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Thermal performance analysis of porous medium solar receiver with quartz window to minimize heat flux gradient

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Abstract

Exposure under concentrated solar radiation increases the temperature of volumetric receiver which can cause high thermal stress and damage the receiver. The Plano-convex quartz window is introduced with the aim to minimize heat flux gradient of porous medium receiver. Thermal performance of porous medium receiver with quartz window is numerically studied while the fluid inlet is located at the side wall which would be more practicable. The Monte Carlo ray tracing (MCRT) method is used to calculate the radiative heat transfer in the solar collector system with quartz window, and the local thermal non-equilibrium (LTNE) model with the consideration of radiative heat transfer in the porous medium receiver is used to calculate the fluid phase and solid phase temperature distribution of the porous medium receiver. The numerical results indicated that the pressure distribution and temperature distribution for the condition of fluid inlet located at the side wall is different from that for the condition of fluid inlet located at the front surface.

Keywords: Volumetric receiver; Porous medium; Radiative transfer; Local thermal non-equilibrium; Quartz window; Thermal performance

1. Introduction

The comprehensive utilization of solar radiation, effective conversion of solar radiation to heat and chemical energy is a subject of primary technological interest (Segal and Epstein, 2000; Jin et al., 2010). All of these routes utilize concentrated solar radiation as the energy source of high temperature process heat (Pitz-Pall et al., 1997; Hunter and Guo, 2014). The combinations of high speed fluid flow and elevated temperature encountered in concentrated solar utilization have established porous medium receiver as the primary choice (David et al., 2011). Porous medium has the advantages of high fluid–solid contact surface, low pressure drop with good heat and mass transfer performance, high anti-oxygenic properties, excellent thermal shock resistance and mechanical strength (Fend et al., 2004; Bai, 2011).

Silicon carbide (SiC) porous medium demonstrates superior thermo-mechanical performance and can be coated with catalyst layer for thermochemical reaction. Due to its naturally black color and high conductivity, the porous medium receiver or reactor made of SiC enables the high performance of concentrated solar radiation collection (Fend et al., 2004). With the advantage of high efficiency and low cost, volumetric porous medium receiver had been put forth through the SOLAIR project to promote its installation in the next generation European solar

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Nomenclature

c_p	specific heat, J/(kg K)
d_p	particle diameter, mm
E_{sun}	solar irradiance, W/m^2
h_v	volumetric heat transfer coefficient, W/(m^3 K)
k_α	absorption coefficient
k_e	extinction coefficient
k_s	scattering coefficient
n	Refractivity
p	pressure, pa
R	radius, m
R_r	random number
Re_d	Reynolds number
T	temperature, K
u	velocity in x direction, m/s
v	velocity in y direction, m/s
x	coordinates in x region, m
y	coordinates in$y$ region, m

Greek symbols

ρ	density, kg/m^3; reflectivity
ϕ	porosity
α	absorptivity
μ	dynamic viscosity, kg/(m s)
α_{sf}	surface area per unit volume, 1/m
λ	conductivity, W/(m K)
ε	emissivity
σ	Stefan–Boltzmann constant
ω	albedo coefficient
τ	transmissivity
ξ	characteristic parameter

Subscripts

e	effective
f	fluid phase
r	radiative heat transfer
s	solid phase
w	wall

thermal power plant (STPP) (Fend et al., 2004). Besides, the porous medium solar thermochemical reactor coated with catalyst was adopted for thermochemical reaction by both the CNRS-PROMES laboratory (Villafán-Vidales et al., 2011) and CETRH/CPERI laboratory (Agrafiotis et al., 2007).

Many numerical researches of porous medium receiver under concentrated solar radiation have been conducted, and the numerical studies can be useful for porous medium receiver design and operation improvement. The steady state heat and mass transfer characteristics of porous medium receiver for the tower type STPP were numerically investigated by Xu et al. (2011), and the fluid entrance surface was subjected to a uniform solar radiation during the numerical simulation. The MCRT and Finite Volume Method (FVM) coupling method was developed by Wang et al. (2013, 2014) to research the thermal performance of porous medium solar receiver, and the MCRT method was used to calculate the concentrated solar radiation distribution on the fluid entrance surface. Villafán-Vidales et al. (2011) had investigated the temperature distribution of porous medium solar thermochemical reactor under Gaussian heat flux distribution, and the fluid entrance surface was irradiated by concentrated solar radiation during the numerical simulations. A coupled numerical model for volumetric porous medium receiver was developed by Wu et al. (2011), and several cases of heat flux distribution change on the fluid entrance surface were conducted. Wang et al. (2014) had developed a heat and mass transfer model coupled with radiative heat transfer and thermochemical reaction kinetics for the volumetric porous medium solar thermochemical reactor, and the fluid inlet surface under Gaussian heat flux distribution was adopted to study the thermal performance and hydrogen production performance.

Fig. 1 shows the volumetric solar receiver designed and manufactured by ETH Zurich (Chueh et al., 2010) and German Aerospace Center (DLR) respectively (Röger et al., 2006). As seen from this figure, a quartz window with high transmissivity was assembled on the front surface of volumetric solar receiver or reactor with the aim to decrease heat losses, maintain operating pressure (above or below atmospheric) and isolate the receiver from the ambient to prevent undesired reactions (Cui et al., 2013). According to the literature survey, it can be seen that most pervious numerical analyses of volumetric porous medium receiver or thermochemical reactor were conducted with fluid entrance located on the front surface of volumetric porous medium receiver.

Exposure under concentrated solar radiation increases the temperature of volumetric receiver or thermochemical reactor up to 1500 K or even higher (Fend et al., 2004). The highly non-uniform heat flux distribution across the solar receiver during operation induces thermal stress which can cause the mechanical failure of solar receiver (Khanna et al., 2014). Therefore, an operational design that can minimize the development of thermal stress is very essential.

In this study, thermal performance of porous medium receiver with quartz window is numerically studied and