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Heat transfer in a directly irradiated ceria particle bed under vacuum conditions

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ABSTRACT

Vacuum particle receivers have been proposed recently for the reduction of redox material in solar thermochemical redox cycles. To assess the performance of these receivers, it is essential to describe the heat transfer in particle beds correctly. A widely used model for effective thermal bed conductivity is the one developed by Zehner, Bauer and Schlünder, which was derived for the steady state case without interstitial gas flow. In this study it was investigated if the model is also applicable for suddenly irradiated ceria particle beds in a typical solar vacuum receiver environment. Therefore a particle bed of ceria was irradiated with a solar simulator under vacuum conditions to peak temperatures above 1300°C. Within the bed, temperatures were measured at different locations for various pressures between 25 Pa and ambient conditions. The experimental results were compared to heat transfer simulations in ANSYS Workbench incorporating the aforementioned bed conductivity model. A good agreement between experiment and simulation was found and the model was considered applicable.

1. Introduction

Solar thermochemical redox cycles are a promising candidate to provide sustainable fuels in the future due to their high predicted efficiency (Ermanoski and Siegel, 2014; Siegel et al., 2013). One of these cycles is based on ceria as a redox material and can be divided into two steps. In the reduction step ceria is reduced with solar energy at high temperature and releases oxygen:

$$CeO_2 \rightarrow CeO_{2-\delta} + \frac{\delta}{2}O_2$$

In the following oxidation step at lower temperatures the oxygen-deficient metal oxide is oxidized by water and hydrogen is formed:

$$CeO_{2-\delta} + H_2O \rightarrow CeO_2 + \delta H_2$$

The reduction extent δ is a function of temperature and oxygen partial pressure (Bulfin et al., 2013). The oxidation step can also be conducted with CO_2 or with a mixture of CO_2 and H_2O (Agrafiotis et al., 2015). In the latter case, syngas is produced, a precursor for many chemical processes, for example for the production of fuel by the Fischer-Tropsch synthesis (Häring and Ahner, 2008).

For the reduction step several solar receiver types were proposed by various authors (Bader et al., 2015; Chueh et al., 2010; Diver et al., 2010; Ermanoski et al., 2013; Kaneko et al., 2007; Koepf et al., 2012; Marxer et al., 2017; Oles and Jackson, 2015; Yuan et al., 2015). In some designs the metal oxide is in a granular form and moves through the solar receiver reactor (Ermanoski et al., 2013; Oles and Jackson, 2015). When modeling these solar receiver reactors with reacting particles, a correct representation of heat transfer between the particles is essential to obtain accurate results for reaction rates and overall efficiency. However, under vacuum conditions like in recently proposed systems (Ermanoski et al., 2013; Singh et al., 2017), heat transfer of irradiated reacting particle beds differs substantially from ambient pressure conditions and available experimental data for thermal properties of these beds under vacuum conditions is limited. This is especially true for the high temperatures during reduction, where radiation is the dominant heat transfer mechanism. The radiation strongly contributes to the effective thermal bed conductivity, a property describing the particle bed as a whole and including all heat transfer modes in the bed, namely solid conduction, gas phase conduction, gas phase convection, radiation and combinations of these modes. In vacuum the effective bed conductivity is lower than at ambient conditions due to missing gas conduction and convection in the bed void space. In this study an experiment is conducted to understand the behavior under high temperature vacuum conditions and to validate a heat transfer model for ceria particles under typical conditions in a solar receiver.

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Fig. 1. Microscope image of ceria particles.

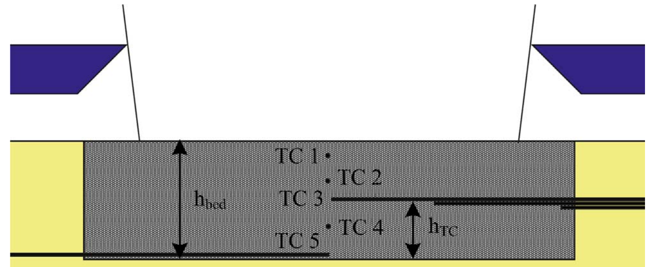

Fig. 3. Positioning of thermocouples within the particle bed.

2. Experimental setup

2.1. General

A sample of the ceria particles used in the experiment is shown in Fig. 1. The same particles are used in a prototype system for solar hydrogen generation (Ermanoski et al., 2016; Singh et al., 2017). The particle size distribution of the particles was measured with an optical method; the mean Sauter diameter is 277µm. The density of the particles was determined with a pycnometer to be 6636 kg/m^3.

