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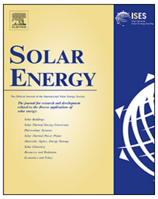

Optical design and experimental characterization of a solar concentrating dish system for fuel production via thermochemical redox cycles

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ABSTRACT

The design, fabrication, and on-sun characterization of a solar dish concentrating system for performing the two-step thermochemical redox splitting of H_2O and CO_2 is presented. It comprises a primary sun-tracking 4.4 m-dia. solar dish concentrator coupled to a secondary planar rotating reflector. This optical arrangement enables the operation of two (or more) solar reactors side-by-side for performing both redox reactions simultaneously by alternating the solar input between them while making continuous and uninterrupted use of the incoming concentrated sunlight. On-sun characterization of the complete concentrating system revealed a peak solar concentration ratio of 5010 suns and an average of 2710 suns measured over the 30 mm-radius aperture of the solar reactor. A detailed optical analysis elucidates measures to increase the optical efficiency and concentration ratio.

1. Introduction

Solar splitting of H_2O and CO_2 is performed using a thermochemical cycle based on the reduction-oxidation (redox) of metal oxides (Romero and Steinfeld, 2012), comprising two steps: (1) a high-temperature solar endothermic reduction step, and (2) a subsequent low-temperature exothermic oxidation step with CO_2 or H_2O to generate H_2 and CO – syngas, the precursor of liquid hydrocarbon fuels. In the framework of the EU-project SOLARJET, we have experimentally demonstrated, at lab scale, the first ever production of solar jet fuel from H_2O and CO_2 via such a thermochemical redox cycle (Marxer et al., 2015). In this two-step cyclic process, only the first endothermic step requires concentrated solar energy as the source of high-temperature process heat. By operating two or more solar reactors side-by-side and alternating the solar input between them, it is possible to perform both redox reactions simultaneously but separately in each reactor while making uninterrupted use of the incoming solar radiation.

Ceria (CeO_2) has emerged as the benchmark redox material because of its fast reaction kinetics and crystallographic stability (Chueh et al., 2010). Its thermal reduction proceeds to a reasonable extent at a temperature of 1500 °C (Panlener et al., 1975; Scheffe and Steinfeld, 2012). This corresponds to a required solar concentration ratio[1] above 2000 suns for efficient operation (Romero and Steinfeld, 2012), which can be obtained by point-focus concentrating systems, either in centralized solar towers or decentralized solar dishes. In general, solar dish systems can reach higher concentrations and higher optical efficiencies compared to solar towers, but are limited to smaller unit sizes. In contrast, line-focus trough and Fresnel systems are theoretically bounded by the much lower 2D-concentration limit of 215 suns compared to the 3D-concentration limit of 46,250 suns (Winston, 1970), and are thus unsuitable for achieving the temperatures required for thermochemical redox cycles.

In this paper, we present the design, fabrication, and characterization of a high-flux solar dish system that enables the operation of two adjacent solar reactors performing both steps of the ceria-based redox cycle simultaneously while utilizing the incoming solar radiation uninterruptedly.

2. Optical design

Fig. 1 depicts various optical design configurations for the solar concentrating dish system for the simultaneous operation of two or more adjacent solar reactors. Table 1 summarizes the corresponding key parameters. To ensure comparability of all designs, the primary

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[1] The mean solar concentration ratio C_{mean} is defined as $C_{mean} = \dot{Q}_{reactor}/(A_{reactor}E_{bn})$, where $\dot{Q}_{reactor}$ is the solar radiative power intercepted by a reactor aperture of area $A_{reactor}$ normalized to the direct normal beam irradiance (DNI) E_{bn}. C_{mean} is often expressed in units of “suns”.

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Nomenclature

Latin characters

A_{reactor}	solar reactor aperture area, m^2
A_{dish}	dish aperture area, m^2
C_{mean}	mean solar concentration ratio over a given area, suns
c_p	mass-specific heat capacity of the calorimeter cooling water, kJ/(kg K)
C_{peak}	peak solar concentration ratio, suns
E_{bn}	direct normal beam irradiance (DNI), $W\,m^{-2}$
f	focal length, m
$\dot{Q}$	solar radiative power, W
$\dot{Q}_{\text{cal}}$	solar radiative power incident at calorimeter aperture, W
$\dot{Q}_{\text{dish}}$	solar radiative power incident at solar dish aperture, W
$\dot{Q}_{\text{reactor}}$	solar radiative power incident at solar reactor aperture, W
r	radius, m
R_f	radial displacement of focal point away from central axis, m
R_i	inner dish truncation radius, m
R_o	outer dish radius, m
R_r	outer reactor shell radius, m
T_{in}	calorimeter inlet temperature, °C
T_{out}	calorimeter outlet temperature, °C

