cobalt and manganese oxides for hybrid sensible/thermochemical heat storage

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ABSTRACT

Cascaded ThermoChemical Storage (CTCS) of solar energy is a concept targeted to increase the volumetric energy storage density and address the thermocline temperature distribution inside regenerative sensible-only storage systems. CTCS involves the use of cascades consisting of different thermochemical systems, distributed in a rational pattern inside the storage module tailored to their thermochemical characteristics and to the local heat transfer medium temperature. In the case of air-operated Solar Thermal Power Plants such cascades can consist of porous structures incorporating different redox pair oxide materials that can come in direct contact with the air stream used as heat transfer fluid and operate as compact, hybrid sensible-thermochemical storage modules in series.

Having previously identified the Co_3O_4/CoO and Mn_2O_3/Mn_3O_4 redox pairs as the most promising single-oxide systems for solar energy thermochemical storage, lab-scale ($\varnothing$ 25 mm), Co_3O_4- and Mn_2O_3-coated, porous cordierite honeycombs and foams were prepared and tested with respect to their thermochemical characteristics in one- and two-oxides cascaded configurations employing redox oxide quantities in the range 15–150 g. For such Co_3O_4-loaded cascades thermochemical storage was clearly demonstrated as heat uptake/release at constant temperature under proper testing conditions. Besides, the additive effect of thermochemical on sensible storage within the same storage volume was visualized. The operating conditions of cascades including both Co_3O_4 and Mn_2O_3 were dictated by the redox behaviour of the Mn_2O_3/Mn_3O_4 pair. Under proper conditions, such two-oxides-cascades could undergo cyclic reduction-oxidation and operate in complementary temperature ranges during oxidation; however the thermal effects of only the CoO oxidation reaction could be materialized into temperature rise of the air stream exiting the cascade.

1. Introduction

A major advantage of Solar Thermal Power Plants (STTPs) operating with Concentrated Solar Power (CSP) vs. other solar energy technologies is that electricity production can be decoupled from sunshine hours by storing the heat and converting it to electricity when needed allowing thus a fully-dispatchable supply. Among the various CSP technologies, solar towers offer the potential of high temperatures and thus high thermodynamic conversion efficiencies. In the other hand, the technology of volumetric ceramic receivers – where concentrated radiation is absorbed inside the volume of a porous structure that is used to transfer this heat to a fluid passing through it – provides for the efficient use of air as heat transfer medium despite its low heat transfer coefficient. This receiver technology has been developed on a solar tower since the early 1990s over a series of projects culminating to the first-of-its-kind, 1.5 MW_{el} such CSP plant, Solar Tower Jülich (STJ) in Germany. In STJ (Alexopoulos and Hoffschmidt, 2010) air at atmospheric pressure flows through a solar-irradiated volumetric receiver made of SiC honeycombs, being thus heated up to ≈700 °C to power a steam generator. In parallel, a part of the solar-heated air is diverted to a regenerative, sensible heat, Thermal Energy Storage (TES) system (Tamme et al., 1991) where it transfers its enthalpy to a solid medium as it flows through it ("charging"). The storage module consists of a 7 m × 7 m × 6 m housing (Fig. 1b) filled with flow-through ceramic honeycombs to provide a large air-solid heat exchange surface, according to the results of studies on