A packed bed of these particles was placed in a vacuum chamber and irradiated by the high-flux solar simulator of DLR in cologne, Germany. A schematic of the experimental setup is shown in Fig. 2. The concentrated flux of the solar simulator hits a water cooled mirror and is directed downwards through a 32 mm thick quartz glass window into the main vacuum chamber. Within this chamber the flux impinges on a cylindrical bed of ceria particles, which is surrounded by vacuum-formed alumina insulation of cylindrical shape. The insulation itself is surrounded by a water cooled black enclosure to maintain well defined boundary conditions and to protect the vacuum chamber from overheating.

Within the particle bed the temperature is measured at various positions in the vertical and radial direction, see Fig. 3. For TC 1 and TC 2 alumina-sheathed type R thermocouples were used, for the others steel-sheathed type K thermocouples with a diameter of 1 mm. They were placed horizontally in the bed and at a circumferential angle of 90° to each other to reduce impacts on the temperature distribution within the bed. The connection to the data acquisition system was established via an electrical feedthrough; therefore the cold junction compensation was made at the plug within the vacuum chamber. To check the complete measurement chain, all thermocouples were tested with a thermocouple calibrator at temperatures of 600, 900 and 1200 °C, once before the experiments and once after the experiments to check for temperature drifts. No significant drift was observed and the difference to the reference thermocouple was always below 1% for all thermocouples used in this study. The vertical positions of the steel-shielded thermocouples in the bed were measured before and after the experimental campaign with a caliper, the uncertainty in the measurement was assumed to be ± 0.5 mm. As the fixation of the ceramic-shielded type R thermocouples was more difficult, the uncertainty in their position was expected to be higher. Pictures without particles present were taken over the mirror by an optical camera placed sideways behind the xenon arc lamp to determine the thermocouple positions in the lateral directions relative to the cooling frame. With the same camera pictures and videos of the particle bed surface were taken during irradiation through a radiation protection glass.

To monitor the bed surface and the cooling frame a Logitech webcam was used. Additionally an infrared camera with a filter for glass windows measured the surface temperature of the particle bed. To verify that the measurement through the window is possible, preliminary tests were conducted where the temperature of ceria particles in an oven was measured with and without the window present in the optical path; the temperature of the IR camera was also compared with the temperature of a thermocouple which was placed into the particle bed in the oven. These pre-tests showed in general good measurability through the window; for temperatures below 1000 °C the deviation between thermocouple measurement and IR measurement was between 0 and 5%. However, for higher temperatures the deviations were higher, with a maximum of 13% for one measurement at an oven temperature of 1350 °C. Therefore it was decided to use the IR measurements just as a qualitative measure and not investigate the

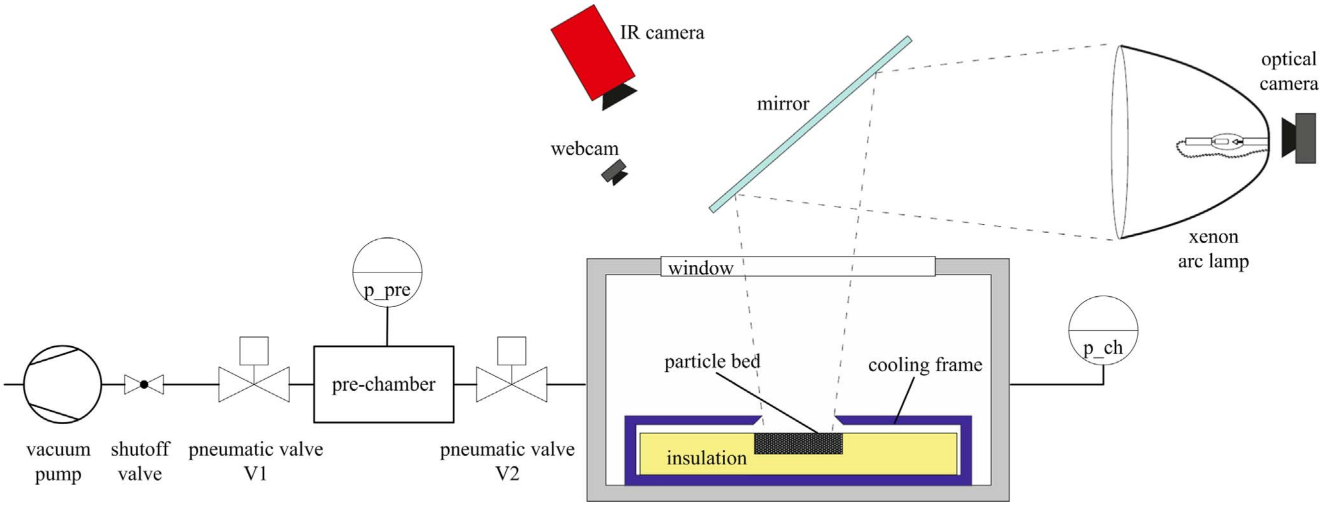

Fig. 2. Schematic of the experimental setup.