Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 99 (2014) 299–311

SOLAR ENERGY

www.elsevier.com/locate/solener

Optimization of the optical particle properties for a high temperature solar particle receiver

Freddy Ordóñez [a,*], Cyril Caliot [a], Françoise Bataille [c], Guy Lauriat [b]

[a] Processes, Material and Solar Energy Laboratory, PROMES-CNRS, 7 rue du Four Solaire, 66120 Font-Romeu-Odeillo, France

[b] Université Paris-Est, Laboratoire de Modélisation et Simulation Multi Echelle, MSME UMR 8208 CNRS, 5 Bvd Descartes, 77454 Marne-la-Vallée, France

[c] Florida State University, Department of Mathematics, 1017 Academic Way, Tallahassee, FL, USA

Received 15 July 2013; received in revised form 7 November 2013; accepted 15 November 2013

Communicated by: Associate Editor Michael EPSTEIN

Abstract

A non-homogeneous slab of particle dispersion composed of two-layers at high temperature, submitted to a concentrated and collimated solar radiation flux with a reflective receiver back wall is considered as a model of a solar particle receiver. The Radiative Transfer Equation (RTE) is solved using a two-stream method and an appropriate hybrid modified Eddington-delta function approximation. The single particle optical properties are modeled using the Lorenz–Mie theory, the single particle phase function is approximated by the Henyey–Greenstein phase function. A Particle Swarm Optimization (PSO) algorithm is used to optimize the particle radius ($0.1\ \mu m \leqslant r \leq 100\ \mu m$), the volume fraction ($1 \times 10^{-7} \leqslant f_v \leqslant 1 \times 10^{-4}$) and the refractive index ($2.0 \leqslant n \leq 4.5$ and $0.0001 \leqslant k \leq 25$) of an ideal theoretical material to use in a solar particle receiver. Single- and two-layer receivers with known temperature profiles were optimized to maximize the receiver efficiencies. Spectral selective behavior of the optimized refractive index is discussed with the influence of particle radii and volume fractions. The theoretical ideal optical properties found for the particles have given the maximum efficiency reachable by the studied receivers and have shown that an optimized single-layer receiver will perform as well as a two-layer receiver.

Keywords: Solar particle receiver; Receiver efficiency; High temperature; Optimization; Particle-Swarm algorithm; Two-stream method

1. Introduction

The efficiency of Solar Thermal Power Plants (STPPs) needs to be improved to become competitive in the energy market. This can be achieved by increasing the working temperature of the solar thermodynamic cycle. That means increasing the temperatures at the receiver outlet. Volumetric receivers, and more specifically solar particle receivers (SPRs), are relevant candidates to achieve high temperatures.

Particle receivers driven with solar energy are proposed for the first time by Hunt (1978) and Abdelrahman et al. (1979). They may play an important role in solar electricity production (Romero et al., 2002) or solar chemical reactions such as the solar hydrogen production (Tan and Chen, 2010). Hunt (1978) proposed submicron particles of graphite and vitreous carbon as the best absorber in a particle receiver, but iron and silicon were also suggested as alternative materials. Receiver efficiency above 95% and high attainable temperature (2375 K) were estimated. Following this study, a design and construction of a Small Particle Heat Exchanger Receiver (SPHER) of 30 kW was carried out. Experimental output temperatures of 1023 K were reported (Hunt and Miller, 2010). A numerical study (Crocker and Miller, 2011) of coupled heat and mass transfers, using the Monte Carlo method for radiation (Ruther

* Corresponding author. Tel.: +33 4 6830 7763.
E-mail address: f.ordonez.m@gmail.com (F. Ordóñez).