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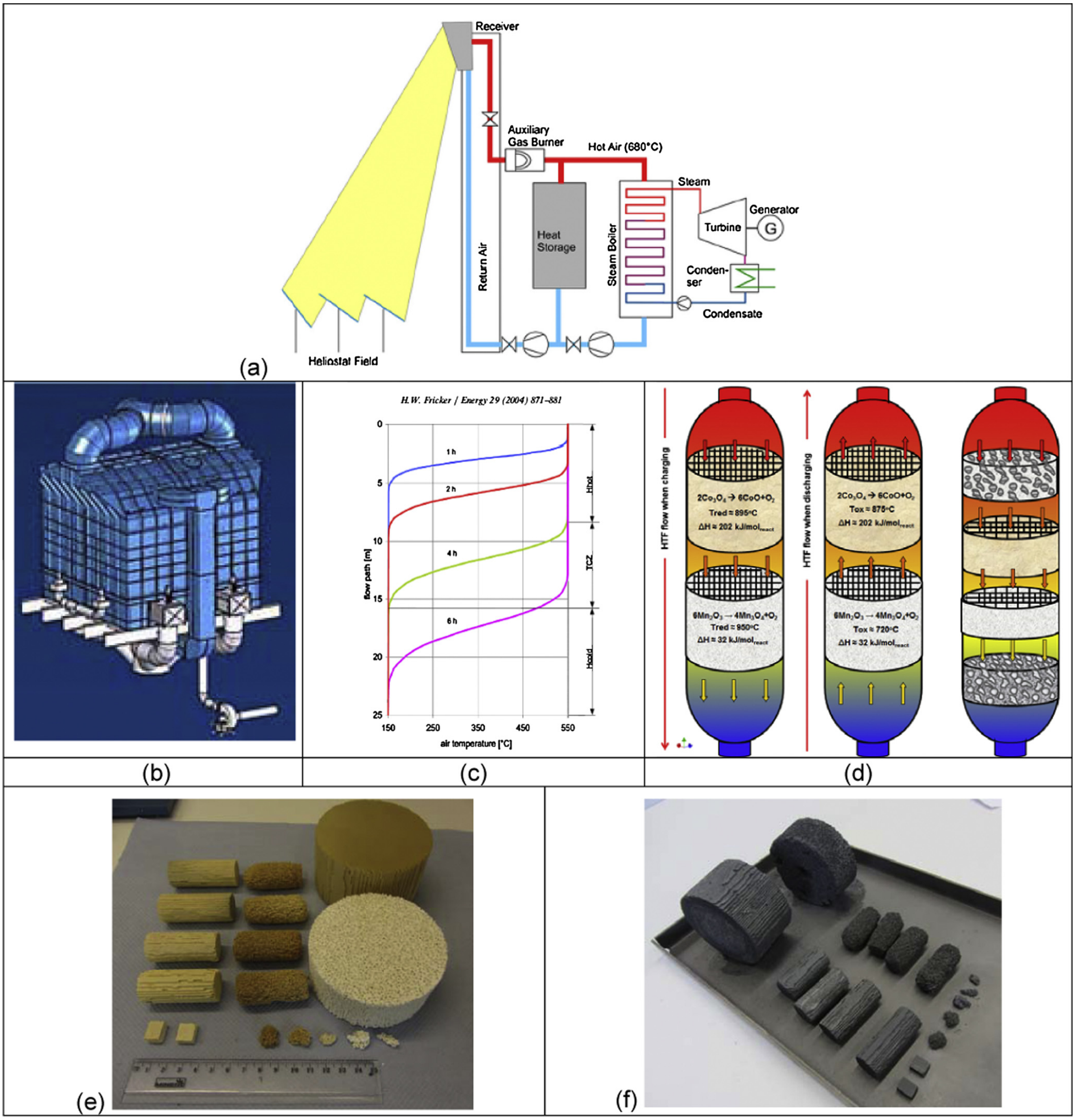

Fig. 1. (a) Layout of Solar Tower Jülich (STJ) power plant and (b) schematic of its sensible regenerative heat storage subsystem based on ceramic honeycombs (Zunft et al., 2011); (c) example of air temperature distribution in such a regenerative atmospheric air storage system of an air-operated solar power plant (Fricker, 2004); (d) principle of cascaded thermochemical storage configuration and operation during charging (left) and discharging (middle) of such a system, tailored to the characteristics of the Co_3O_4/CoO and Mn_2O_3/Mn_3O_4 redox pairs and exemplary schematic (right) with such oxides coated/shaped in various porous supports with possibilities of porosity variation along and across the cascade; (e) and (f) porous cordierite honeycombs and foams from various suppliers and of various sizes (<20 mm, ∅ 25 mm and ∅ 90 mm for testing in a TGA, the current testing rig and a solar receiver respectively) before and after their coating with Mn_2O_3.

optimization of volumetric energy storage density (kWh/m^3) and pressure drop (Zunft et al., 2014, 2011). During off-sun operation ("discharging") the air flow is reversed: "warm" air is introduced through the lower end of the storage medium to be heated by that as it flows towards the already "hotter" top end, before introduced again to the power block.

In a regenerative sensible TES system, operation starts from an isothermal cold or hot core, charging or discharging it with a constant air mass flow rate of constant temperature. The heat transfer from the air to the solid and vice versa must take place with a small temperature difference, i.e. with a small exergy loss. The result is a small temperature drop when discharging and a good storage material utilization. Initially, during charging for example, the temperature profile along the solid storage medium is stratified as it is shown in Fig. 1c (Fricker, 2004). At first the layer of the solid medium adjacent to the air inlet is heated to the constant, inlet air

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