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Review of experimental investigation on directly irradiated particles solar reactors

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ABSTRACT

Solar thermochemistry is a technology that has been demonstrated to contain a high potential development capability. In order to carry out efficient solar chemical reactions, optimized reactors adapted to each chemical process are necessary. In last 30 years many solar reactors of different configurations, performances and sizes have been designed and fabricated by the main solar chemistry research groups. Among them, directly irradiated particles solar reactors operate in a high temperature range that usually correspond to gas–solid thermochemical reactions. This work compiles more than 20 directly irradiated particles reactors designed, constructed and experimentally investigated in the last 30 years. Their description, schemes and main parameters of their performance are given. Detected problems associated are also mentioned. Reactors are classified from the point of view of chemical engineering in entrained, fluidized and stacked beds. Finally, a summary of the main characteristics of reviewed reactors is provided.

Contents

1. Introduction

The objective of solar chemistry is to use solar radiation for producing fuels and chemicals [1]. It transforms solar energy in long-term storable and transportable energy carriers, what represents a significant contribution to the requirements for improving the current energetic system. In order to increase the efficiency, these processes should be performed at an upper temperature as high as possible because the rate of chemical reaction increases

Abbreviations: SNL, Sandia National Laboratories; SPCR, solid particle central receiver; NREL, National Renewable Energy Laboratory CNRS-ENSIC; NG, natural gas; CPC, compound parabolic concentrator; CSIRO, Commonwealth Scientific and Industrial Research Organization; PSI, Paul Scherrer Institut; ETH, Eidgenössische Technische Hochschule; DLR, Deutschen Zentrums für Luft- und Raumfahrt

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exponentially with temperature. To achieve that, apart from an adequate concentration system, optimized solar reactors capable to withstand high temperatures, minimizing heat loss and favouring mass and heat transfer between chemicals involved are required. Solar reactors are particular cases of solar receivers where the absorber heat is employed to carry out endothermic chemical reactions. Thus, a preliminary classification of solar reactor could correspond to that generally used to categorize solar receivers. According to the heat integration mode into the reaction chamber, solar reactors are indirectly or directly irradiated [2].

1.1. Indirect reactors

The external opaque walls of the reaction chamber are heated by solar energy. Endothermic reactions are promoted by the heat flux transferred by conduction from the walls to the reactants. Most of indirect irradiated reactors found in literature are catalytic tubular reformers [3–7] where the catalyst is fixed inside a tube and the gas is forced to flow across. The solar flux is distributed along the external walls of the tubes. Additional concepts of indirect reactors have been also developed for thermochemical applications, such as double-cavity reactors with a reaction chamber physically separated from the one that receives the radiation [8–10].

1.2. Direct reactors

Reactants are directly irradiated and heated by incoming solar concentrated radiation. Reactors are opened to air or closed by a transparent window through which radiations enters into the reaction chamber. Due to the absorption of radiation occurs on the reactants surface, higher temperatures are expected by working with directly irradiated reactors. Apart from volumetric reactors, which physical processes have been widely studied from the point of view of volumetric absorbers [11,12], particles solar reactors represents the largest group of studied solar reactors, particularly in a laboratory scale. Thus, a compilation and examination of designed, constructed and experimentally investigated hitherto particles solar reactors are the aims of the present work.

2. Early studies on particles absorbance

Sandia National Laboratories (SNL) was pioneer in proposing solid particles as heat absorber medium for concentrated solar systems. The initial study was made by Martin and Vitko [13]. Pebbles and sand were tested as heat solid carriers with successful results. Detected advantages of such as scheme included direct absorption of the incident radiation, direct heat transfer, use of the working fluid as a storage medium, and ease of hybridizing with a fossil-fired system. Moreover, higher temperatures were theoretically possible. Their study led to the first concept of Solid Particle Central Receiver (SPCR) consisting in a falling cloud of 100–1000 μm solid particles [14]. Solar energy was directed to the particles through the aperture of a cavity receiver [14,15]. By means of a theoretical parametric study they analyzed how the material kind, the particles size or the infrared scattering albedo affected to the particles temperature, the convective loss and the optical thickness. Further studies were done on this topic, most of them collected on internal reports of SNL [16–20]. Such as research line concluded to a prototype of SPR that was tested on top of Sandia's 61 m tall central receiver located at the National Solar Thermal Test Facility in Albuquerque, NM. The heliostat field of this facility is able to provide 5 MW_{th} [21].The SPR consisted of a 6 m tall cavity through where a 1 m wide curtain of spherical ceramic particles was dropped and directly heated with

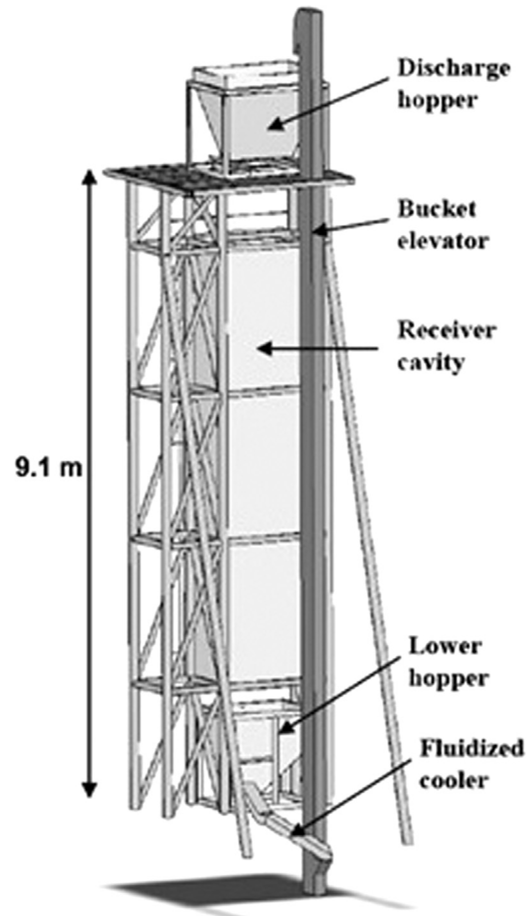

Fig. 1. Lay out of the SPCR developed in SNL [21].

concentrated solar energy. Particles were collected in an internally insulated lower hopper. Fig. 1 shows the system layout. First experimental research demonstrated a cavity temperature higher than 1000 °C, receiver efficiency in excess of 55% and particle exit temperature in excess of 200 °C, depending on the operating conditions. Siegel and Kolb [21] reported an expected improvement of the results after an optimization of the receiver design.

In fact, SNL are still in the process of developing SPCR. In 2012 DOE's SunShot Initiative awarded three research projects in this area that currently have been developed by SNL, NREL and San Diego State University.

Some other studies on particles receivers have been found in literature. For example, Bertocchi et al. [22] reported experimental evaluation of a solar particle receiver designed for a power input of 10 kW. It consisted of a conical cavity of 40 mm high and 78 mm of inner diameter close to the ambient by a quartz window. Particles were injected in a gas/particle suspension at the focal plane through a duct placed close to the window. The exit takes place at the rear of the receiver. Achieved exit gas temperatures exceeded 2100 K.

3. Particles reactors classification

The knowledge developed on particles receivers helped to the conception of the first receiver-reactors where particles perform both heat absorption and chemical transformation. Particles may be arranged with different configuration depending on their required residence time inside the reactor and the existence of a