Greek characters

α	absorptance, %
β	angle between optical axis before and after reflection at secondary reflector, °
γ	intercept factor, %
ζ	active area fraction, %
η_{opt}	optical efficiency, %
θ_{off}	tracking offset, °
θ_{os}	oversizing angle for secondary dish, °
θ_{sun}	angular radius of the solar disk, 4.65 mrad
ρ	reflectance, %
σ	standard deviation of reflector slope error, mrad
ϕ	rim angle, °

Subscripts

1	primary reflector
2	secondary reflector
f	focus

Abbreviations

DNI	direct normal irradiance, W/m^2
SMS	simultaneous multiple surface optical design method

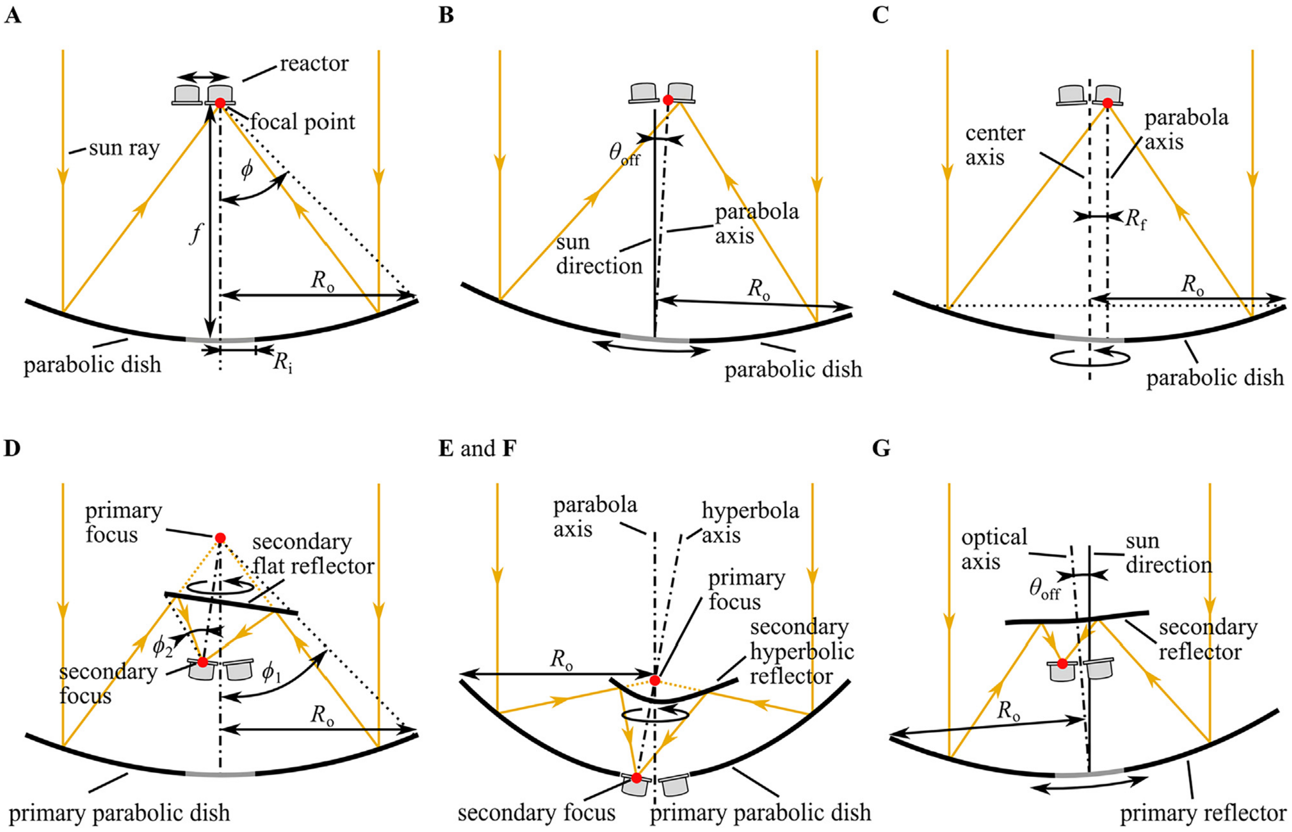

Fig. 1. Optical design configurations of the solar concentrating dish system for the simultaneous operation of two or more adjacent solar reactors. A–E: Primary parabolic dish with $R_o = 2.2$ m, $\phi = 45°$ and $f = 2.65$ m; F: primary parabolic dish with $R_o = 2.2$ m, $\phi = 90°$, and $f = 1.1$ m; G: revolved free-form curve. A–C use a single primary reflector; D–G use both primary and secondary reflectors. The focal point is shifted by moving the solar reactors (A), introducing a tracking offset $\theta_{\text{off}} = 4°$ (B and G), rotating primary reflector (C), and rotating secondary reflector (D–F).