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Experimental investigation of ZnO powder flow and feeding characterization for a solar thermochemical reactor

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ABSTRACT

The past two decades have seen a surge in applications of concentrated solar power (CSP) technology. The generation of solar-fuels, such as hydrogen, via CSP-thermal receiver/reactor technology has progressed from large scale demonstration to preliminary commercial venture. Solar receiver/reactors vary widely, and one of the distinguishing characteristics between reactors is the way in which reactants are introduced into the high-temperature reaction environment. Here, we focus on gravity-driven feeding of solid-particle reactants via hoppers and metering splines which can be employed for solar-thermochemical dissociation of metal oxides during continuous or batch processing. This relatively simple method can provide consistent and uniform reactant flow with high durability and low maintenance. We present experiments and analysis of gravity feeding of solid particles for CSP applications, focusing on the case study of 1–5 μm ZnO powder at mass flow rates of 0–2 g/s. ZnO powder feeding is facilitated by adding vibration to the hopper followed by metering past a rotating spline, and delivered via gravity to an ultra-high temperature reaction cavity comprised of inclined alumina tile reaction surfaces. This paper will address hopper and spline design, feed rate characterization and modeling, particle residence time, and the effect of moisture and hopper vibration on the effective delivery of ZnO powder to the thermochemical reactor.

1. Introduction

The production of hydrogen from sunlight and water could represent an efficient, economic, and environmentally benign approach to energy sustainability in the US and the world. As a solar fuel, hydrogen combines characteristics such as high exergy efficiency, long and short-term storage capability, and life-cycle material simplicity and recyclability [1]. While there are multiple ways to produce hydrogen from sunlight and water [2], one attractive and large-scale approach is to use thermal energy from highly concentrated sunlight coupled to a solar receiver/reactor [3].

Water can be split directly into hydrogen and oxygen inside an ultra-high temperature receiver/reactor above 4000 K [4,5]. However, the material challenges are extreme at these elevated temperatures, in addition to the fact that the resulting mixture of hydrogen and oxygen is difficult and dangerous to separate. Thermochemical cycles can address both of these issues by reducing the temperature required to split water, while also separating the steps where hydrogen and oxygen are evolved. In the first step of a typical solar-thermochemical cycle, high temperature produced from concentrated solar energy is used to thermally reduce a metal oxide where the oxygen is released. In the second step, the reduced metal oxide is combined with water to generate hydrogen and recover the original metal oxide. The two steps represent a closed-loop cycle with a net reaction of hydrogen produced from sunlight and water [6]. ZnO has been identified as a promising metal oxide candidate for water-splitting thermochemical cycles [7].

To accomplish the first step of a ZnO/Zn water-splitting thermochemical cycle where ZnO is reduced to metallic Zn, many types of solar-receiver/reactors have been designed and tested on various scales [8–12]. Typical designs include packed-bed reactors [13], aerosol reactors [14], and continuous feed reactors [15]. For solar-receiver/reactors relying on the continuous feeding of ZnO powder, the reactant delivery system must be reliable, tunable, accurate, and stable at high-temperature.

For solar-receiver/reactors feeding ZnO powder into a cavity reaction chamber, it is of primary importance to deliver the reactant in a manner that effectively and uniformly delivers and distributes the powder over a large portion of the reaction cavity surface area. Typically, bulk ZnO powder of rated size 1–5 μm is used; this powder is difficult to handle due to its aversion to free flow. Unlike packed-bed reactors, continuous feed reactors cannot interrupt operation to restock reactants, which means that the feeding system must operate under high temperature and high solar flux environments. One approach to deliver the powder-form reactant makes use of a hopper, feed screw, and gas-driven sprayer coupled to a rotating cavity [10]. Another similar design

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also uses a screw feeder and driving inert gas flow [16]. While driving gas-flows are convenient to disseminate and carry powder-form reactants, inert gas is expensive. To minimize the use of inert gas while still obtaining satisfactory powder delivery and dispersion inside the reactor, the GRAFSTRR (Gravity-Fed Solar-Thermochemical Receiver/Reactor) reactor design utilizes gravity to drive reactants into the high temperature reaction cavity [15]. The GRAFSTRR system utilizes a stationary reaction cavity coupled to a ring of powder-feeding eccentric hoppers and rotary-type metering splines, driving the reactant by gravity onto the inclined ceramic reaction surface.

Powder processing, handling and conveying are also an important research area in fields such as food science, agriculture, pharmaceuticals, mining, plastics, and bulk chemistry. The powder handling industry commonly employs a system comprised of a hopper coupled to a rotary feeder. The two components have received much attention and research, mainly focused on the free-flow characteristics of different hopper designs [17–19], and the defining parameters and powder feeding metrics of rotary designs and their operation [20,21]. In some cases, practical considerations can dictate the design of a specific powder delivery system. For example, eccentric hopper designs have been extensively researched and modeled [22] because of their space-saving nature in an industrial environment. Other powder metering apparatuses have been investigated for difficult and non-flowing powders [23]. For the GRAFSTRR design, the unique powder feeding challenge is to simultaneously meet criteria of feed-rate range, space-constraint, high-temperature operation, and also the form in which the powder is delivered to the reaction chamber (continuous falling sheet).

