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ScienceDirect

Solar Energy 85 (2011) 334–343

SOLAR ENERGY

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Heliostat field layout optimization for high-temperature solar thermochemical processing

Robert Pitz-Paal [a,*], Nicolas Bayer Botero [a], Aldo Steinfeld [b,c]

[a] *DLR, Institute of Technical Thermodynamics, Linder Höhe, D-51147 Köln, Germany*
[b] *ETH Zurich, Department of Mechanical and Process Engineering, 8092 Zurich, Switzerland*
[c] *Paul Scherer Institute, Solar Technology Laboratory, 5232 Villigen, Switzerland*

Received 6 July 2009; received in revised form 13 October 2010; accepted 18 November 2010
Available online 30 December 2010

Communicated by: Associate Editor L. Vant-Hull

Abstract

The layout of the heliostat field of solar tower systems is optimized for maximum annual solar-to-chemical energy conversion efficiency in high-temperature thermochemical processes for solar fuels production. The optimization algorithm is based on the performance function that includes heliostat characteristics, secondary optics, and chemical receiver–reactor characteristics at representative time steps for evaluating the annual fuel production rates. Two exemplary applications for solar fuels production are selected: the thermal reduction of zinc oxide as part of a two-step water-splitting cycle for hydrogen production, and the coal gasification for syngas production.

Keywords: Solar chemistry; Solar tower; Central receiver; Heliostat field; High temperature; Thermochemical

1. Introduction

Solar thermochemical reactors for fuels production operating at above 1000 K are being designed for solar tower systems capable of delivering high solar flux densities in the multi-MW power scale (Steinfeld, 2005). The design and optimization of such receiver–reactors are usually performed on the basis of a pre-defined solar flux density as boundary condition (Pitman and Vant-Hull, 1986). Because of the high temperature requirement, the desired solar concentration ratios should be significantly higher than those encountered in solar power tower systems for Rankine-based electricity generation, which typically operate at an upper temperature of about 750 K and solar concentration ratios around 500 suns (1 sun = 1 kW/m^2). In contrast, solar thermochemical plants usually operate at above 1000 K and require solar concentration ratios exceeding 1500 suns. Thus, as higher solar flux densities have a direct impact on the optical performance of the solar field, the overall optimization for maximum solar-to-chemical energy conversion efficiency needs to consider the coupled field and receiver design parameters.

Several authors have discussed the layout of central receiver concepts for applications requiring high-flux densities and high-temperature levels (Pitman and Vant-Hull, 1986; Segal and Epstein, 1999, 2003; Vant-Hull et al., 1999). In these previous studies, the energetic characteristics of the conceptual application were not integrated directly into the layout developing procedure. Instead, a fixed flux density was used as boundary condition.

This paper presents a novel approach to optimize the heliostat field design and layout for high-temperature solar thermochemical processes that integrates the energetic behavior of the intended application. The approach is

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[*] Corresponding author. Tel.: +49 2203 601 2744; fax: +49 2203 601 4141.
E-mail address: robert.pitz-paal@dlr.de (R. Pitz-Paal).

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doi:10.1016/j.solener.2010.11.018

Nomenclature

A_{helio}	reflective area of heliostat field (m^2)
A_{aperture}	aperture area of cavity-receiver (m^2)
A_{reaction}	surface available to chemical reaction (m^2)
c_p	specific heat capacity of reacting stream ($kJ\ kg^{-1}\ K^{-1}$)
ΔH_r	specific enthalpy change of reaction ($kJ\ kg^{-1}$)
E_A	apparent activation energy ($kJ\ mol^{-1}$)
η_0	optical efficiency
$\eta_{\text{solar-to-chemical}}$	solar-to-chemical energy conversion efficiency
η_{reactor}	reactor efficiency
DNI	direct normal irradiance (W/m^2)
k_0	pre-exponential kinetic factor ($kg\ s^{-1}\ m^{-2}$)
v	reaction rate ($kg\ s^{-1}$)
P_{reaction}	power consumed by chemical reaction (kW)
P_{solarin}	solar power into receiver aperture (kW)
$P_{\text{thermallosses}}$	reactor thermal losses (kW)
R	specific ideal gas constant ($J\ kg^{-1}\ K^{-1}$)
χ	chemical conversion

based on the HFLCAL modeling code (Schwarzbözl et al., 2009), originally developed for solar electricity generation systems. The optimization procedure is applied to two exemplary processes for solar fuels production, namely: the solar thermal reduction of zinc oxide at 2000 K as part of a two-step water-splitting cycle for hydrogen production (Schunk et al., 2009b), and the coal gasification at 1400 K for syngas production (Z'Graggen et al., 2006). The annual efficiency data obtained for the optimized high-flux solar tower systems are compared with those obtained with the conventional low-flux solar tower systems for power levels of 1, 10, and 100 MW. A sensitivity analysis is performed for the heliostat beam quality, tower height, and reactive surfaces.

2. Model description

The calculation of the field performance is briefly sketched here; a more detailed description of the computing code has been previously presented (Schwarzbözl et al., 2009).

2.1. Field performance

The calculation of the annual field performance is based on the hourly performance on the 21st of every month with clear sky conditions. The sunshape is assumed as a circular-normal distribution with the same root-mean-square deviation from the central ray which has been shown to be an appropriate statistical approximation (Pettit et al., 1983). The code considers the changing solar position and accounts for cosine losses, imperfect reflections, atmospheric attenuation, shading and blocking, spillage transmissions losses in the secondary concentrator, and receiver losses. The determination of a specific field layout is depicted in Fig. 1. Starting with a set of hypothetical heliostat positions, the performance of each heliostat is calculated. Afterwards, the set of heliostats is ranked based on the annual energy performance per area of reflective surface to determine the best set of heliostats yielding a given design power. In earlier studies, the performance calculation for a single time point was compared to that obtained with complex ray-tracing software with good agreement (Schmitz et al., 2006). Temporal disturbances are not considered by the present quasi-dynamic approach. As the integration of irradiated solar energy during a typical meteorological year matches the sum of irradiated energy during the time step series, the annual performance estimation can be considered as a theoretical maximum achievable.

2.2. Receiver model

The main fundamental difference between the present optimization applied for solar chemical tower systems using a specified chemical process and that applied for solar power tower systems using a specific heat transfer fluid (e.g. steam, salt, air) is that the chemical reaction rate cannot be controlled independently (e.g. by adjusting the mass flow rates), but strongly depends on the reaction temperature, which in turn is a function of the solar concentration ratio delivered by the heliostat field and the heat/mass transfer within the receiver–reactor.

The receiver–reactor model links the intercepted solar radiation with the specific chemical reaction and computes the reactor efficiency in terms of

$$\eta_{\text{reactor}} = \frac{v(T) \cdot \chi(T) \cdot \Delta H_r(T)}{P_{\text{solarin}}} \tag{1}$$

with χ being the chemical conversion. For the coal gasification case, χ is calculated based on the chemical equilibrium. For the zinc oxide reduction case, χ is set to zero below the boiling point of zinc otherwise to one. The nominal reaction temperature results from the energy balance in the reactor,

$$\eta_0 P_{\text{solarin}} = P_{\text{reaction}}(T) + P_{\text{thermallosses}}(T) \tag{2}$$

where P_{solarin} denotes the solar power input, and the two terms on the right hand side denote the power consumed by the endothermic chemical reaction and the thermal