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Numerical optimization of catalyst configurations in a solar parabolic trough receiver–reactor with non-uniform heat flux

Zhang-Jing Zheng [a], Yan He [b], Ya-Ling He [a,*], Kun Wang [a]

[a] Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

[b] School of Mechanical and Electrical Engineering, Qingdao University of Science and Technology, Qingdao, Shandong 266061, China

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Abstract

A three-dimensional numerical model of a solar parabolic trough receiver–reactor (SPTRR) with methanol steam reforming reaction was developed. Based on this model, the characteristics of hydrodynamics, heat transfer and chemical reaction of SPTRR were studied. Also, the effects of non-uniform heat flux boundary condition, catalyst layout and mass flow rate on the performances of SPTRR were analyzed. The results showed that SPTRRs partially filled with catalyst have better comprehensive performance than those fully filled with catalyst, and the SPTRR with horizontal cylindrical segment shaped catalyst in the lower part of receiver tube is recommended to substitute the fully catalyst-filled SPTRR. The chemical energy conversion per unit pump power of the proposed partially catalyst-filled SPTRR is one order of magnitude larger than that of the fully catalyst-filled SPTRR, and the mean outer surface temperature and maximum outer surface temperature difference of the proposed partially catalyst-filled SPTRR can be as low as that of the fully catalyst-filled SPTRR, when the mass of the catalyst in the partially catalyst-filled SPTRR is 0.4 times as much as that in the fully catalyst-filled SPTRR.

Keywords: Solar energy utilization; Solar parabolic trough receiver–reactor (SPTRR); Non-uniform heat flux boundary condition; Methanol steam reforming reaction

1. Introduction

Solar thermochemical reactions are one of the primary ways for large-scale utilization of solar energy, and mainly include solar hydrogen, solar chemical heat pump, solar thermal reduction of metal oxides, etc. (Steinfeld, 2005; Wu et al., 2014). The solar thermochemical processes are always combined with solar concentration systems to achieve a high reaction conversion, because the solar concentration systems can provide high-temperature process heat for the endothermic chemical reactions. Currently, there are four main types of solar concentration systems: parabolic trough, linear Fresnel, tower and dish (Zheng et al., 2014). Among the four types of solar concentration systems, the parabolic trough system generally operates at a relatively moderate solar concentration ratio and the working temperature is usually below 500 °C (Agrafiotis et al., 2014). Therefore, the solar parabolic trough technology can be employed for methanol steam reforming reaction whose appropriate temperature ranges from 150 to 300 °C (Hong et al., 2009).

* Corresponding author.
E-mail address: yalinghe@mail.xjtu.edu.cn (Y.-L. He).

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Nomenclature

A_c	flow cross-sectional area (m^2)
c_p	specific heat of the mixture ($J\ kg^{-1}\ K^{-1}$)
C_{si}, C_{sia}	catalyst surface concentration of site types i or ia ($i = 1, 2$), ($mol\ m^{-2}$)
d_p	diameter of the catalyst particle (m)
D	diameter (m)
D_i/D_o	inner/outer diameter of SPTRR (m)
D	mass diffusion coefficient ($m^2\ s^{-1}$)
D_t	effective mass diffusion coefficient due to turbulence
f	friction factor
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h'	height of catalyst (m)
$h_{o,i}$	enthalpy of formation of species i ($J\ mol^{-1}$)
H	dimensionless height of catalyst
I_b	direct normal irradiance ($W\ m^{-2}$)
k_i	rate constant for reaction i ($m^2\ s^{-1}\ mol^{-1}$)
k_p	permeability (m^2)
k	turbulence kinetic energy ($m^2\ s^{-2}$)
K_i	equilibrium constant of reaction i or adsorption coefficient for surface species i
L	length (m)
m_i	mass fraction of species i
M_i	mole fraction of species i
$M_{w,i}$	molecular weight of species i ($kg\ mol^{-1}$)
n_i	molar flow rate ($mol\ s^{-1}$)
N_R	number of reactions
Nu	Nusselt number
p	pressure (Pa)
P_w	pump power (W)
q	heat transfer rate per unit area ($W\ m^{-2}$)
q_m	mass flow rate ($kg\ s^{-1}$)
Q	total heat transfer rate (W)
r_i	rate of reaction i ($mol\ m^{-3}\ s^{-1}$)
Re	Reynolds number
R	universal gas constant ($J\ mol^{-1}\ K^{-1}$)
$R_{i,r}$	rates of creation and destruction of species i in the reaction r ($mol\ m^{-3}\ s^{-1}$)
S_g	surface area of fresh catalyst ($m^2\ kg^{-1}$)
Sc_t	effective turbulent Schmidt number
T	temperature (K)
$\vec{u}$	velocity vector ($m\ s^{-1}$)
u, v, w	x, y, z velocity components ($m\ s^{-1}$)
U	dimensionless axial velocity
x, y, z	Cartesian coordinates (m)

Greek symbols

β	inertial loss coefficient (m^{-1})
δ_{ij}	Kronecker's delta
ε	turbulent energy dissipation rate ($m^2\ s^{-3}$)
ε_p	porosity
η_c	methanol conversion
η_{sc}	chemical energy conversion per unit pump power
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	kinetic viscosity (Pa s)
μ_t	turbulent viscosity (Pa s)
θ	circle angle (deg)
ρ	density ($kg\ m^{-3}$)

subscripts

cat	catalyst
eff	effective
f	fluid
in	inner
m	mean
max	maximum
out	outlet
ref	reference
s	solid
w	wall

The receiver–reactor provides a direct and efficient approach to convert sunlight into chemical energy, because the heat converted from solar radiation can enter the reactor directly and the heat transfer irreversibility can be decreased. However, the concentrated radiation results in non-uniform heat flux distribution on the outer surface of receiver–reactor (Cheng et al., 2013, 2014). The non-uniform temperature distribution caused by the non-uniform heat flux distribution increases the thermal stress and the possibility of degradation of the selective absorbing coating (Boerema et al., 2013; Qiu et al., 2015). Also, the local high temperature can lead to strong local chemical reaction, which raises the control difficulty of receiver–reactor since chemical reaction is sensitive to the temperature change.

Many studies have focused on the performance analysis and improvements of solar parabolic trough receiver (SPTR) without chemical reaction under non-uniform heat flux boundary condition. These studies can be classified into two groups. One is that new models or methods were proposed to accurately predict the performances of SPTR under non-uniform heat flux boundary condition. Eck and Steinmann (2005) developed a three-dimensional model of SPTR with non-uniform solar heat distribution by finite element method (FEM). The circumferential non-uniform temperature distribution of receiver tube was studied to find out the hotspot. Cheng et al. (2012a) and He et al. (2011) studied the SPTR by combining the Monte Carlo ray trace method (MCRTM) and the finite volume method (FVM). The MCRTM was employed to precisely describe the non-uniform solar heat distribution. Wu et al. (2014a, 2014b) also numerically studied the SPTR by combining MCRT and FVM/FEM. The structural