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Conjugate radiation-convection-conduction simulation of volumetric solar receivers with cut-back inlets

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ABSTRACT

This study analyzes the effect of cut-back inlets on the conjugate heat transfer of honeycomb-channel solar receivers. Two-way coupling simulations are reported for a plane-surface inlet, and five kinds of cut-back inlet receivers. The receivers are based on a 1.9-mm × 1.9-mm square cell with a 1.0-mm wall thickness. The cut-back inlet receivers have different amounts of material removed from the walls at the channel inlets. Numerical simulations demonstrate that receivers with a 2.4-mm cut from the channel inlet increased the exit temperature by 20.0 K or more, and decreased the pressure drop relative to the plane-surface receiver. Therefore, the results indicate that the cut-back inlet receiver's thermal, and hydrodynamic performance is better for industrial use than is the plane-surface receiver. This performance is then explained with detailed examinations of the individual heat-transfer processes in the model. These detailed comparisons indicate that the top cuts reduce shadow effects as light irradiates the channel walls, allowing more direct irradiation to reach the wall surface, thus improving the overall performance.

1. Introduction

This paper analyzes the conjugate heat transfer of honeycomb solar receivers with cut-back inlets for optimization of the geometry of receiver channels. Conjugate radiation-convection-conduction heat-transfer problems have been studied in solar receivers (Cagnoli et al., 2017; Capuano et al., 2016; , 2017; Chen et al., 2016; Du et al., 2017; Gomez-Garcia et al., 2014; Kasaeian et al., 2017; Lee et al., 2012; Zhu and Xuan, 2017). Concentrated solar light from the reflectors is independent of the flow and temperature fields around, and within the receiver. However, the thermal radiation emitted from the receiver is proportional to the fourth power of the temperature, and this causes radiation to be interrelated with convection and conduction. Therefore, numerical simulation is required to model the interactions between the three interconnected mechanisms of heat transfer in a solar receiver. The numerical methodology adopted in this study considers the full range of interactions between radiation, convection, and conduction using the discrete ordinates (DO) method. Generally, numerical simulations of solar receivers have been using the P1 or surface-to-surface radiation models that are coupled with Monte Carlo ray tracing (MCRT) (Kim et al., 2015; Teng and Xuan, 2018). The P1 radiation model simplifies the radiative heat transfer in the receiver so that its computational load is relatively low (Chen et al., 2017). However, the model is not suitable for computing incident radiation. The surface-to-surface radiation model, likewise, are not suitable for analysis of incident radiation. This method have been coupled with a ray tracing model for such applications (Daabo et al., 2017). MCRT can precisely compute incident radiation; however computational load becomes huge for sequential calculations when MCRT is combined with convection and conduction solvers.

The present study coupled with DO radiation model with convection and conduction solvers. The DO model directly computes the radiation incident to the receiver (Moghimi et al., 2015). This radiation model solves the field equation for radiation intensity of each discrete ordinates (DO). The DO solver is compatible with convection and conduction solver, since the numerical procedure is similar between three approaches.

Conjugate problems are encountered in industrial applications such as; laser cladding for metal powder (Janicki, 2017), thermal damage caused by laser operation in human tissue (Liu and Wang, 2014), catalytic combustion (de Lemos and Coutinho, 2017; Pramanik and Ravikrishna, 2017), pulverized fuel combustion (Yin, 2015), and

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Nomenclature

a	absorption coefficient, [–]
C_f	skin friction coefficient, [–]
c_p	specific heat at constant pressure, [J/kg K]
G	incident radiation, [W/m^2]
g	gravitational acceleration, [m/s^2]
I	radiation intensity, [W/m^2·sr]
$\dot{m}$	air-mass flow rate, [g/s]
N_θ	number of theta division for DO model, [–]
N_φ	number of phi division for DO model, [–]
n	refractive index, [–]
$\vec{n}$	normal vector, [–]
p	pressure, [Pa]
q	wall heat-flux, [W/m^2]
q_{cond}	conduction heat-flux, [W/m^2]
q_{conv}	convection heat-flux, [W/m^2]
q_{in}	incident radiation to the wall, [W/m^2]
q_{out}	net radiation emitted from the wall surface, [W/m^2]
q_r	radiative heat-flux, [W/m^2]
q_{rad}	wall radiative heat-flux, [W/m^2]
$\vec{r}$	position vector, [–]
S	source term for continuity (=2936), [kg/m^3 s]
$\vec{s}$	direction vector, [–]
$\vec{s}'$	scattering direction vector, [–]
T	temperature, [K]
T_w	wall temperature, [K]
u, v, w	velocity components in Cartesian coordinates, [m/s]
v_{ref}	reference velocity (=1), [m/s]
x, y, z	Cartesian coordinates, [m]
α	beam angle, [rad]
ε_w	wall emissivity, [–]
θ	polar angle to denote the direction of the radiation intensity, [rad]
λ	thermal conductivity, [W/m K]
μ	dynamic viscosity, [Pa s]
ρ	density, [kg/m^3]
ρ_{ref}	reference density (=1.225), [kg/m^3]
σ	Stefan–Boltzmann coefficient (=5.669 × 10^{-8}), [W/m^2 K^4]
σ_{sca}	scattering coefficient, [–]
τ_w	wall shear stress, [Pa]
Φ	scattering phase function, [1/sr]
φ	azimuthal angle to denote the direction of the radiation intensity, [rad]
Ω, Ω'	solid angle, [sr]