0038-092X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.solener.2013.11.014

Nomenclature

c_1, c_2	local and global acceleration in the PSO algorithm
f_v	volume fraction
g	asymmetry factor
$\tilde{g}$	single-particle asymmetry factor
I	total intensity (W/m^2 sr)
I_b	blackbody emission intensity (W/m^2 sr)
I_c	collimated intensity (W/m^2 sr)
I_d	diffuse intensity (W/m^2 sr)
k	imaginary part of refractive index
L	receiver depth (m)
m	complex refractive index
n	real part of refractive index
p	scattering phase function
$\tilde{p}$	single-particle scattering phase function
q_0	collimated solar flux (W/m^2)
$q^{\pm}$	forward and backward radiative heat fluxes (W/m^2)
Q_{abs}	single-particle absorption efficiency
Q_{ext}	single-particle extinction efficiency
Q_{sca}	single-particle scattering efficiency
r	particle radius (μm)
r_1, r_2	uniform random number for the PSO algorithm
T_s	temperature into the receiver (K)
T_w	wall temperature (K)
v	velocity in PSO algorithm
w	inertia weight in PSO algorithm
x	parameter size
y	particle position in the PSO algorithm
z	axial coordinate (m)

Greeks

β	volume extinction coefficient (m^{-1})
γ	velocity factor in the PSO algorithm
η	receiver efficiency
κ	volume absorption coefficient (m^{-1})
λ	wavelength (μm)
μ	cosine of the polar angle $\mu = cos\theta$
μ_0	cosine direction of the collimated incident flux
ρ_w	wall reflectivity
σ	volume scattering coefficient (m^{-1})
τ	optical depth
τ_c	cumulative optical depth
χ_0	term for the modified Eddington approximation
ω_0	volume scattering albedo
$\tilde{\omega}_0$	single-particle scattering albedo

and Miller, 2010), was presented for the case of a cylindrical, small particle solar receiver (SPHER receiver). Their theoretical results show that receiver efficiencies greater than 90% may be achieved for an output temperature of 1400 K when carbon particles having a mean radius of 0.2 μm and a mass loading of 0.3 g/m^3 are used in a receiver made with Al_2O_3 walls.

In the same way, Bertocchi et al. (2004) reported an experimental evaluation of a 10 kW solar particle receiver, using sub-micron carbon particles with diameters smaller than 0.6 μm. This receiver was conceived to work under atmospheric pressure but closed with a window to maintain a controlled atmosphere. Temperatures above 2100 K were reported when the working gas was nitrogen, and of 1900 K for CO_2. An efficiency that exceeds 80% was estimated. Klein et al. (2007) developed a refined model for this receiver. Their results suggest that carbon particles with an effective radius smaller than 0.1 μm do not absorb enough energy. A particle radius between 0.1 μm and 1 μm was suggested as the best size for carbon particles. However, the great advantages in terms of selectivity given by small particles may also lead to great inconveniences. Small particles tend to agglomerate because the large surface forces (Hunt, 1978). Moreover, the use of complex and non-friendly environmental methods is required to produce the carbon particles in situ, such as the pyrolysis of hydrocarbons (Kitzmiller and Miller, 2010).

Another kind of particle receiver which was investigated is the free-falling particle receiver: sand refractory particles are falling down freely inside a solar receiver to form a curtain that directly absorbs the concentrated solar radiation. This solar receiver was conceived for solar-driven water-splitting thermo-chemical process to produce hydrogen (Tan and Chen, 2010). Martin and Vitko (1982) gave a first approach for this kind of receiver. Next, Falcone et al. (1985) proposed a design of a particle falling down receiver having a 100 MW thermal power. A simplified model and some possibilities of materials were presented. A more complete feasibility study was presented by Hruby (1986). Special attention was taken to the receiver design and to the particle material selection by Stahl et al. (1986). A two-dimensional model was presented and validated against experiments by Evans et al. (1987). A cavity efficiency of 60% was estimated using alumina based commercial particles of 650 μm for a particle mass flow rate of 4 kg/s. More recently, a detailed three dimensional Computational Fluid Dynamics (CFD) model was used to analyze the increase of performances for such a receiver when no bottom opening exists (Chen et al., 2007). The influence of the wind in the free-falling receiver was extensively studied using modeling and some experimental set-up (Kim et al., 2009; Kim et al., 2010; Tan et al., 2009). The on-sun testing of a prototype of 2 MWth and its optical characterization were conducted by Siegel and Kolb (2008). The receiver efficiency was close to 60% with a particles temperature increment from 900 K to 1200 K. A modification of the original design, called face-down solid particle receiver, was also modeled to increase the receiver