Model of an integrated solar thermochemical reactor/reticulated ceramic foam heat exchanger for gas-phase heat recovery

Rohini Bala Chandran, Robert M. De Smith, Jane H. Davidson *

Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN, United States
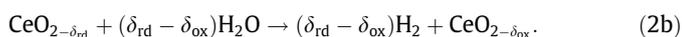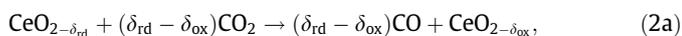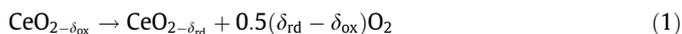
ARTICLE INFO

ABSTRACT

The efficiency of solar thermochemical cycles to split water and carbon dioxide depends in large part on highly effective gas phase heat recovery. To accomplish this goal, we present the design and analysis of the thermal and hydrodynamic performance of a counter-flow, tube-in-tube alumina heat exchanger operating at temperatures of 1500 °C and integrated with a solar thermochemical reactor for isothermal production of syngas via the ceria redox cycle. The heat exchanger tubes are filled with alumina reticulated ceramic to enhance heat transfer. The effects of foam morphology and heat exchanger size on heat transfer, pressure drop, and process solar-to-fuel efficiency are explored by coupling a computational fluid dynamic model of the heat exchanger, including radiative transport, with the overall reactor energy balance. We examine foam pore densities of 10, 20 and 30 PPI, and porosities of 65–90%. The 10 PPI foam yields the best heat transfer performance and lowest pressure drop, as the larger pores enhance radiative heat transfer and decrease fluid phase drag forces. Although lower porosity is preferred to improve solid phase conduction in the RPC, the tradeoff in heat transfer and pressure drop point to use of higher porosity foam. Optimization for solar-to-fuel reactor efficiency is achieved with 85–90% porosity, 10 PPI RPC.

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1. Introduction

Water and carbon dioxide splitting via thermochemical metal oxide reduction/oxidation cycles driven by concentrated solar energy is a promising means of storing solar energy in chemical bonds via the production of hydrogen or synthesis gas (a mixture of H_2 and CO). The products can be used directly in fuel cells or in the case of synthesis gas converted to liquid transportation fuels. In the present work we consider the non-stoichiometric cerium dioxide (ceria) cycle with a focus on the design of an integrated reactor/heat exchanger for gas-phase heat recovery. The ceria redox cycle consists of an endothermic reduction step (Eq. (1)) and an exothermic oxidation step with CO_2 and/or H_2O (Eqs. (2a) and (2b)).

$$CeO_{2-\delta_{ox}} \rightarrow CeO_{2-\delta_{rd}} + 0.5(\delta_{rd} - \delta_{ox})O_2 \quad (1)$$

$$CeO_{2-\delta_{rd}} + (\delta_{rd} - \delta_{ox})CO_2 \rightarrow (\delta_{rd} - \delta_{ox})CO + CeO_{2-\delta_{ox}}, \quad (2a)$$

$$CeO_{2-\delta_{rd}} + (\delta_{rd} - \delta_{ox})H_2O \rightarrow (\delta_{rd} - \delta_{ox})H_2 + CeO_{2-\delta_{ox}}. \quad (2b)$$

Fuel production is related directly to the change in the number of oxygen vacancies, or equivalently non-stoichiometry of ceria, between reduction and oxidation ($\delta_{rd} - \delta_{ox}$). Chemical thermodynamics favors reduction at high temperature (1400–1600 °C) and low O_2 partial pressure, and reoxidation at a lower temperature, typically 800–1100 °C [1,2]. However, this approach creates the need for solid phase heat recovery to achieve high reactor efficiencies [3–5]. Another option is to carry out the process isothermally or with a much smaller swing in temperature between reduction and oxidation (~100–200 °C) [6–9]. Isothermal or "near isothermal" cycling eliminates or decreases the requirement for solid-phase heat recovery of the ceria and simplifies the design of reactor components due to reduced thermal stresses. However, in comparison with the larger temperature swing cycle, isothermal cycling requires a lower oxygen partial pressure during reduction to produce an equivalent amount of fuel. For both cycling options, the overall process solar-to-fuel efficiency is improved dramatically with effective gas phase heat recuperation of any inert sweep gas used to maintain a low O_2 partial pressure during reduction and of the oxidizing gas (H_2O or CO_2) [3–9]. To date, demonstrations of the ceria redox cycle in prototype reactors [10–13] have not included gas phase heat recovery.

The major challenges of designing a gas phase heat recovery system are operation at temperatures as high as 1500 °C in a highly

* Corresponding author. Tel.: +1 612 626 9850.
  E-mail address: jhd@me.umn.edu (J.H. Davidson).

