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Effect of directional dependency of wall reflectivity and incident concentrated solar flux on the efficiency of a cavity solar receiver

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Abstract

Managing the optical properties of a cavity solar receiver to create spectral and directional selectivities is a solution to improve receiver efficiencies. A reduction in the incident solar power lost by reflection and by emission in a solar receiver allows the absorption of the solar flux to be maximized. This report investigates the influence of the cavity walls directional reflectivity on the thermal radiative efficiency of a cubic cavity solar receiver. A Monte Carlo ray-tracing method is used to calculate the power lost by reflections and by emission with respect to the incident radiation angular distribution and the bidirectional reflectance distribution function of the cavity walls. To study the influence of the directional dependency of the incident flux on the radiative efficiency, four patterns are considered: collimated, diffuse, focused, and Themis incidences. The directional-hemispherical reflectivity for the bottom wall (face to aperture) and lateral walls are distinguished. For diffuse walls, the absorption efficiency is primarily affected by the lateral walls reflectivity because of the back reflection losses. For specular walls, the driving parameter is the bottom wall reflectivity. In addition, the radiative efficiency with thermal emission was studied for the Themis configuration and a slightly weakest dependency of the efficiency on the lateral walls reflectivity was found.

Keywords: Solar cavity efficiency; Reflection and thermal emission radiative losses; Directional selectivity and specular and diffuse reflectivity; Monte Carlo ray tracing

1. Introduction

Concentrated solar power (CSP) technology is an alternative for renewable thermal energy generation. A CSP system is a promising solution for converting solar flux into thermal energy for industrial heat delivery, electricity generation, solar chemistry or seawater desalination. However, the optimization of the solar flux conversion into heat in the receiver is the key step that governs the system thermal efficiency and the cost. Concentrated solar power facilities use a set of mirrors to concentrate the solar flux onto a receiver to heat a Heat Transfer Fluid (HTF) to high temperatures. Concentrating technologies are subdivided into line-focusing systems, such as linear Fresnel and parabolic trough collectors, and point-focusing systems, such as solar tower and dishes, which enable higher concentration ratios. For a solar thermoelectricity plant, the thermal energy of the HTF is then converted into electricity by a turbine. The Solar Tower Technology (STT, also called central receiver concentrating solar technology) is considered one of the most promising solution for high efficiency thermodynamic

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Nomenclature

a_d	diffuse ratio
d	standard dispersion
I	total radiative intensity, W/m^2 sr
f	bidirectional reflectance distribution function
H	test function
n	unit normal vector
$\widetilde{M}$	Monte Carlo estimate
N	number of ray bundles
N_R	number of reflections
P	power, W
$\vec{r}$	position vector
R	recursive term
S	surface, m^2
T	temperature, K
W	Monte Carlo weight

Greek symbols

α	absorptivity
δ	delta function
ε	emissivity
η	efficiency
θ	polar angle in spherical coordinates, degree
λ	wavelength, μm
ρ	reflectivity
σ	normalized rms roughness, μm
σ_{SB}	Stefan-Boltzmann constant, W/m^2 K^4
φ	azimuth angle in spherical coordinates, degree
ω	unit vector for a given direction
Ω	solid angle, sr

Subscripts

A	absorption
a	cavity aperture
b	bottom wall
c	cavity
d	diffuse
E	thermal emission
e	effective
I	incident
i	index
j	index
k	index
l	lateral wall
m	middle of the aperture
op	opening
pdf	probability density function
R	reflection
S	specular
$them$	Themis
0	starting point or direction

conversion of solar energy because of the capability to reach high temperature (up to 1000 °C) and thus high efficiency of the power conversion system (Behar et al., 2013) by using combined cycles. For STT, several receiver designs have been developed: flat, segmented, external cylindrical, volumetric and cavity absorbers (Ho and Iverson, 2014). The primary advantages of solar cavity receivers are (1) the effective absorption of solar radiation due to the *cavity effect* (i.e., internal multiple reflections), (2) low requirements in mechanical strengths for the wall materials because of limited temperature gradients, and (3) the possibility to vary the HTF as a function of the expected working temperature (although it is not specific to the cavity-type receiver). Compared to external-type receivers, the cavity-type receivers are generally expected to have a lower radiation heat loss and higher convective heat loss than that for external receivers (Ho and Iverson, 2014).

The global efficiency of a central receiver solar facility depends on the optical efficiency of the heliostats field, the thermal efficiency of the solar receiver, and the thermodynamic cycle efficiency. The receiver efficiency is a function of the receiver geometry (shape), the optical properties (spectral and directional) and the temperatures of the walls. From a thermodynamic perspective and based on the Carnot principle, one of the solutions to maximize global efficiency is to operate at the highest possible temperature. As a result, the radiation losses of the cavity receiver increase significantly due to the thermal emission of the walls which are proportional to the temperature raised to the fourth power. Consequently, a tradeoff exists and is defined by an optimum receiver temperature that leads to a maximum global efficiency. The reduction of these thermal losses will result in an increase of the tradeoff temperature and of the global efficiency.

This study focuses on the thermal radiative losses of a cavity receiver, neglecting conduction and convection losses to the environment. The radiative efficiency of a cavity receiver η_R depends on the effective solar absorbance α_e, the effective thermal emittance ε_e, the surface area of the cavity aperture S_a, the wall temperature T (assumed constant in the cavity for simplicity) and the incident power intercepted by the cavity P_I (Steinfeld and Schubnell, 1993) and can be given as follows:

$$\eta_R = \frac{\alpha_e P_I - \varepsilon_e S_a \sigma_{SB} T^4}{P_I} \quad (1)$$

For flat, segmented or external cylindrical receivers, both reflected and emitted radiations are lost. However, for a cavity solar receiver the multiple reflections of the concentrated solar flux will result in an increase of the effective absorptivity (cavity effect) and a reduced aperture size will decrease the view factor from the hot wall towards the