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Modeling of a concentrated-solar, falling-particle receiver for ceria reduction

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Abstract

This paper presents a steady-state model coupling three-dimensional, spectral radiation heat-transfer to a quasi-one-dimensional particle flow model for assessing performance of a directly-irradiated, falling-particle solar receiver with a closed cavity for thermochemical reduction of ceria. A semi-empirical gas-phase flow entrainment model captures the heat and mass exchange between the surrounding gas and the reducing ceria particles. With bulk and surface thermochemistry for the oxide-ion transport and surface reduction kinetics, model results indicate that for particle diameters under 500 μm, surface chemistry controls the rate of ceria reduction in the receiver-reactor. For the range of particle inlet temperatures, flow rates, and diameters studied, the degree of ceria reduction correlates well with particle outlet temperature and increases to as high as 6% at maximum outlet temperatures of 1900 K. However, with the relatively low absorptivity of ceria, higher outlet temperatures lower the fraction of solar energy absorbed by the particles from approximately 30% at outlet temperatures of 1500 K to just above 10% at outlets of 1900 K. Most of the heat recovered in the ceria is due to sensible heating, and re-radiation losses can account for as much as 60–75% of the solar energy input due to the required high reduction temperatures and radiation properties of the ceria particles. The predicted low efficiencies show that ceria particle reduction must utilize significant heat recovery and alternative receiver optics other than simple direct radiation to improve the feasibility of solar-driven ceria redox cycles based on falling particle receivers.

Keywords: Concentrated solar; Particle receiver; Ceria redox; Reactor modeling

1. Introduction

Concentrated solar power (CSP) plants with central tower receivers are attractive renewable energy systems capable of not only making renewable electricity, but also driving chemical processes, such as fuel production from H_2O and/or CO_2, that require high-temperature (>1000 K) heat input. While many developed receiver designs have lower operating temperatures (<1000 K for commercial plants utilizing molten salt), solid-particle receivers have been proposed as an approach for efficiently achieving higher temperatures (Tan and Chen, 2010). These high receiver temperatures drive not only more-efficient power cycles but also endothermic chemical processes, such as for fuel production and/or integrated long-term storage. This paper explores the design of a central tower receiver that captures solar energy in falling cerium oxide ($CeO_{2-\delta}$) particles through both sensible heating and high-temperature oxide reduction. Reduced

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Nomenclature

A	geometric area of a cell face
a	geometric area per particle, m^2
C_D	single particle drag coefficient
C_S	stream coefficient
d	diameter, m
D	species mass diffusivity, $m^2\,s^{-1}$
f_D	diffusion correction factor
$f_{v,p}$	particle volume fraction
f_{λ_m}	fraction of radiant energy in mth λ-bin
F_{i-j}	view factor of cell j for cell i
g	acceleration due to gravity, $m^2\,s^{-1}$
h	specific enthalpy, $J\,kg^{-1}$
h_T	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
j''_{diff}	diffusion flux, $kmol\,m^{-2}\,s^{-1}$
k	reaction rate-constant
k_T	conductivity, $W\,m^{-1}\,K^{-1}$
M	total number of radiation bins
$\dot{n}''$	reaction rate per unit area, $kmol\,m^{-2}\,s^{-1}$
N_p	number density of particles, m^{-3}
Nu	Nusselt number
P	partial pressure, bar
Pr	Prandtl number
$\dot{q}''$	surface heat flux, $W\,m^{-2}$
$\dot{q}'''$	volumetric heat transfer, $W\,m^{-3}$
$\overline{R}$	universal gas constant, $J\,kmol^{-1}\,K^{-1}$
Re	Reynolds number
t	time, s
t_w	receiver wall thickness, m
T	temperature, K
$\bar{u}$	mean directional velocity, $m\,s^{-1}$
v	volume per particle, m^3
$\overline{W}$	molar mass, $kg\,kmol^{-1}$
X	species mole fraction
x, y, z	Cartesian coordinates
Y	species mass fraction

Greek symbols

α	entrainment constant
β	excess parameter
δ	degree of phase reduction
ε_λ	emittance or material emissivity
θ	surface site density
θ_λ	angle of incident ray
λ	wavelength, μm
μ	chemical potential, $J\,kmol^{-1}$
η	energy efficiency
ρ	mass density, $kg\,m^{-3}$
$\bar{\rho}$	molar density, $kmol\,m^{-3}$
ρ_λ	bulk reflectance
σ	Boltzmann's constant, $W\,m^{-2}\,K^{-4}$
σ_k	sticking probability for species k
τ_λ	bulk transmittance
Γ	site density per unit area, $kmol\,m^{-2}$

Subscripts

b	bulk
c	curtain
conv	convective heat transfer
eq	equilibrium
ext	external wall face or conditions
g	gas
i, j	computational cell or face indices
int	internal wall face
k	species index
m	radiation bin index
p	particle
R1, R2	reaction 1, 2
rad	radiation heat transfer
red	reduction reaction
ref	reflected radiation
s	surface
sb	sub-surface
sol	solar irradiation
w	receiver wall
wind	receiver window
λ	wavelength bin

Superscripts

ex	excess properties
0	ideal-state, reference-state

$CeO_{2-\delta}$ particles can be reoxidized in a separate reactor by splitting CO_2 and/or H_2O as part of a solar fuel production plant as proposed in several studies (Abanades et al., 2010; Chueh and Haile, 2010; Lapp et al., 2012; Scheffe and Steinfeld, 2012).

Recent research and development on receivers using direct heating of solid particles have demonstrated the effectiveness of sub-mm-diameter particles to directly absorb incident solar radiation (Siegel et al., 2010; Tan and Chen, 2010). Particle receivers have many advantages for solar energy absorption and storage with operating temperatures well above the limits of molten salts and other storage media. Particle receiver designs can mitigate many thermal stress issues associated with fixed storage media if the particles are transported through a simple, open geometry (Kim et al., 2009; Siegel et al., 2010). Some proposed particle receiver configurations utilize absorption of solar heat in tubular reactors, which encapsulate the particle flow and allow for controlled environments (Maag et al., 2009; Martinek et al., 2012), but these arrangements do not provide the rapid heating of receiver designs with direct particle irradiation. Direct particle irradiation can