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The promise and challenge of solar volumetric absorbers

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Abstract

This study investigates the potential performance of volumetric absorbers as a function of geometric and material properties, aiming to identify the best absorber design parameters and the highest efficiency that may be expected. A simplified one-dimensional model was used to represent a planar slab of ceramic foam absorber, with local thermal non-equilibrium and effective volumetric properties. Three approaches for modeling the radiative transfer were considered, and the S_4 discrete ordinates model was selected based on validation against a detailed Monte-Carlo simulation. The boundary conditions were investigated in detail. This model is simple enough for fast computation and parametric study, yet reasonably realistic to represent real absorbers. The results reveal several guidelines to improve the absorber performance. Optimization of geometry (porosity and characteristic pore diameter) is insufficient to reach high efficiency. A significant increase in convection heat transfer is required, beyond the normal behavior of ceramic foams. A reduction in the thermal conductivity of the absorber material is also needed to maintain the desired temperature distribution. Finally, spectral selectivity of the absorber material can also help to further increase the absorber efficiency, in contrast to the common opinion that it is effective only at low temperatures. With a combination of these measures, absorber efficiencies may be increased for example from around 70% to 90% for air heating to 1000 °C under incident flux of 800 kW/m^2.

Keywords: Solar receiver; Volumetric effect; Porous medium

1. Introduction

Electricity generation from solar energy by thermo-mechanical conversion is currently limited in worldwide implementation. A major reason is the relatively low conversion efficiency (typically 15–18% annual average), which contributes to the high cost of the produced electricity, 2–3 times higher than electricity produced from conventional fossil fuels (Pitz-Paal et al., 2012). This level of performance and cost is achieved today in solar thermal power plant technologies (parabolic trough and power tower) that are based on steam cycles at moderate temperatures of 400–550 °C. The solar dish-Stirling technology is capable of achieving much higher efficiency, but it has not been able so far to demonstrate the reliability and cost that would make it a serious contender, and it is considered a niche solution for small distributed generation plants. A breakthrough in the competitiveness of utility-scale solar thermal electricity may occur if the conversion efficiency from sunlight to electricity can be significantly increased. An important candidate to achieve high conversion efficiency is solar heating of air for high-temperature Combined Cycles (gas and steam turbines operating in series).

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Nomenclature

C	empirical constant in Eq. (4)
C_p	specific heat (J kg^{-1} K^{-1})
d	typical pore size (m), $d = 1/PPC$
d_m	typical passage size, $d_m = \sqrt{4\phi/\pi}/PPC$
e_b	blackbody emissive power (W m^{-2})
F	blackbody fraction function
$\overline{F}$	complimentary blackbody fraction, $\overline{F}(\lambda) = 1 - F(\lambda)$
G	incident radiation (W m^{-2})
h_v	volumetric convection coefficient (W m^{-3} K^{-1})
i	radiation intensity (W m^{-2} sr^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	absorber thickness (m)
$\dot{m}$	mass flow rate per unit area (kg s^{-1} m^{-2})
Nu_v	volumetric Nusselt number ($=h_{vre}d^2k_f^{-1}$)
p	pressure (Pa)
PPC	pores per cm
q	heat flux (W m^{-2})
q_R	radiative heat flux (W m^{-2})
Re	Reynolds number ($=\dot{m}\,d\mu^{-1}$)
T	temperature (K)
u	velocity (m s^{-1})
w	quadrature weight
w'	summed quadrature weight

Greek

α	surface absorptance and emittance (–)
α_v	volumetric absorption coefficient (m^{-1})
β	extinction coefficient (m^{-1})
λ_c	cutoff wavelength (μm)
η	efficiency (–)
μ	viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
σ_v	volumetric scattering coefficient (m^{-1})
ϕ	porosity (–)
Φ	scattering phase function (–)
Ω	Albedo ($=\sigma_v\beta^{-1}$)

Subscripts

a	aperture
b	back
ex	exit
ext	external
f	fluid
in	inlet
s	solid
v	volumetric
LW	long wave spectral band, $\lambda > \lambda_c$
SW	short wave spectral band, $\lambda < \lambda_c$

Conventional Combined Cycles can reach high conversion efficiency of around 60% from heat to electricity, that would correspond to overall solar to electricity conversion efficiency of 25–30% (Kribus et al., 1998). A Combined Cycle requires heating compressed air to temperatures above 1000 °C. Providing solar heat at these temperatures faces significant challenges, including materials for high temperature, optimization of radiative and convective heat transfer in the receiver, optics for high concentration, and adapting gas turbines for solar or hybrid operation. Some major advances were achieved at the lab level for high-temperature receivers, for example heating air at 20 bar to 1200 °C (Kribus et al., 2001). However, most of the R&D work done in recent years focused on lower-temperature versions of air-heating receivers, intended for indirect steam generation with air at temperature of around 700 °C (Hoffschmidt et al., 2003), or for simple cycle gas turbine plants with solar air preheating to about 800 °C (Schwarzbözl et al., 2006). These lower temperature applications can be viewed as intermediate steps in the long-term vision, not yet reaching the highest possible efficiency, but providing valuable experience with solar air heating technologies.

A key component in the solar thermal conversion process is the radiation absorber located at the focus of the concentrator field. For high temperature, a porous volumetric absorber should provide higher efficiency compared to a tubular receiver, due to the so-called "volumetric effect" (Ávila-Marín, 2011). This effect is defined as the existence of low absorber temperature at the front side of the absorber, such that the loss due to emission of radiation to the environment is reduced. The volumetric effect is expected due to the convective cooling of the front of the absorber by the incoming cold air. However, volumetric absorbers tested to date do not show the expected effect: they produce high temperature at the front face and their efficiency is usually around 70%, even for air temperature well below 1000 °C. For example the TSA receiver used a wire-knit volumetric absorber, with reported air exit temperatures up to 780 °C and efficiency around 70% (Tyner et al., 1996). The ceramic grid HITREC absorber reported efficiency around 76% at 700 °C, and 72% at 800 °C (Hoffschmidt et al., 2003). The low efficiency is related to the high temperatures found at the absorber front surface, similar to or even higher than the air outlet temperature (Hoffschmidt et al., 2003; Fend et al., 2004), indicating that the 'volumetric effect' was not achieved. This has also been confirmed in detailed simulations of volumetric absorbers (Wu et al., 2011), as shown in Fig. 1. Higher efficiency in the range 80–90% at air exit temperature of >1100 °C were reported (Kribus et al., 2001) but this was under very high incident radiation flux of several thousand suns, which is impractical for commercial-scale central receiver plants. High efficiency was also reported with a high-temperature