Subscripts

f	fluid region
s	solid region

intermediate heat exchangers in fast reactors (Zhang et al., 2017). Therefore, the presently proposed two-way coupling simulation methods may be useful in a range of applications in which all three heat-transfer mechanisms are relevant.

In concentrated solar power plants, various types of volumetric solar receivers have been developed to absorb concentrated radiation, typically over 1000 kW/m^2, using porous or honeycomb structures (Ávila-Marín, 2011). Gomez-Garcia et al. (2014) analyzed the optical properties of volumetric receivers with different-size channels using MCRT. Cagnoli et al. (2017) investigated the optical effects of the tilt angle of the receiver channel with MCRT and the surface-to-surface radiation model. Capuano et al. (2016) coupled MCRT model with three-dimensional convection and conduction heat-transfer modes to investigate the thermal performance of receivers, and Capuano et al. (2017) optimized the channel geometry in tests with a 3:1 scale demonstrator. Chen et al. (2016) developed a porous receiver model by using MCRT for incident rays and the P1 radiation model for internal heat transfer to analyze the effects of the tilt angle of a dish-type concentrator. Kasaeian et al. (2017) studied the heat-transfer performance of multi-channel absorbers with square, triangular, hexagonal, and circular structures. Fleming et al. (2017) analyzed the thermal performance of multi-cavity receivers with CFD coupled with MCRT. Zhu and Xuan (2017) simulated incident rays using MCRT for packed-bed volumetric solar receivers with simple cubic, body-centered cubic, and face-centered cubic unit cells to investigate effect of different pore structures on receiver performance. Du et al. (2017) took X-ray computed tomography images of a porous structure to implement its 3D structure in a CFD model of conjugate heat transfer. Lee et al. (2012) simulated the concentrated radiation in a receiver channel using MCRT and solved a one-dimensional heat transfer model to evaluate the results.

In spite of these efforts, the conjugate heat-transfer problems involved in volumetric receivers have not been sufficiently understood to elucidate the complex interactions between heat-transfer mechanisms. The literature indicates that most studies have mainly focused on ray tracing models, simplifying the mechanism of re-radiation from heated surfaces in the receivers while ignoring the influence of air flow at the inlet. To address these shortcomings, this study develops a numerical model that couples the conduction, convection, and radiation heat-transfer processes as well as including the air flow to the receiver inlet. Fig. 1 shows a schematic of the system investigated in this study. As shown in the figure, concentrated radiation irradiates the porous channels. The air flow extracts heat from the channel walls and flows toward the bottom of the receiver. The DO radiation model is used to solve the incident radiation, reflection, and re-radiation heat-transfer mechanisms.

This study considers the effect of the channel inlet geometry on receiver performance. In order to improve the thermal performance, this paper examines complex channel receivers made by metal material

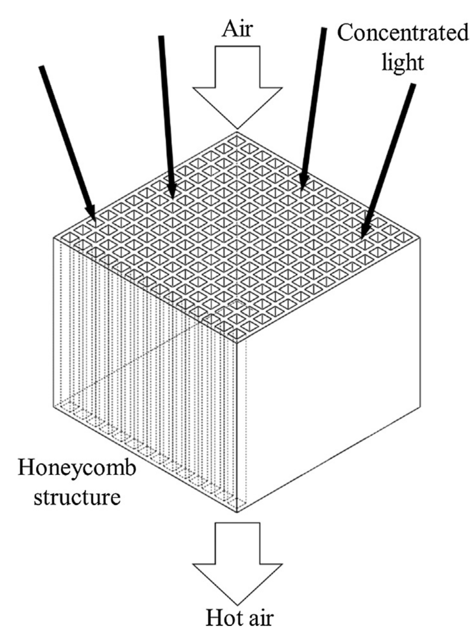

Fig. 1. Conjugate convection-conduction-radiation heat transfer problem for honeycomb structure.