This paper will address the design of a solid-particle reactant feeding system coupled to a laboratory-scale (10–20 kW_{th}) beam-down solar-thermochemical receiver/reactor named GRAFSTRR for the creation of solar fuels. The design consists of a series of eccentric, vibrated hoppers coupled to carefully designed rotary spline feeders to deliver non-free flowing ZnO powder in a manner that sufficiently and consistently covers the reaction cavity surfaces. The GRAFSTRR design will be briefly described, followed by a detailed description of the ZnO powder feeding system. Finally, results from extensive feed rate calibration and characterization experiments will be presented in detail.

2. Materials and methods

2.1. The solar-thermochemical receiver/reactor

A complete description of the GRAFFSTR solar-thermochemical reactor concept and design can be found in [15]. A summary of the relevant details of the receiver/reactor will be presented here. The reactor is cylindrical in shape with an overall diameter of 864 mm and a height of 451 mm. The axisymmetric reactor has a pentadecagon design comprised of 15 alumina tile reaction surfaces in the lower chamber which form an inverted cone shape. Fig. 1 shows a cross-section of the reactor, and Fig. 2 shows the details of a single tile section along with a single hopper and feeding mechanism that delivers ZnO powder to the tile surface. Process heat in the form of concentrated solar energy is delivered to the reactor through a transparent quartz window at the top. The beam of radiation converges in the upper chamber of the reactor, passes through its focal point at the aperture plane, and then diverges into the lower chamber where the reaction occurs. The array of hoppers on top of the reactor is designed to not interfere with this converging cone of concentrated sunlight. The small aperture through which the radiation enters into the reaction cavity allows for extremely high and uniform temperatures inside the reactor, known as the cavity-effect. The reactor is designed to thermally dissociate ZnO powder into vapor-state Zn and O_2 at temperatures approaching 2000 K. As products evolve off the reaction surface, they are entrained by a vortex flow and delivered to the centrally located product outlet at the bottom of the reactor. The vortex flow simultaneously removes product vapors from the reaction surface while also preventing aerosolized reactant particles and product vapor from entering the upper chamber of the reactor and fouling the window [24]. ZnO powder is fed from above to each reaction tile surface (composed of 99.999% pure Al_2O_3) individually. The ZnO powder flows down the surface of the inclined tile and either reacts directly, sinters to the tile surface, or passes unreacted through the cavity and exits through an annular solids exit at the bottom.

2.2. The feeding mechanism

Rotary feeders are commonly used to regulate the flow of powdered solids from hoppers. The concept of a rotary feeder is quite simple:

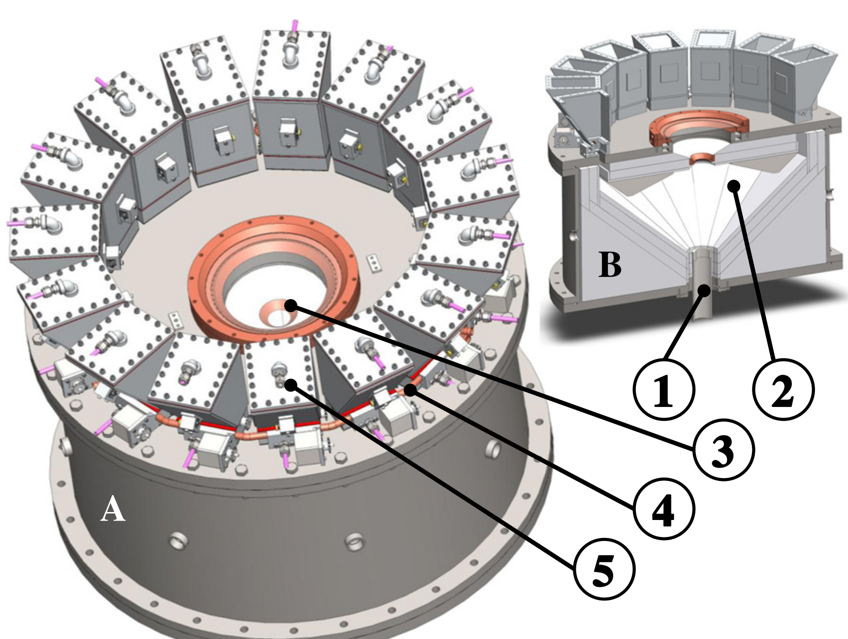

Fig. 1. Top–down view of the solar reactor (A) depicting the aperture (3), assembly of 15 powder-feeding hoppers (5), and water-cooling loop (4). A cross section of the reactor (B) shows the 15 inclined reaction-surface tiles (2), and the product gas and excess powder outlets (1).