Nomenclature

a_{sf}	specific surface area, m^{-1}
A	area, m^2
C	solar concentration ratio
C_E	Ergun coefficient, m^{-1}
d	diameter, m
F_L	convective loss fraction
G	incident radiation, $W\,m^{-2}$
$\bar{h}$	molar enthalpy, $J\,mol^{-1}$
h	enthalpy, $J\,kg^{-1}$
h_{sf}	interfacial convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
ΔH_r	enthalpy change of CO_2 splitting, $J\,mol^{-1}$
HHV	higher heating value, $J\,mol^{-1}$
I	radiation intensity in Eq. (8), $W\,m^{-2}\,sr^{-1}$
I	direct normal solar irradiance in Eq. (22), $W\,m^{-2}$
I_b	black body radiation, $W\,m^{-2}$
K	permeability, m^2
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
l	length scale, m
L	length, m
m_{CeO_2}	mass of ceria, g
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
$\dot{n}$	molar flow rate, $mol\,s^{-1}$
Nu_{sf}	Nusselt number for interfacial heat transfer
p	pressure, Pa
Pr	Prandtl number
$\mathbf{q}$	heat flux vector, $W\,m^{-2}$
q''	heat flux, $W\,m^{-2}$
q_{solar}	average solar radiation input per unit mass of ceria, $W\,g^{-1}$
Q	power, W
$\bar{R}$	universal gas constant, $J\,mol^{-1}\,K^{-1}$
Re	Reynolds number
r	radial position, m
$\mathbf{r}$	position vector
$\hat{s}$	unit vector
S_m'''	momentum source term, $kg\,m^{-2}\,s^{-2}$
S_q'''	energy source term, $W\,m^{-3}$
t	thickness, m
T	temperature, °C, K
$\mathbf{u}$	velocity vector, $m\,s^{-1}$
U	overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
z	axial position, m

Greek symbols

β	extinction coefficient, m^{-1}
δ	non-stoichiometry
ε	heat recovery effectiveness
η	efficiency
μ	viscosity, $kg\,m^{-1}\,s^{-1}$
γ	heat capacity ratio
Ω	solid angle, sr
ω	scattering albedo
ϕ	porosity
ρ	density, $kg\,m^{-3}$
σ	Stefan–Boltzmann constant, $5.67 \times 10^{-8}\,kg\,s^{-3}\,K^{-4}$
τ	time duration, s
ζ	optical thickness

Subscripts

a	annulus
amb	ambient conditions of pressure (100 kPa) and temperature (25 °C)
b	black body
c	cold
cav	cavity
cond	conduction
comp	compressor
conv	convection
e	electric
eff	effective
f	fluid, fuel, fiber
h	hot
HX	heat exchanger
i	inner tube
in	inlet
iw	inner wall of the inner tube
loss	heat losses
net	net heat flux
pump	pump
out	outlet
ox	oxidation, oxidizer flow
p	pore
rd	reduction
rad	radiation
R	refers to temperature of solar reactor
RE	reactive element
s	solid
sf	solid–fluid
sg	sweep gas
solar	solar energy
th	thermal

Superscripts

′	per unit mass of ceria
–	overbar indicates time averaged/area averaged/bulk mean values

Abbreviations

CFD	computational fluid dynamic
OD	outer diameter
PPI	pores per inch
RPC	reticulate porous ceramic

oxidizing environment and close coupling of the heat exchanger with the solar reactor. The extreme operating temperature and the requirement for chemical compatibility with ceria and the oxidizing gases constrain the choice of materials for construction. While metals provide high thermal conductivity, the long-term service temperatures of even superalloys are no more than 950 °C due to corrosion and the onset of creep [14,15]. Ceramic materials are an excellent alternative because they can withstand temperatures of 1500–2500 °C [14–17]. Heat exchanger designs using ceramic materials have been developed for solar receivers [18], coal or oil fired steam turbines [16] and hydrogen production from sulfuric acid [15,19–21]. The prior work has focused on silicon carbide (SiC) due to its high mechanical strength (tensile strength of 250 MPa at 1500 °C), low coefficient of thermal expansion ($5.5 \times 10^{-6}\,K^{-1}$), and high thermal conductivity ($\sim25\,W\,m^{-1}\,K^{-1}$ at 1500 °C) as compared to other ceramics [16,22]. However, SiC oxidizes at the conditions anticipated in a reactor for reduction and oxidation of ceria [23–25] and has been observed to react vigorously with ceria at high temperatures [26]. In view of these factors, the present study considers the use